New Constraints on Global Snowfall From CloudSat

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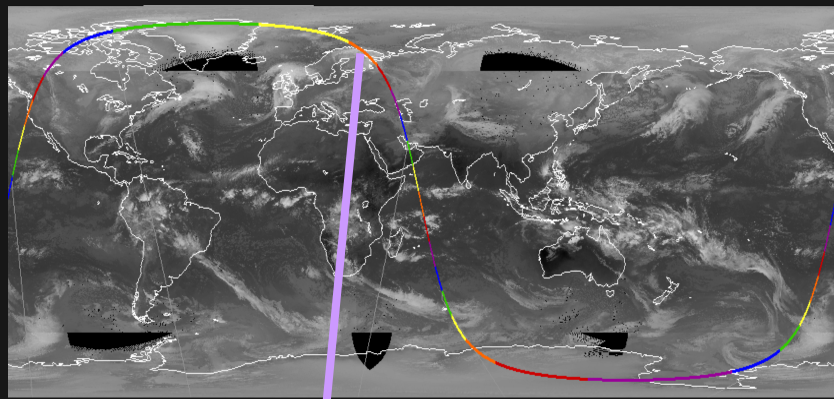
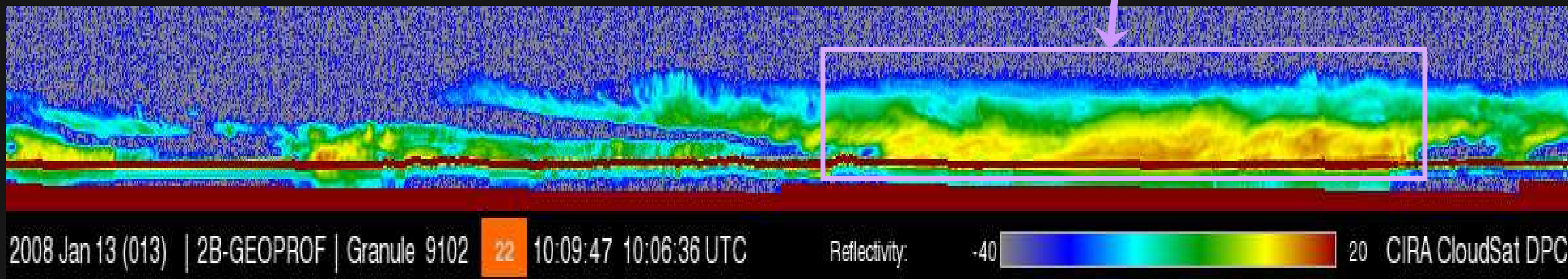
Observing Snow with CloudSat



Strengths:

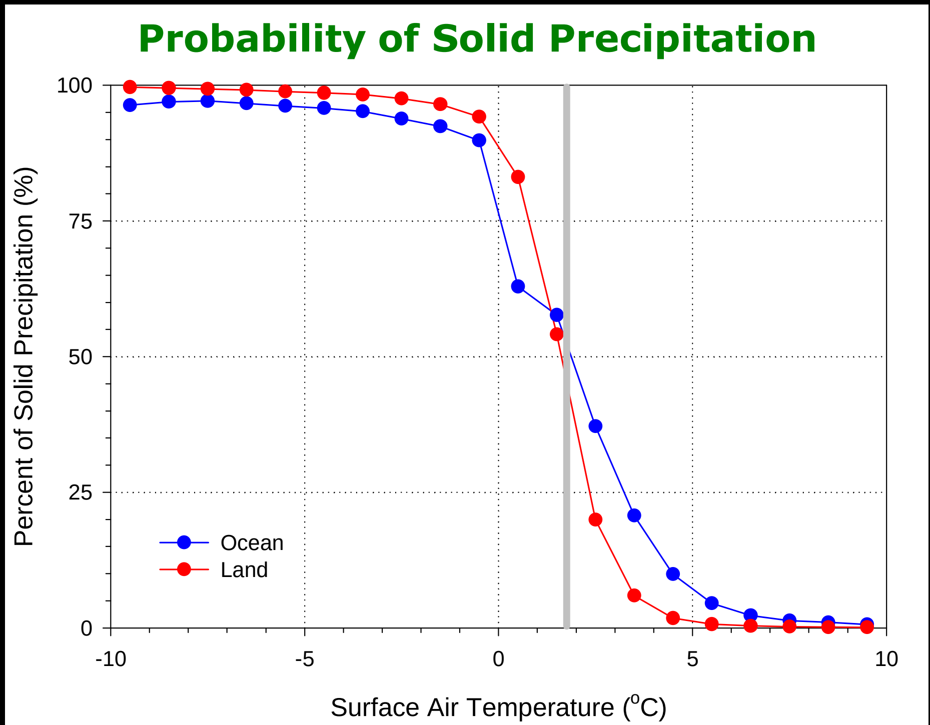
- Active sensor (W-band)
- Excellent sensitivity (-30 dBZ)
- Near-global coverage (±82°)
- High spatial resolution (~1.5 km)
- Coincident measurements from other A-Train sensors (eg. PMW)



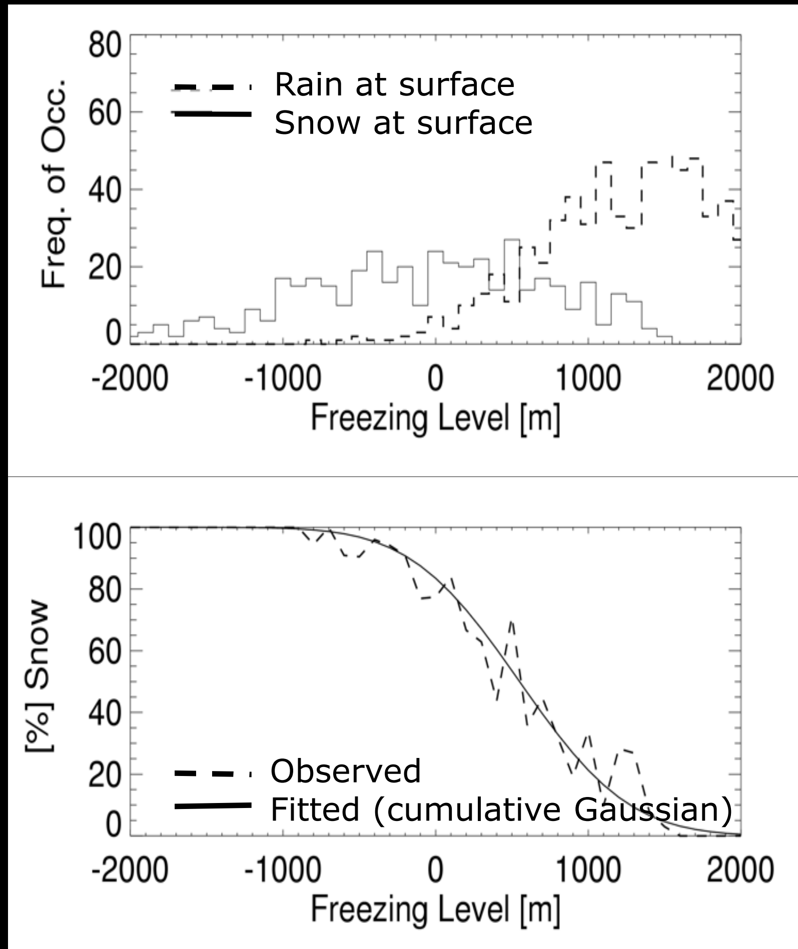
Challenges:

- Rain/snow discrimination (single-wavelength/pol, no Doppler)
- Complex relationship between reflectivity and snowfall rate/IWC
- Sampling (nadir-only)
- Ground Clutter (~750 m)

Identifying Snowfall



Liu (2008)

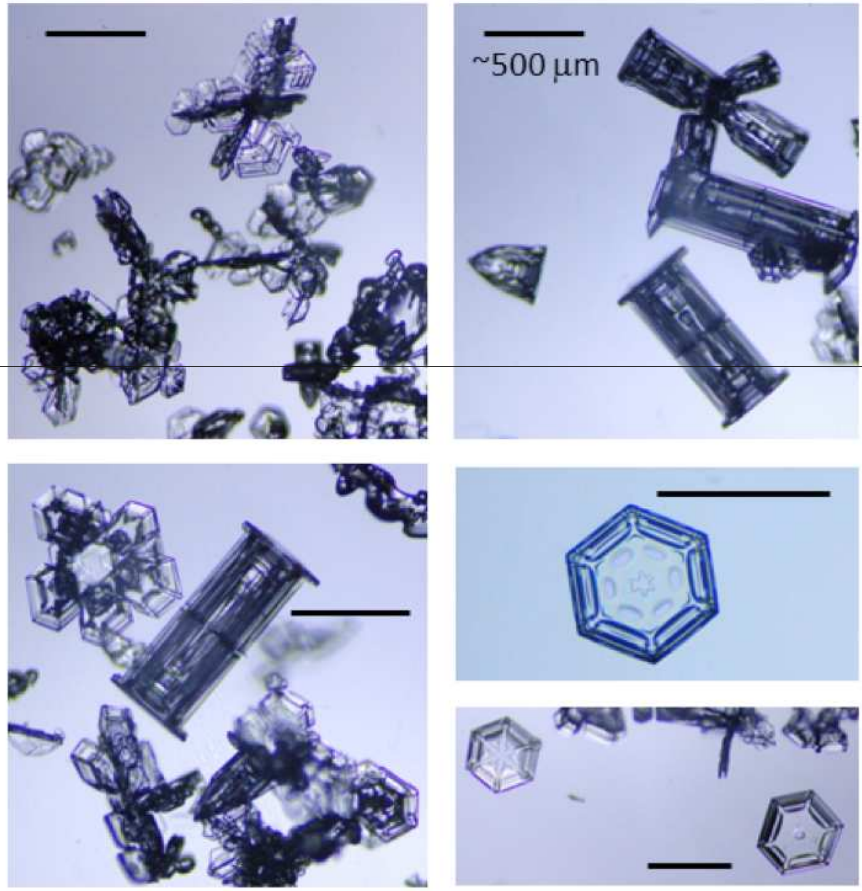


Bennartz (2007)

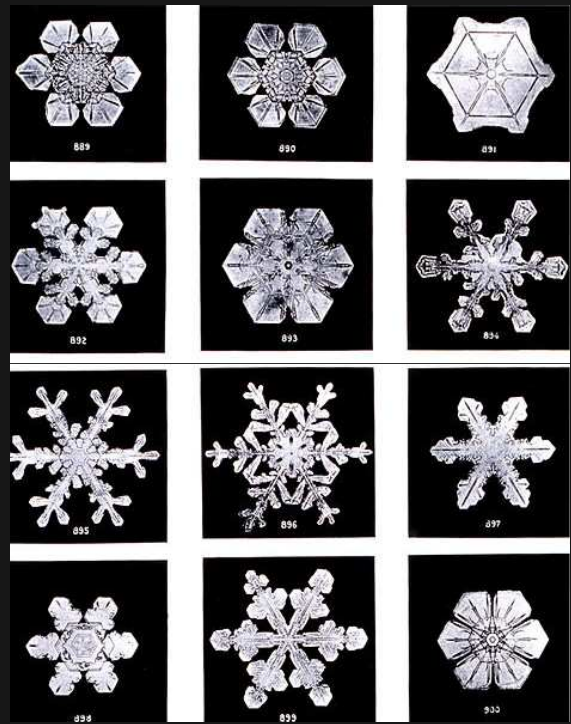
Globally, an ECMWF 2 m air temperature of +2ºC corresponds to a 50% probability of observing snow at the surface.

Snowflake Shape, Size, Density

FIG 7. IcePIC ice crystal photographs taken at approximately 17:40 on 21 Sept. In each individual photograph a reference bar of 500 μm length is provided for scale.

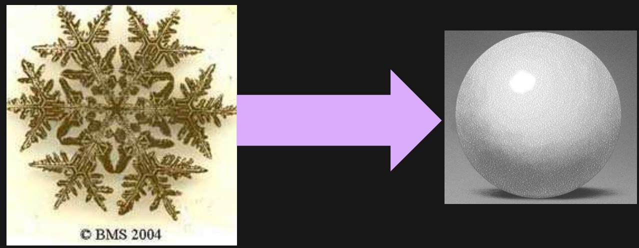


Summit Observatory – Greenland Shupe et al. (2012)

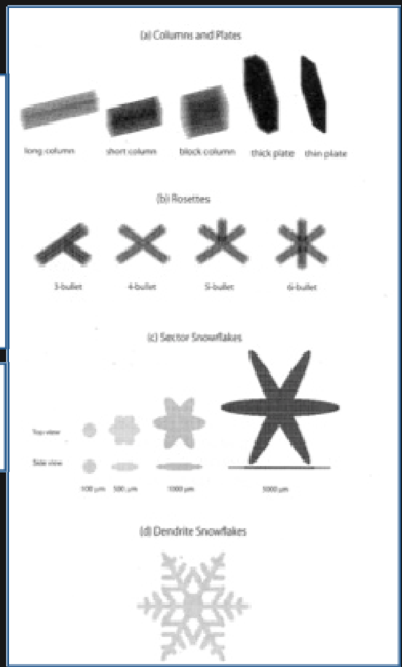


Vermont – Bentley (ca. 1902)

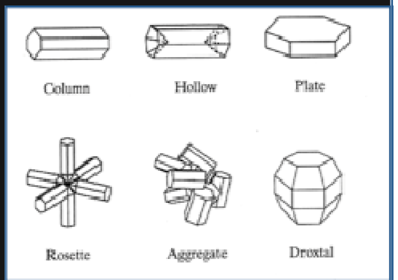
Modeling Non-spherical Particles

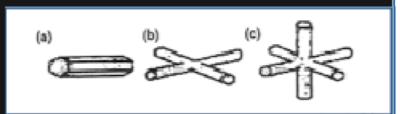


Liu (2004,2008)



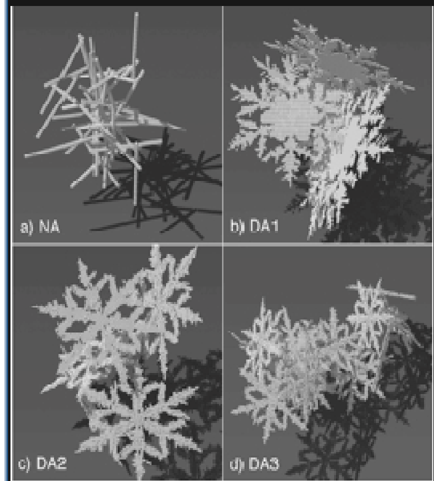
Hong (2007)





Kim et al. (2007)

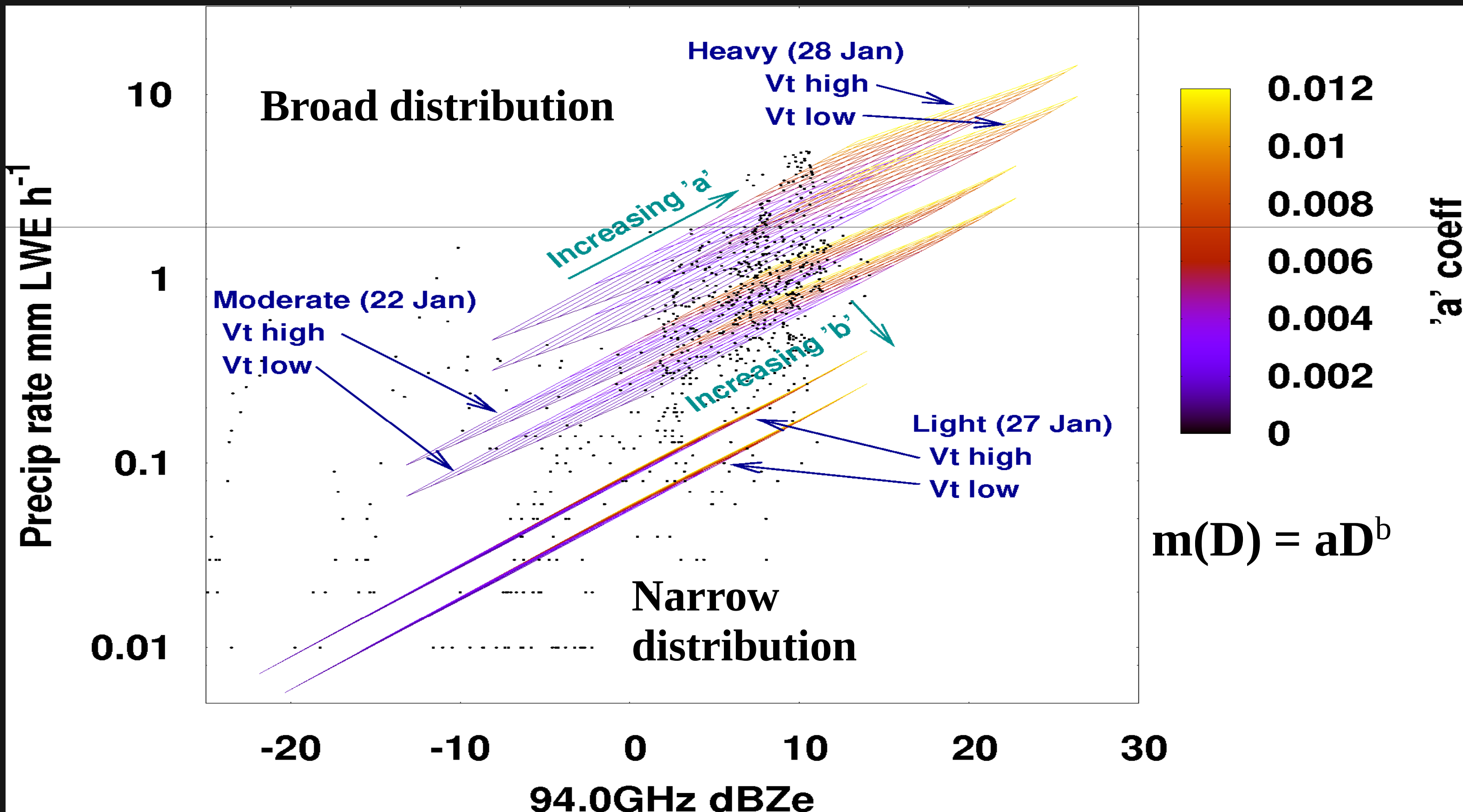
Petty and Huang (2010)



- In the last 5 years significant progress has been made in modeling non-spherical ice optical properties
- Numerous models are now available
- How can this information be best used?

Influence of Microphysics

Variability in snow particle mass, shape, size distribution → uncertainty in the observed relation between Z_e and S (green points).



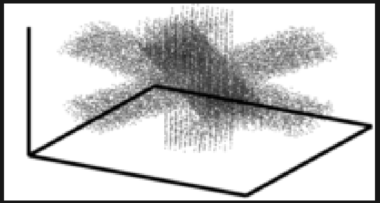
Role of In Situ Observations

- Develop *a priori* constraints on particle mass, cross-sectional area, and size distribution.
- Eliminate unrealistic scattering models (e.g. spheres).
- Constrain solutions to be radiatively consistent over a wide range of frequencies both active and passive channels
- Document and provide to users resulting range of uncertainty
- Evaluate results: long-term accumulations and field campaigns

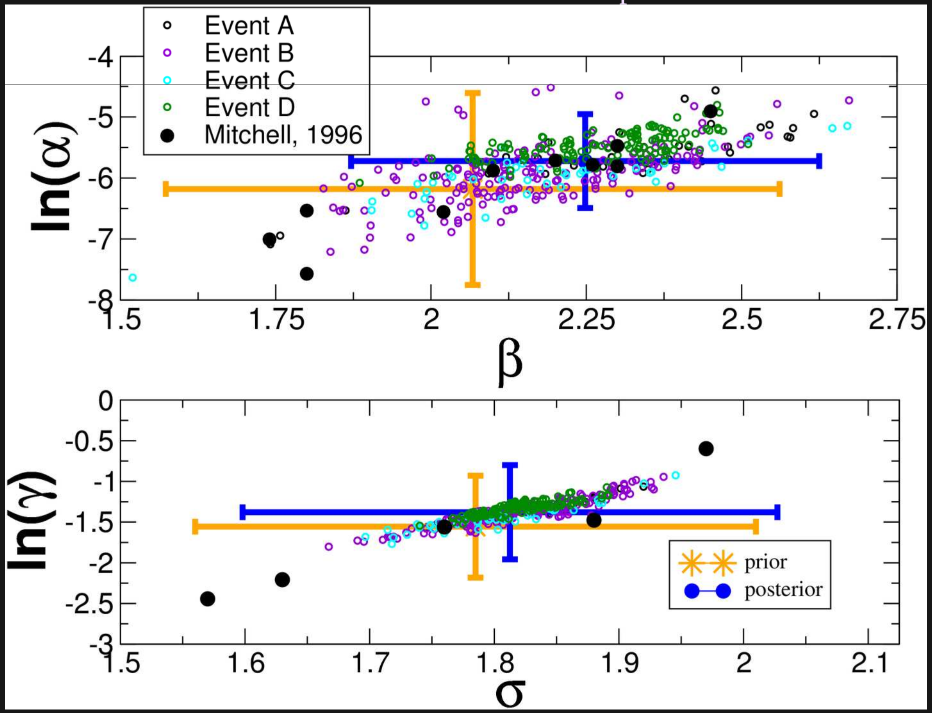
CloudSat's Approach

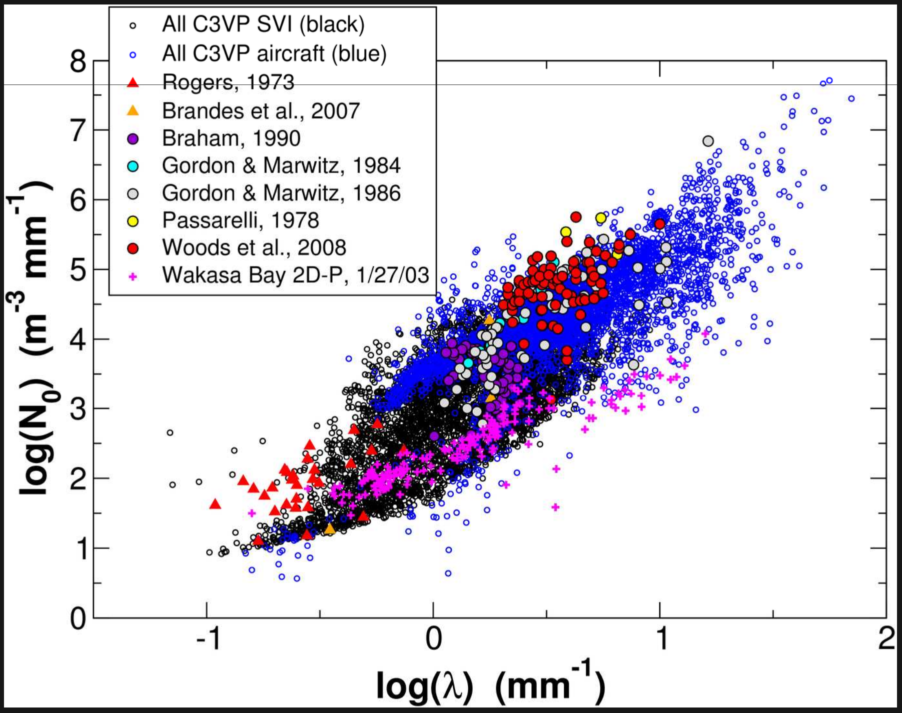
- Utilize ground validation data to establish *a priori* information about snow microphysical properties and size distributions.
- OE algorithm derives mass and projected area relationships from X-band radar, 2DVD, and Pluvio snowfall rate measurements.

$m(D) = \alpha D^{\beta}$ $A_p(D) = \gamma D^{\sigma}$



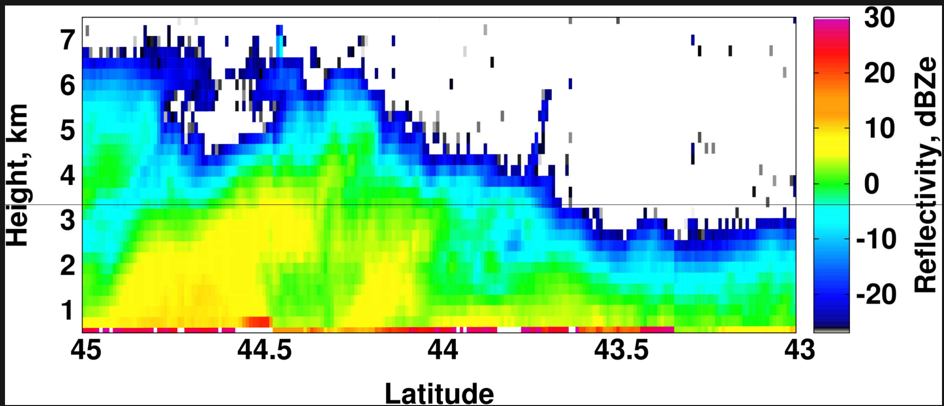
Values of α, β, γ, σ are then used to constrain discrete dipole models for radar scattering properties.

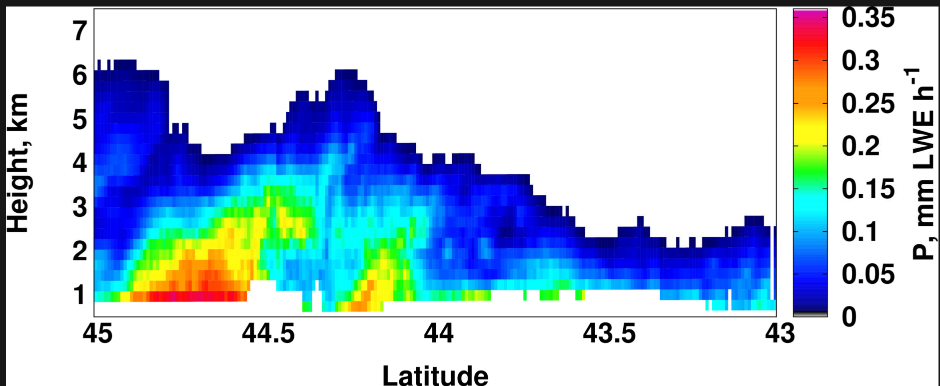




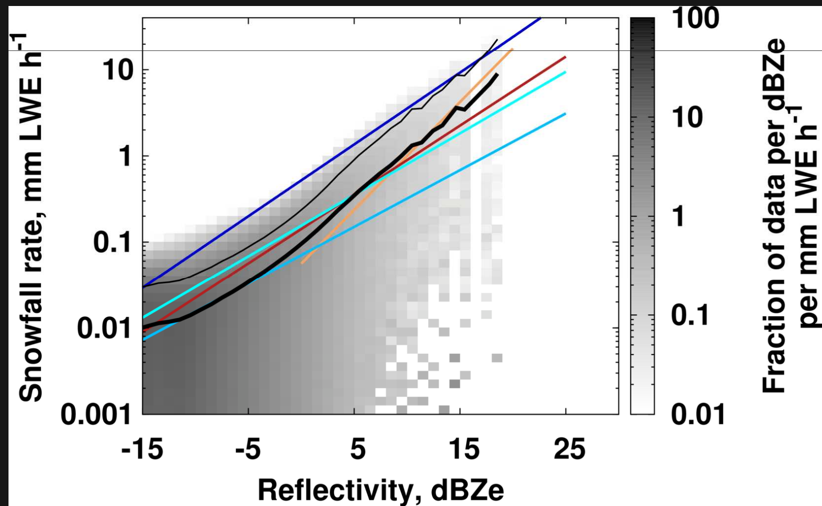
CloudSat Snowfall Retrievals

Profiles of IWC and surface snowfall rates over land and ocean with rigorous uncertainty estimates.





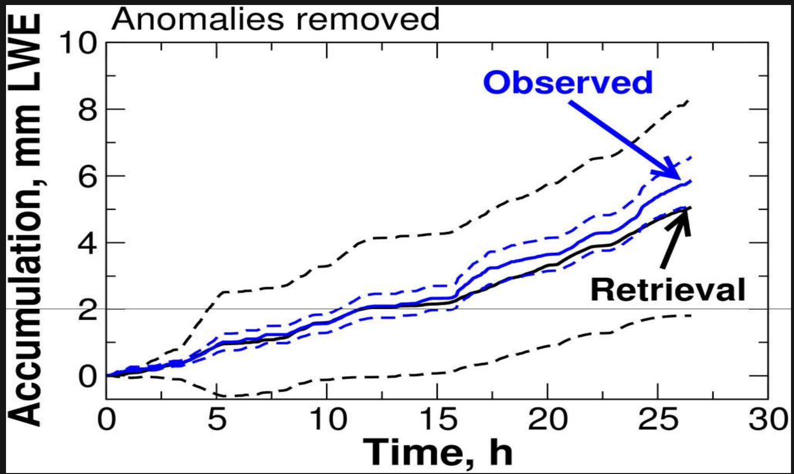
Retrieval-derived Z_e-S (black) and uncertainties (gray) capture variability in observed Z_e-S (earlier slide)

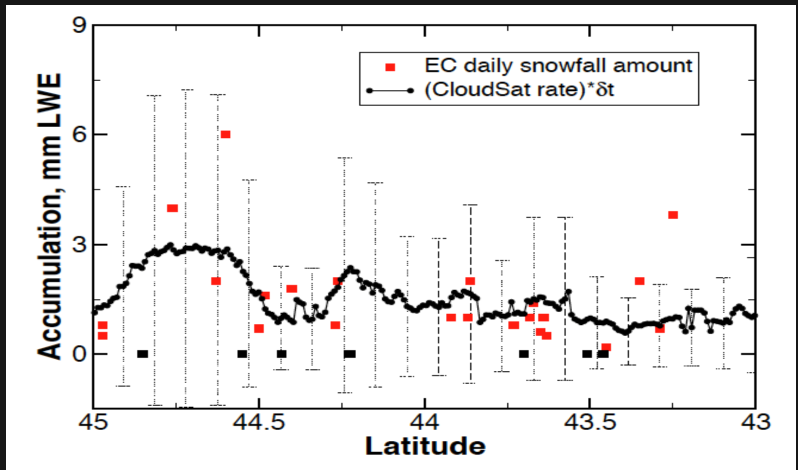


Orange: Matrosov (2007)
Red: Liu (2008)
Blues: Kulie and Bennartz (2009)

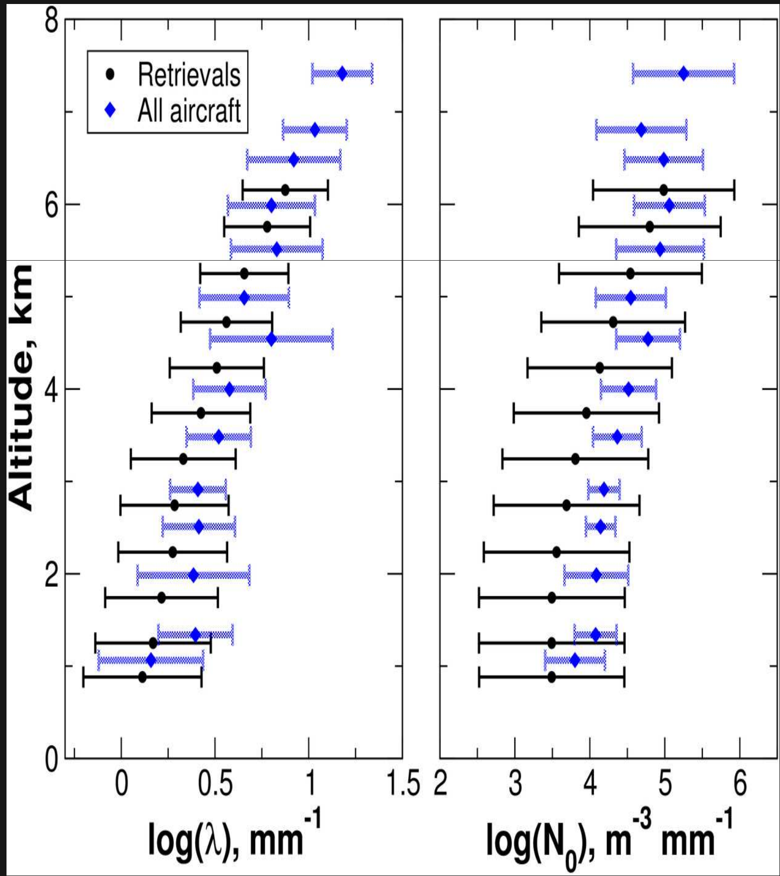
Evaluation

Accumulations from ground-based W-band and CloudSat retrievals are consistent with gauge observations.



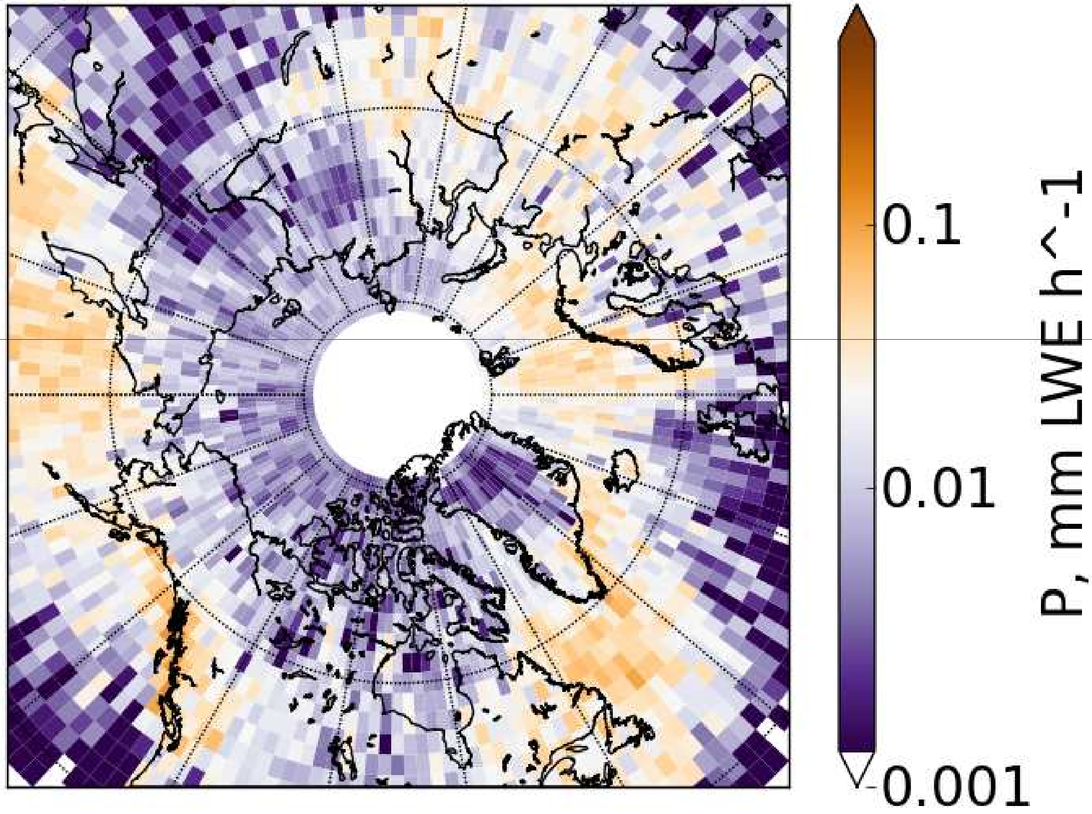


Above surface, size distribution parameters agree well with aircraft observations.



Mapping Arctic Snowfall Intensity

Mean Snowfall Rate (DJF 2006-07)



Accumulations vs. Surface Observations

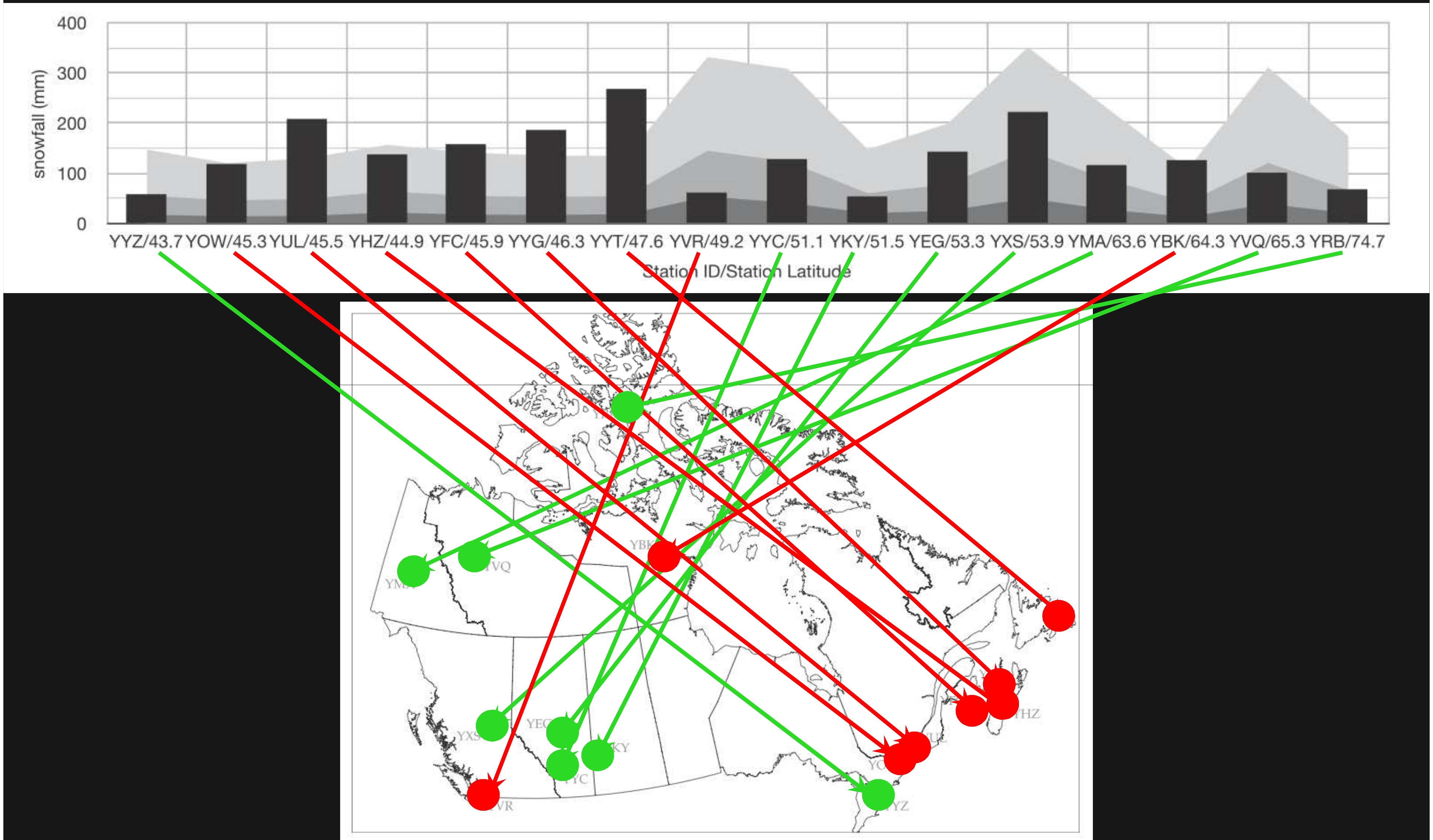
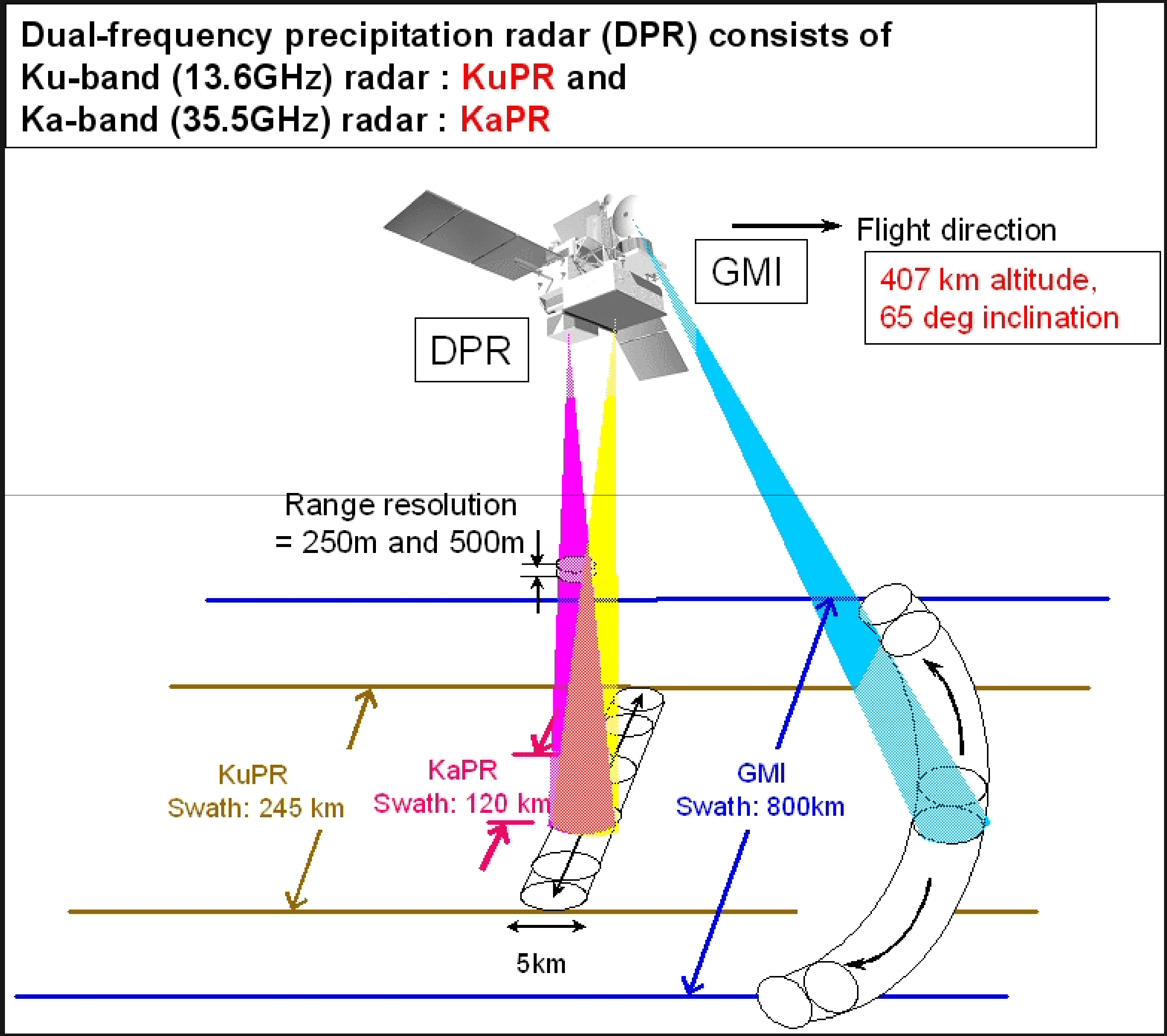


FIG. 13. Map of Canada showing locations of surface stations referenced in section 4g and its associated figures.

Conclusions

- Space-borne W-band radars provide valuable information about high-latitude precipitation.
- Snowflake size, shape, density, and projected area must be constrained using ground-based observations and remaining uncertainties should be accounted for and reported.
- CloudSat operational snowfall product 2C-SNOW-PROFILE will be available soon.
- Exciting advances on the way ...

Global Precipitation Measurement (GPM)



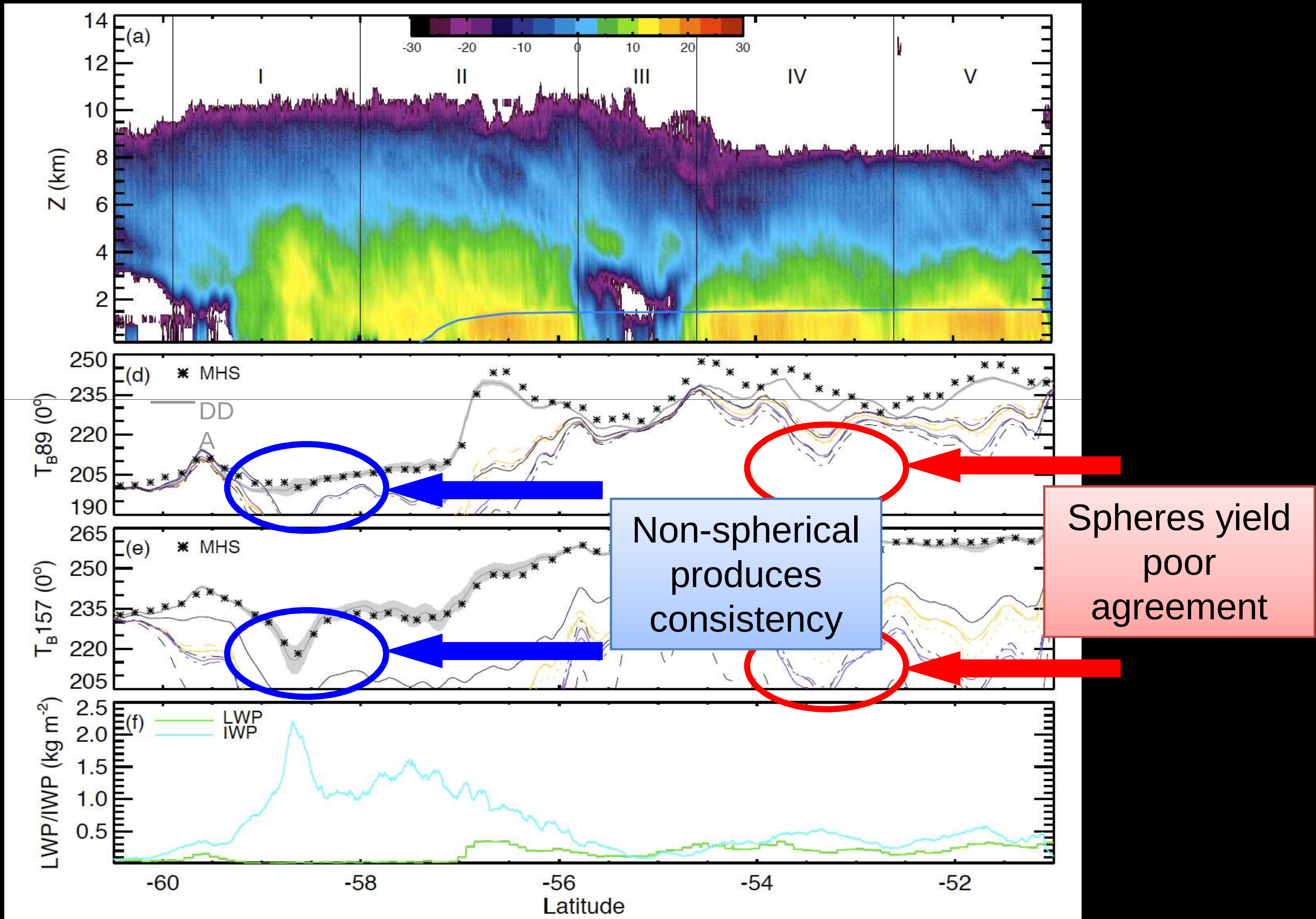
GPM - Courtesy of NASA GSFC

Active: Dual-frequency (Ka/Ku) Precipitation Radar (DPR) 12/17 dBZ MDS

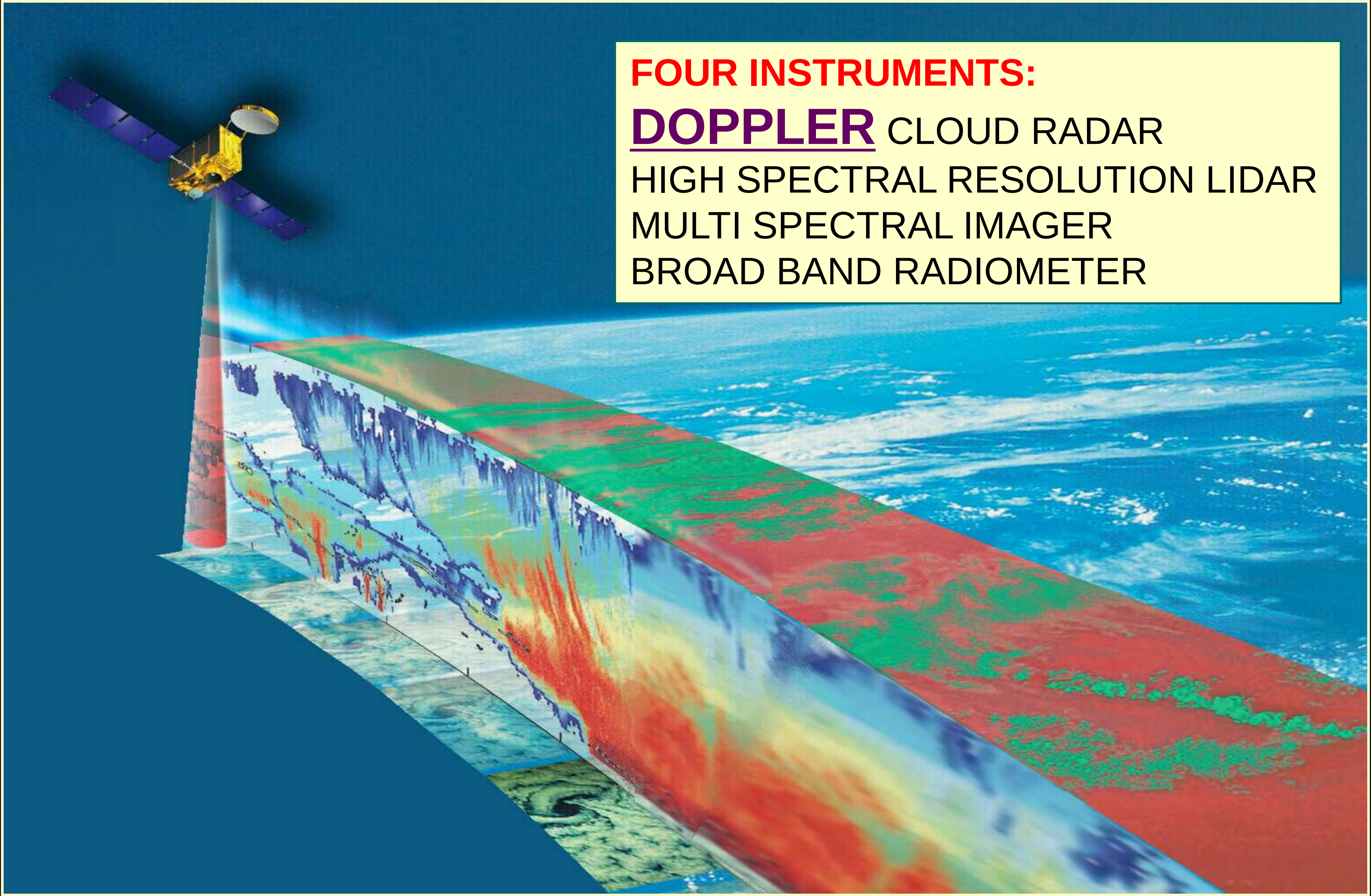
&

Passive: Multi-frequency GPM Microwave Imager (GMI): 13 channels (10-183 GHz)

Complementary Information

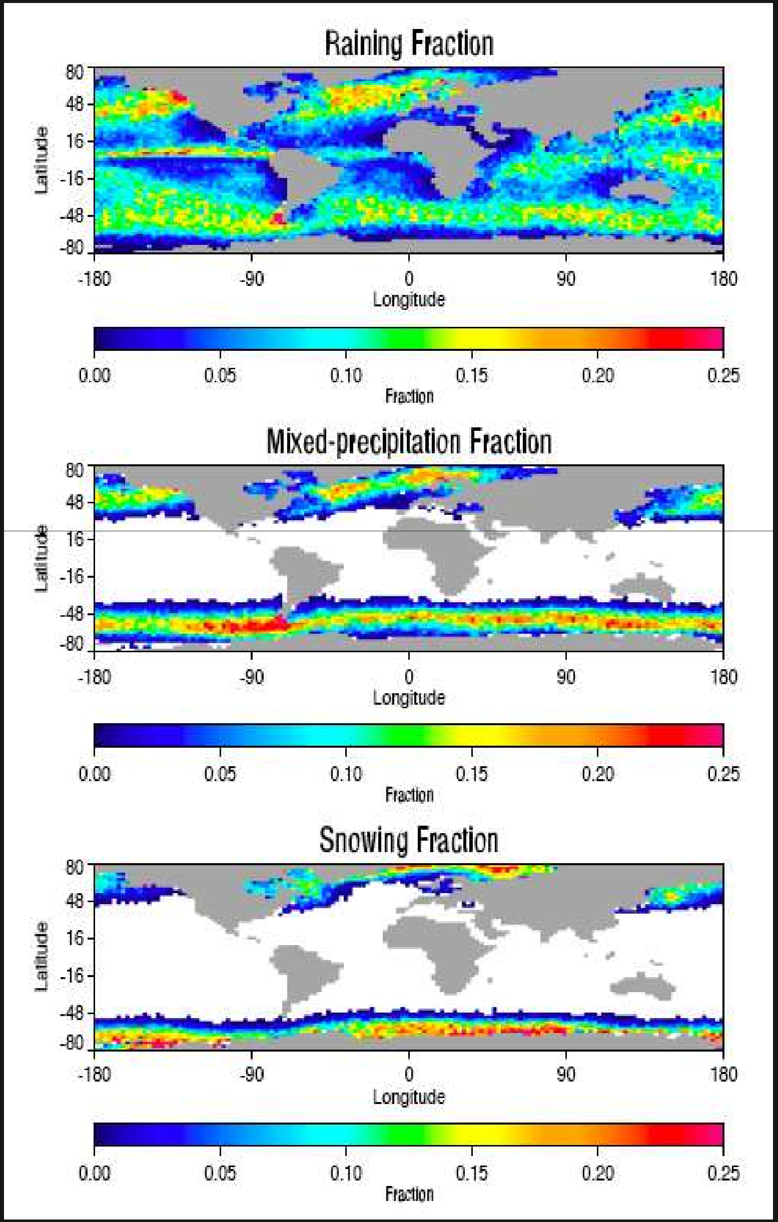


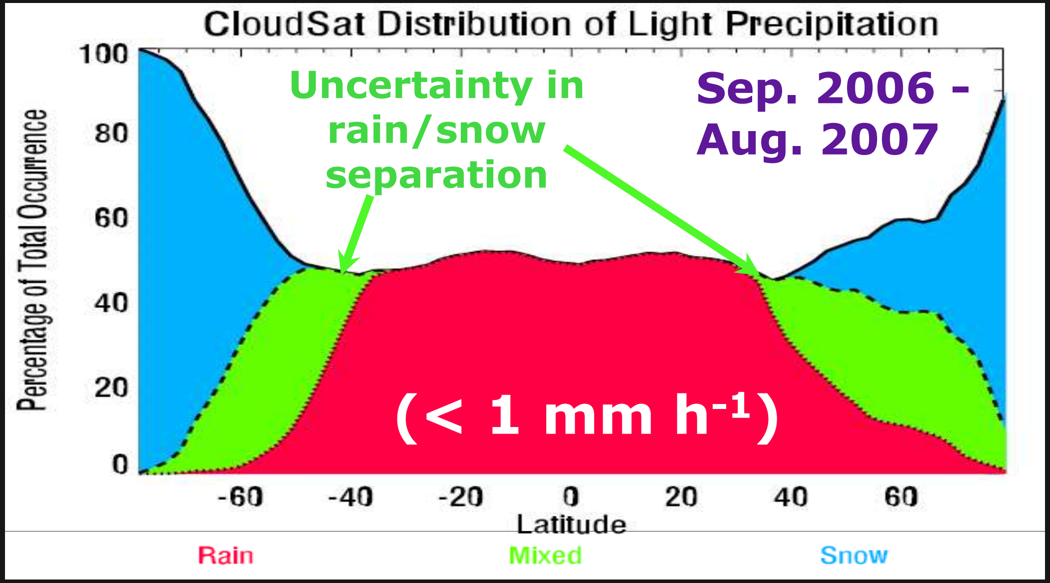
EarthCARE

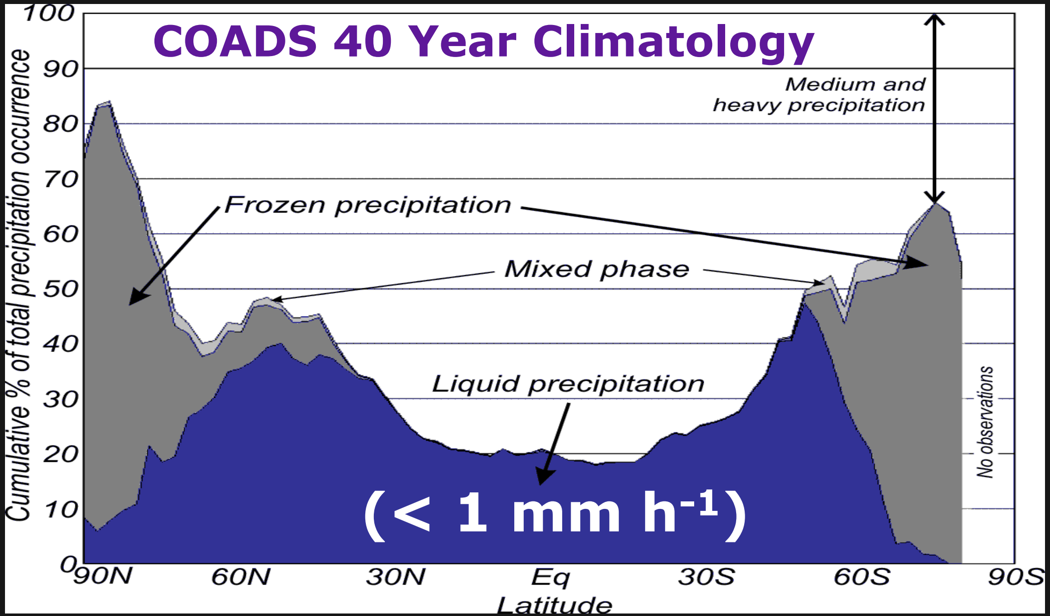

FOUR INSTRUMENTS:
DOPPLER CLOUD RADAR
HIGH SPECTRAL RESOLUTION LIDAR
MULTI SPECTRAL IMAGER
BROAD BAND RADIOMETER

Backup Slides

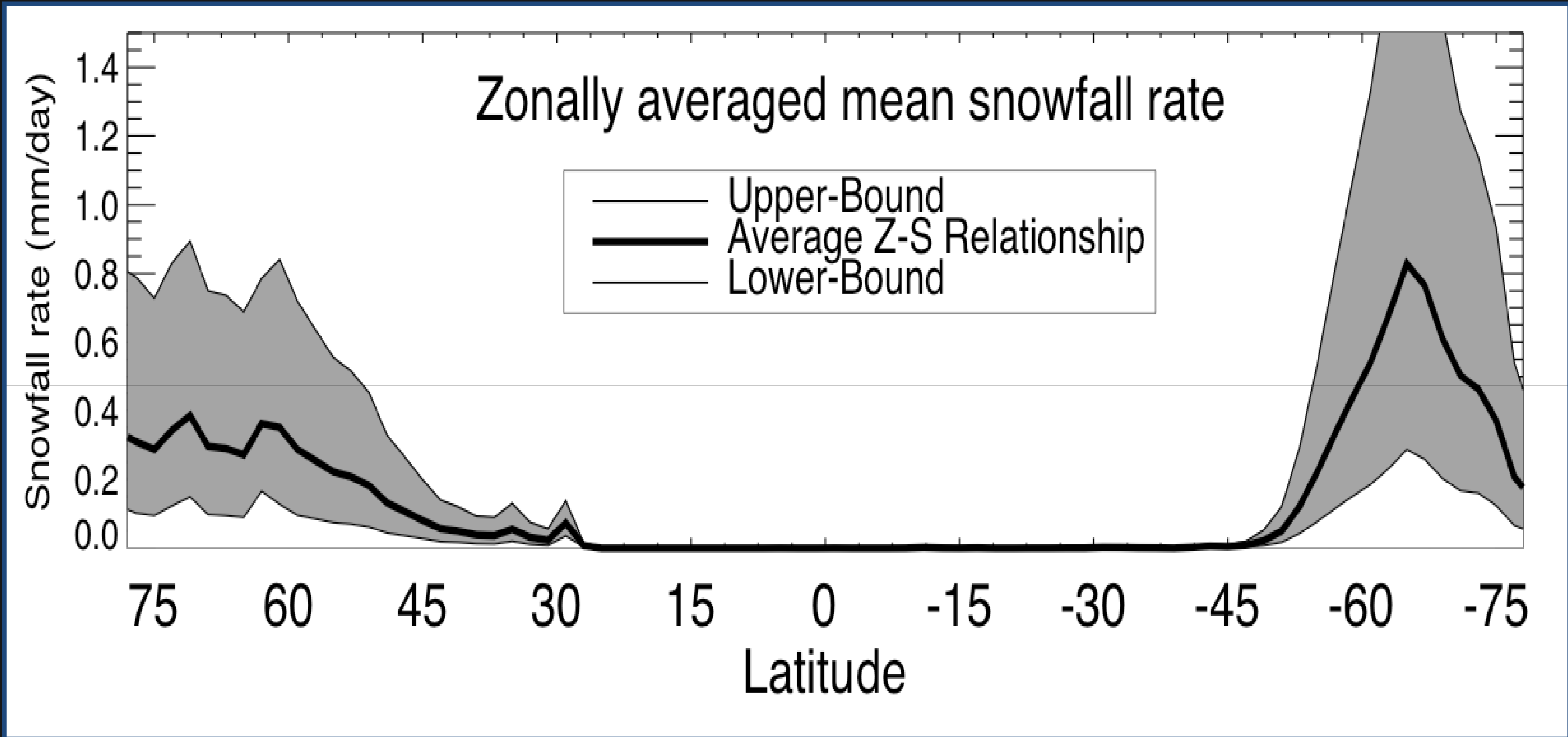
Global Snowfall Occurrence







Zonal Accumulations



Hiley et al. (2011)

CloudSat Data Products

Product	Resolution	Accuracy	Description
Standard Products			
Cloud Mask	240 m	N/A	Cloud geometric distribution
Cloud Classification	N/A	N/A	Cloud type identification
Cloud IWC	240 m	30-50 %	Vertical profile of cloud IWC
Cloud LWC	240 m	30-50 %	Vertical profile of cloud LWC
Radiative Fluxes	240 m	10 Wm^{-2}	Broadband radiative fluxes
Heating Rates	240 m	1 K d^{-1}	Broadband heating rates
Experimental Products			
Precipitation Occurrence	**Surface**	**N/A**	**Identification of liquid and solid precipitation occurrence**
Path-integrated Attenuation	Column	TBD	Surface return-based estimate of radar attenuation
Radar-lidar Combined Products	240 m	TBD	CPR+CALIOP+MODIS versions of all standard products
Rainfall Rate	**240 m**	**TBD**	**Rainrate in light precipitation**
Snowfall Rate	**240 m**	**TBD**	**Rate of falling snow**

C3VP Scientific Goals

- Funded by CSA, this project will undertake a thorough and careful evaluation of the CloudSat products
- Their applicability to the Canadian climate will be emphasized.
- The program will focus on stratiform **cold-season** cloud systems. These are frequently mixed phase in nature and occur throughout Canada much of the year. The widespread and slowly changing nature of these systems are particularly well suited to validation studies.

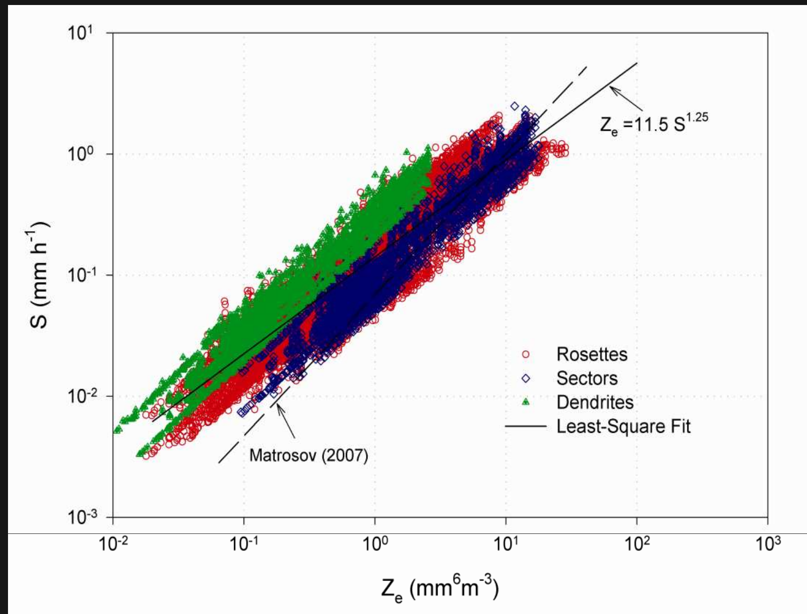
C3VP Instrumentation

- **Ground-based:**
  - Alaska W-band polarimetric radar
  - X-band radar
  - Wind profiler
  - Precipitation Occurrence Sensor System (POSS)
  - Hot plates
  - ALIAS lidar
  - Microwave radiometer
  - McGill University video disdrometer
  - Penn. State Spectrometer
  - Ceilometer
  - Visibility meter
  - Meteorological measurements
  - Radiation flux measurements
- **Aircraft (NRC Convair-580):**
  - AERIAL cloud lidar
  - PMS LWC probe
  - Nevzorov LWC/TWC hot-wire
  - Counterflow Virtual Impactor for TWC/IWC
  - CSU Ice nucleus counter
  - Small ice detector
  - W/X-band radar
  - 2 PMS FSSP probes (2-47 µm)
  - PMS 2D2-C probe (25-800 µm)
  - PMS 2DC-grey probe (15-960 µm)
  - PMS 2D-P probe (200-6400 µm)
  - SPEC 2D-S (10-1280 µm)
  - PMS PCASP aerosol spectrum probe
  - Nevzorov extinction probe
  - Rosemount Ice detector
  - LICOR water vapour measurement system

Possible Additions (CSU Ice nucleus counter, Small ice detector, W/X-band radar)

From Z to S

- **Needed for relating Z to S:**
  - mass, shape, size distribution, orientation(?), terminal velocity
- **e.g. *ad hoc* (for now):**
  - six idealized shapes (Liu, 2004)
  - size distributions from field obs.
    - Lo and Passarelli, 1982
    - Braham, 1990
  - random orientation
  - DDA simulations



Impacts of Crystal Habit