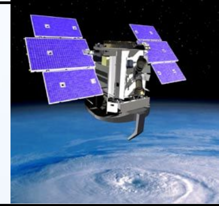


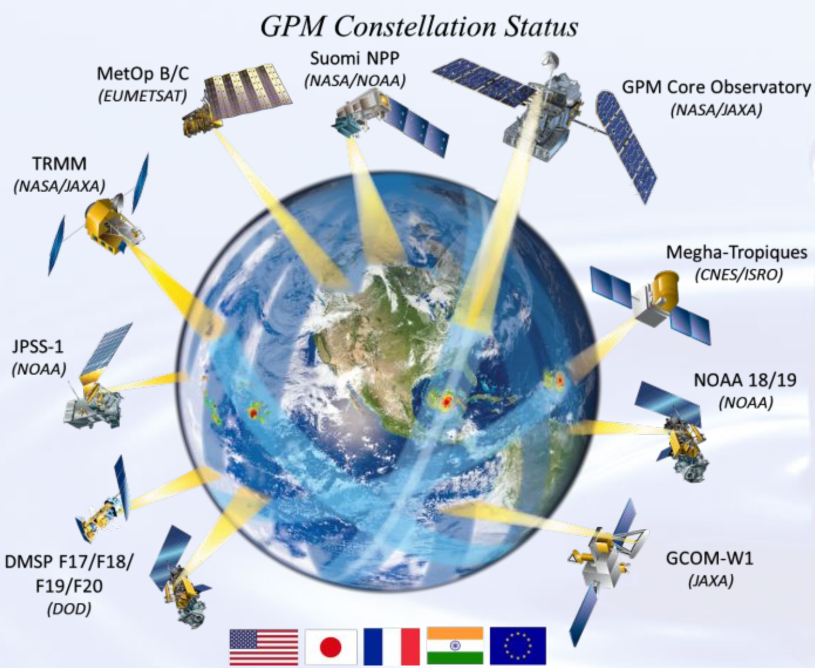
Contributions from CloudSat to Understanding Global Precipitation

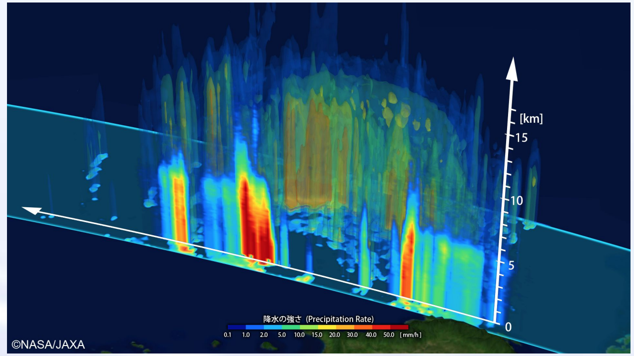
Matthew Lebsock
Jet Propulsion Laboratory
California Institute of Technology

Contributions from:

Tristan L'Ecuyer, John Haynes, Norm Wood, Anita Rapp

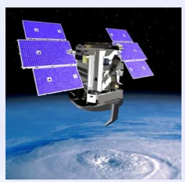
The Precipitation Observing System





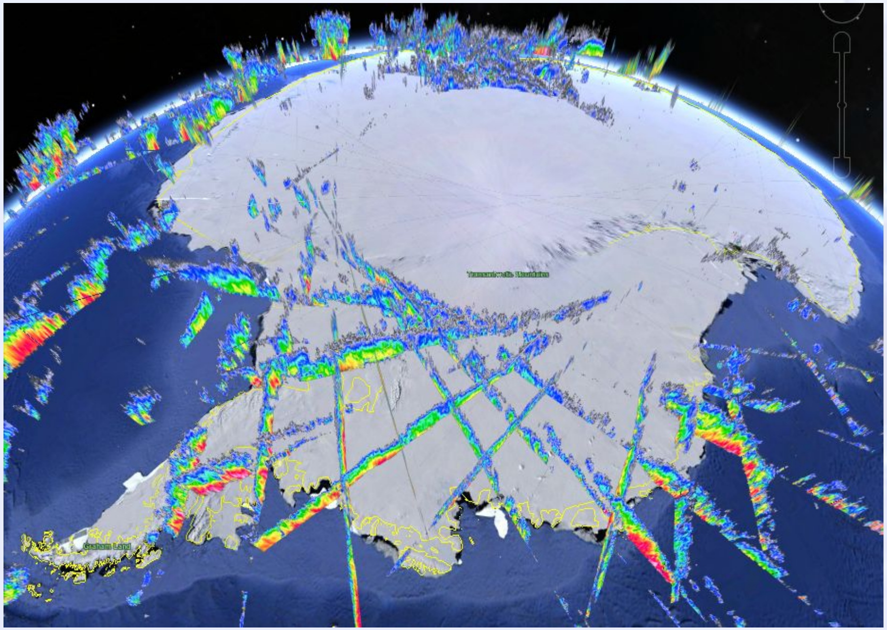
- GPM/TRMM Radars: high quality precipitation profiles
- Radiometers: high-frequency sampling and climate record

- CloudSat complements the precipitation observing system:
  1. Precise detection
  2. Light shallow rainfall
  3. Snowfall

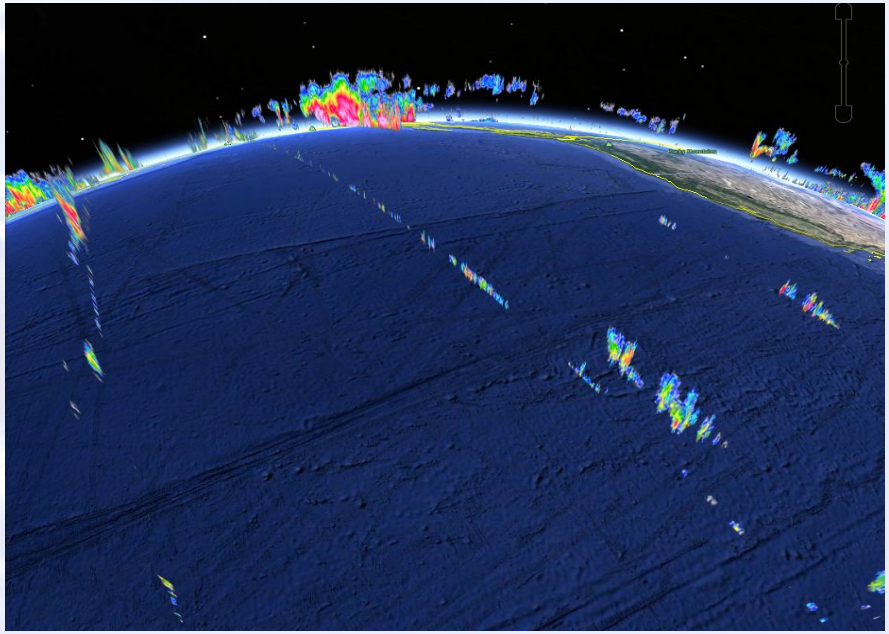


Examples

Snowfall



Light Rain



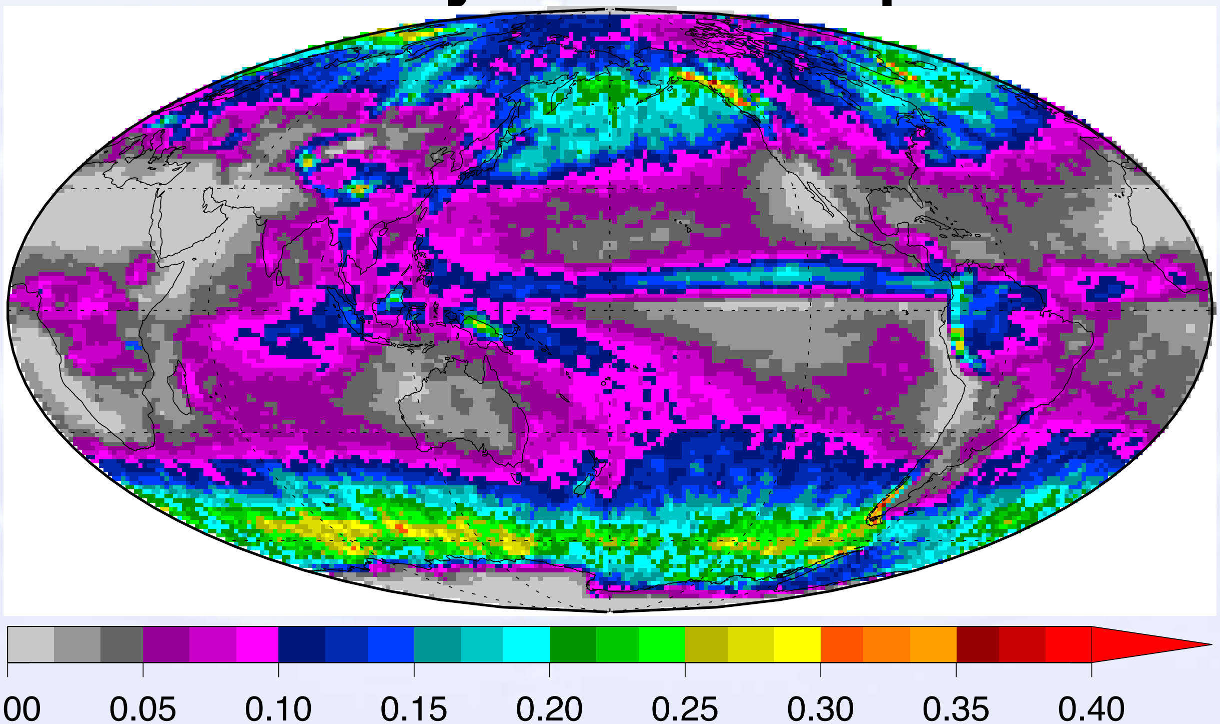
- CloudSat provides precise detection and quantification of snowfall and light rain.

Courtesy: Chip Trepte

Precipitation Detection

How Often Do We Get Precipitation?

Probability of Precipitation



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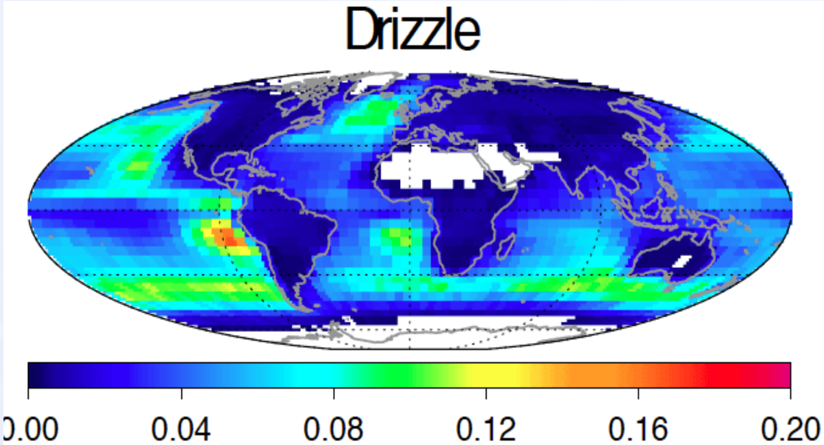
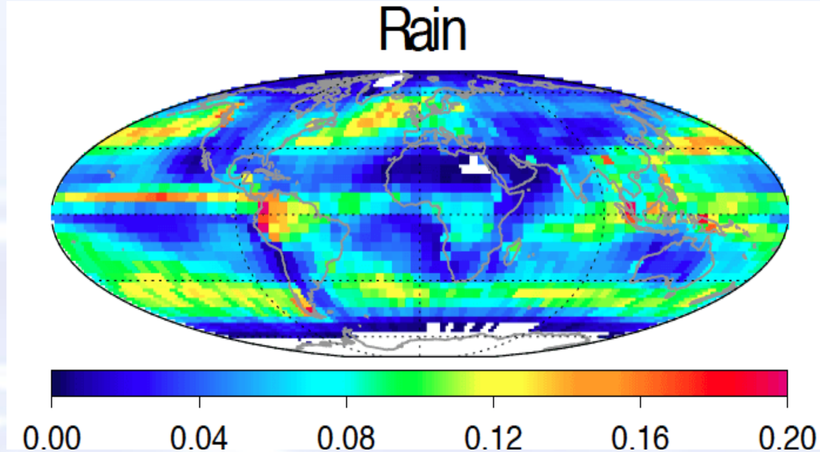
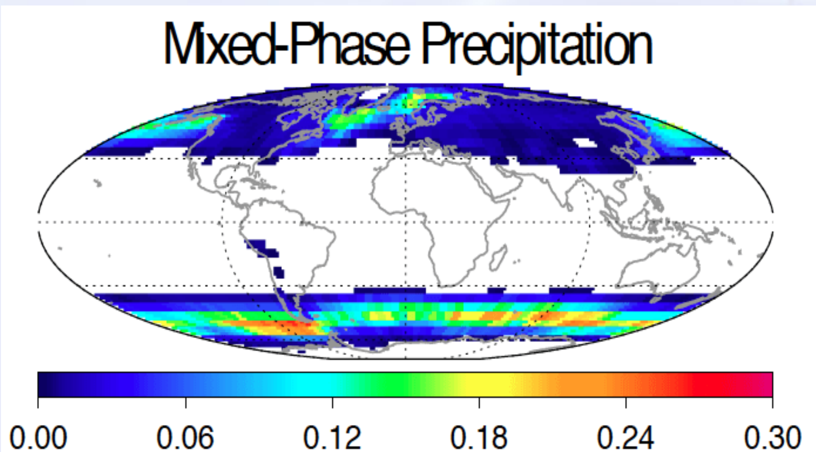
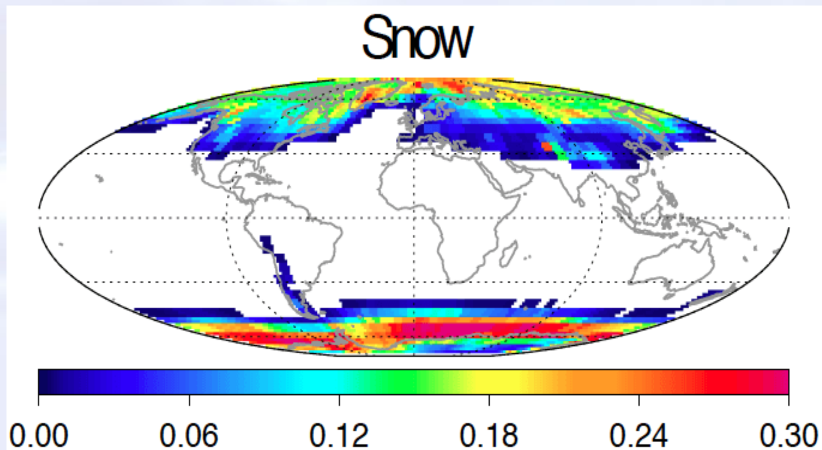
How Often Does it Rain, Snow, or Drizzle Around the World?



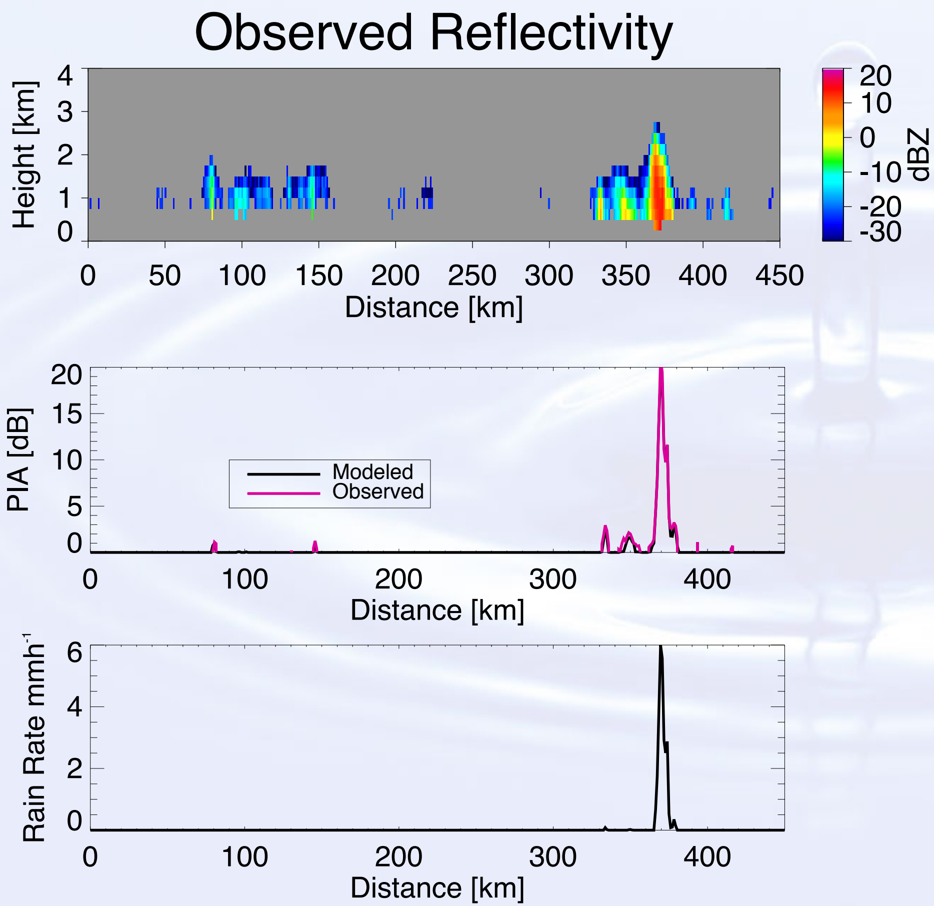






Light Rain

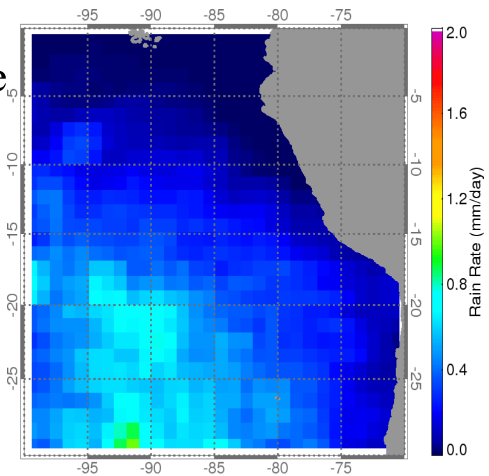
Rainfall Retrieval



- Variational Approach
- Path Integrated Attenuation Constraint
- Multiple Scattering Model
- Predicts Uncertainties
- Sensitive @ 720m above sea level

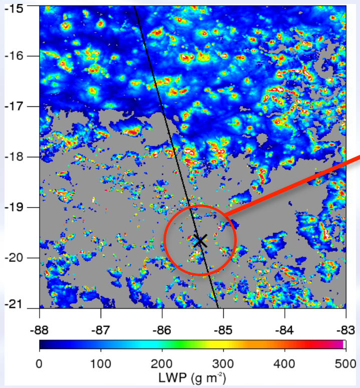
Rainfall Validation

Daily Average Precipitation (2006-2009)

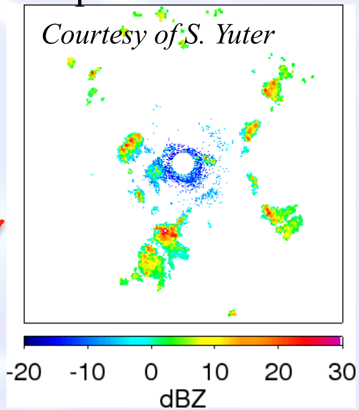


	Precipitation (mm/day)
CloudSat	0.23
EPIC In Situ *(Comstock et al. 2004)*	0.20
VOCALS C-Band In-Situ	0.18

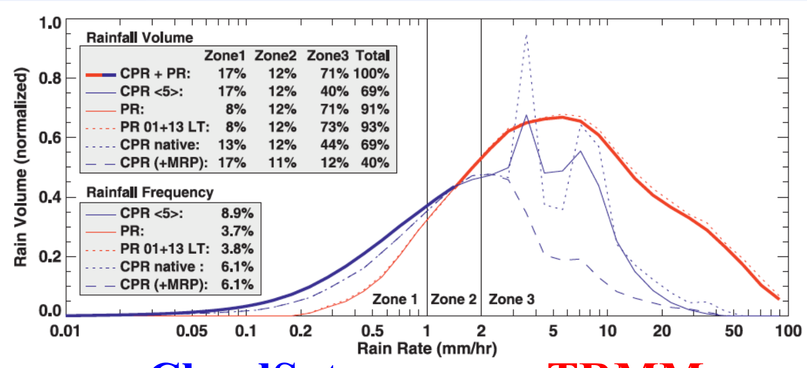
MODIS LWP – 27 Oct 2008 POC



Shipborne C-Band

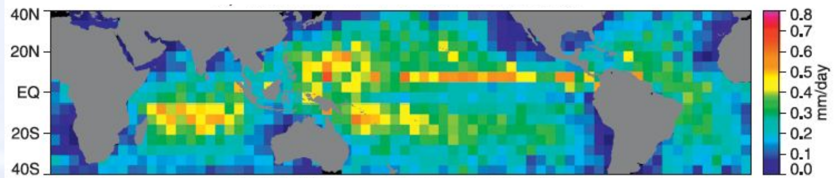


How Much Rain Did CloudSat Add?

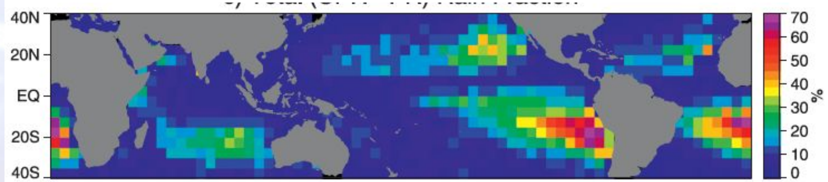


CloudSat **TRMM**

CloudSat Volume



CloudSat Fraction

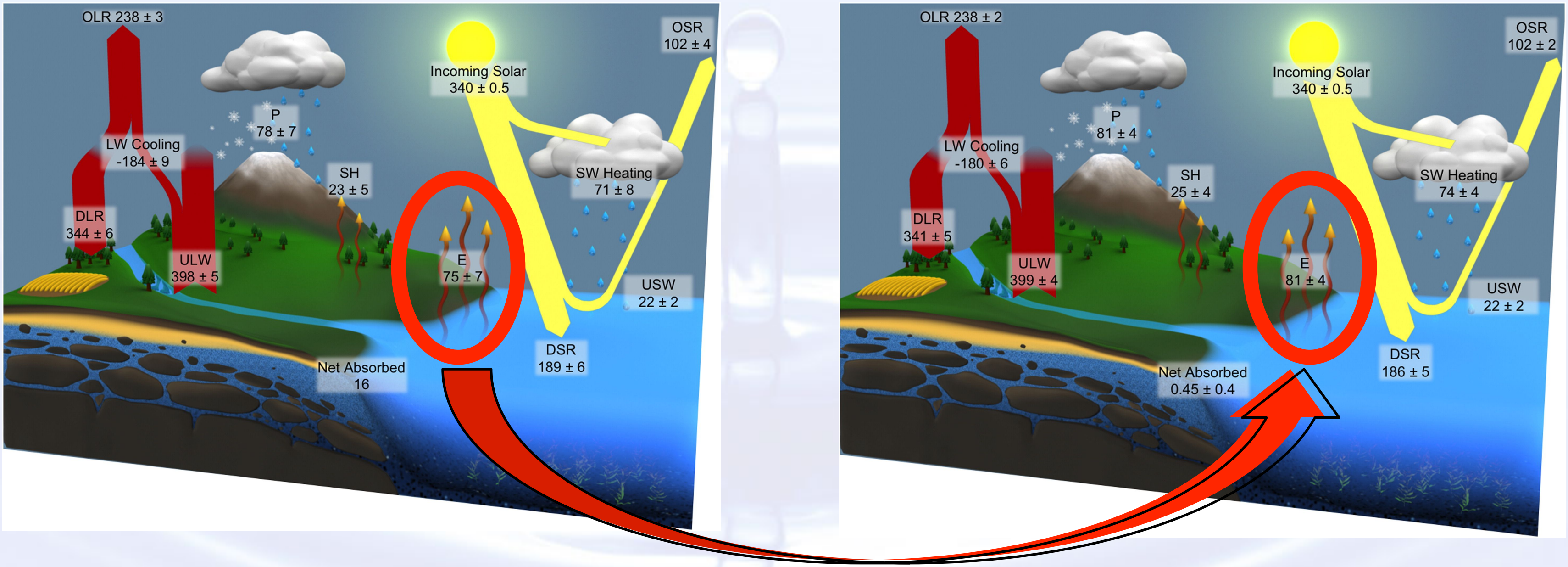


- CloudSat adds: 0.15-0.35 mm/day
- CloudSat adds significantly in shallow marine clouds

Berg et al., 2010

How Does Added Precipitation Contribute to Earth's Energy Budget

Before Adjustment / After Adjustment

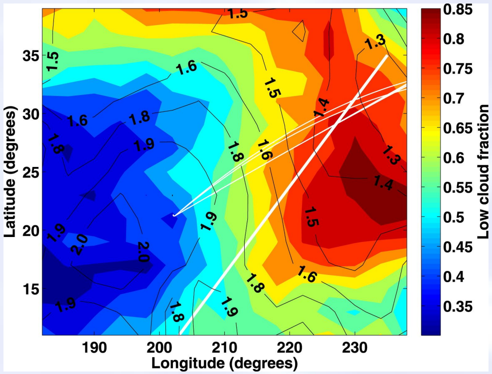


- Increases the surface latent heat flux 5-10 W (6-12%)
- Consistency with recent surface radiation calculations

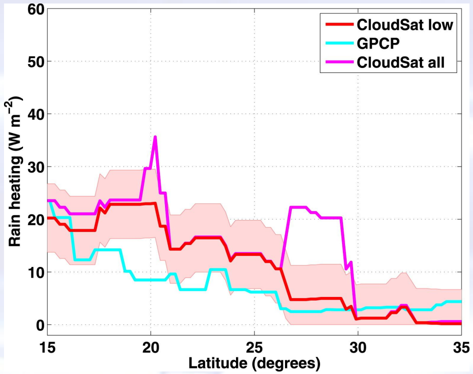
L'Ecuyer et al., 2015

Regional Energy Budgets

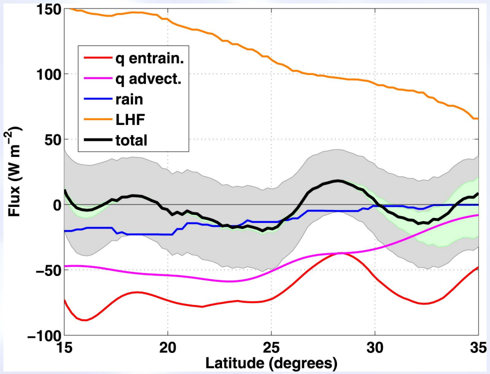
CloudSat used to close the water and energy budgets regionally.



The transition in cloud cover



CloudSat shows more rain than GPCP

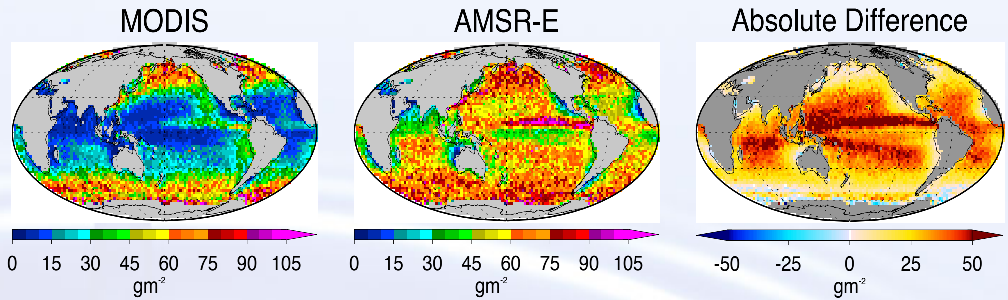


The energy and water budgets were closed.

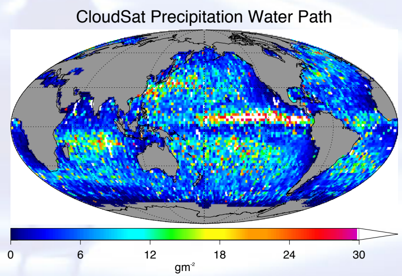
Kalmus et. al, 2014

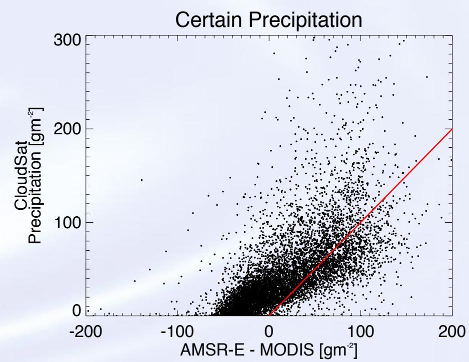
CloudSat Rainfall Explains Bias in Cloud Water

AMSR-E (microwave) cloud water is double the MODIS (solar) cloud water.



AMSR-E misinterprets precipitation as cloud water.

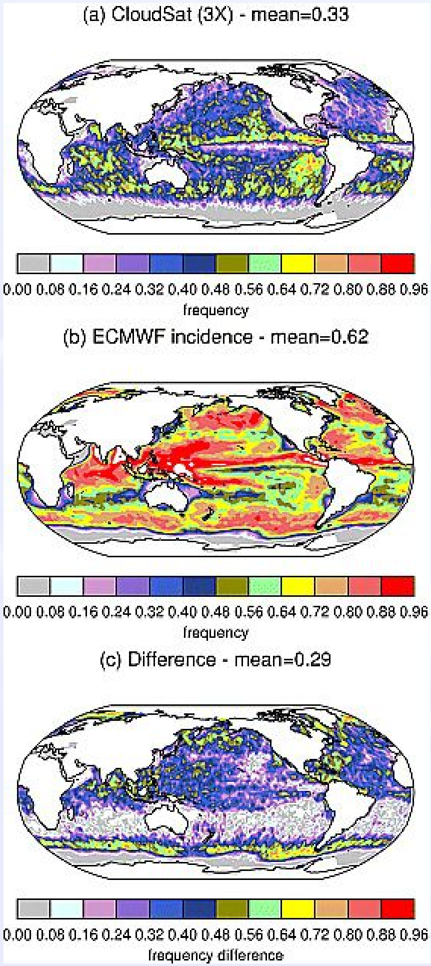


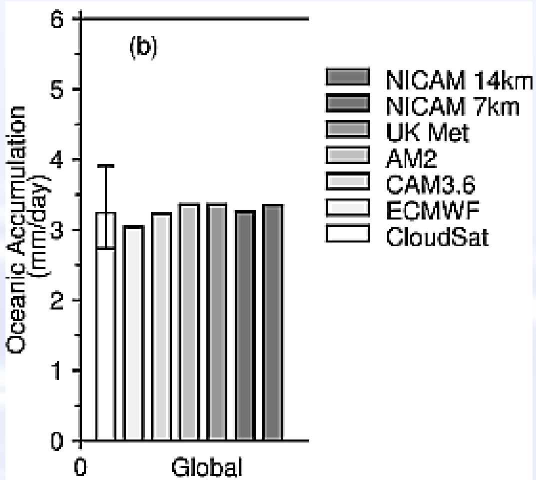


- Microwave cloud water biases explained by precipitation.
- Synergy in multiple sensors (CloudSat, MODIS, AMSR-E)
- Provides uncertainty in climate data records

Lebsock, M. and H. Su (2014)

Model Misrepresent the Character of Precipitation





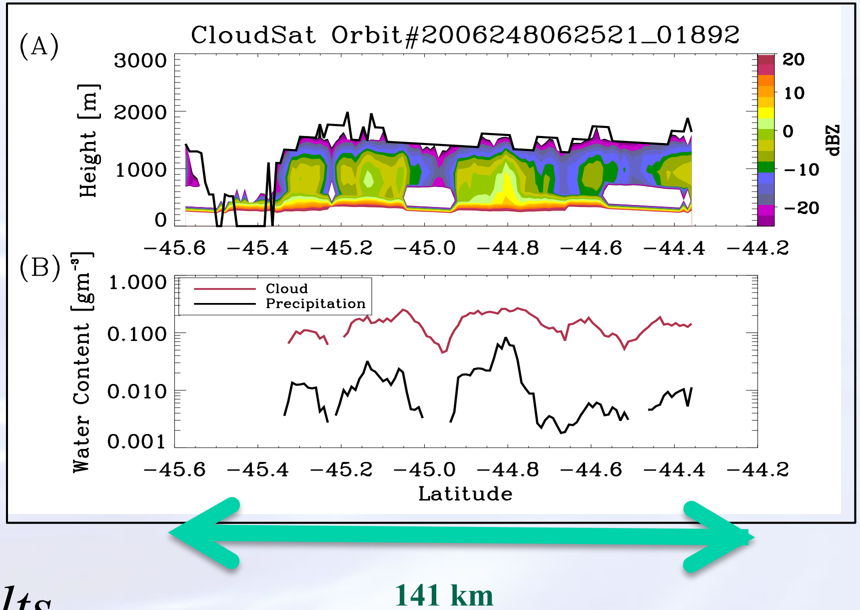
- Models constrained to have correct accumulation.
- Models precipitate too frequently.

Stephens et al., 2010

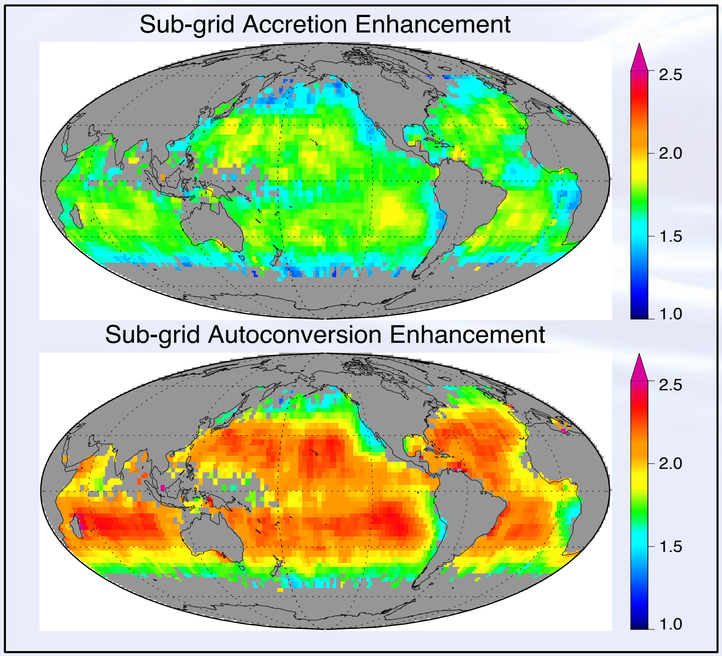
Examining Precipitation Processes in Models

Joint CloudSat and MODIS Analysis

- CloudSat: sensitive to precipitation
- MODIS: sensitive to cloud



Model Bias



Results

- Quantified sub-grid scale **correlations** between cloud & precipitation
- Distinct **regional** patterns
- Correlations missing in model physics
- Identified specific model **processes**

Lebsock et al., (2013)

Snowfall

Snowfall Intensity Retrieval

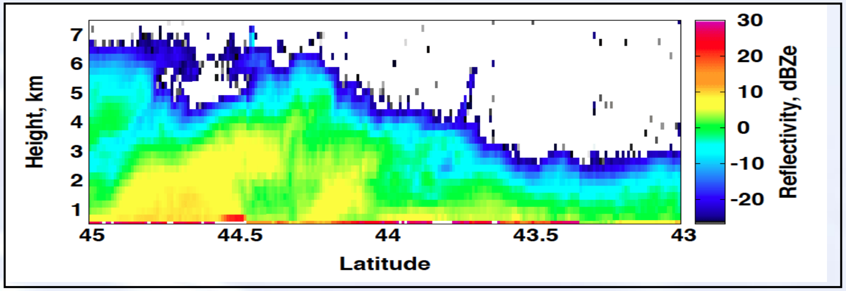
Highlights

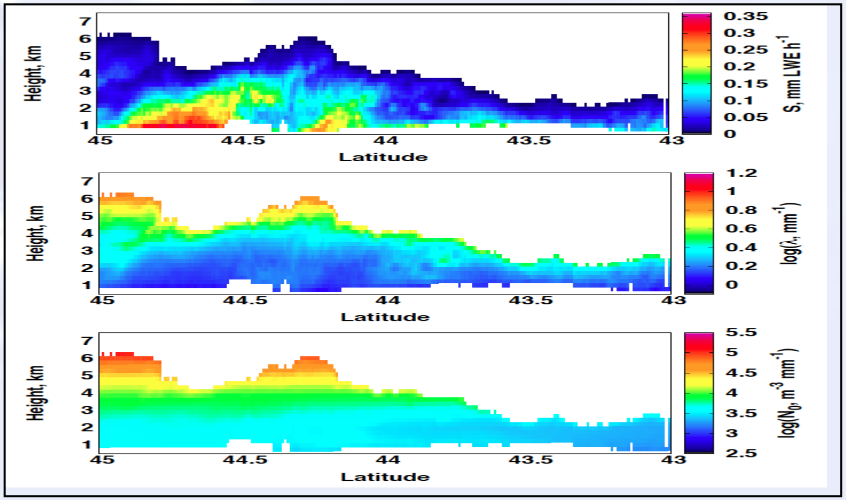
- Variational Approach
  - Allows prior information
  - Predicts uncertainties
- Retrieve intercept and slope of exponential particle size distribution

$$N(D) = N_0 e^{-\Lambda D}$$

- Scattering properties, PSD, and density based on field observations

Example





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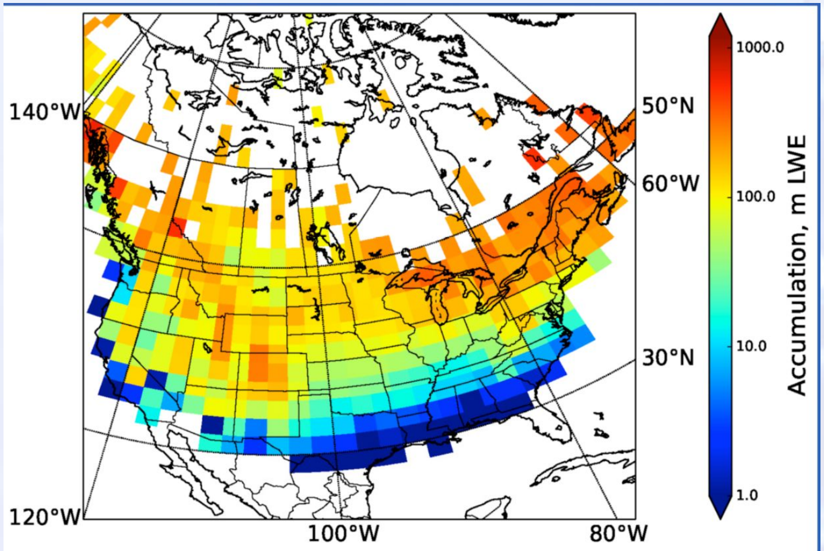
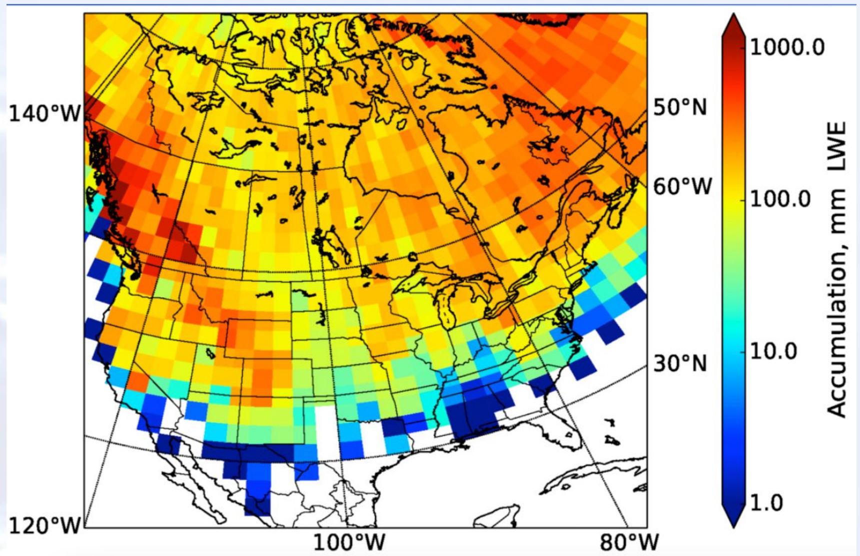
CloudSat Snowfall Validation

GHCN



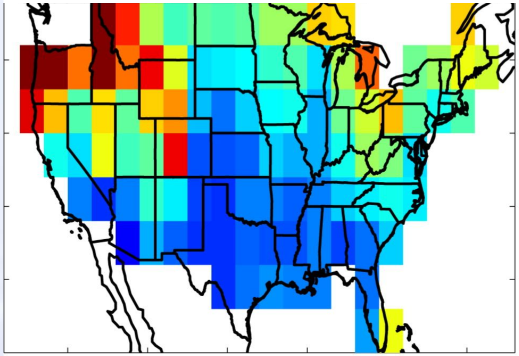
CloudSat



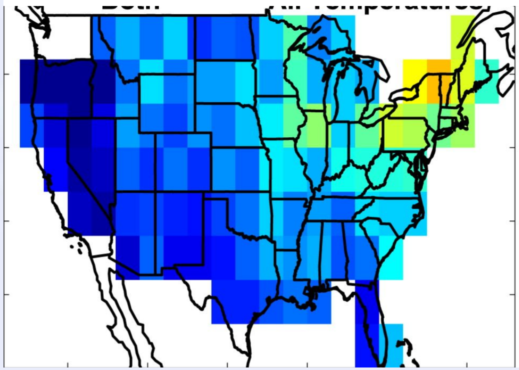
- Generally good agreement
- CloudSat has more snowfall in mountain areas

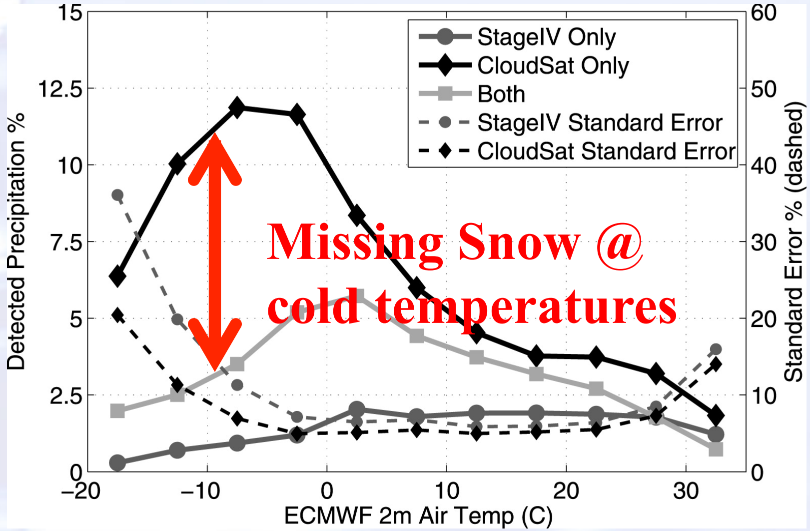
Detection Errors in in Ground Based Radar

CloudSat



Ground Radar

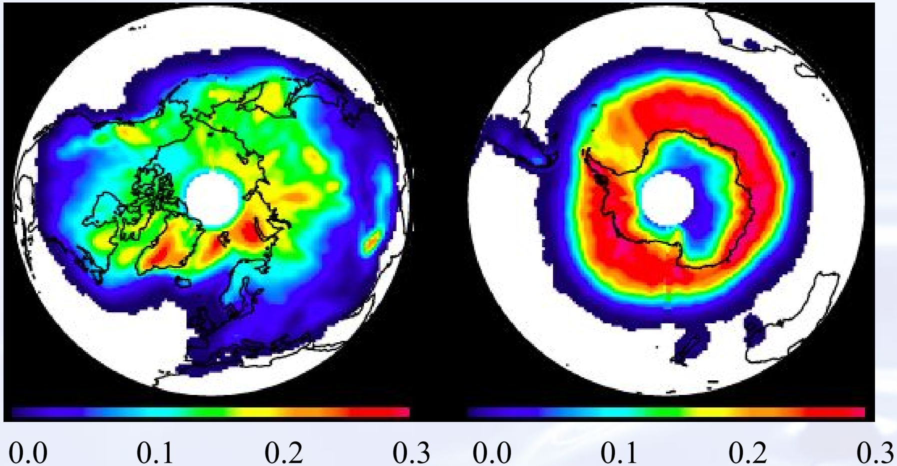




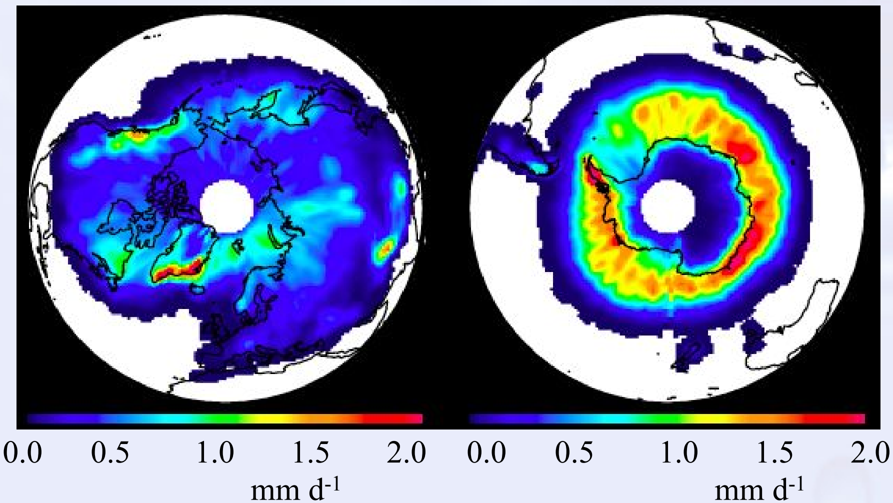
- Ground based radar frequently miss detections of snowfall

Smalley M. et al. (2014)

How much Snow?



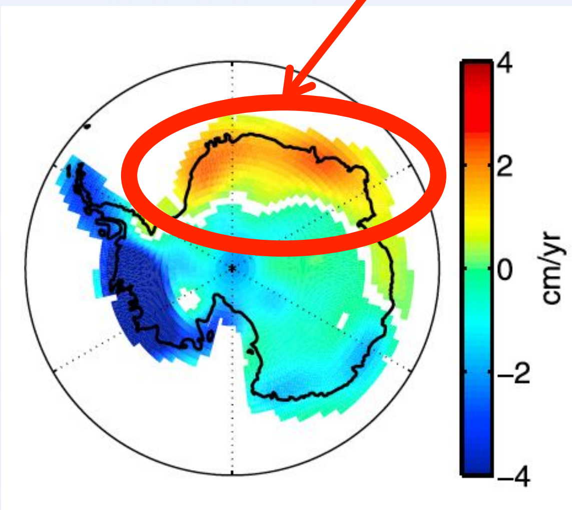
Global Mean = 6.8%

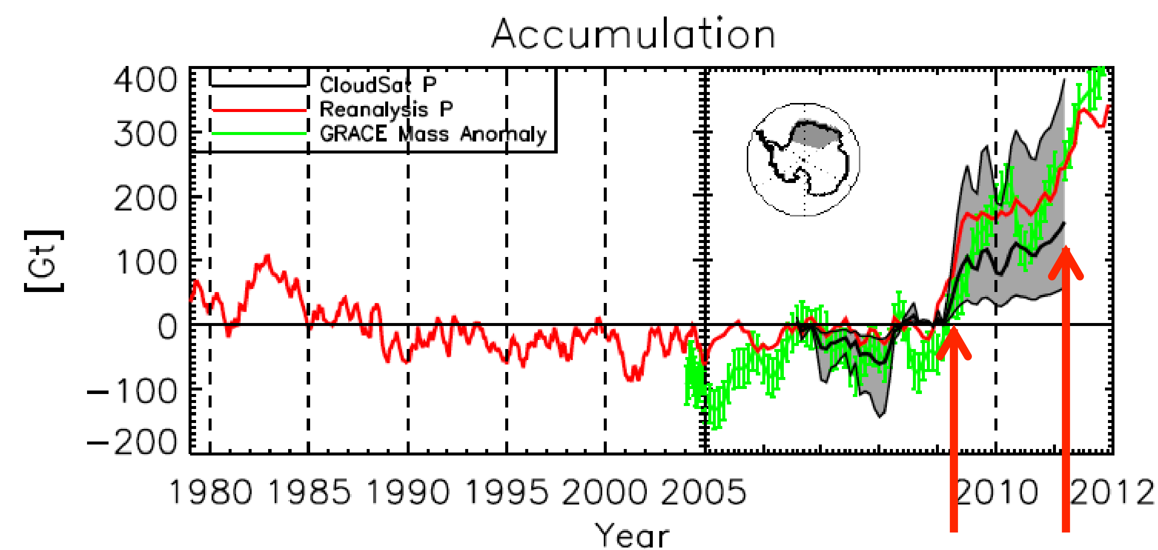


Global Mean = 62 mm yr^{-1}
(By comparison it rains ~ 1000 mm yr^{-1})

Antarctic ice mass gain explained by anomalous snowfall events

Mass trend (2004-2011) from GRACE ~0.32 mm/year sea level rise.



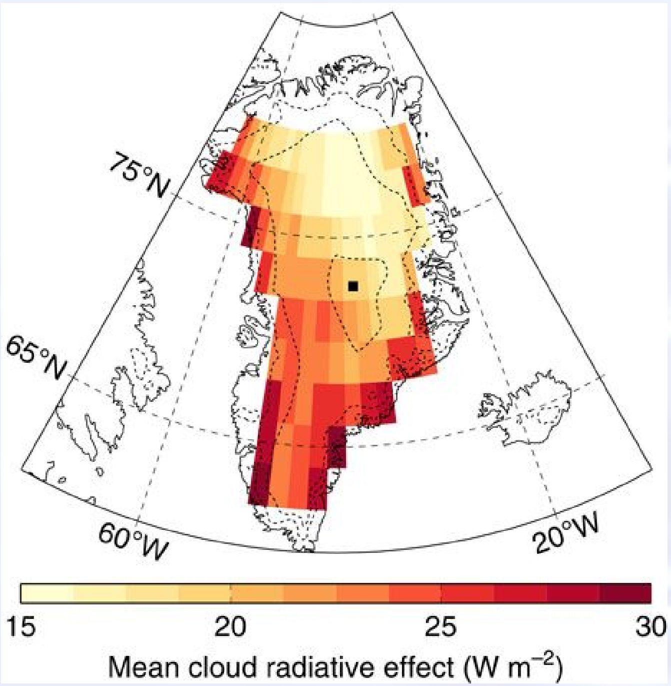


Storm Events

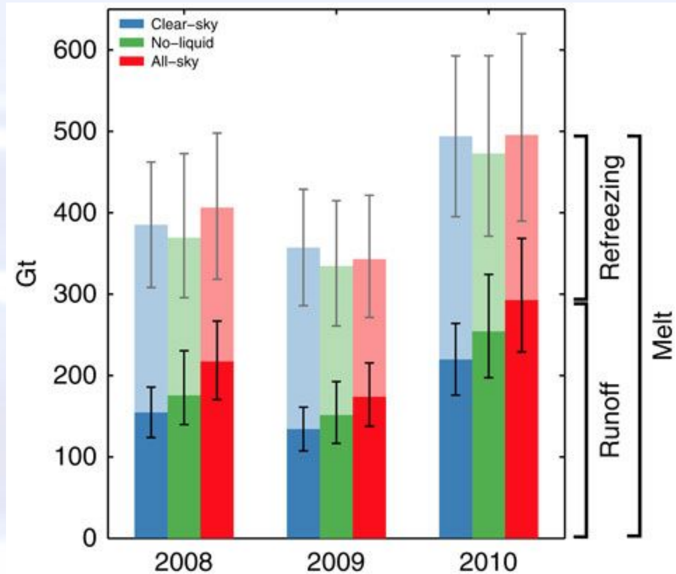
- 5 warm and moist storms account for unprecedented mass gain.
- Synergy in multiple sensors (CloudSat, GRACE) and weather reanalysis.

Boening, C. et al., (2016)

Clouds enhance Greenland ice sheet meltwater runoff



The longwave warming effect of clouds dominates the shortwave cooling effect.



A snowpack model shows that the primary effect of clouds is not to increase the total amount of melt. Instead clouds prevent meltwater from refreezing leading to increased runoff.

Van Tricht, K. et al., 2016.

CLOUDSAT

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Model Biases in Antarctic Snowfall

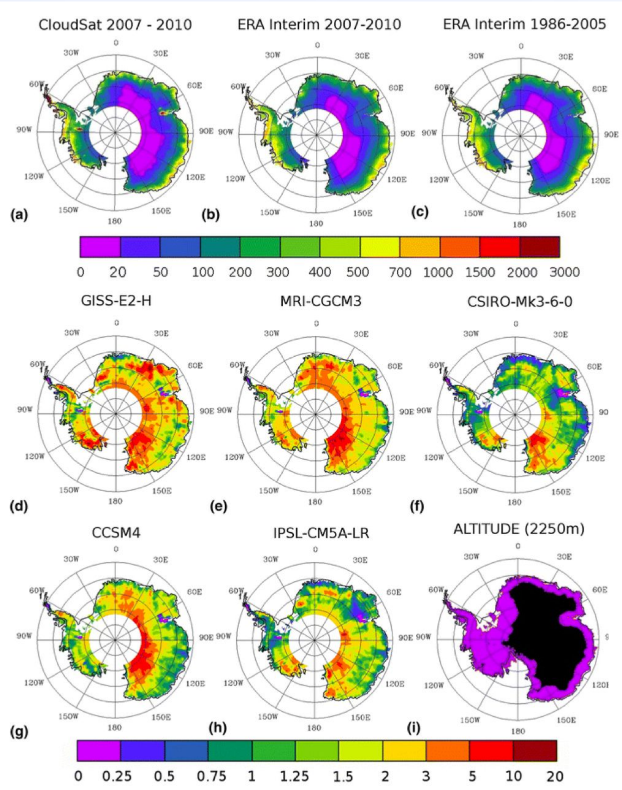
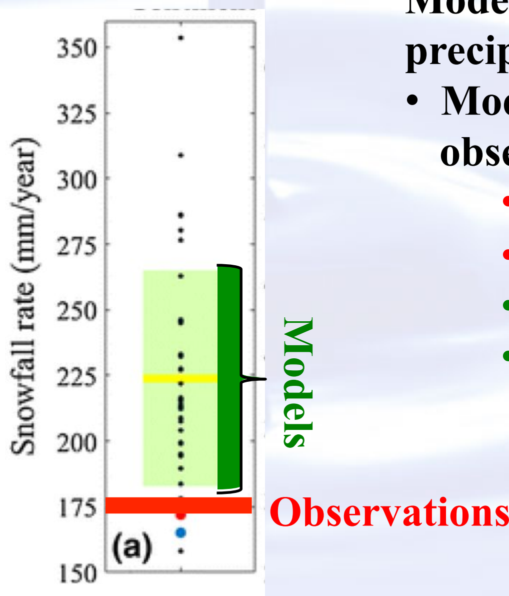


Fig. 2

Mean annual snowfall rate (mm water equivalent / year) north of 82°S observed with CloudSat during the period 2007–2010 (**a**), and simulated by ERA Interim during the periods 2007–2010 (**b**) and 1986–2005 (**c**). Ratio of the snowfall rate simulated by five CMIP5 models during the period 1986–2005 in the Historical scenario over the snowfall rate observed with CloudSat (**d**, **e**, **f**, **g**, **h**). The regions with surface elevation higher than 2250 m (*black*) and lower than 2250 m (*purple*) are shown on the last map (**i**)



Climate Models overestimate Antarctic snowfall

- **Many by more than 100%**

Models predict increases in Antarctic precipitation and sea level rise

- **Models that agree with CloudSat observations predict larger increases**
  - $\Delta snow_{all}$ = 5.5-24.5%
  - Δsea_level_{all} = 19-71 mm
  - $\Delta snow_{good}$ = 7.4-29.3%
  - Δsea_level_{good} = 25-85 mm

Palerme, C. et al., (2016)