Snowfall in the GPM Era: Assessing GPM Snowfall Retrievals Using Independent Spaceborne, Reanalysis, and Ground-Based Datasets

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ISAC/CNR: G. Panegrossi, D. Casella, A. C. Marra, J. F. Rysman, P. Sano, V. Levizzani

CSU: D. Randel, C. Kummerow

Particle Size Distribution (PSD) Working Group (C. Williams)

Michigan Technological University

The Status of the Tropical Rainfall Measuring Mission (TRMM) after Two Years in Orbit

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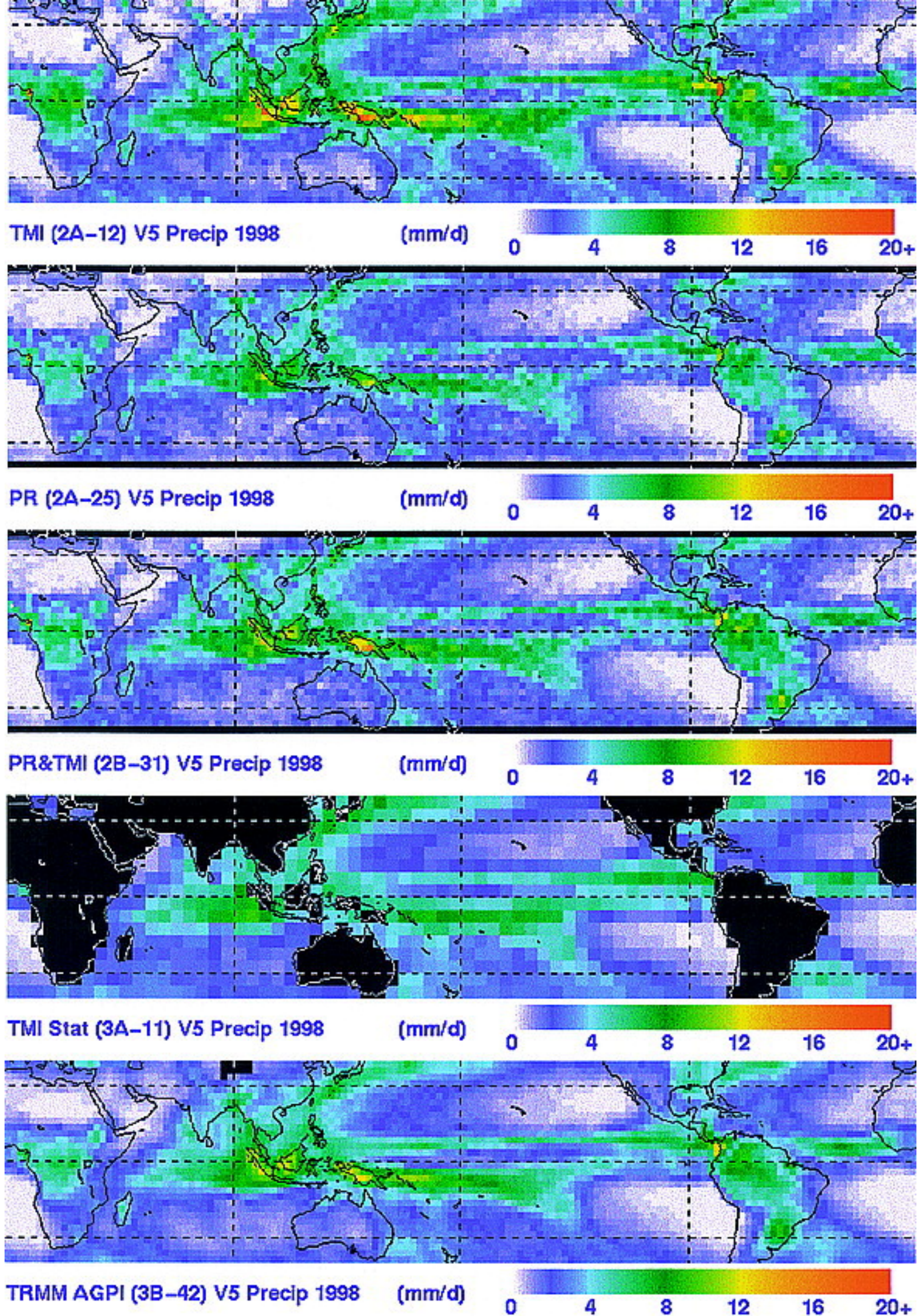
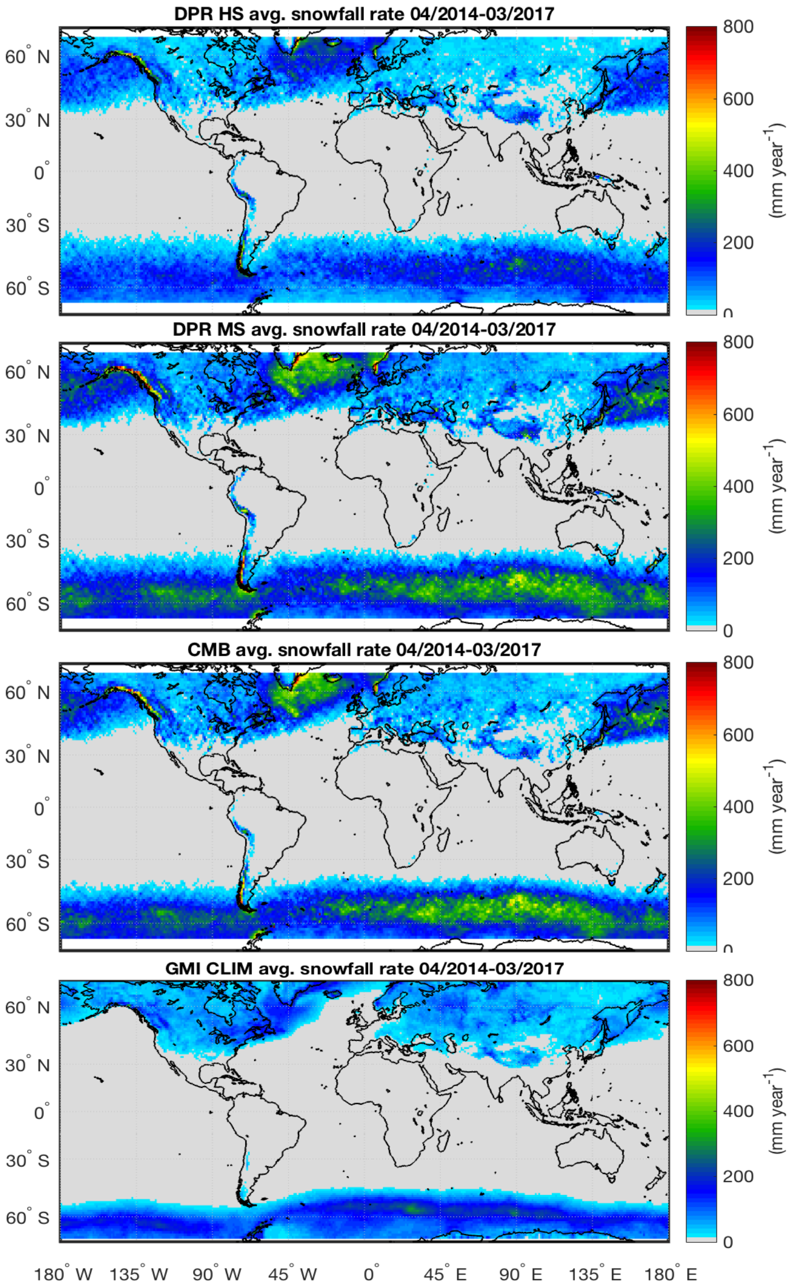
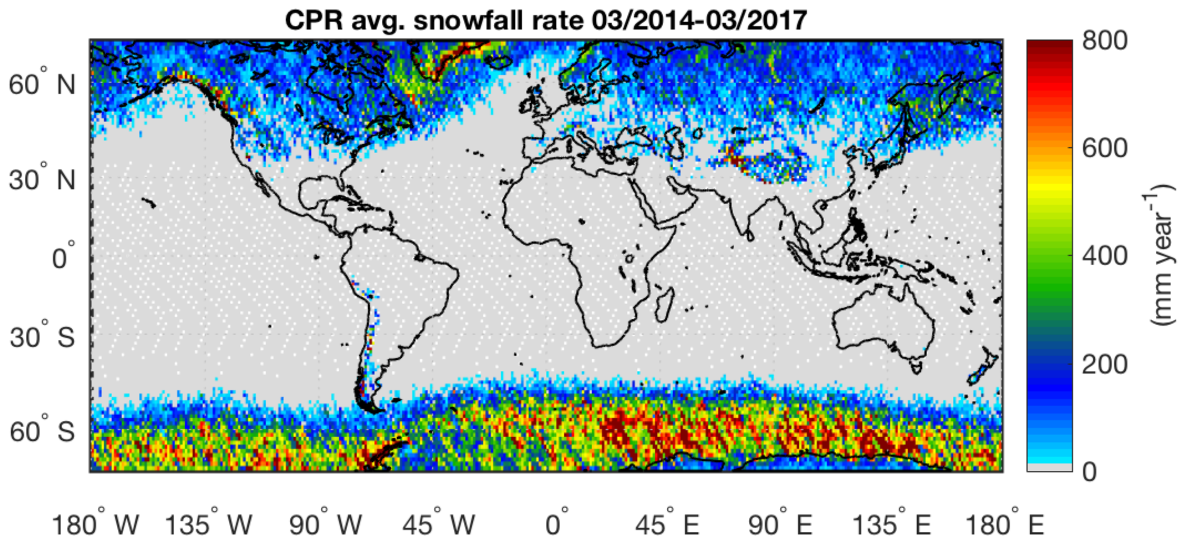

TMI (2A-12) V5 Precip 1998
(mm/d)
0 4 8 12 16 20+
PR (2A-25) V5 Precip 1998
(mm/d)
0 4 8 12 16 20+
PR&TMI (2B-31) V5 Precip 1998
(mm/d)
0 4 8 12 16 20+
TMI Stat (3A-11) V5 Precip 1998
(mm/d)
0 4 8 12 16 20+
TRMM AGPI (3B-42) V5 Precip 1998
(mm/d)
0 4 8 12 16 20+


DPR HS avg. snowfall rate 04/2014-03/2017
DPR MS avg. snowfall rate 04/2014-03/2017
CMB avg. snowfall rate 04/2014-03/2017
GMI CLIM avg. snowfall rate 04/2014-03/2017
60° N
30° N
0°
30° S
60° S
800
600
400
200
0
(mm year-1)
180° W
135° W
90° W
45° W
0°
45° E
90° E
135° E
180° E

GPM Snowfall

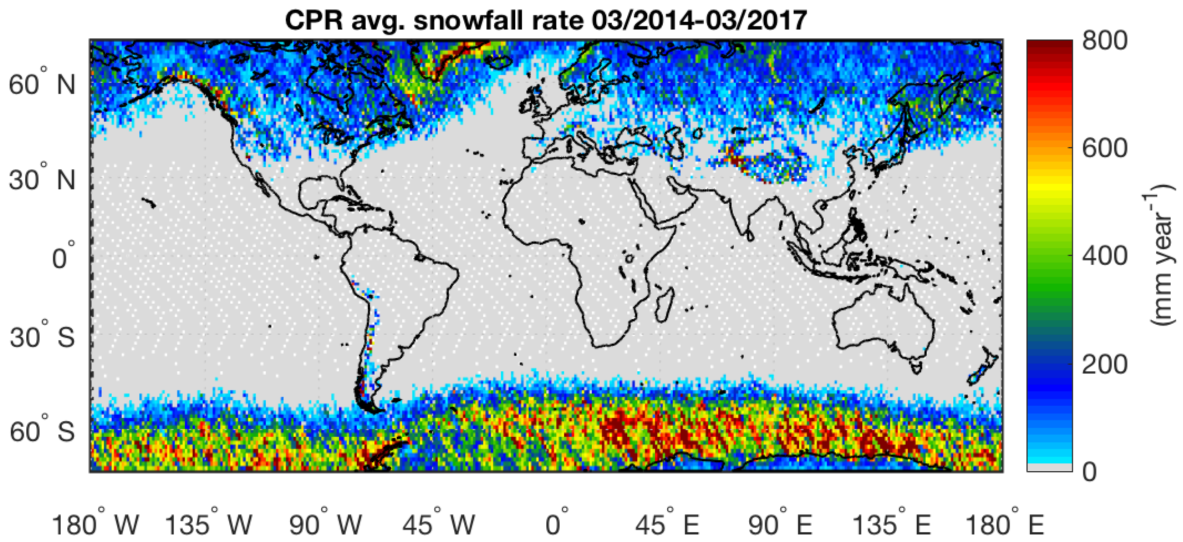
- Mission mandate: snowfall *detection* capabilities

GPM Snowfall Retrieval Assessment



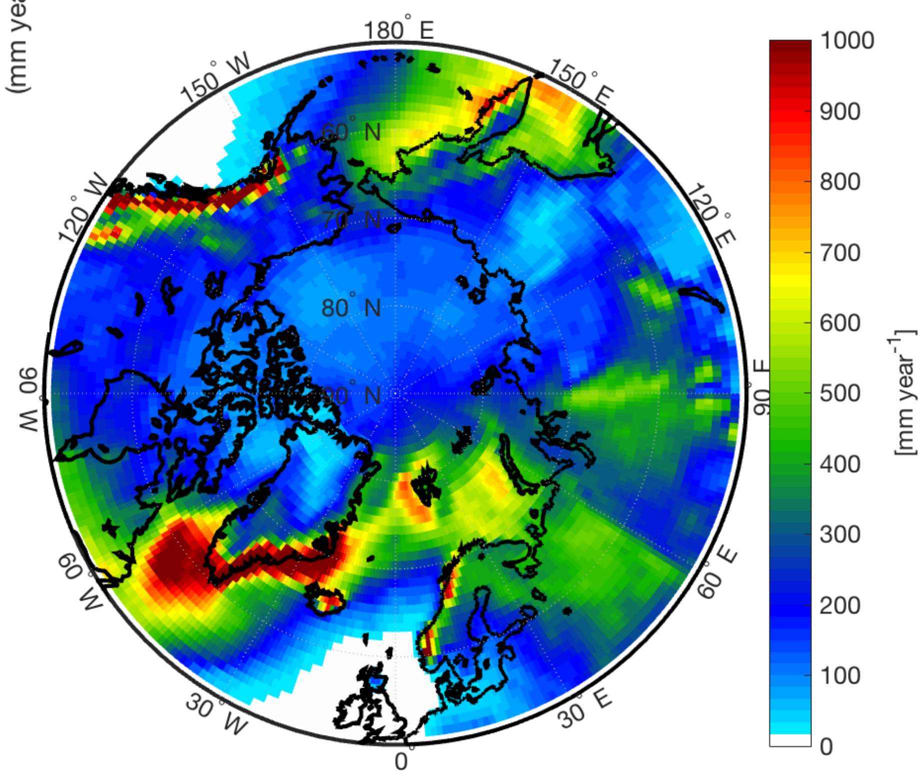
CloudSat (CPR)

GPM Snowfall Retrieval Assessment

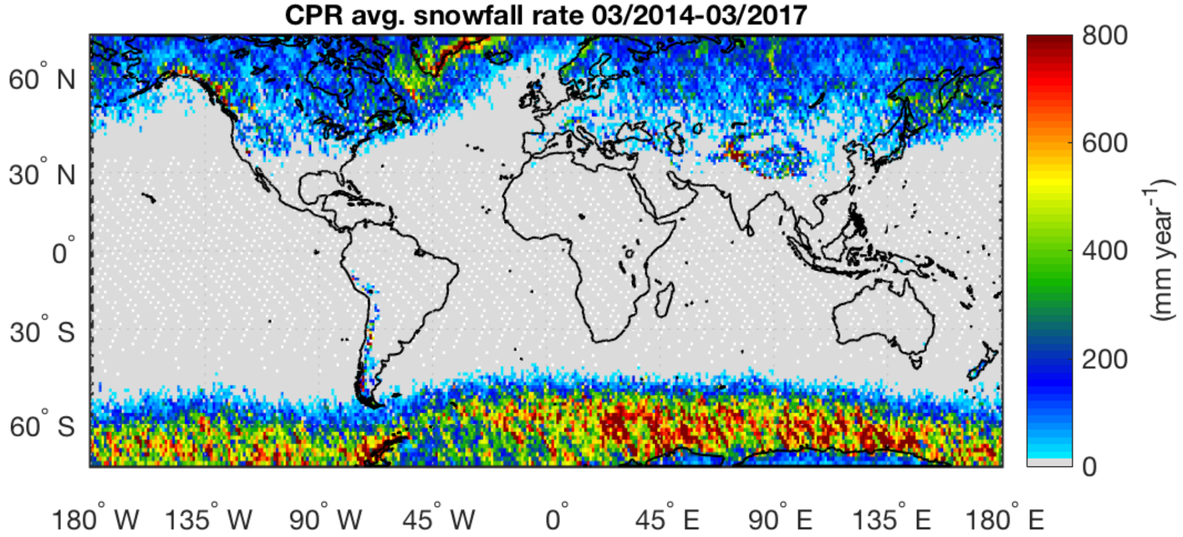


CloudSat (CPR)

Reanalysis

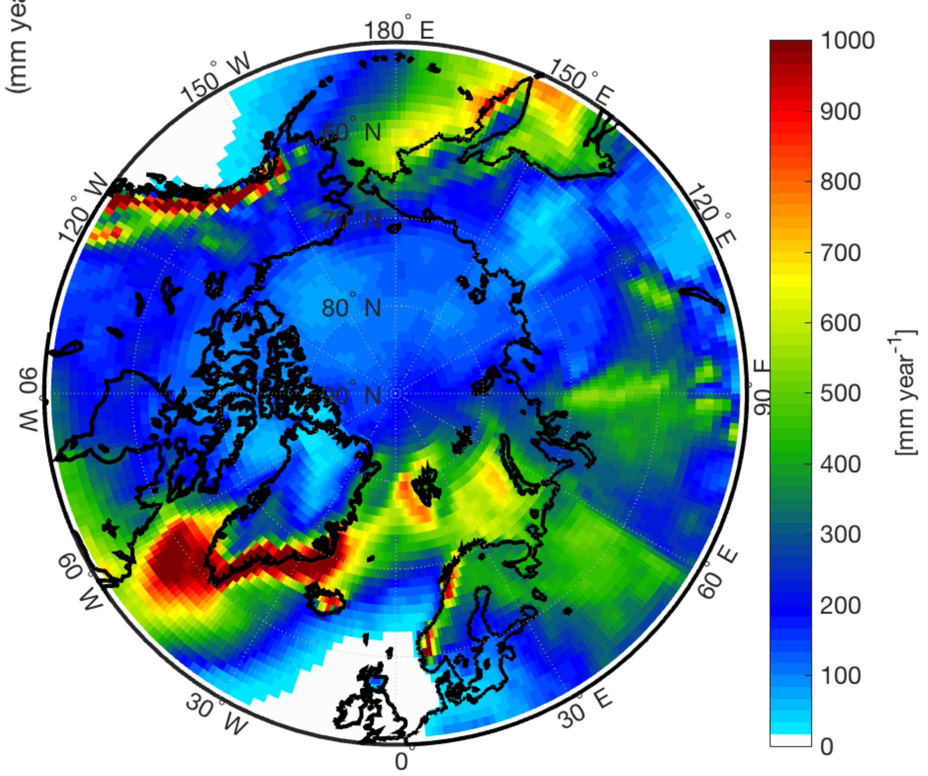


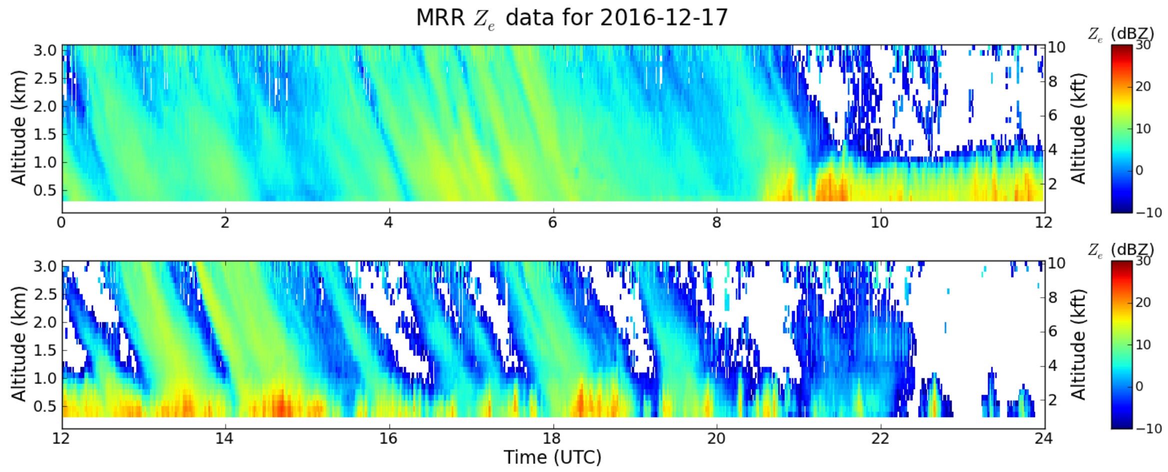
GPM Snowfall Retrieval Assessment



CloudSat (CPR)

Reanalysis

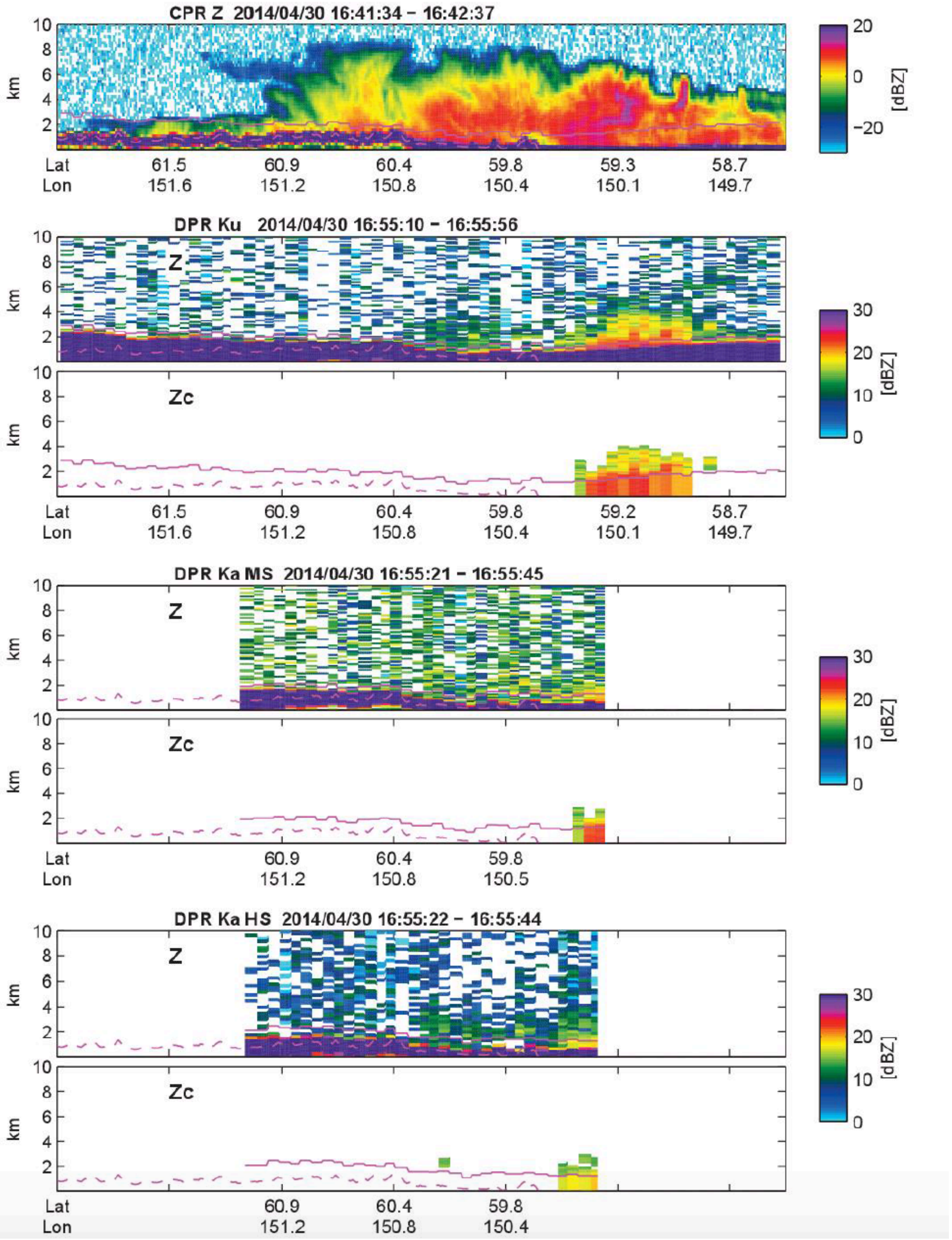




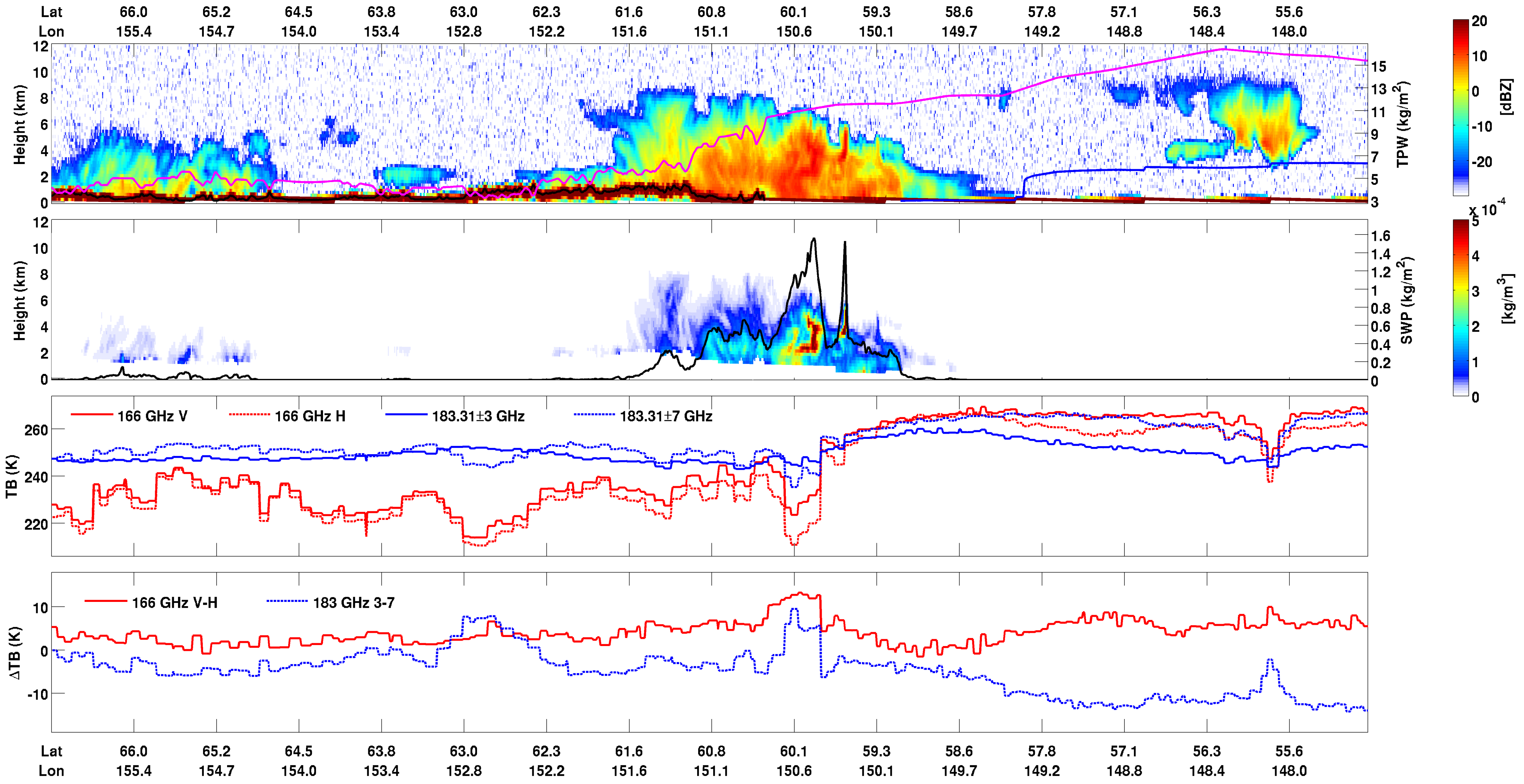
Profiling Radars

GPM-CloudSat Synergy

DPR/CPR Coincident Dataset (J. Turk)



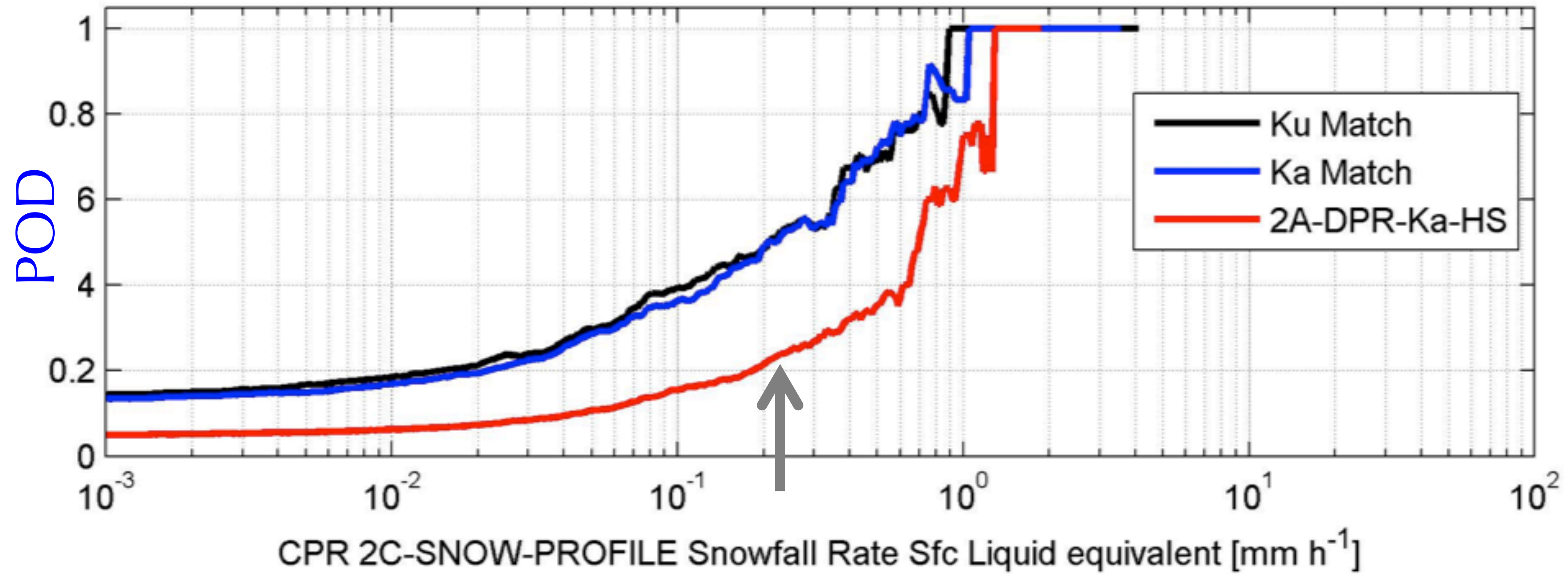
GPM-CloudSat Synergy



Panegrossi et al. (2017)

GPM-CloudSat Synergy

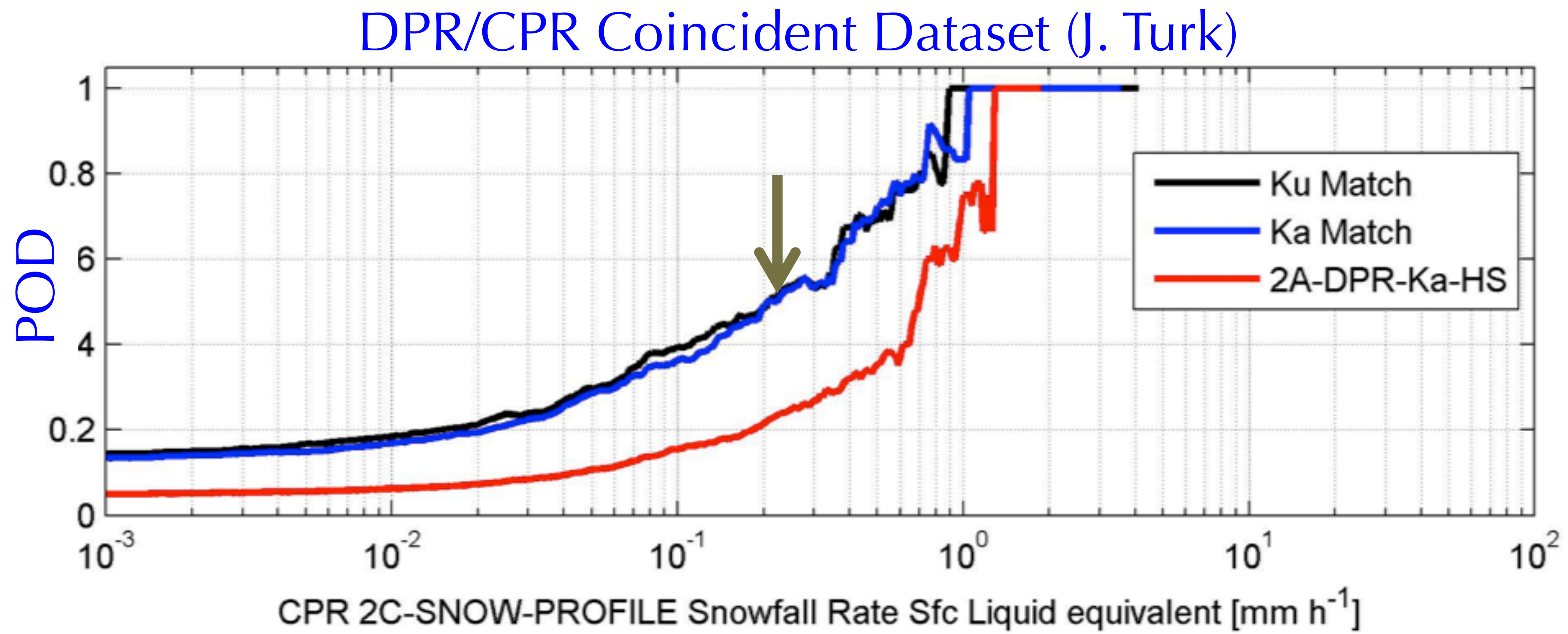
DPR/CPR Coincident Dataset (J. Turk)



Snow POD (mass): ~29-34%

D. Casella, G. Panegrossi, P. Sanò, A. C. Marra, S. Dietrich, B. T. Johnson, M. S. Kulie, 2017: Evaluation of the GPM-DPR Snowfall Detection Capability: Comparison with CloudSat-CPR, *Atmos. Res., Accepted for publication*.

GPM-CloudSat Synergy



Snow POD (mass): ~54-59%

D. Casella, G. Panegrossi, P. Sanò, A. C. Marra, S. Dietrich, B. T. Johnson, M. S. Kulie, 2017: Evaluation of the GPM-DPR Snowfall Detection Capability: Comparison with CloudSat-CPR, *Atmos. Res., Accepted for publication.*

GPM-CloudSat Synergy

		SH Ocean	NH Ocean	SH Land	NH Land	NH All	SH All	Global
Mean unconditional snowfall rate (mm y^{-1})	**GPM Ku**	**92.3**	**61.4**	**75.5**	**37.2**	**46.0**	**92.4**	**35.1**
	Uncertainty (%)	8.1	9.5	5.6	2.8	5.0	8.0	3.3
	CPR	**237.6**	**109.7**	**117.2**	**123.8**	**117.9**	**235.7**	**71.1**
	Uncertainty (%)	7.9	8.3	6.7	8.9	5.0	8.0	5.6

Adhikari, A, C. Liu, and M. Kulie, 2017: Global distribution of snow precipitation features and their properties from three years of GPM observations. *J. Clim*. In Review.

GPM-CloudSat Synergy

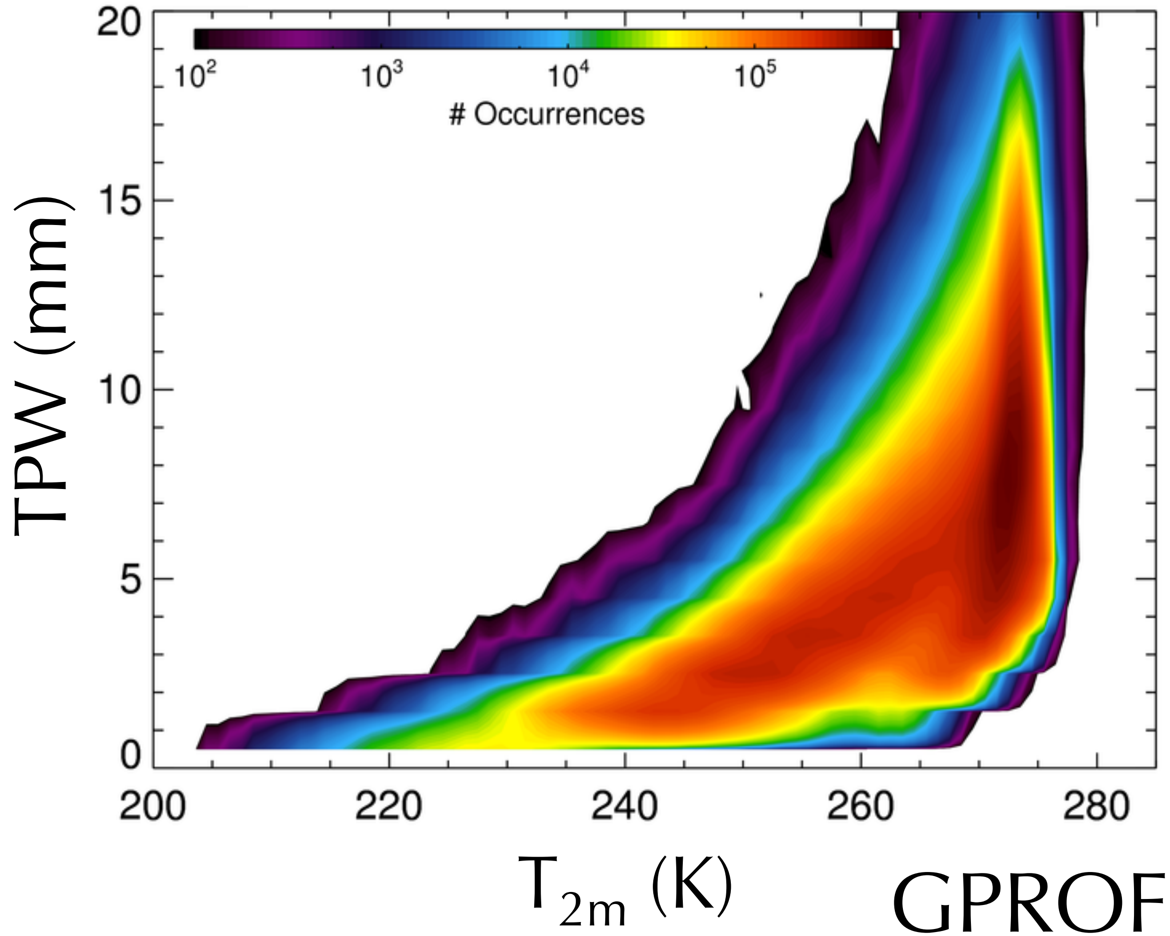
	SH Ocean	NH Ocean	SH Land	NH Land	NH All	SH All	Global
Estimated total snow rate ($mm\ y^{-1}$)	**242.09**	**117.12**	**135.4**	**125.2**	**119.8**	**240.8**	**72.8**

Blended DPR-CPR Snowfall Estimates

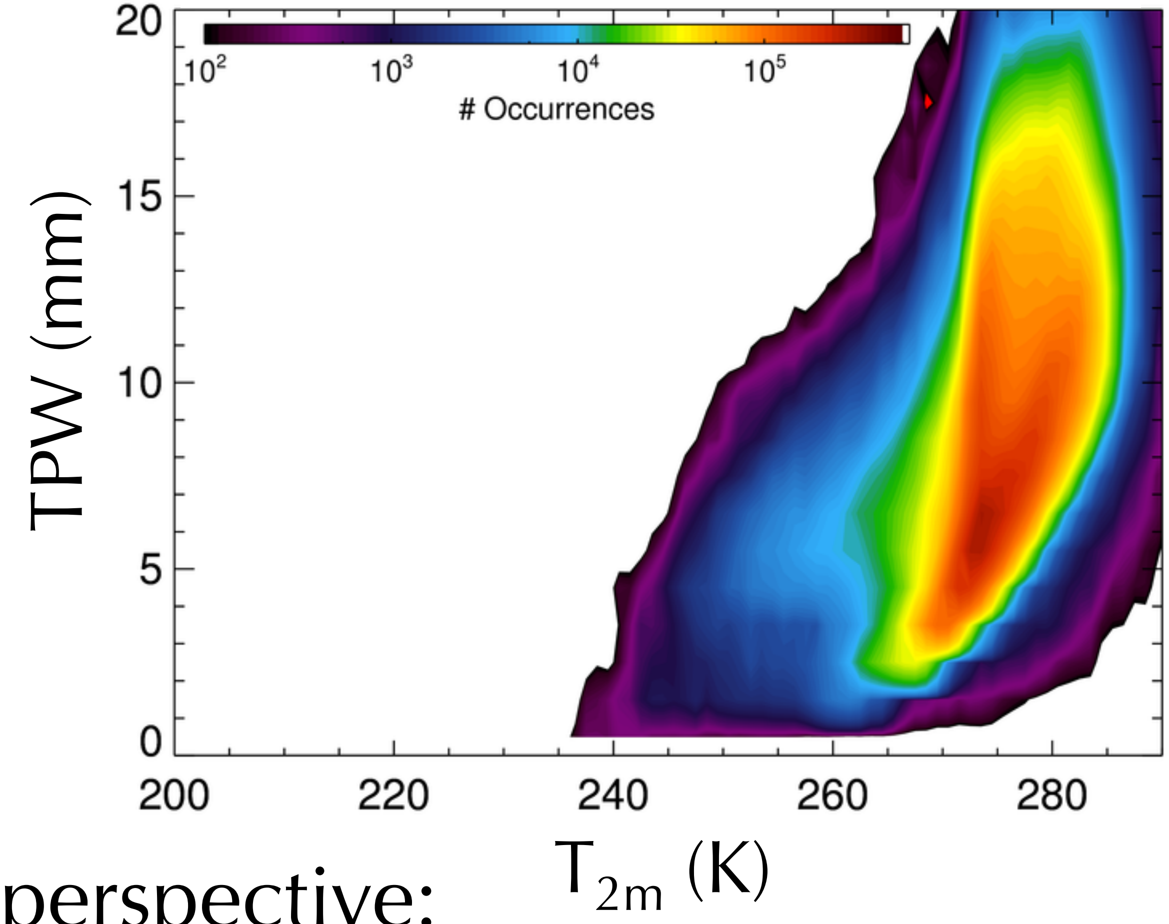
Adhikari, A, C. Liu, and M. Kulie, 2017: Global distribution of snow precipitation features and their properties from three years of GPM observations. *J. Clim*. In Review.

GPM-CloudSat Synergy

All Snowfall Events – CPR



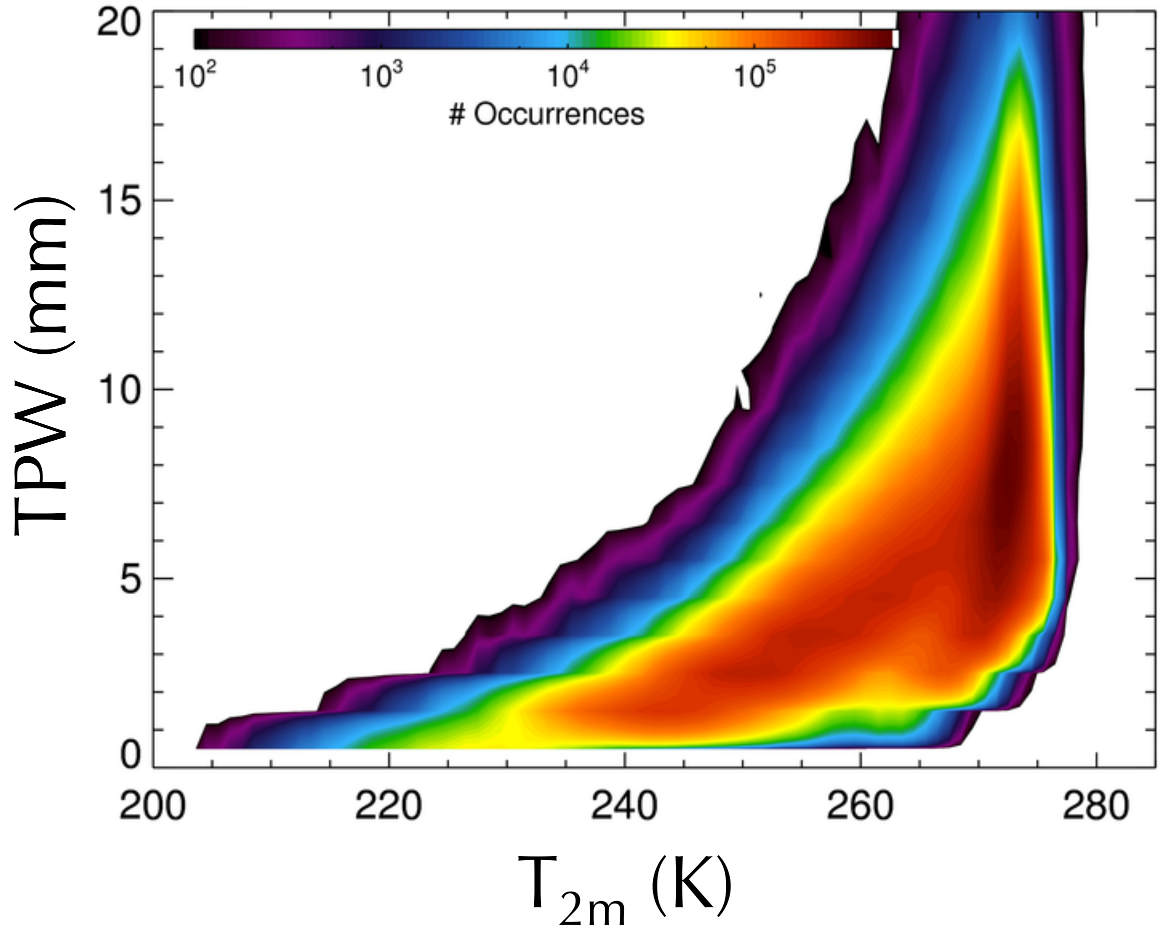
All Snowfall Events – DPR Ku



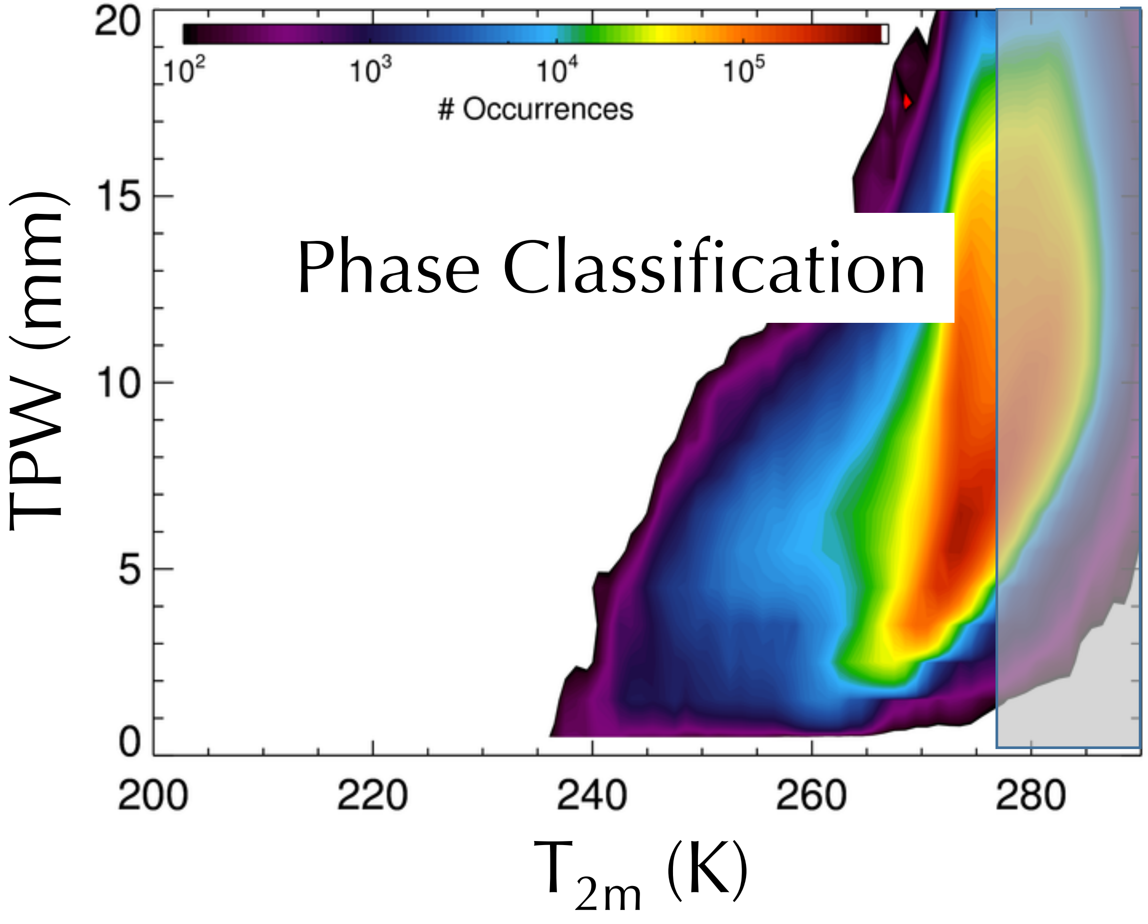
GPROF perspective:
A priori database population

GPM-CloudSat Synergy

All Snowfall Events – CPR



All Snowfall Events – DPR Ku



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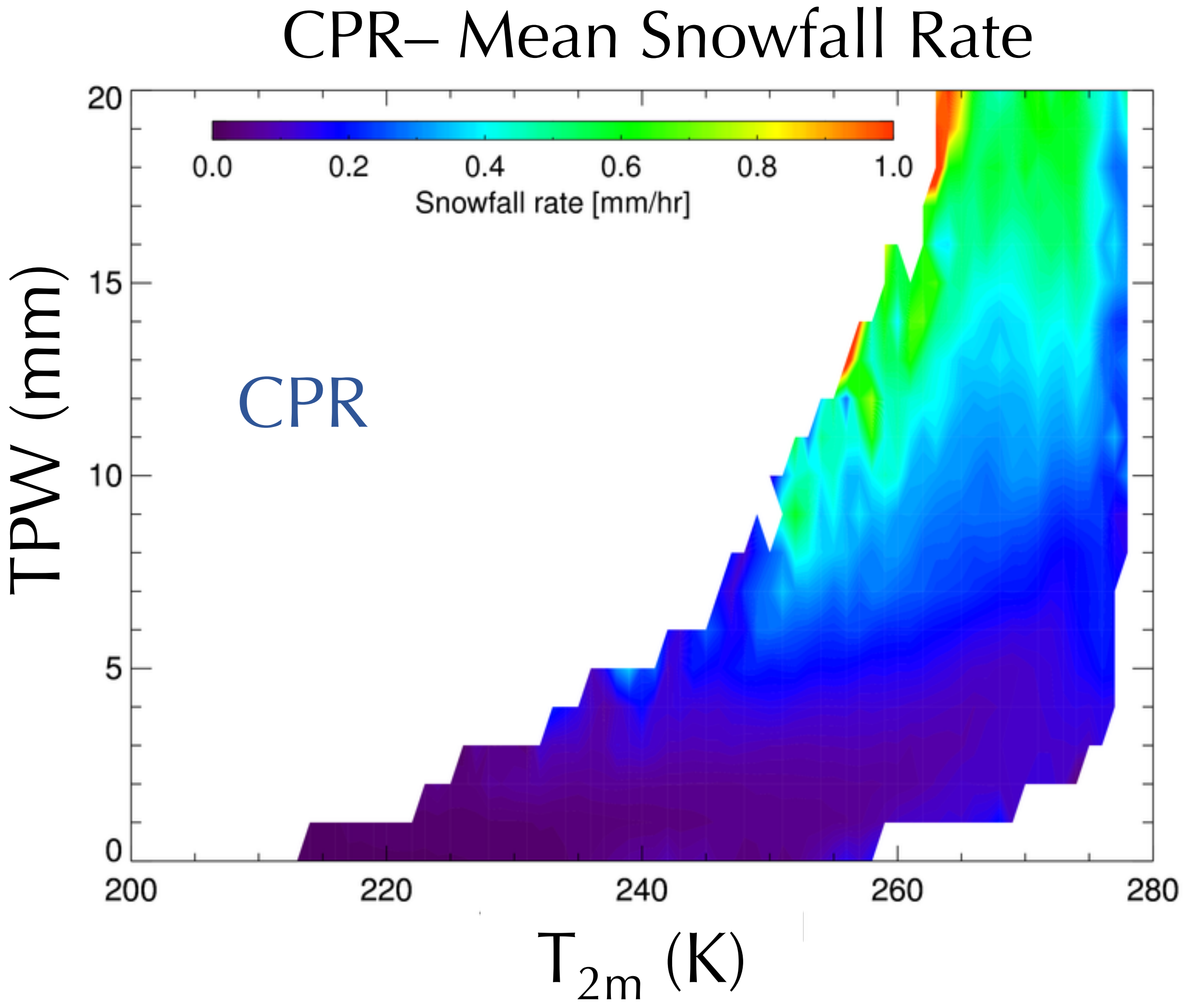
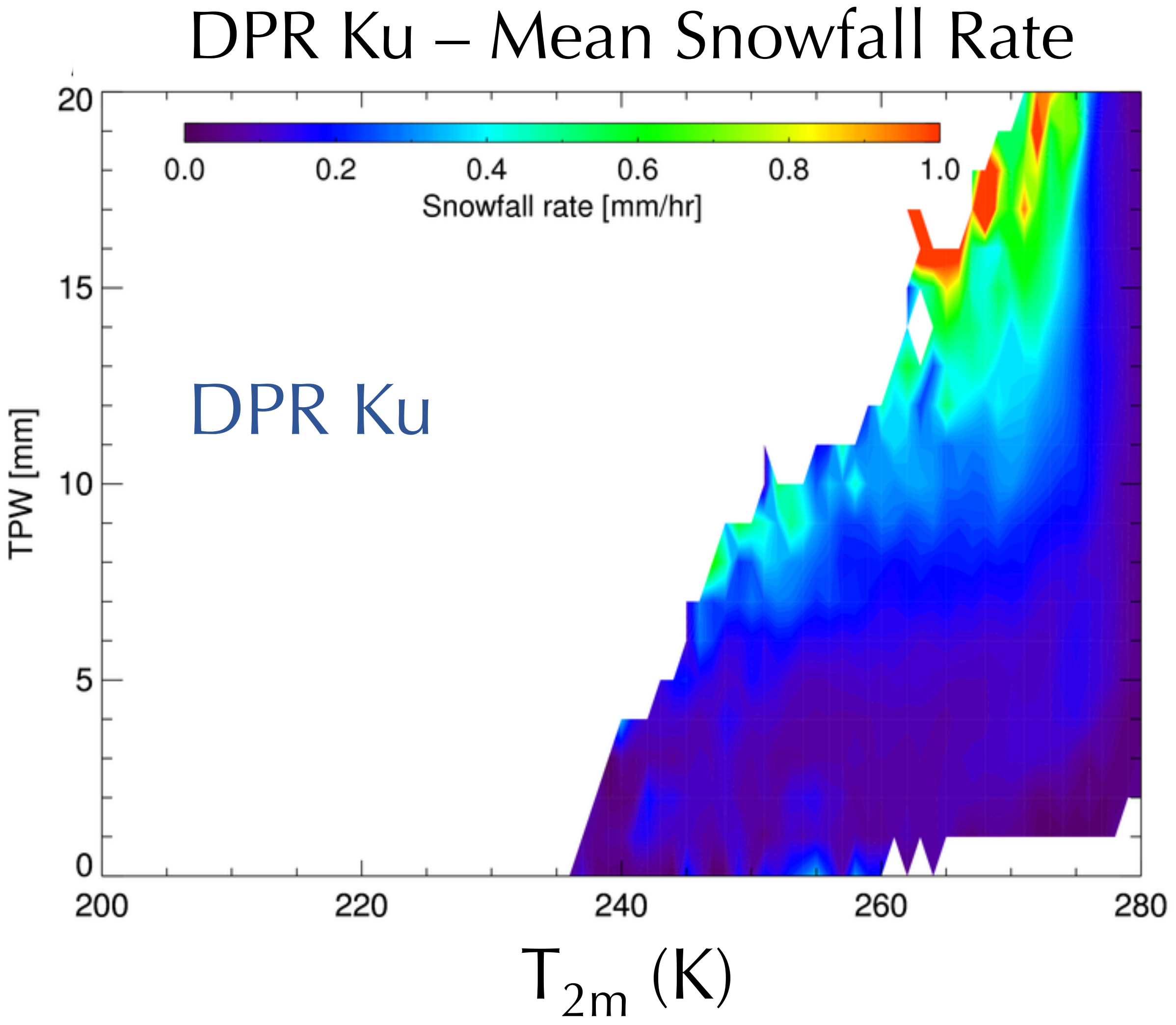
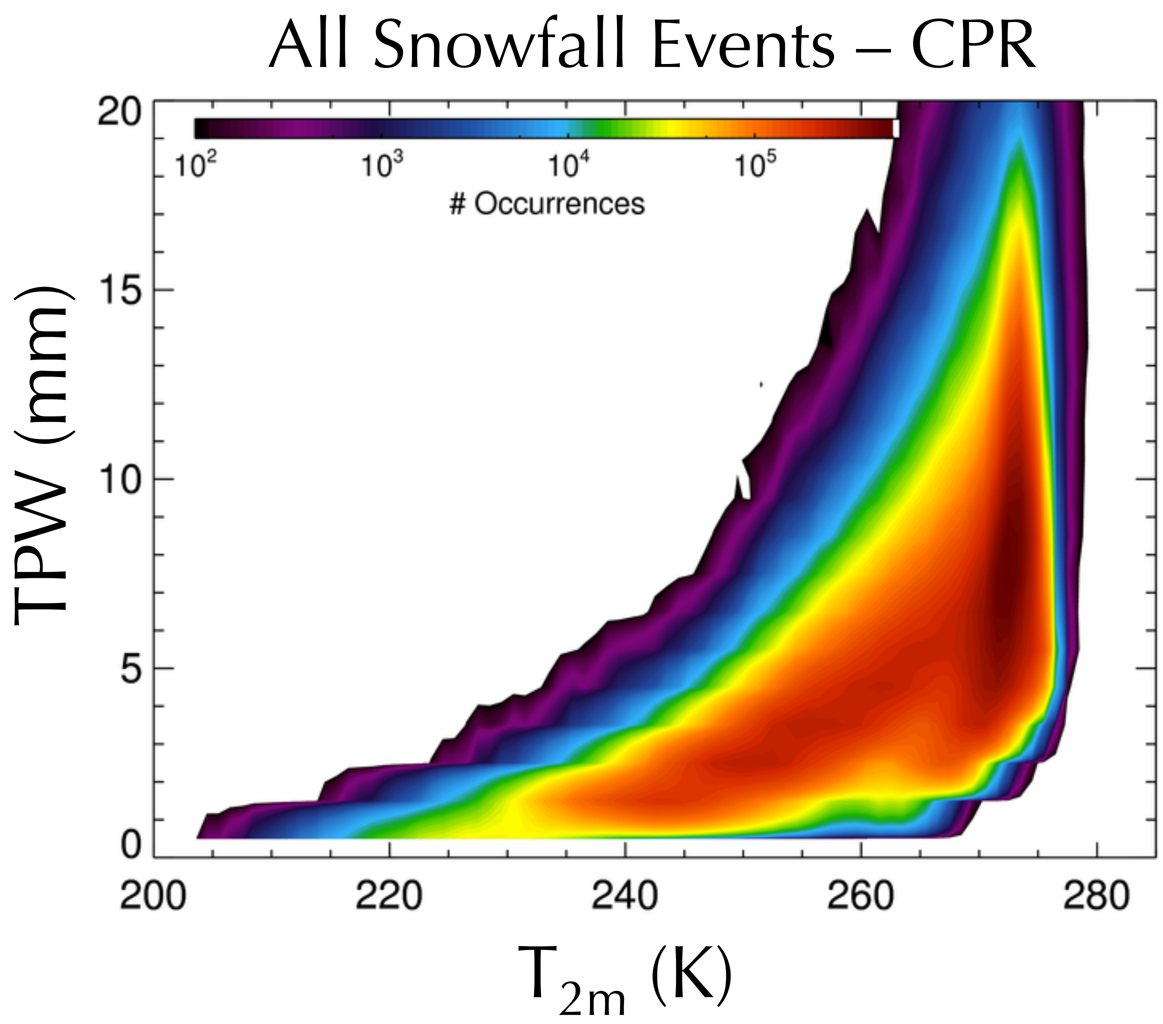
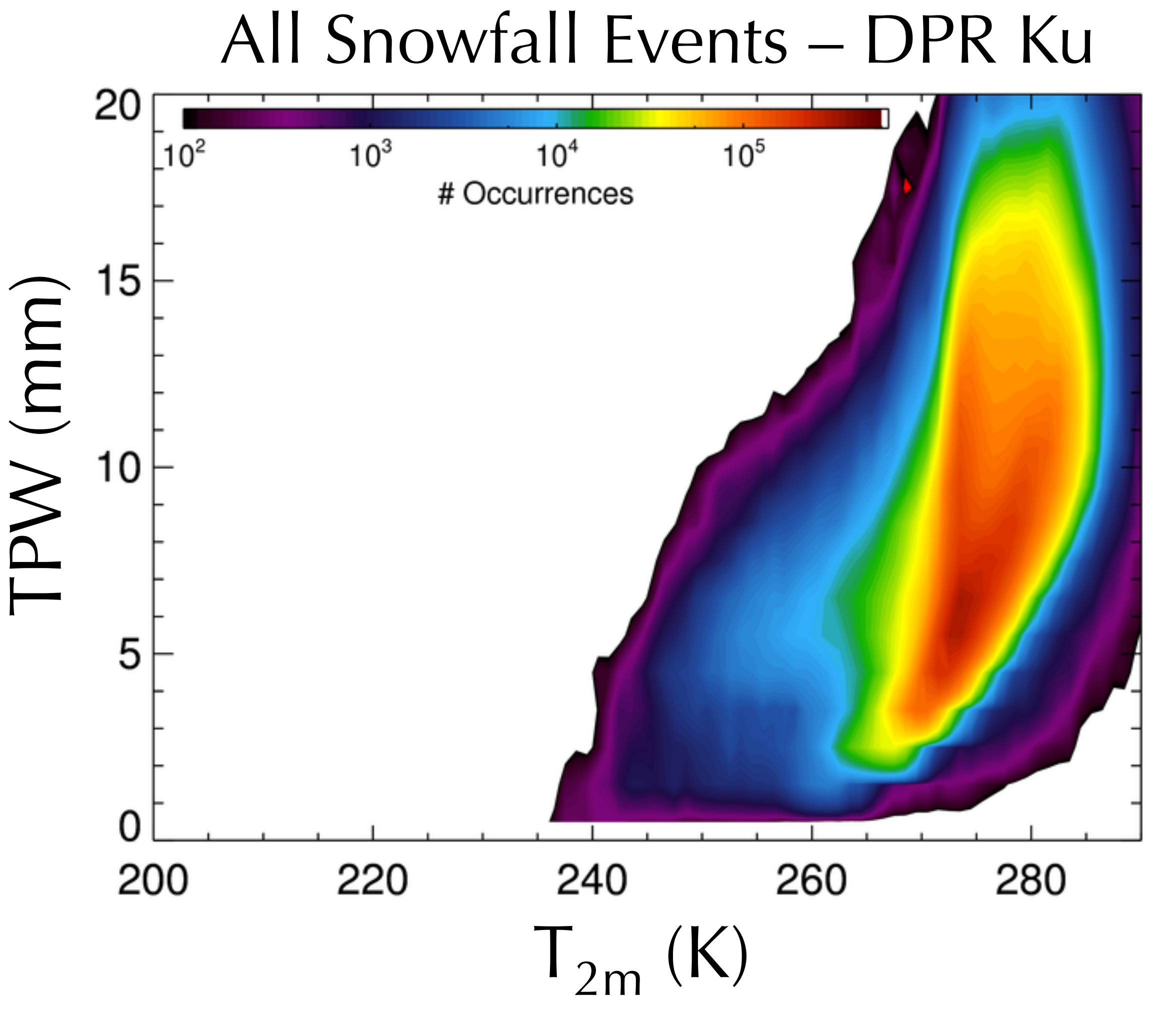




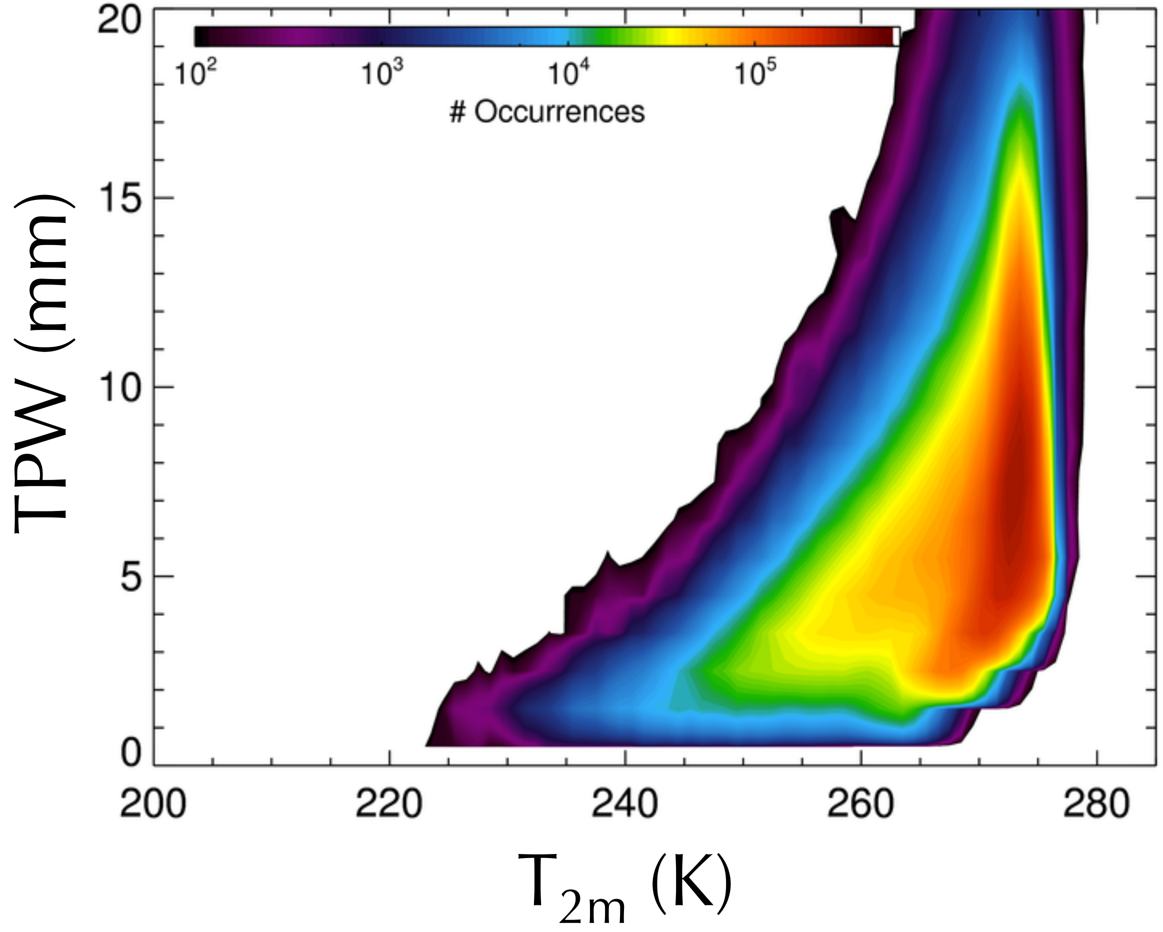
GPM-CloudSat Synergy



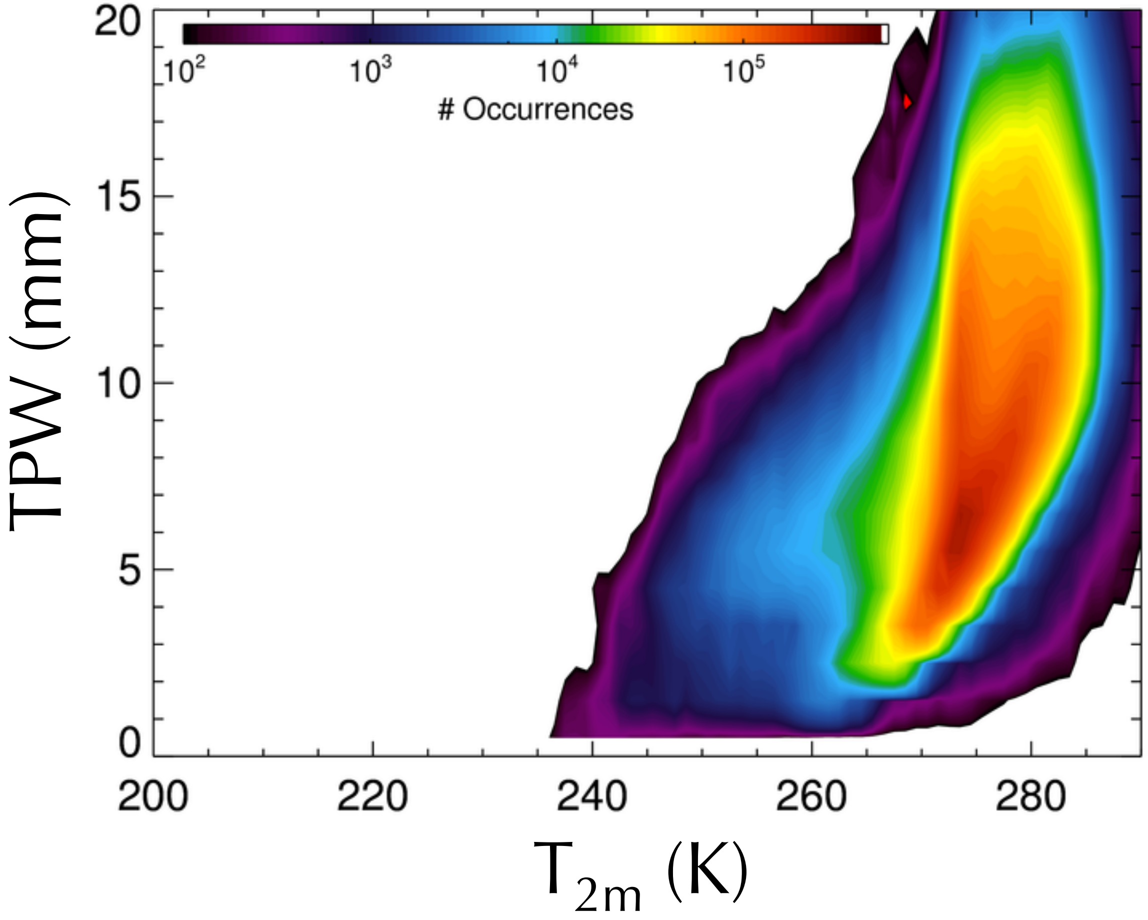


GPM-CloudSat Synergy

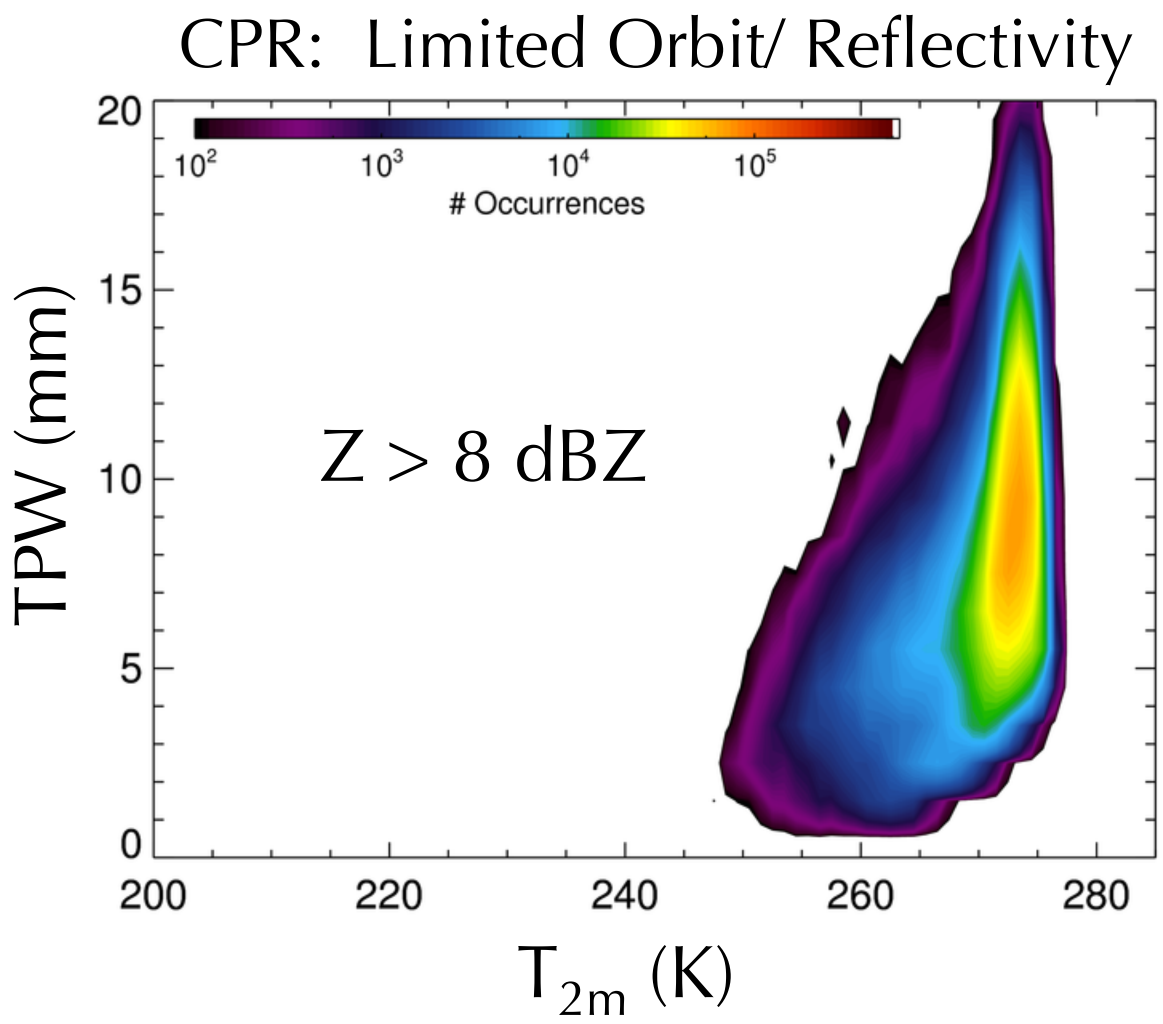
CPR: Limited Orbital Range

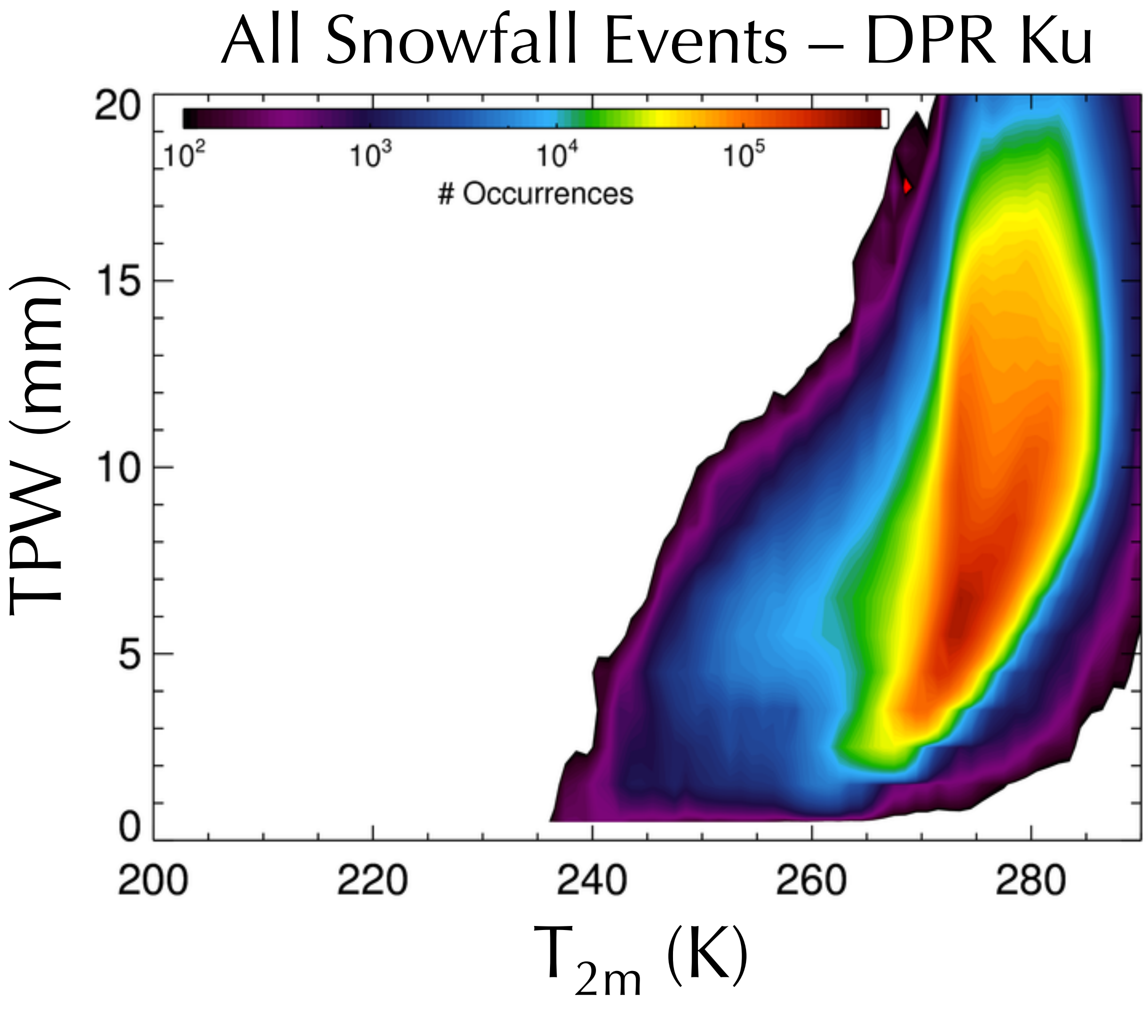


All Snowfall Events – DPR Ku

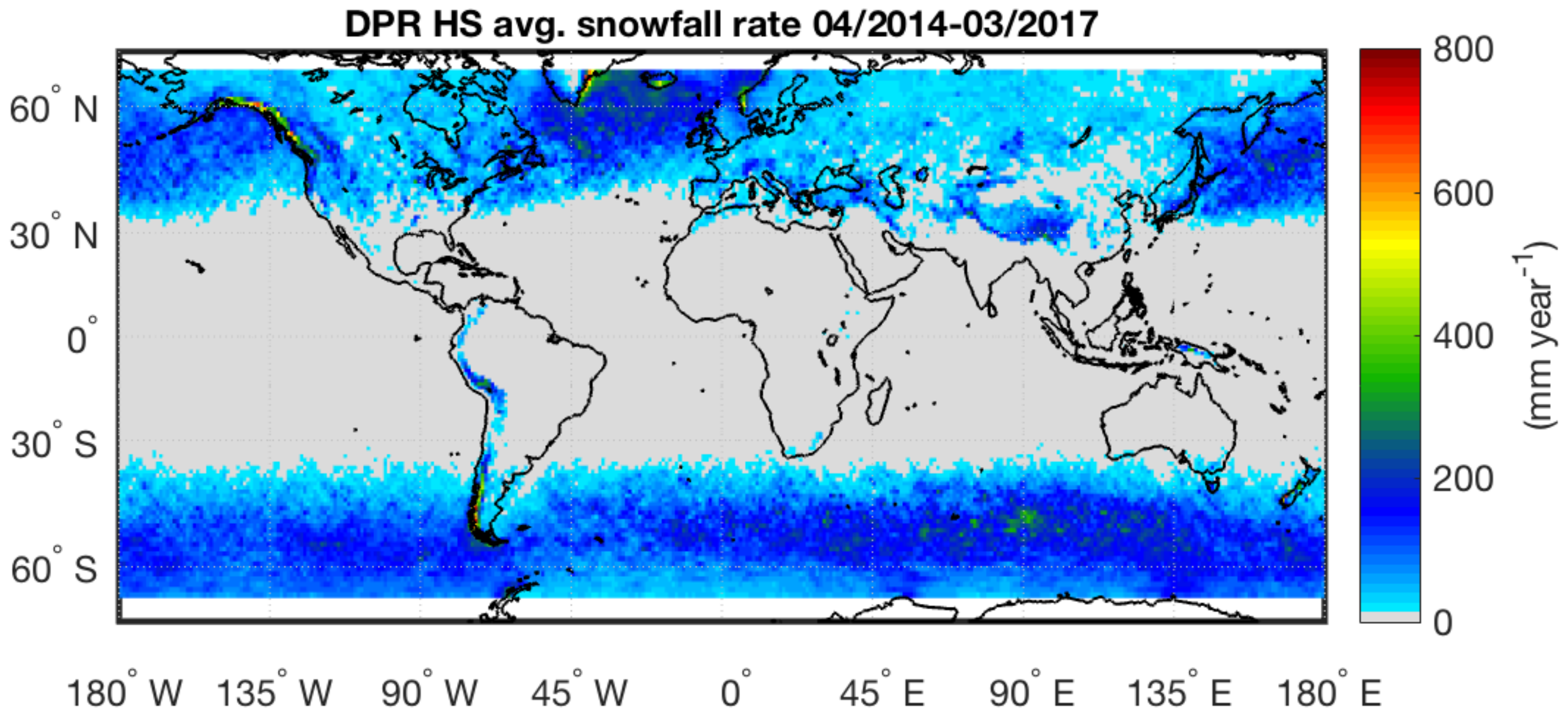


GPM-CloudSat Synergy



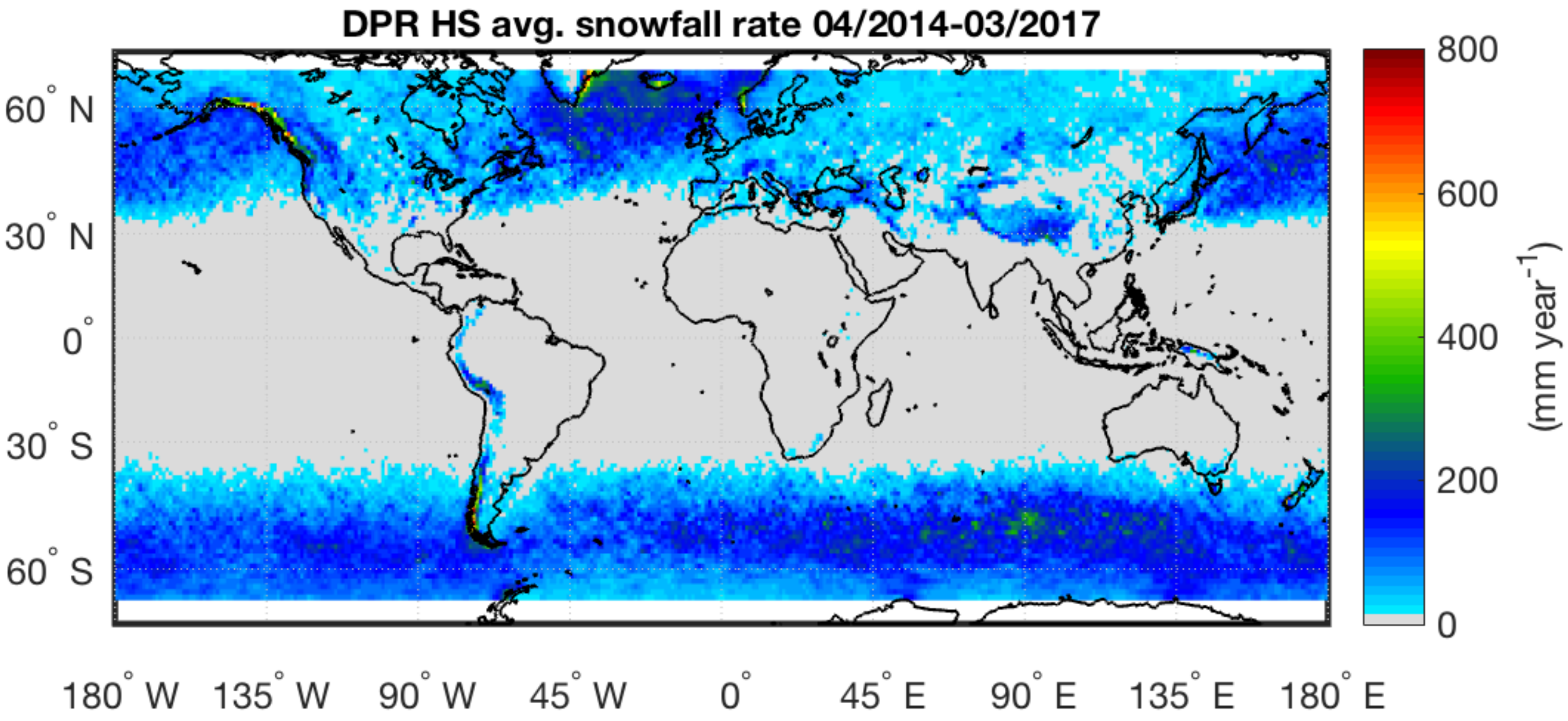


GPM Snowfall Retrievals



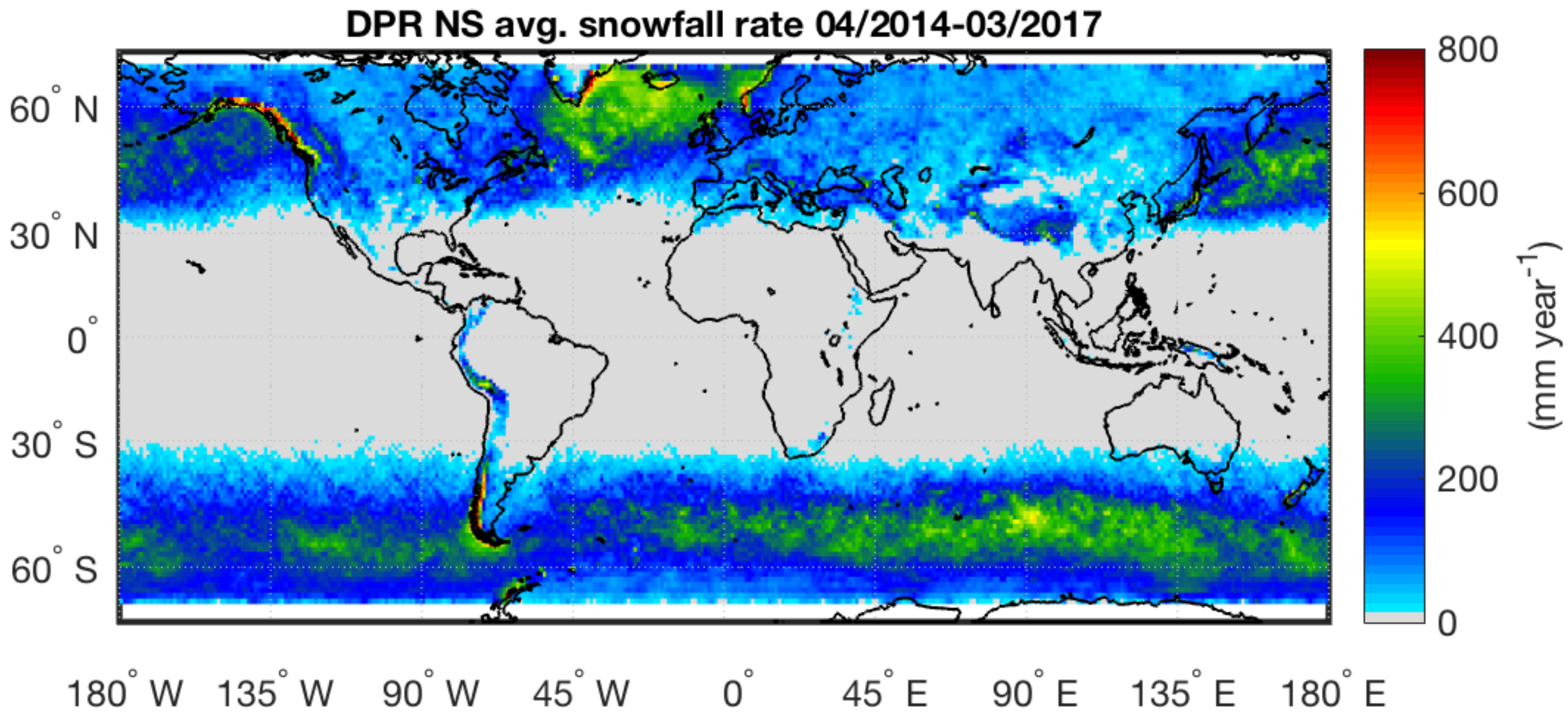
Version 05 Products

GPM Snowfall Retrievals



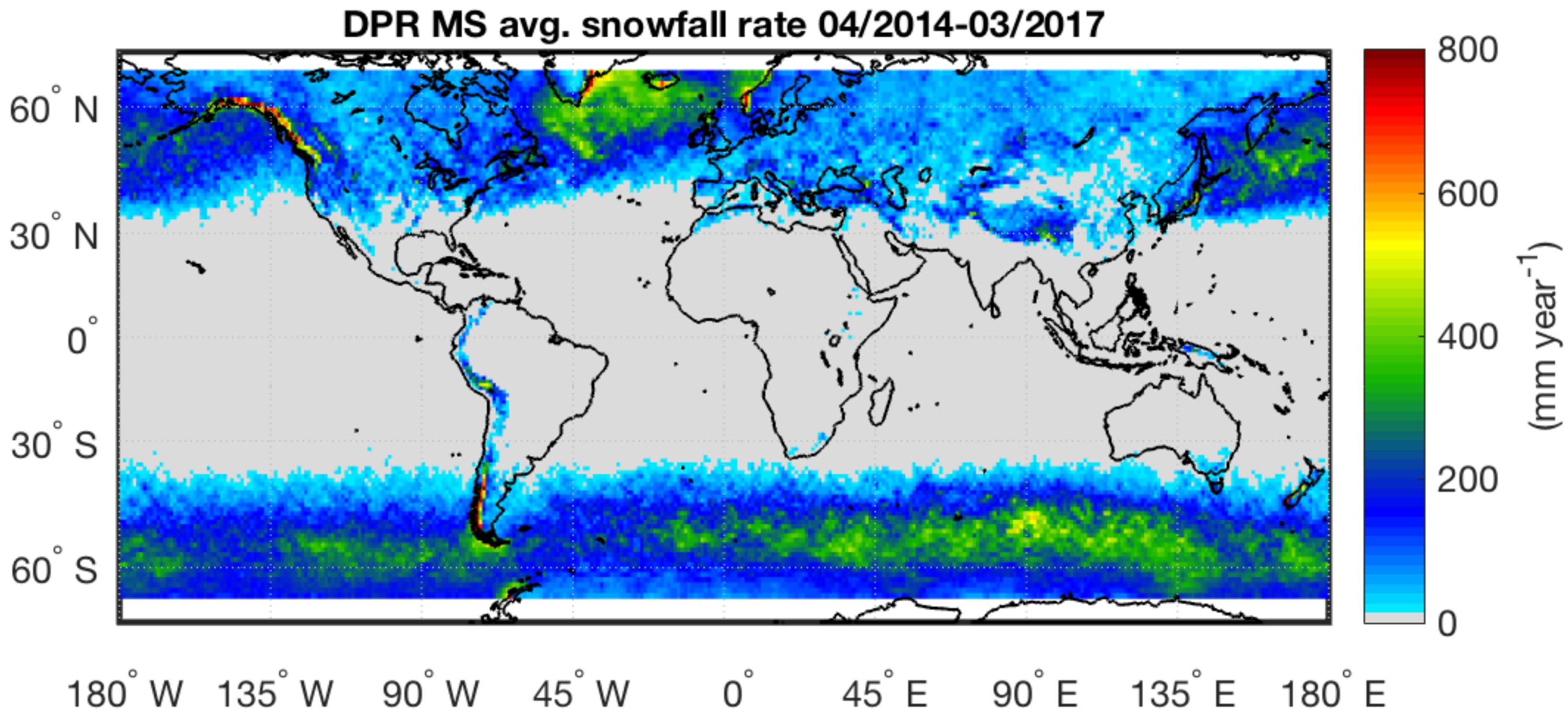
High Sensitivity HS (Ka-Band)

GPM Snowfall Retrievals



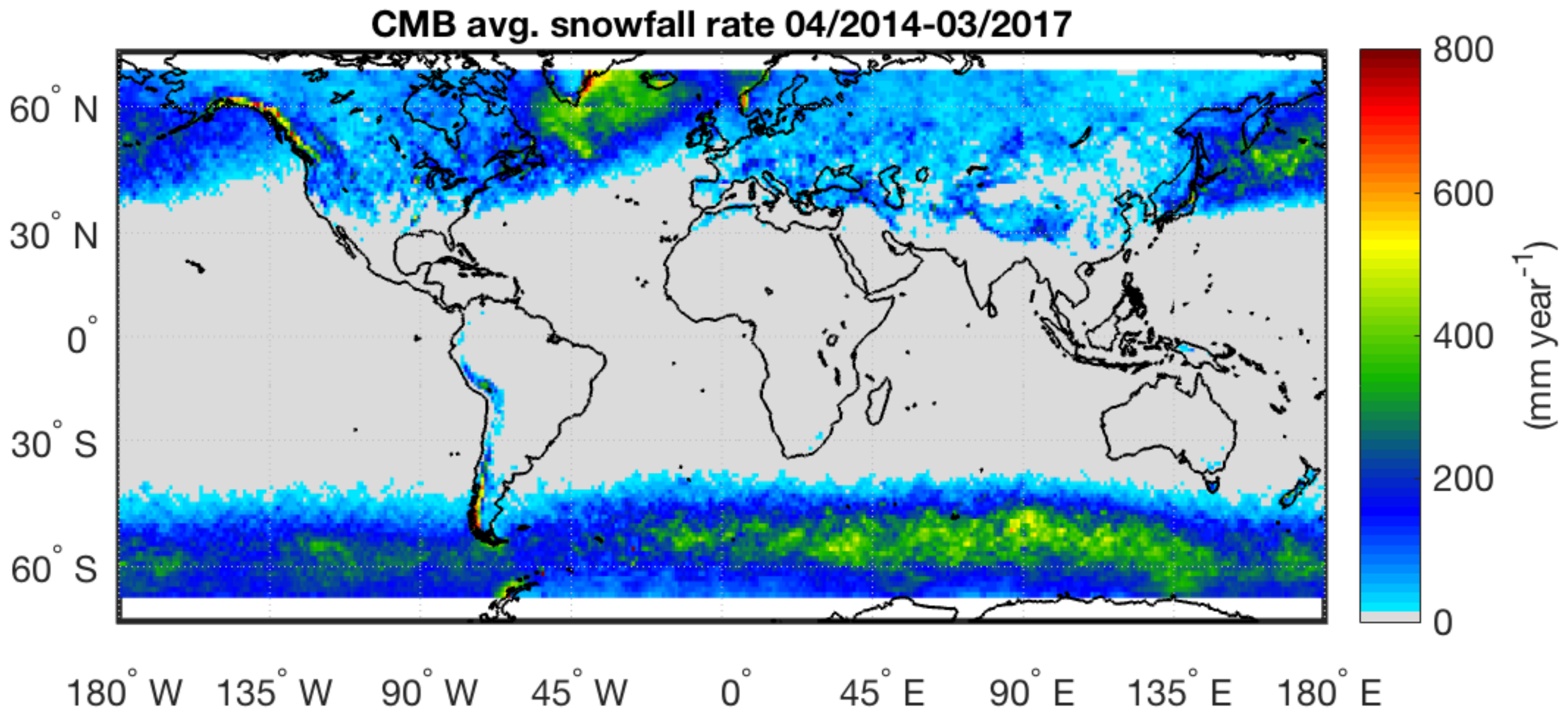
Normal Scan NS (Ku-Band)

GPM Snowfall Retrievals



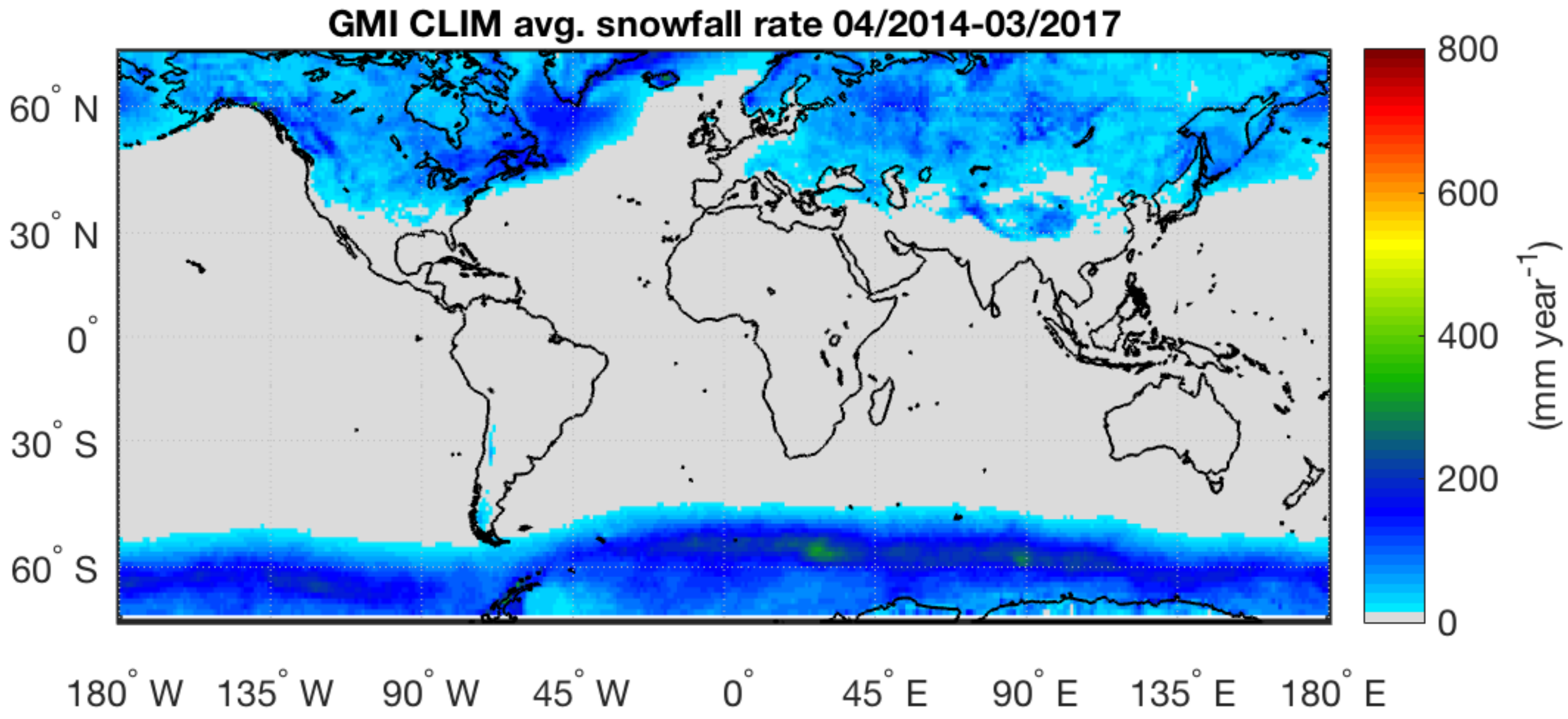
Matched Scan MS (Ku + Ka-Band)

GPM Snowfall Retrievals



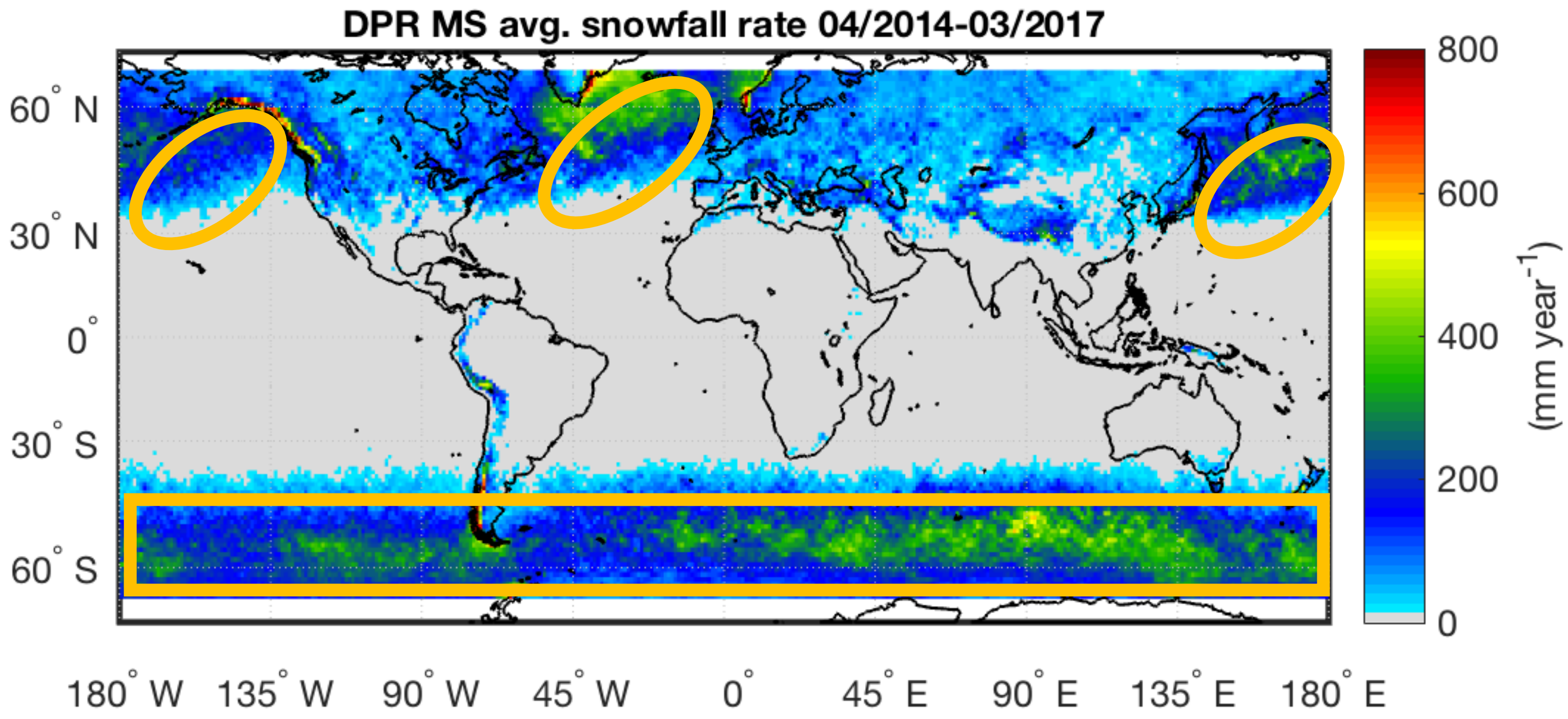
Combined (DPR + GMI)

GPM Snowfall Retrievals



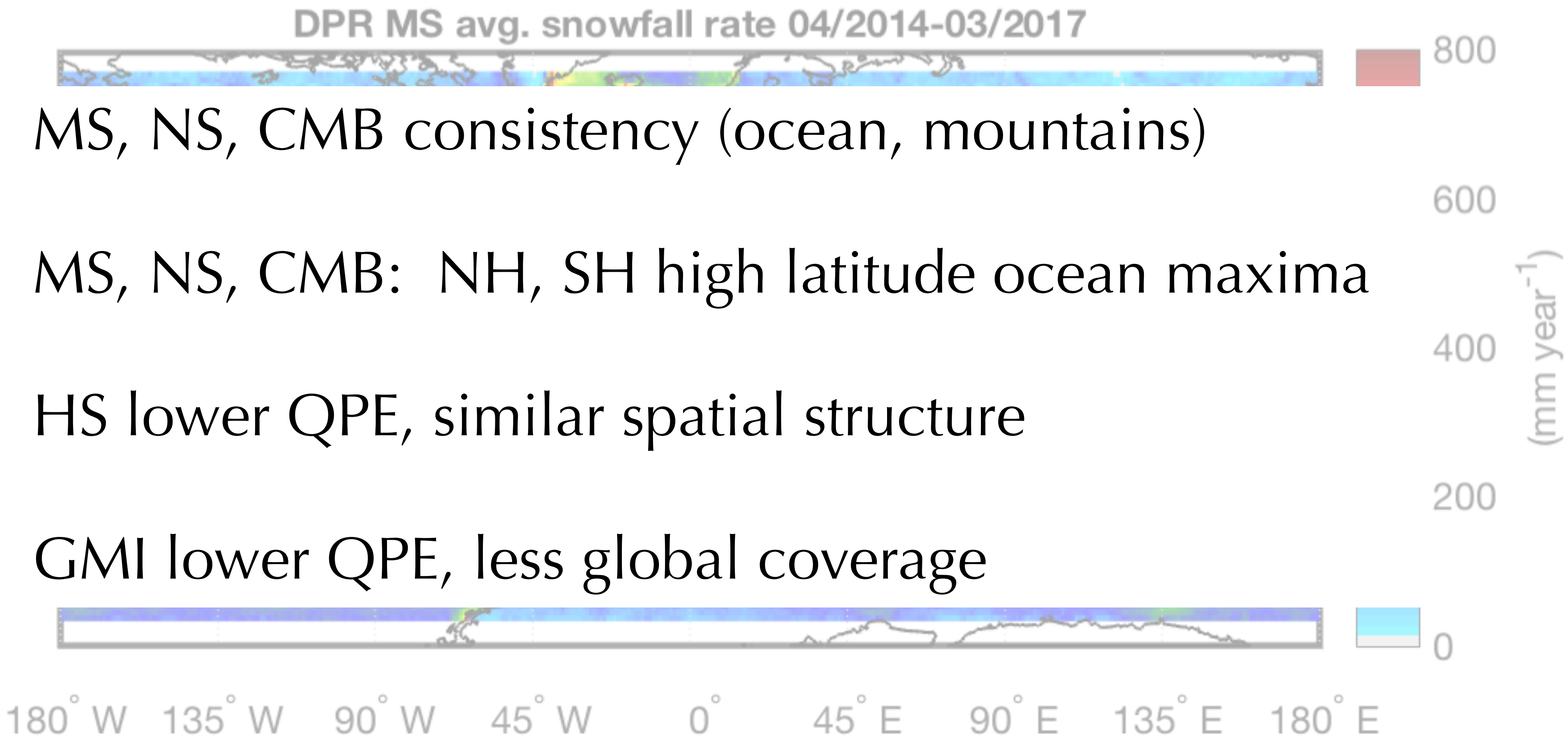
GMI (GPROF - CLIM)

GPM Snowfall Retrievals



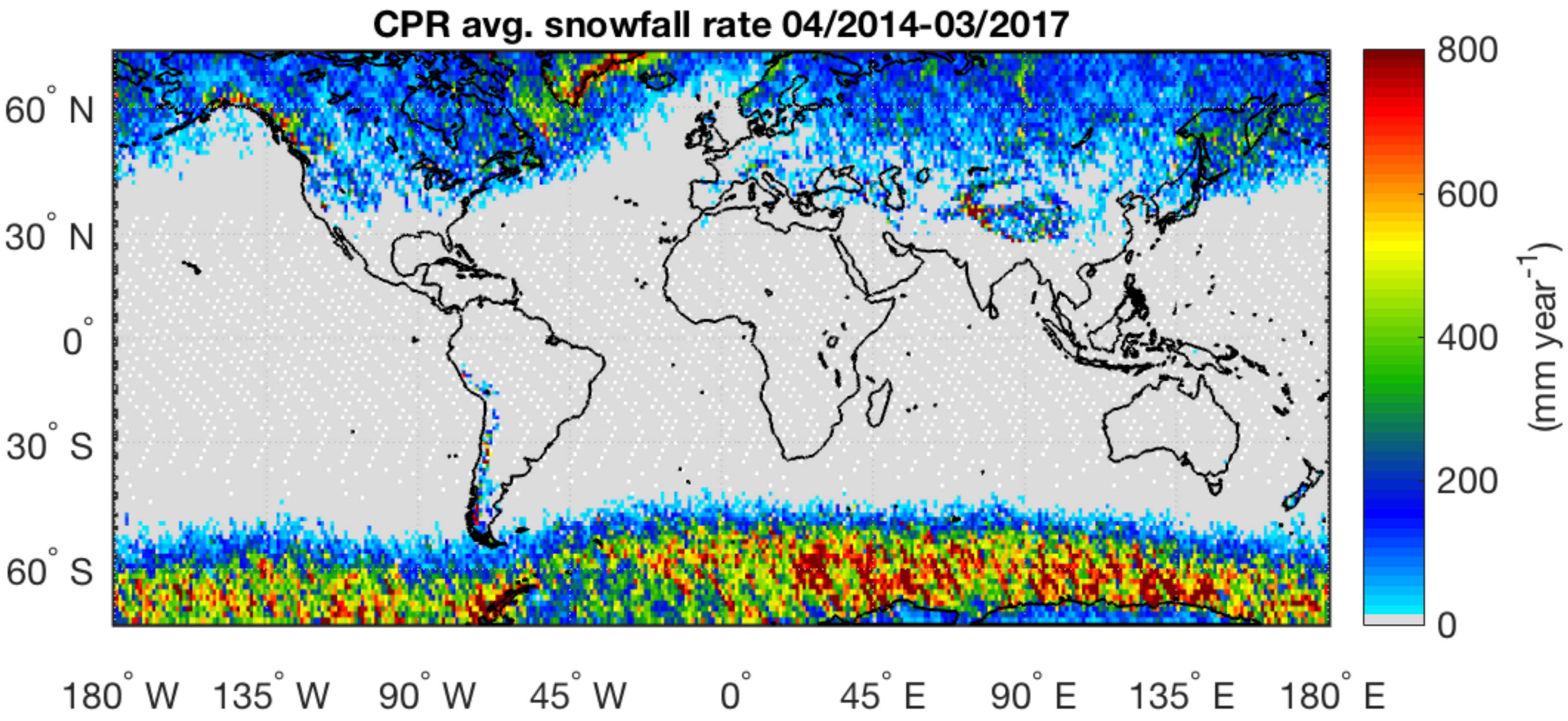
Matched Scan (Ku + Ka-Band)

GPM Snowfall Retrievals

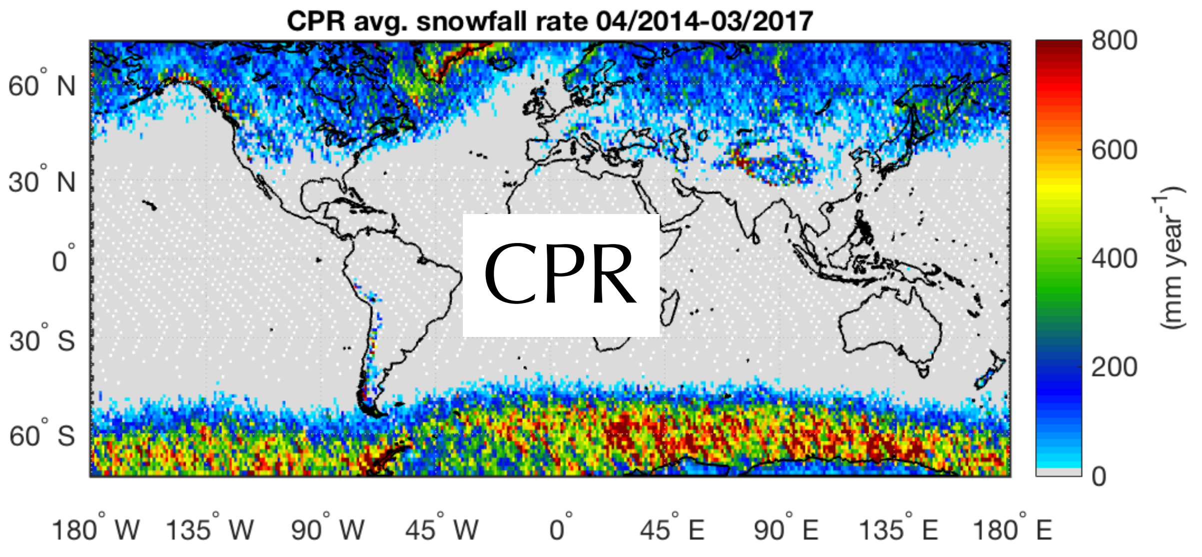


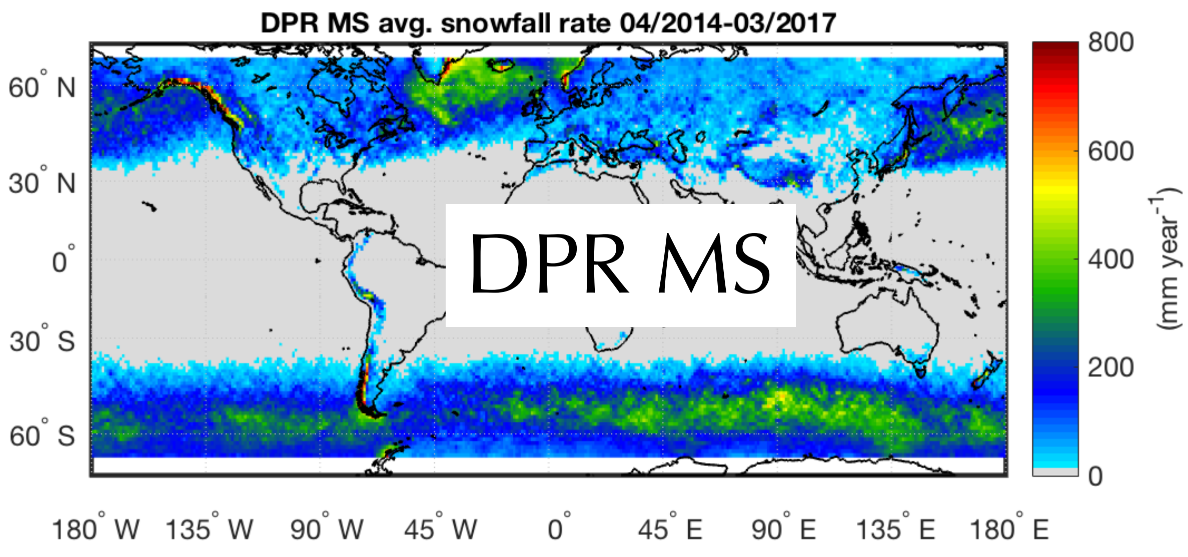
- MS, NS, CMB consistency (ocean, mountains)
- MS, NS, CMB: NH, SH high latitude ocean maxima
- HS lower QPE, similar spatial structure
- GMI lower QPE, less global coverage

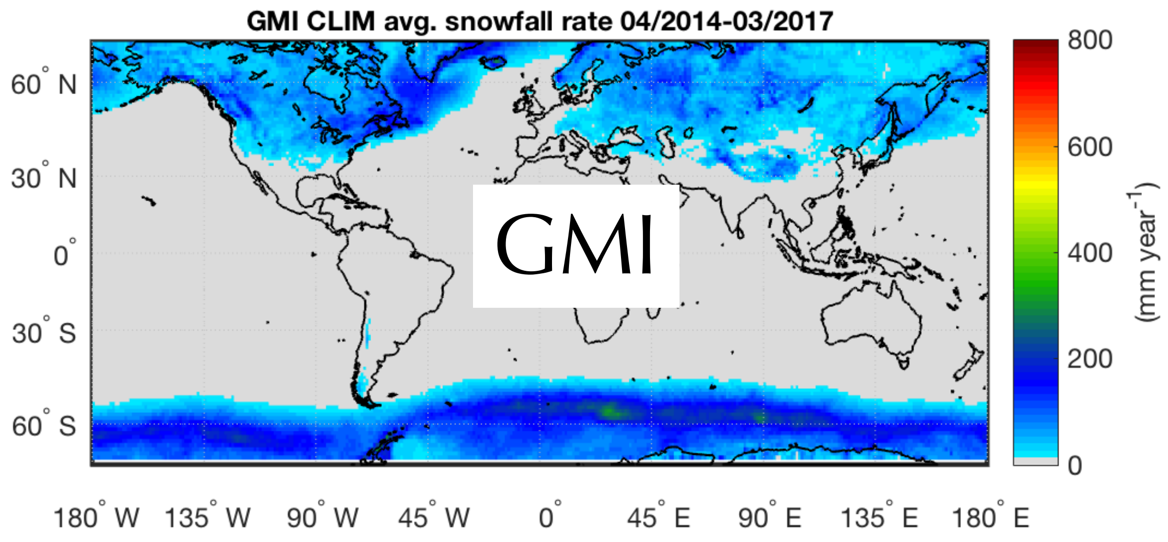
CloudSat Snowfall Retrievals

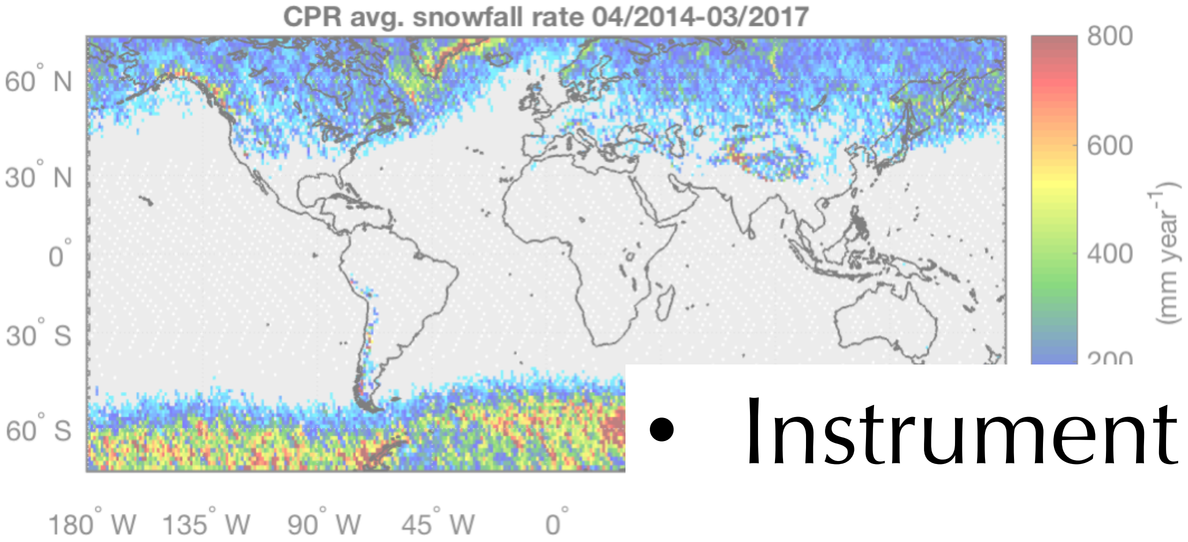


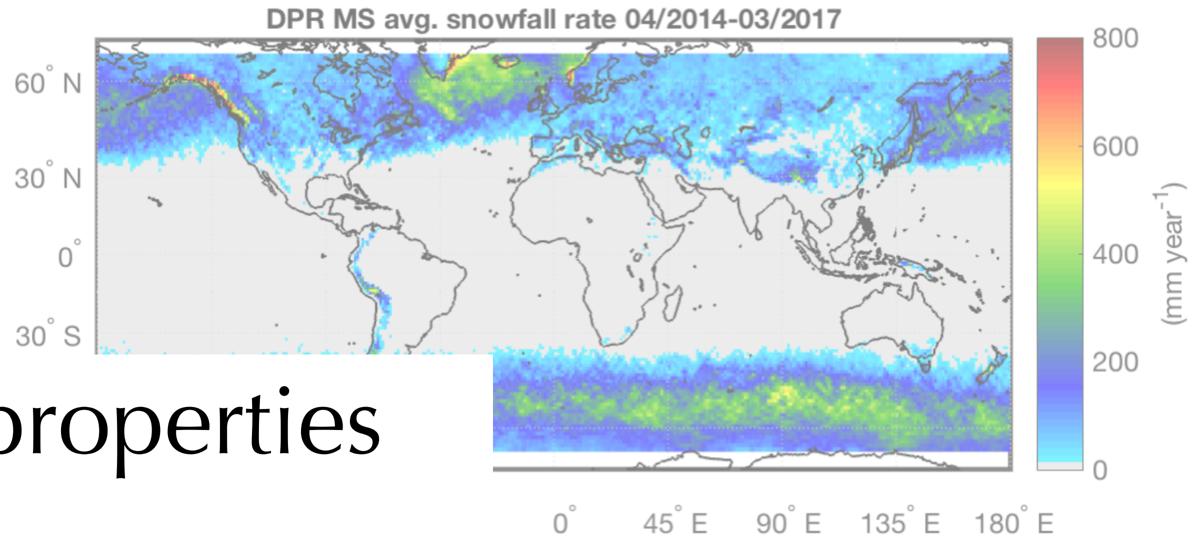
CPR (Nadir only)


CPR avg. snowfall rate 04/2014-03/2017
CPR
60° N
30° N
0°
30° S
60° S
180° W
135° W
90° W
45° W
0°
45° E
90° E
135° E
180° E
800
600
400
200
0
(mm year^-1)

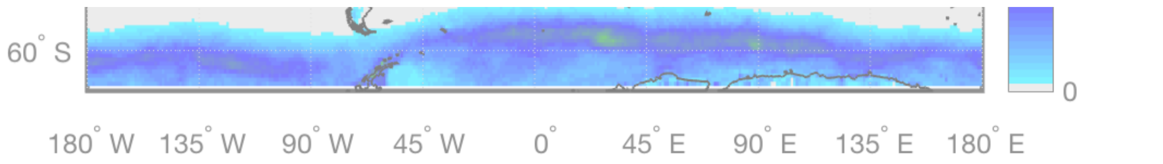

DPR MS avg. snowfall rate 04/2014-03/2017
DPR MS
60° N
30° N
0°
30° S
60° S
180° W
135° W
90° W
45° W
0°
45° E
90° E
135° E
180° E
800
600
400
200
0
(mm year^-1)


GMI CLIM avg. snowfall rate 04/2014-03/2017
GMI
60° N
30° N
0°
30° S
60° S
180° W
135° W
90° W
45° W
0°
45° E
90° E
135° E
180° E
800
600
400
200
0
(mm year^-1)

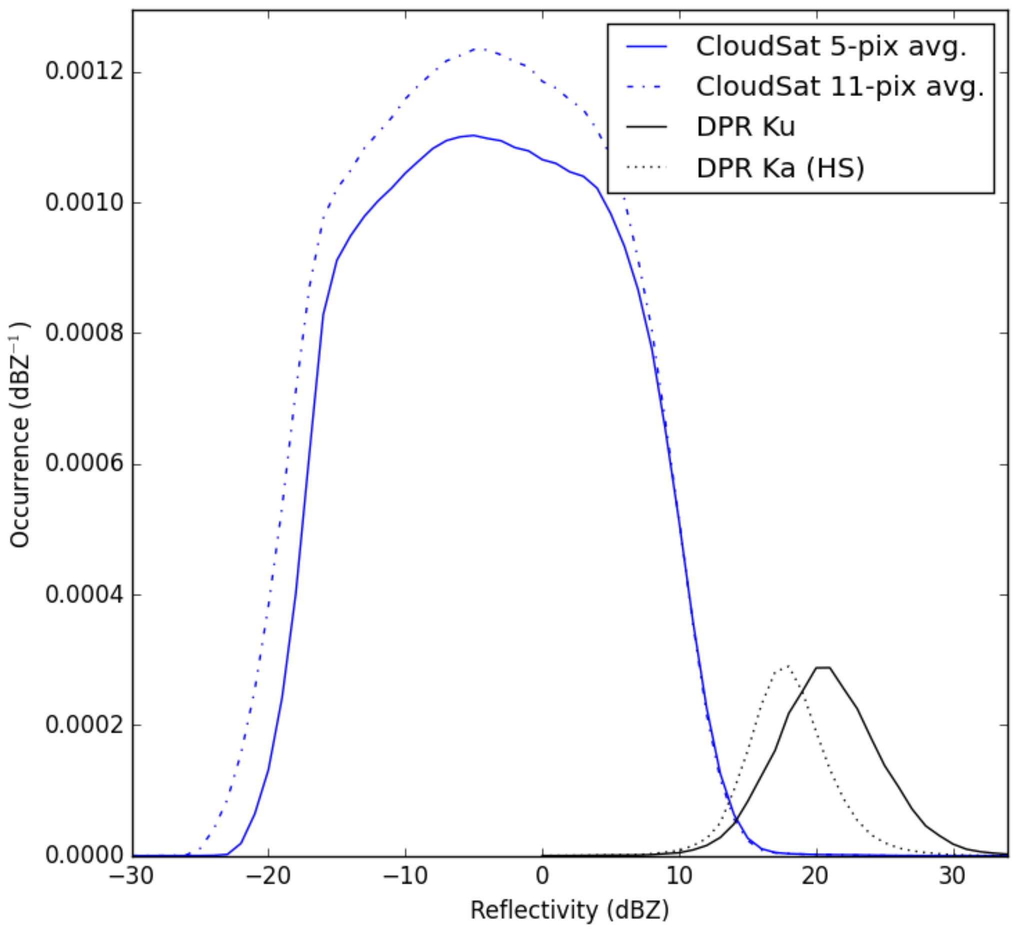


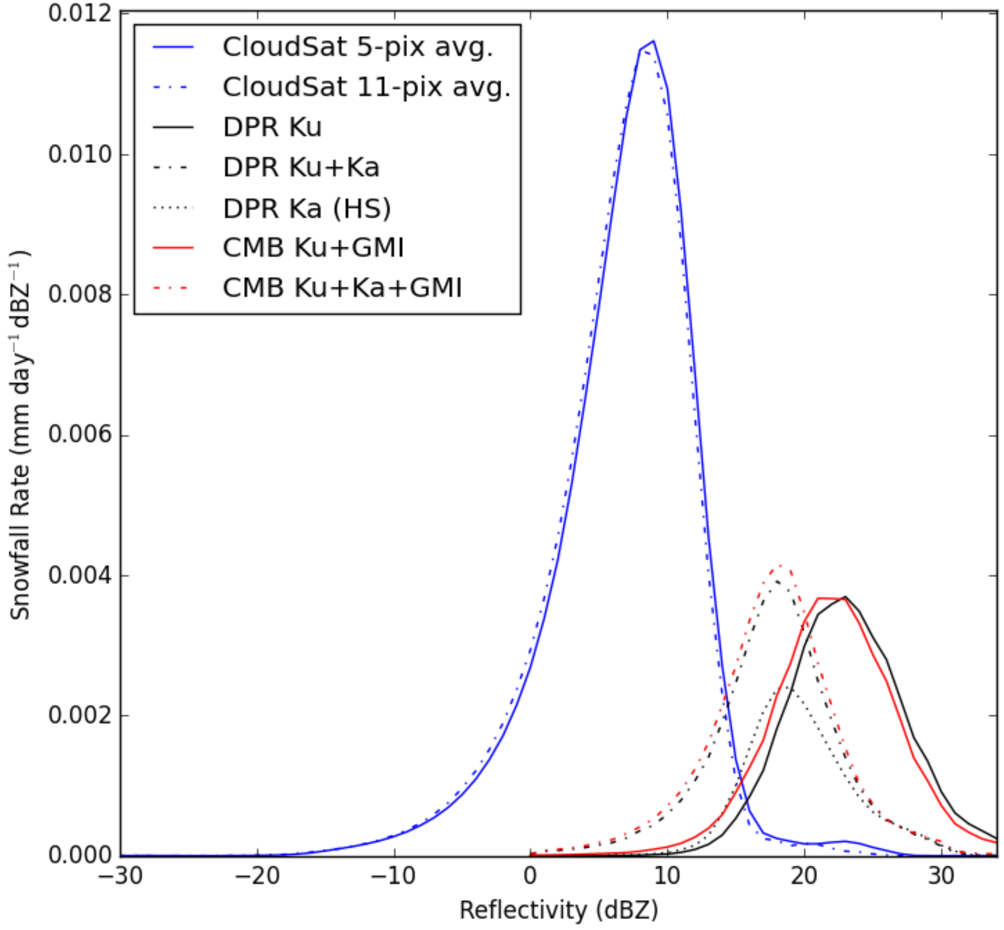


- Instrument properties
- Phase discrimination
- Algorithm differences



Instrument Differences

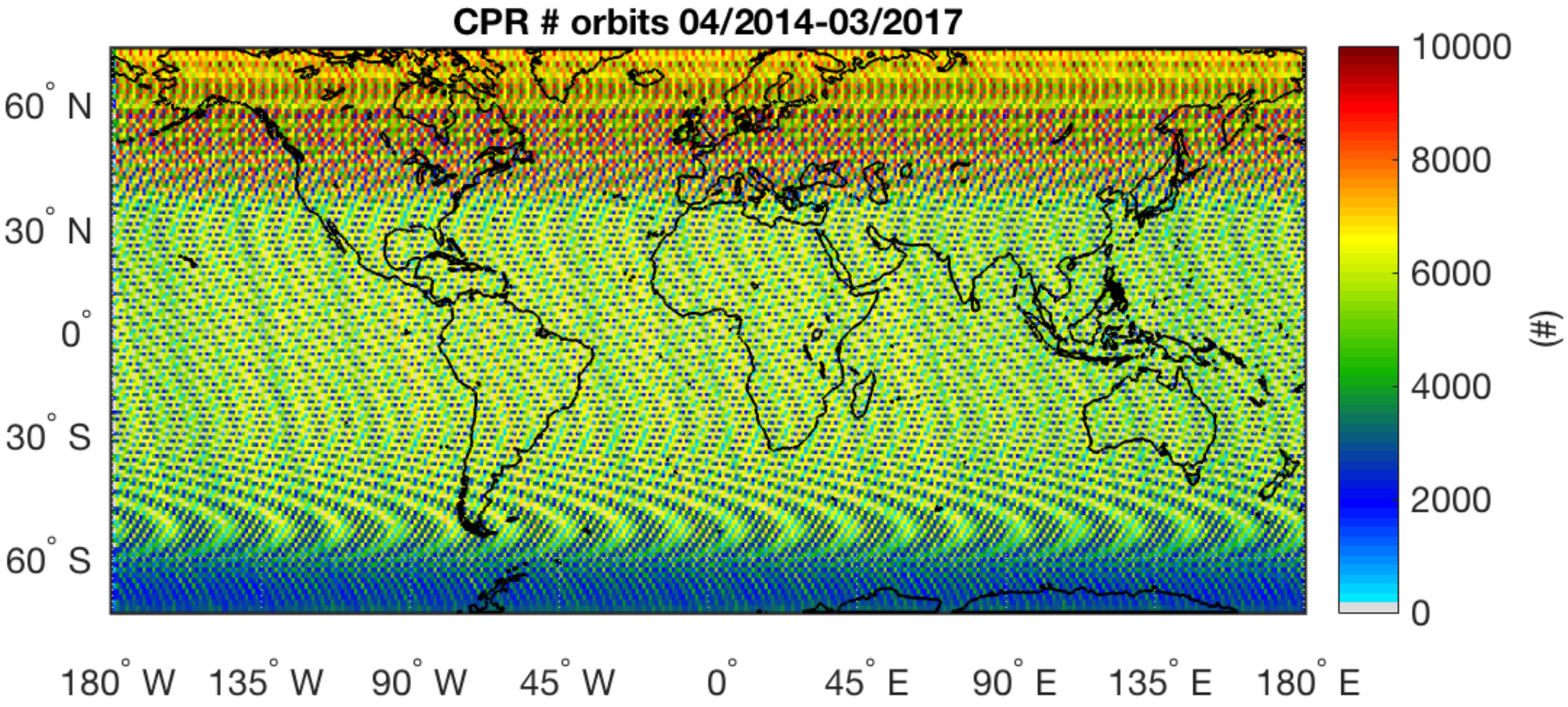




Radar Sensitivity

Courtesy of S. J. Munchak

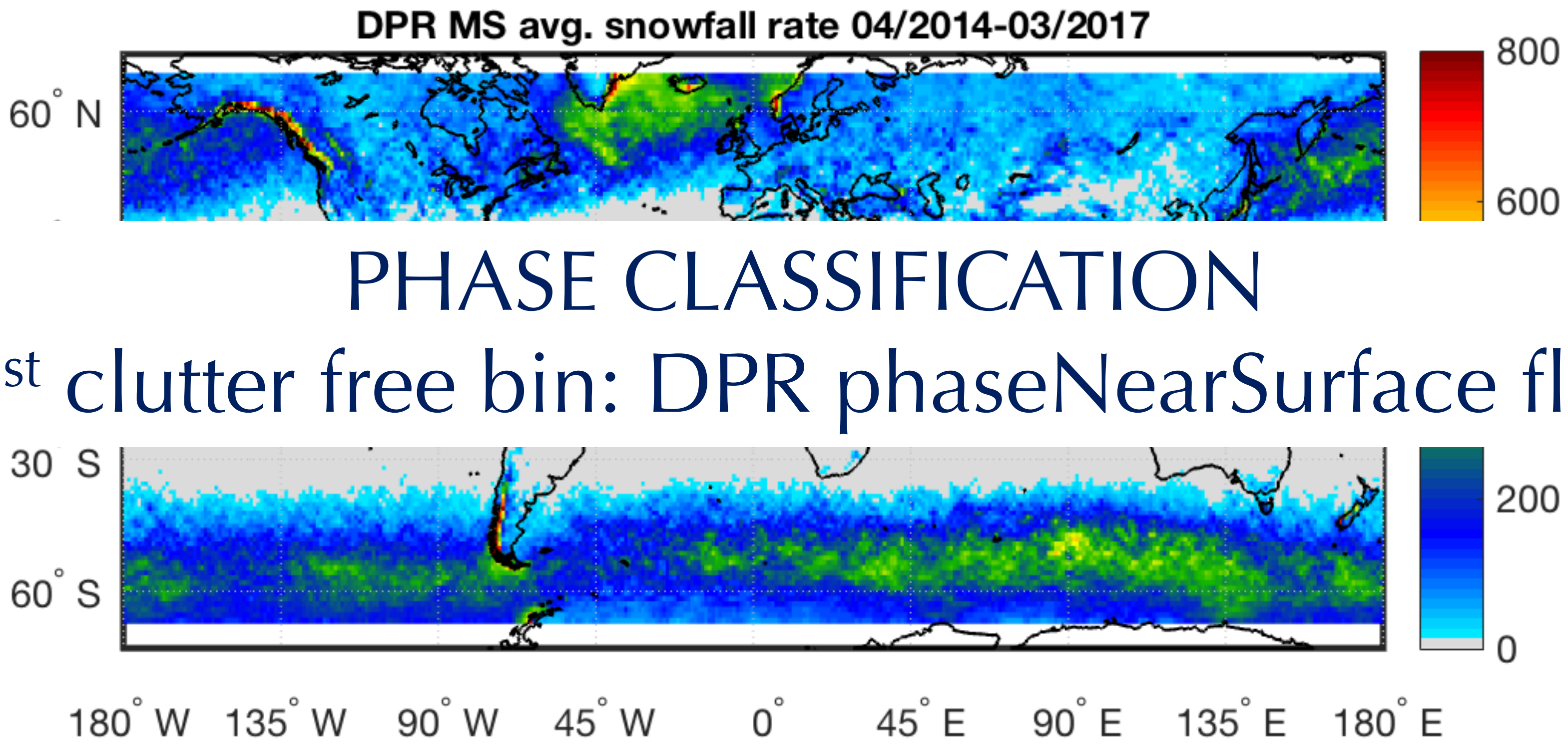
Instrument Differences



Reduced S. Hemispheric Sampling

Courtesy of L. Milani

Algorithm differences

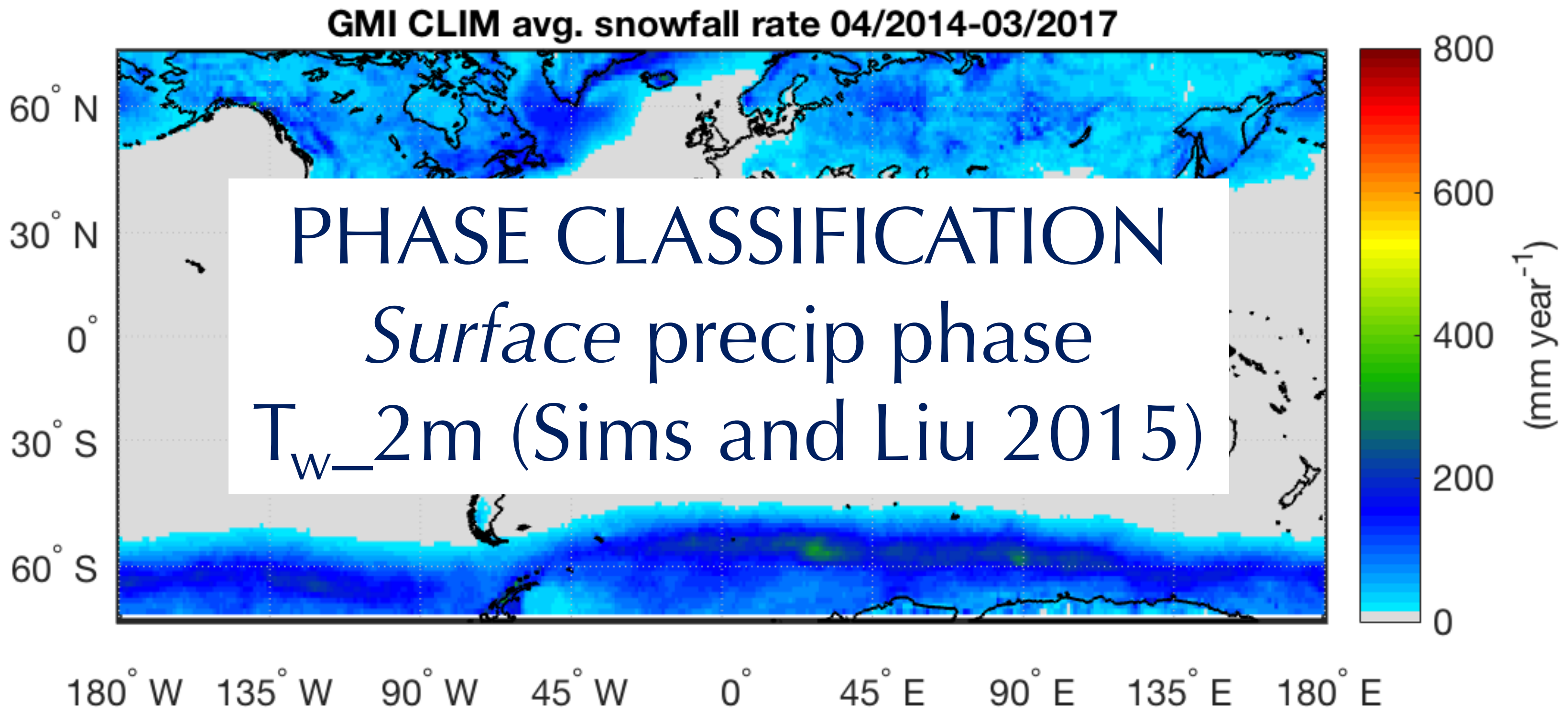


PHASE CLASSIFICATION

1st clutter free bin: DPR phaseNearSurface flag

Matched Scan (Ku + Ka-Band)

Algorithm differences



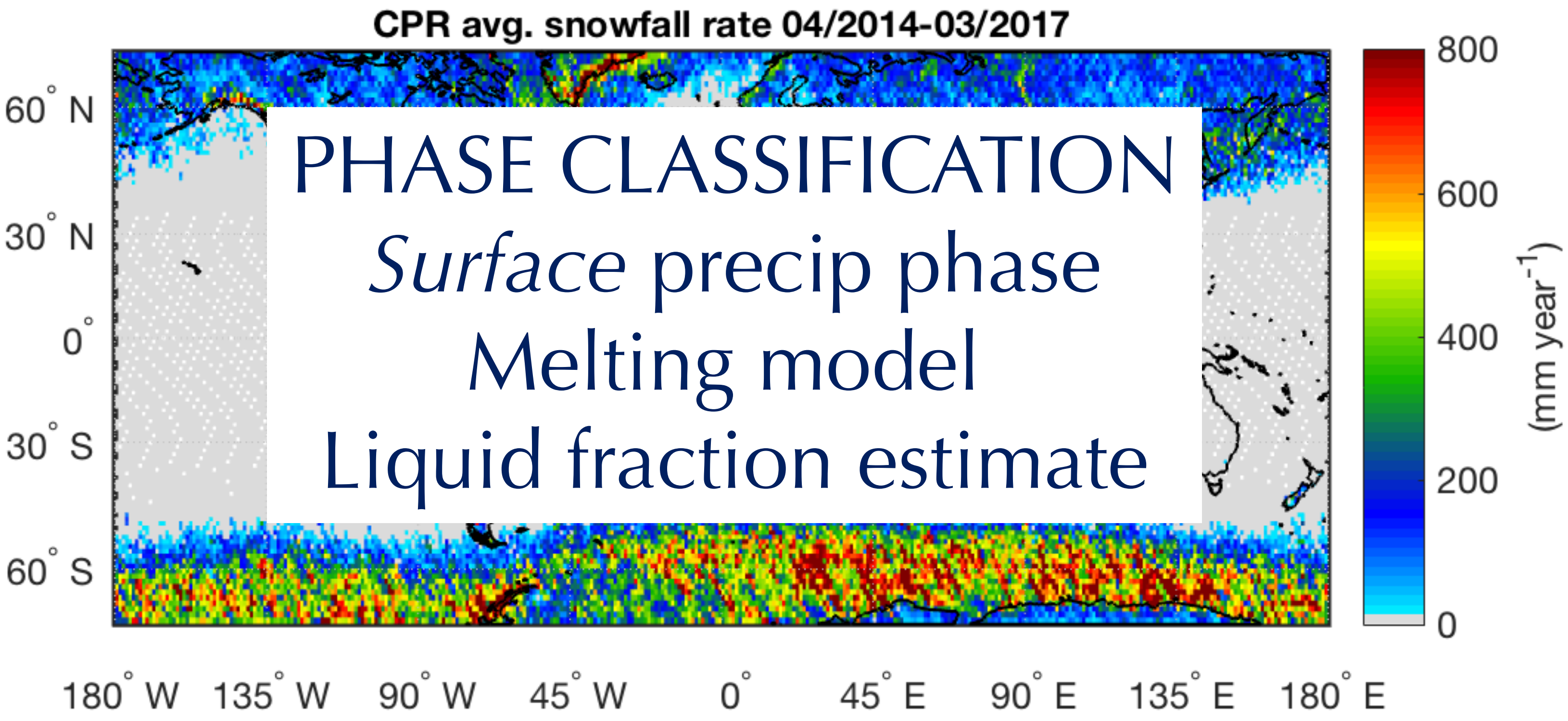
PHASE CLASSIFICATION

Surface precip phase

T_w_2m (Sims and Liu 2015)

GMI (GPROF - CLIM)

Algorithm differences



PHASE CLASSIFICATION

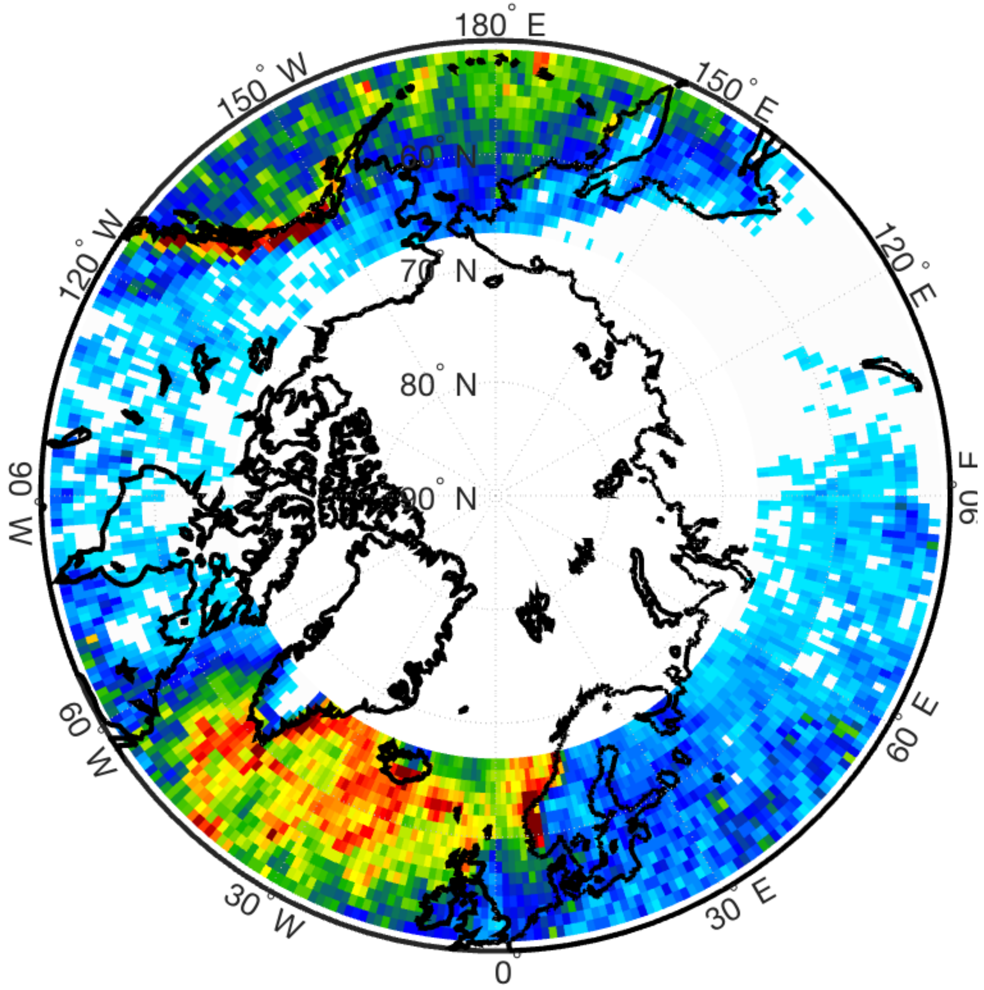
Surface precip phase

Melting model

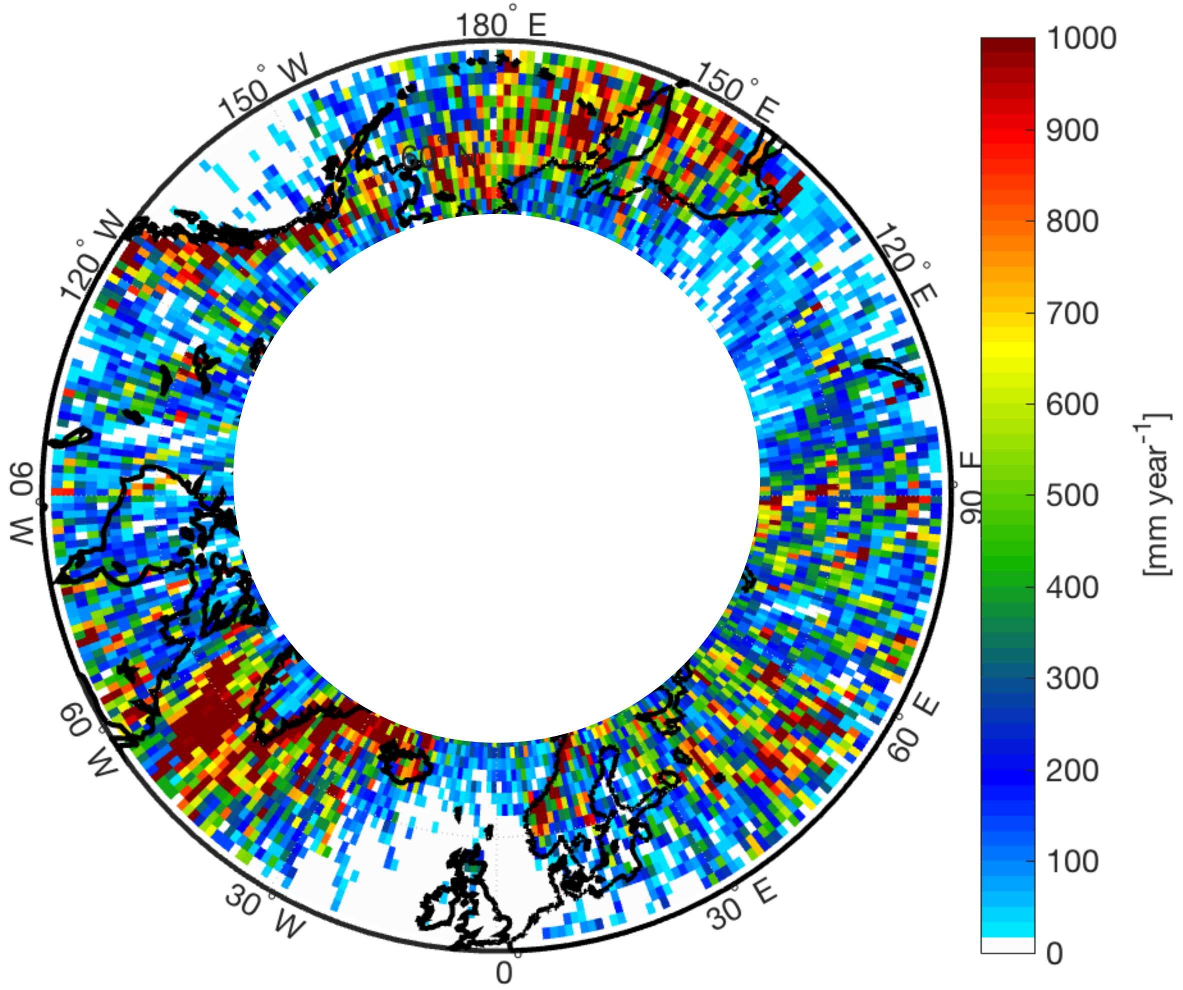
Liquid fraction estimate

CPR

Mean Annual Snowfall Rate



DPR MS



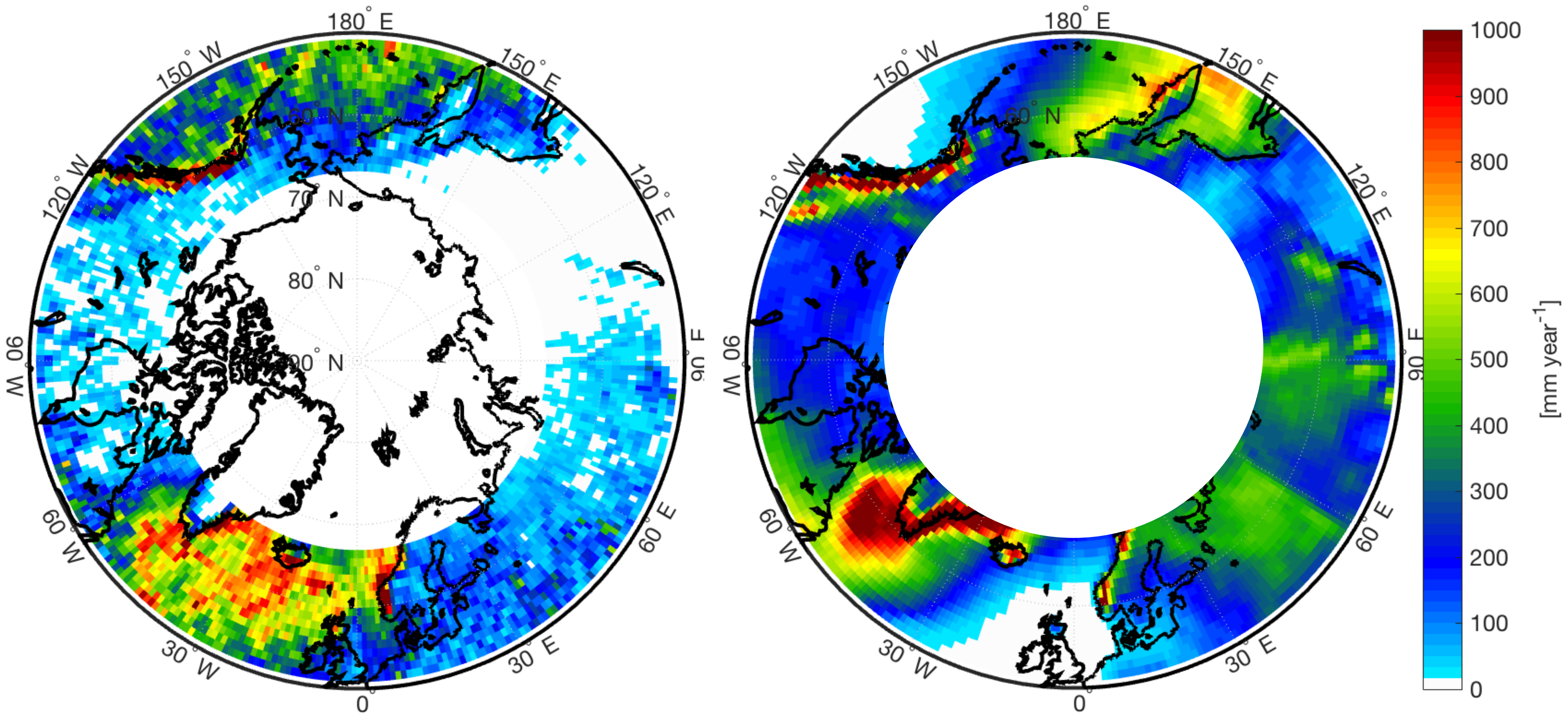
CPR

04/2014-03/2017

Michigan Technological University

PMM 2017

Mean Annual Snowfall Rate

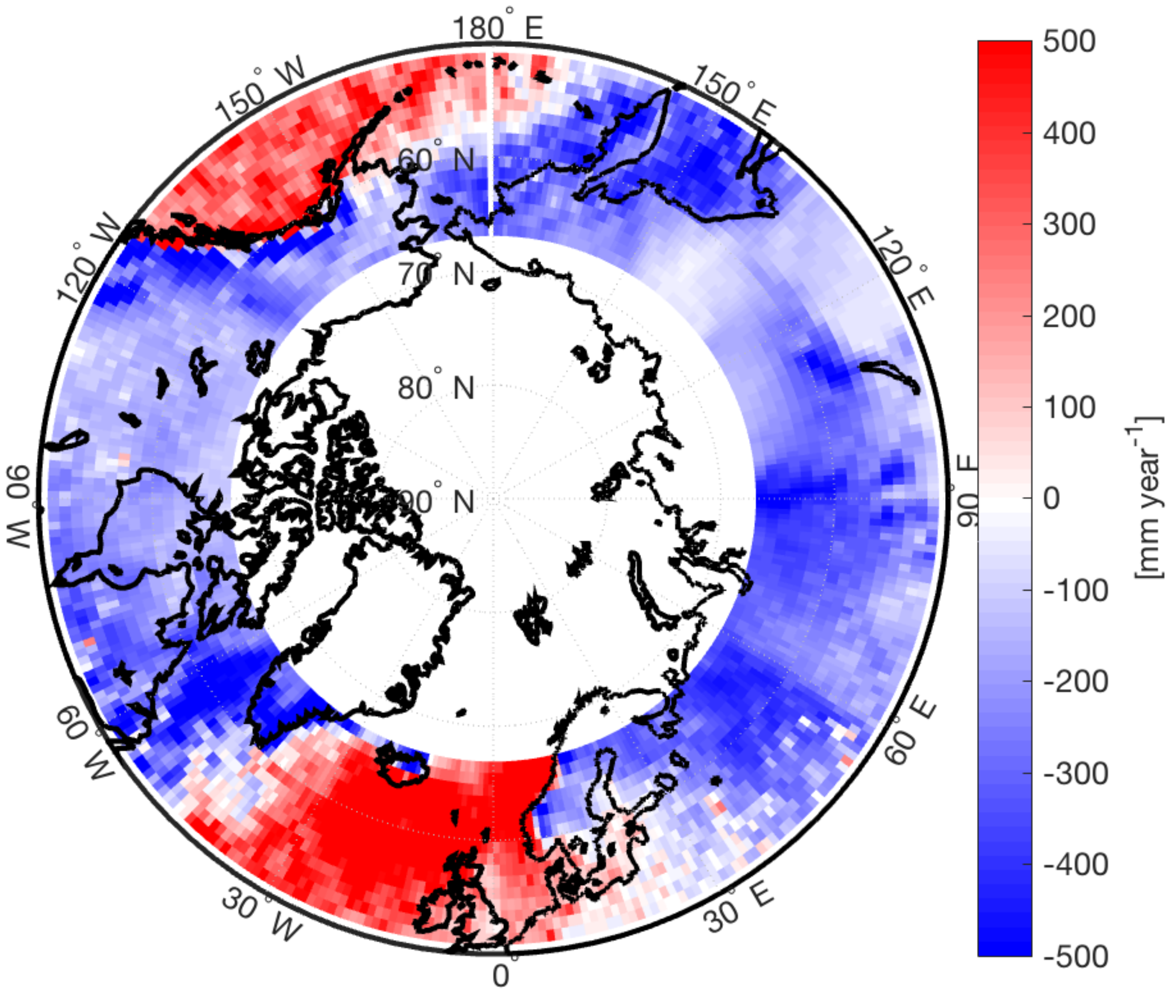


DPR MS

ERA-I

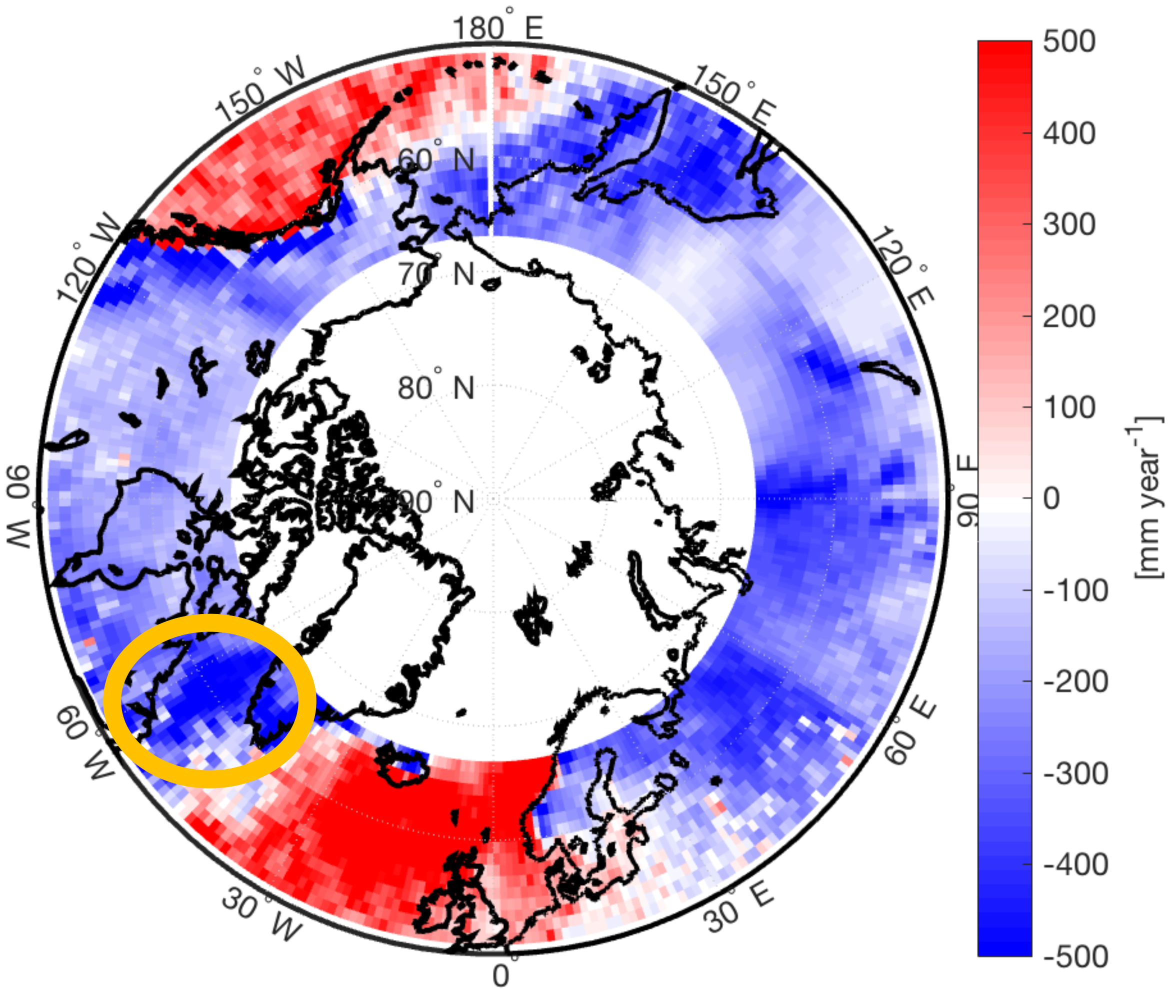
04/2014-03/2017

04/2014-03/2017

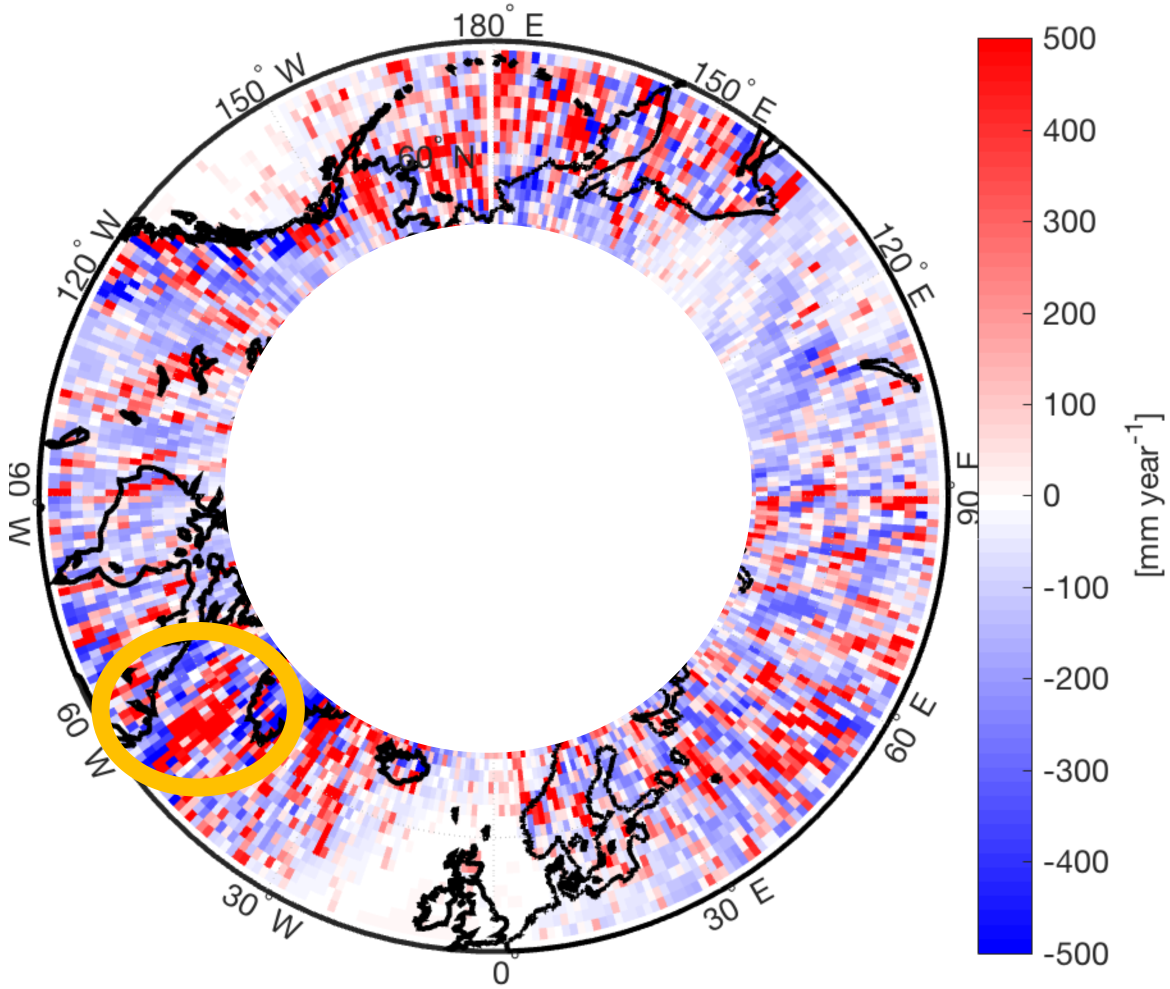


DPR – ERA-I

04/2014-03/2017

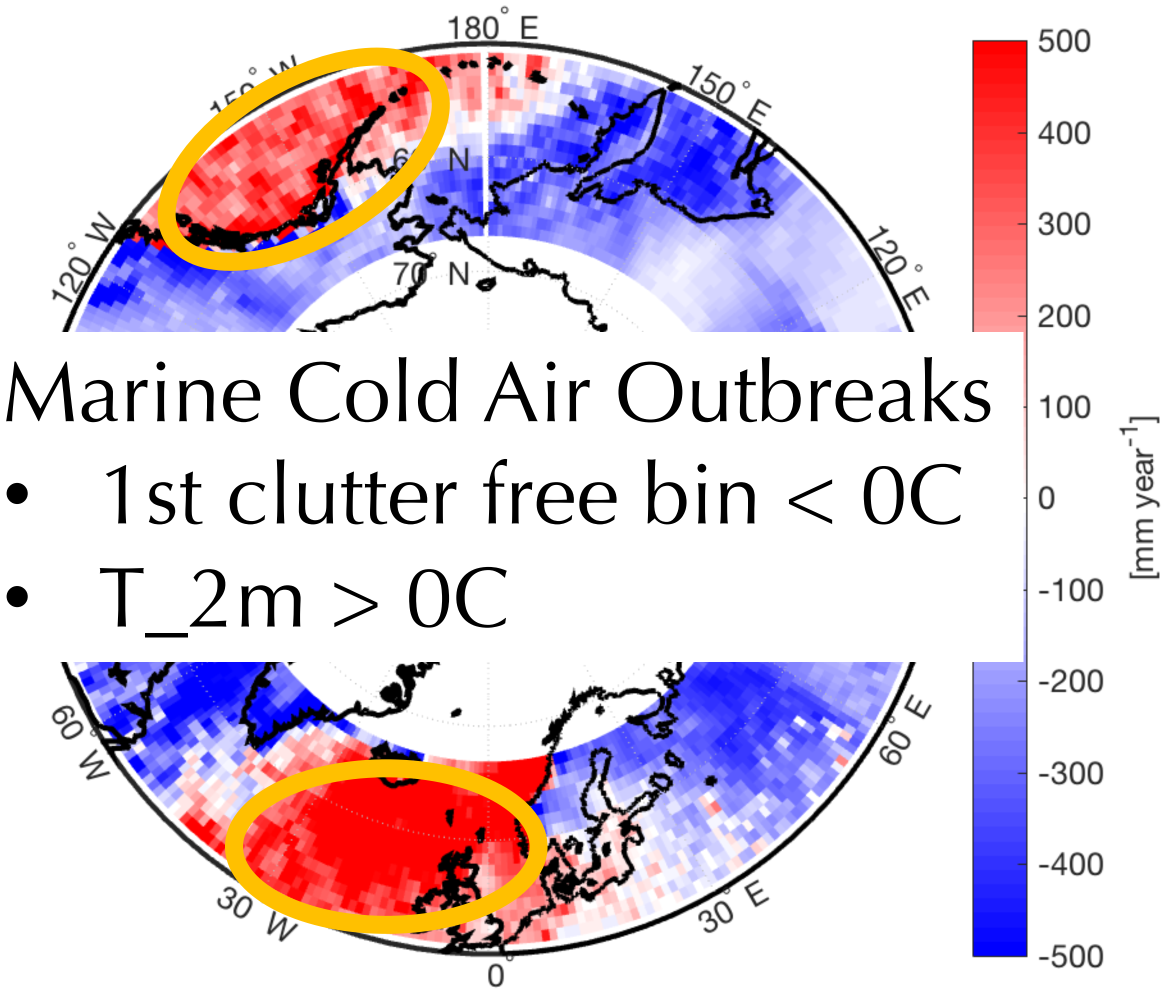


DPR – ERA-I



CPR – ERA-I

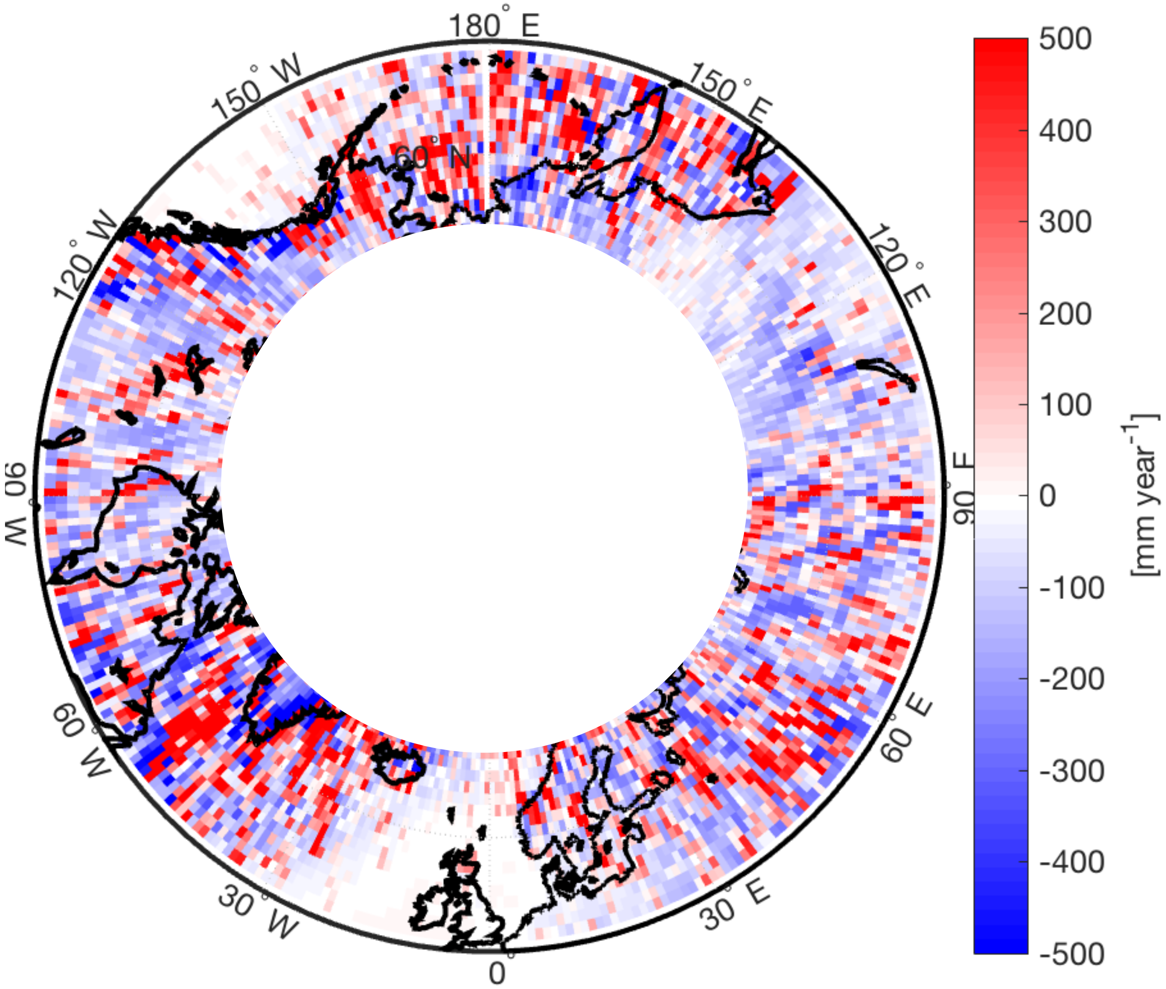
04/2014-03/2017



Marine Cold Air Outbreaks

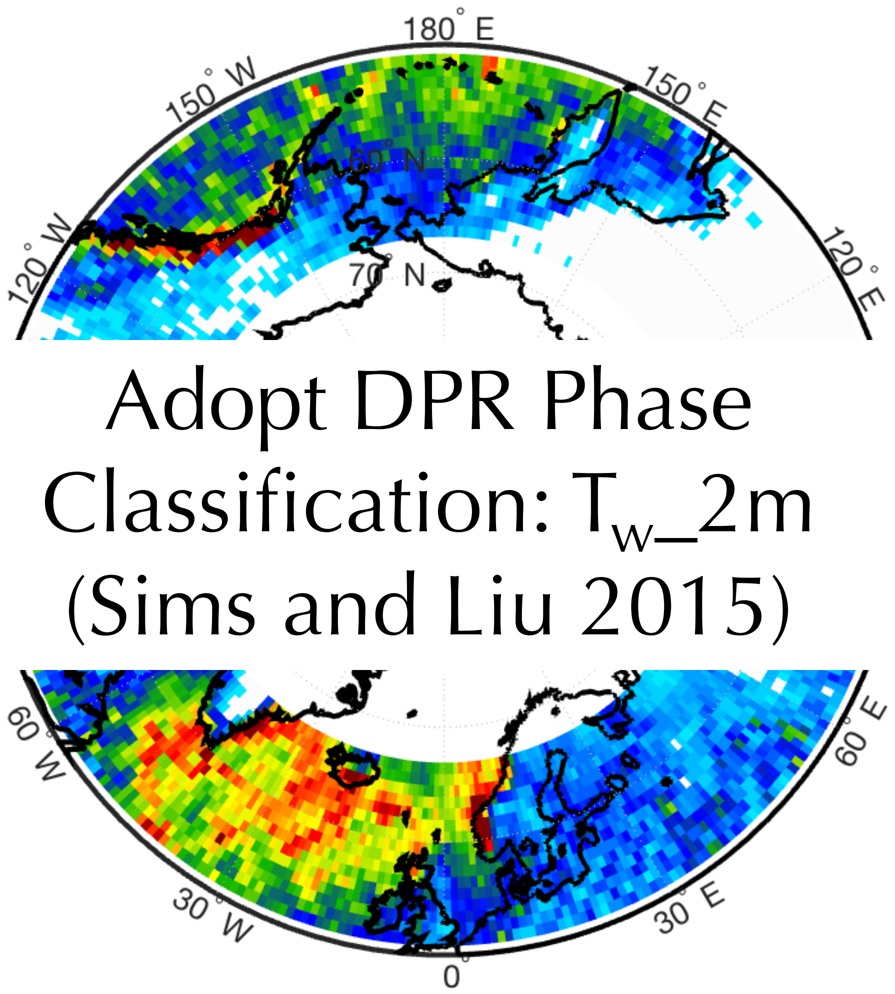
- 1st clutter free bin < 0C
- T_2m > 0C

DPR – ERA-I



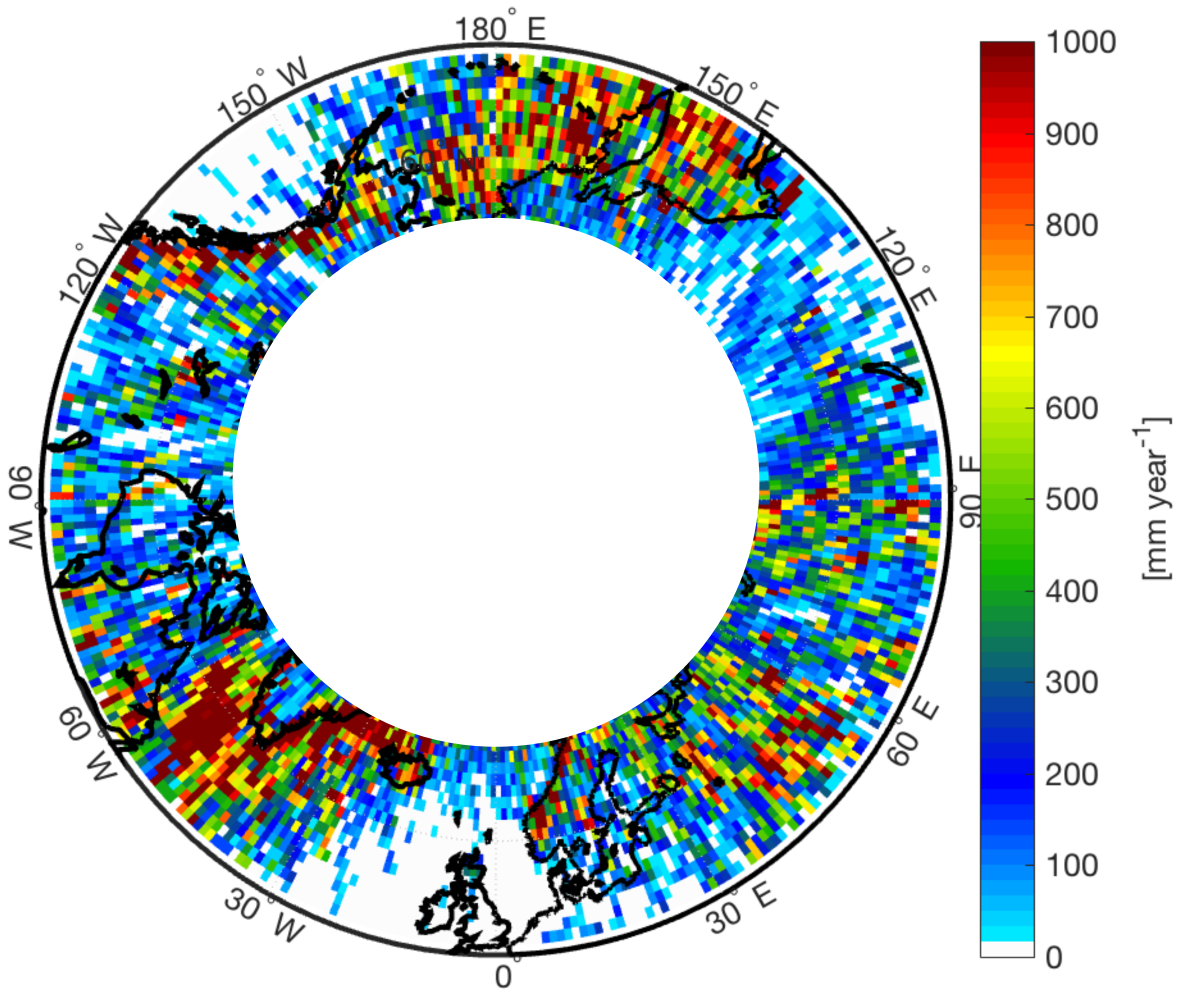
CPR – ERA-I

04/2014-03/2017



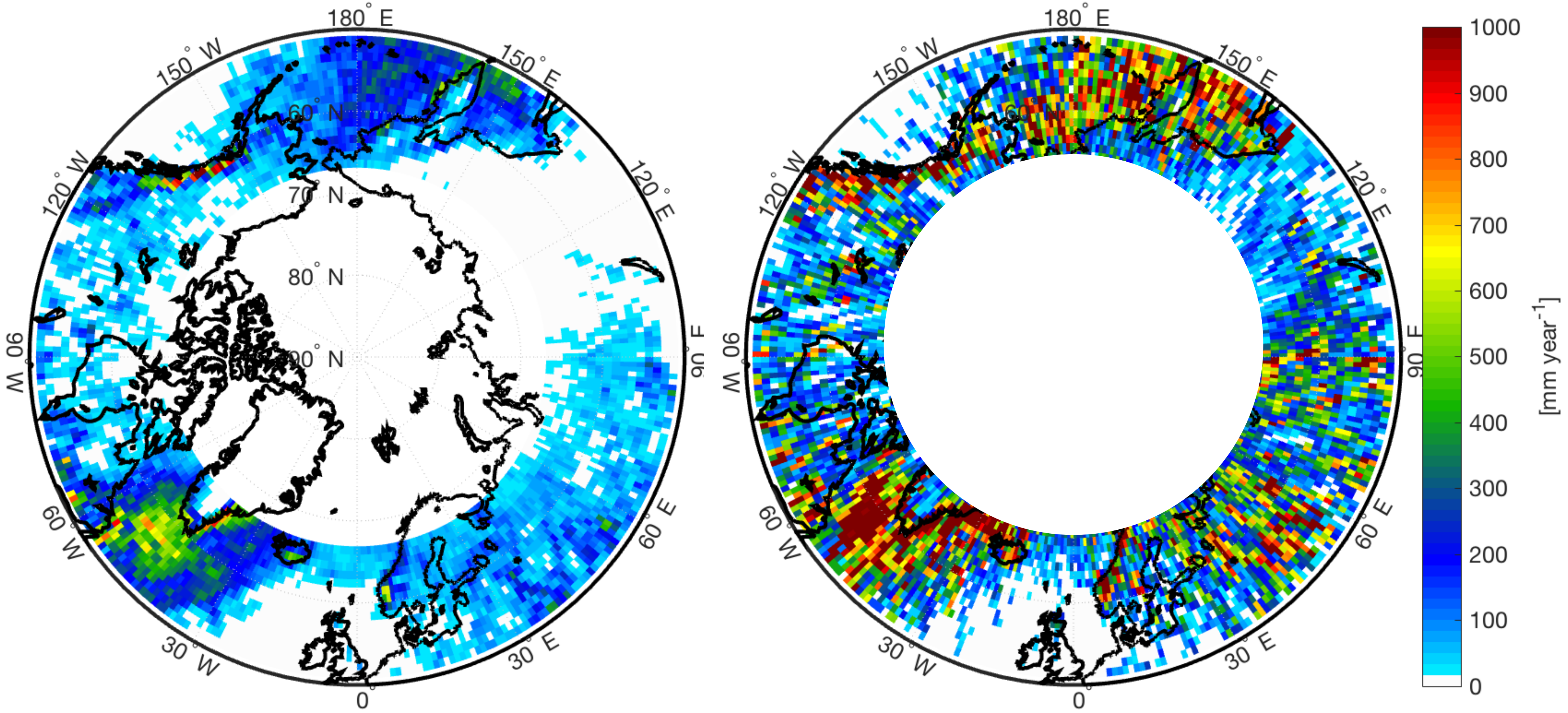
Adopt DPR Phase Classification: T_w_2m (Sims and Liu 2015)

DPR MS



CPR

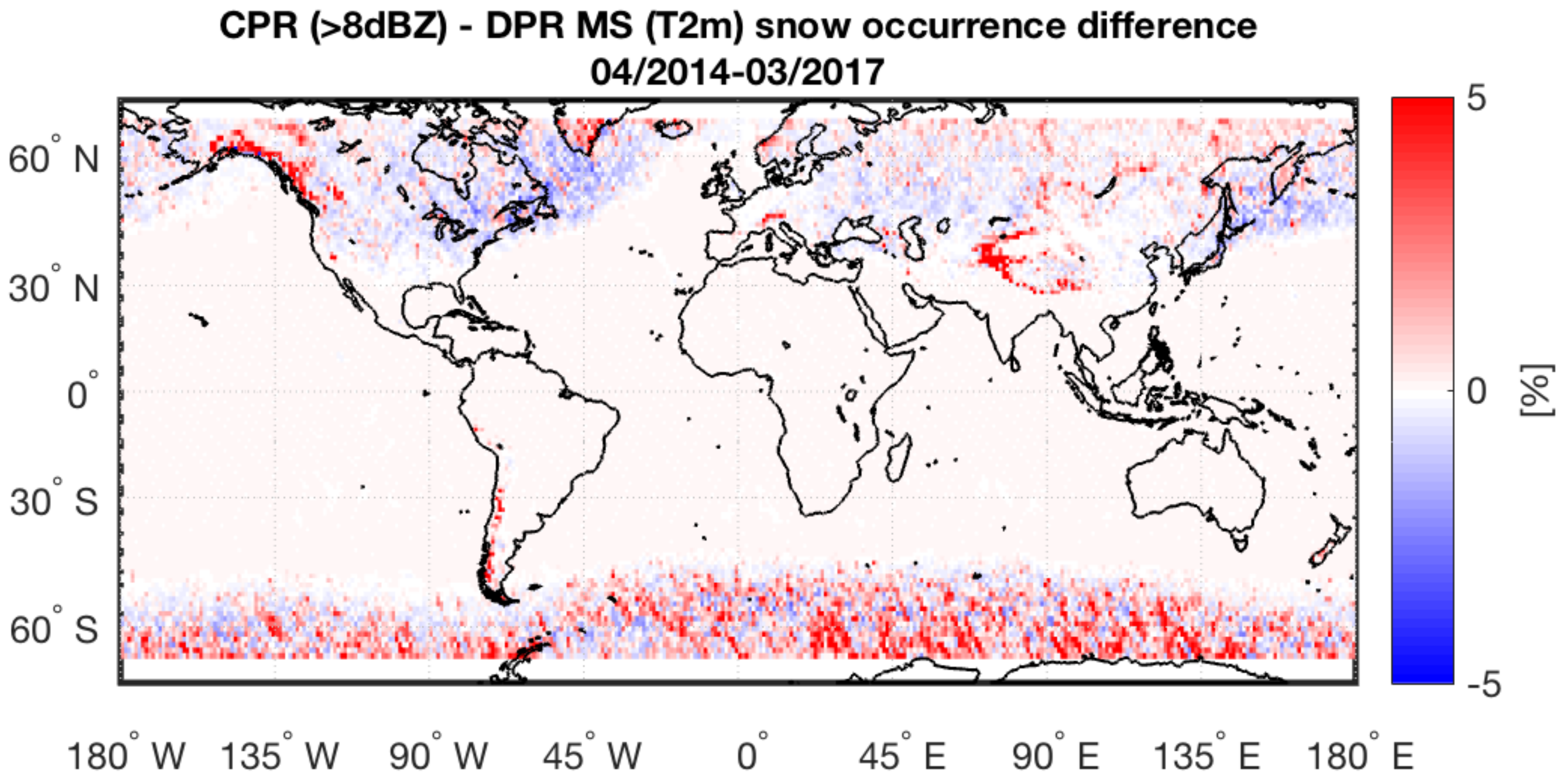
04/2014-03/2017



DPR MS: T_w_2m

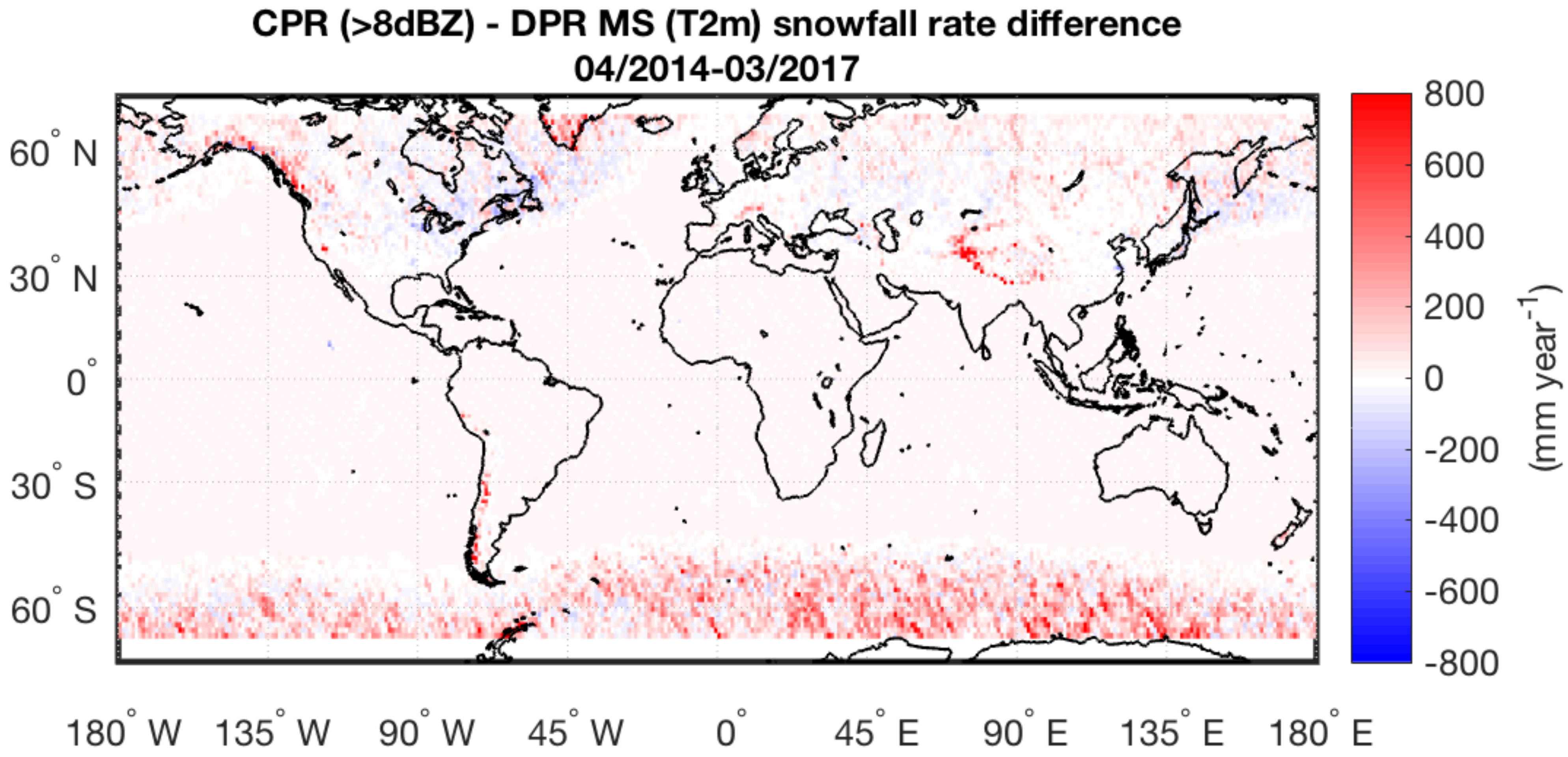
CPR

CPR/DPR Differences – Snowfall Occurrence %

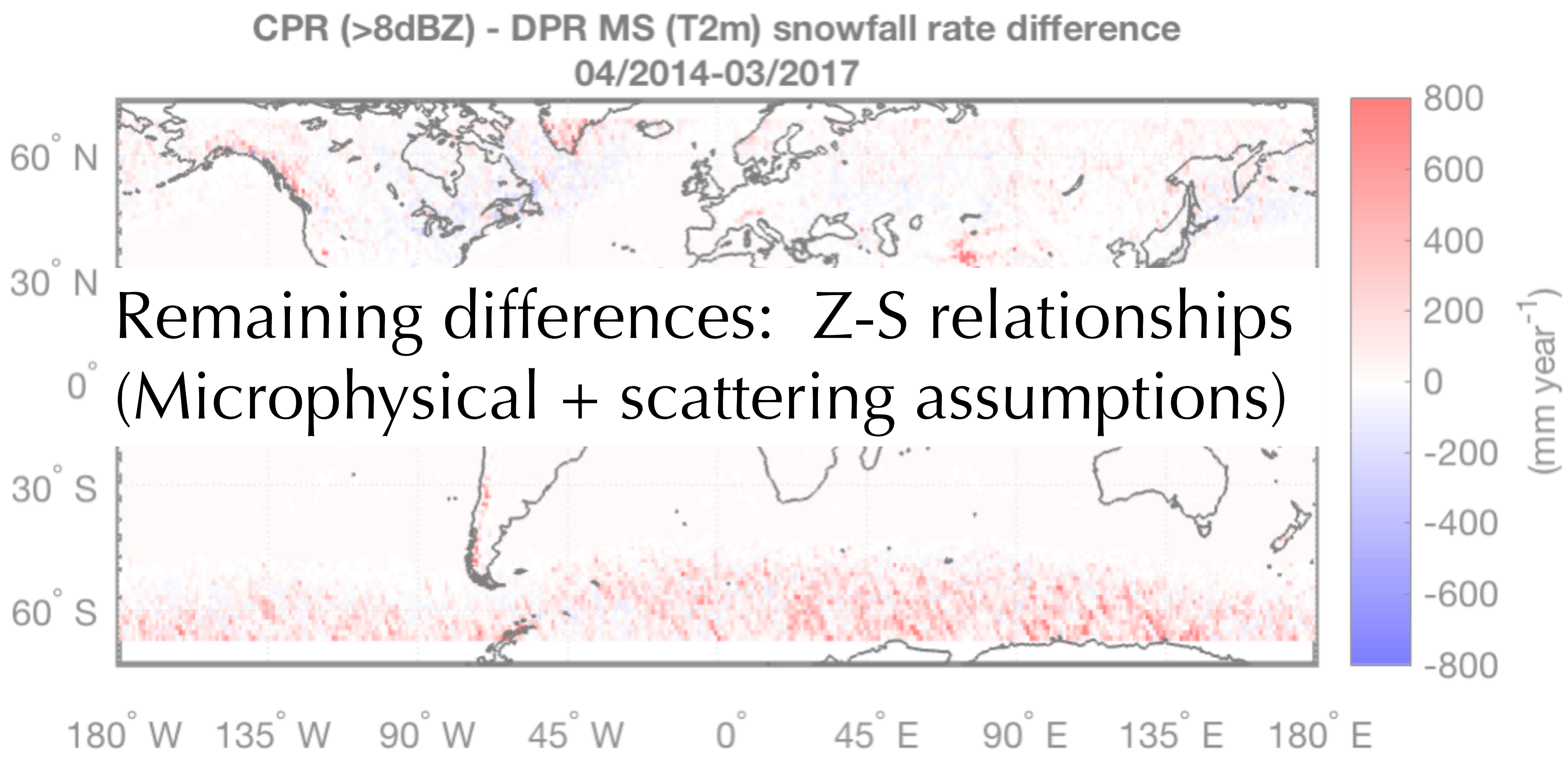


CPR Reflectivity Threshold + DPR T_w_2m Phase Classification

CPR/DPR Differences – Mean Annual Snowfall Rate

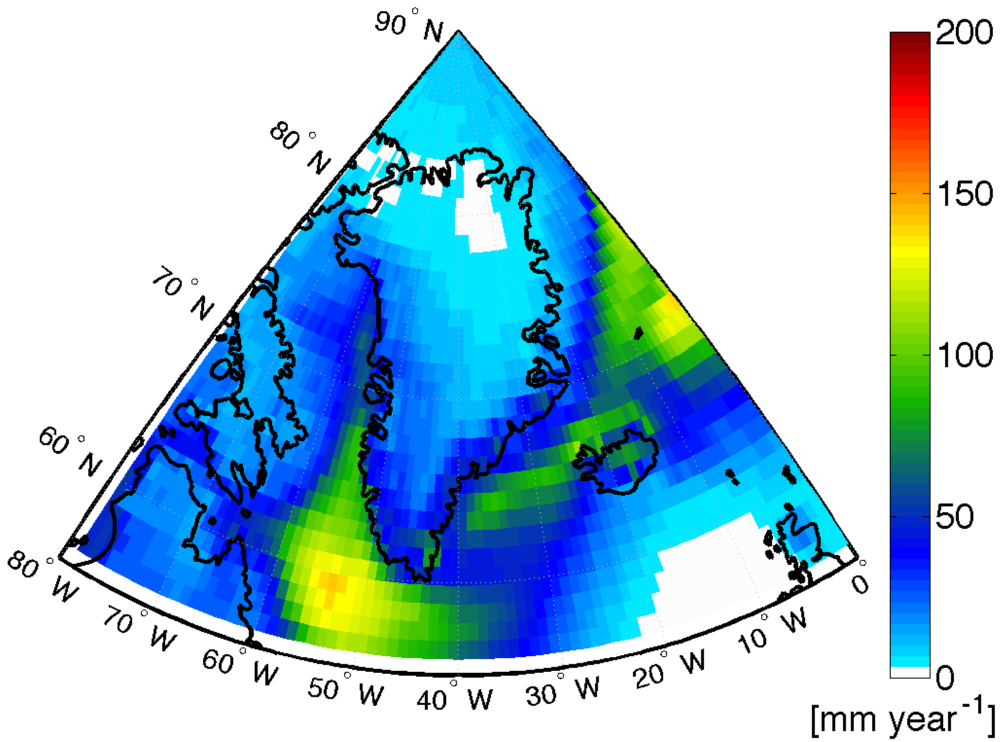


CPR Reflectivity Threshold + DPR T_w_2m Phase Classification

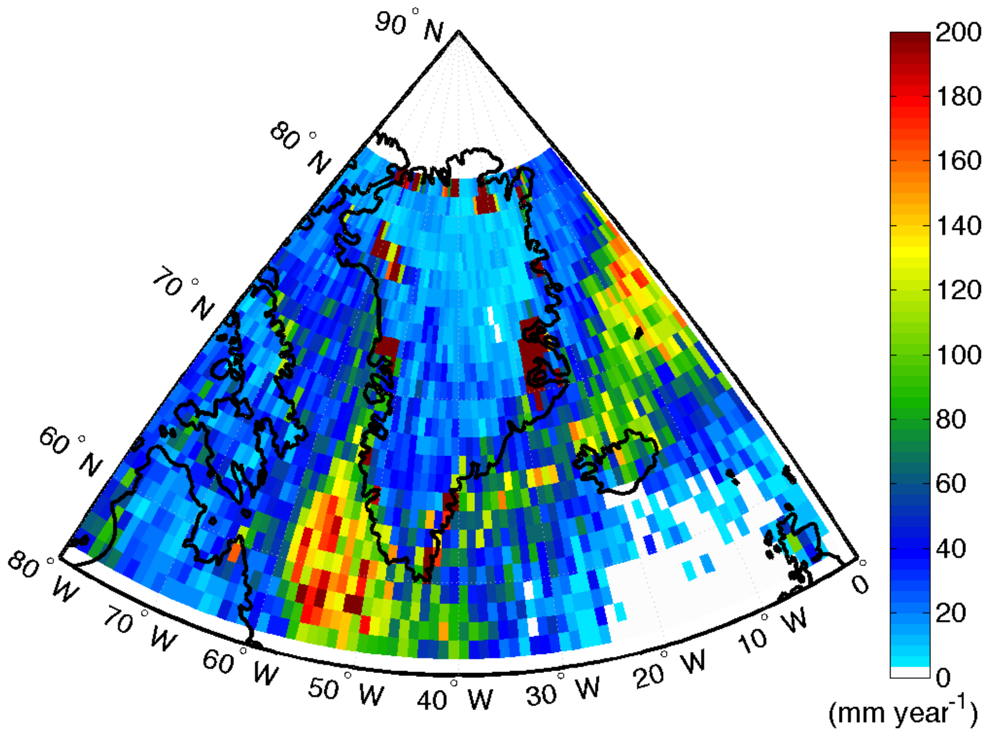


Remaining differences: Z-S relationships
(Microphysical + scattering assumptions)

Convective Snow – CloudSat Perspective



ERA-Interim

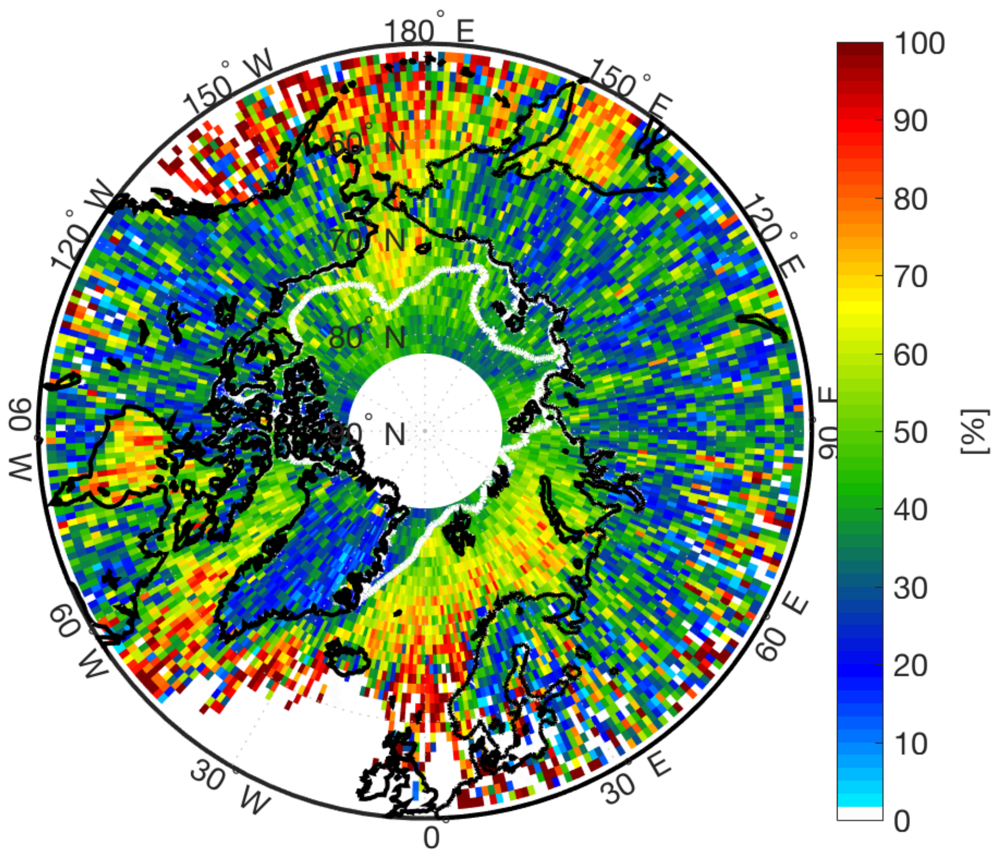


CPR

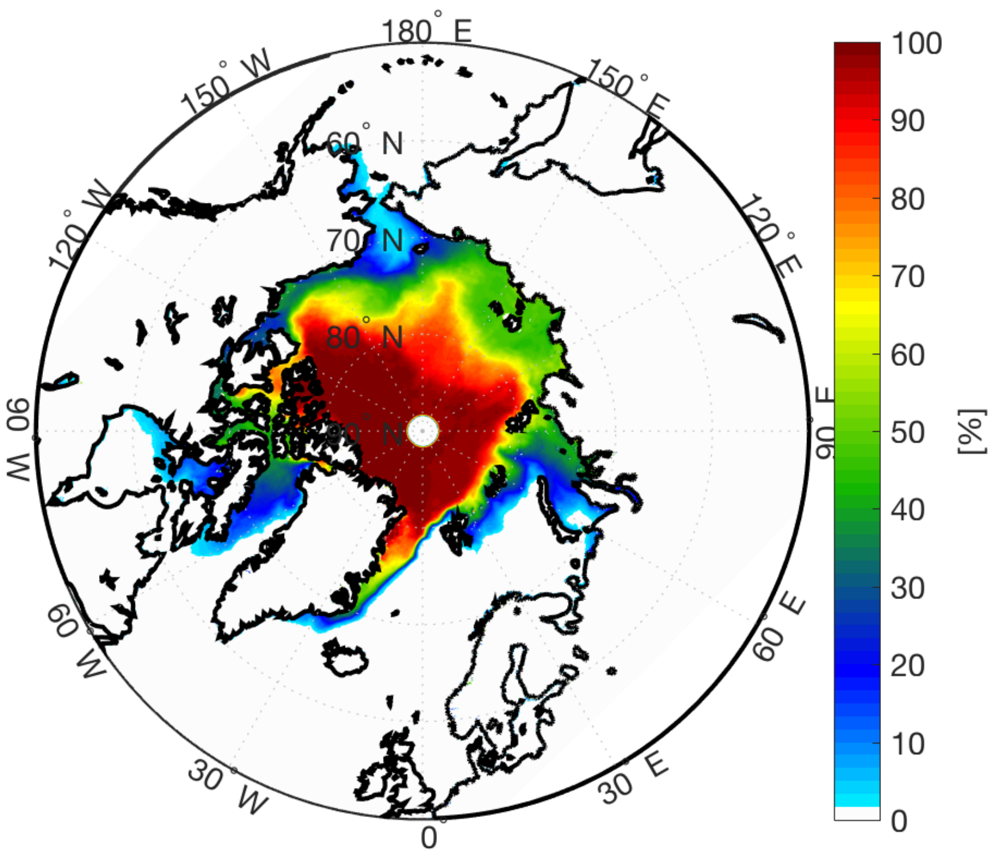
Mean Annual Convective Snowfall Rate

Convective Snow – CloudSat Perspective

SON



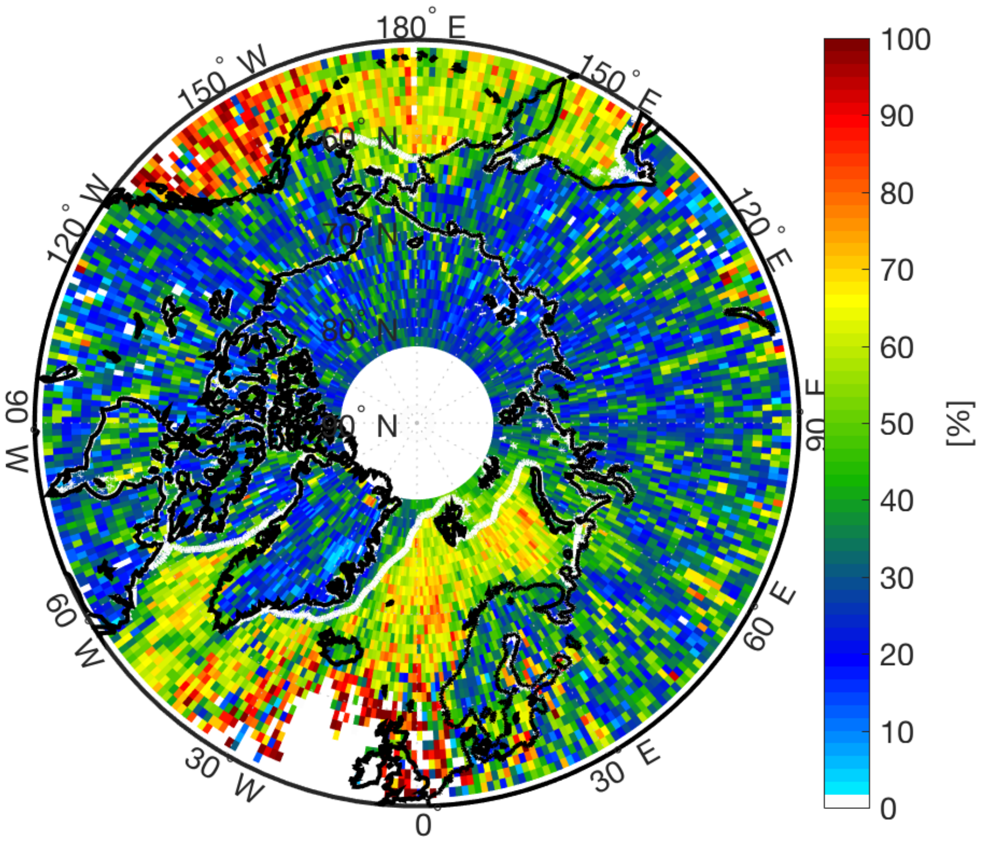
Occurrence [%]



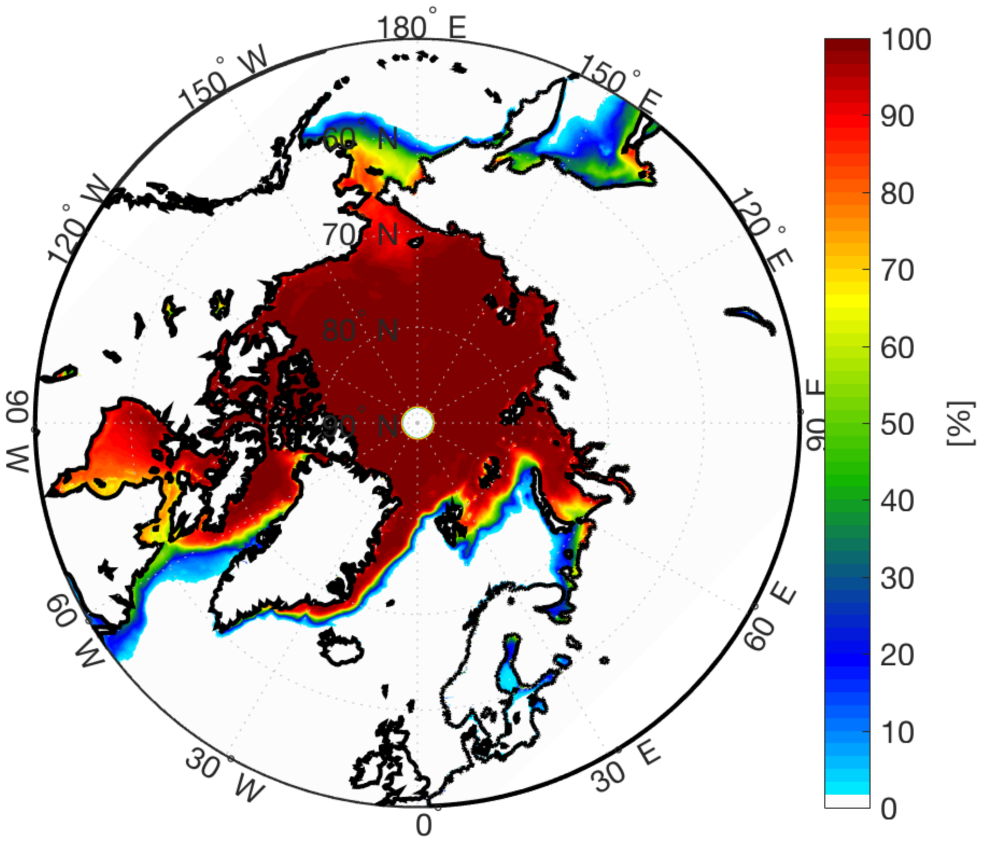
Sea Ice Fraction[%]

Convective Snow – CloudSat Perspective

DJF

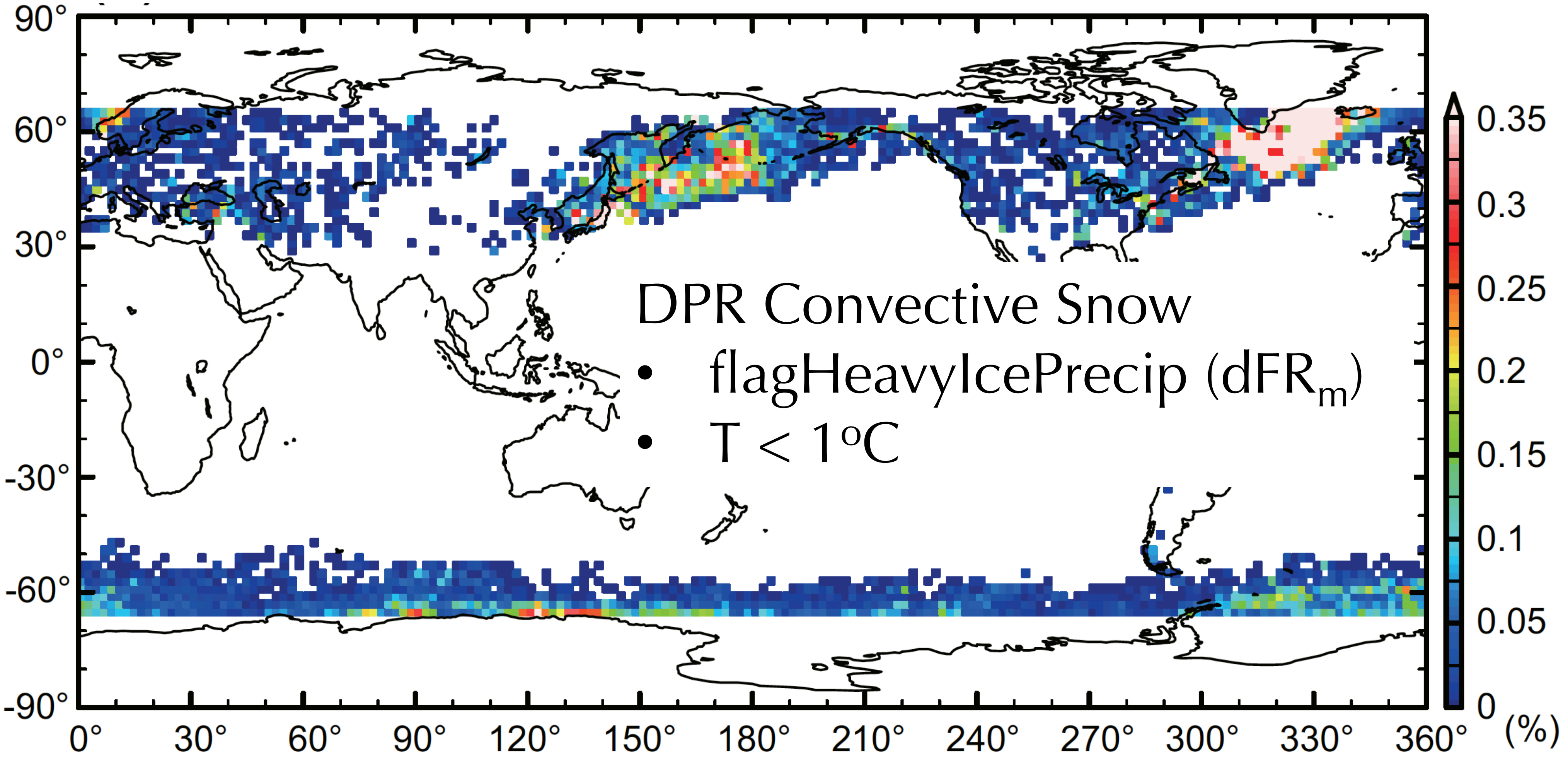


Occurrence [%]



Sea Ice Fraction[%]

GPM DPR: Convective Snow Occurrence

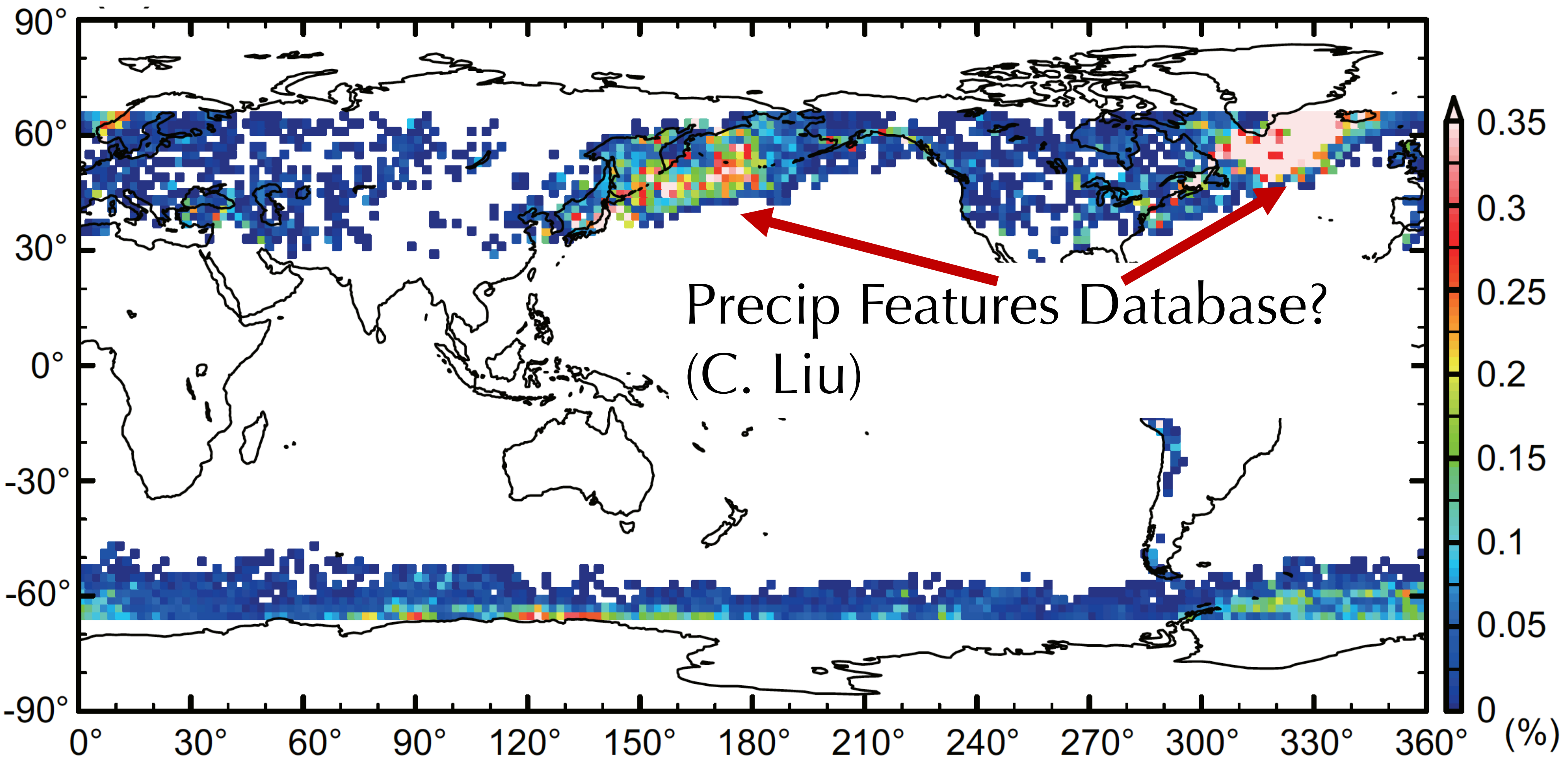


DPR Convective Snow

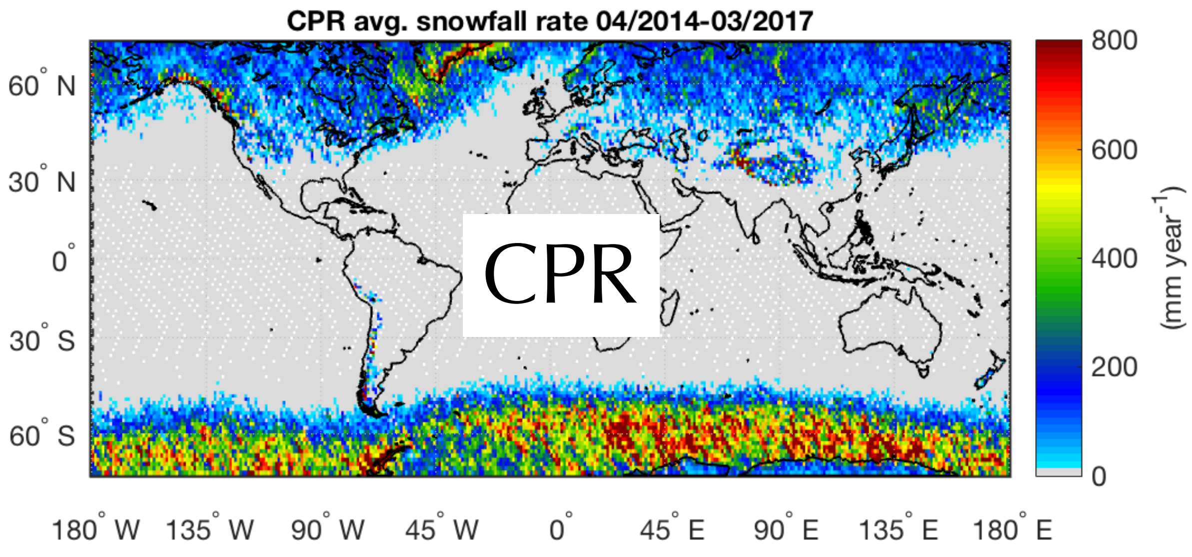
- flagHeavyIcePrecip (dFR_m)
- T < 1°C

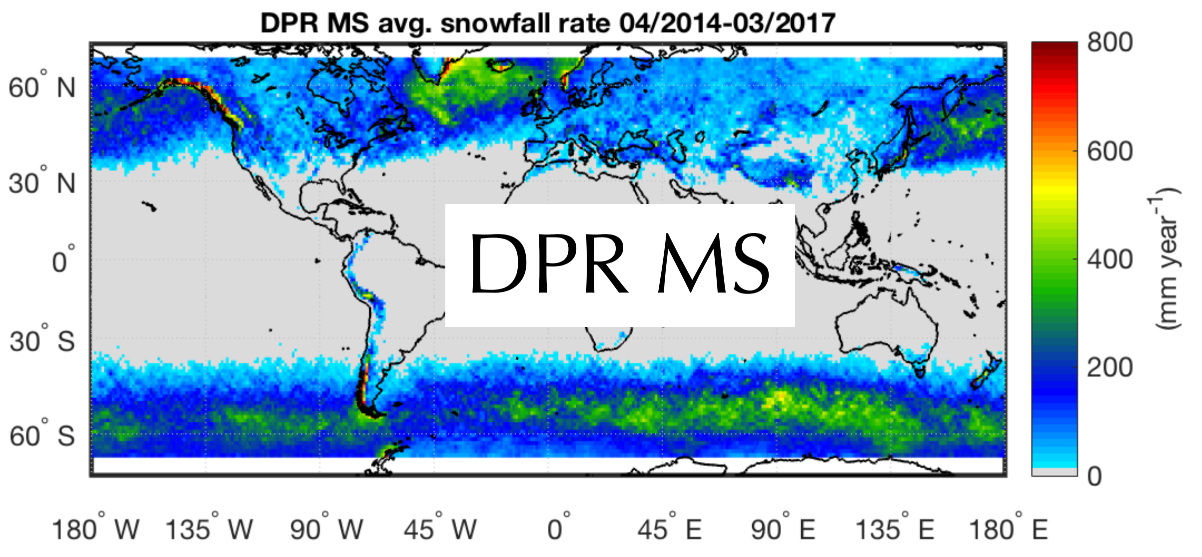
Courtesy T. Iguchi

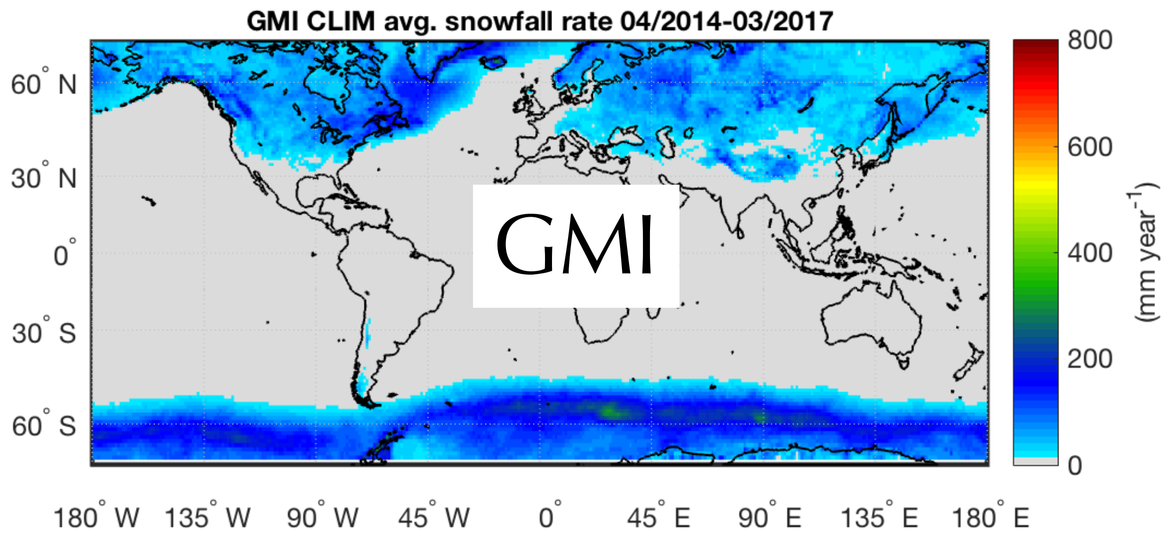
GPM DPR: Convective Snow Occurrence

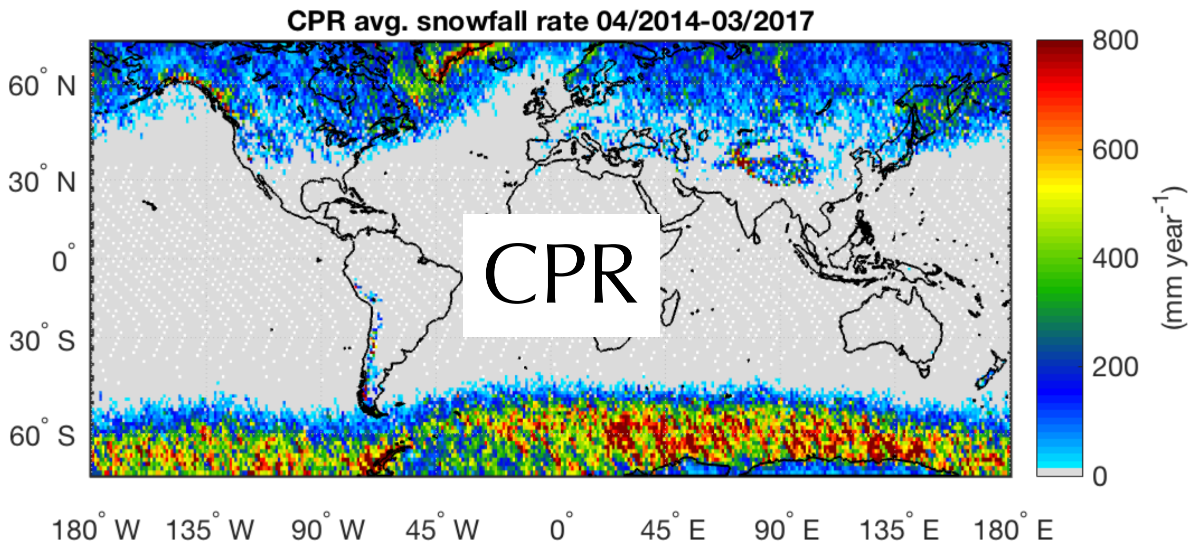


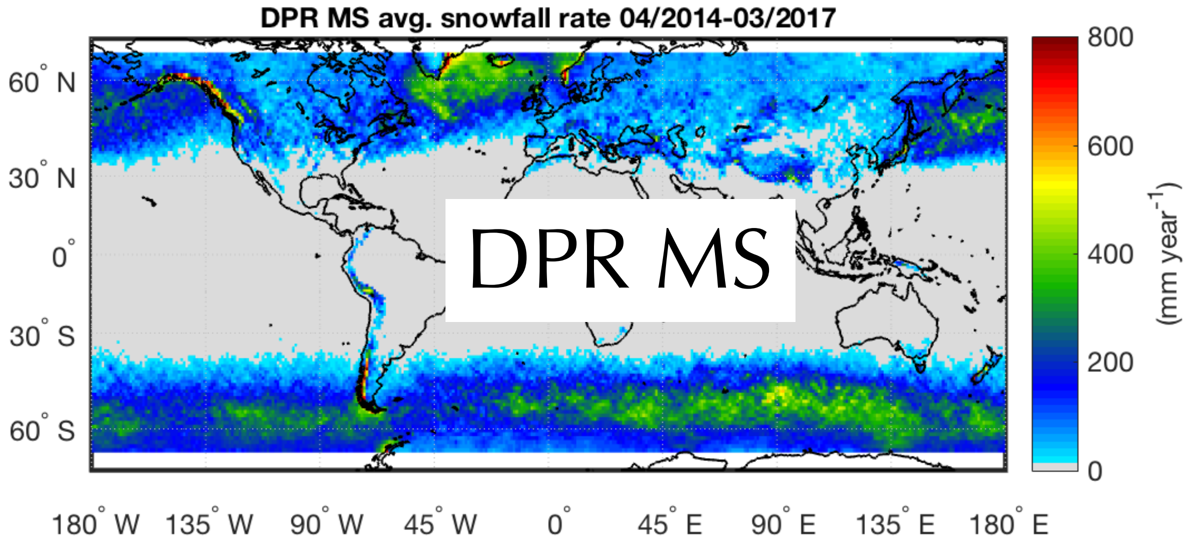
Courtesy T. Iguchi

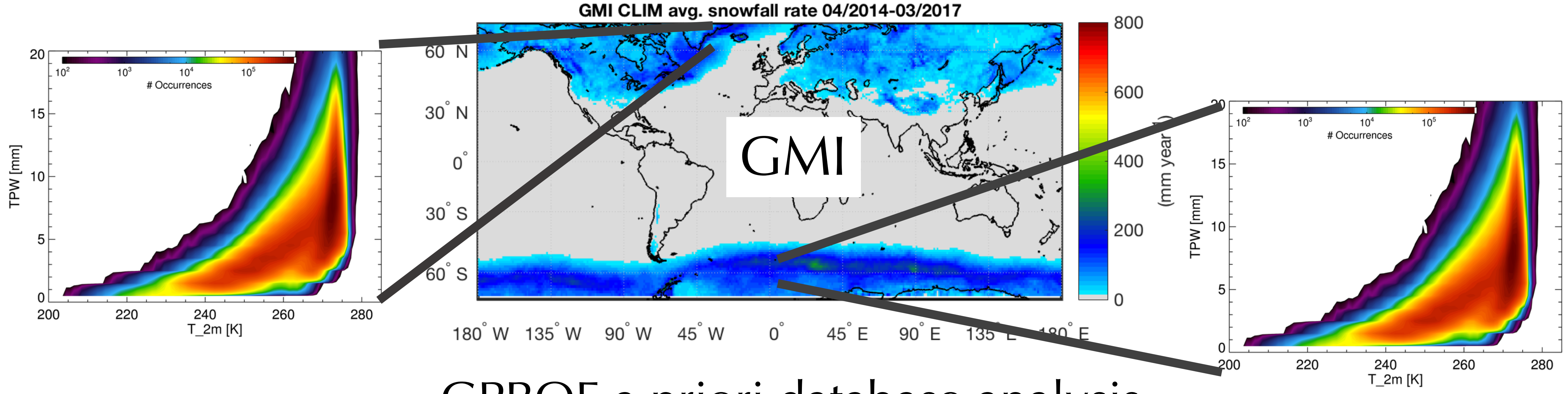

CPR avg. snowfall rate 04/2014-03/2017
CPR
60° N
30° N
0°
30° S
60° S
180° W
135° W
90° W
45° W
0°
45° E
90° E
135° E
180° E
800
600
400
200
0
(mm year^-1)


DPR MS avg. snowfall rate 04/2014-03/2017
DPR MS
60° N
30° N
0°
30° S
60° S
180° W
135° W
90° W
45° W
0°
45° E
90° E
135° E
180° E
800
600
400
200
0
(mm year^-1)


GMI CLIM avg. snowfall rate 04/2014-03/2017
GMI
60° N
30° N
0°
30° S
60° S
180° W
135° W
90° W
45° W
0°
45° E
90° E
135° E
180° E
800
600
400
200
0
(mm year^-1)







GPROF a priori database analysis

The Performance and Validation of GPM's Falling Snow Retrieval Algorithms

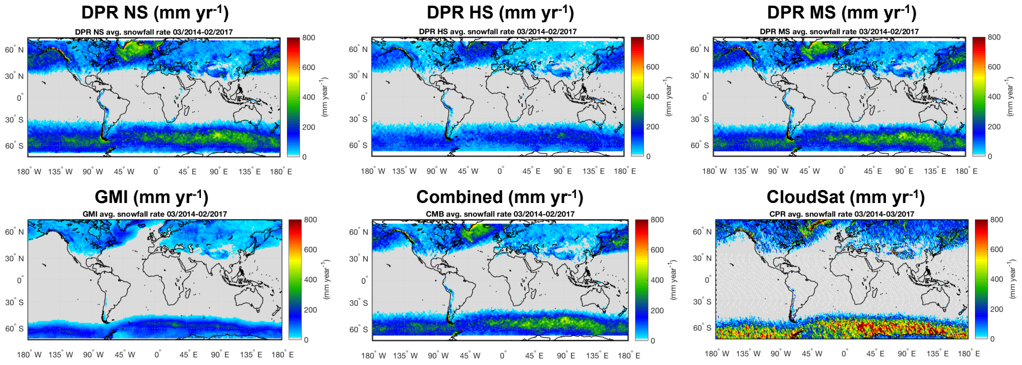
Gail Skofronick-Jackson[1], Joe Munchak[1], Mark Kulie[2], Norm Wood[3], Lisa Milani[2]
[1]Mesoscale Processes Branch, Code 612, NASA Goddard Space Flight Center, Greenbelt, MD, USA, Gail.S.Jackson@nasa.gov
[2]Michigan Technological University, [3]University of Wisconsin

Introduction:

Precipitation falling in the form of snow is vitally important for society and the Earth's climate, geology, agriculture, and ecosystem. In some parts of the world, snow is the dominant precipitation type and relied upon year round for fresh water. The Global Precipitation Measurement (GPM) mission (launched 2014 in a partnership between NASA and JAXA) was specifically designed to remotely sense (estimate) both liquid rain and falling snow. This poster describes **preliminary results and performance evaluations of falling snow estimates** using the GPM Microwave Imager (GMI) and the Dual-frequency Precipitation Radar (DPR) on board GPM. All snow estimates are in liquid equivalent units.

To compare GPM falling snow estimates with other sources of falling snow estimates, such as from CloudSat, we must ensure that the analysis is done properly as there are several factors that limit raw-product comparisons. These include those induced by: **phase classification, sampling, instrumentation (resolution/ sensitivity), and algorithm differences**. Classification refers to the method used to assign rain or snow at the surface. Sampling due to differing swath widths and orbits causes additional disparities between the products. The instruments have different design features, most notably minimum detectable reflectivity and frequency sensitivities. Algorithm assumptions lead to dissimilarities that are more difficult to reconcile. A discussion of these four factors is also presented.

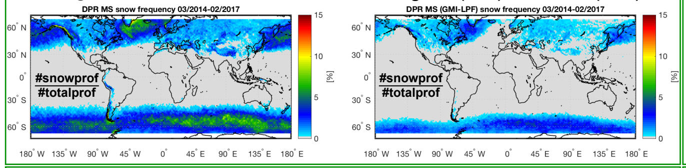
Global Falling Snow Estimates from GMI, DPR, and Combined (March 2014-February 2017)



Challenges in Comparing GPM and CloudSat Falling Snow Estimates

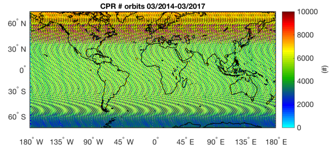
Classification of phase at surface:

Using DPR T at lowest detected Z — Using GMI (T2m) Sims & Liu (2015)



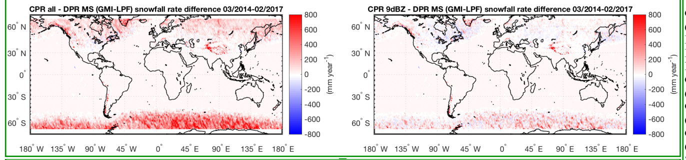
Sampling:

CloudSat NH bias due to daylight ops



Instrument Induced:

CPR (all) – DPR MS (T2m) — CPR (>9 dBZ) – DPR MS (T2m)



Algorithm Induced:

Instrument	Snow Occurrence (%)	Mean Snow Rate (mm/day)
CloudSat (native res)	2.422	0.1229
DPR-NS	0.262	0.0401
DPR-MS	0.262	0.0402
DPR-HS	0.199	0.0208
CloudSat (5-pixel)	2.879	0.1212
CloudSat (15-pixel)	3.516	0.1208
CloudSat (15-pixel, 8 dBZ cutoff)	0.276	0.0556

Table data uses DPR T2m

Despite yielding a similar occurrence, a cutoff of 8-9 dBZ for CPR yields a mean snowfall rate 30-40% higher than DPR-MS. The algorithm differences lead to higher snowfall rates from CPR than DPR, even when the same events are being observed.

Acknowledgments

We thank the GPM algorithm developers and the Precipitation Processing System for retrieval estimates and data processing. Funding for this work comes from NASA Headquarters Ramesh Kakar for PIs Skofronick-Jackson (8th PMM Science Team), Munchak/Kulie/Wood, (9th Science team). Milani is funded through Kulie's PMM grant and via other sources. The GPM Project also supports Skofronick-Jackson.

Ground-Based Profiling Radar Applications for Spaceborne Snowfall Retrievals

Mark Kulie[1,*], Claire Pettersen[2], William Hahn[2] ,Tim Wagner[2], Tristan L'Ecuyer[2], Larry Bliven[3], David Wolff[3], Walt Petersen[4]

[1]Michigan Technological University, Houghton, MI, [2]University of Wisconsin-Madison, Madison, WI, [3]NASA WFF, [4]NASA MSFC

Michigan Tech

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Research Support Acknowledged from NASA PMM Grant NNX16AE21G

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I. Profiling Radar Datasets

Ground-based profiling radars offer unique observational capabilities that can be exploited for Global Precipitation Measurement (GPM) mission snowfall retrieval applications. Profiling radars provide scientifically useful long-term datasets associated with snowfall events, serve as excellent GPM evaluation datasets, and provide valuable guidance for future spaceborne radar missions. Two profiling radar datasets are used for snowfall radar retrieval applications (**Figs. 1 and 2**).

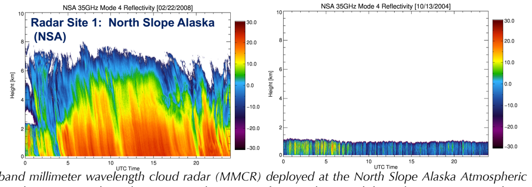


FIG. 1: Ka-band millimeter wavelength cloud radar (MMCR) deployed at the North Slope Alaska Atmospheric Radiation Measurement Climate Research Facility. MMCR observations for 22 Feb 2008 (left) and 13 Oct 2004 (right) respectively illustrate synoptic/frontal deep and boundary-layer shallow convective snow events.

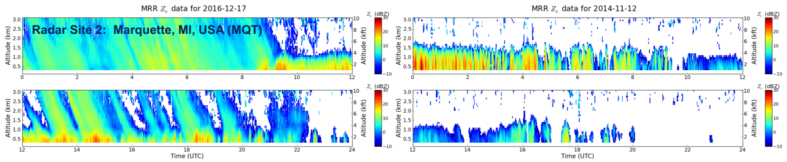


FIG. 2: A Ka-band Micro Rain Radar (MRR) has been deployed at the Marquette, MI National Weather Service Weather Forecast Office since January 2014. MRR observations for 17 Dec 2016 (left) illustrate synoptic/frontal deep snow (0000-0900 UTC), shallow orographic snow (0900-1200 UTC), and orographically enhanced synoptic snow (near 0900 UTC and intermittently between 1200-2200 UTC). MRR observations for 12 Nov 2014 (right) show convective boundary layer lake-effect snow showers.

- Snowfall modes discernible from profiling radars (**Figs. 1 and 2**):
  - I. Synoptic/frontal snow
  - II. Shallow convective snow (e.g., lake-effect and/or Arctic stratocumulus)
  - III. Orographic
  - IV. Embedded orographic or lake-effect within synoptic/frontal
- Extreme particle growth in lowest 0.5-1.0 km AGL complicates spaceborne retrievals (**Fig. 2**)
- Snowfall mode variability and mixed snowfall modes in aggregate reflectivity analyses (**Figs. 3 and 4**)
- NSA: Distinct snowfall mode interannual variability (**Fig. 3**)
- MQT: Extremely shallow snowfall modes like lake-effect and orographic commonly occur (**Fig. 4**)
- Shallow, light snowfall events create difficult snowfall retrieval situations for GPM DPR (**Figs. 3 and 4**)

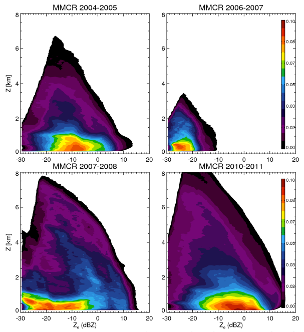


FIG. 3: MMCR reflectivity/height normalized occurrence 2D histograms for select winter seasons.

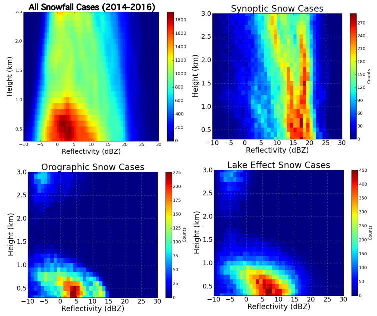


FIG. 4: MQT MRR reflectivity/height occurrence 2D histograms for all snowfall cases in the 2014-2016 dataset (top left) and for a subset of synoptic (top right), orographic (bottom left), and lake-effect (bottom right) snowfall cases

II. Spaceborne Radar Snowfall Retrieval Applications

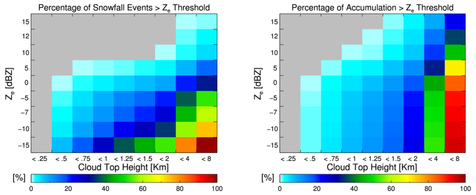


FIG. 5: Percentage of snowfall events (left) and estimated snowfall accumulation (right) within various radar reflectivity and cloud top height thresholds for the 2004-2011 MMCR snowfall dataset.

Spaceborne radar snowfall retrieval efficacy

- Radar sensitivity thresholds as functions of MMCR-derived cloud top height (**Figs. 5 and 6**)
- Assumptions:
  - I. -15 dBZ lower threshold applied to MMCR dataset to mimic common spaceborne radar precipitation threshold
  - II. Matrosov et al. (2007) 35 GHz Z-S relationship for snowfall accumulation statistics (no snowfall mode dependence)
- Useful statistics for high-latitude locations
  - I. Percentage of snowfall events/accumulation missed by current and future proposed sensors
  - II. Guidance for future spaceborne radar development
- Interannual and monthly variability at NSA site (**Fig. 6**)

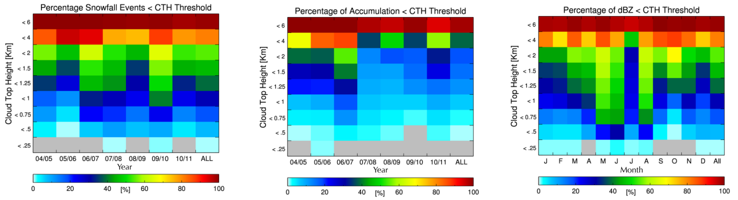


FIG. 6: Percentage of annual snowfall events (left), annual estimated snowfall accumulation (center), and monthly snowfall events (right) within various cloud top height thresholds for the 2004-2011 MMCR snowfall dataset.

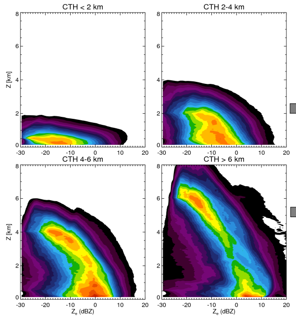


FIG. 7: MMCR reflectivity/height normalized occurrence 2D histograms based on four cloud top height categories.

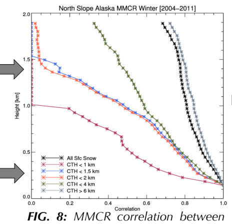


FIG. 8: MMCR correlation between the lowest usable radar bin and various height bins for different snow-producing cloud regimes.

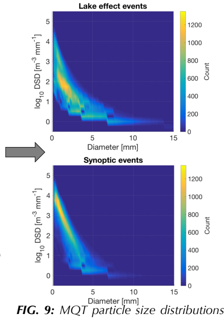


FIG. 9: MQT particle size distributions for lake-effect (top) and synoptic/frontal (bottom) snow events measured by the NASA Precipitation Imaging Package optical disdrometer.

Snowfall modes present unique retrieval challenges

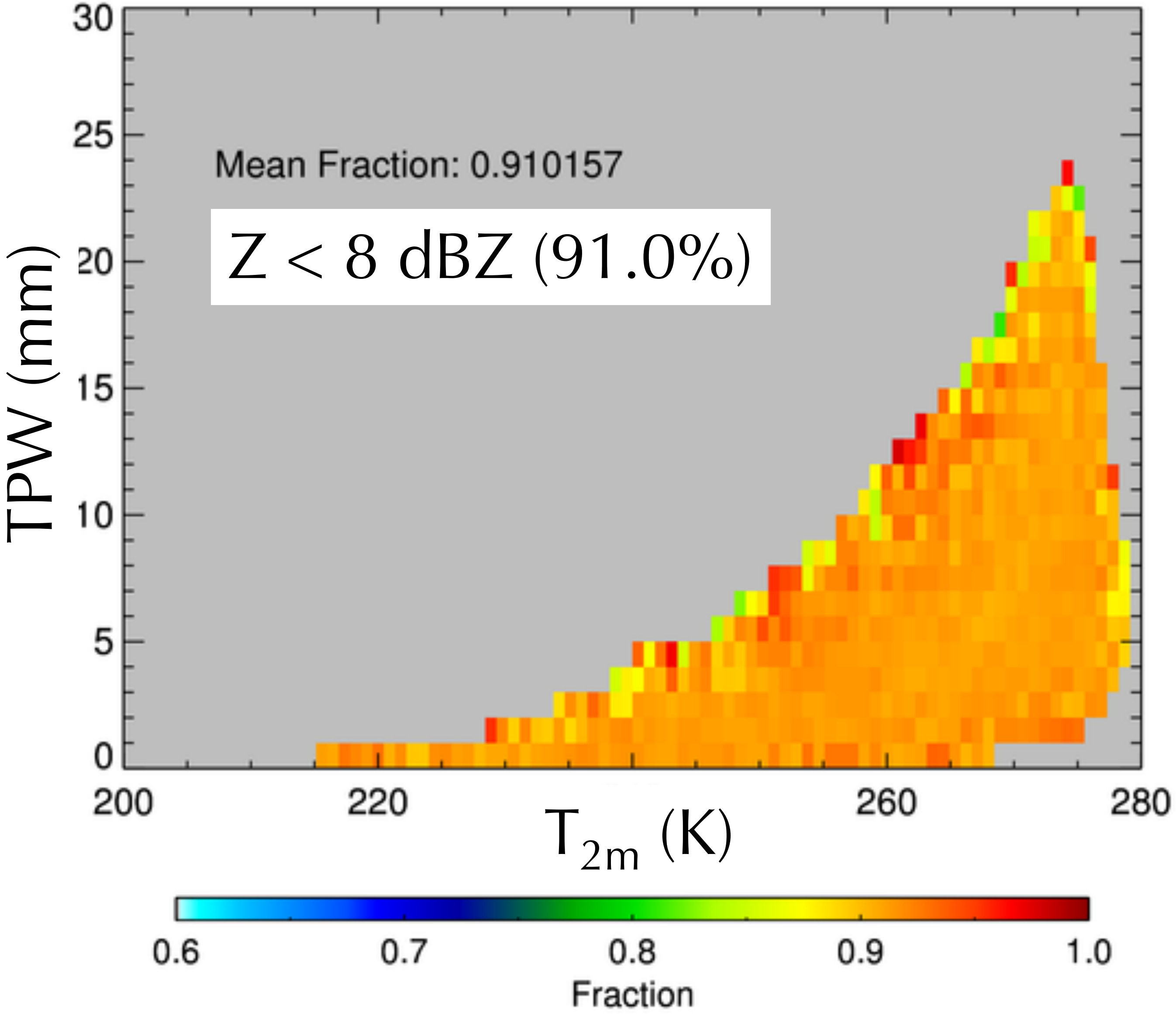
- I. Radar blind zone and near-surface bin designation (growth, decay, stable in lowest levels?) (**Fig. 7**)
- II. Is near-surface bin used for snowfall rate retrievals correlated to actual surface snowfall? (**Fig. 8**)
- III. Snow microphysical properties can change drastically in different snowfall types (**Fig. 9**)

Summary

- GPM snowfall retrieval era has commenced
- Leverage independent (imperfect) datasets for assessment
- GPM/CloudSat synergy
- Equitable dataset comparisons
- Ground evaluation: Continued importance

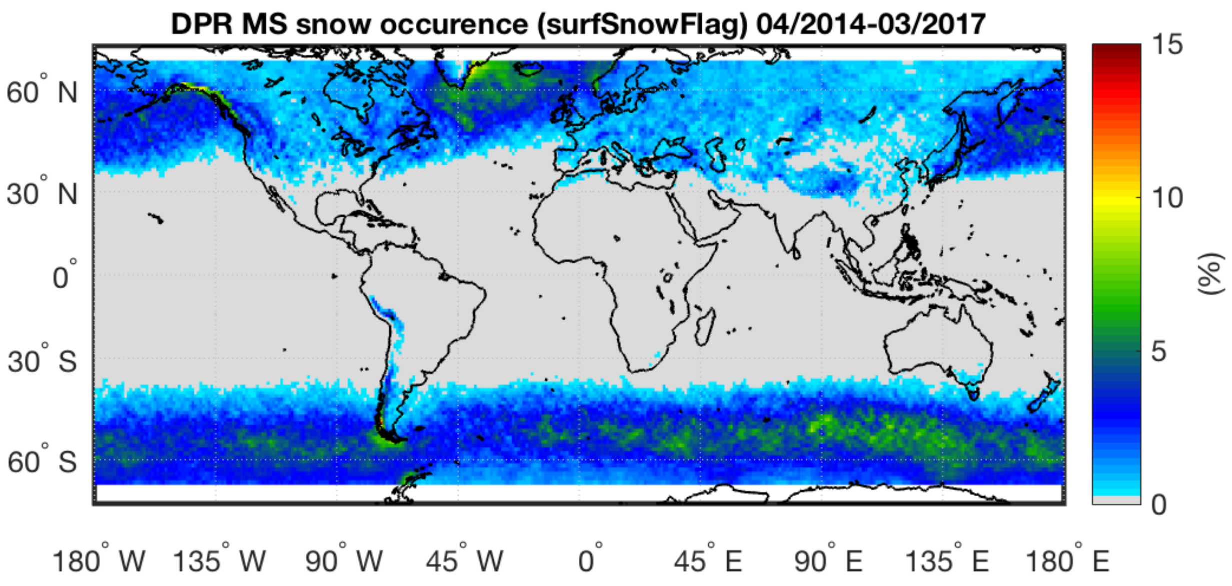
GPM-CloudSat Synergy

% CPR Snowfall Events < 8 dBZ

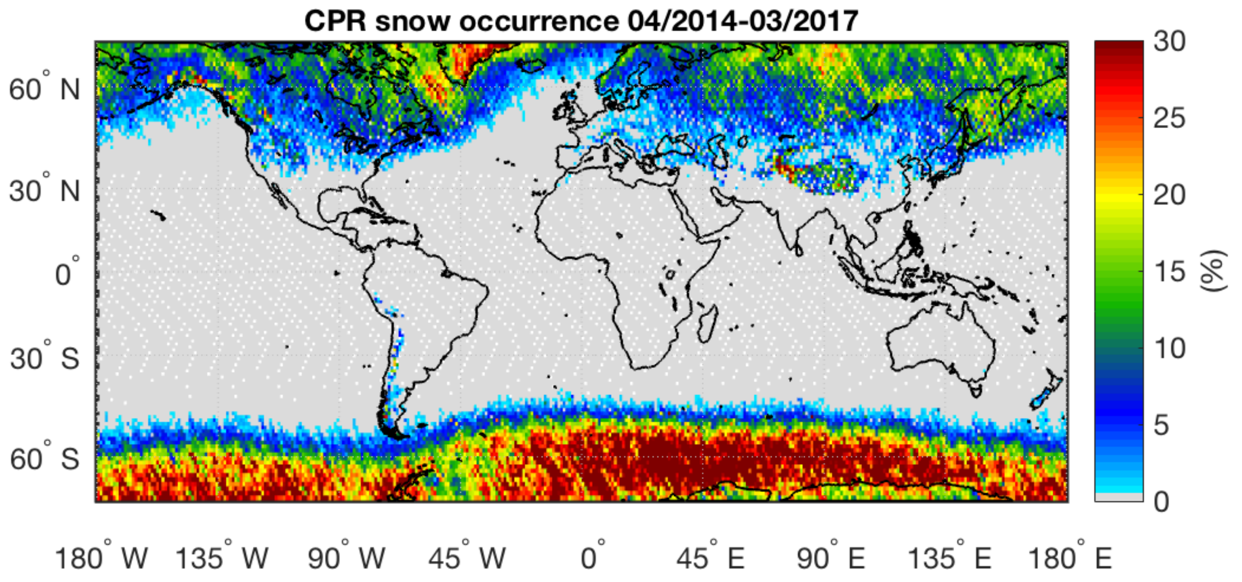


Snowfall Occurrence Fraction

04/2014-03-2017



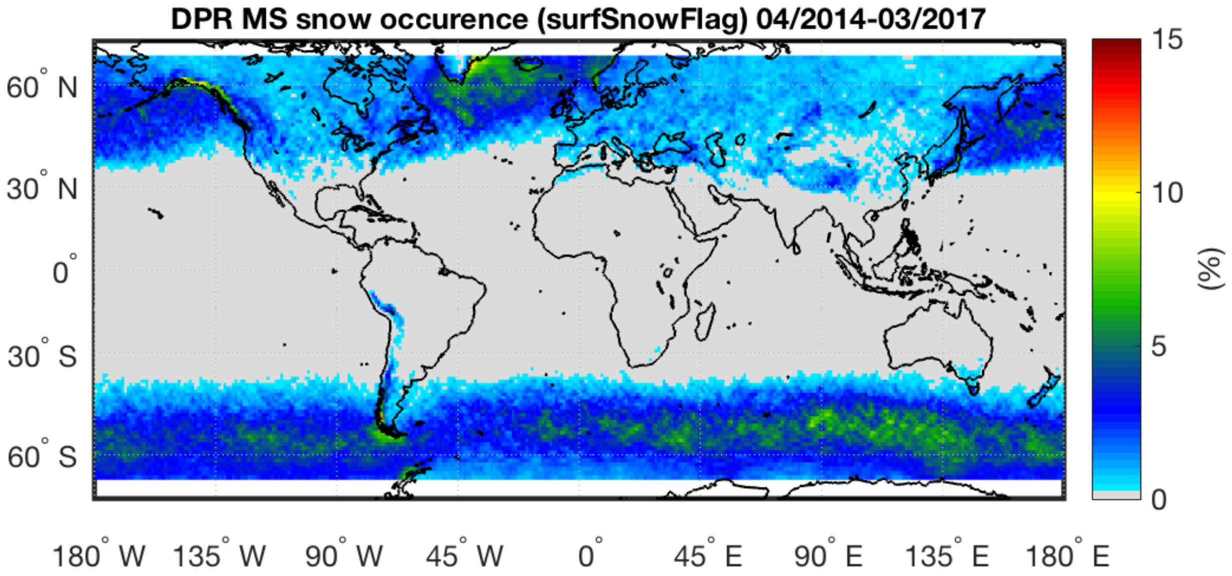
DPR - flagSurfaceSnow



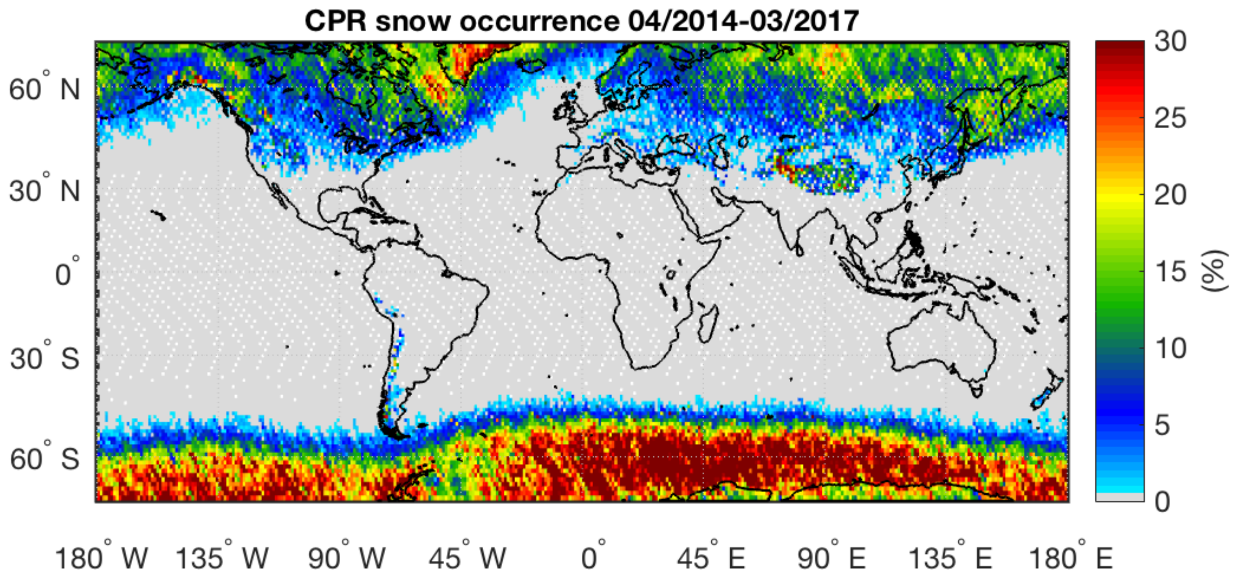
CPR

Snowfall Occurrence Fraction

04/2014-03-2017

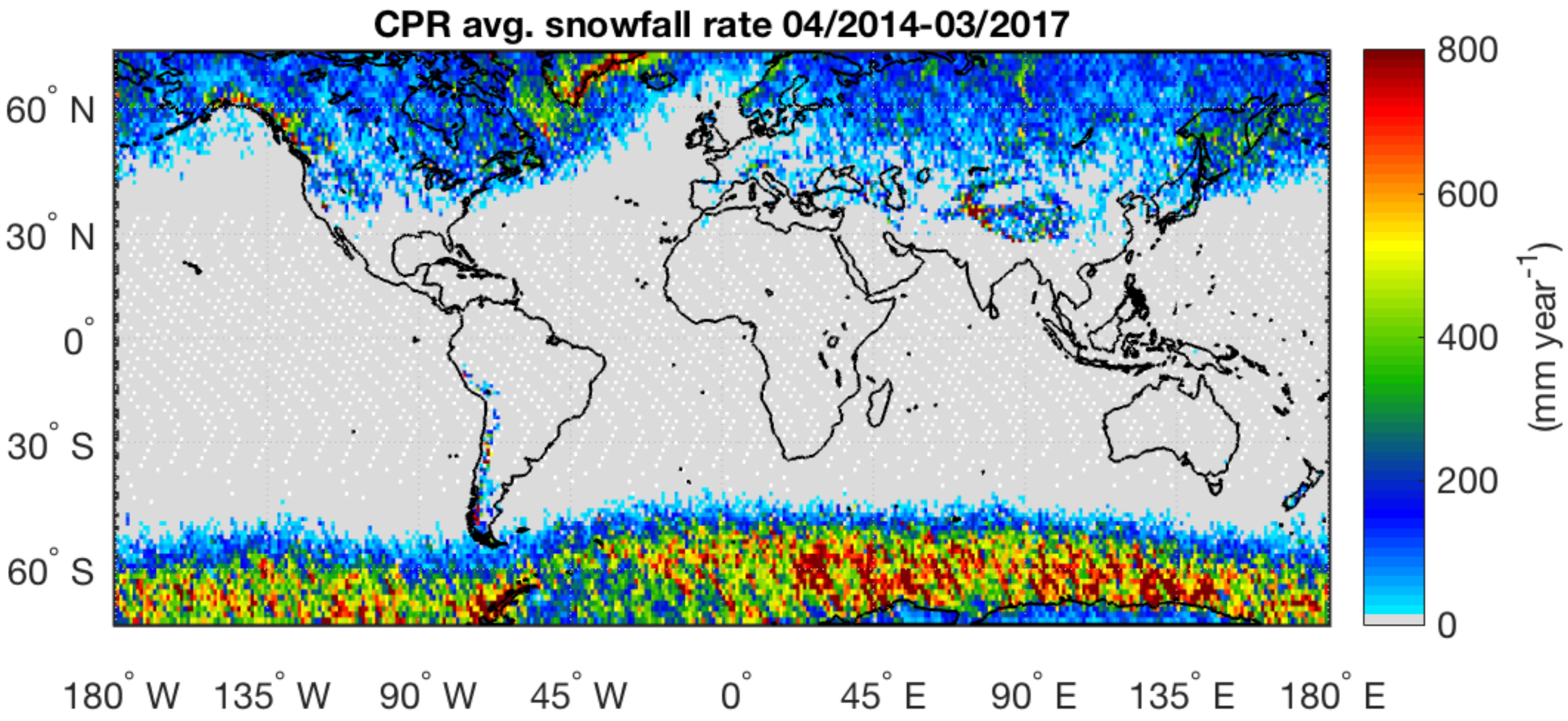


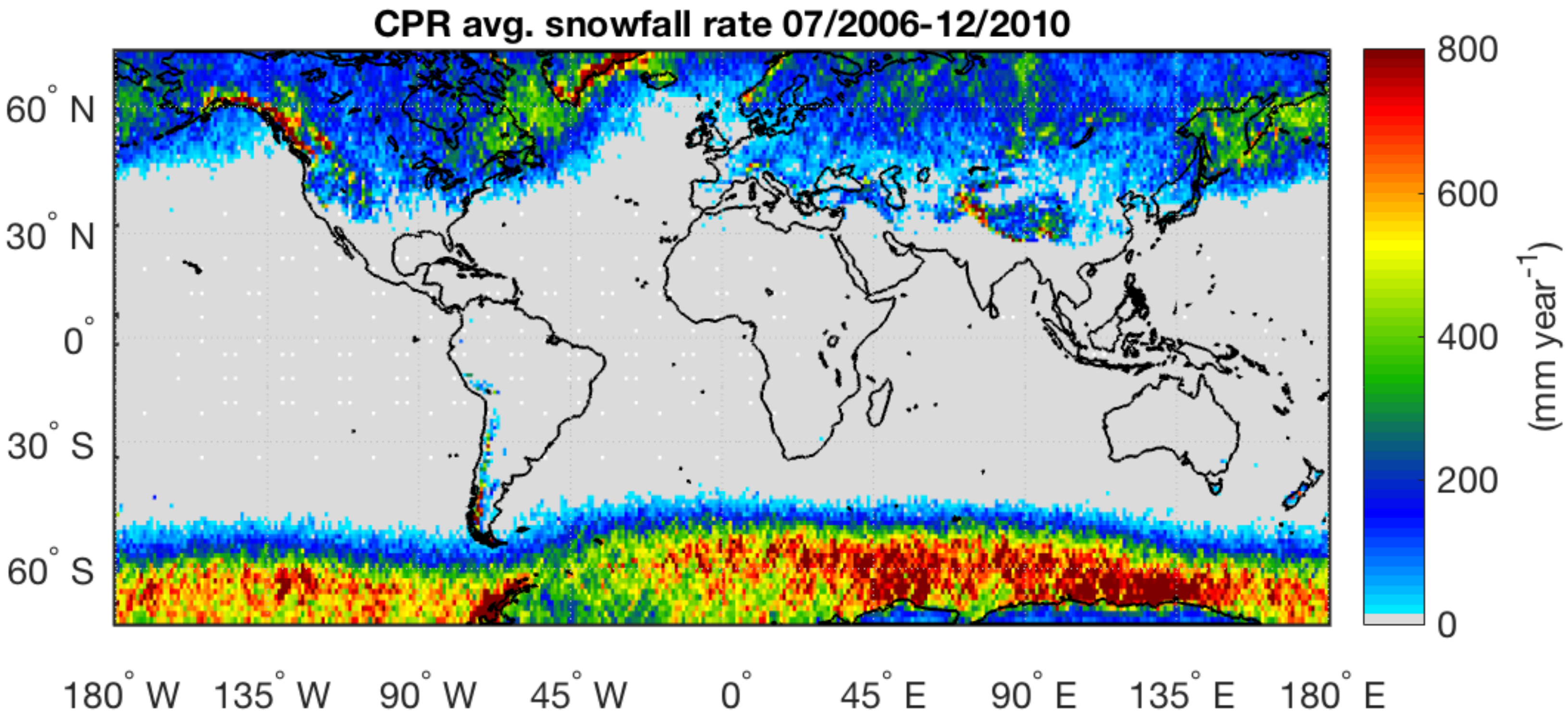
DPR - flagSurfaceSnow

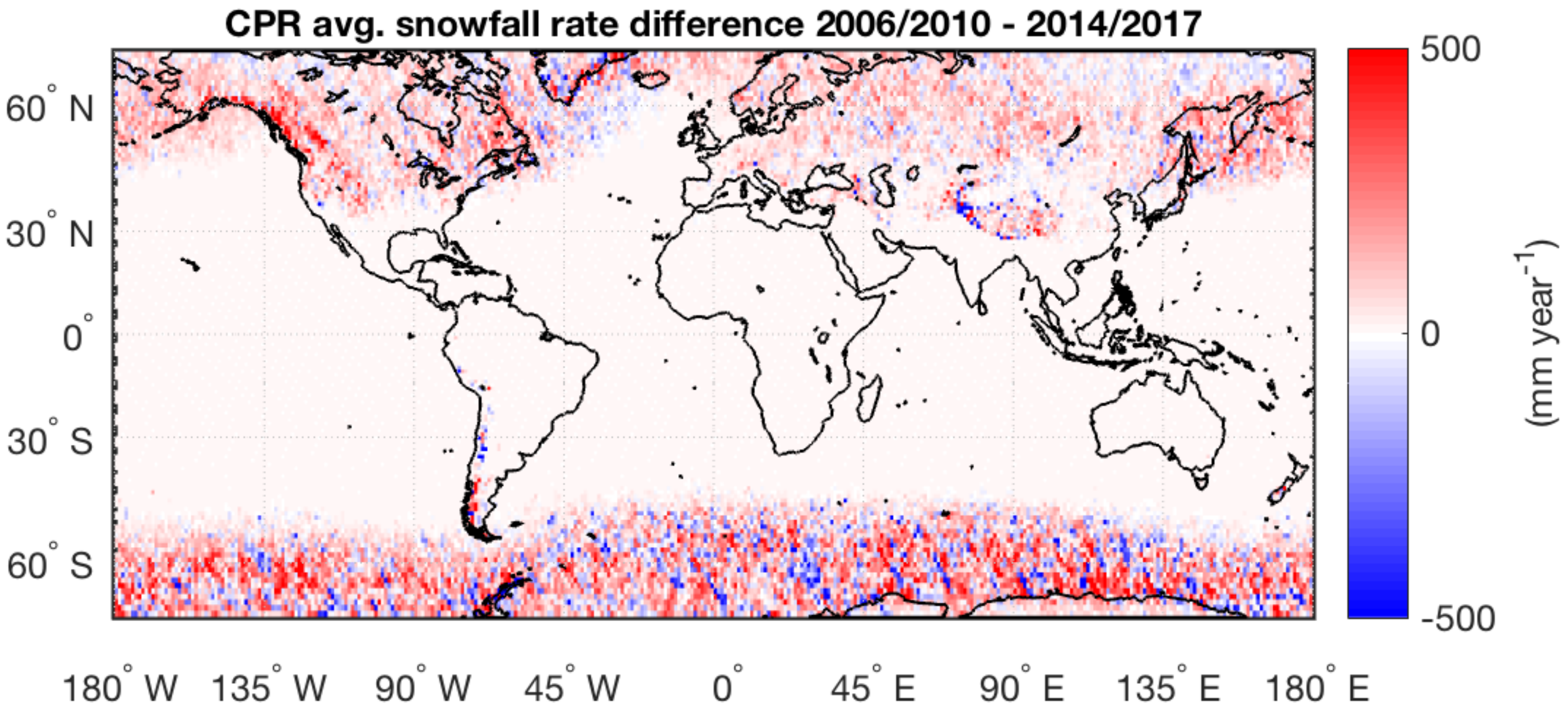


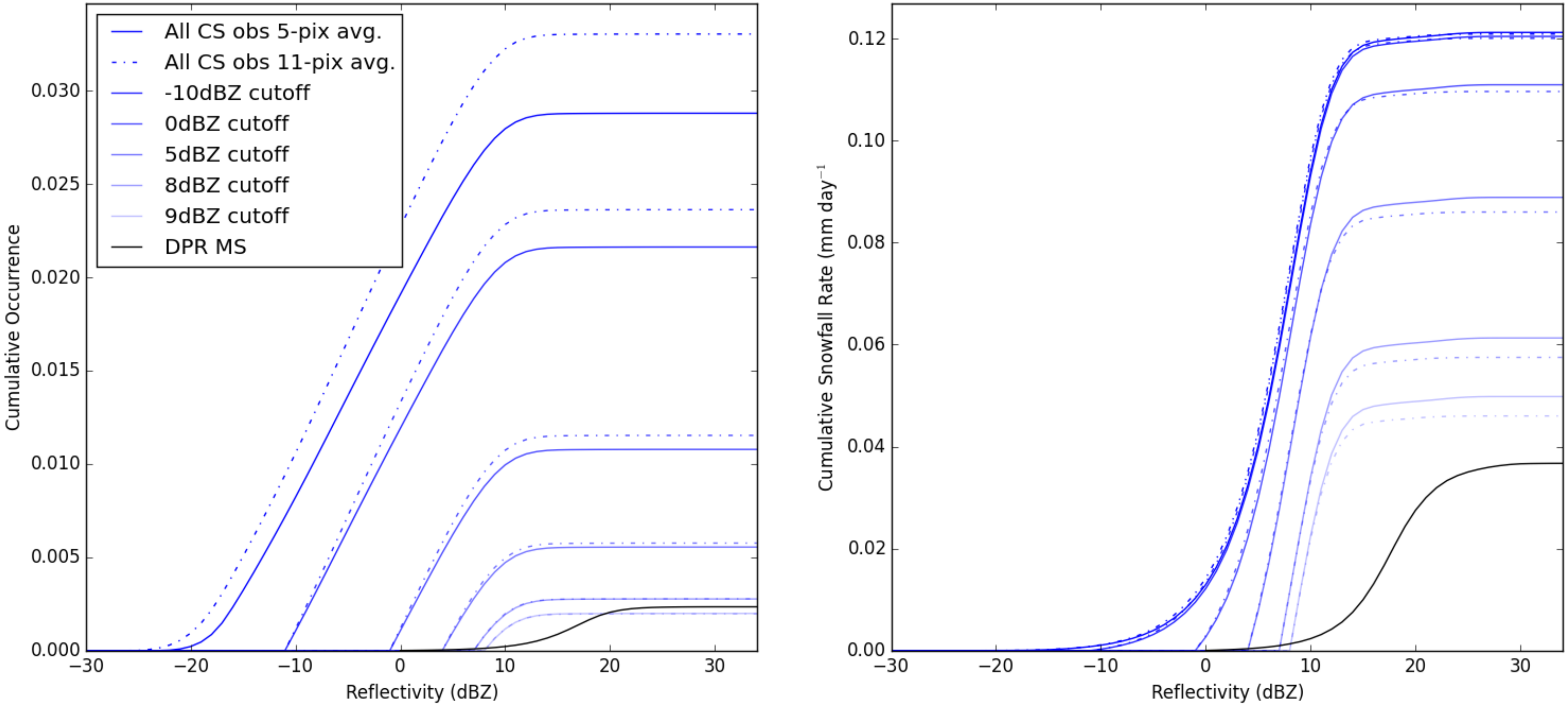
CPR

Radar Sensitivity + Phase Classification


CPR avg. snowfall rate 04/2014-03/2017
60° N
30° N
0°
30° S
60° S
180° W
135° W
90° W
45° W
0°
45° E
90° E
135° E
180° E
800
600
400
200
0
(mm year^{-1})


CPR avg. snowfall rate 07/2006-12/2010
60° N
30° N
0°
30° S
60° S
180° W
135° W
90° W
45° W
0°
45° E
90° E
135° E
180° E
800
600
400
200
0
(mm year^{-1})


CPR avg. snowfall rate difference 2006/2010 - 2014/2017
60° N
30° N
0°
30° S
60° S
180° W
135° W
90° W
45° W
0°
45° E
90° E
135° E
180° E
500
0
-500
(mm year⁻¹)


All CS obs 5-pix avg.
All CS obs 11-pix avg.
-10dBZ cutoff
0dBZ cutoff
5dBZ cutoff
8dBZ cutoff
9dBZ cutoff
DPR MS
Cumulative Occurrence
0.000
0.005
0.010
0.015
0.020
0.025
0.030
−30
−20
−10
0
10
20
30
Reflectivity (dBZ)
Cumulative Snowfall Rate (mm day^{-1})
0.00
0.02
0.04
0.06
0.08
0.10
0.12
−30
−20
−10
0
10
20
30
Reflectivity (dBZ)