SNOWFALL ALGORITHM

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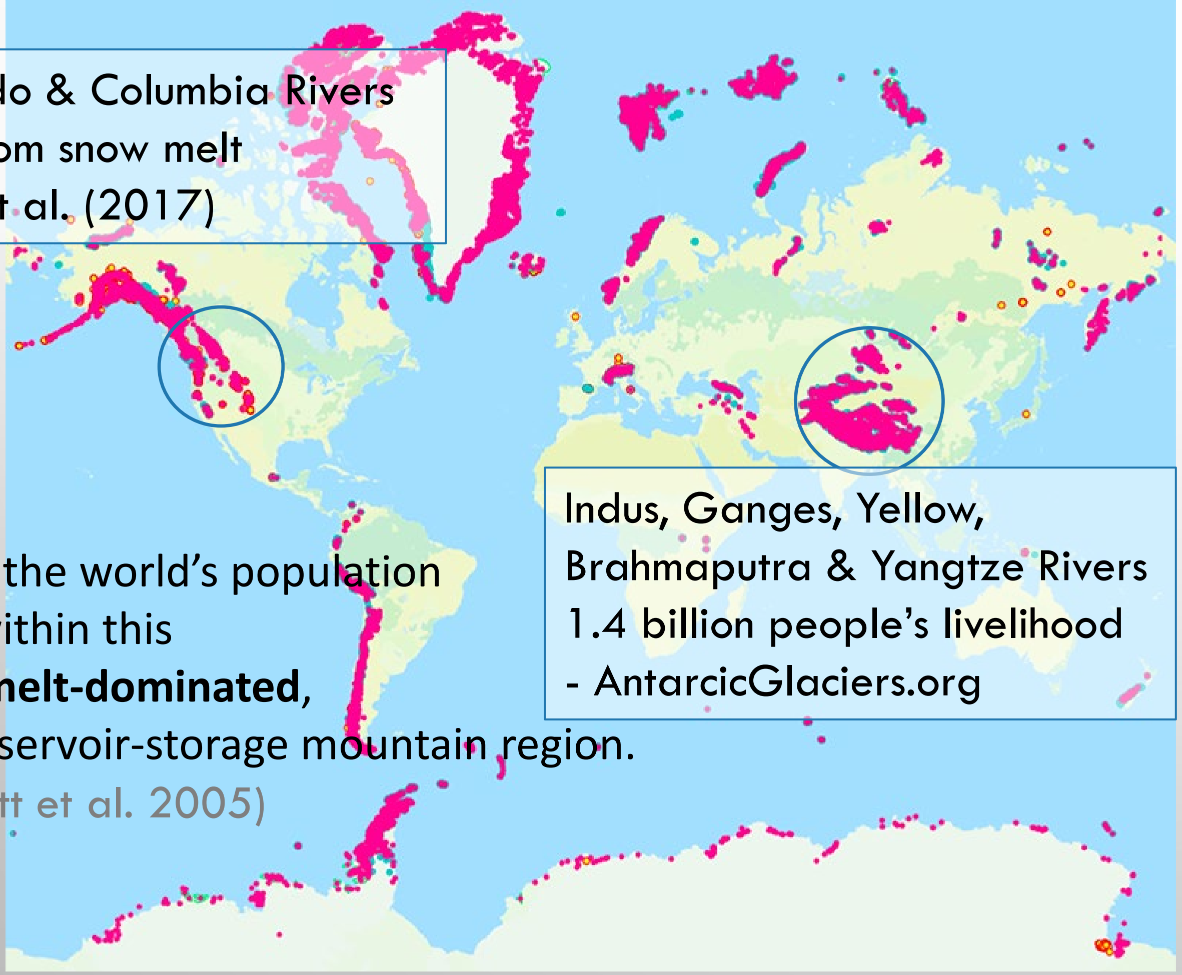
SNOWFALL: SCIENTIFIC AND SOCIETAL SIGNIFICANCE

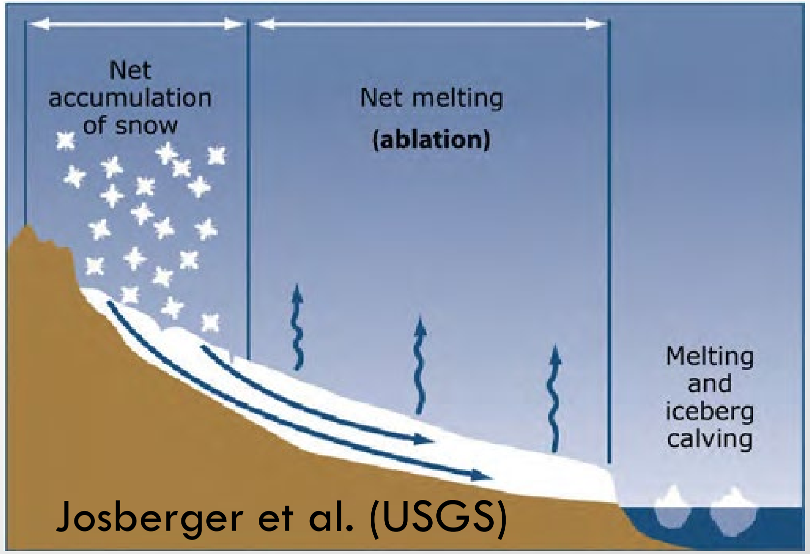


Colorado & Columbia Rivers
70% from snow melt
Sturm et al. (2017)

Indus, Ganges, Yellow,
Brahmaputra & Yangtze Rivers
1.4 billion people's livelihood
- AntarcicGlaciers.org

1/6 of the world's population lives within this **snowmelt-dominated**, low-reservoir-storage mountain region.
(Barnett et al. 2005)

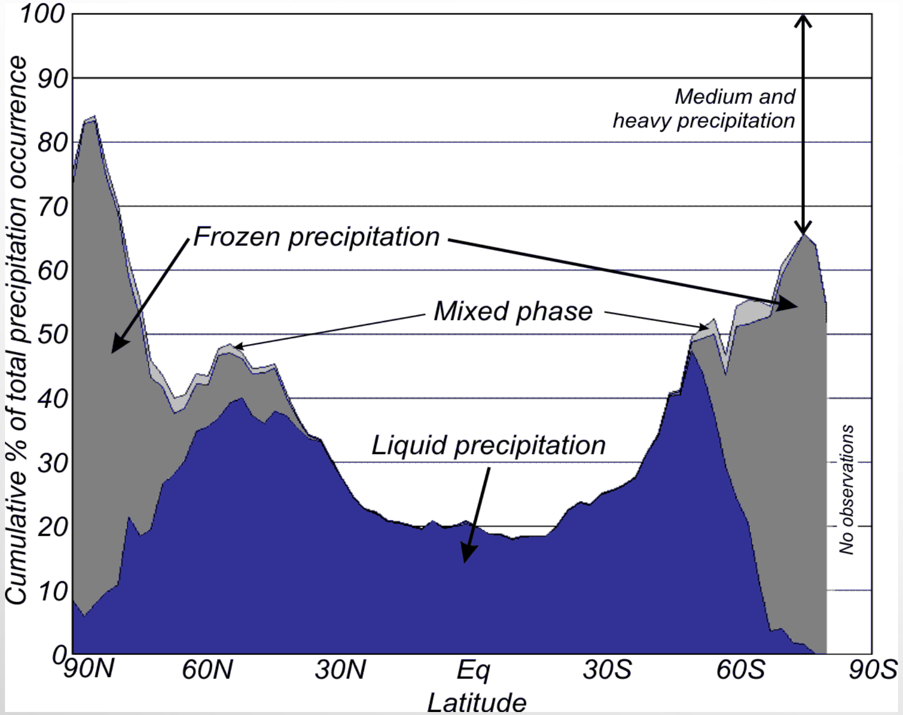
Glacier map from NSIDC



Josberger et al. (USGS)

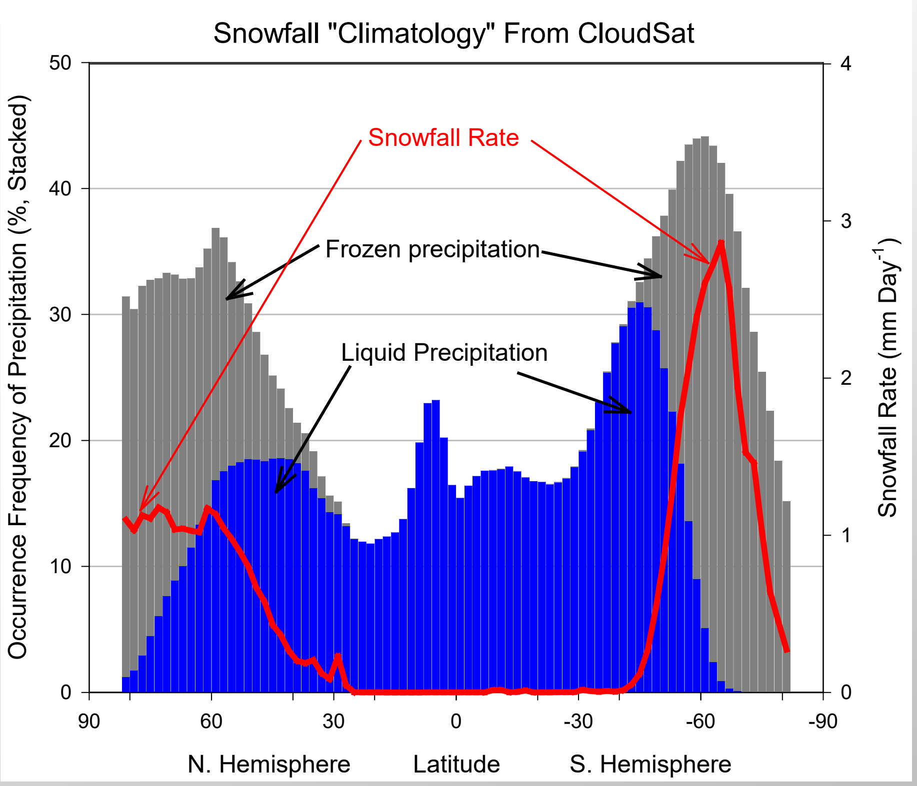
- Glacier & snow melt is an important water resource
- Snowfall is the major source for glacier & snowpack growth
- Whether precipitation falls as rain or snow has great impact on glacier & snowpack growth/ablation

SNOWFALL "CLIMATOLOGY"



Mean Zonal occurrence of oceanic light precipitation (<1.0 mm/h) as a percentage of total precipitation occurrence, derived from COADS ship-borne data (1958-1991).

Occurrence Frequency and Snowfall rate, averaged over all observations of CloudSat from 2006 to 2010.



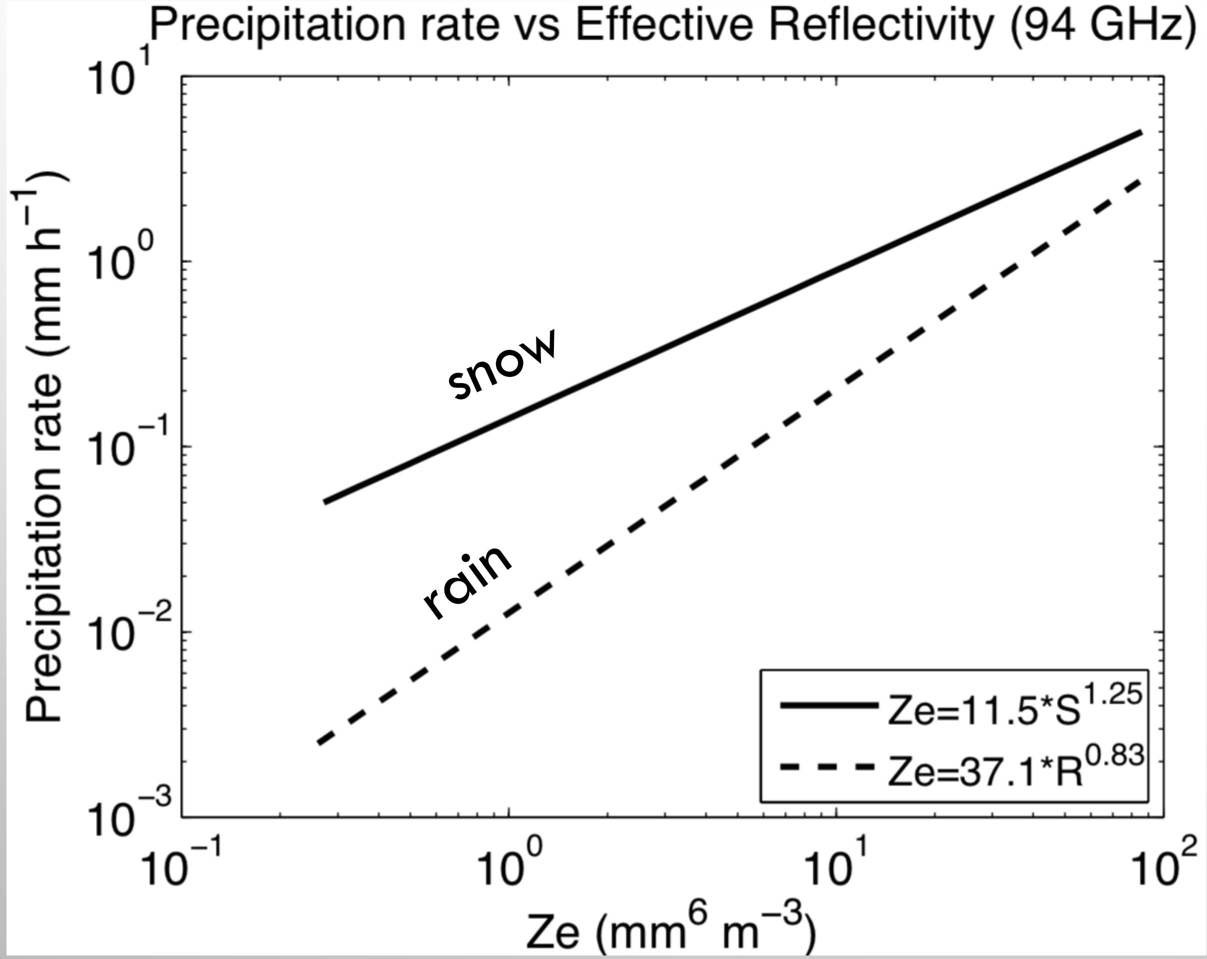
Difficulties for Satellite Snowfall Retrievals

- Signal Weak – Except for Graupels, Snowflakes' Signal is Generally
  - <50 K (from background) for Radiometers at Microwave Channels
  - < 20 dBZ for mm-Wave and Microwave Radars
- Complication from Variable Particle Shape, Size Distribution, etc.
  - Equally Difficult for Both Active and Passive Sensing
- Surface Contamination - Snow Cover for Passive Sensing
- Supercooled Liquid in Snowing Clouds – Masking Scattering Signature for Passive Sensing

TWO STEPS FOR SNOWFALL RETRIEVAL

1. Rain-Snow Separation
   - Given a satellite observation (radar reflectivity or brightness temperature), it is difficult to tell whether it is raining or snowing at surface by satellite data alone. Ancillary data (temperature, humidity, etc.) are needed to determine the "condition" of the observed scene.
   - See how big difference it makes by not knowing the phase.
2. Signal to Precipitation Conversion
   - For radar, convert dBZ to snowfall rate. Need Z-S relation which depends on particle size distribution, particle shape, etc.
   - For radiometers, convert TBs to snowfall rate. In addition to information mentioned above, surface emissivity, water vapor and cloud water in the atmosphere are all needed. – more number of unknowns.

Z-R OR Z-S



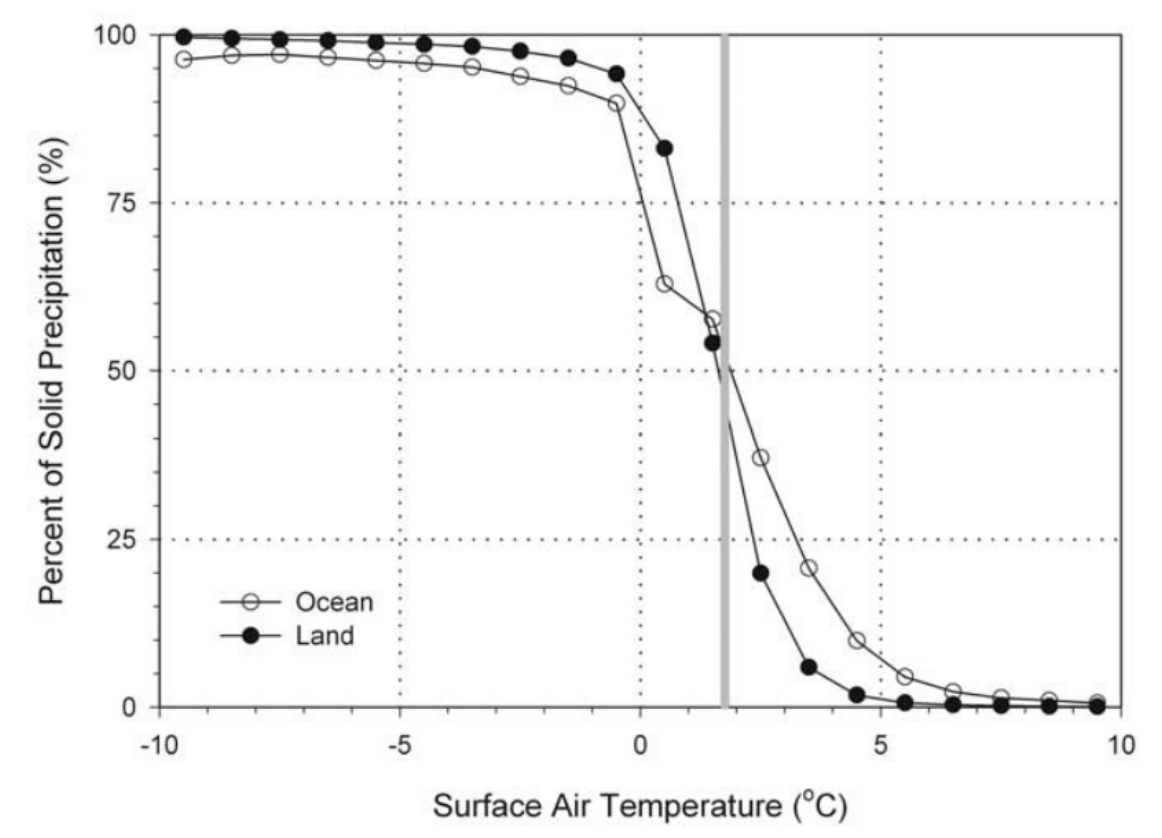
Given a measured 10 dBZ at 94 GHz, it translates to 0.1 mm h^{-1} rain, but 1 mm h^{-1} (liquid-equivalent) snow. So, knowing whether the target is rain or snow is critical.

WHAT MAKES IT SNOW NOT RAIN AT SURFACE?

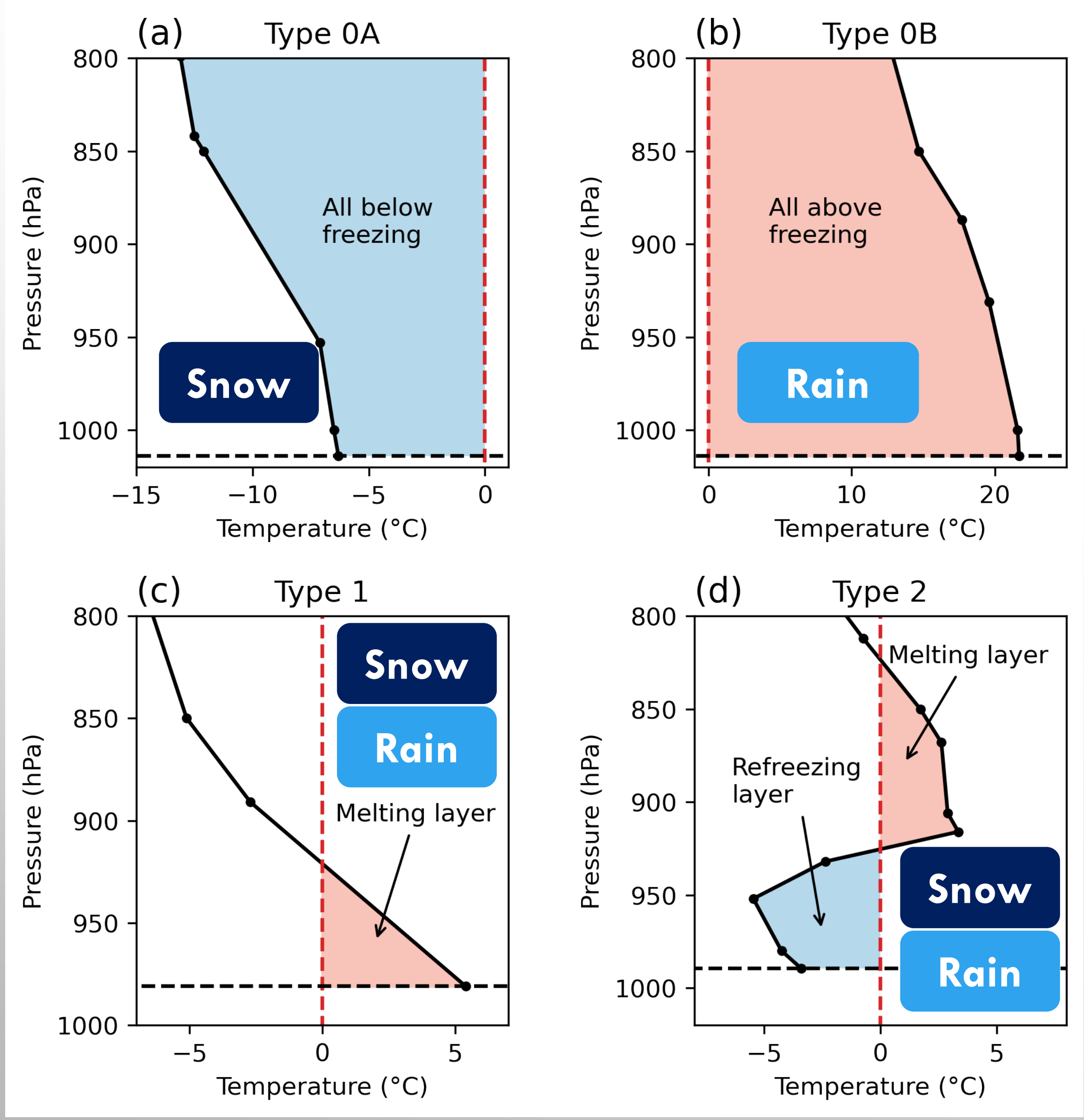
- OF COURSE, LOW TEMPERATURE

But this is not the whole story, because melting needs some time as particles fall, during which

- they may be cooled by sublimation,
- they may be refrozen if passing a colder layer
- their fall speed may vary depending on particle shape, air pressure, air motion, …



Typical temperature profiles



Probsnow

Sims and Liu (2015)

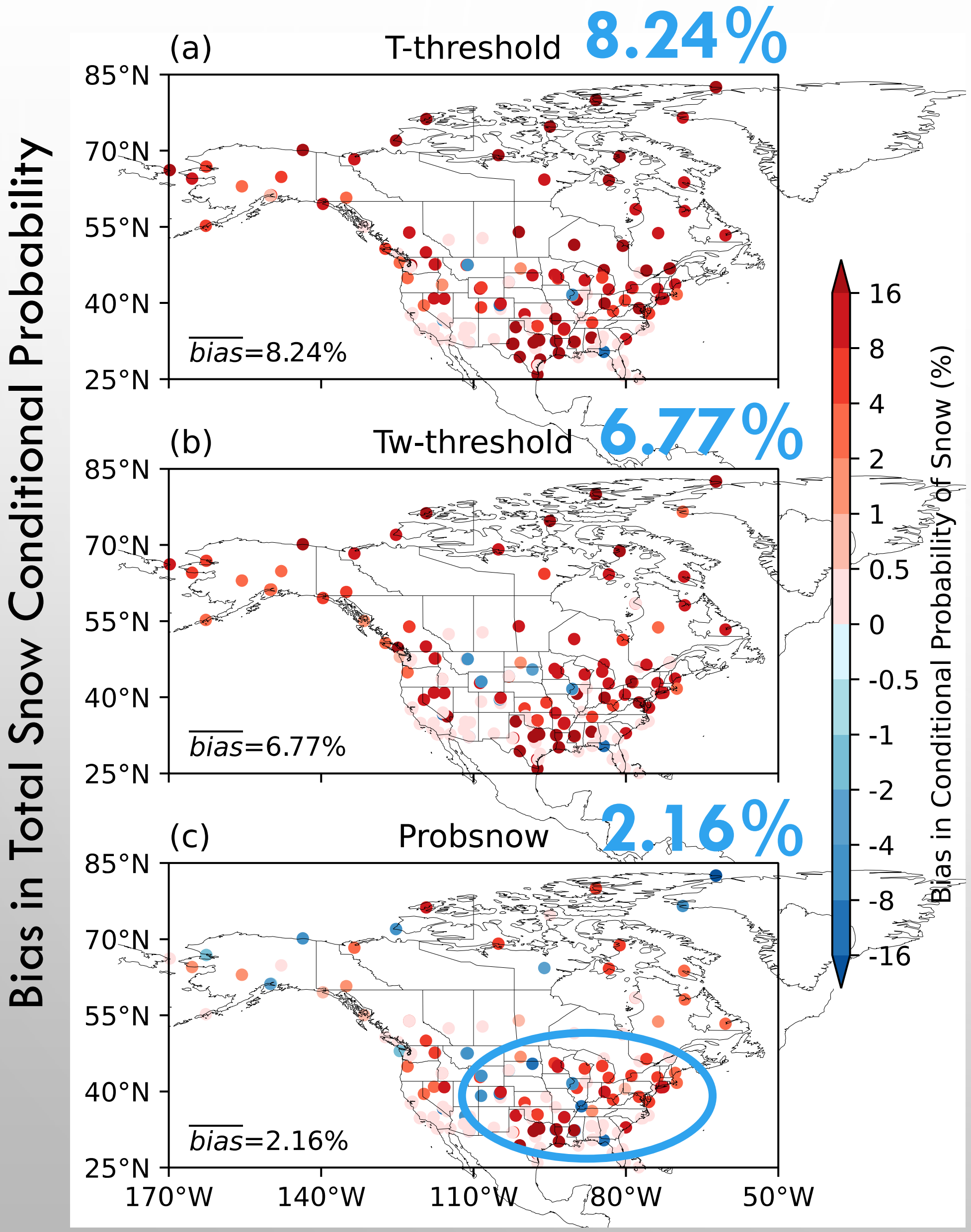
Key inputs:

- Surface temperature (Ts),
- Relative humidity (RH),
- Lower 500m lapse rate (Γ)

Incorporates Atmospheric Information

- Good for Type 1
- Bad for Type 2

Shi, S and G. Liu (2024)
JGR-A

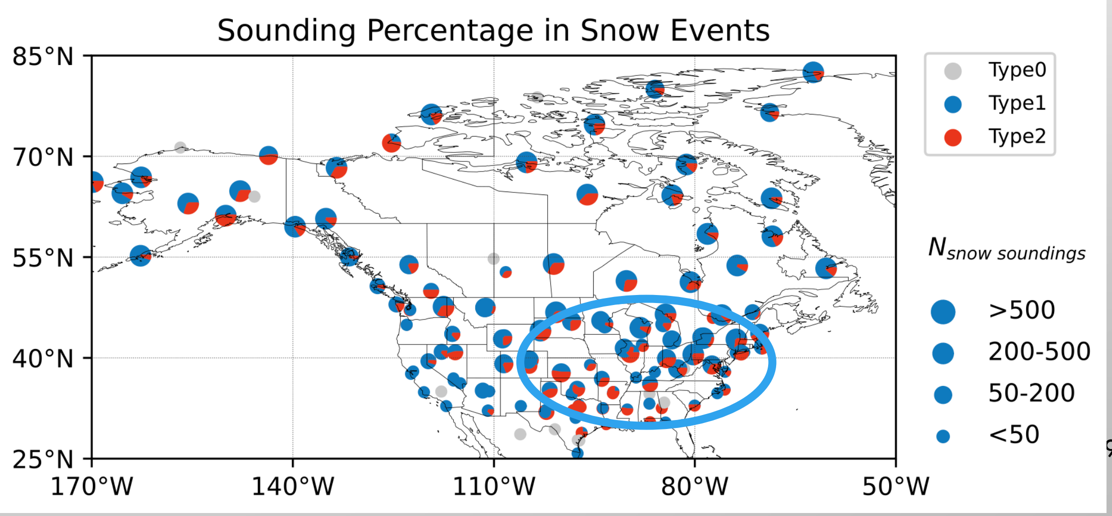


Better phase classification if:

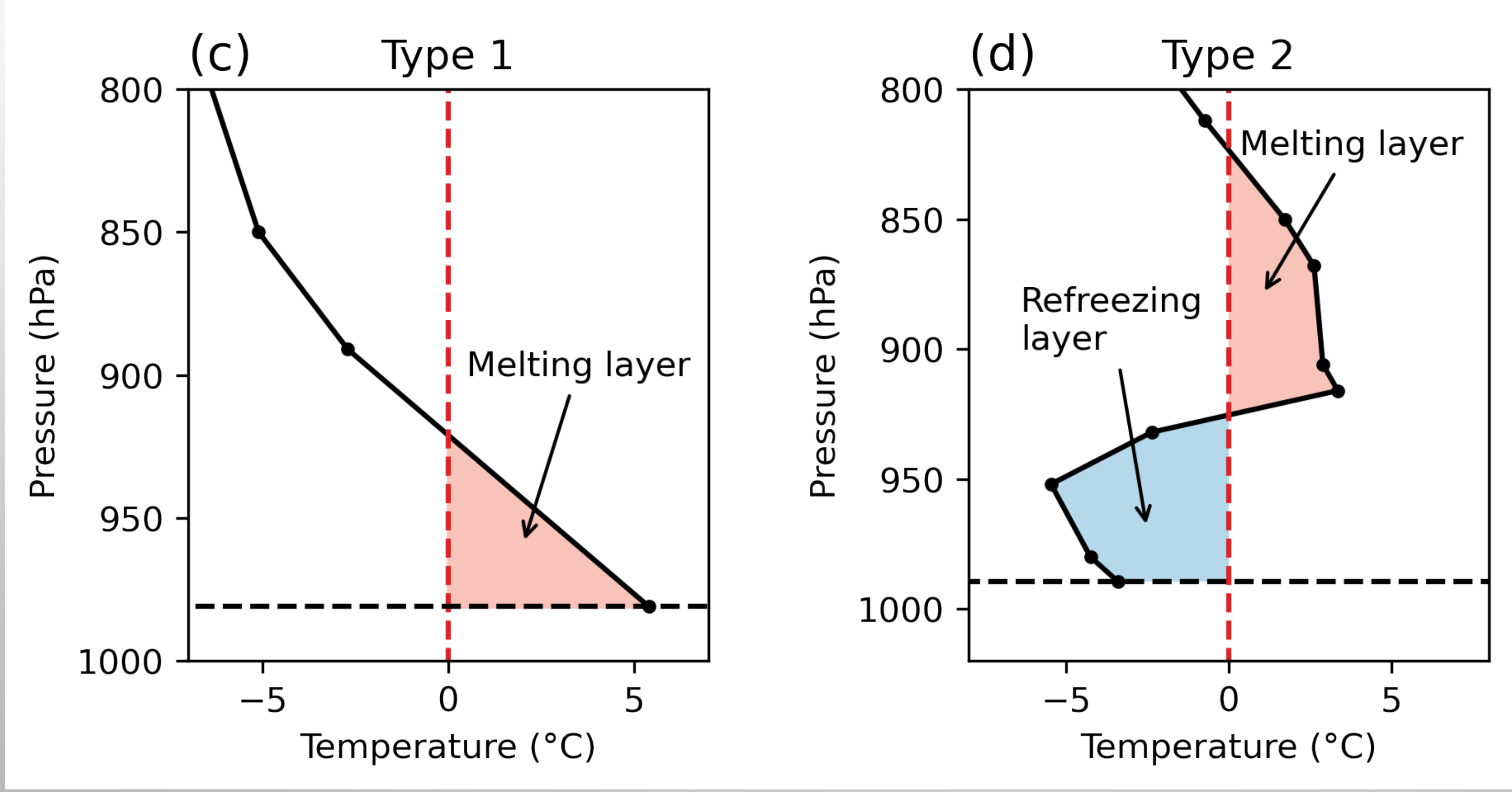
- Includes near-surface RH (tw vs. T)
- Includes vertical information (probsnow for type 1)

However,

Probsnow exhibits large bias in stations with more Type 2 soundings



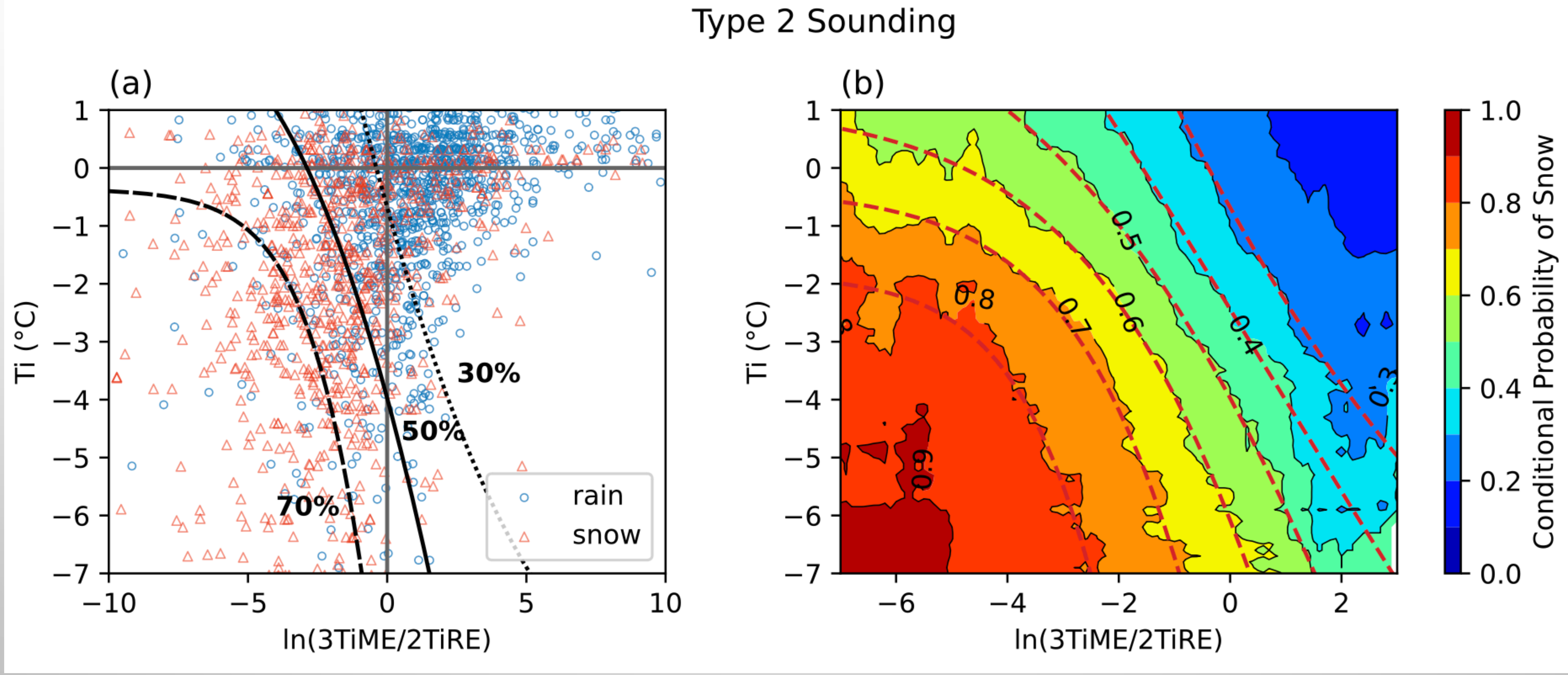
INTRODUCE "MELTING-"/"REFREEZING-ENERGY"



Red area: Melting energy
Blue area: Refreezing energy

These two areas influence whether a particle reaches surface as snow or rain.

IMPROVE RAIN-SNOW SEPARATION FOR TYPE-2 SOUNDING

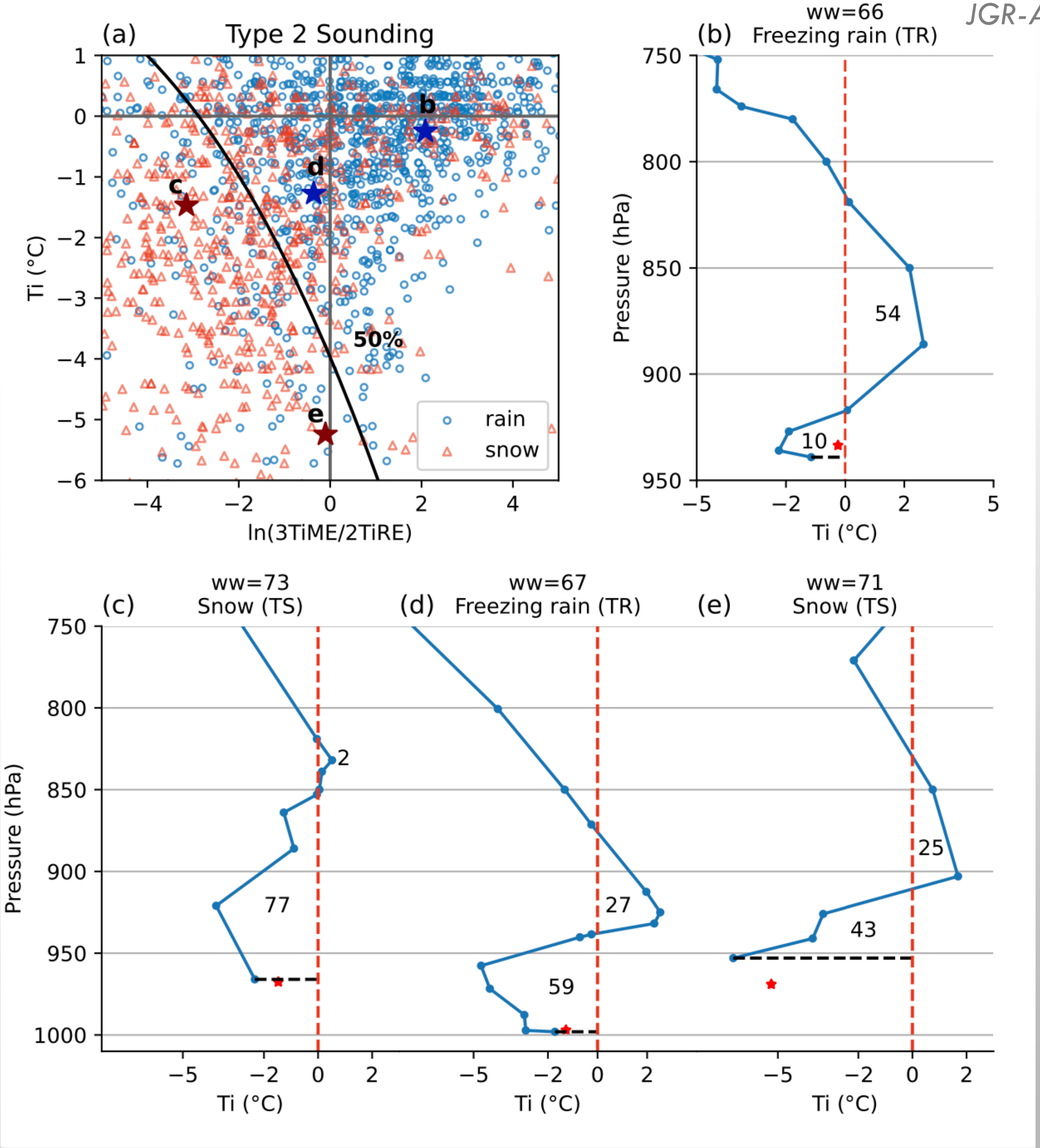


Ti: ice-bulb temperature at 2-m. TiME: melting energy computed using ice-bulb temperature.
TiRE: refreezing energy computed using ice-bulb temperature

Type 2 Classification Examples

Shi., S and G. Liu (2024) *JGR-A*

- (b) warm, large melting: rain
- Same Ti (c, d): phase determined by the ratio between melting and refreezing energies
- Same energy ratio (d, e): Ti determines the phase.



Skill Scores Comparison for Type 2 Classification

Shi., S and G. Liu (2024)
JGR-A

Snow ConProb	Method	POD	FAR	HSS
50%	Probsnow	0.91	**0.64**	0.25
	Energy	0.76	0.17	**0.47**
70%	Probsnow	0.75	**0.44**	0.31
	Energy	0.36	0.05	**0.33**

Probsnow: predicting as much snow as possible (large POD) at the price of more errors (**large FAR**)

The Energy method has significant improvements,

Featuring more balanced prediction (High Heidke Skill Score)

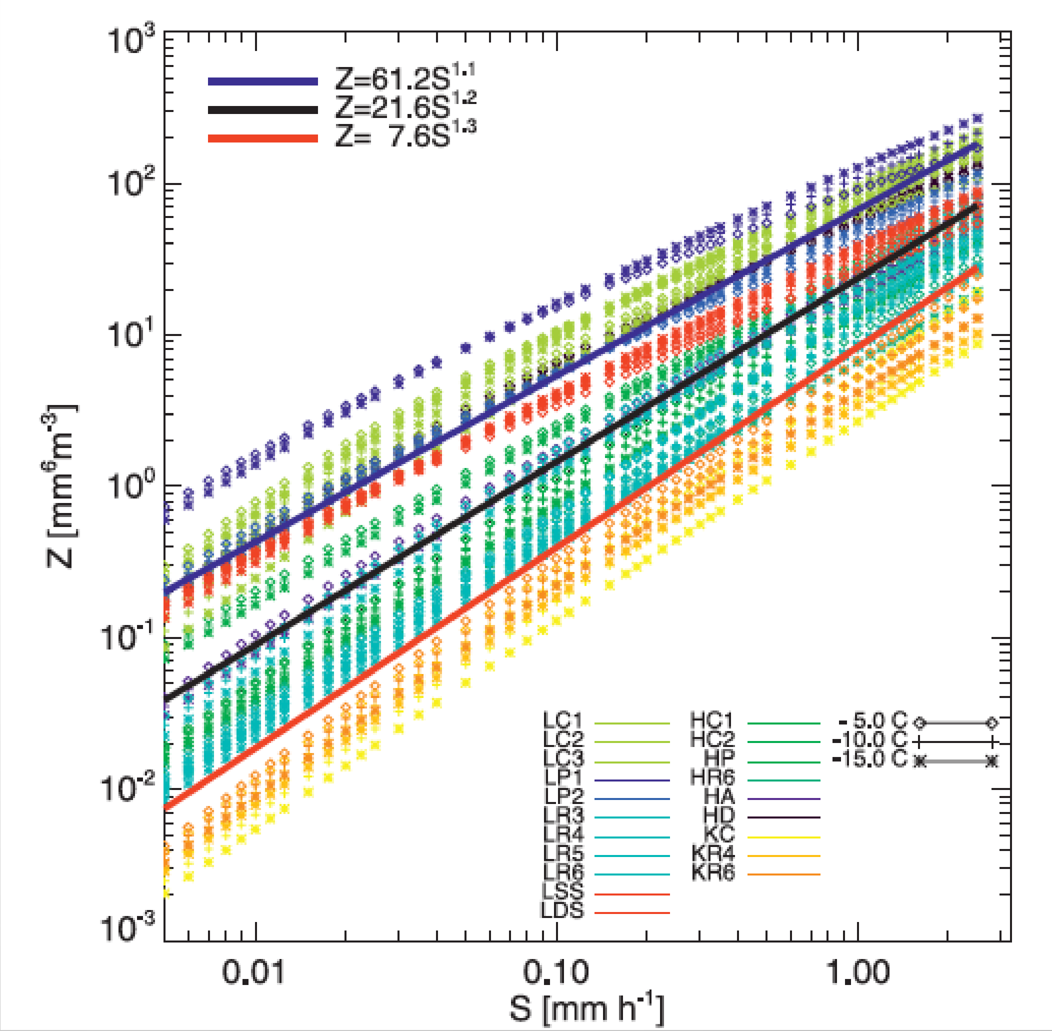
SNOWFALL FROM ACTIVE SENSORS

- CloudSat Cloud Profiling Radar (CPR): W-band (94 GHz)
- GPM Dual-frequency Precipitation Radar (DPR): Ka- and Ku-band
- EARTHCARE radar a great opportunity

Main task → convert radar reflectivity to snowfall rate

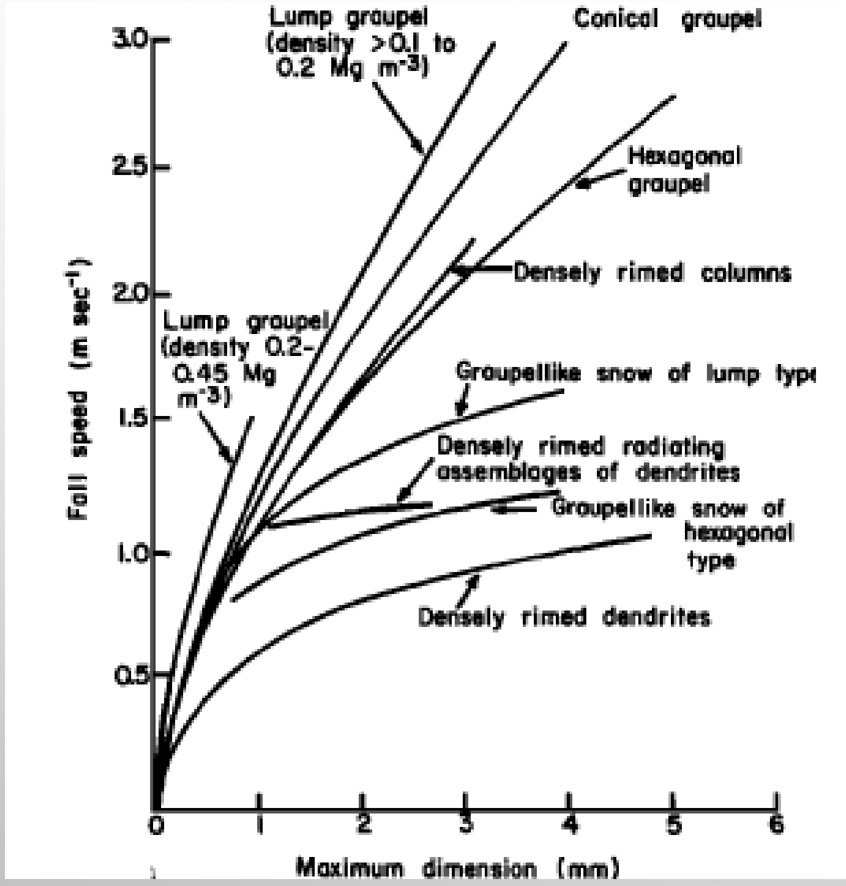
CONVERT RADAR REFLECTIVITY TO SNOWFALL

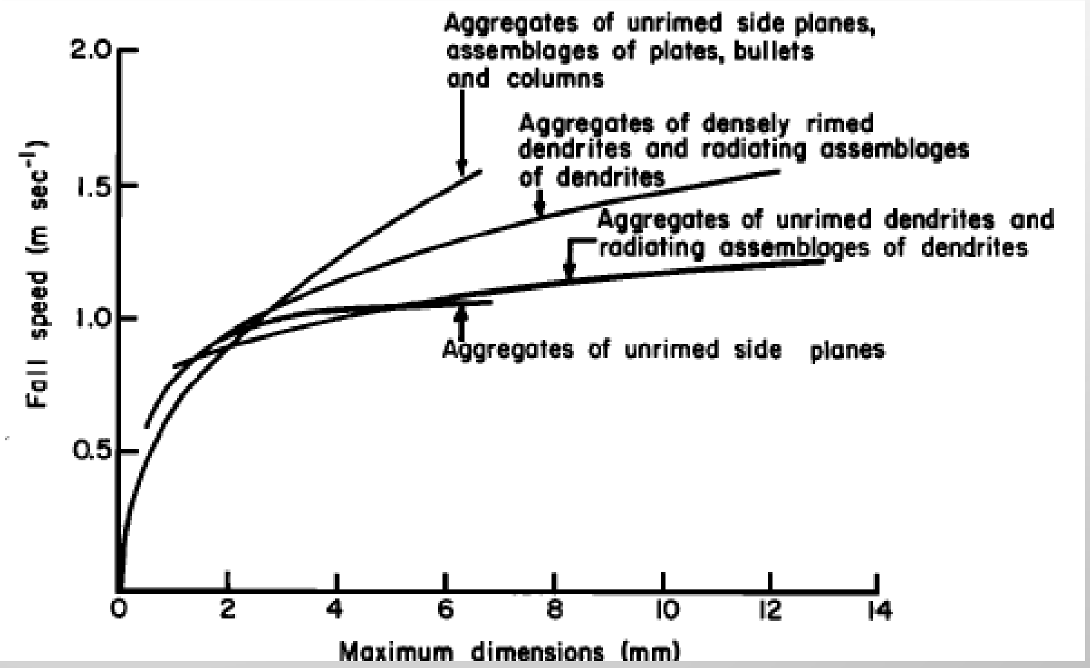
- Many possibilities of Z-S relations. Compared to rain (Z-R), Z-S has one extra complication of variable/unknown particle shapes.
- The right figure is from Hiley et al. (2011), who showed the dependence of W-band Z-S on assumed particle shapes.



TERMINAL VELOCITY OF SNOWFLAKES

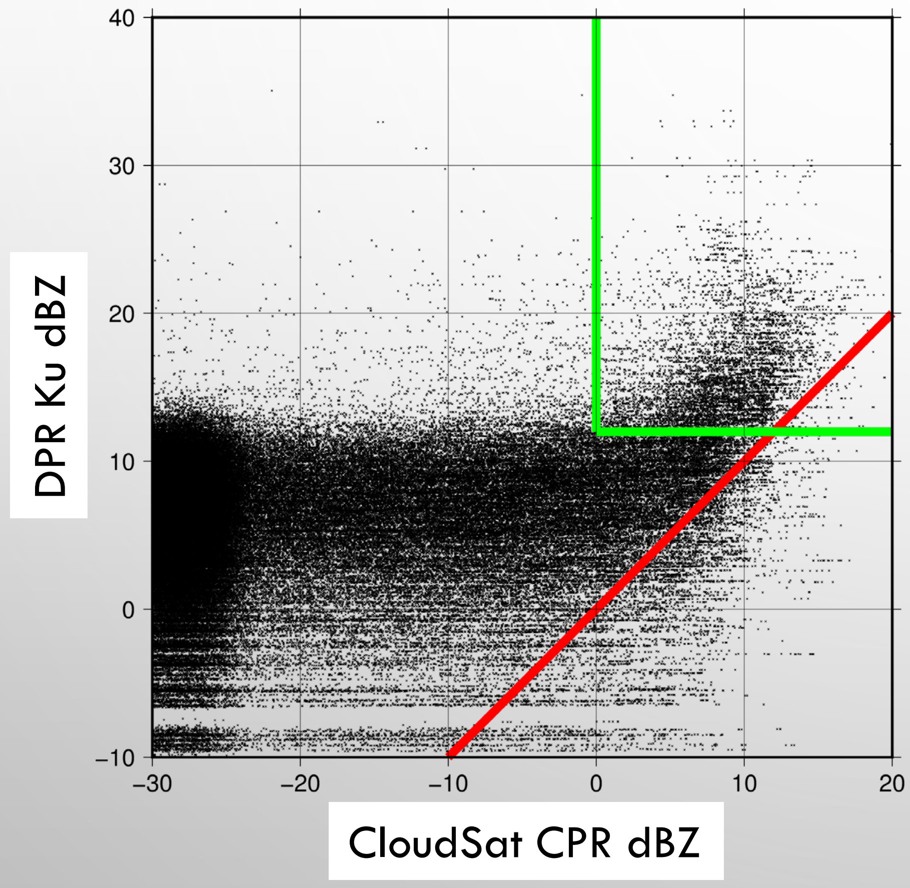
Locatelli & Hobbs, 1974





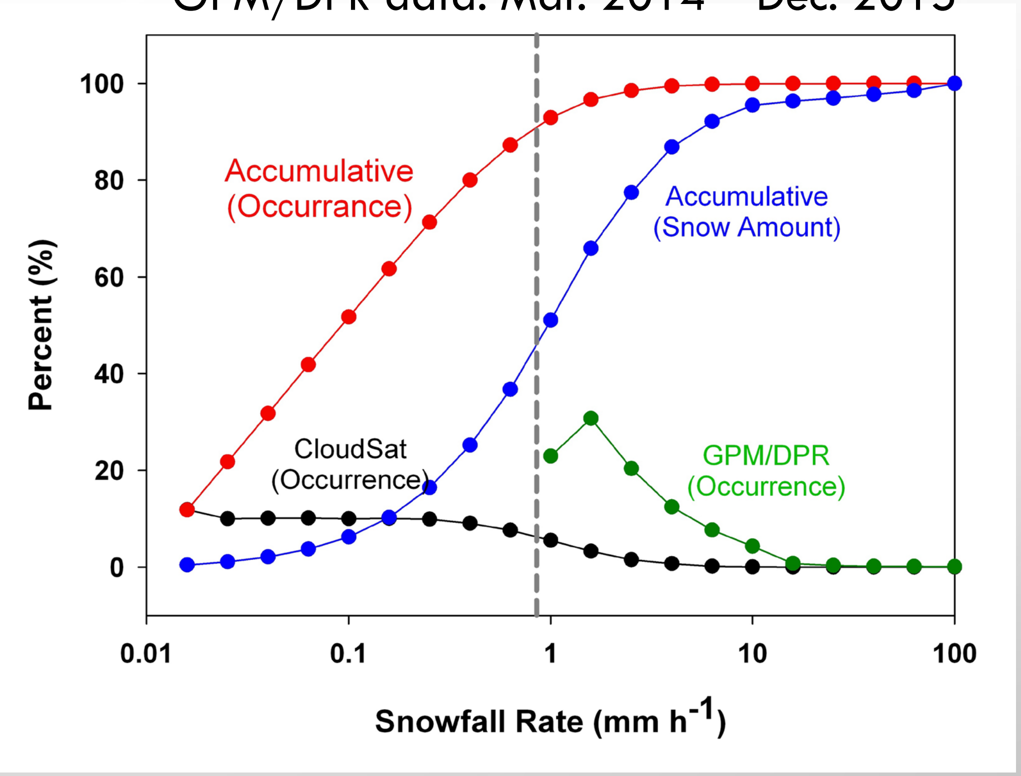
Since snowfall rate is downward water flux, how fast particles fall is another factor of complication.

GPM/DPR MISSES MANY SNOWFALL DUE TO LOW DETECTION CAPABILITY (~13 DBZ)



Use 2BCSATGPM dataset of Turk (2015)

Based on collocated CloudSat/CPR - GPM/DPR data: Mar. 2014 – Dec. 2015



DPR misses ~90% of snowfall pixels

~40% of snowfall amount

Z-S RELATIONS

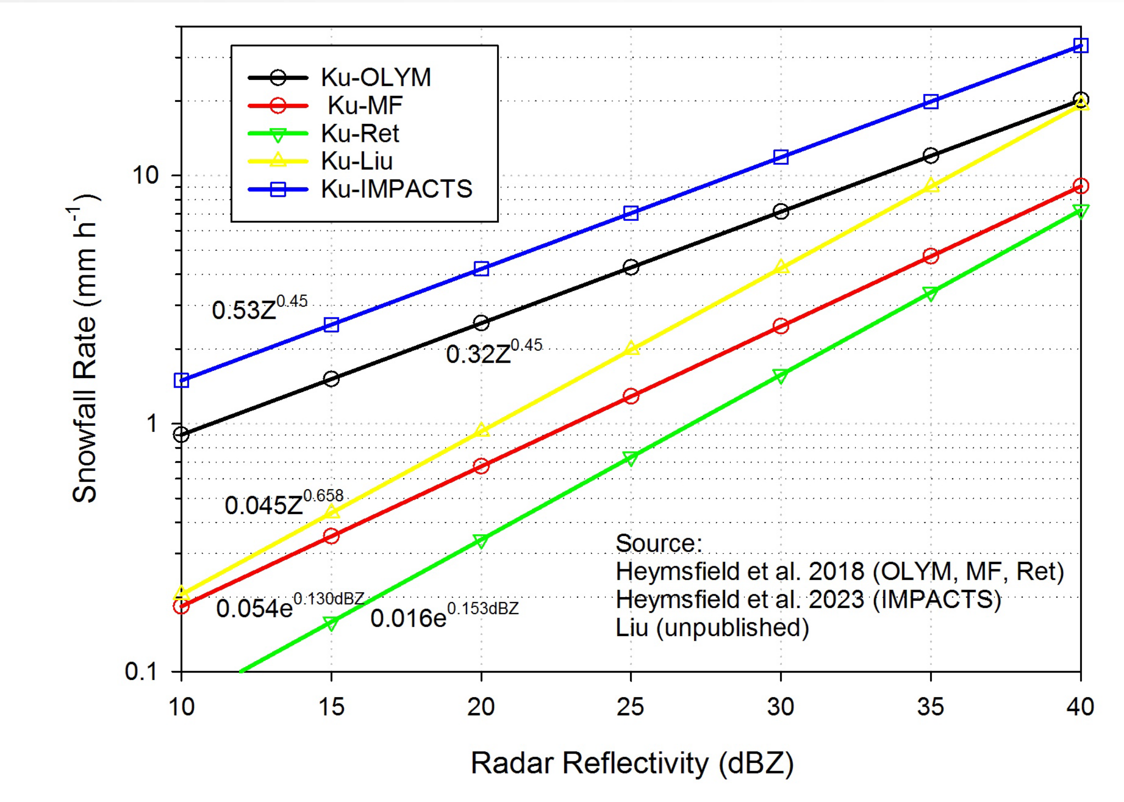
Heymsfield et al. (2018; 2023):

- Ret – based on Z – S matchups from DPR/CPR products
- MF – based on “cross-melting layer” method of Heymsfield
- OLYM – based on OLYMPEX field experiment
- IMPACTS – based on IMPACTS field experiment

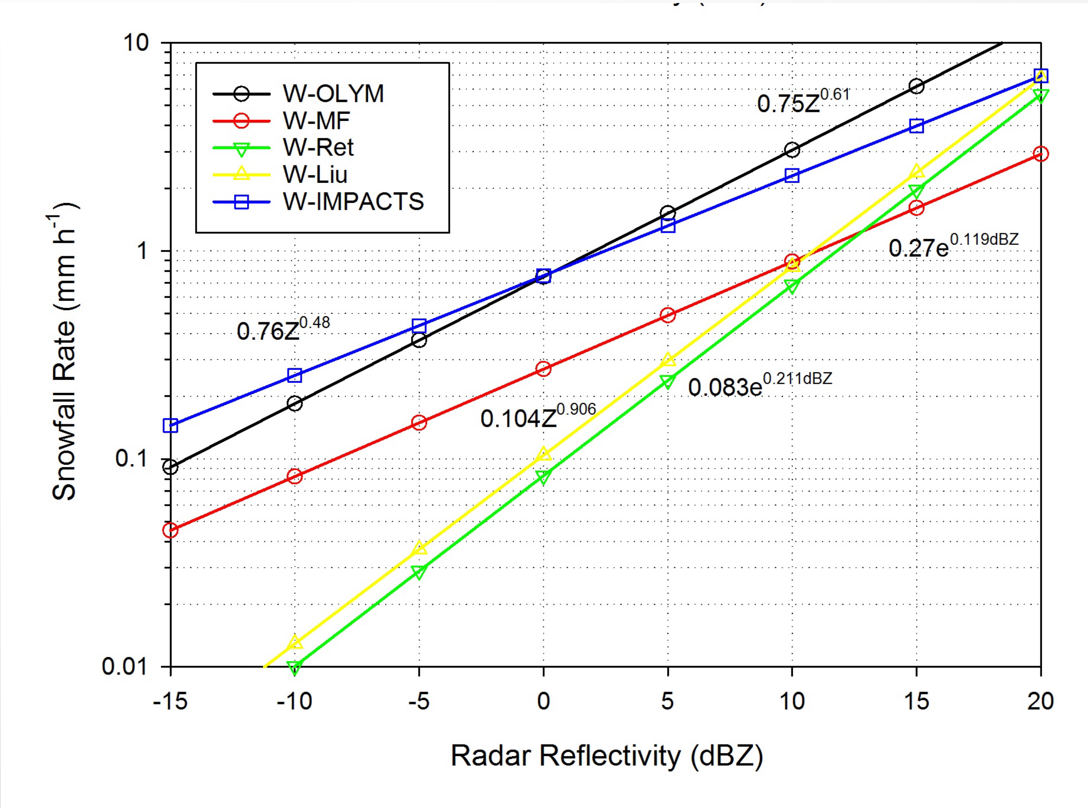
Liu (2008; unpublished):

- derived by assumed particle shape and PSD

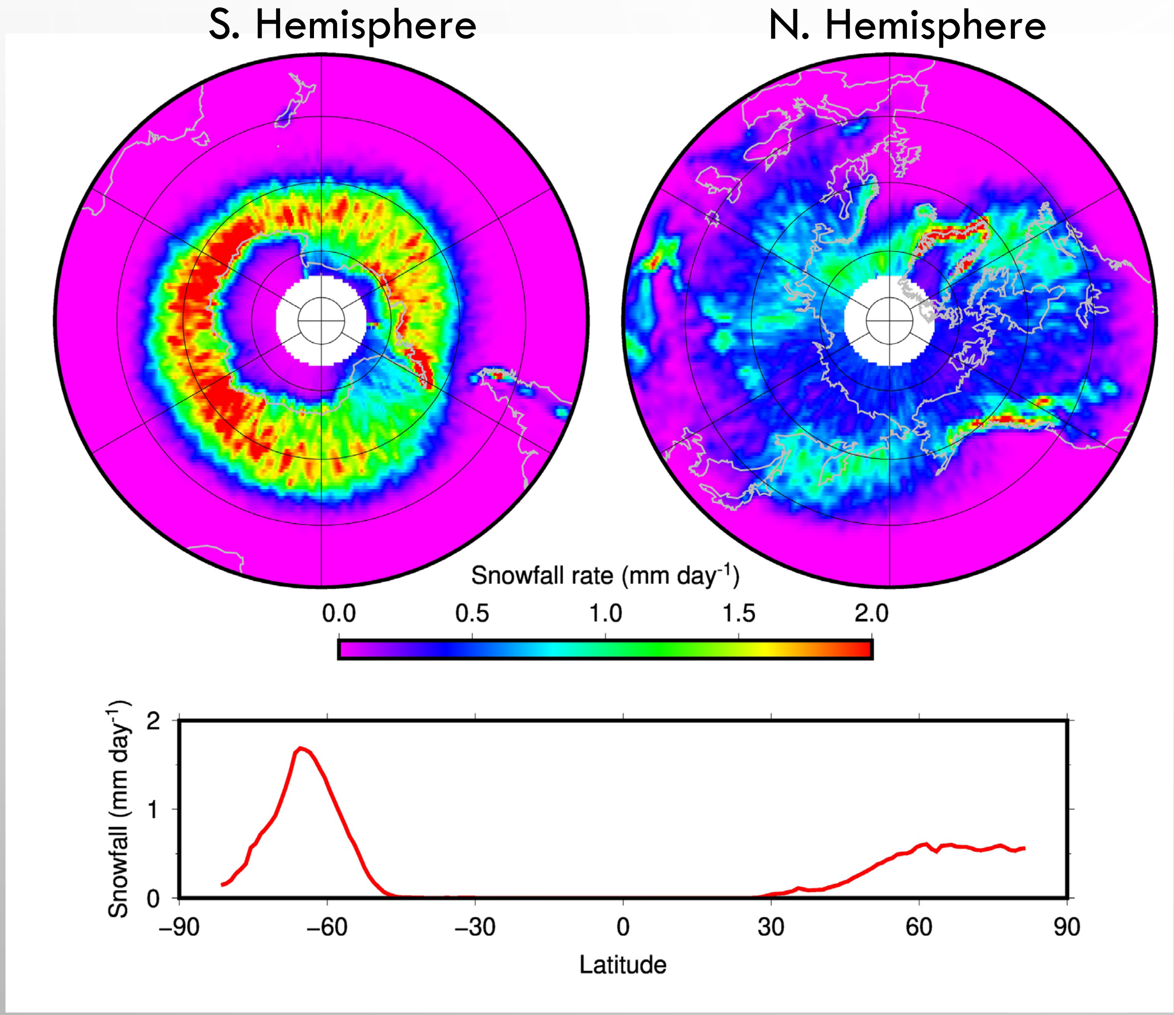
Ku - band



W - band



GLOBAL SNOWFALL FROM CloudSat



CloudSat CPR operated from 2006 to 2023, although it turned to daylight only mode after 2011. The left figure was generated using data from 2006 through 2019. We consider it represents the snowfall climatology.

- S. Hemisphere: snowfall belt is centered around 65S latitude;
- N. Hemisphere: snowfall follows storm tracks
- Snowfall over high mountains

SNOWFALL FROM PASSIVE MICROWAVE SENSORS

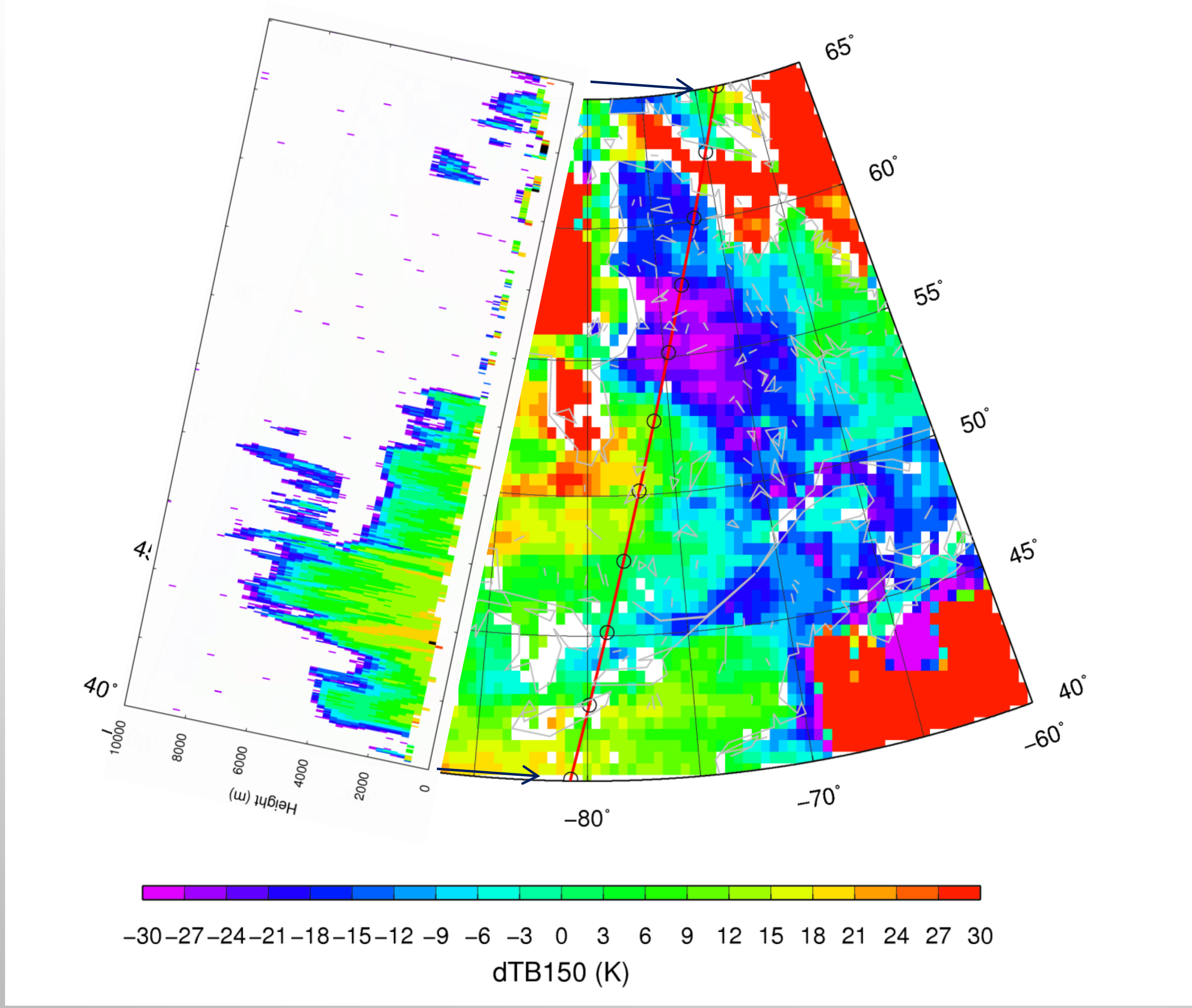
Table 1. Satellites and sensors with high-frequency microwave observations for snowfall retrievals

Satellite	Sensor*	Scan Type	Frequency (GHz)	Launch Date
GOSAT-GW	AMSR3	Conical	6 – 183±7	2024 (scheduled)
GPM Core	GMI	Conical	10 – 183±7	Feb 2014
DMSP F16	SSMIS	Conical	19 – 183±7	Oct 2003
DMSP F17	SSMIS	Conical	19 – 183±7	Nov 2006
DMSP F18	SSMIS	Conical	19 – 183±7	Nov 2009
DMSP F19	SSMIS	Conical	19 – 183±7	Oct 2014
DMSP F20	SSMIS	Conical	19 – 183±7	Jan 2020
Suomi-NPP	ATMS	Cross-track	23 – 190	Oct 2011
NOAA-20	ATMS	Cross-track	23 – 190	Jan 2018
NOAA-21	ATMS	Cross-track	23 – 190	Nov 2022
MetOp-A	MHS	Cross-track	89 – 183±7	Oct 2006
MetOp-B	MHS	Cross-track	89 – 183±7	Sep 2012
MetOp-C	MHS	Cross-track	89 – 183±7	Nov 2018
NOAA-15	AMSU-B	Cross-track	89 – 183±7	May 1998
NOAA-16	AMSU-B	Cross-track	89 – 183±7	Sep 2000
NOAA-17	AMSU-B	Cross-track	89 – 183±7	Jun 2002
NOAA-18	MHS	Cross-track	89 – 183±7	May 2005
NOAA-19	MHS	Cross-track	89 – 183±7	Feb 2009

* AMSU-B: Advanced Microwave Sounder Unit – B; MHS: Microwave Humidity Sounder; SSMIS: Special Sensor Microwave Imager Sounder; ATMS: Advanced Technology Microwave Sounder; GMI: Global Precipitation Measuring Mission (GPM) Microwave Imager. AMSR3: Advanced Microwave Scanning Radiometer 3.

- Major signature is scattering by ice particles to upwelling radiation
- Need high frequency (>100 GHz) observations to have strong enough signal
- Many satellites/sensors available
- Noisier than radar signals (for snow retrieval)

ONE OF THE PROBLEMS IN DETECTING SNOWFALL BY PASSIVE MW OBSERVATIONS – SUPERCOOLED LIQUID

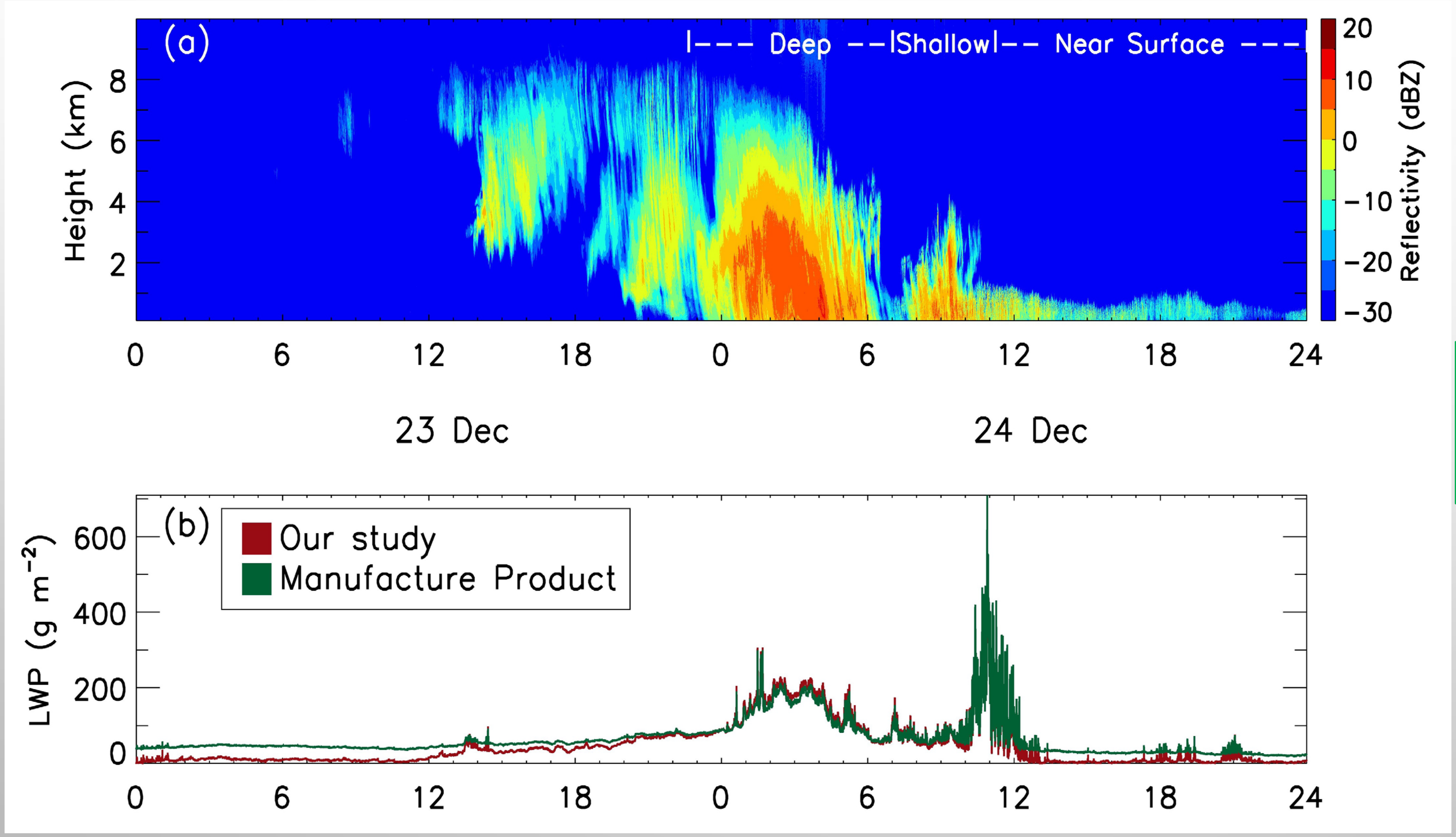


- The principle to detect snowfall from microwave obs. is to use TB decrease caused by ice-scattering
- Largest TB depression does NOT necessarily correspond to heavy snowfall
- Why ?

Scattering by snowflakes competes with emission from cloud liquid.

Jan 22 2007 C3VP case w/CloudSat Over Pass ~ 0700UTC

Simultaneous Obs of Snowfall and Liquid Water by W-band Radar and 89 GHz Radiometer Over S. Korea for 6 Months

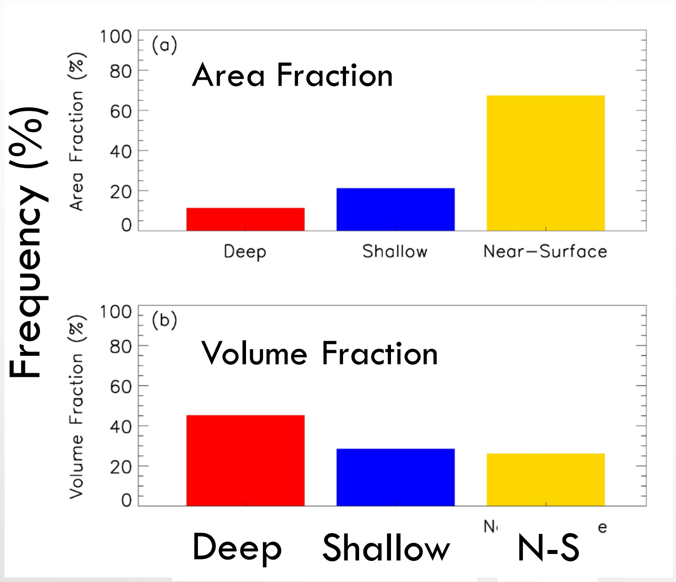


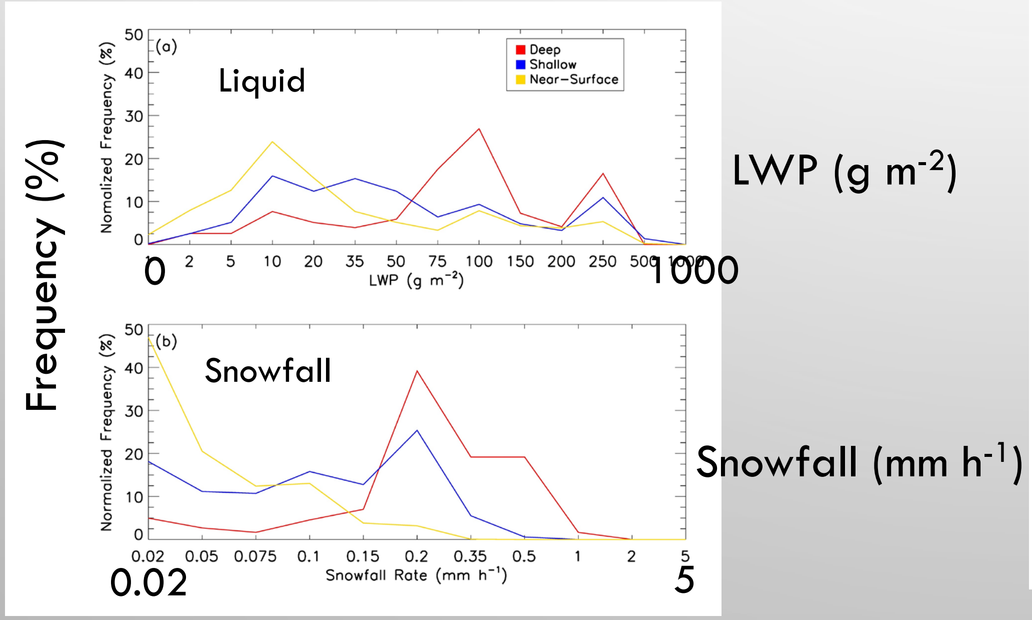
Near-surface: top <1.5 km
Shallow: top 1.5 – 4.0 km
Deep: top > 4.0 km

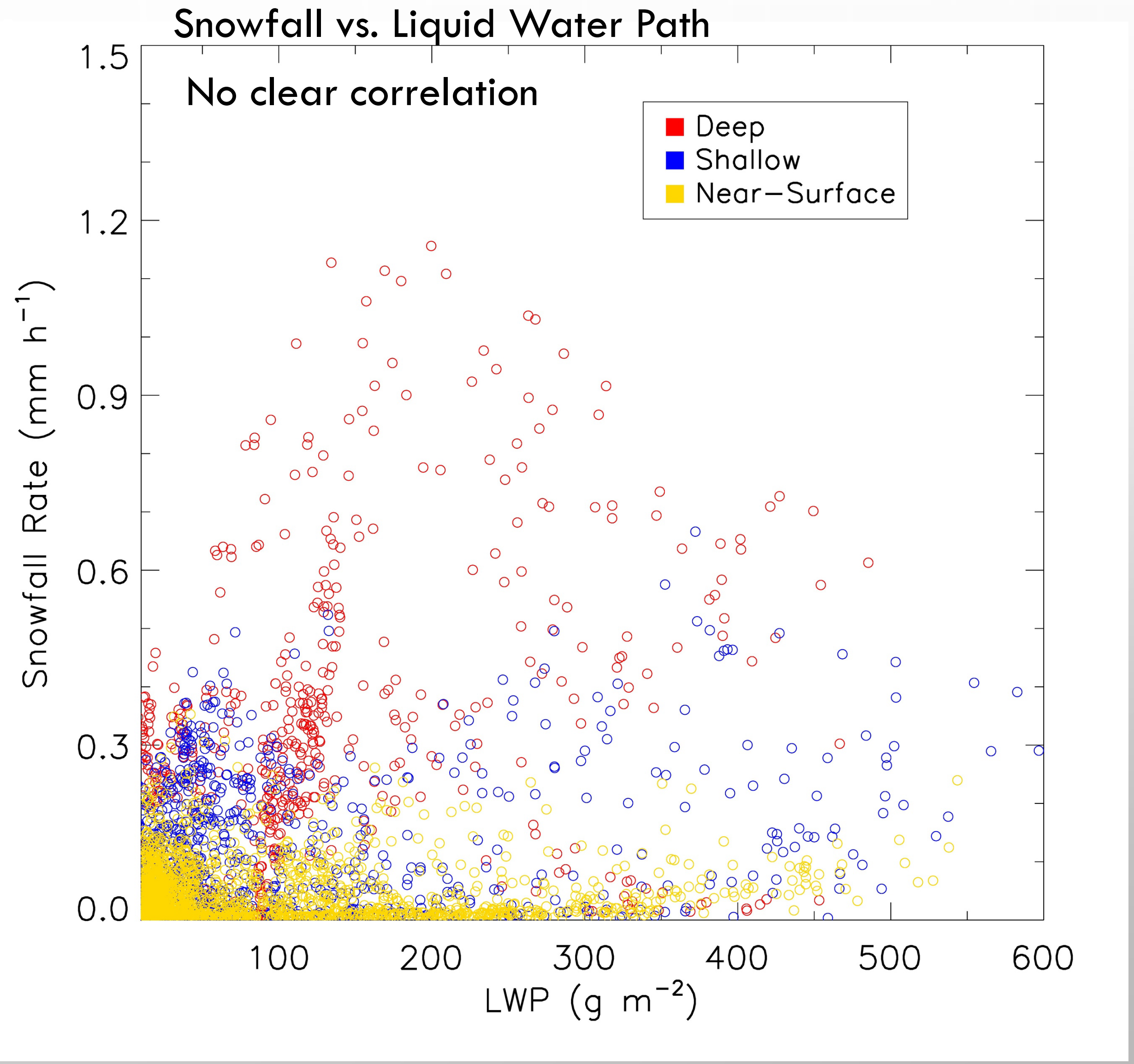
Jeoung et al. (2020), ACP.

MICROPHYSICAL PROPERTIES

Jeoung et al. (2020), ACP.



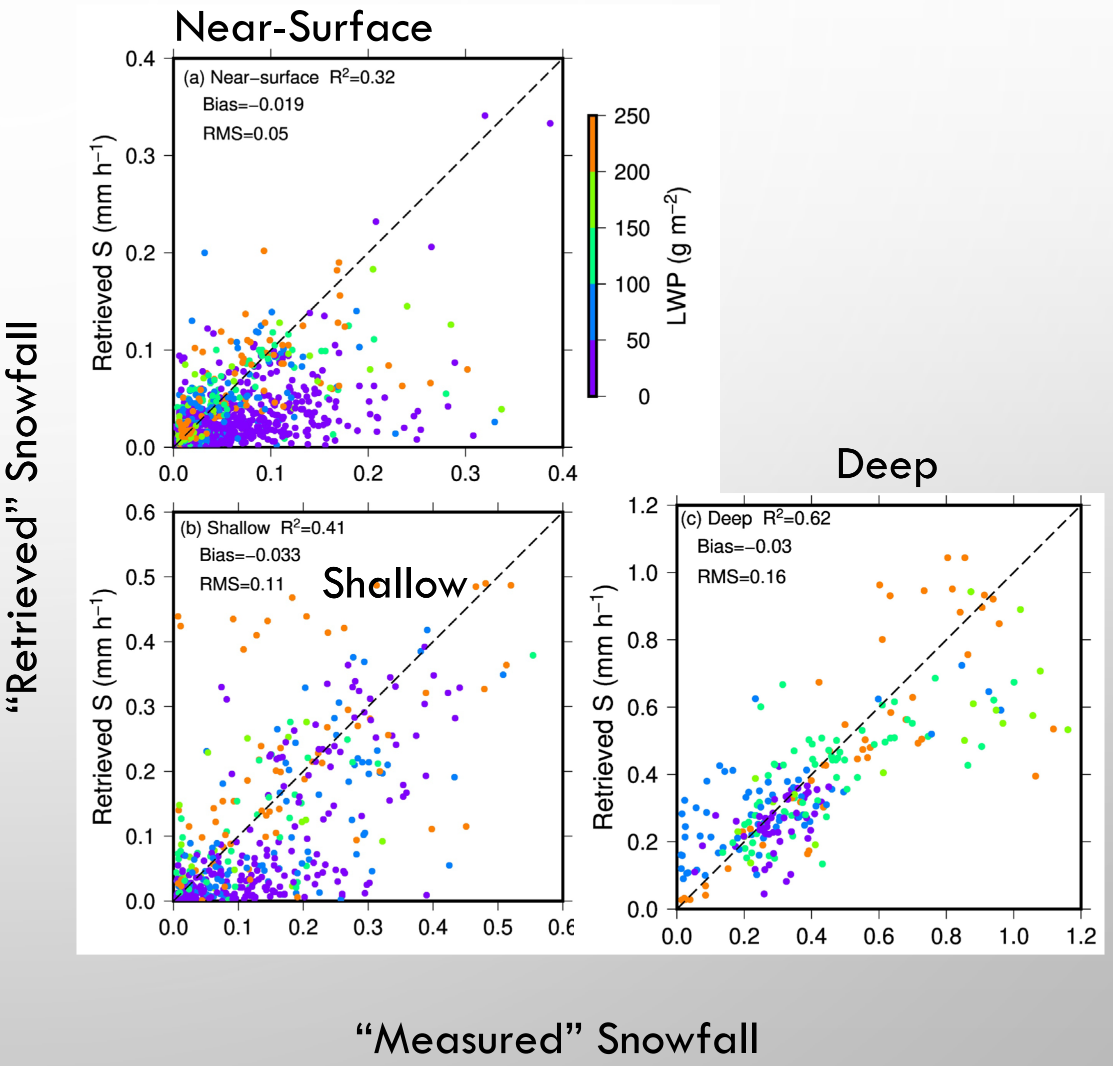




STUDIES BASED ON 4500 SNOWFALL AND 26,500 NO-SNOWFALL PROFILES

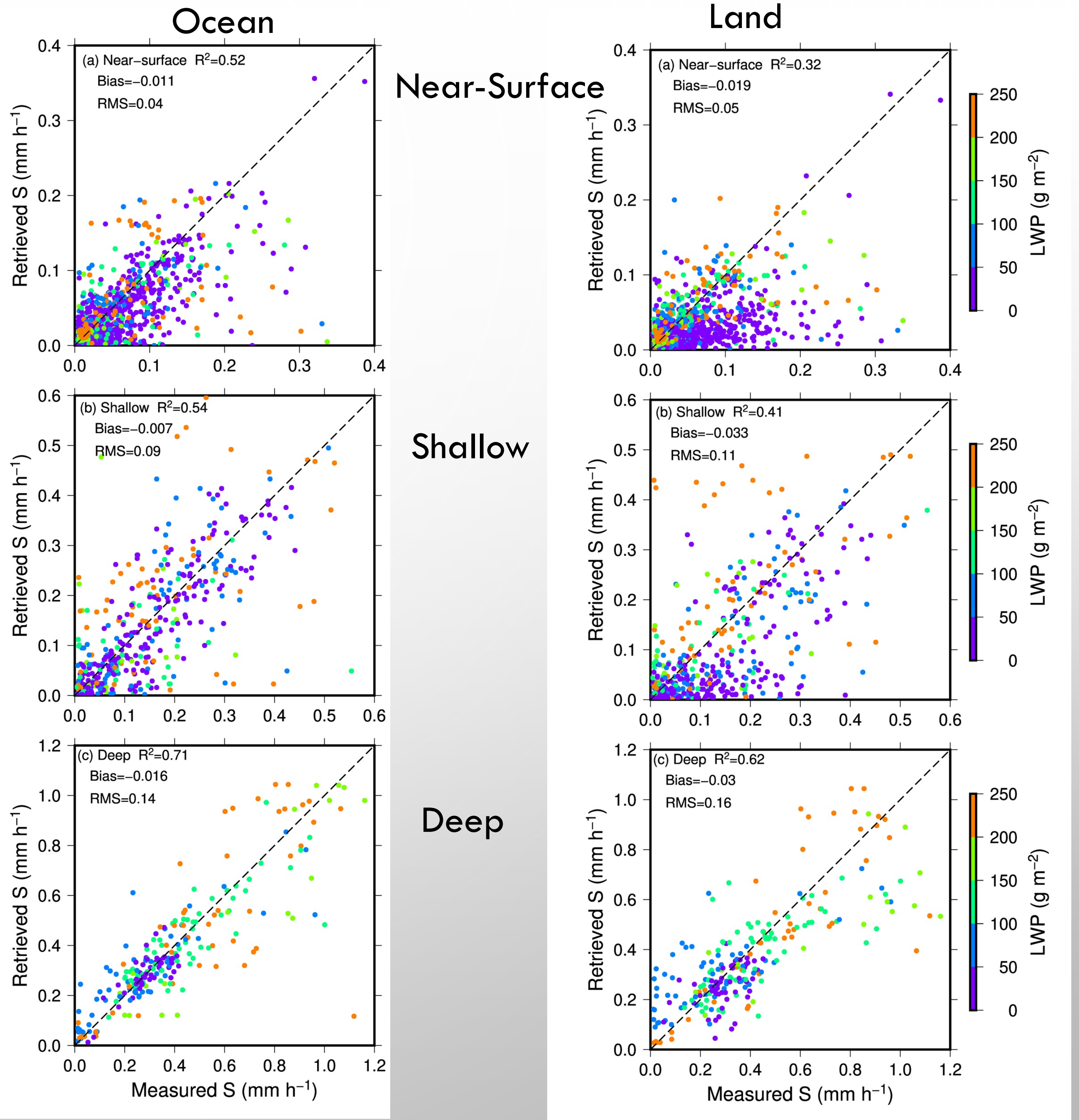
- Use RT Model generate GMI Tbs
- Separate profiles into training set and testing set.
- Test how a Bayesian algorithm would perform

Under ideal conditions (know surface emissivity, particle size distribution, etc.), how good a Bayesian algorithm can do (upper limit) – error only due to the randomness of cloud structure, liquid – ice composition.



WHAT IF OVER OCEAN?

Over ocean, due to liquid water info can be resolved by lower frequency channels. Snowfall retrieval can be improved compared to over land. But major improvement is only seen in the near-surface cloud types.



SNOWFALL BY PASSIVE MICROWAVE OBSERVATIONS

- Need high-frequency channels to pickup ice scattering information
- Need multichannel combination to take care of “contaminations” by other factors than snow
- Better skill over ocean
- Better skill for deeper clouds
- Algorithms include:
    - optimization (1d-var) - seek consistency among observables and model results
    - a-priori database - use “relative” truth to teach radiometer observations

THE JAXA SNOWFALL ALGORITHM FOR GMI & AMSR3

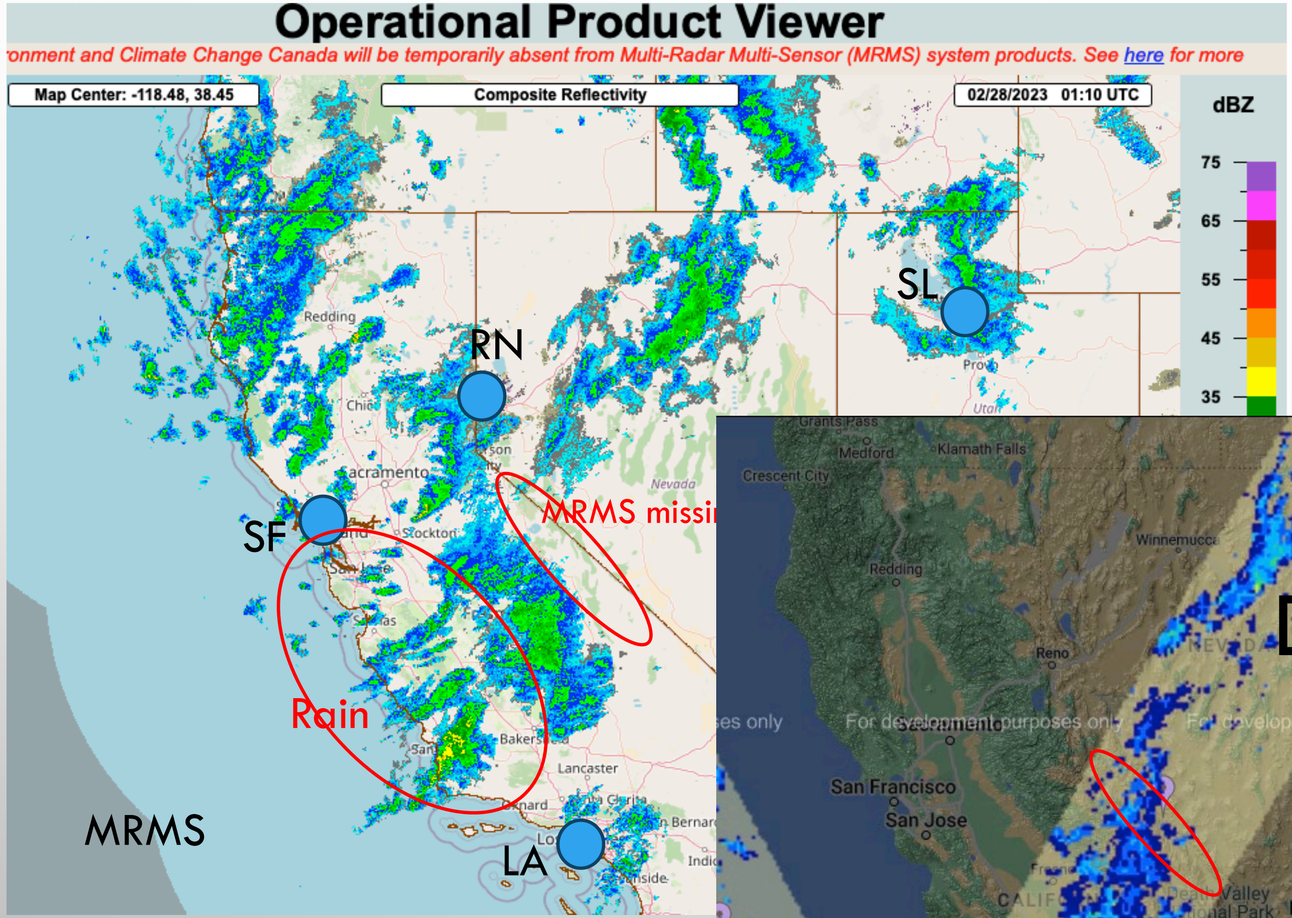
- Snowfall Rate vs. Brightness Temperature Database Based on CloudSat (+DPR) Snow and GMI TBs; Divide Database into 10 Regimes
- Determine Snowfall Possible Condition Using Environmental Variables (Sims And Liu, 2015), to be upgraded to Shi and Liu (2024)
- Inversion of TBs to Snowfall Using Lookup Table (Liu et al., 2013) and Bayesian (new) Method

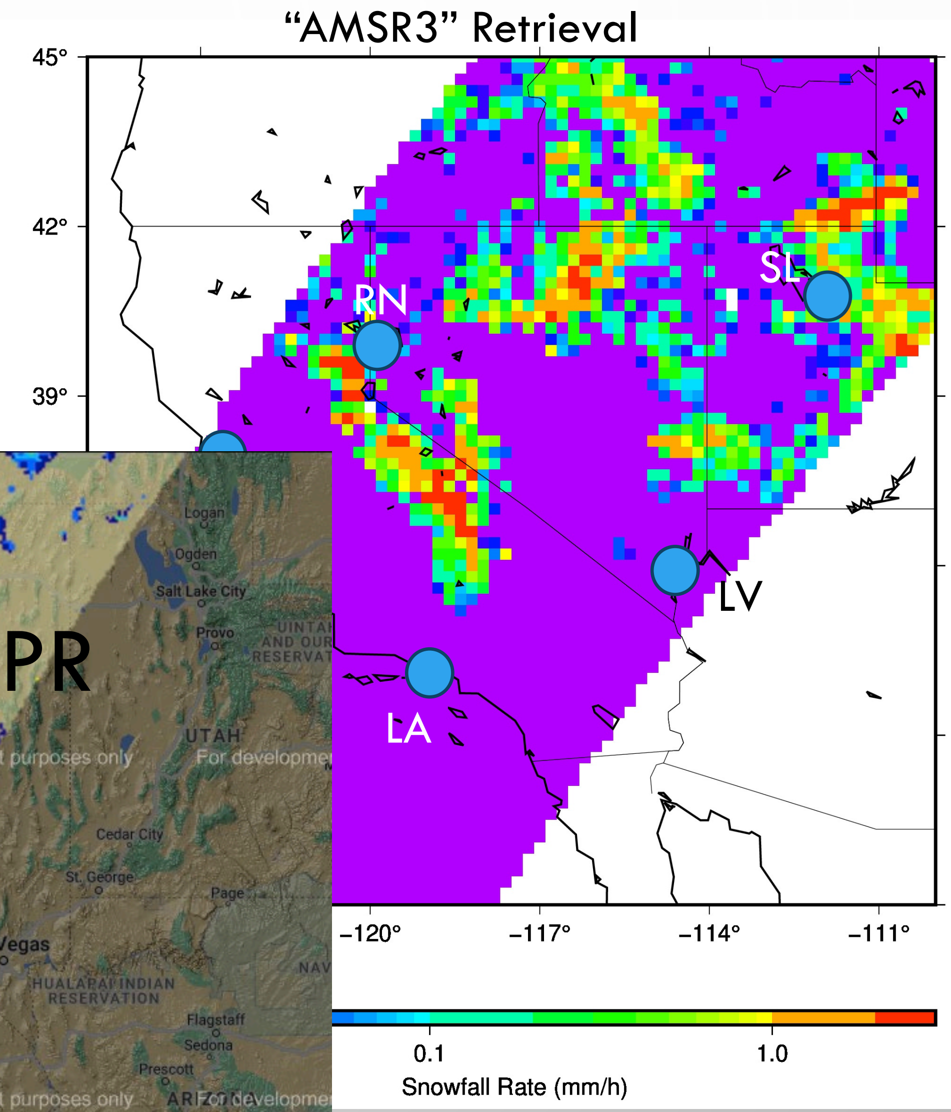
REGIMES FOR DATABASE

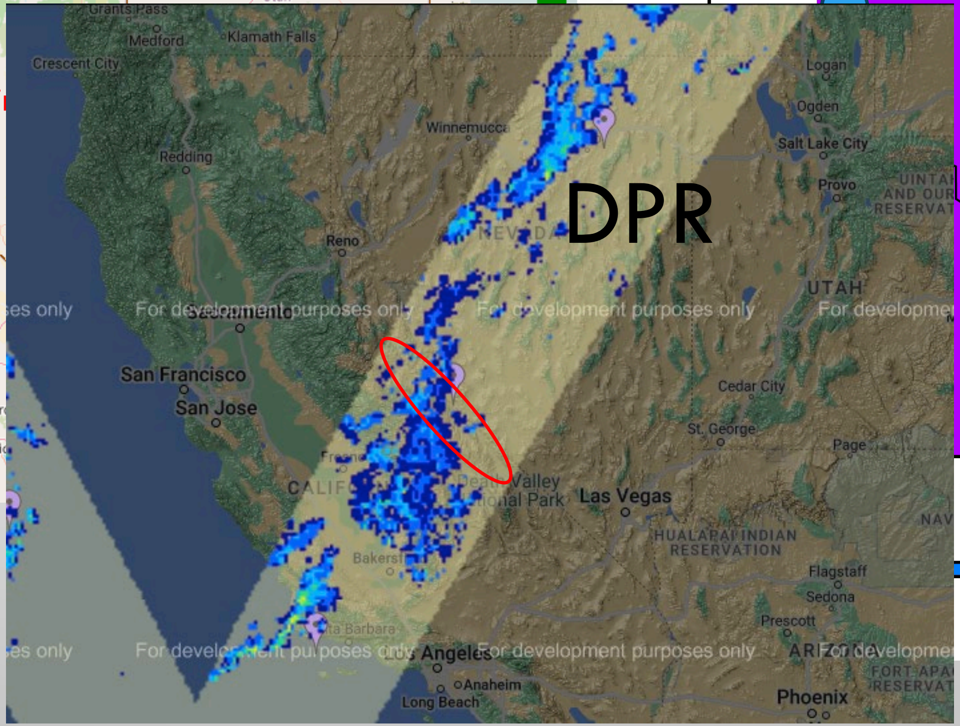
1. Open Water, Dry (TPW<5 Kg M^{-2})
2. Open Water, Moderate Wet (5 –7 Kg M^{-2})
3. Open Water, Wet (> 7 Kg M^{-2})
4. Land
5. Snow Covered Land, Dry (TPW<2.5 Kg M^{-2})
6. Snow Covered Land, Moderate Wet (2.5 -5.0 Kg M^{-2})
7. Snow Covered Land, Wet (> 5.0 Kg M^{-2})
8. Sea Ice
9. Greenland
10. Coast

TPW: Total Precipitable Water

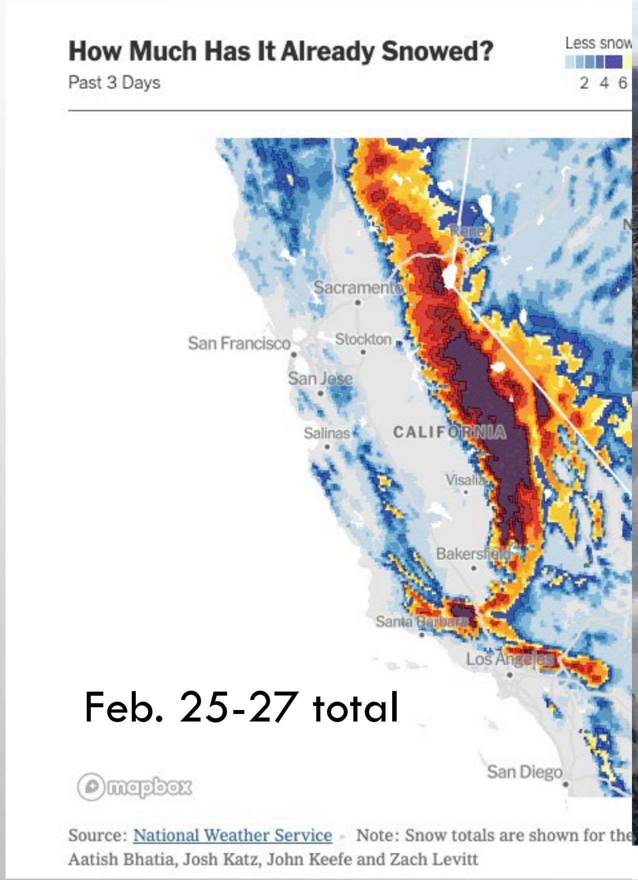
FEB. 28, 2023 SNOWSTORM OVER WESTERN U.S.







NWS FORECASTS

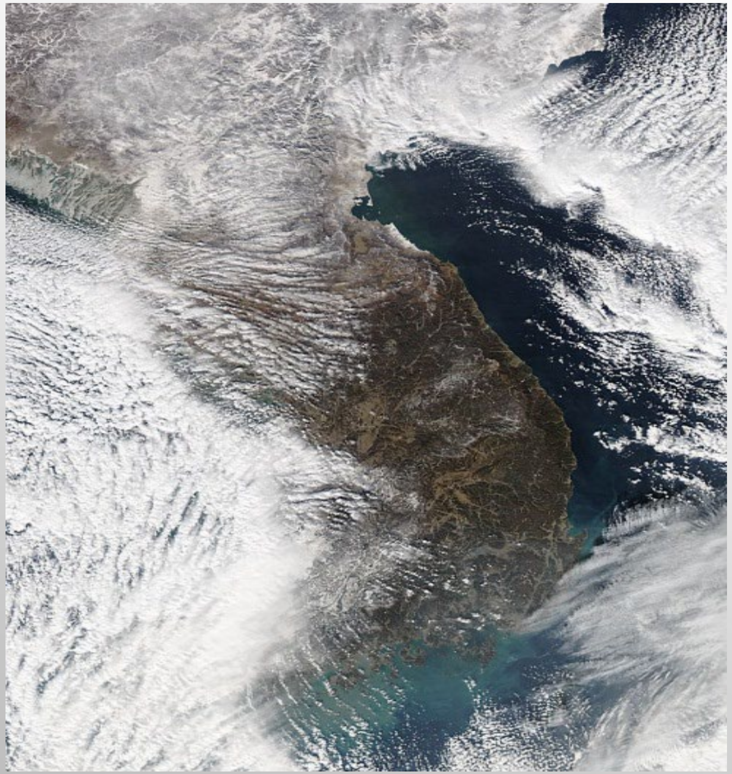


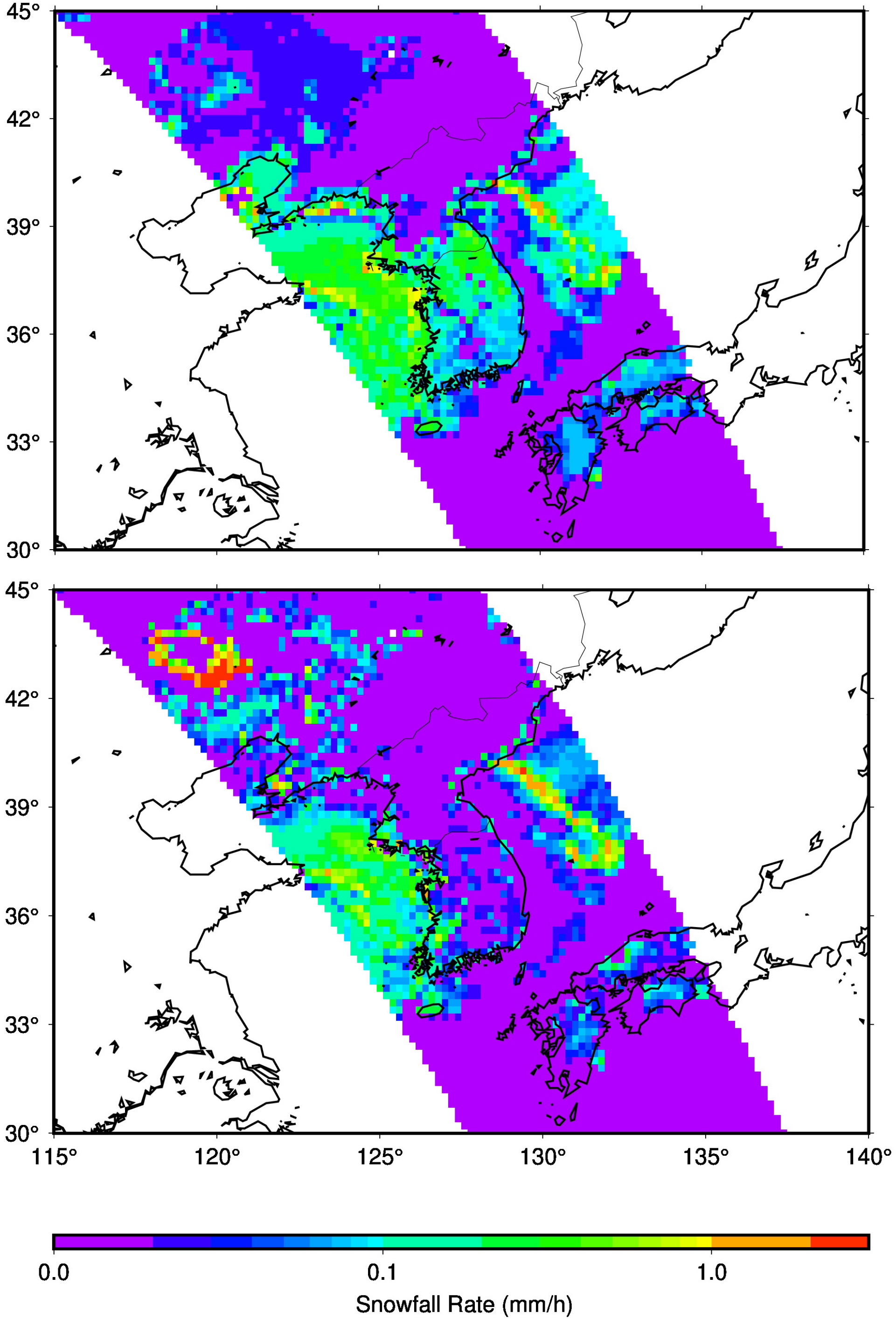
March 12: An aerial view of Mammoth Lakes California in the Sierra Nevada mountains. The eastern Sierra Nevada area is currently holding 243 percent of its regular snowpack for this time of the year. Photo by Mario Tama/Getty Images

From: https://www.nytimes.com/2023/02/24/us/california-snow-tracker-map.html

JAN 23, 2016 COLD AIR OUTBREAK

Aqua MODIS true color image for a snowfall case on 23 Jan 2016 (from *NASA/EOSDIS*)





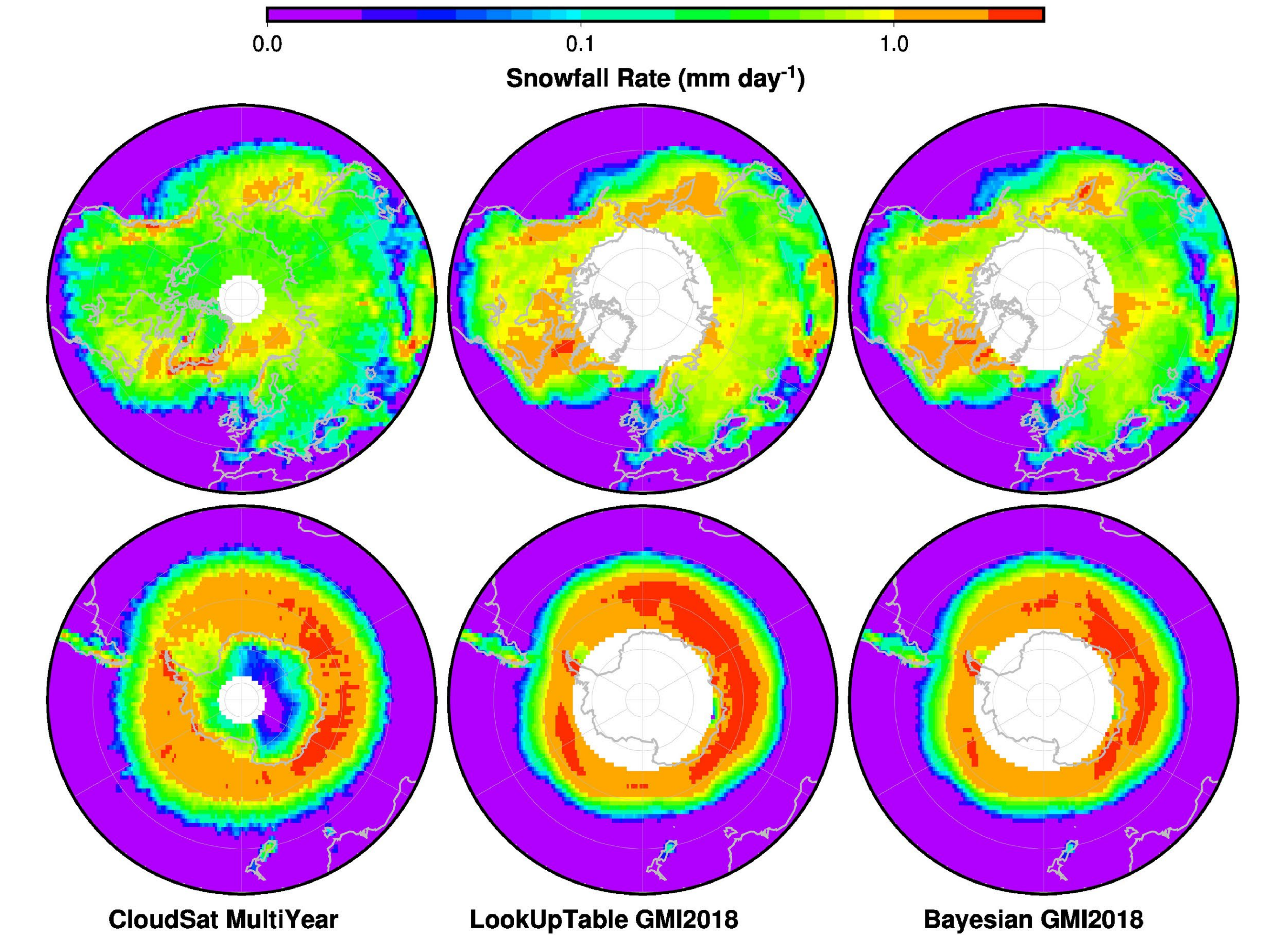
LUT

BAYES

GLOBAL MEAN

- CloudSat: 2006-2019 2CSNOW Mean of All available data
- GMI: One Year (2018)

1. Patterns very similar
2. Bayesian results closer to CloudSat 2CSnow product's



MOVING FORWARD FOR PASSIVE MEASUREMENTS

- Algorithm Improvements can be done by:
  - Improving training database (EarthCARE will be a great help)
  - Improving rain-snow separation
  - Validation
- Passive Measurements Have Great Potentials Because of Broader Area and Longer Time Coverage
  - Imagers: GMI, AMSR3, SSMIS
  - Sounders: ATMS, MHS,…

CONCLUSIONS

- Snowfall may be retrieved by
  - radars with high detection capability (better than -10 dBZ)
  - radiometers with high frequency channels (high than 100 GHz)
- Complications include:
  - particle shapes, PSDs
  - surface contaminations - radiometers
  - masking by liquid water – radiometers
- Improving database is key for better retrievals
  - whether to use look-up-table, Bayesian, or machine-learning, cannot have skillful retrieval without a good database