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Satellite-based snowfall detection and estimation: challenges and future perspectives within H SAF

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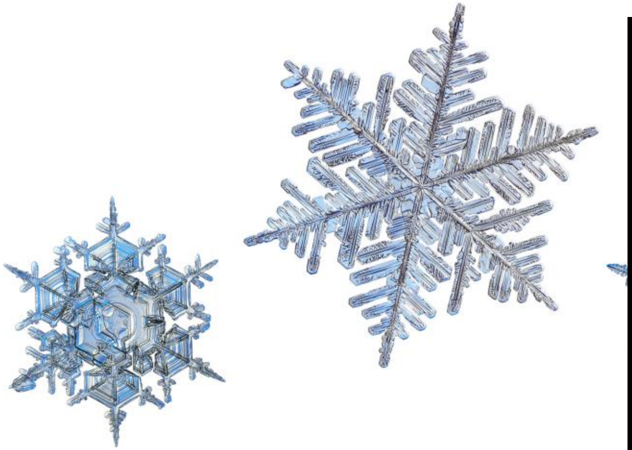
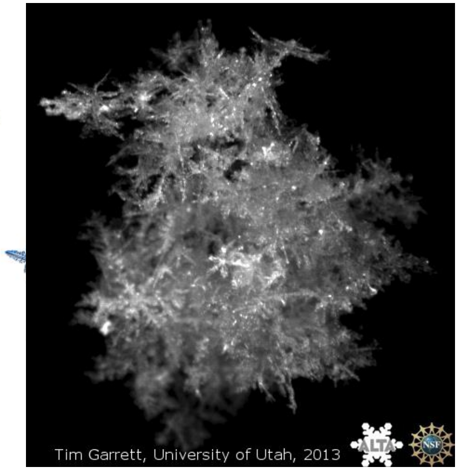
Outline

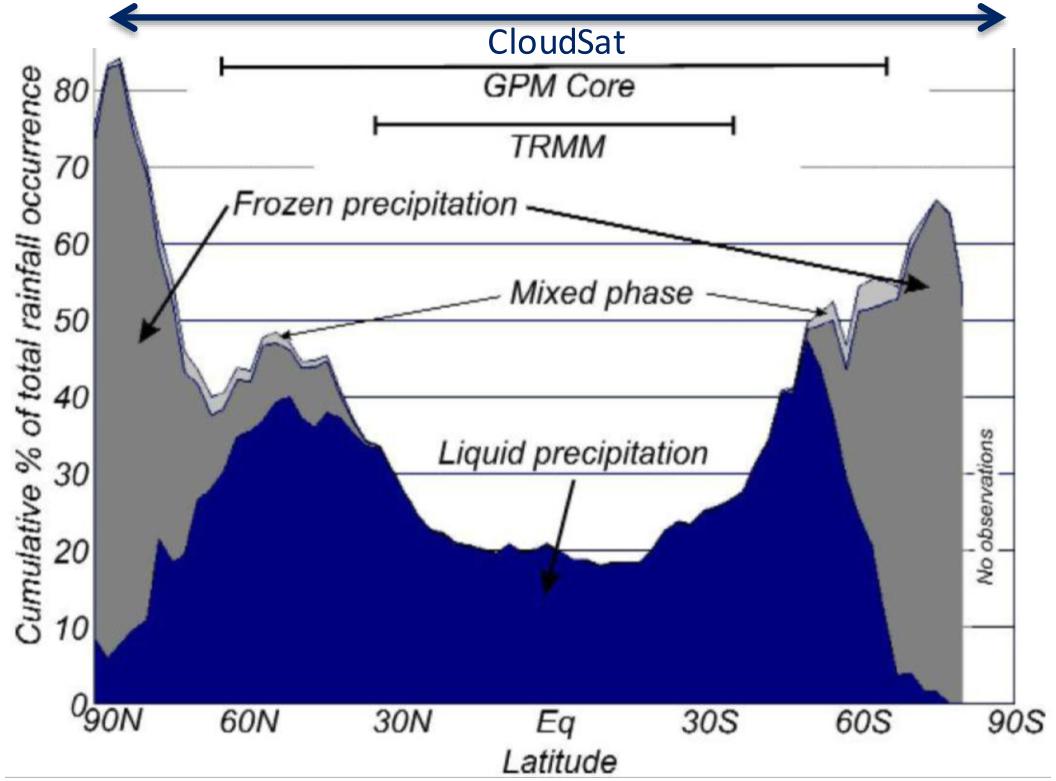
- Challenges in satellite-based snowfall quantification
- Recent advancements in satellite-based snowfall quantification and global monitoring
- H SAF strategies for snowfall detection and quantification (focus on higher latitudes)





Snowfall: Why is it important?

- Snow plays an important role in the Earth energy exchange processes, and is a fundamental element of the water cycle
- The use of satellites for snowfall monitoring and quantification and for retrieving snow cover properties and variability is necessary to globally quantify water resources
- Growing interest in the hydrological scientific community and operational services in global snowfall quantitative estimation
- Satellite-based snowfall detection and surface snowfall rate estimation is one of the main challenges in precipitation retrieval from space

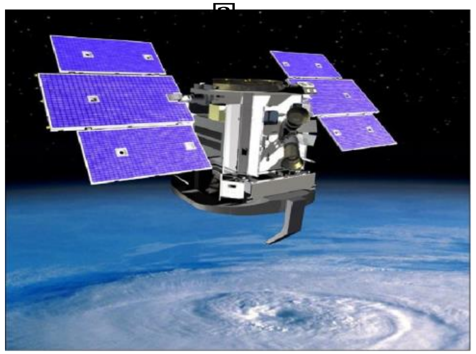


Zonal occurrence of oceanic light precipitation (1958-1991) (adapted from Levizzani et al., 2011)

Golden age for spaceborne radars: GPM-DPR and CloudSat CPR

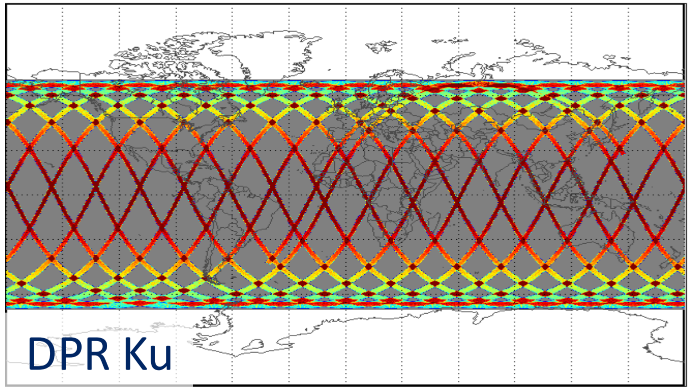
GPM-CO

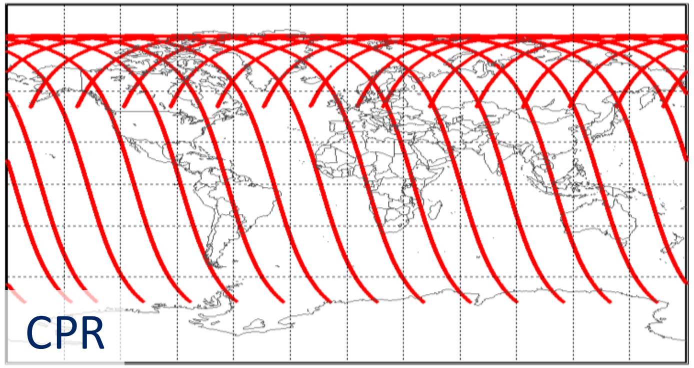
CloudSat



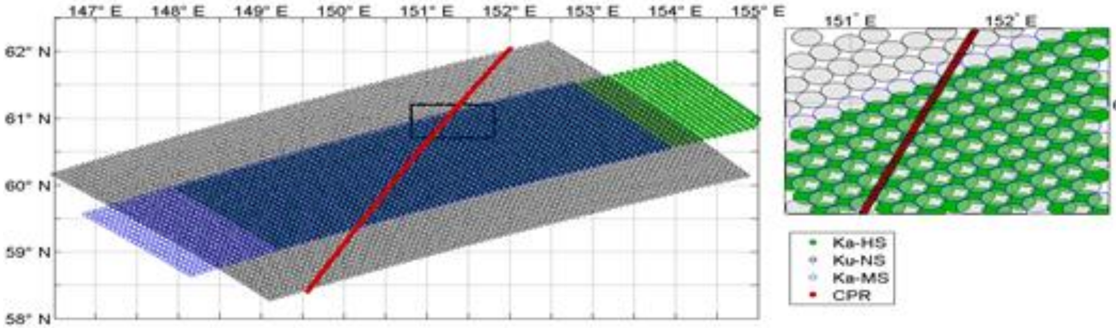
	GPM DPR Ku	GPM DPR Ka	CloudSat CPR W
Frequency	13.6 GHz	35.55 GHz	94.05 GHz
Sensitivity	12-13 dBZ	16.32 dBZ	-28 dBZ
Swath size	245 km	125 km*	1.5 km
Horizontal Resolution	5 km		1.5 km

CloudSat CPR: available since 2006 (day-only mode since 2011)
DPR: available since 2014
EarthCare CPR: Launch date 2021





CloudSat-DPR coincidence segment



Spaceborne radar reduced swath and scarce temporal sampling do not provide the needed coverage for snowfall global monitoring

Golden age for spaceborne radars: GPM-DPR and CloudSat CPR

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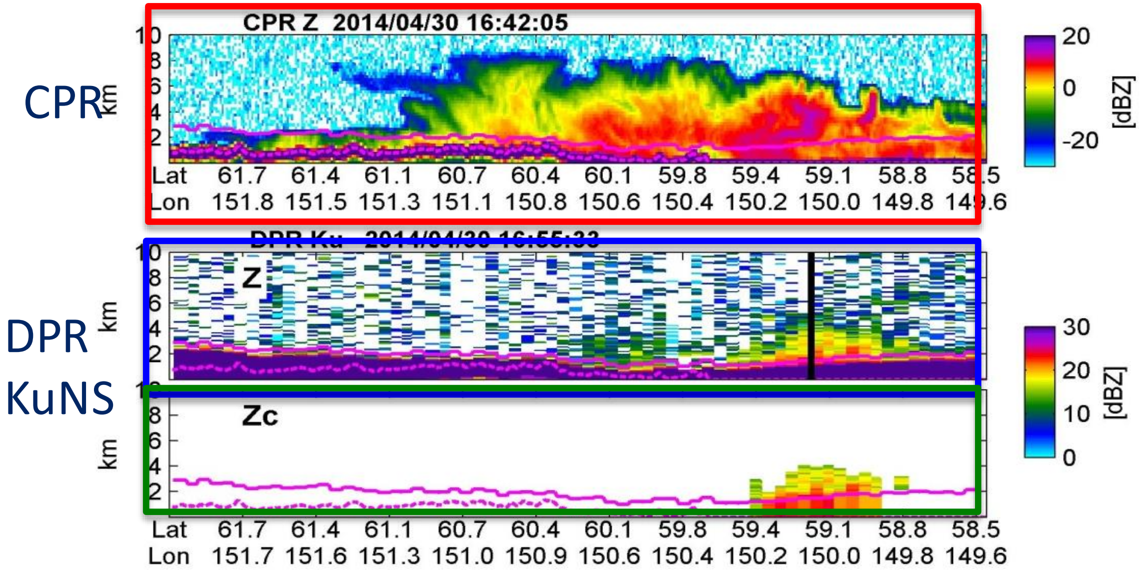
Frontal snowfall event- Eastern Siberia 30 April 2014



CPR Reflectivity factor Z

DPR Measured Reflectivity (Z)

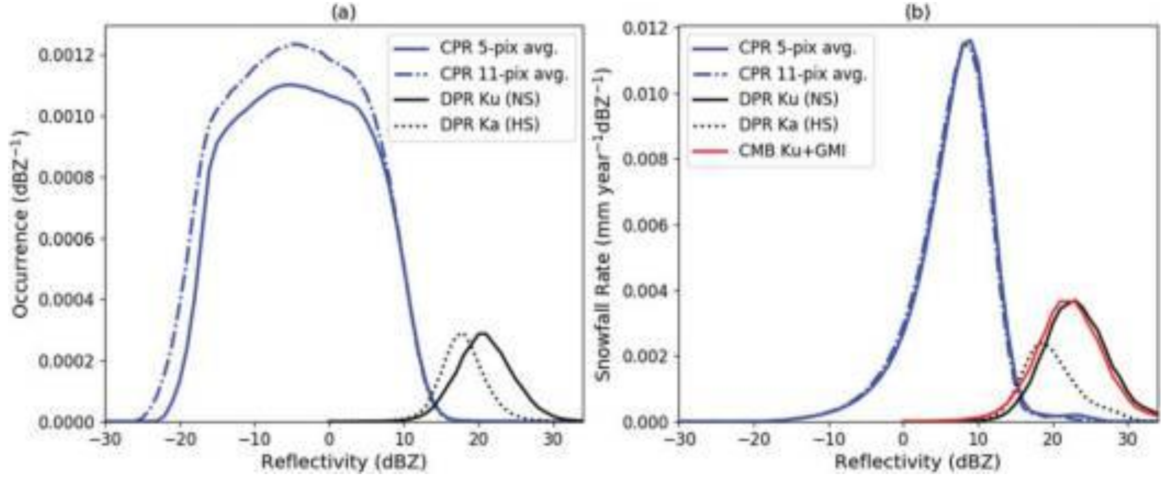
DPR Corrected Reflectivity (Zc)

CloudSat CPR (*and EarthCARE*) offer greater sensitivity to snowfall (and latitudinal coverage 82°N-S), but higher rates are underestimated (attenuation)

DPR products 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.)

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



PDF DPR and CPR calibrated reflectivities a) snowfall occurrence b) snowfall rate April 2014 through March 2017 (Skofronick-Jackson et al., 2019)

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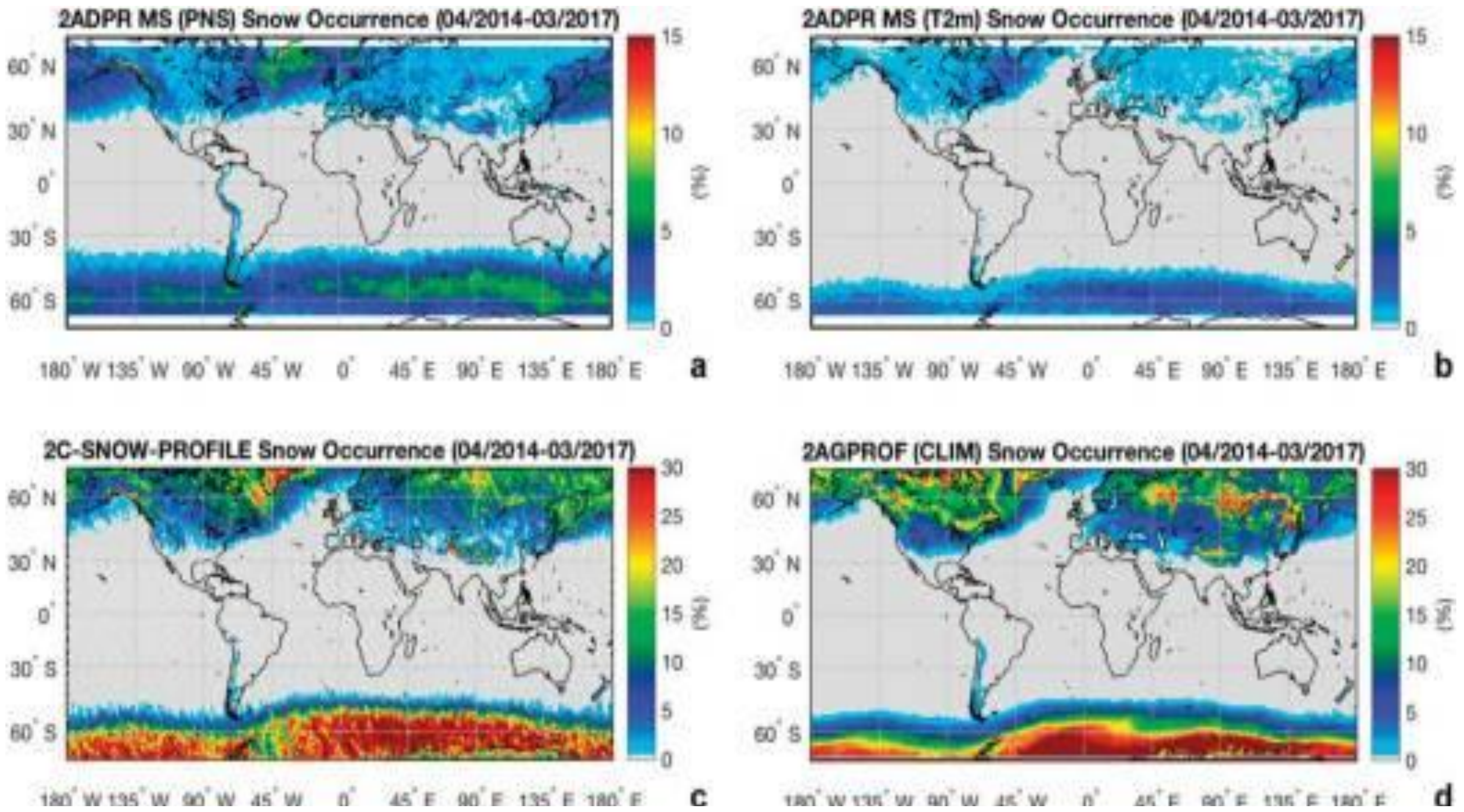
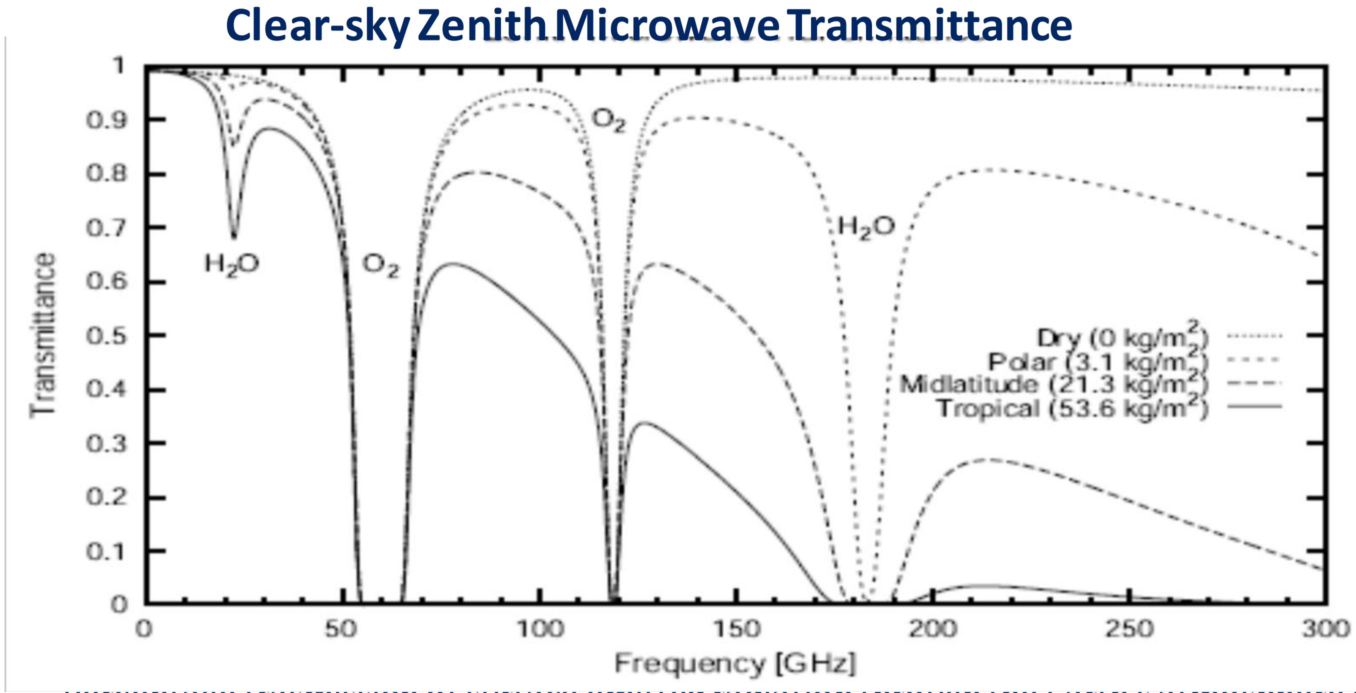
PMW radiometry and snowfall: A few key points

- **PMW sensors are needed for global snowfall climatology.**
- GPM constellation satellites and key future missions (EPS-SG MWI, MWS) need to be fully exploited
- Current state of the art satellite products show large discrepancies in snowfall climatologies
- How to reconcile such descrepancies and how to achieve more “accurate” global snowfall climatology?



Snow occurrence percentage for (a) DPR MS, (b) DPR MS with the GMI (Sims and Liu 2015) T2m snow classification methodology, (c) CloudSat 2CSP, and (d) GMI GPROF retrievals. Different scales are adopted for panels to accentuate regional snowfall occurrence patterns (Skofronick-Jackson et al., 2019)

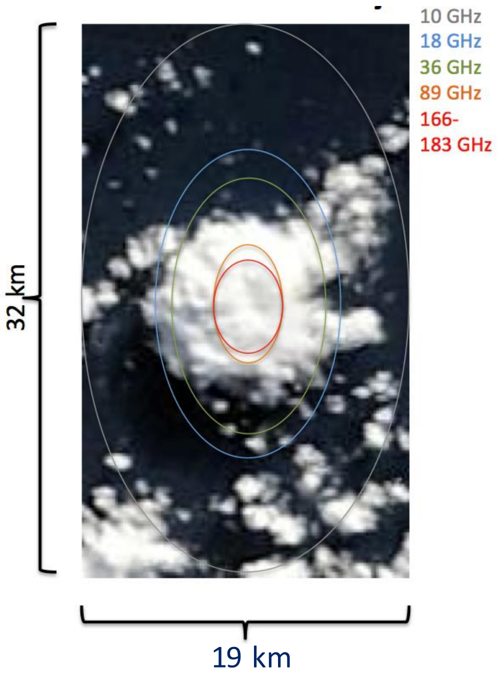
PMW radiometry: a few basic concepts



Percentage trasmission of surface emitted radiation through the Earth's atmosphere along the vertical direction, under clear-sky conditions. *[Adapted from Ulaby et al, 1981]*

Frequency range for precipitation: 10-200 GHz
Wavelength 3 - 0.1 cm
Snowflakes (0.1-2 cm)

- Angular resolution is diffraction limited
- $\sin(\theta) = \lambda/d$ (d = antenna size)
- Low orbits allow higher spatial resolution



Imager IFOV: GMI
d = 1.2 m
Altitude: 407 km

- **High frequency channels (> 90 GHz) are the most suitable for snowfall retrieval because less affected by the background surface emission signal (except in very dry conditions) and sensitive to snowfall scattering (*TB depression*) and cloud liquid water emission (*TB enhancement*)**
- **Lower frequency channels (< 90 GHz) respond to extremely variable background signal (wet/dry, deep/thin snow cover) and sea ice**

PMW Remote Sensing of Snowfall: Challenges

Detection and quantification of snowfall by passive microwave observations remains among the most challenging tasks in global precipitation retrieval (*Levizzani et al*. 2011; *Skofronick-Jackson et al.* 2019, among others).

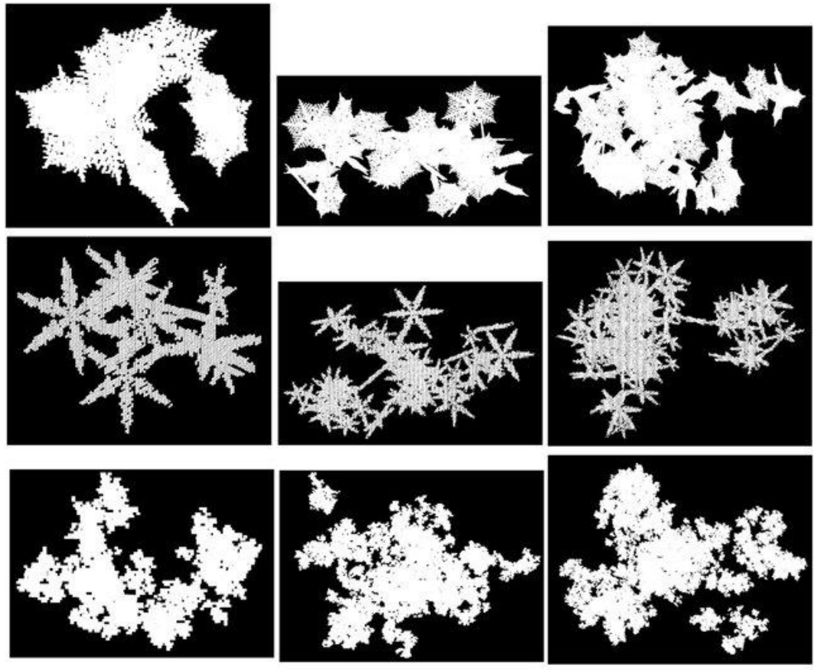
- **Challenge 1**

The *PMW multichannel snowfall signal* is highly dependent on the complex scattering properties of snowfall

- **Challenge 2**

Snowfall scattering signal tends to be *masked by the water vapor and cloud liquid water emission*

Challenge 1



Highly sophisticated single scattering models and cloud microphysics models are now available, but still large uncertainties in cloud-radiation model simulations

Alternative: use of observational datasets relating surface snowfall with PMW measurements

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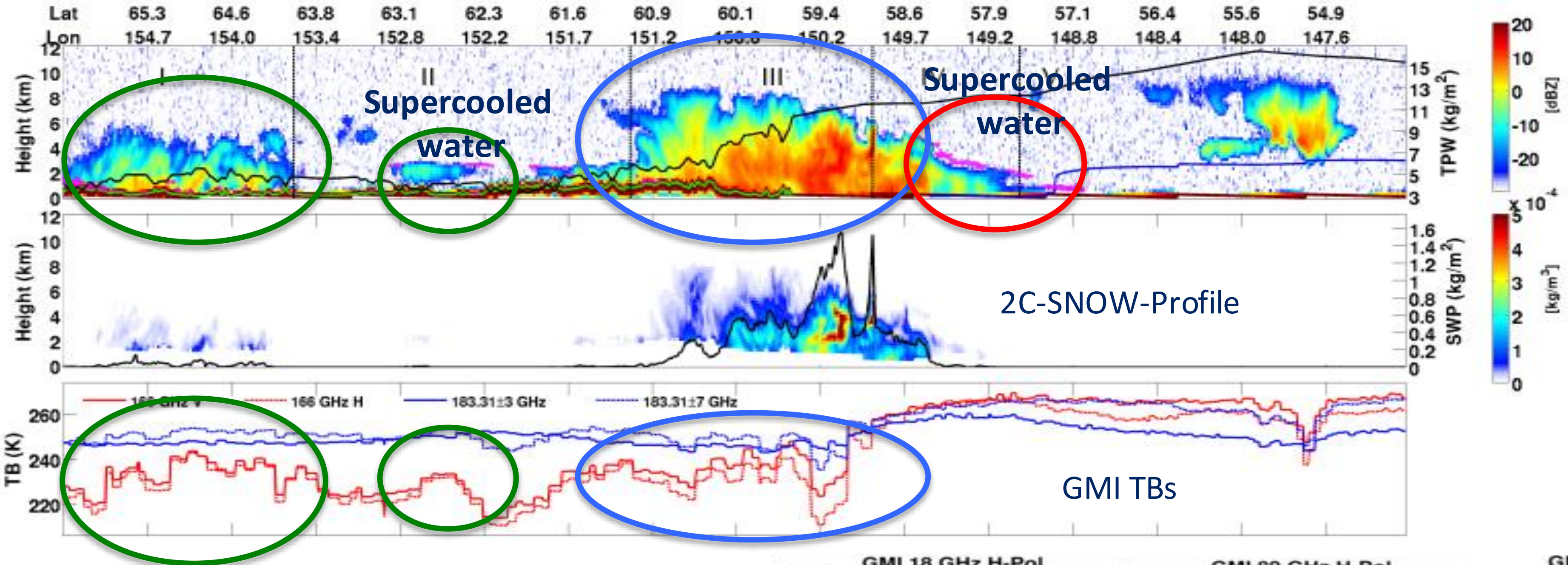
PMW sensitivity to high latitudes snowfall

Challenge 2: Impact of WV and Cloud Water

Frontal snowfall event - Eastern Siberia 30 April 2014



Land/snowcover

Very cold and dry env.

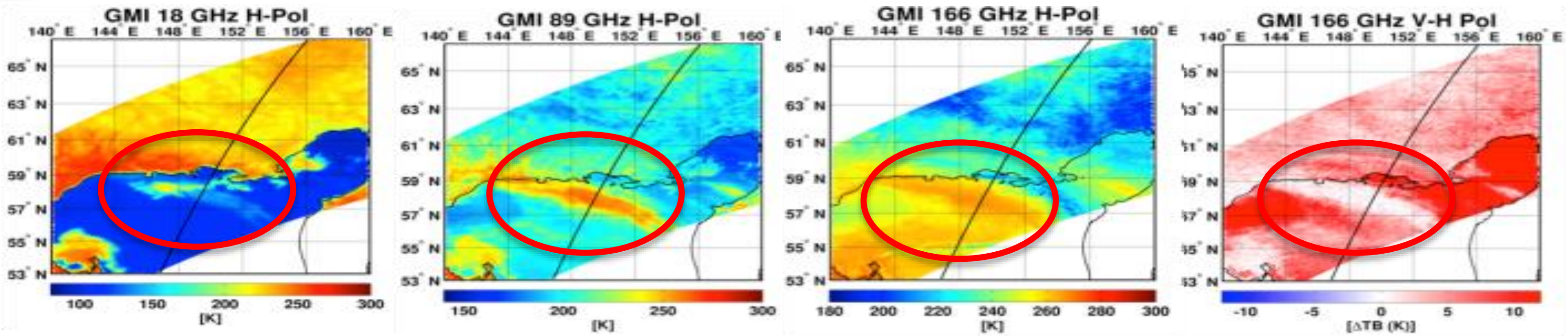
Sector I/II: Shallow/weak snow clouds; sensitivity at 166 GHz *and* impact of **supercooled water thermal emission**

Sector III: Deeper snowfall segment; scattering effects at 166 GHz and 183 GHz (lower TBs up to 30K); 166ΔTB polarization signal up to 12 K

Ocean

Moist and warmer env.

Sector IV/V: Effect of **supercooled droplets** visible mostly at 89 GHz; 18.7 GHz shows presence of low-level mixed phase precipitation (2C-SNOW does not retrieve snowfall). Upper level cloud has strong signal at 166 and 183 GHz



GMI TB maps at 18.7, 89 (H-pol) and 166 GHz (H-Pol), and 166 ΔTB ; black line indicates the CloudSat track

(Panegrossi et al. 2017 Rem. Sens.)

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The *PMW multichannel snowfall signal* is highly dependent on the complex scattering properties of snowfall (*Kneifel et al*. 2020 and references therein)

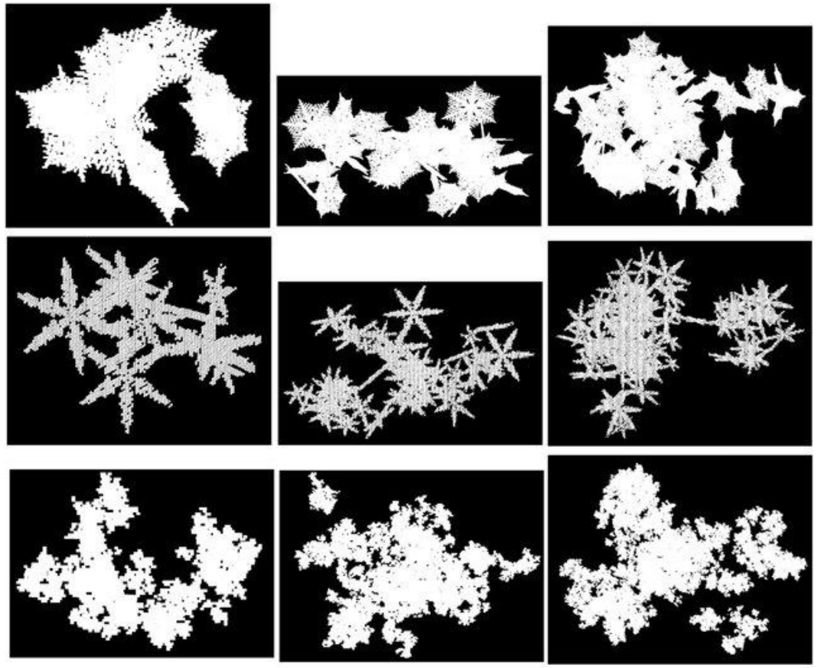
- **Challenge 2**

Snowfall scattering signal tends to be *masked by the water vapor and cloud liquid water emission* (*Liu and Seo*, 2013; *Panegrossi et al*. 2017)

- **Challenge 3**

Snow-covered surface emissivity is extremely variable due to rapid changes of snow cover extent, snow accumulation on the ground, and snowpack radiative properties, with significant effects on the snowfall microwave signal (*Prigent et al.* 2003; *Ebtehaj and Kummerow* 2017; *Takbiri et al*. 2019; *Munchak et al*. 2020)

Challenge 1



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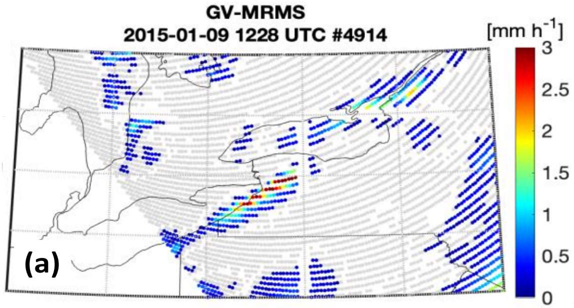
PMW Snowfall signal and background surface contamination

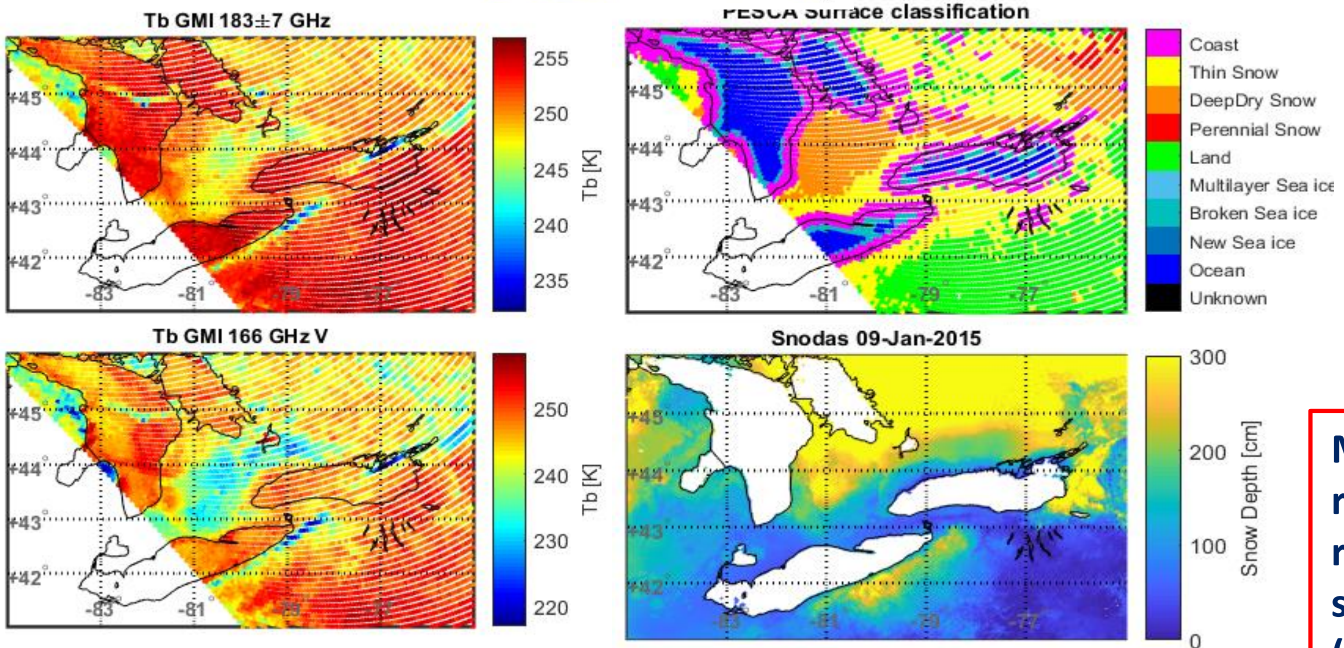
Challenge 2: Example for Lake Effect snow events

- Very intense shallow convective snowfall
- Very dry conditions
- Extremely variable snow-covered background surface

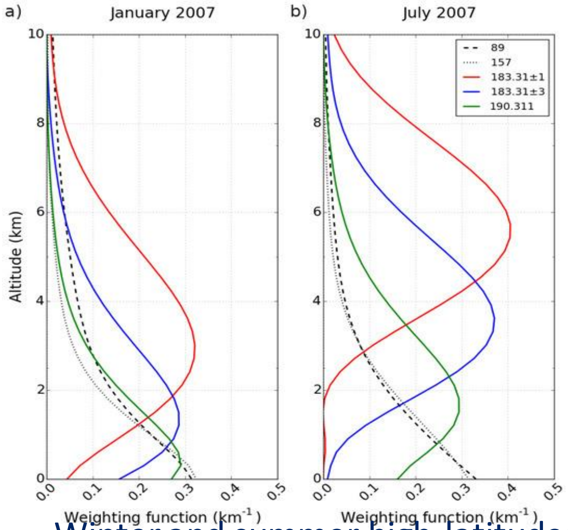
Low frequency channels can be exploited for snow cover and sea ice detection and characterisation at the time of the overpass



Milani et al., JTech, 2020



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



Winter and summer high-latitudes MW channels weighting Functions (Edel et al., 2019)

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

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PMW Remote Sensing of Snowfall: Challenges

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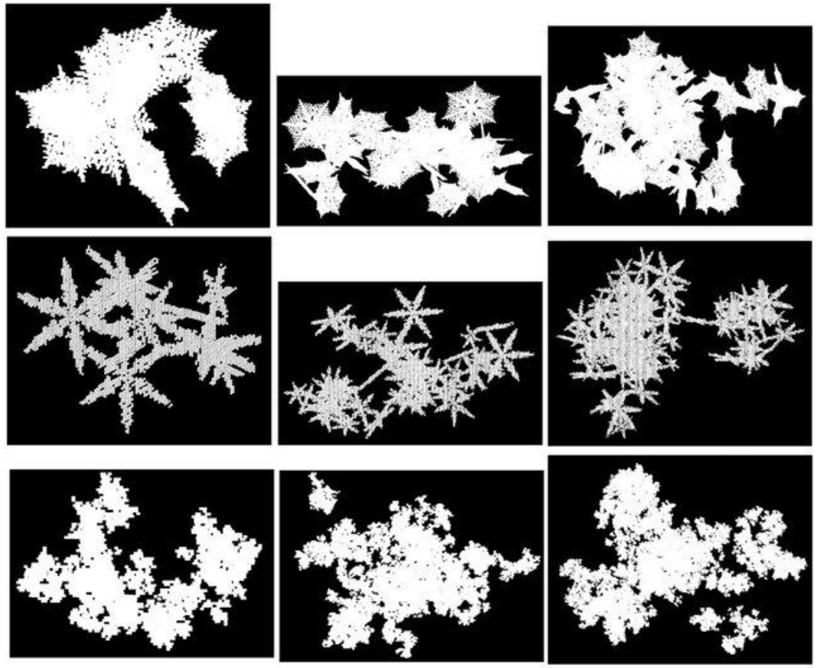
- **Challenge 4**

Need to have a high-quality, global snowfall database (model-based or empirical) to be used as a priori or training information in the retrieval process

Challenge 1



Highly sophisticated single scattering models and cloud microphysics models are now available, but still large uncertainties in cloud-radiation model simulations

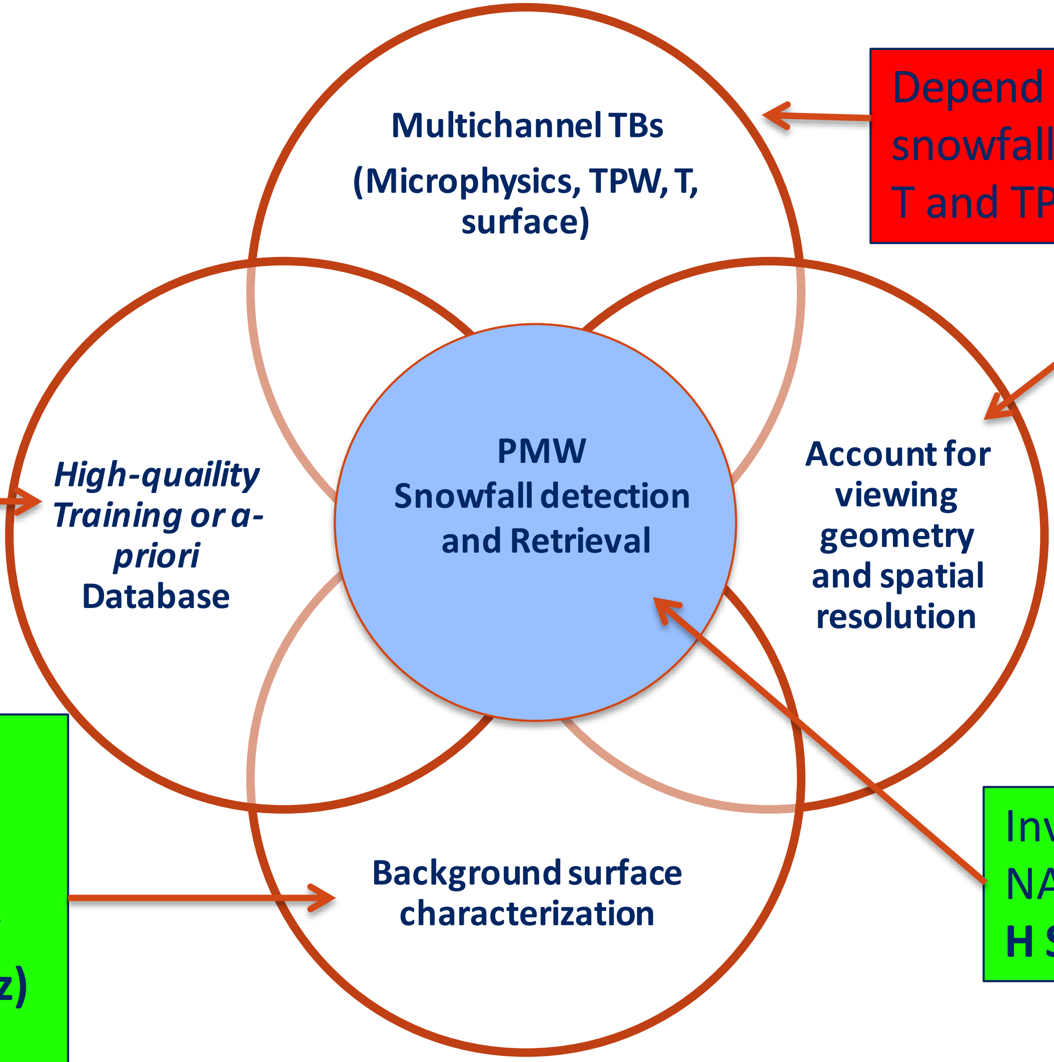
Alternative: use of observational datasets relating surface snowfall with PMW measurements

PMW snowfall retrieval concept

Developer choice

Depend on Radiometer characteristics and snowfall event / atmospheric conditions; T and TPW and generally model-based

NASA GPROF: DPR-based/ ground radar network
H SAF: CloudSat-based



NASA GPROF: Climatological datasets
H SAF: at the time of the overpass, exploitation of low frequency channels (< 37 GHz)

Inversion method:
NASA GPROF: Bayesian
H SAF: Machine learning

CloudSat-based coincidence datasets for ATMS and GMI

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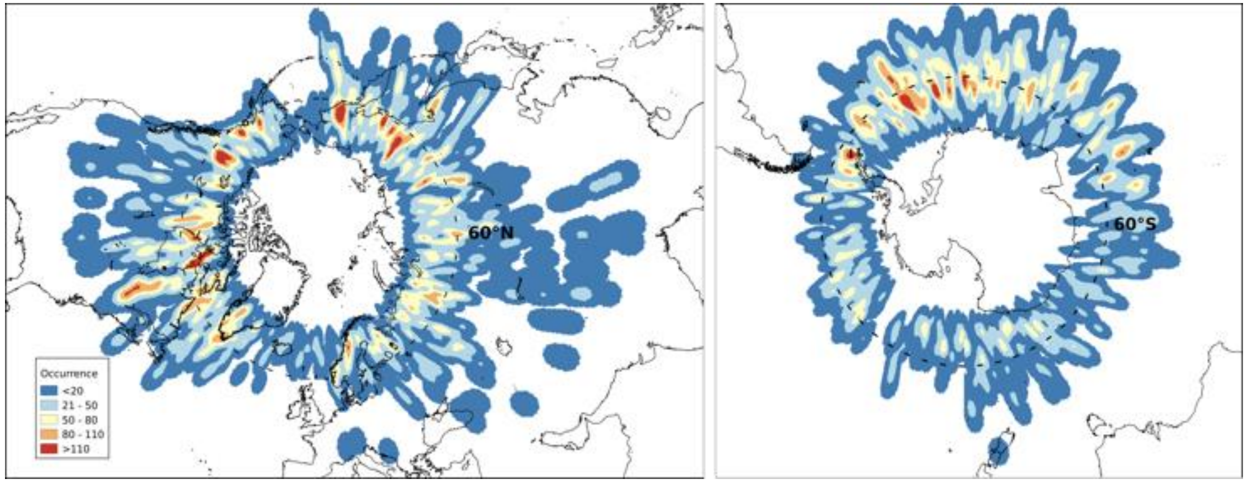
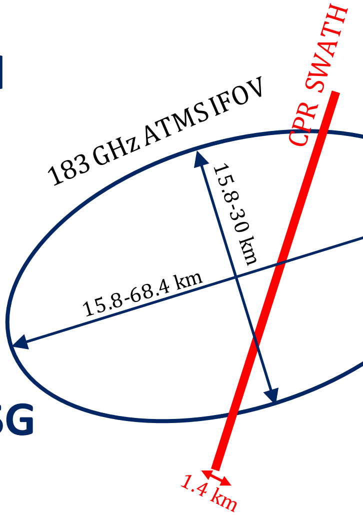
CloudSat/Calipso-GMI (extension of NASA 2B-CSATGPM v4)

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
Horizontal resolution	1.2 km CPR; 10 km GPM



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

- **ATMS (cross-track) and GMI (conical scanning) are the two most advanced spaceborne radiometers in space**
- **They are equipped with low and high frequency channels for background surface characterization and for snowfall retrieval**
- **They are used to develop H SAF EPS-SG MWS and MWI day-1 products**



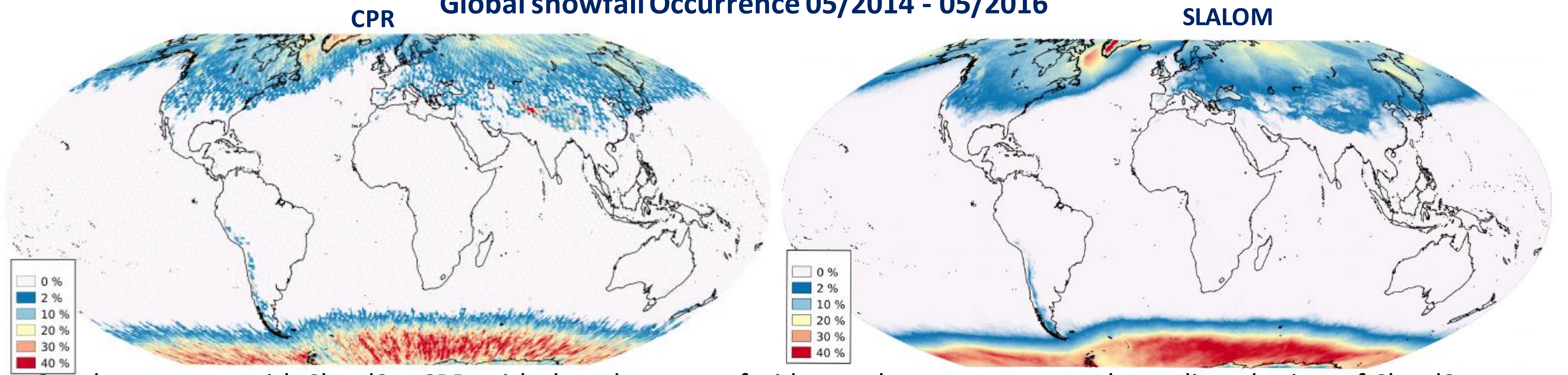
CloudSat/Calipso-ATMS

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
Horizontal resolution (Km)	15.8 x 15.8 (nadir) 30 x 68.4 (scan edge)

SLALOM: Snowfall retrieval algorithm for GMI

It is based on the GMI/CPR coincidence dataset V03B (Joe Turk, JPL); **CPR 2C-SNOW-Profile product is used for training**
Input: GMI L1c TBs (all channels) and auxiliary ECMWF analysis variables
No auxiliary info on background surface conditions;
Random forest modules for snowfall detection and supercooled liquid water detection (***at the cloud top***);
Multi-linear regression: snow water path (SWP) estimates (Rysman et al., Rem. Sens., 2018)

Global snowfall Occurrence 05/2014 - 05/2016



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

Rysman et al., 2018, 2019

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Input: GMI L1c TBs (all channels) and auxiliary ECMWF analysis variables

No auxiliary info on background surface conditions;

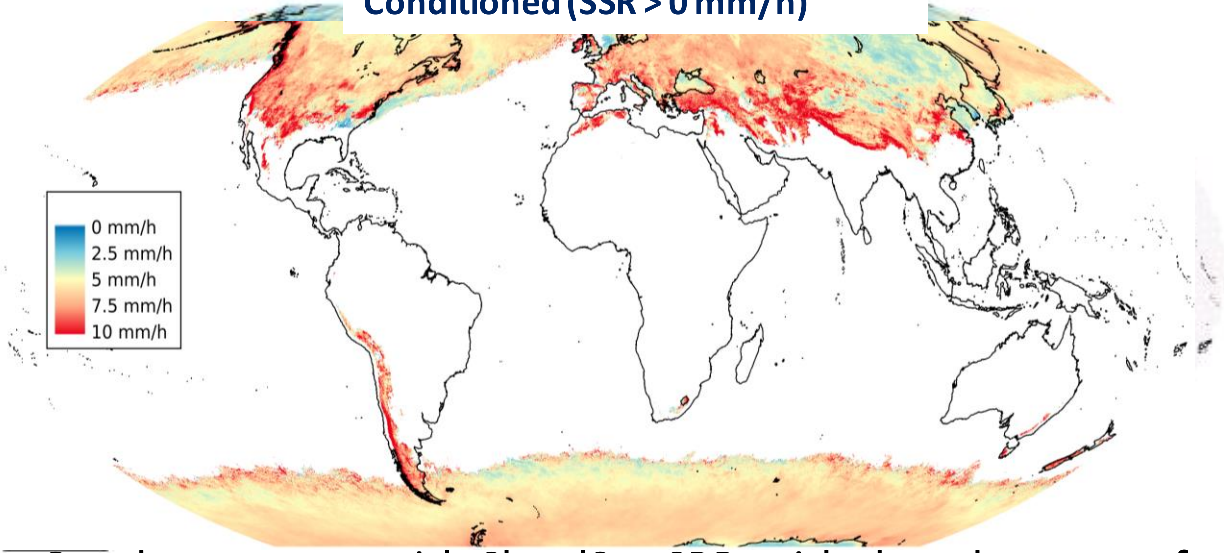
Random forest modules for snowfall detection and supercooled liquid water detection (***at the cloud top***);

Multi-linear regression: snow water path (SWP) estimates (Rysman et al., Rem. Sens., 2018)

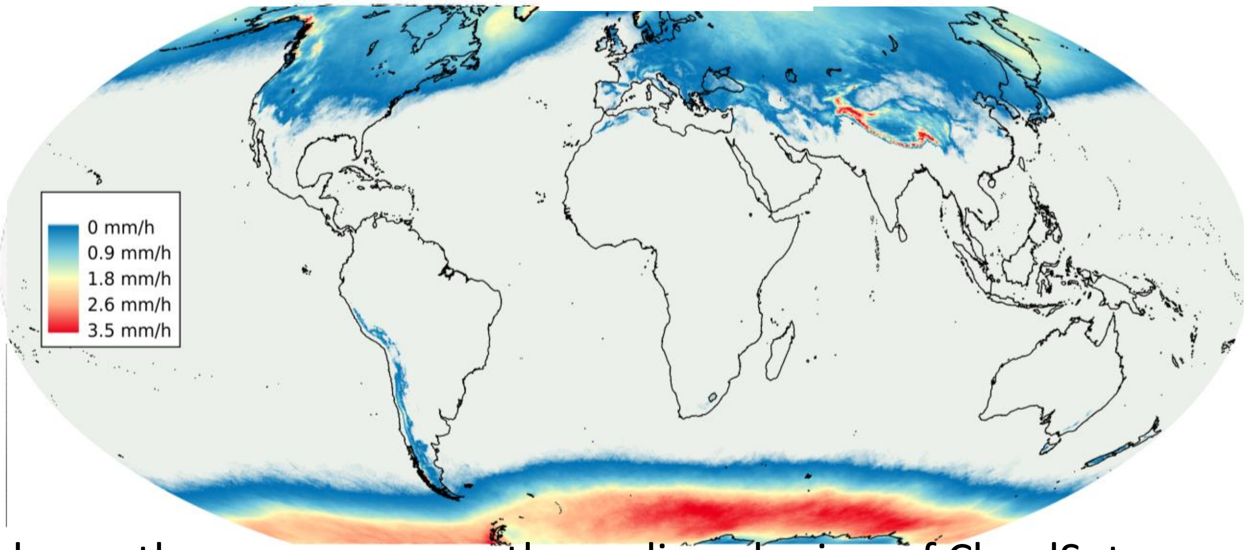
New gradient boosting module for Surface snowfall rate (SSR) (Rysman et al., GRL, 2019)

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

Conditioned (SSR > 0 mm/h)



Unconditioned



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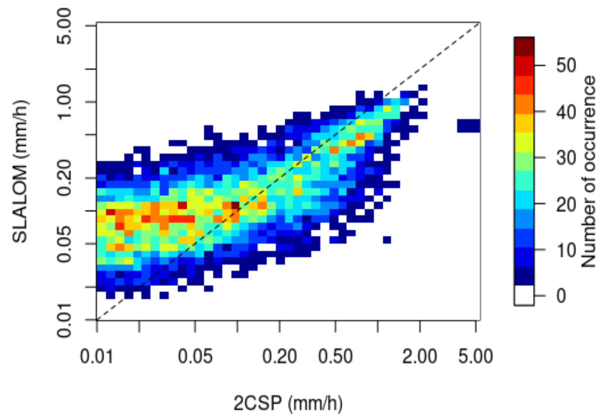
Rysman et al., 2018, 2019

SLALOM: Snowfall retrieval algorithm for GMI

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)



RMSE 0.08 mm/h
CC = 0.7
Bias (%)= 13%

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

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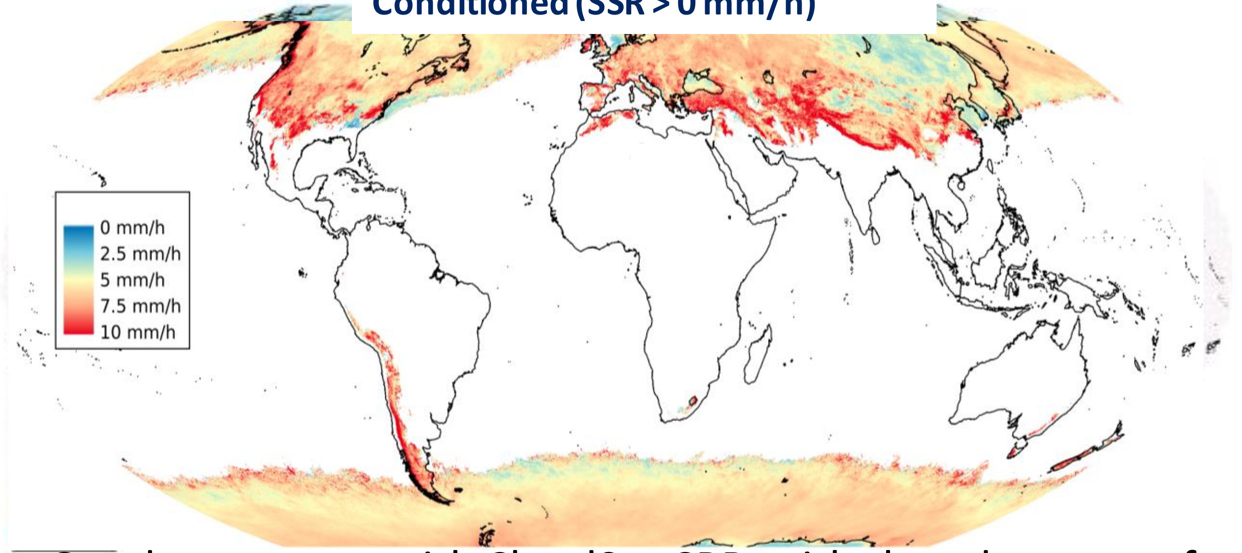

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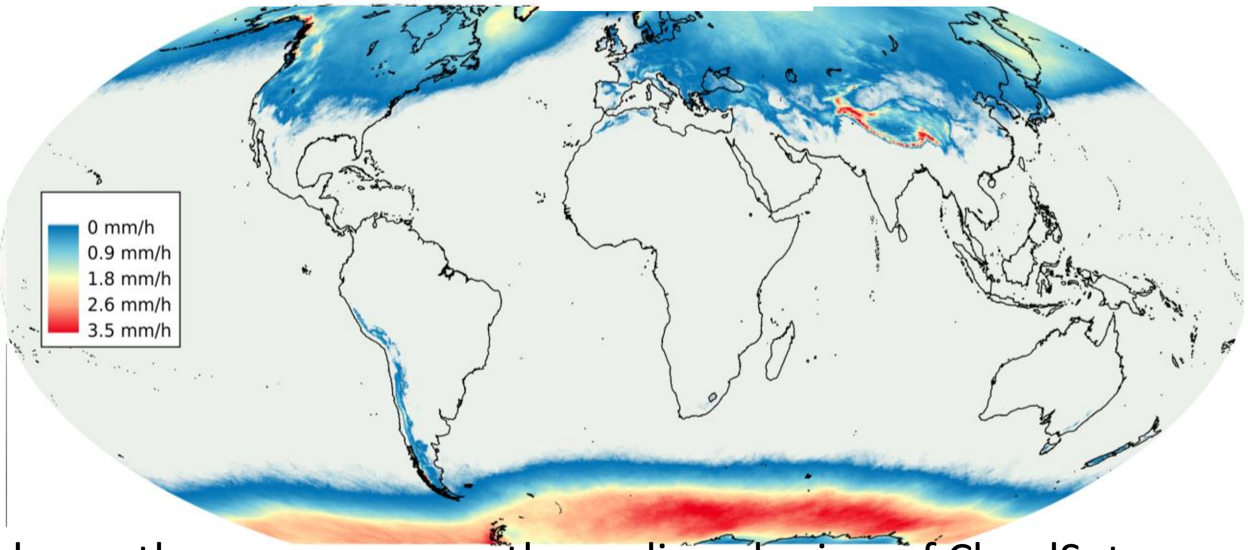

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Rysman et al., 2018, 2019

Eastern Siberia 30 april 2014 – Comparison CPR 2C-SNOW with SLALOM & NASA GPROF

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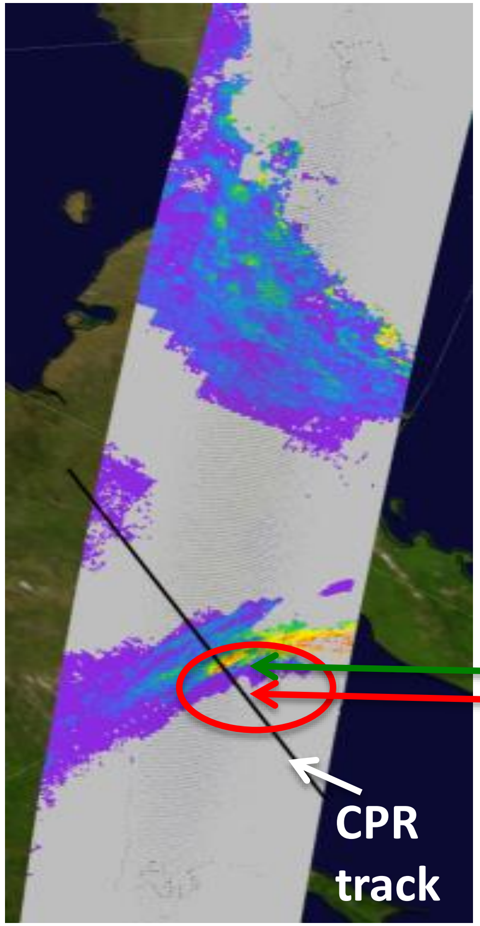
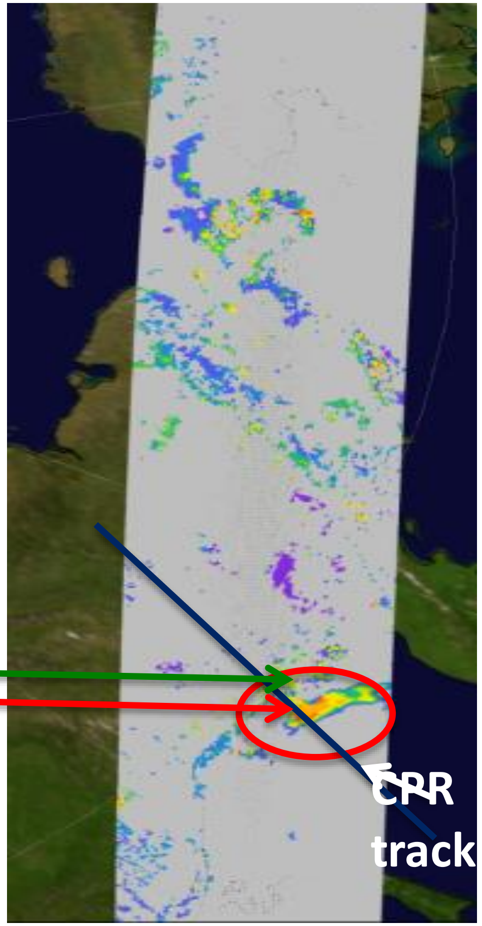
SLALOM SWP

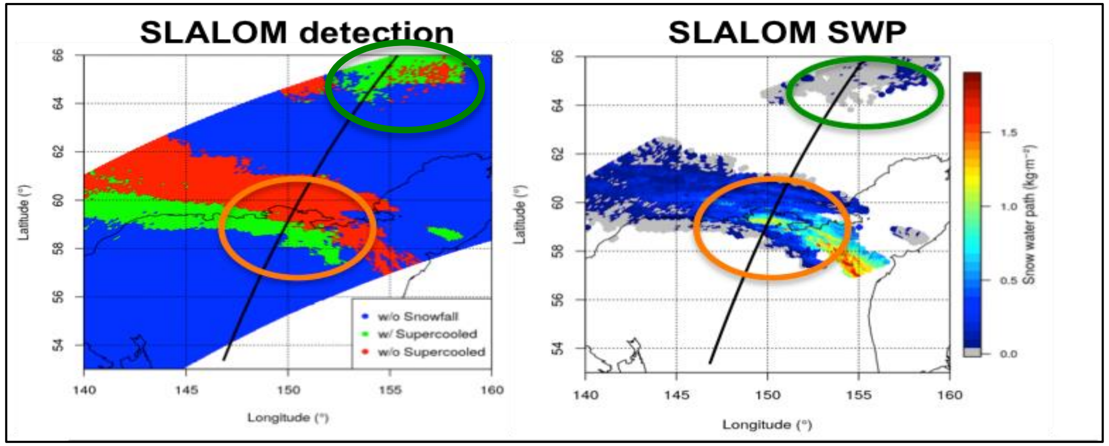


SLALOM predicts two distinct snowfall regions in the frontal system

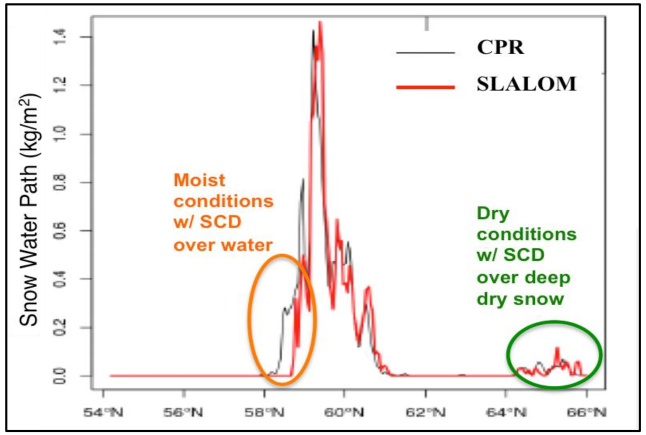
GPROF V05 Frozen Precip > 85%



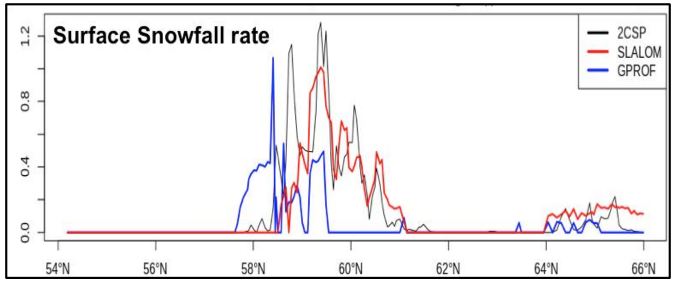
GPROF misses most of the snowfall system



CPR and SLALOM SWP match very well, even in the weaker snow region (around 65 °N) with low TPW and supercooled droplets



SLALOM misses mixed phase precip. captured by GPROF V05



(Rysman et al., 2019, GRL)

GPM and CloudSat Snowfall products validation

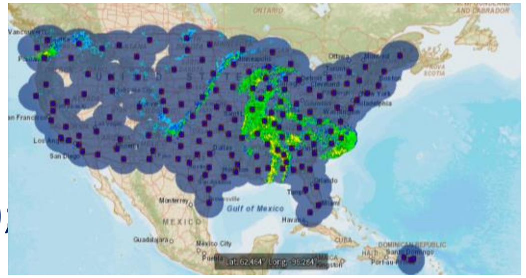
Ground-based radar reference data

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



QPE algorithm for Snow

$S_{MRMS} = 0.12\, Z^{0.5}$ (1)

- Only *Z* >5 dBZ (i.e. 0.2 mm/h);

Datasets used

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

(Mroz et al., JHM, under review)

Satellite Snowfall products

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

SLALOM for GMI (H SAF)

GPROF V05 for GMI (NASA GPM)

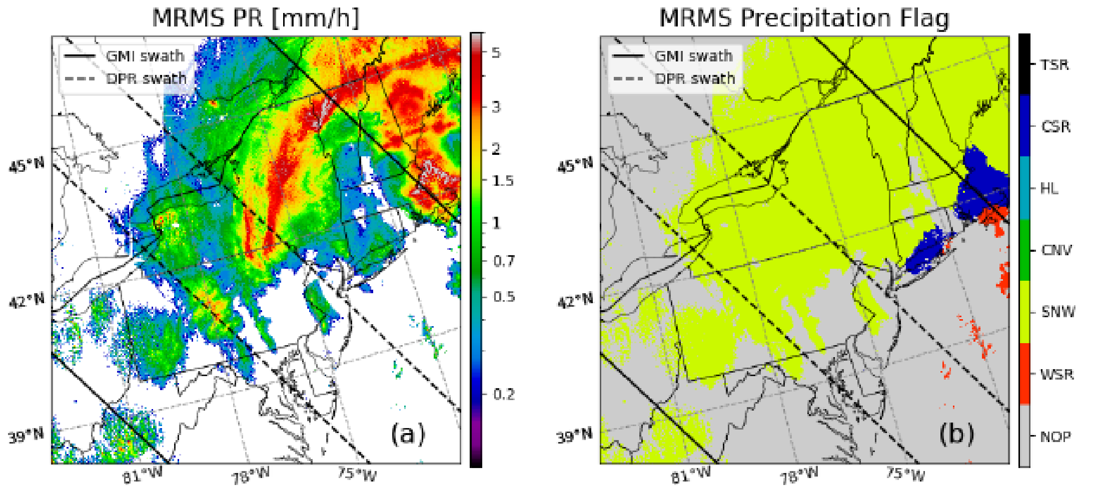
DPR, Ku, Ka V06 (NASA GPM)

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

CloudSat CPR product:

2C-SNOW-PROFILE (NASA)

Snowfall event 14 March 2017 20:02 UTC



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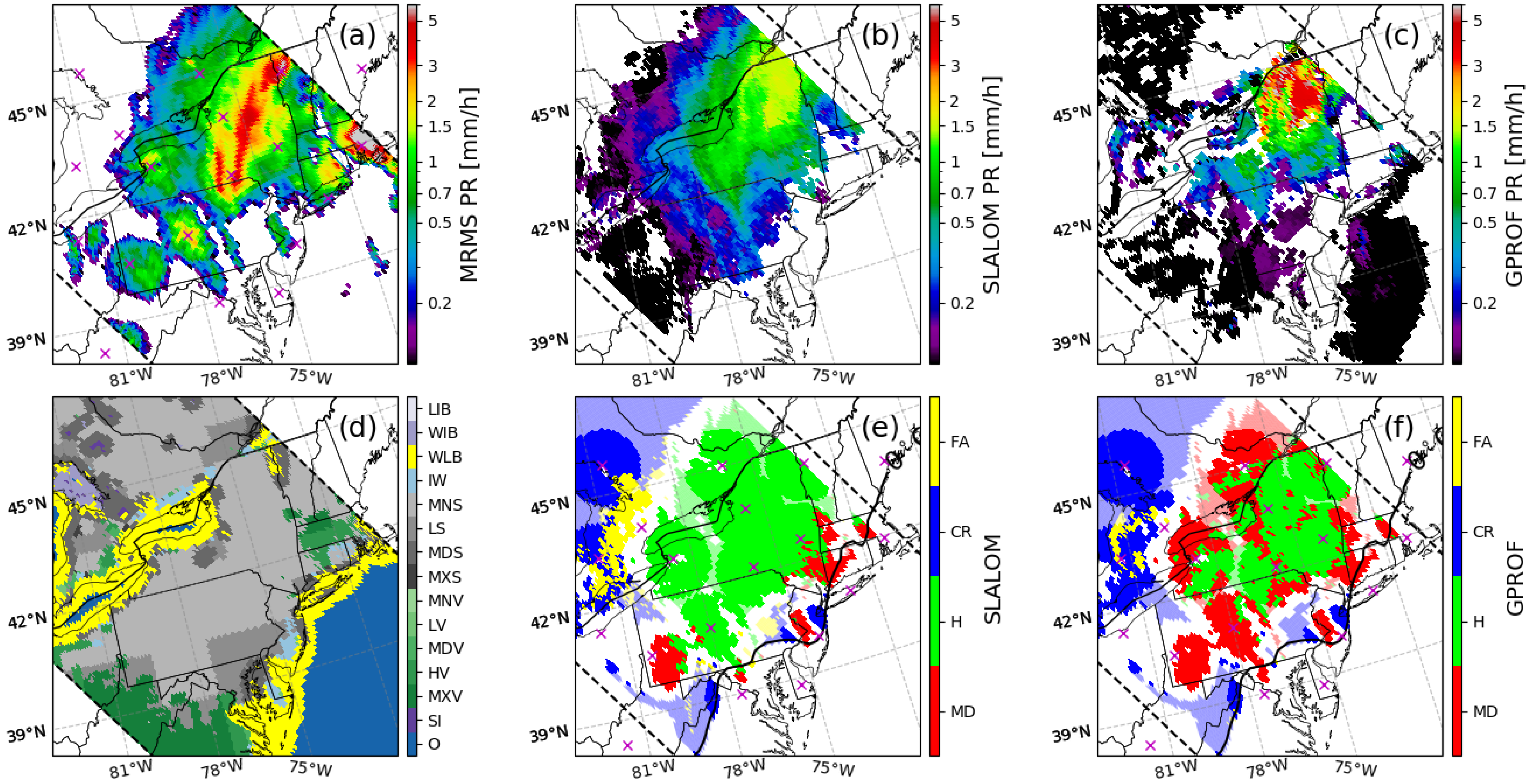

Snowfall: 4-year analysis over CONUS for all surface types (2016-2020)

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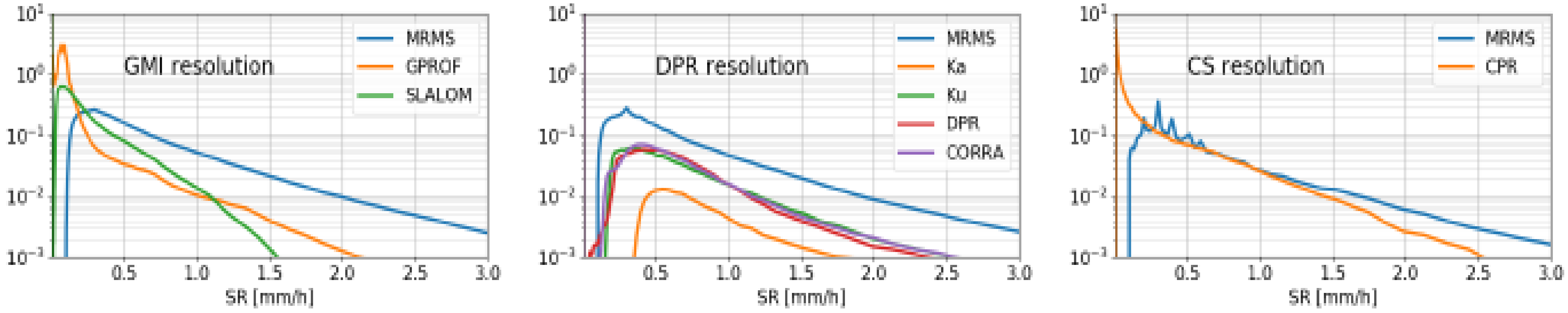
Probability density function of the snowfall rate occurrence



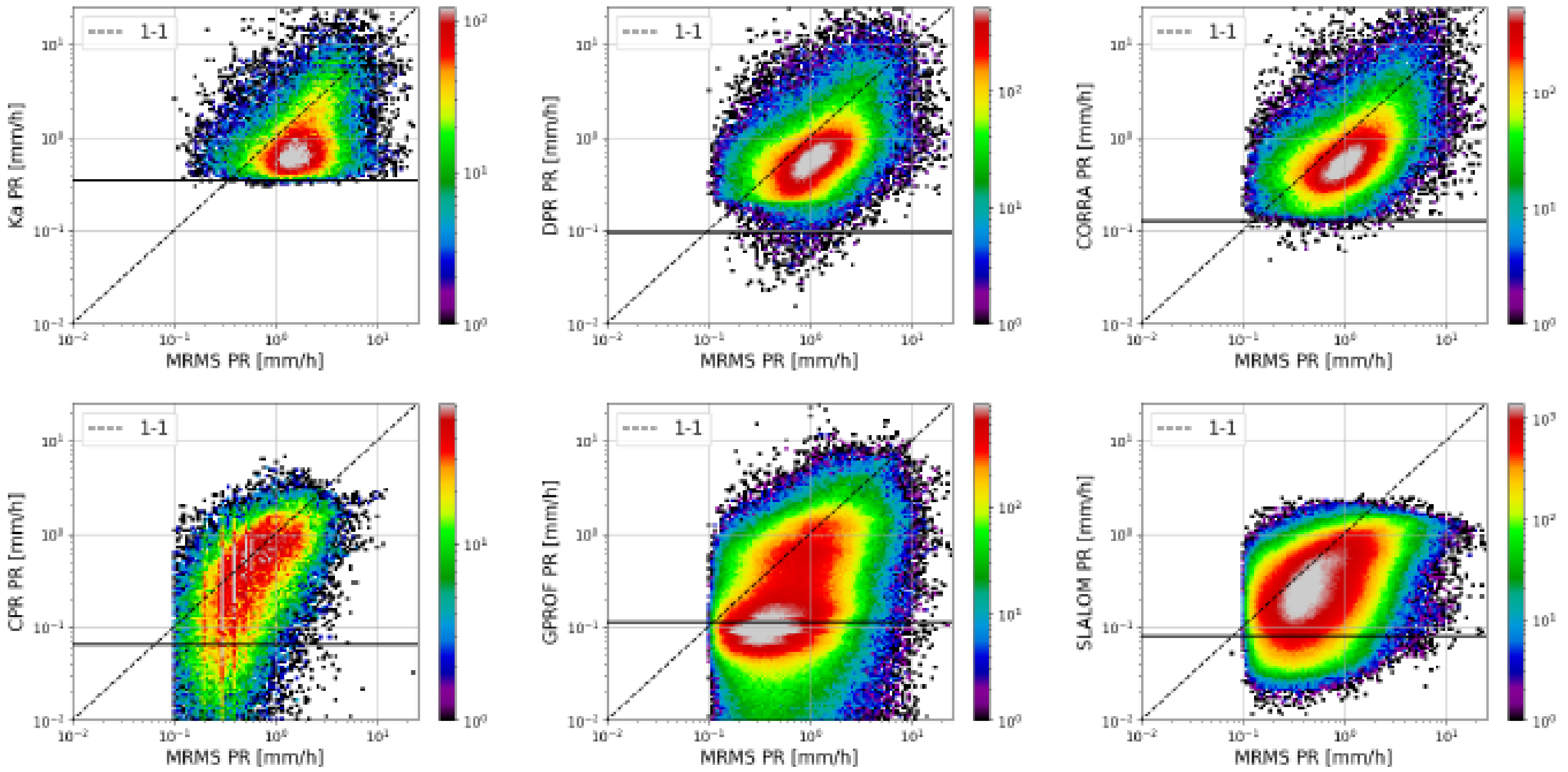
	ME (mm/h)	RMSE (mm/h)	CC	MB %	# of hits
DPR	-0.56	1.08	0.43	56.3	175581
Ku	-055	1.02	0.53	57.3	175274
Ka	-094	1.78	0.38	54.3	30589
CORRA	-0.53	1.07	0.44	57.2	185982
GPROF	-0.54	1.08	0.39	48.4	570736
SLALOM	-0.38	0.74	0.43	48.5	1166181
2C-SNOW	-0.21	0.68	0.45	73.0	50541

- Among all products 2C-SNOW performs best (except CC)
- Negative ME for all products (underestimation)
- Moderate CC (high degree of uncertainty for all products)
- SLALOM and 2C-SNOW are the least biased
- **GMI products produce < 50% of total precip.**
- SLALOM shows better scores than GPROF and lower ME and RMSE than DPR-based products

The best; **second best**,

ME – Mean Error CC – Correlation Coefficient MB – Multiplicative Bias RMSE – Root Mean Square Error

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



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

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GMI products detection scores: 4-year analysis over all surface types (2016-2020)

Score	SLALOM	GPROF	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
N. of MRMS samples no snow/ snow	10664398 / 2034580		91814 13183

MRMS "snow" samples:

- distance to the NEXRAD radar below 110 km;
- 50% of the IFOV filled by native MRMS precipitation
- only snow within IFOV according MRMS classification;
- snowfall rate below 21.3 mm h-1.

MRMS "no-snow" samples:

- distance to the NEXRAD radar below 110 km;
- no single native-resolution MRMS pixel filled by precipitation within the IFOV, i.e. PR_{MRMS} = 0 mm h-1;
- the ECMWF ERA5 T2m below the freezing point.

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Frozen precipitation detection scores over different surface types

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

Sea ice

Snow cover

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

4-year analysis of SLALOM and GPROF (based on GPROF surface classification)

PESCA: Passive microwave Empirical frozen Surface Classification Algorithm for ATMS (MWS) and GMI (MWI)

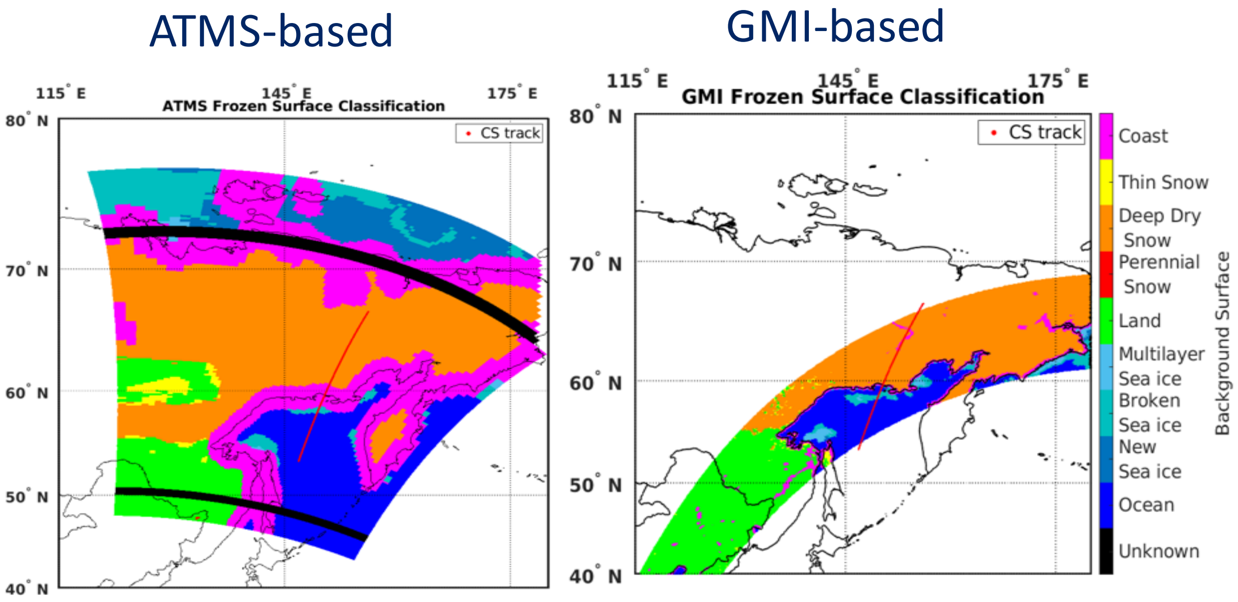
(Camplani et al., JHM, under review)

The microwave signal related to snowfall is strongly influenced by the **different surface conditions** (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 all spaceborne microwave radiometers (conical and cross track) *at the time of overpass*;

Siberia 30 April 2014



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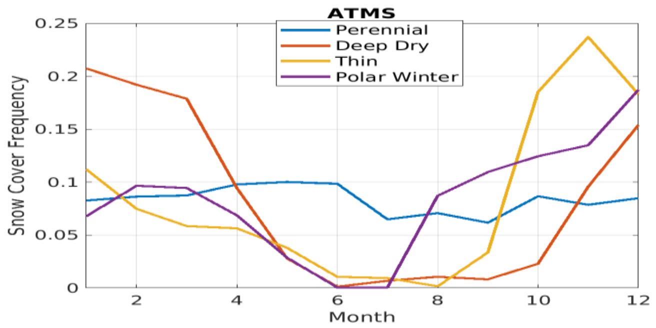
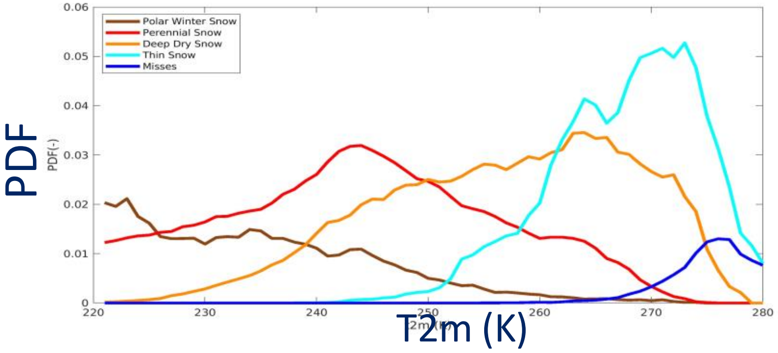
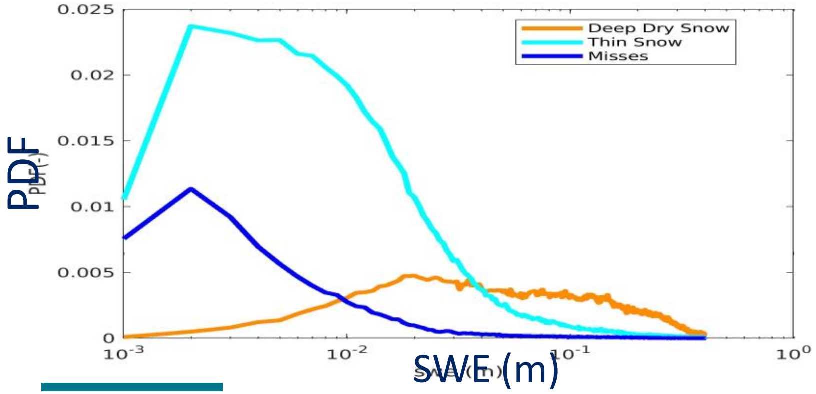
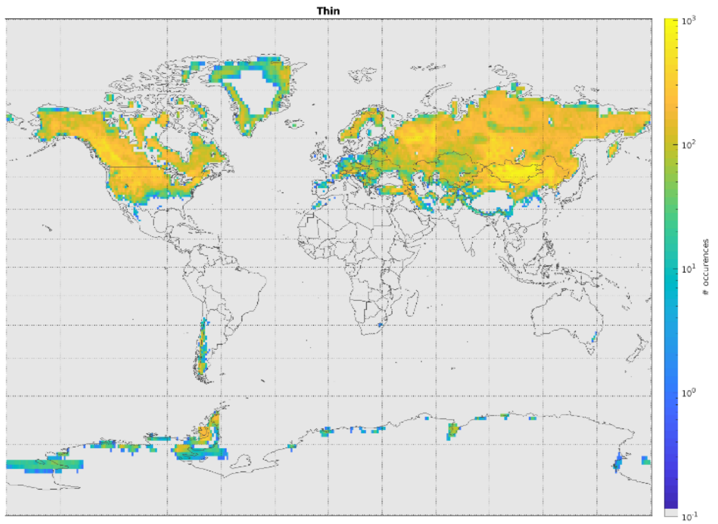
ATMS-based snow cover climatology (2017)



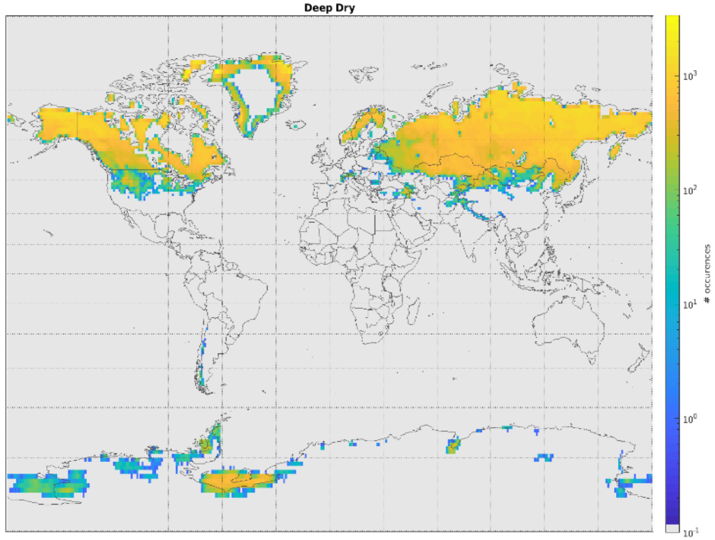




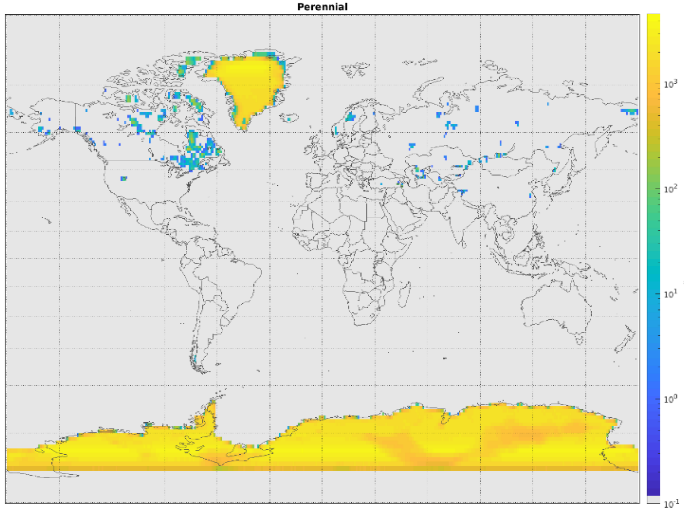
Thin snow



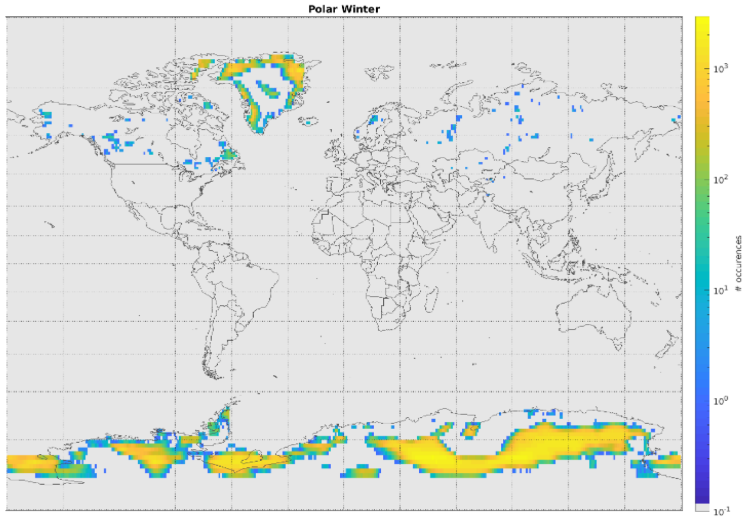
Deep Dry Snow



Perennial



Polar Winter



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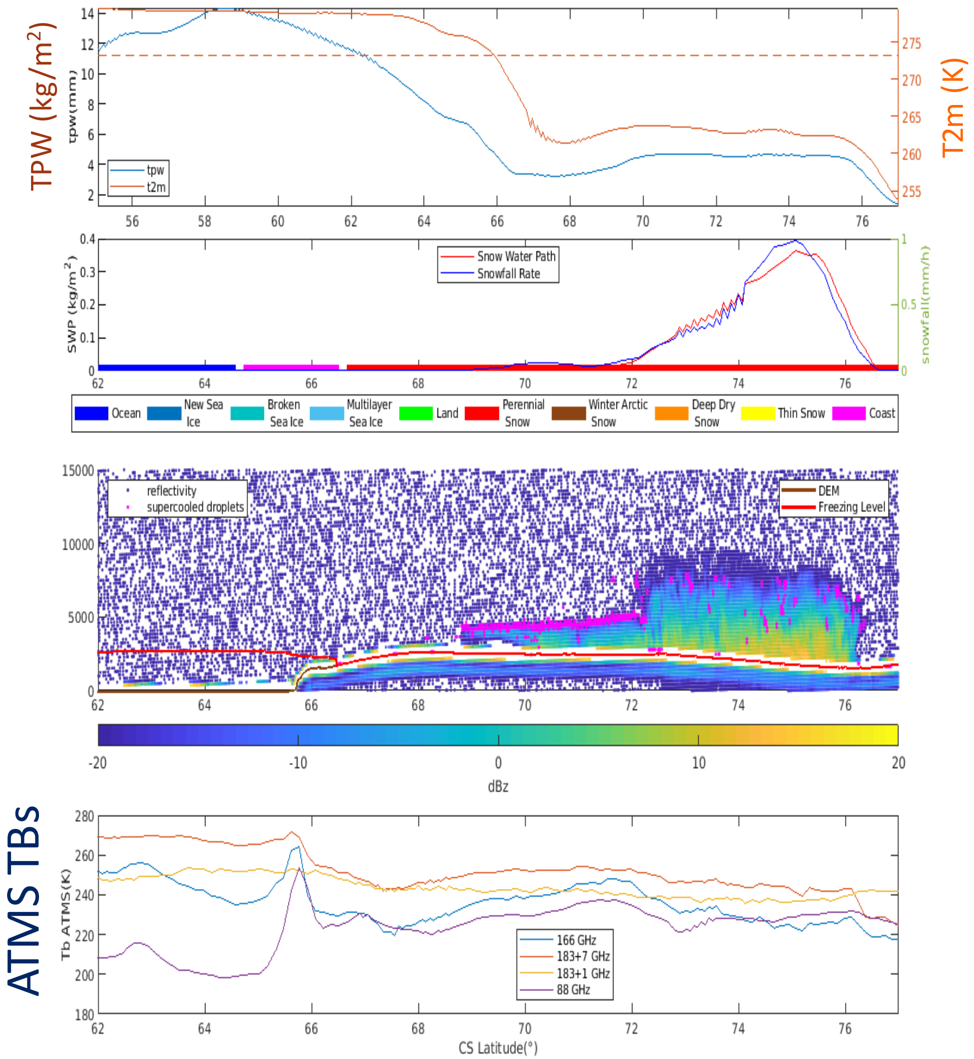
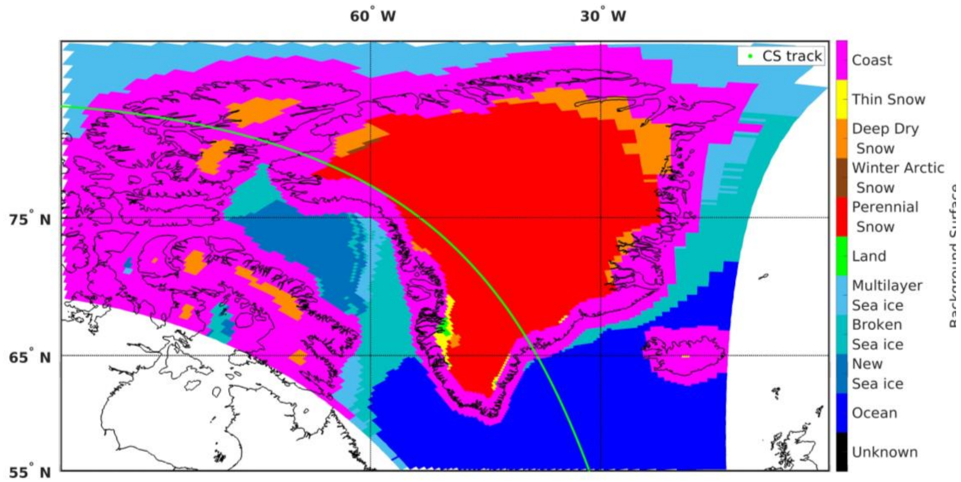
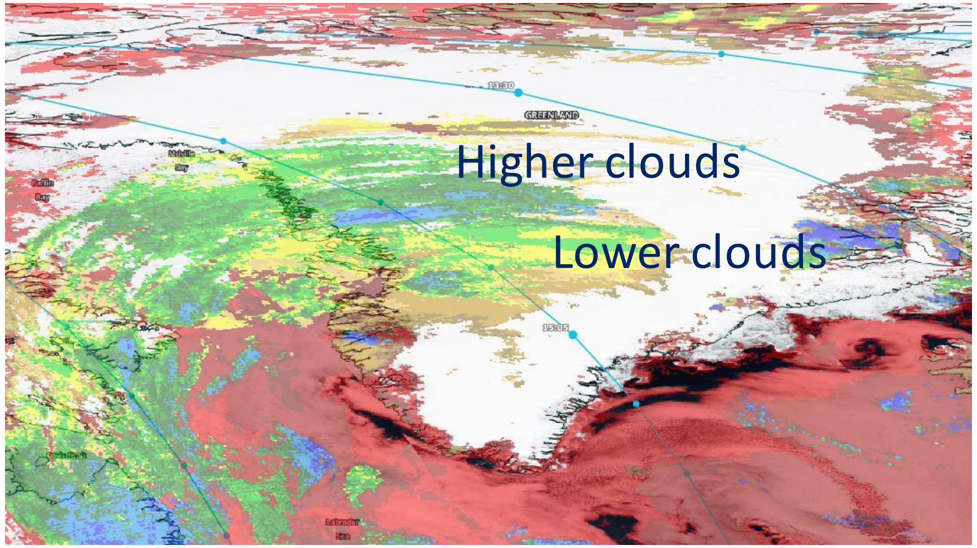
Greenland Case study 24 April 2016



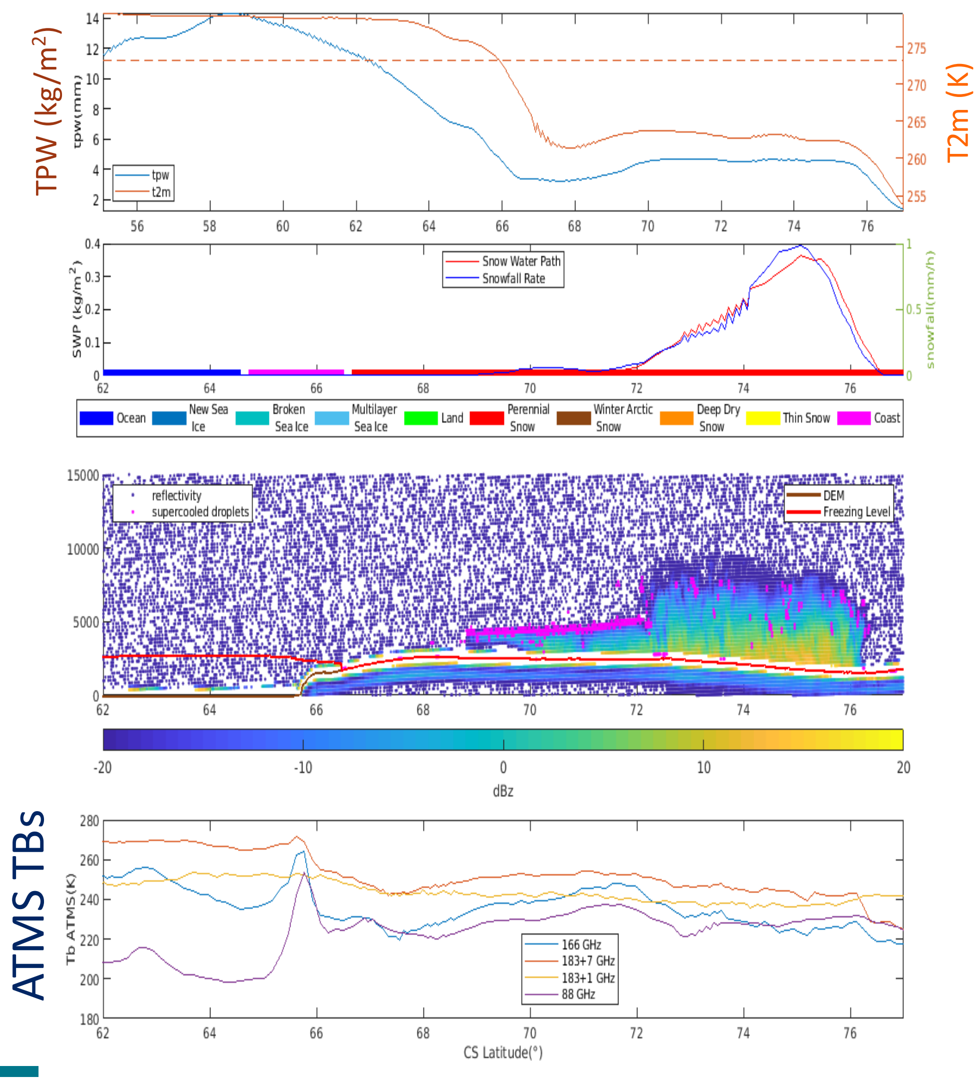
ATMS-based frozen surface classification

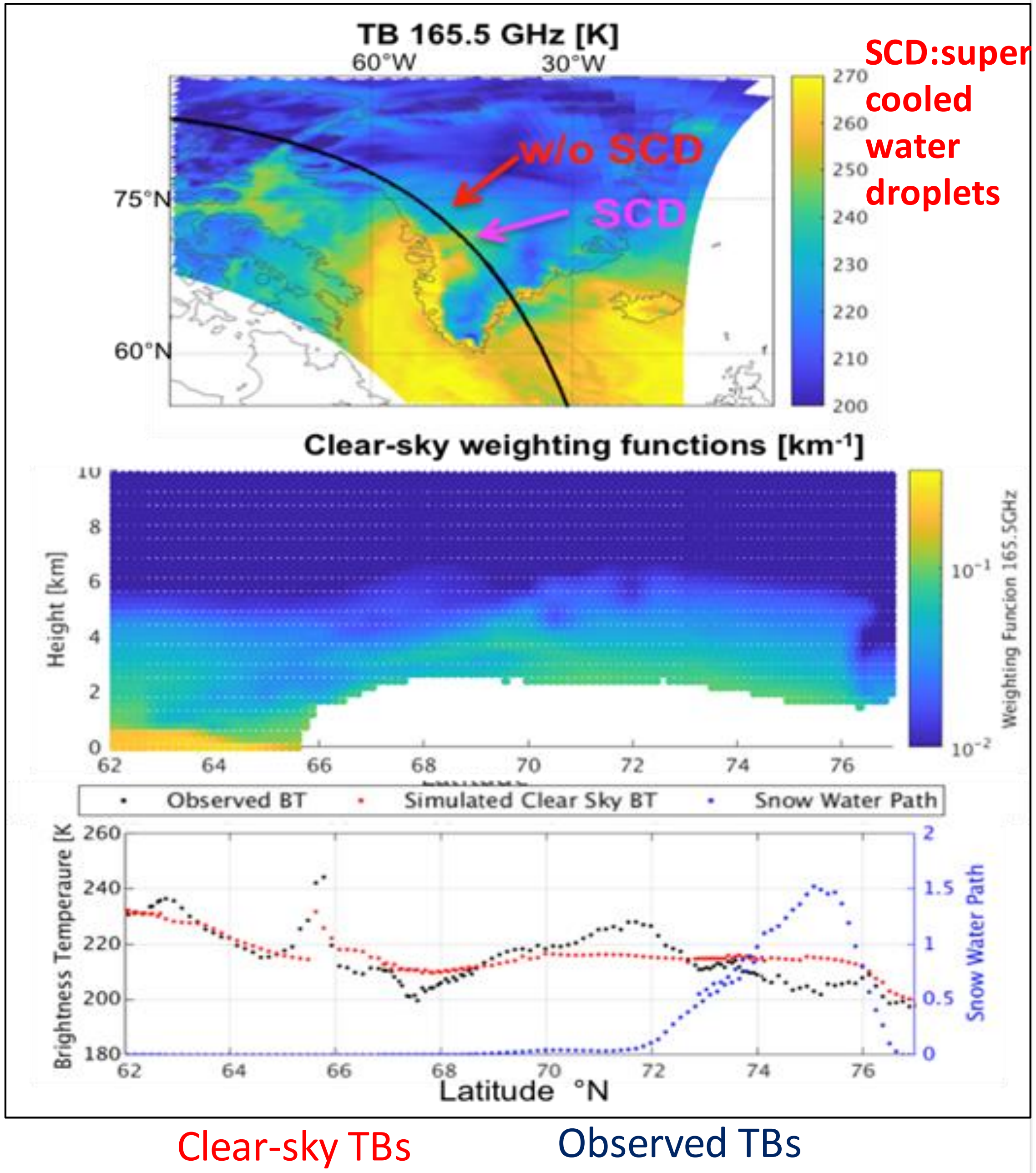


MODIS Cloud Top Height

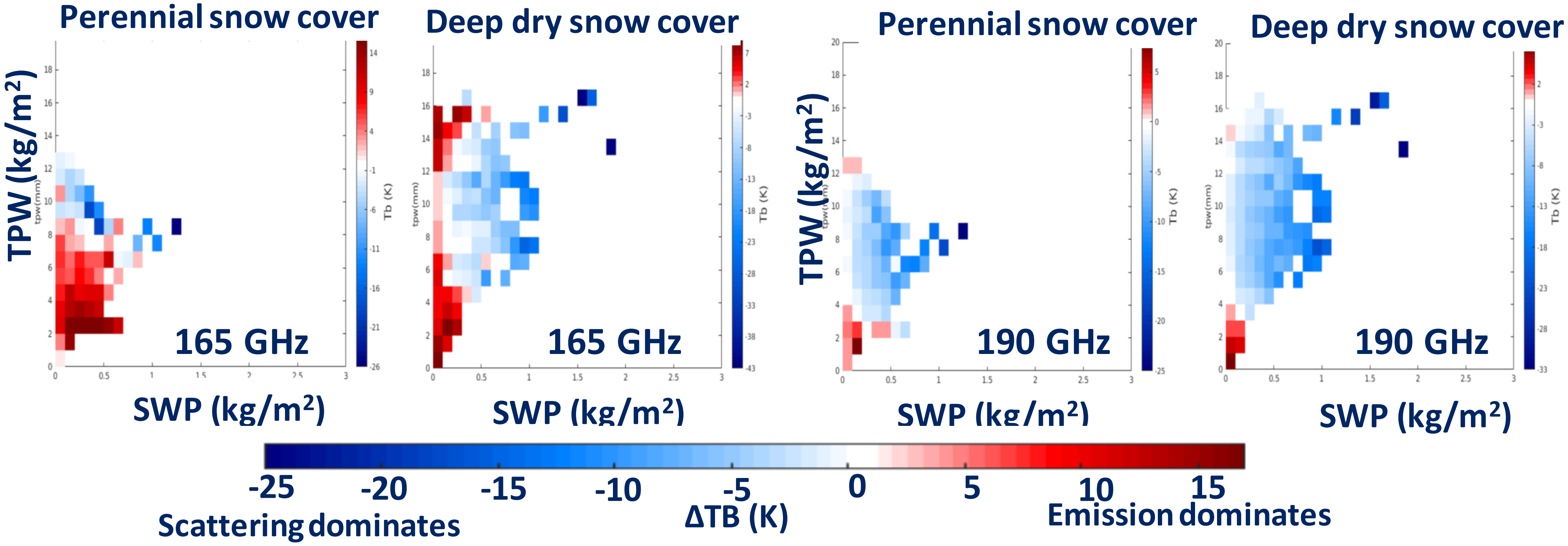


Greenland Case study 24 April 2016





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



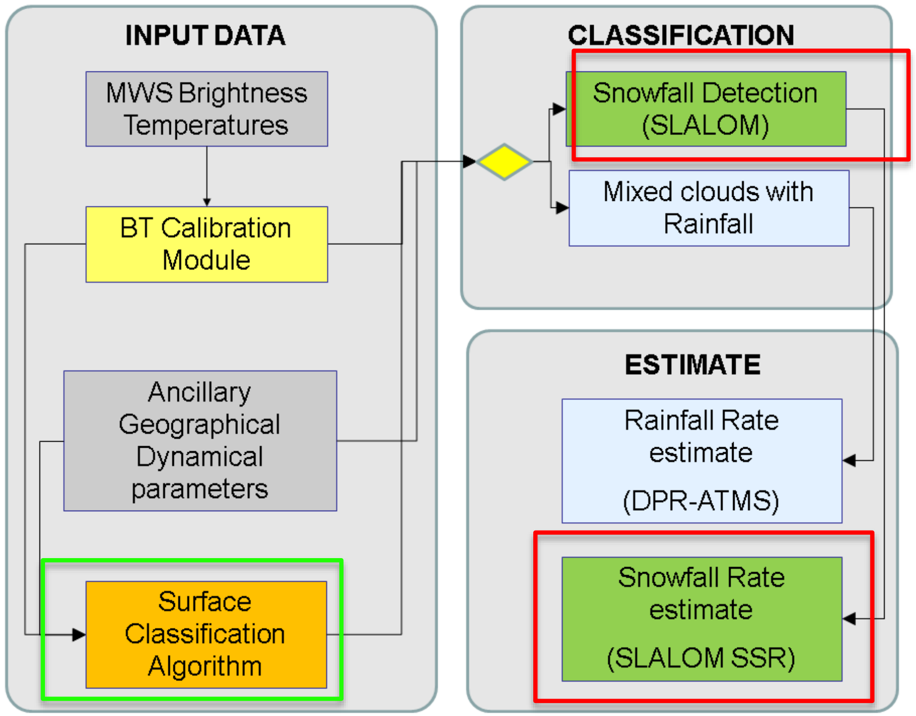
Mean TB difference in TWP/T2m/SWP bins with respect to “clear sky conditions” (SWP=0 kg/m²) for different snow cover categories in CloudSat/ATMS dataset

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)

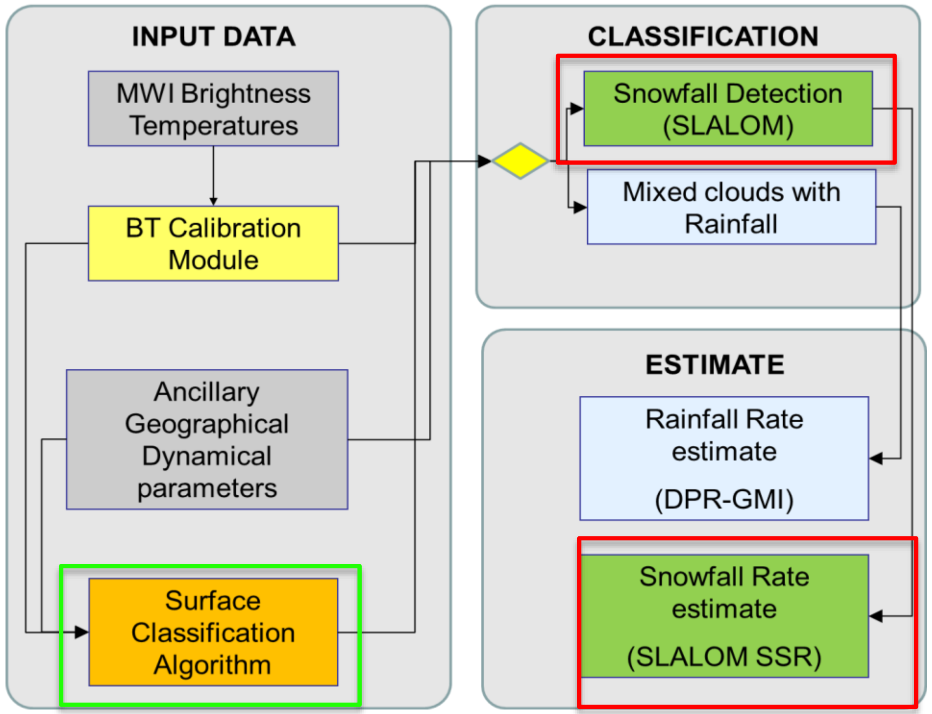
H SAF EPS-SG global ML-based precipitation products

Day-1 EPS-SG Level 2 Precipitation rate products (CDOP-3**)

MWS H70 Day-1



MWI H71 Day-1



SLALOM-based

PESCA-based

**** Exp. operational after EPS-SG-A/B commissioning phases, during CDOP-4**

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

Day-2 EPS-SG products will be developed during CDOP-4 with additional ML-based dedicated modules

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Summary

- **PMW sensors provide the temporal and spatial coverage needed for global snowfall climatology;**
- **Complexity:** Different snowfall spectral signature *at all frequencies* over different surfaces depending on falling snow *and* liquid water paths, T and WV conditions;
- **Low frequency channels needed to correctly interpret background signal and better constrain snowfall detection and quantification;**
- **State-of-the-art products are affected by significant underestimation;**
  - **Demonstrated benefits of using CloudSat/Calipso-based (Machine Learning) approach** (mostly for higher latitudes) exploiting all channels to better constrain environmental conditions;
- ***Paramount role of cloud/precipitation radars as calibrators for PMW snowfall detection/retrieval algorithms (fundamental at higher latitudes):***
  - GPM DPR (Ku/Ka-band) offers better coverage, is valuable for medium/heavy snow conditions; low sensitivity hampers detection/quantification capabilities
  - CloudSat-CPR provides by far the most complete view of snow systems thanks to high sensitivity but:
    - Need to verify Z-S relationship uncertainties associated to snow microphysics;
    - Ground clutter (miss lower 1200 m) affects surface snowfall estimate and detection of shallow snowfall;
    - CPR QPE is affected (higher rates) by **attenuation (by falling snow *and* SLW)**

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Questions?

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Precipitation Event Week

http://hsaf.meteoam.it

Visiting Scientist/Associated Scientist Program

New Call in January 2021

- ***Hydrological applications demonstrating potentials and limitations of H SAF products***

(Soil Moisture, Precipitation, Snow)

- ***Product development and advancement***
- ***Validation strategies***