RainCast study
AO/1-9324/18/NL/NA

Snowfall retrieval activities at CNR-ISAC

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EUMETSAT H SAF

MW radiometry and snowfall: A few key points

Snowfall detection and estimation is one of the main challenges in precipitation retrieval from space

- Current products show large discrepancies in snowfall climatologies (especially higher latitudes)

- ***CloudSat CPR (W band): has been*** considered reference for snowfall global monitoring (up to 82°N/S)
  - high sensitivity, more suitable for light-medium snowfall events
  - Some limiitations
    - Underestimation of heavy snowfall
    - Ground clutter
    - Attenuation (due to Supercooled liquid water)
    - **narrow swath (1.4 km) – limited coverage**

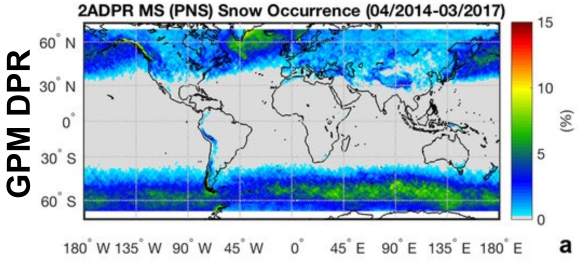
EarthCARE mission is paramount to continue CPR legacy

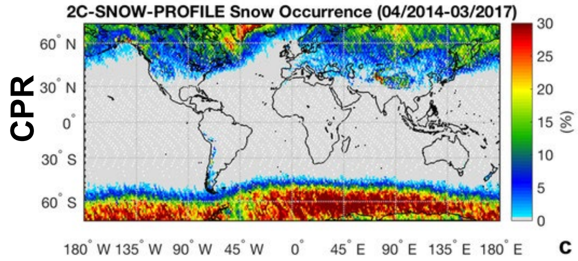
Need to rely on PMW radiometers for global snowfall monitoing: GPM constellation and future European missions

Large fraction of *higher latitudes snowfall* is missed by GPM DPR(Ku Ka-band) (mostly due to sensitivity limits).

DPR vs. CPR	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.)





(Skofronick-Jackson et al., 2019)

PMW Remote Sensing of Snowfall

Passive microwave (PMW) radiometers equipped with high frequency channels have sensitivity to snowfall microphysics and are used for snowfall retrieval

Challenges:

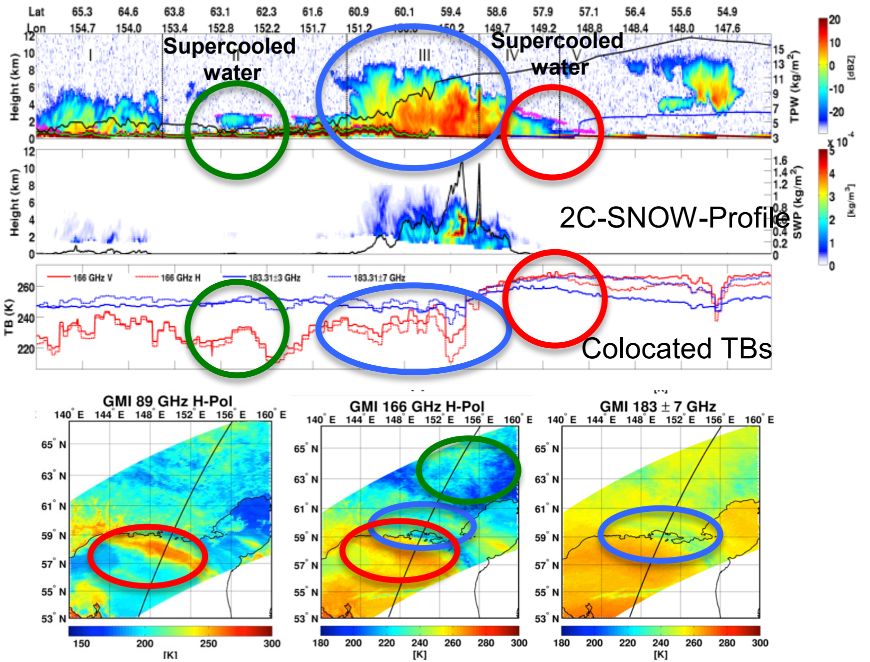
Complex interconnection between snowfall intensity, cloud properties, and environmental conditions (i.e., surface emissivity, atmospheric humidity) on PMW snowfall signature

Weak cloud ice and snowfall scattering signal *at high frequencies*

Emission *by supercooled cloud liquid water (SCLW) produce a TB warming effect* *which tends to mask the TB cooling caused by the scattering by snowflakes;*

Impact of background surface: *sea ice and snow-covered land surface emissivity is extremely variable*

Frontal snowfall over Siberia 30 April 2014
GMI/CloudSat-Calipso co-located observations



Panegrossi et al. 2017 Rem. Sens.

SLALOM: CloudSat-based PMW snowfall retrieval

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

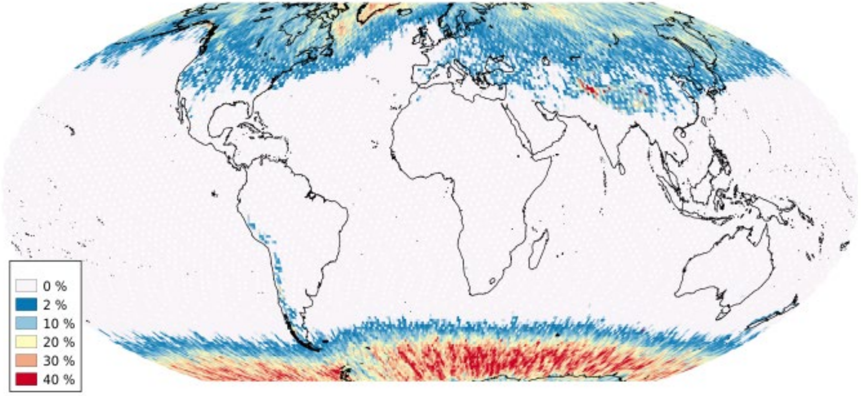
Machine Learning approach based on PMW-CloudSat/Calipso coincidence observational dataset
Input: PMW TBs (all channels) and auxiliary ECMWF analysis variables on atmospheric state (T2m, moisture profiles)
No auxiliary info on background surface conditions. ***CPR 2C-SNOW is used as reference***
SLALOM (for GMI) *((Rysman et al., 2018,2019):*

- Two ML modules for snowfall detection and supercooled liquid water detection;
- Two ML modules for snow water path (SWP) estimates and Surface snowfall rate (SSR)

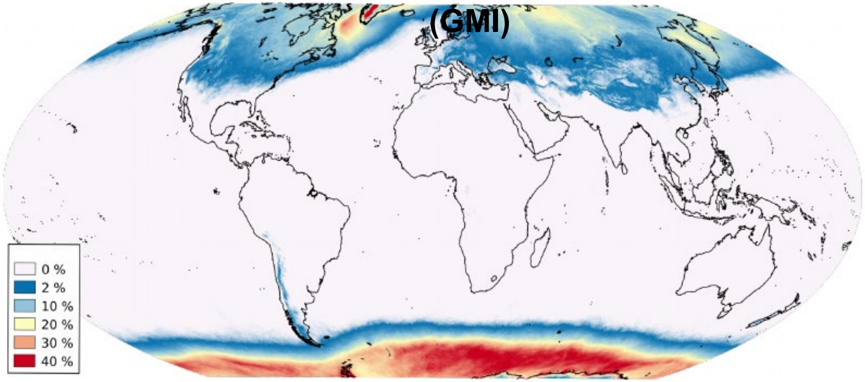
SLALOM-CT (for ATMS) (Sanò et al., 2022): similar modular approach, different ML techniques
SLALOM reproduces CloudSat CPR snowfall climatology over all surfaces; it is affected by the limitations of CPR 2C-SNOW product (Mroz et al., JHM, 2021)

Global snowfall Occurrence 05/2014 - 05/2016

CPR



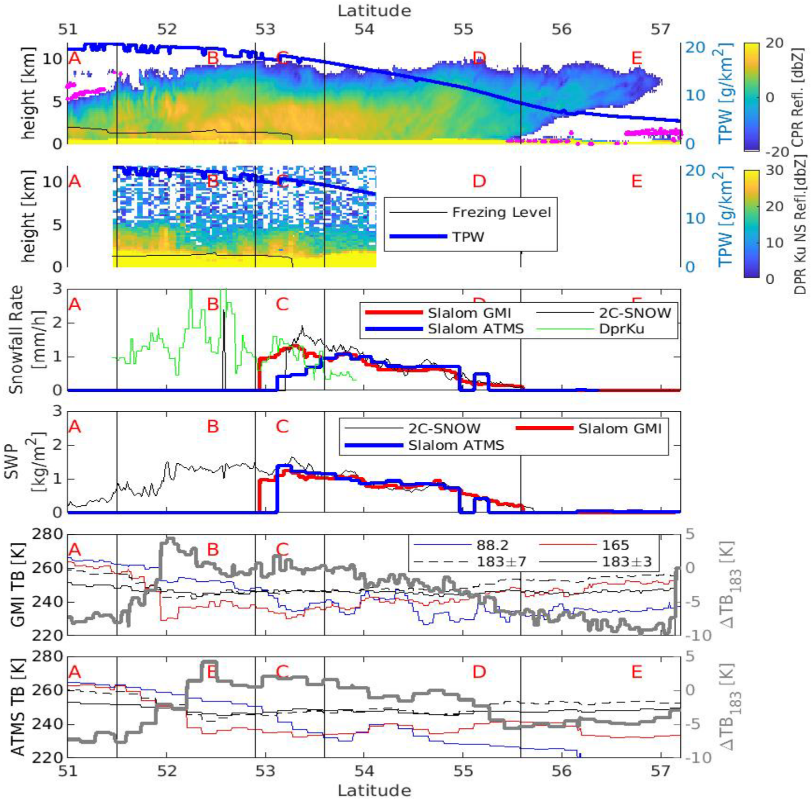
SLALOM (GMI)



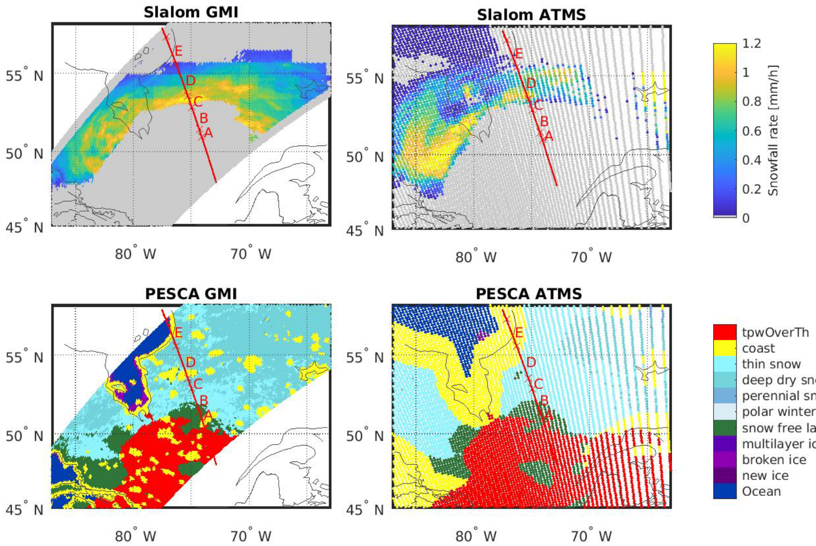
Rysman et al., JRL, 2019

CloudSat-based SLALOM and SLALOM-CT for GMI and ATMS (in preparation for H SAF EPS-SG MWS and MWI day-1 precipitation products)

Snowfall event over Quebec and Ontario on 24 November 2014



Turk et al., Rem. Sens., 2021



Use of low frequency channels for background surface characterisation at the time of the overpass

PESCA PMW Empirical clod surface Classification Algorithm

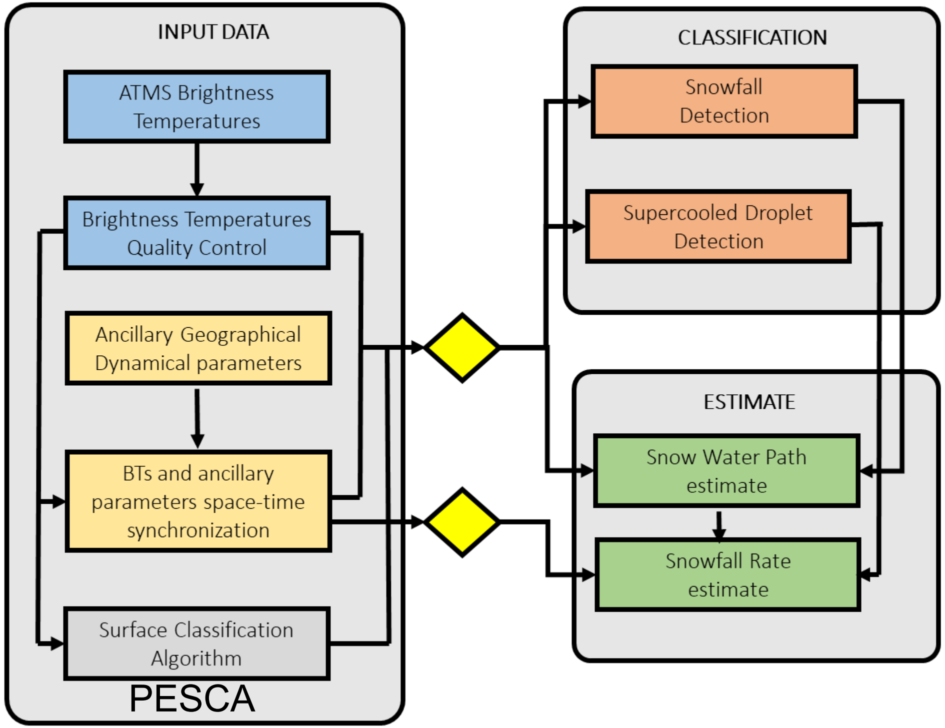
(Camplani et al., JHM, 2021)

Developed for ATMS and GMI, applicable to most PMW radiometers (EPS-SG) Working conditions: dry (TPW < 10 mm), low elevation (DEM < 2500 m); T2m < 280 K

SLALOM-CT: ATMS-CPR Coincidence dataset and flow diagram

Period	16/01/2014 – 31/08/2016
Geographical area	82°S–82°N, 180°W–180°E
Number of database points	6.5 M
Number of database points with snowfall	1.1 M
IFOV size	15.8 x 15.8 (nadir) 30 x 68.4 (scan edge)

INPUT Variables	Data source
ATMS BTs	NOAA
ATMS Scan angle	
Temperature @ 2m	ECMWF
Total column integrated water vapor	
Freezing level Height	
Temperature profile	
Relative humidity profile	
Absolute humidity profile	
REFERENCE Variables	**Data source**
Supercooled Water	DARDAR (raDAR/liDAR) LATMOS-Reading Univ.
Snowfall Rate	2C-SNOW-PROFILE (CPR product)
Snow Water Path	2C-SNOW-PROFILE (CPR product)



Sanò et al., 2022 doi:10.3390/rs14061467

HSAF Support to Operational Hydrology and Water Management

ML-based algorithms High lAtidude sNow Detection and rEtrieval aLgorithm for ATMS (HANDEL-ATMS) (Camplani et al., 2024, AMT)

Motivations

- **Snowfall retrieval at the high latitudes** is more challenging due to cold/dry conditions:
  - extremely variable background surface
  - impact of supercooled water layer on snowfall signature
- development of the day-1 precipitation products for the European MetOp-SG mission at CNR-ISAC within the EUMETSAT HSAF program

HANDEL working limiits: T2m < 280 K TPW < 10 mm

ATMS/Cloudsat CPR coincidence dataset

Period	2014-2016
Area	82°S-82°N 180°W-180°E
Total Observation Number	6.5 M
Snowfall Observation Number	1.1 M
Resolution (km)	15.8 x 15.8 (nadir) 30 x 68.4 (scan edge)

- **Exploits PESCA classification**
- **ML techniques to retrieve frozen surface emissivity at the time of the overpass**
- **Estimates TB-clear-sky (Tb_{sim}) and uses multi-channel TB_{obs}-Tb_{sim} as input**
- **Two ML-based SWP and SSR detection modules**
- **Two-ML based SWP and SSR estimation modules**

SLALOM-CT vs. HANDEL

SLALOM-CT

- Snow retrievaL ALgorithm fOr gpM - Cross Track
- supercooled droplets detection module
- Shallow/Convolutional Neural Networks
- ANN Input dataset: ATMS TBs, PESCA output, environmental single level parameters, temperature/humidity profile PCs

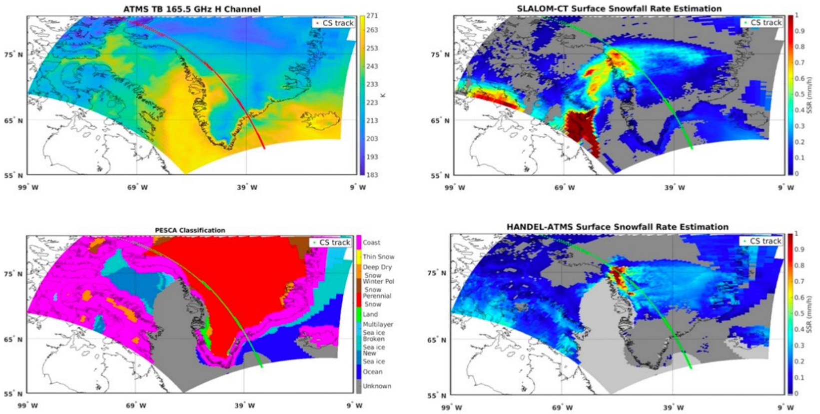
HANDEL-ATMS

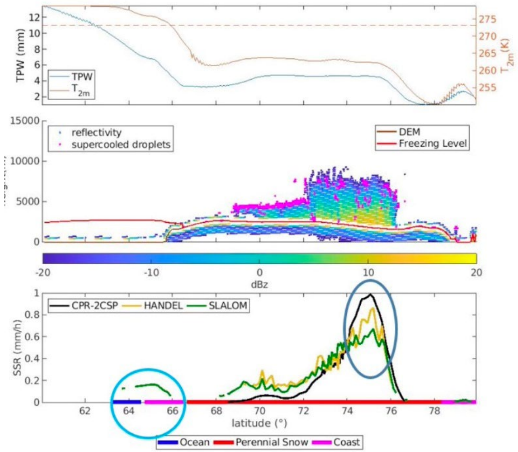
- High lAtitude sNow Detection and rEtrieval aLgorithm for ATMS
- **high-latitude environmental conditions** - dry and cold atmosphere, snowpack over the ground, supercooled water layer in/over the clouds
- Shallow Neural Networks
- ANN Input dataset: ATMS TBs, $\Delta TB_{obs-sim}$, PESCA output

ML-based algorithms High lAtidude sNow Detection and rEtrieval aLgorithm for ATMS (HANDEL) (Camplani et al., 2024, AMT)

Greenland - 2016/04/24

Date	CPR Orbit	ATMS Orbit	CPR Time UTC	ATMS Time UTC
2016/04/24	53148	23271	14:51:23-14:57:27	20:42:09-20:51:02





- SLALOM-CT performs a snowfall retrieval on a global scale
- HANDEL-ATMS is focused on high-latitude conditions

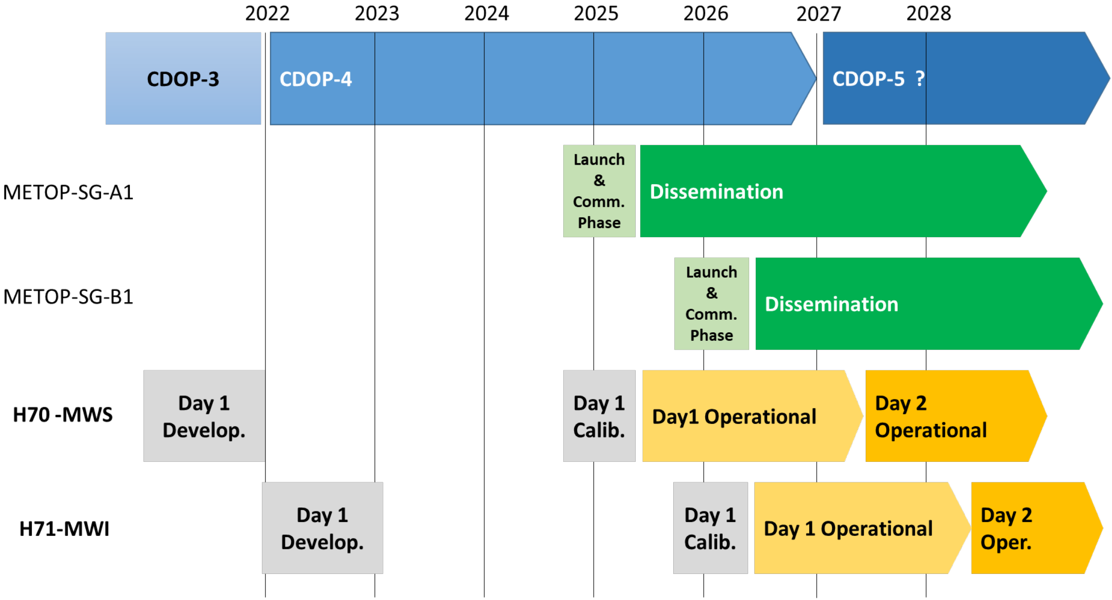
	RMSE	bias	R^2 (-)	POD	FAR	HSS
SWP ($\frac{kg}{m^2}$)	0.047	0.001	0.72	0.85	0.15	0.70
SSR ($\frac{mm}{h}$)	0.079	0.002	0.61	0.84	0.16	0.69

	POD		FAR	
	SLALOM CT	HANDEL ATMS	SLALOM CT	HANDEL ATMS
T2m<280 K TPW<10 mm	0.82	0.84	0.19	0.16
T2m<250 K TPW<5 mm	0.64	0.68	0.27	0.23
T2m<240 K TPW<3 mm	0.45	0.54	0.33	0.28

The H-SAF EPS-SG MWI and MWS Global L2 Products for Snowfall and Rainfall retrieval

see poster 14.7 Tomorrow (Thu. July 17)

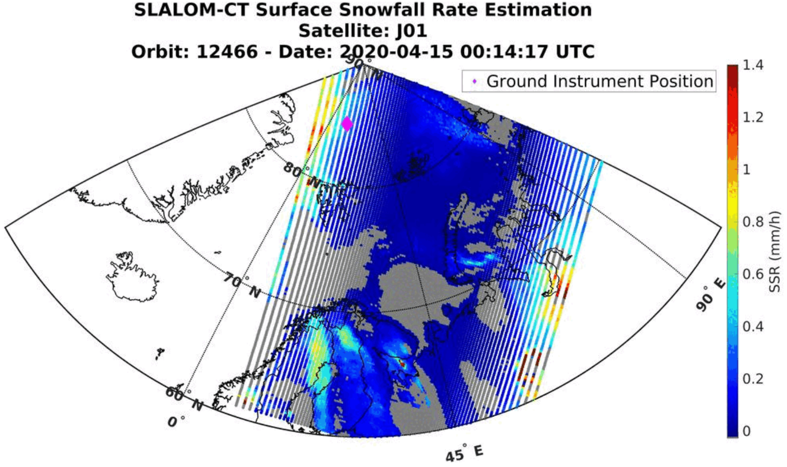
- Level 2 products providing instantaneous precipitation rate, on a global scale, from the EPS-SG MWS – MWI brightness temperatures.
- Designed as the Day 1 operational precipitation product for the Metop-SG series (A&B), include different modules specifically designed for the detection and estimate of rainfall and snowfall.
- Developed using the ATMS cross-track radiometer and GMI conical scanning radiometer, similar in terms of channel frequencies and spatial resolution to MWS and MWI.
- Different modules are based on machine learning approach trained using GPM-CO and CloudSat spaceborne radar precipitation products as reference

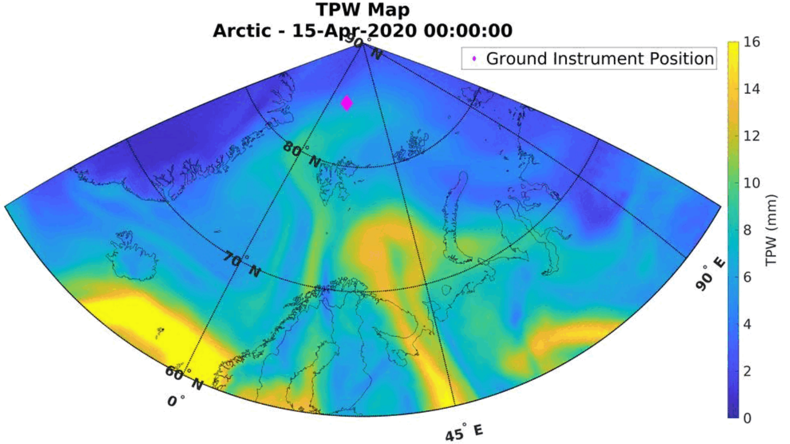


Ongoing collaboration with University of Cologne (S. Crewell, M. Mech)

ArctiC Amplification:
Climate Relevant Atmospheric and SurfaCe Processes
and Feedback Mechanisms (AC)³

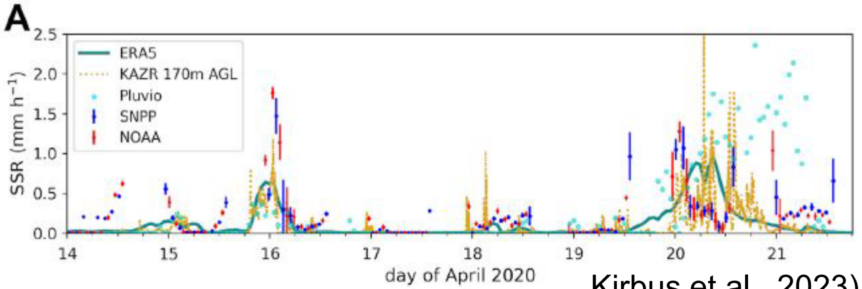
Extreme event in central Arctic Ocean on April 15-16 2020





- The AR event on April 15 had his origin in the Atlantic moved northward, across central Europe and Svalbard and hit the Polarstern on 15 April at 19 UTC and lasted until 16 April 20 UTC.

- **Comparisons with AFLUX P5 and HALO AC3 measurement are ongoing**



Kirbus et al., 2023)

RainCast study
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Analysis of the Arctic Weather Satellite snowfall osbervation capabilities

AWS: Forerunner of the potential EPS-Sterna mission conceived as a constellation of small (120 kg) polar-orbiting satellites

Launch of the ESA AWS prototype scheduled in July 2024

AWS Microwave Radiometer (MWR)

- 19 channel cross-track scanning
- Frequency range 50–325 GHz

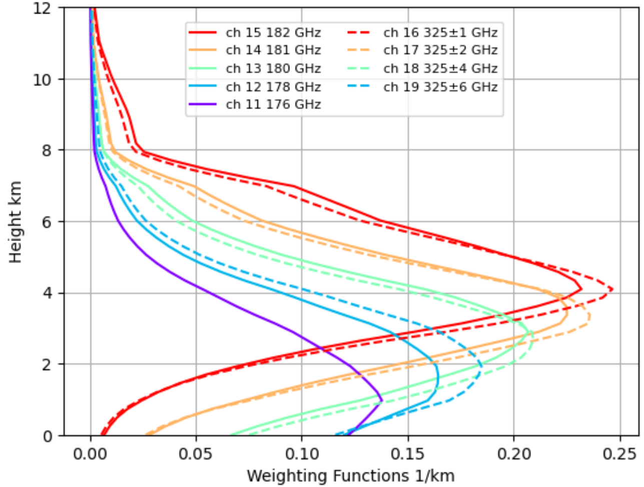
No	Central Frequency(GHz)	Bandwidth (MHz)	NEΔT (K)	IFOV (km)	Pol.	Primary Utilization
1	50.3	180	<0.6	≤40	QV	Temperature Sounding
2	52.8	400	<0.4	≤40	QV	Temperature Sounding
3	53.246	300	<0.4	≤40	QV	Temperature Sounding
4	53.596	370	<0.4	≤40	QV	Temperature Sounding
5	54.4	400	<0.4	≤40	QV	Temperature Sounding
6	54.94	400	<0.4	≤40	QV	Temperature Sounding
7	55.5	330	<0.5	≤40	QV	Temperature Sounding
8	57.290344	330	<0.6	≤40	QV	Temperature Sounding
9	89	4000	<0.3	≤20	QV	Window/Cloud Detection
10	165	2800	<0.6	≤10	QV	Window/Humidity Sounding
11	176.311	2000	<0.7	≤10	QV	Humidity Sounding
12	178.311	2000	<0.7	≤10	QV	Humidity Sounding
13	180.311	1000	<1	≤10	QV	Humidity Sounding
14	181.311	1000	<1	≤10	QV	Humidity Sounding
15	182.311	500	<1.3	≤10	QV	Humidity Sounding
16	325.15±1.2	800	<1.7	≤10	QV	Humidity Sounding/ Cloud Detection
17	325.15±2.4	1200	<1.4	≤10	QV	Humidity Sounding/ Cloud Detection
18	325.15±4.1	1800	<1.2	≤10	QV	Humidity Sounding/ Cloud Detection
19	325.15 ±6.6	2800	<1	≤10	QV	Humidity Sounding/ Cloud Detection

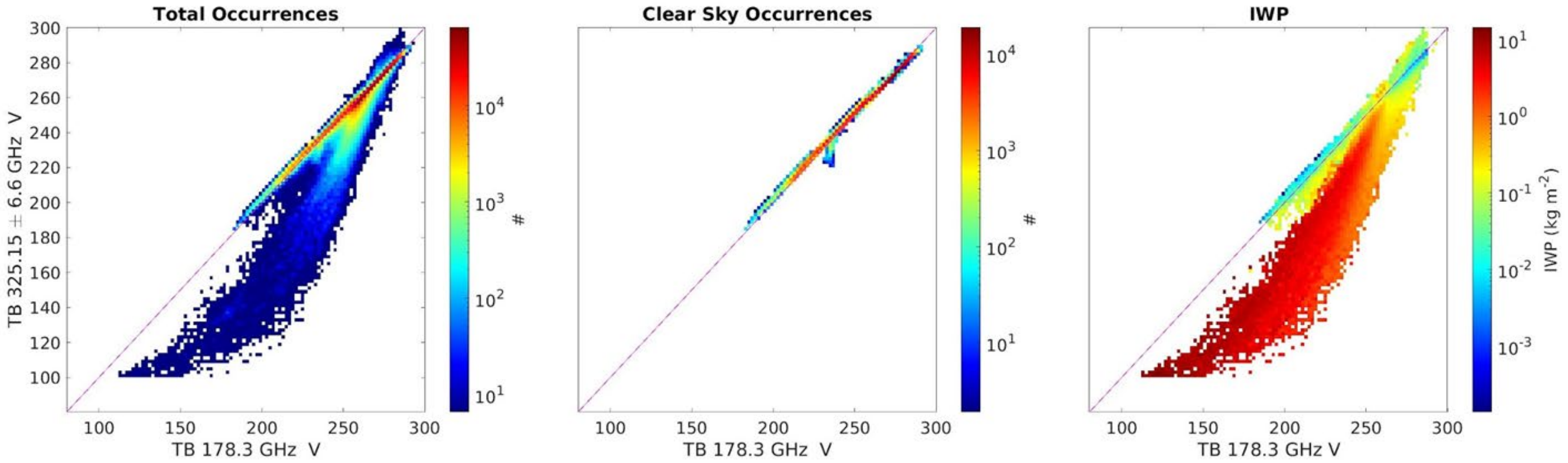
Analysis of AWS coupled channels

Coupled Channels at 183.31 GHz and 325.15 GHz

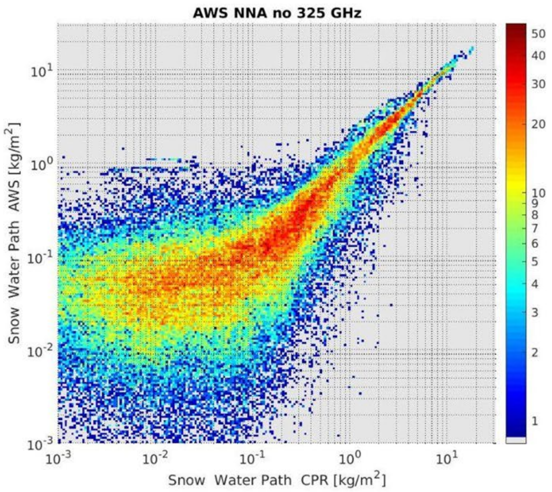
- share very similar weighting functions in clear sky
- have very different response to the presence of cloud ice

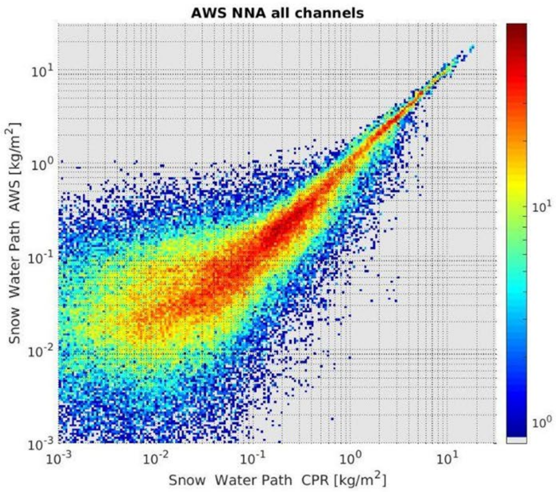
Weighting functions - subarctic-winter standard atmosphere





ANN snowfall retrieval with and w/o 325.15 GHz channels





	IWP		Snowfall Rate	
	AWS full	AWS 15ch	AWS full	AWS 15ch
RMSE	0.18 kg/m²	0.22 kg/m²	0.64 mm/h	0.73 mm/h
R^2	0.95	0.94	0.65	0.54
ME	-0.0037 kg/m²	-0.0064 kg/m²	-0.030 mm/h	-0.033 mm/h
CC	0.98	0.97	0.80	0.73

AWS sounding channels in the 325.15 GHz water vapour absorption band contribute significantly to the improved estimation of the IWP and to a less extent of the surface snowfall rate
(the surface snowfall rate ANN retrieval is affected by the limited size of the **training dataset)**

increased sensitivity of ANN using 325.15 channels to **very light snowfall** typical of the high latitudes.

Impact of (unseen) SLW embedded in clouds

Impact of supercooled liquid water on PMW snowfall observation capabilities

Case Study: Snowfall event - Terranova Bay over ice-free ocean

Date: 2007/01/01

Location: North Atlantic

Radiometer: MHS

Radar: CPR

CPR Time: 05:32:07

05:37:27 U.T.C.

MHS Time: 05:11:03

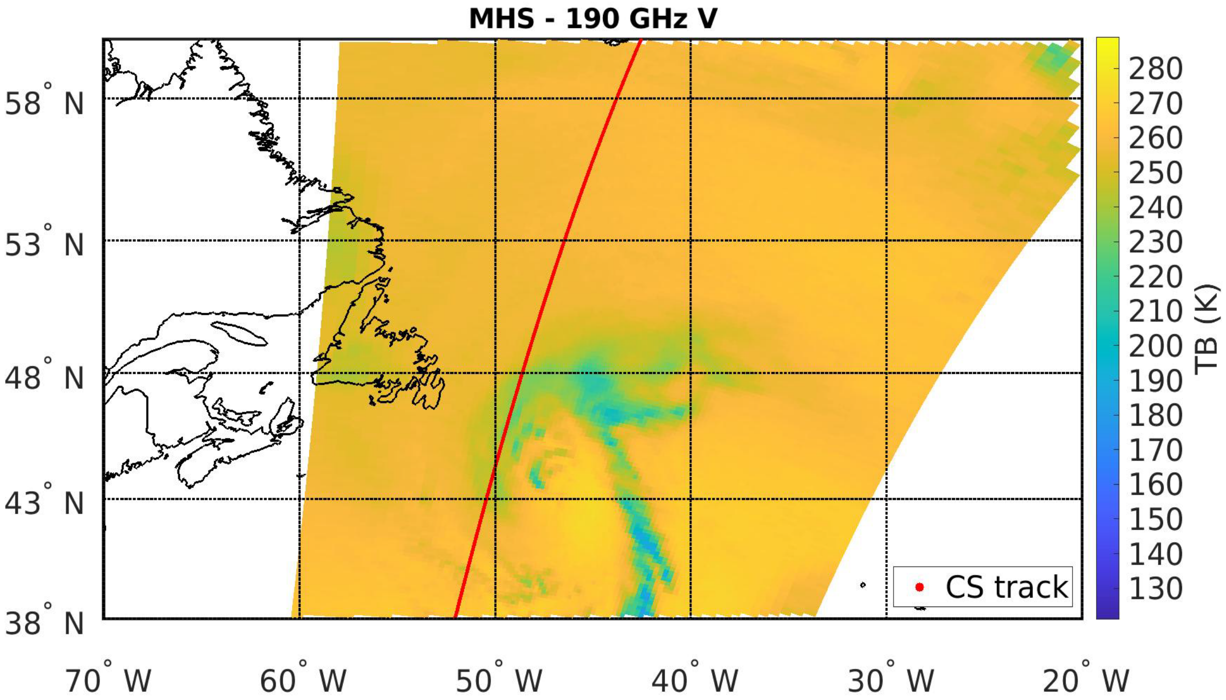
05:16:34 U.T.C.

CPR Orbit: 3609

MHS Orbit: 8329

Time Span: 21 min

MHS viewing angle: 20° - 22°



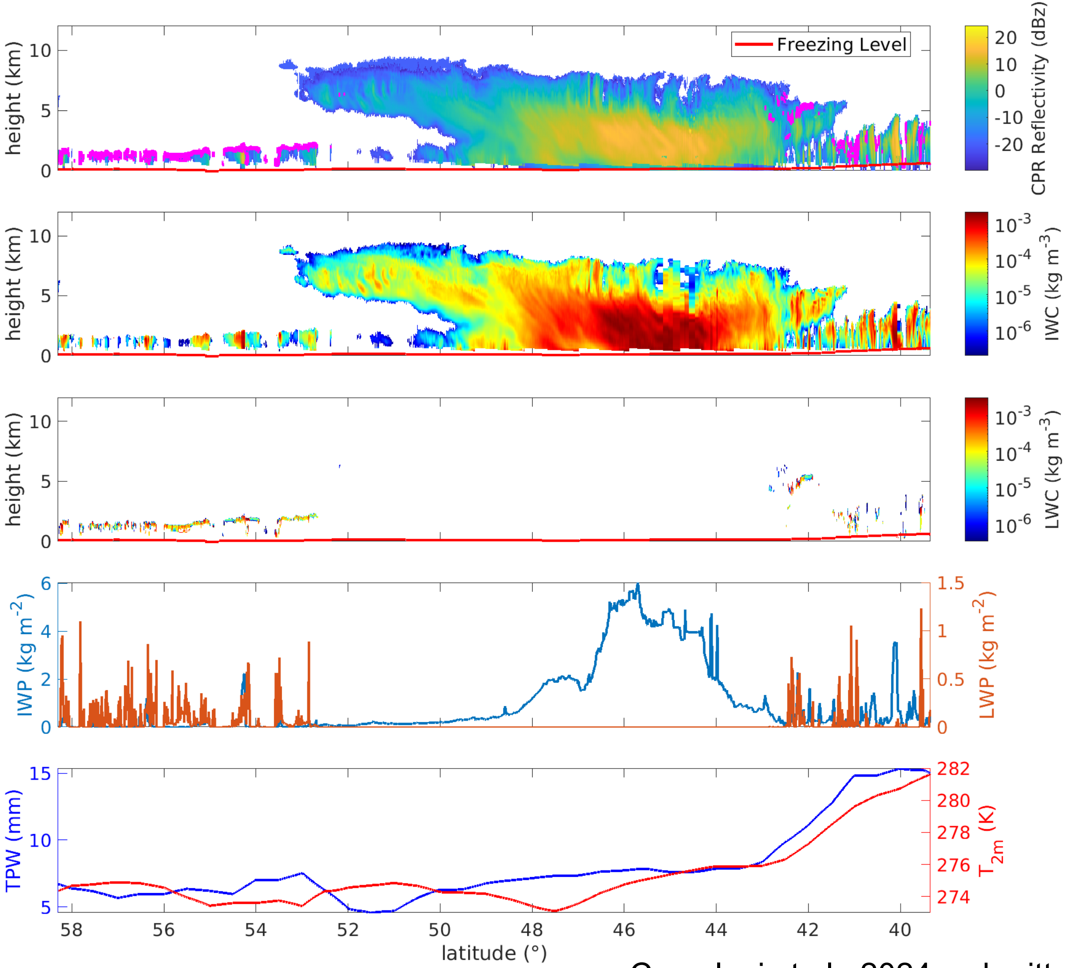
Camplani et al., 2024, submitted

Case Study: Snowfall event - Terranova Bay over ice-free ocean

- Shallow snowfall structures in the northern part (from 52 ° N to 58 ° N)
- cloud between 43 ° N and 48° N shows deep convection features
- large anvil extending to the north (from 48 ° N to 52 ° N)

Captivate product

- identifies the presence of supercooled liquid water (SLW) only in the northern part
- does not identify the presence of supercooled water layers in correspondence with the deep and intense snowfall event
- retrieves high IWC values in correspondence with the deep cloud, with IWP values reaching 6 kg m^{-2}



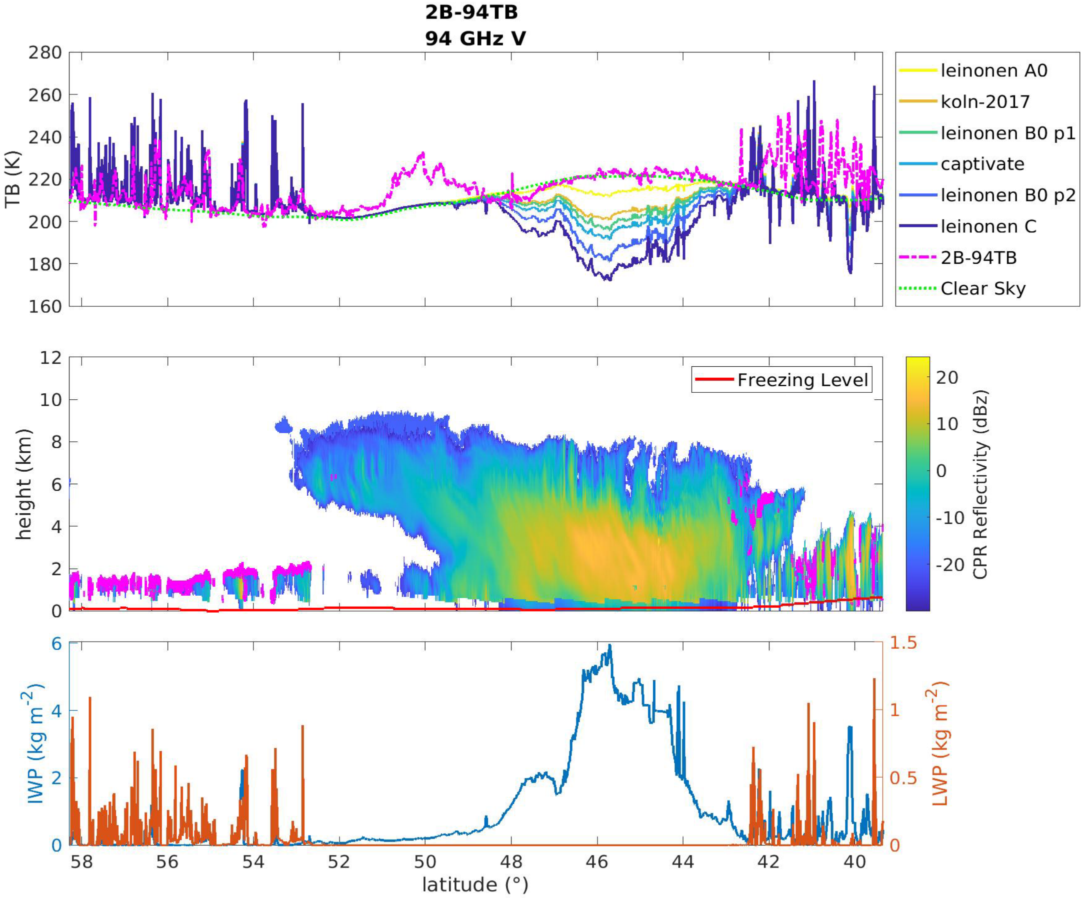
Camplani et al., 2024, submitted

Case Study: Snowfall event - Terranova Bay over ice-free ocean

Comparison between CPR-2B-TB94 (TB_{obs}) and simulated TBs (TB_{sim}) at 94 GHz

CAPTIVATE IWC and LWC profiles and several R-G models

- Good agreement between TB_{sim} (regardless of the R-G model used) and TB_{obs}, for the shallow cloud system north of 52°N
- 2B-TB94 increase in correspondence with the anvil is not identified by the models
- TB_{sim} decrease due to scattering by ice hydrometors (for any R-G model) such effect is not observed in the 2B-TB94



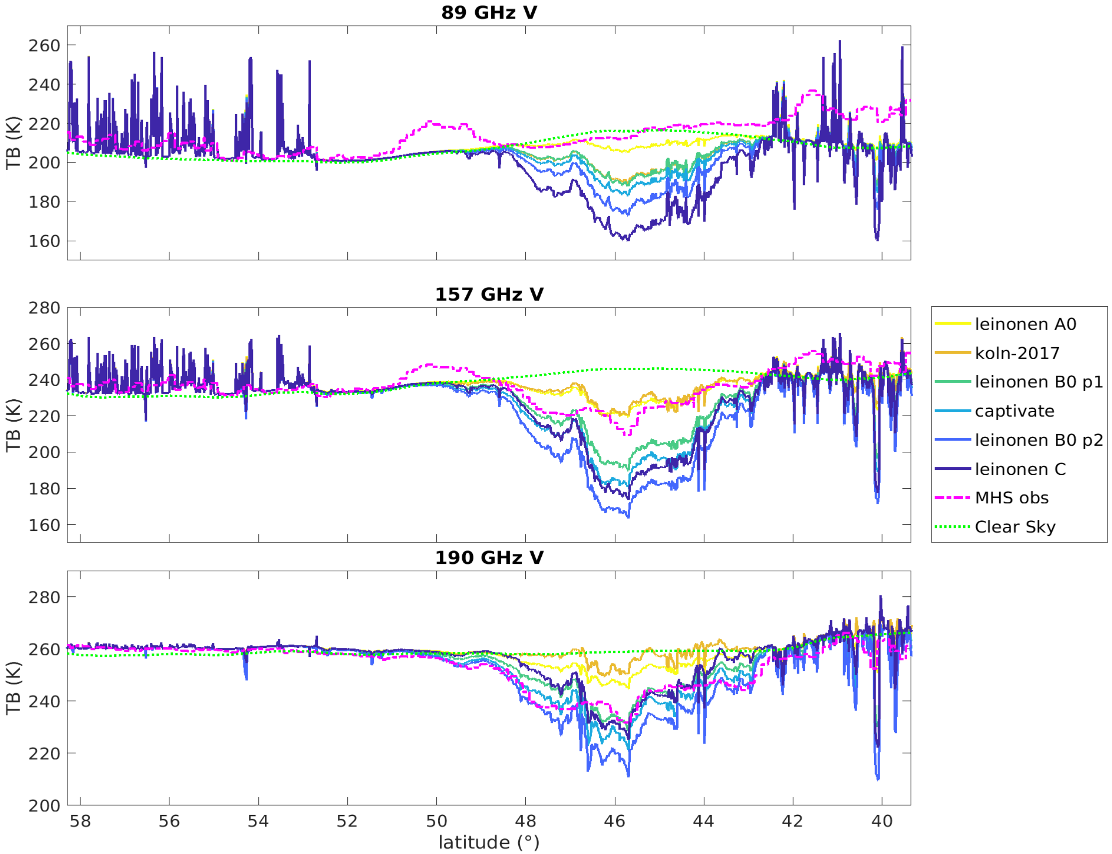
Camplani et al., 2024, submitted

Case Study: Snowfall event - Terranova Bay over ice-free ocean

Comparison between MHS TB_{obs} and Tb_{sim}

CAPTIVATE IWC and LWC profiles and several R-G models

- 89 and 157 GHz: TBobs increase in correspondence with the anvil - not identified in TB_{sim}
- 89 GHz: TBsim decrease in correspondence with deeper cloud (scattering effect not present in TB_{obs})
- A good agreement between for some of the models at 190.31 GHz between TB_{sim} and TB_{obs}



Camplani et al., 2024, submitted

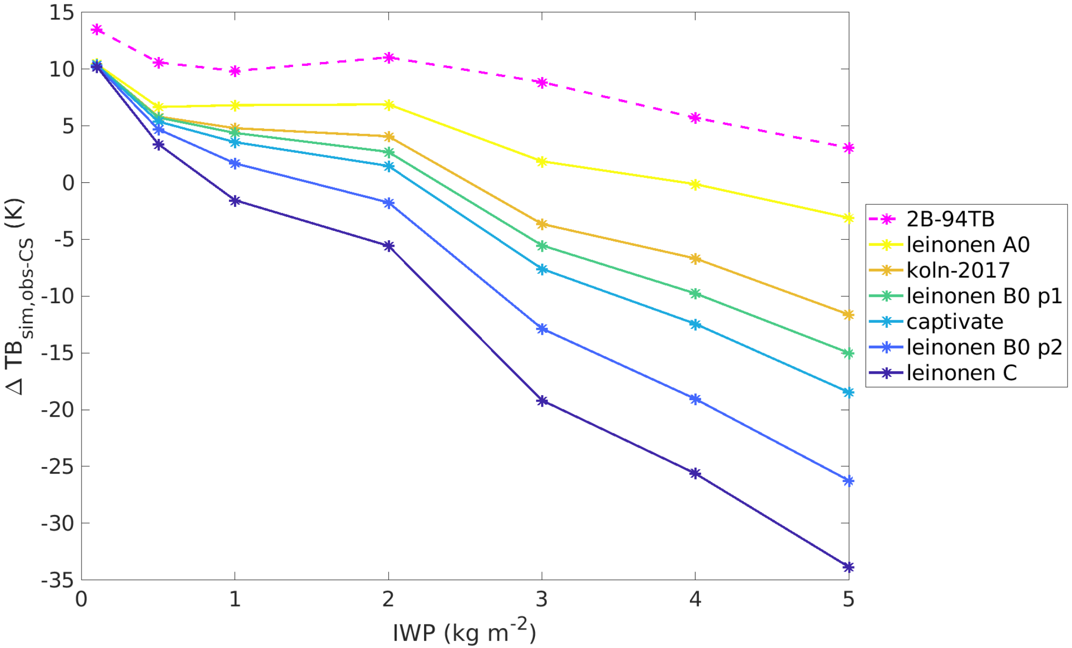
Impact of SLW on snowfall signature at 94 GHz

analysis over the whole dataset (over ice free ocean)

$\Delta TB_{obs\text{-}cs}$ Differences between CPR passive mode 2B-94TB and the corresponding simulated clear-sky TBs (mean values for IWP bins)

$\Delta TB_{sim\text{-}CS}$ Differences between the simulated TBs obtained from CAPTIVATE profiles and the corresponding clear-sky TBs (mean values for IWP bins)

- mean $\Delta TB_{obs\text{-}cs} > 0$ K (emission signal for all IWP values)
- $\Delta TB_{sim\text{-}CS} < 0$K (scattering signal) difference increases with IWP values and depends on the single scattering model

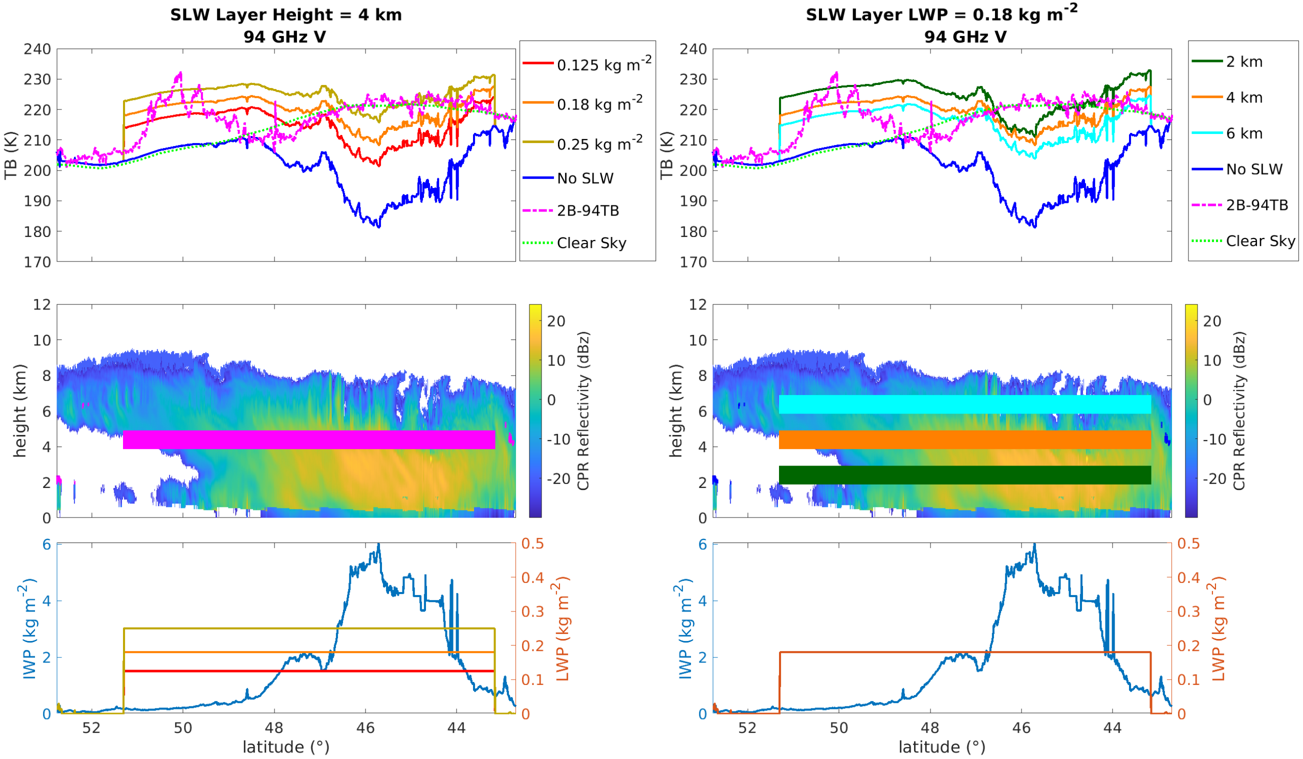


Camplani et al., 2024, submitted

Case Study: Snowfall event - Terranova Bay over ice-free ocean

Sensitivity analysis to the presence of SLW @ 94 GHz

- CloudSat CPR 2B-TB94 product
- R-G model: Leinonen B0 p2
- Supercooled Water Layer:
  - 1 km depth
  - Same height (4 km), different LWP (0.125, 0,18, 0,25 kg m^{-2})
  - Same LWP (0,18 km m^{-2}) different heights (2, 4, 6 km)

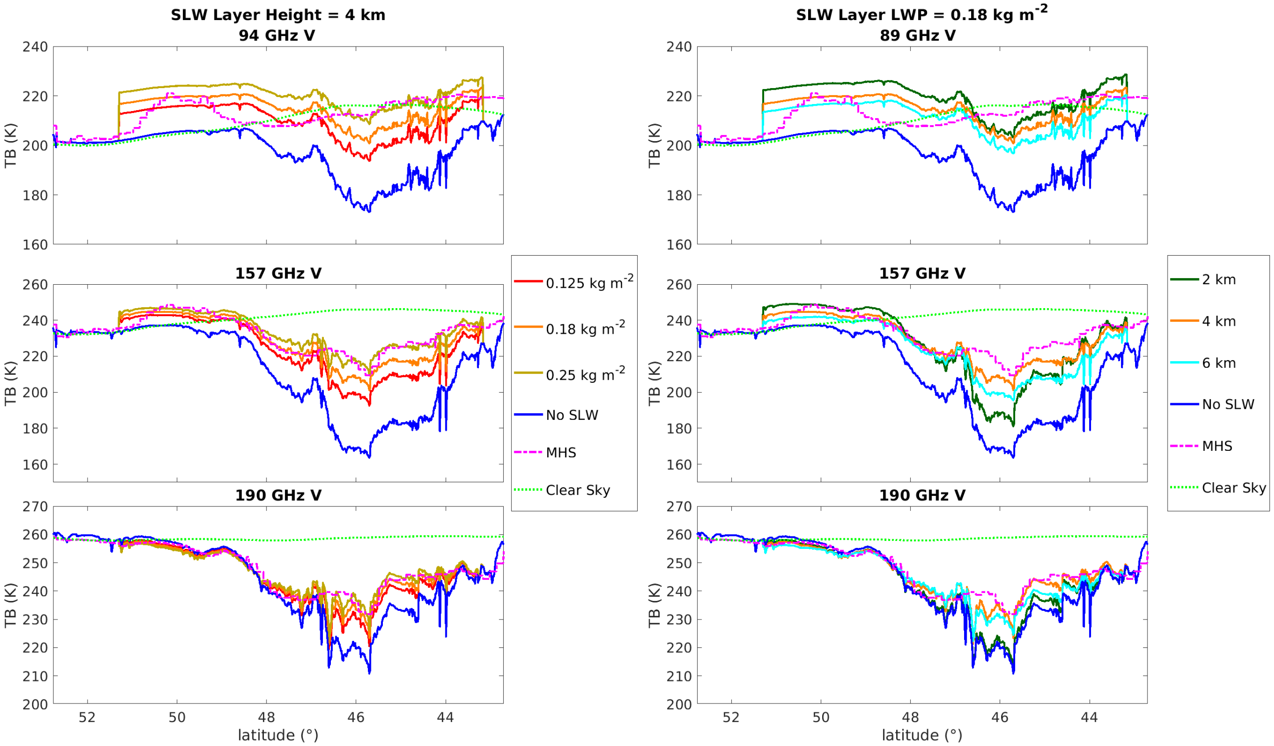


Camplani et al., 2024, submitted

Case Study: Snowfall event - Terranova Bay over ice-free ocean

Sensitivity analysis to the presence of SLW – MHS (or AWS) channels

- R-G model: Leinonen B0 p2
- Supercooled Water Layer:
  - 1 km depth
  - Same height (4 km), different LWP (0.125, 0,18, 0,25 kg m^{-2})
  - Same LWP (0,18 km m^{-2}) different heights (2, 4, 6 km)



Camplani et al., 2024, submitted

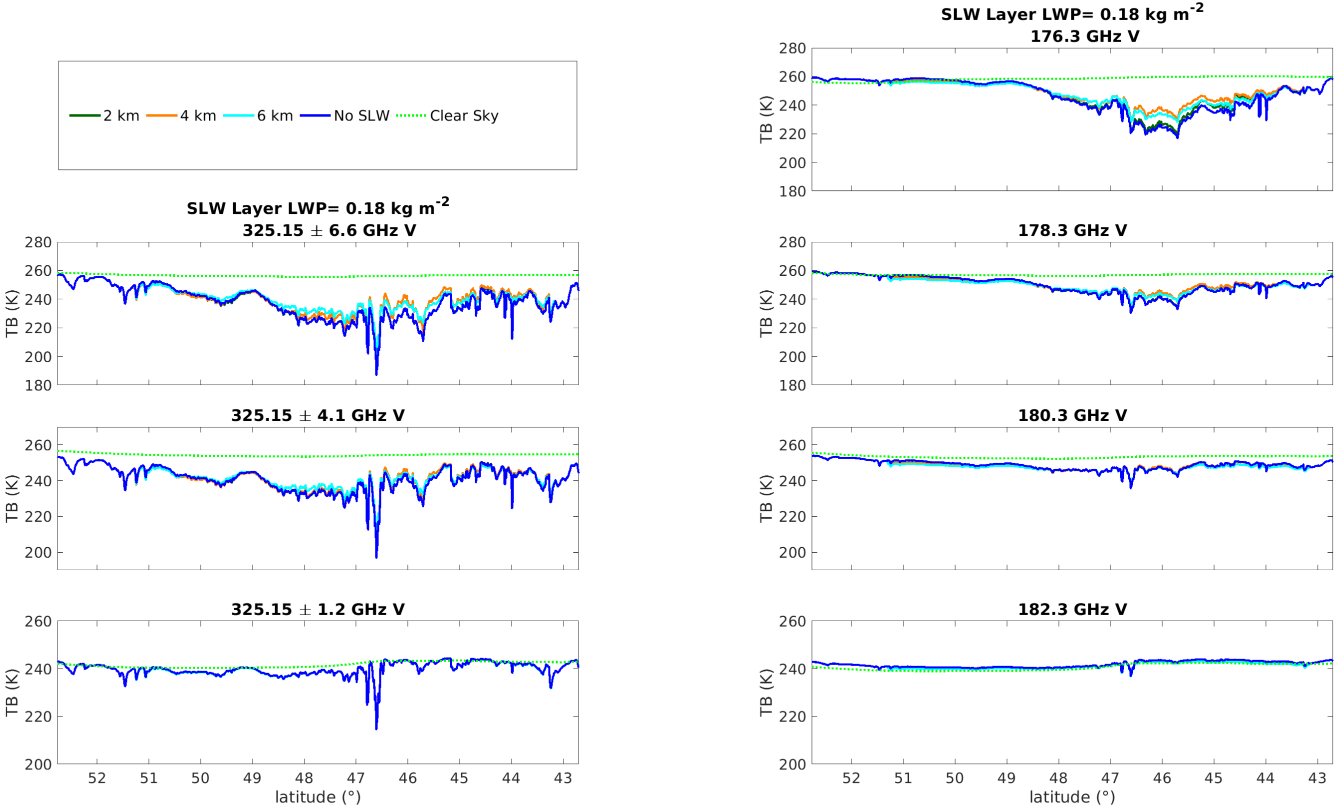
Case Study: Snowfall event - Terranova Bay over ice-free ocean

Sensitivity analysis to the presence of SLW – AWS-MWR coupled channels

AWS-MWR 325.15 GHZ and 183.31 GHz channels

- viewing angle: nadir

  - The new 325.15 GHz channles are higly sensitive to IWC
  - the external channels of the two bands are slighlty sensitive to supercooled water layer position



Camplani et al., 2024, submitted

Take home messages from RainCast study on AWS

1) Impact of the lack of low frequency channels is lower than expected

2) the 325.15 GHz sounding channels improve IWP and of SSR retrieval, with increased sensitivity to very light snowfall typical of the high latitudes.

3) There are very useful indications that the AWS-MWS channels have the potential to be used for microphysics characterization of high latitude snowfall (including SLW embedded inn clouds)

AWS-MWR new capabilities can contribute to better quantify high latitude precipitation (e.g., very light snowfall events) and to gain new insights about key microphysical processes (presence of supercooled water also when embedded in the cloud). EPS-Sterna constellation will improve our ability to monitor high latitude precipitation patterns and intensity from space

To reach this goal, it will be essential to exploit the synergy with EarthCARE (CPR + ATLID)

esa
European Space Agency

RainCast study
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