Remote sensing of ice clouds

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Outline

1. Introduction:

    ice clouds and the climate system

2. Observing **techniques**:

    VIS-NIR, IR, mm/sub-mm, active

3. Observing in the **mm/sub-mm**

    principles, measurements, inversions

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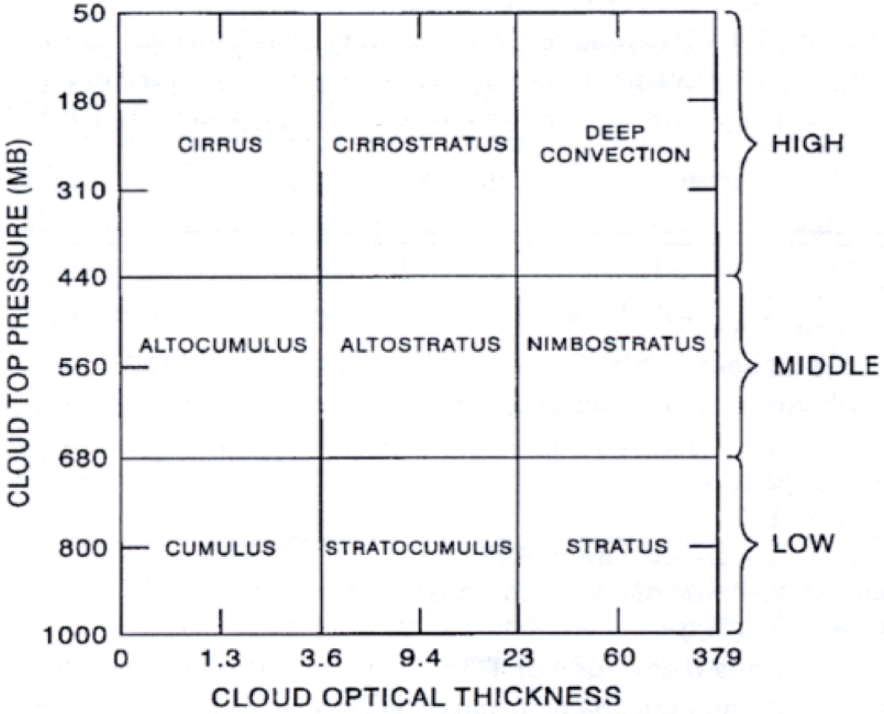
- **Clouds** are the major source of uncertainty in understanding and predicting Earth's climate variability and change.

Randall et al., (2007), Climate models and their evaluation, Climate Change 2007: The Physical Sciences Basis, Chap.8.



ISCCP cloud classification

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- **Ice clouds (IC)**: made of ice particles (cirrus, cirrocumulus and cirrostratus) and without being mainly composed of ice (stratus, nimbostratus, altocumulus, cumulonimbus).

cirrus   cirrostratus   cirrocumulus

from ESTEC 19053/05/NL/AR (2007), Establisment of Mission and Instrument Requirements to Observe Cirrus Clouds at Sub-milimeter Wavelengths.

- ~ 30% of globe is covered by cirrus

8 year (1987-1995) **TOVS Path-B** *(ISCCP)*

	globe	NH midlat.	tropics	SH midlat.
Cirrus amount (%):	27 *(19)*	25 *(20)*	45 *(25)*	22 *(17)*

Courtesy of CIRAMOSA team (2004), EGS presentation

Importance of ice clouds for the **climate system:**

- Major component of the **hydrological cycle** in the upper troposphere.
- Strong impact on atmospheric **radiative exchanges** by reflecting solar radiation but also trapping long-wave radiation and reducing the thermal energy escaping the Earth.
- The **net forcing** depends on the cloud's horizontal extent, vertical position, ice water content and ice microphysical properties, so the characterization of ice clouds is critical for a full description of the climate system.

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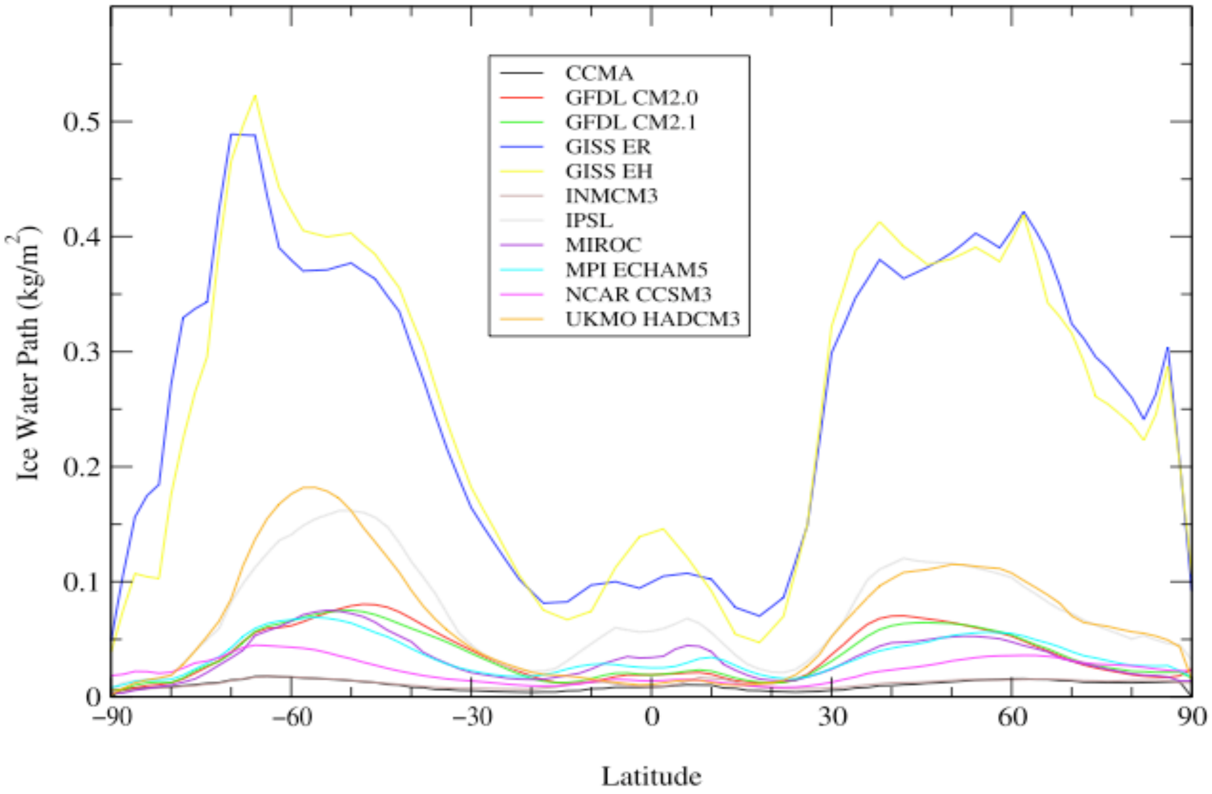
How well represented are ice clouds in current **climate models**?

e.g. climatology of zonal annual mean IWP from GCMs in the IPCC AR4 archive.



Courtesy of John and Soden (2006) Temperature and humidity biases in GCMs and their impact on climate feedbacks

- **Ice clouds observational data** and their correlations with the atmosphere state needed to validate ice cloud properties in climate models and improve climate predictions.

Observing techniques

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- What do we want to **measure** from ice clouds?

  Areal coverage, top and base altitude, top and base temperatures, optical depth, effective particle size and shape, ice water content, size and shape of the cloud cells and their spacing, and so on.

- What are the **difficulties** to measure ice clouds?

  Cloud variability and microphysics are so complicated that no single instrument, single technique, or single platform can measure them all.

Stephens and Kummerow (2007), The Remote Sensing of Clouds and Precipitation from Space: A Review.

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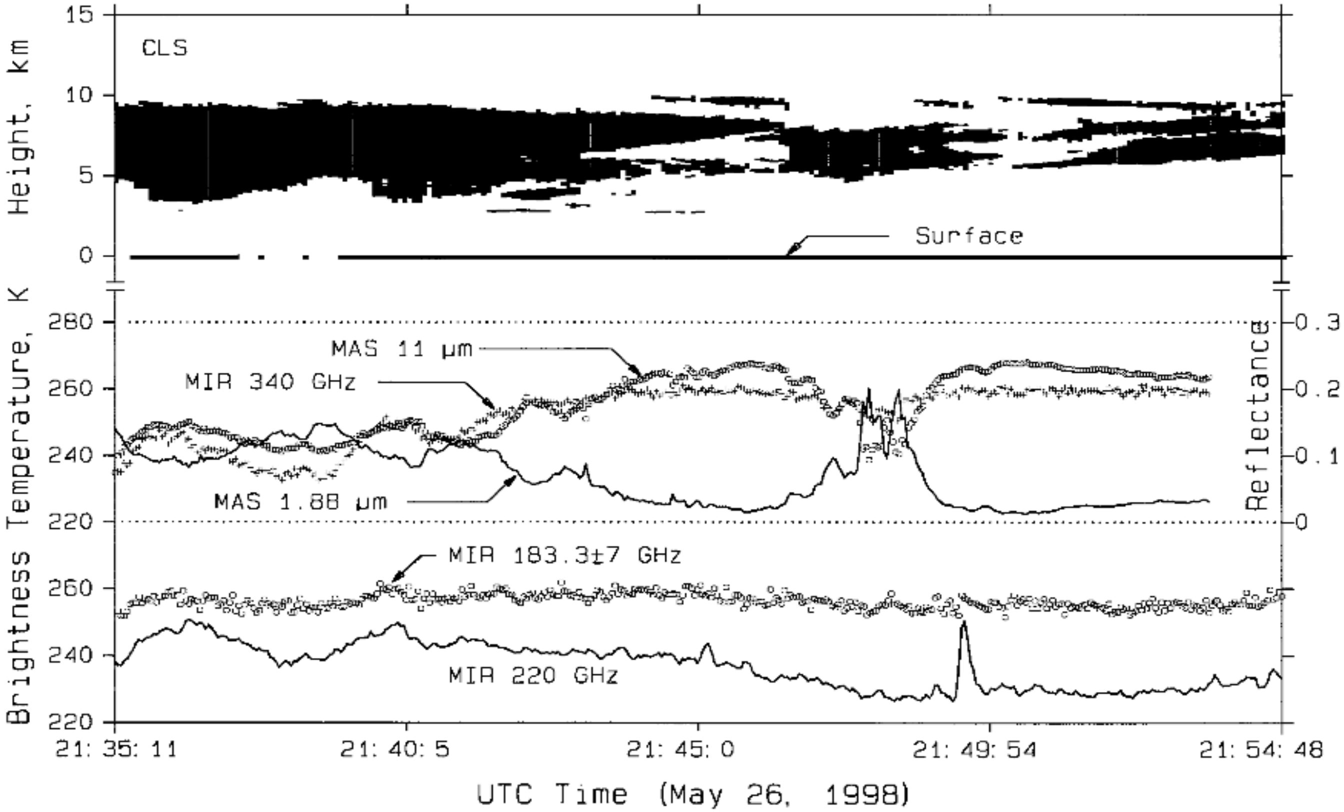
Observing techniques

e.g. simultaneous measurement at near-IR, IR, mm and sub-mm from an aircraft over an ocean area north of Alaska

NASA ER-2 MIR - MAS- CLS FIRE-III Artic Cloud Experiment, May 26 1998



Courtesy of Wang et al. (2001) Observations and retrievals of cirrus cloud parameters using multichannel millimeter-wave radiometric measurements

Observing techniques: **VIS** and **NIR**

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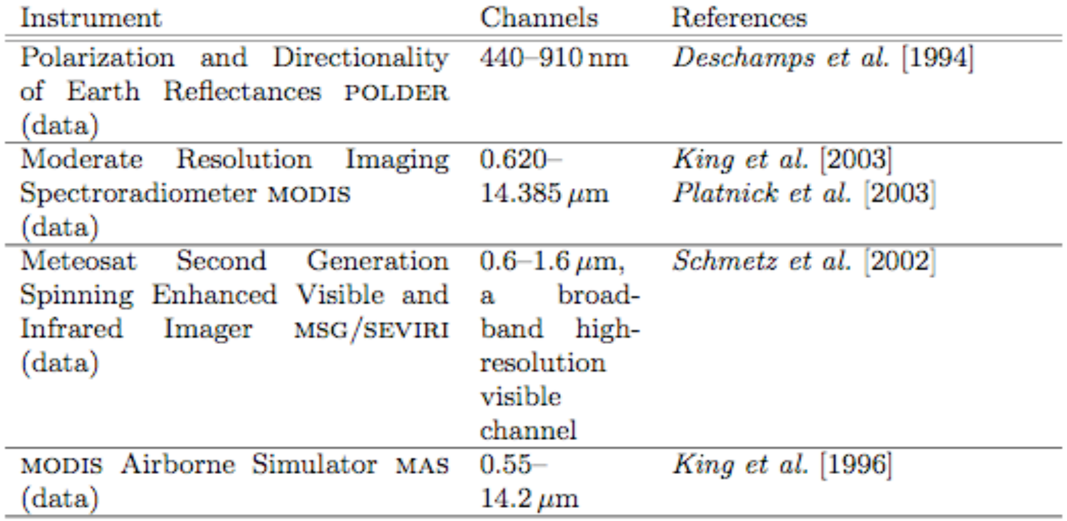
- Measuring **cloud reflectivity**, polarized reflectances sensitive to crystal size and shape.
- Deriving cloud **optical depth**, effective **particle size** and rough **crystal habit** classification (but only information from the top for optically thick clouds).

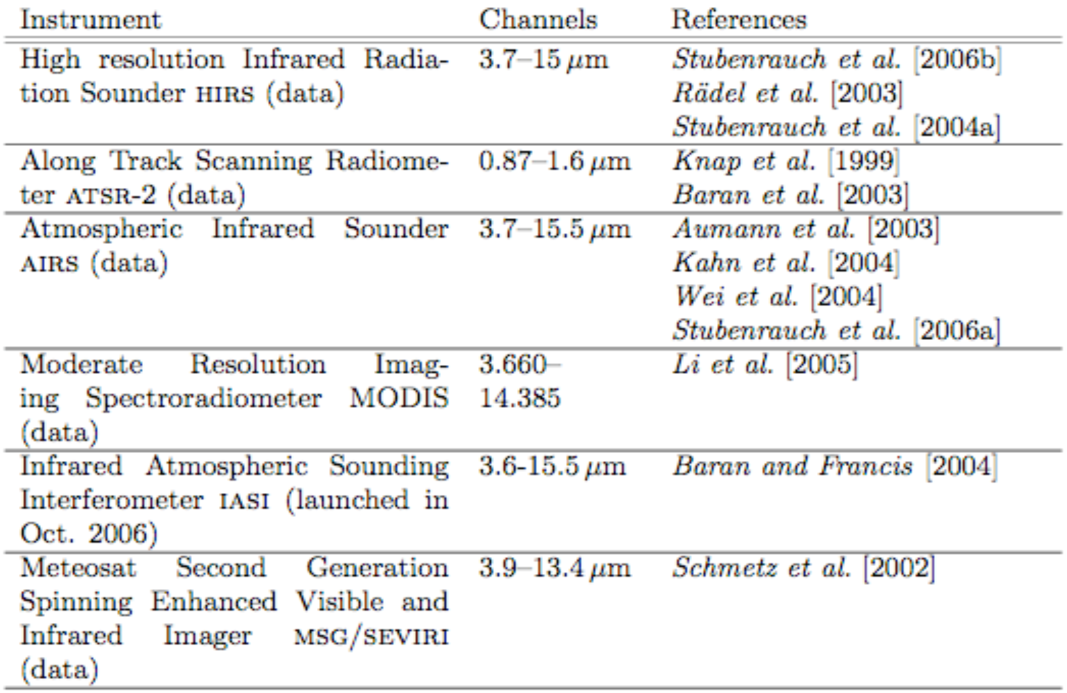


Instrument	Channels	References
Polarization and Directionality of Earth Reflectances POLDER (data)	440–910 nm	*Deschamps et al.* [1994]
Moderate Resolution Imaging Spectroradiometer MODIS (data)	0.620–14.385 μm	*King et al.* [2003] *Platnick et al.* [2003]
Meteosat Second Generation Spinning Enhanced Visible and Infrared Imager MSG/SEVIRI (data)	0.6–1.6 μm, a broad-band high-resolution visible channel	*Schmetz et al.* [2002]
MODIS Airborne Simulator MAS (data)	0.55–14.2 μm	*King et al.* [1996]

from ESTEC 19053/05/NL/AR (2007

Observing techniques: **IR**

- Measuring **cloud emissivity**, difference between IR emissivities sensitive to the mean effective ice crystal size.
- Deriving cloud **top pressure** and effective **particle size** and **IWP** (but only for semitransparent cirrus clouds, ~ 1/2 of high ice clouds, and particle sizes < ~ 70um).



Instrument	Channels	References
High resolution Infrared Radiation Sounder HIRS (data)	3.7–15 μm	*Stubenrauch et al.* [2006b] *Rädel et al.* [2003] *Stubenrauch et al.* [2004a]
Along Track Scanning Radiometer ATSR-2 (data)	0.87–1.6 μm	*Knap et al.* [1999] *Baran et al.* [2003]
Atmospheric Infrared Sounder AIRS (data)	3.7–15.5 μm	*Aumann et al.* [2003] *Kahn et al.* [2004] *Wei et al.* [2004] *Stubenrauch et al.* [2006a]
Moderate Resolution Imaging Spectroradiometer MODIS (data)	3.660–14.385	*Li et al.* [2005]
Infrared Atmospheric Sounding Interferometer IASI (launched in Oct. 2006)	3.6-15.5 μm	*Baran and Francis* [2004]
Meteosat Second Generation Spinning Enhanced Visible and Infrared Imager MSG/SEVIRI (data)	3.9–13.4 μm	*Schmetz et al.* [2002]

from ESTEC 19053/05/NL/AR (2007)

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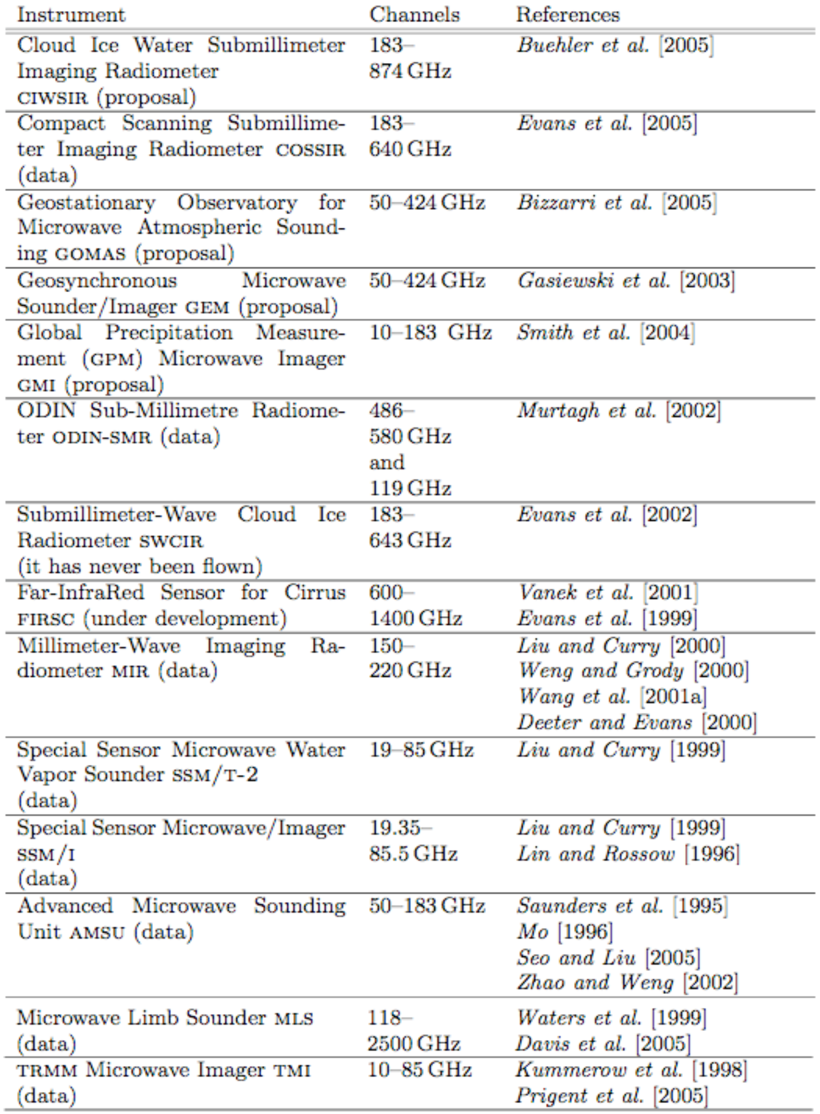
Observing techniques: **mm and sub-mm**

- Measuring **cloud transmission**, scattered radiation sensitive to ice crystal properties.
- Deriving **IWP** and effective **particle size** (but only for thick cirrus clouds with large crystals in the mm range, the sub-mm range remains to be exploited).



Instrument	Channels	References
Cloud Ice Water Submillimeter Imaging Radiometer CIWSIR (proposal)	183–874 GHz	*Buehler et al.* [2005]
Compact Scanning Submillimeter Imaging Radiometer COSSIR (data)	183–640 GHz	*Evans et al.* [2005]
Geostationary Observatory for Microwave Atmospheric Sounding GOMAS (proposal)	50–424 GHz	*Bizzarri et al.* [2005]
Geosynchronous Microwave Sounder/Imager GEM (proposal)	50–424 GHz	*Gasiewski et al.* [2003]
Global Precipitation Measurement (GPM) Microwave Imager GMI (proposal)	10–183 GHz	*Smith et al.* [2004]
ODIN Sub-Millimetre Radiometer ODIN-SMR (data)	486–580 GHz and 119 GHz	*Murtagh et al.* [2002]
Submillimeter-Wave Cloud Ice Radiometer SWCIR (it has never been flown)	183–643 GHz	*Evans et al.* [2002]
Far-InfraRed Sensor for Cirrus FIRSC (under development)	600–1400 GHz	*Vanek et al.* [2001] *Evans et al.* [1999]
Millimeter-Wave Imaging Radiometer MIR (data)	150–220 GHz	*Liu and Curry* [2000] *Weng and Grody* [2000] *Wang et al.* [2001a] *Deeter and Evans* [2000]
Special Sensor Microwave Water Vapor Sounder SSM/T-2 (data)	19–85 GHz	*Liu and Curry* [1999]
Special Sensor Microwave/Imager SSM/I (data)	19.35–85.5 GHz	*Liu and Curry* [1999] *Lin and Rossow* [1996]
Advanced Microwave Sounding Unit AMSU (data)	50–183 GHz	*Saunders et al.* [1995] *Mo* [1996] *Seo and Liu* [2005] *Zhao and Weng* [2002]
Microwave Limb Sounder MLS (data)	118–2500 GHz	*Waters et al.* [1999] *Davis et al.* [2005]
TRMM Microwave Imager TMI (data)	10–85 GHz	*Kummerow et al.* [1998] *Prigent et al.* [2005]

from ESTEC 19053/05/NL/AR (2007)

Observing techniques: **active**

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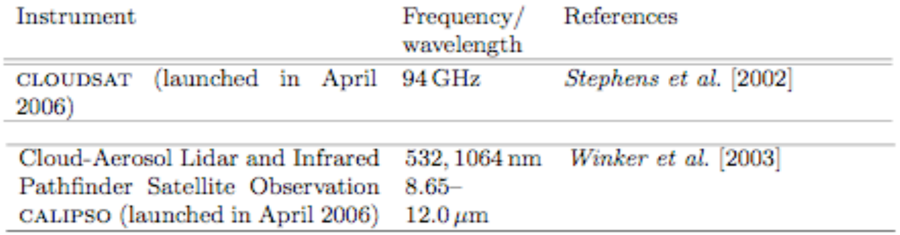
- Measuring **radar reflectivity** or **light extinction**, providing cloud properties with very high vertical resolution (but radar miss thin clouds and lidar cannot penetrate thick clouds)



Instrument	Frequency/ wavelength	References
CLOUDSAT (launched in April 2006)	94 GHz	*Stephens et al.* [2002]
Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation CALIPSO (launched in April 2006)	532, 1064 nm 8.65–12.0 μm	*Winker et al.* [2003]

from ESTEC 19053/05/NL/AR (2007)

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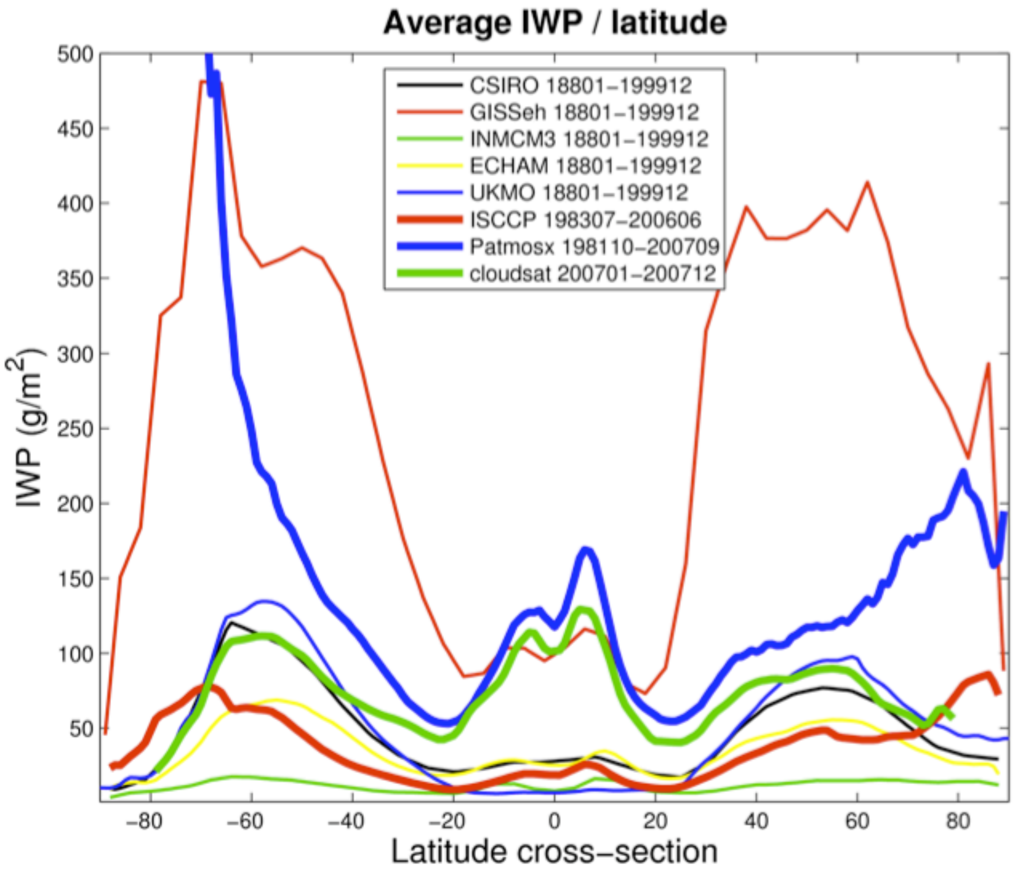
- Previous and present efforts are a great step in characterizing ice clouds, but there are still not a consistent view for even basic variables.

e.g. IWP annual means from observations and models



Courtesy of Eliasson et al. (2008), A study on the Ice Water Path discrepancies between some Global Climate

mm/sub-mm: principles

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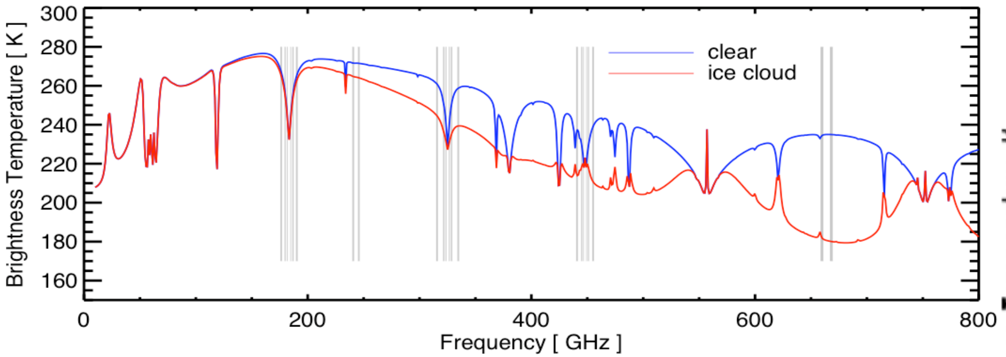
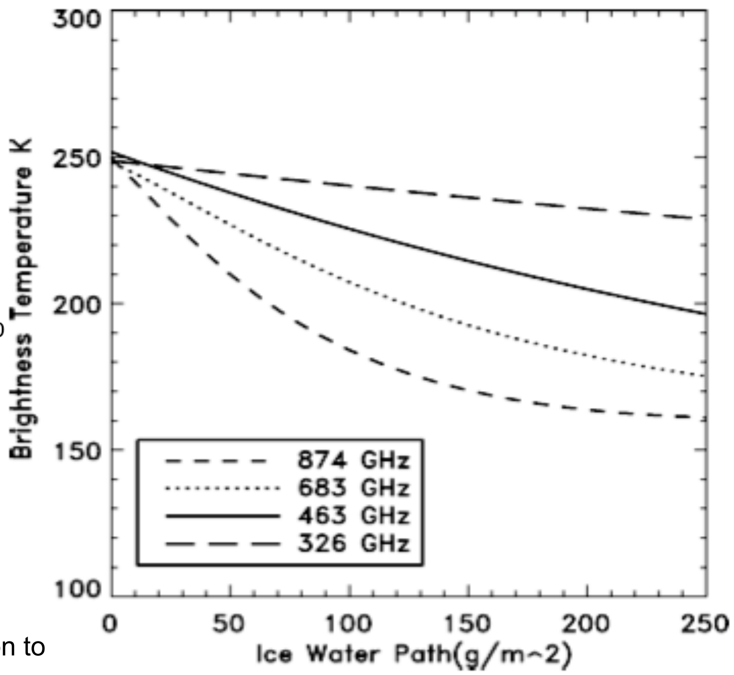
- For high enough frequencies, the lower atmosphere is opaque (strong H_2O emission) and the cloud-radiation interaction is though **scattering** of the up-welling radiation.
- The brightness temperature depressions are **proportional** to the **IWP**, except for saturation effects at high frequencies.



Homogeneous cloud from 8 to10 km with an IWC of 0.04 g/m^3, consisting of spherical ice particles with 100 µm radius.



Courtesy of Buehler et al. (2008), A concept for a satellite mission to measure cloud ice water path, ice particle size, and cloud altitude

mm/sub-mm: principles

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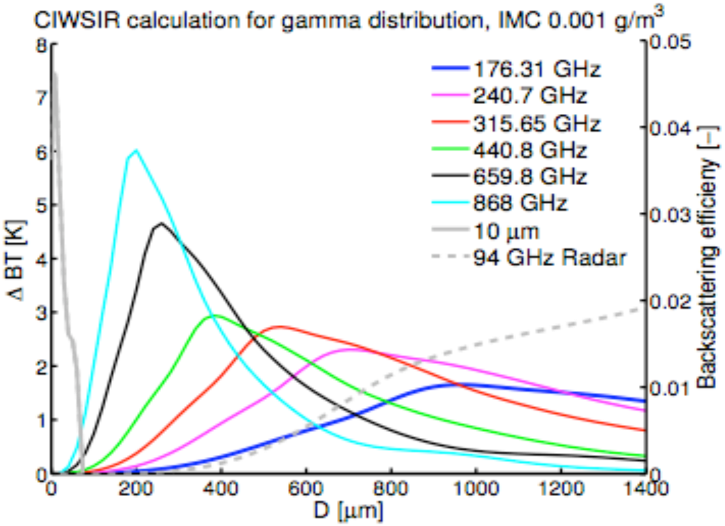
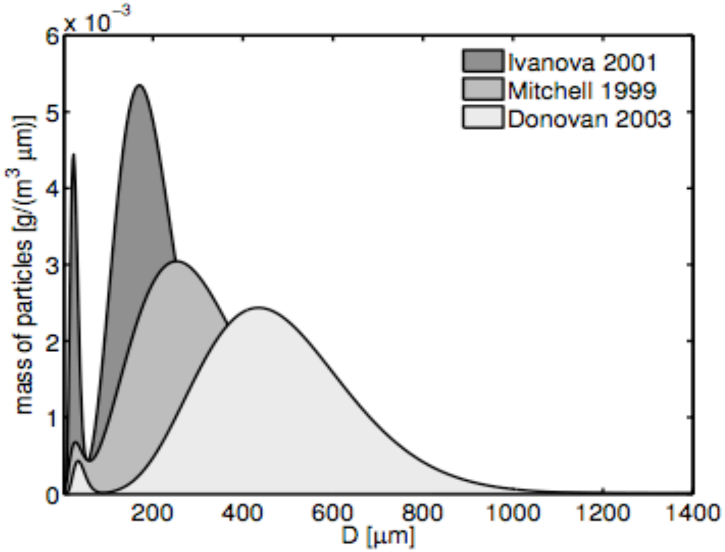
- For accurate estimation of IWC is necessary to sample at significant (containing significant fraction of ice mass) parts of the **size distribution**.





from ESTEC 19053/05/NL/AR (2007)

- Different **mm/sub-mm frequencies** can be used to quantify the size distribution and provide accurate measurements of IWP.

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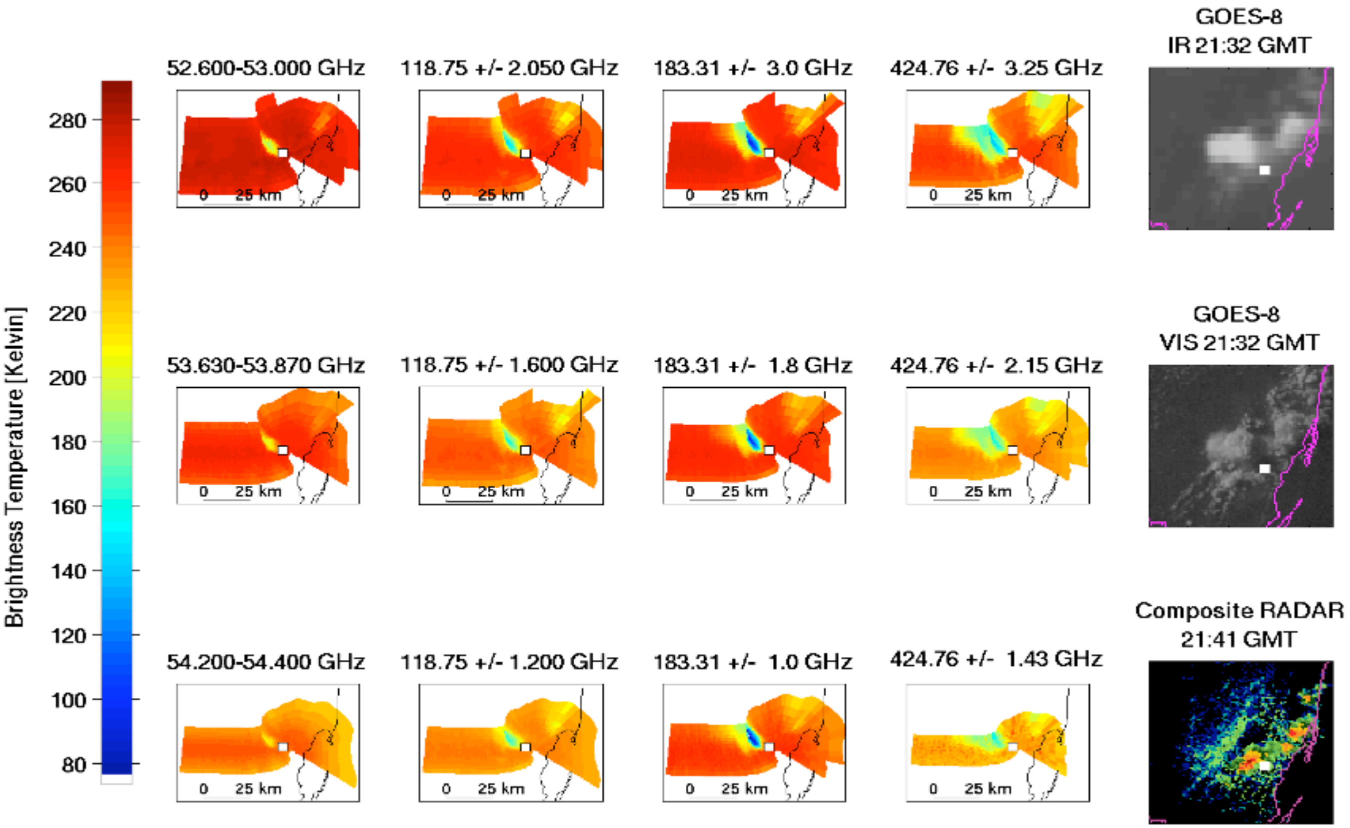
mm/sub-mm: observations

- In the **mm** range, **satellite** sounders/imagers (SSM/I-T, AMSU-A/B) with mm frequencies up to 190 GHz.
- In the **sub-mm** range, **aircraft** sounders to test the observation concept.

e.g. NPOESS Aircraft Sounder Testbed - Microwave (NAST-M) [ER-2] CRISTAL FACE, July 13 2002



Courtesy of Leslie et al. (2003), Cloud and Precipitation Observations With the NPOESS Aircraft Sounder Testbed - Microwave (NAST-M) Spectrometer Suite at 54/118/183/425 GHz

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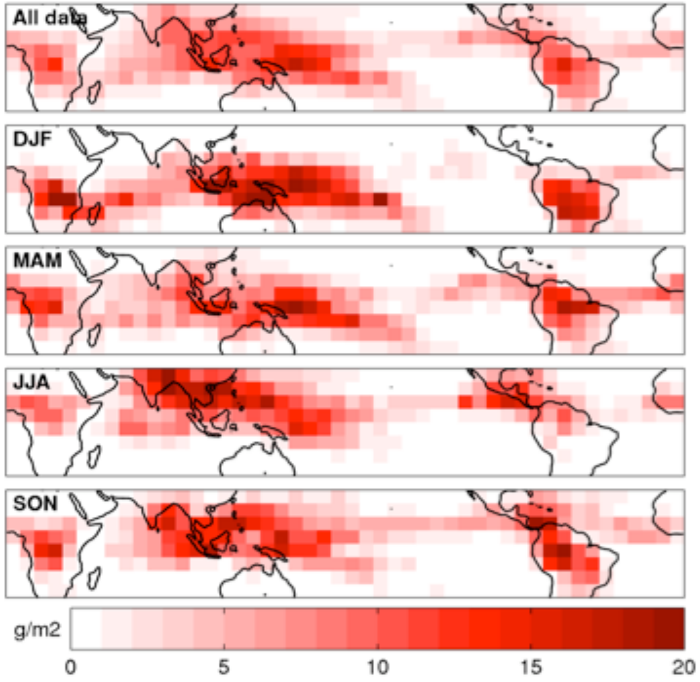
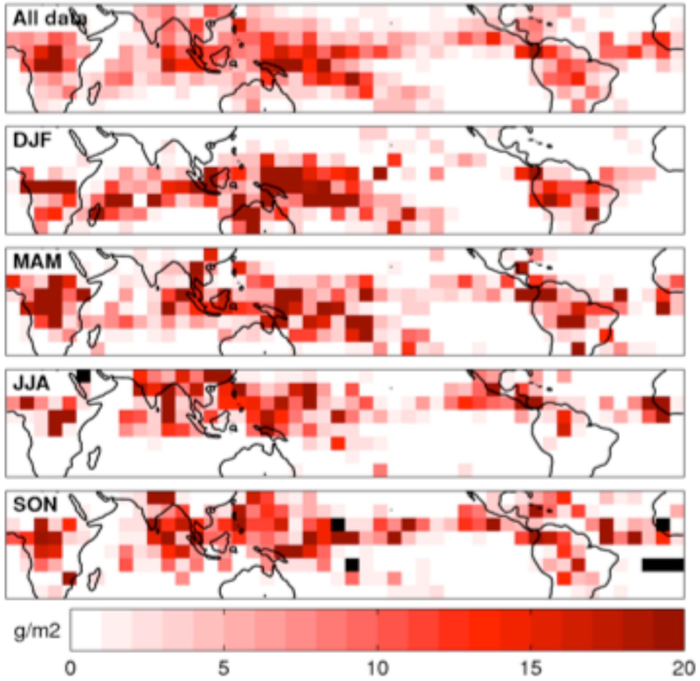
mm/sub-mm: observations

- In the **sub-mm** range, also satellite instruments but so far only in a **limb sounding** geometry (Odin-SMR, EOS-MLS).
- The high incident observing angle results in a limited altitude coverage (**partial IWP**, e.g from 12 km for Odin-SMR) and poor horizontal resolution (lengths of more than 100 km).

EOS-MLS (240 GHz) [06/07]



Odin-SMR (501/544 GHz) [01/07]



Courtesy of Eriksson et al. (2008), Comparison between early Odin-SMR, Aura MLS and CloudSat retrievals of cloud ice mass in the upper tropical

mm/sub-mm: simulations

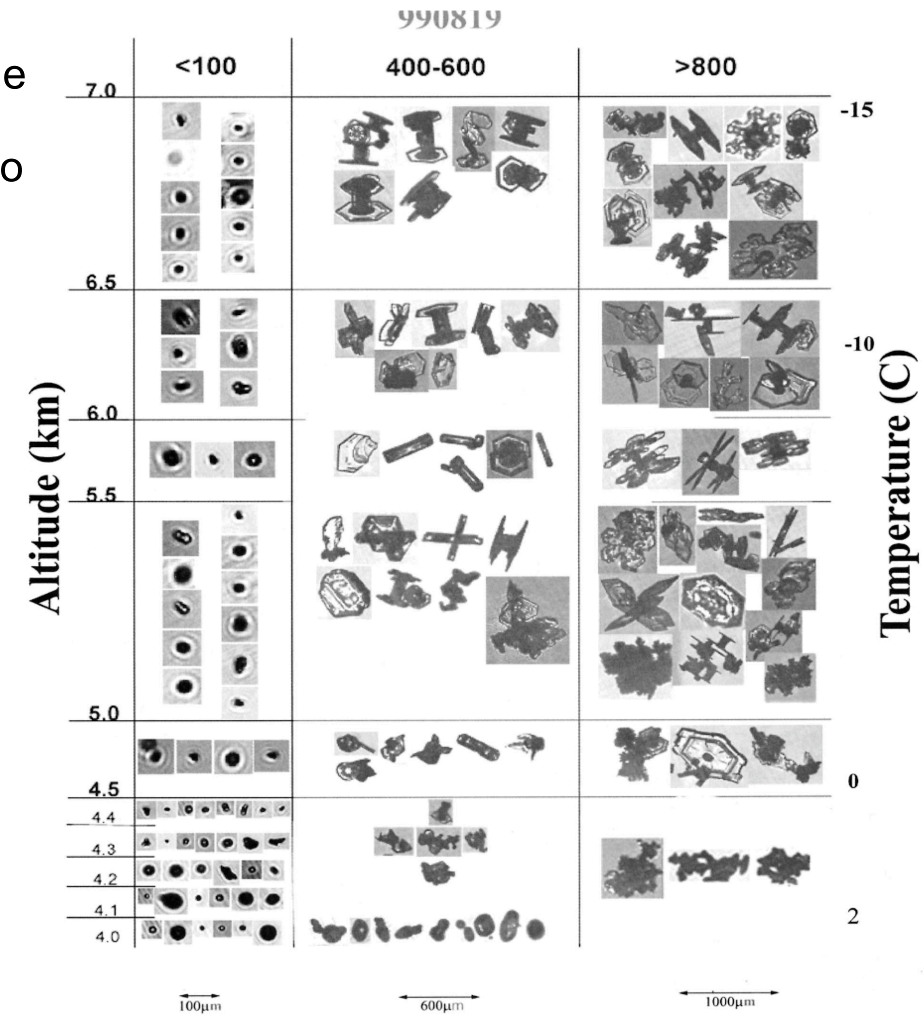
- To understand and exploit the observations we need accurate **radiative transfer** calculations and realistic parameterizations of the **microphysical properties** of the ice crystals.

- The **inversion** of the mm/sub-mm measurements are in most cases performed by regression algorithms requiring an **a priori database** of simulated atmospheric and cloud parameters and corresponding radiances.

- The scattering properties of the ice particles depend on the particle **size** and **shape** distributions, the **density** of the particles, and the **orientation** of the particles.

mm/sub-mm: simulations

- The **shapes** and **sizes** of ice particle are observed in measurement campaigns. The shapes are found to be highly variable and irregular.



e.g. particles shapes vs altitude and temperature in tropical ice clouds.

(CPI on UND Citation aircraft)

Courtesy of Heymsfield et al. (2002) Observations and Parameterizations of Particle Size Distributions in Deep Tropical Cirrus and Stratiform Precipitating Clouds: Results from In Situ Observations in TRMM Field

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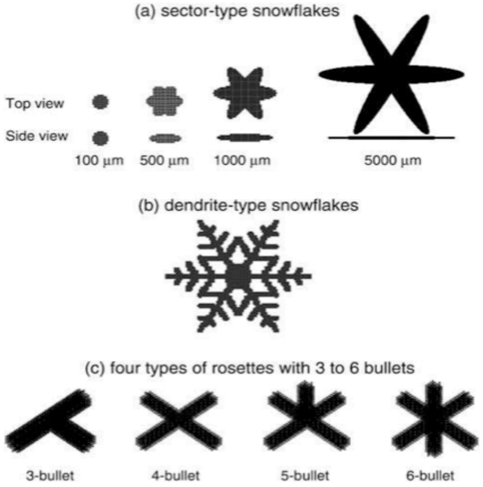
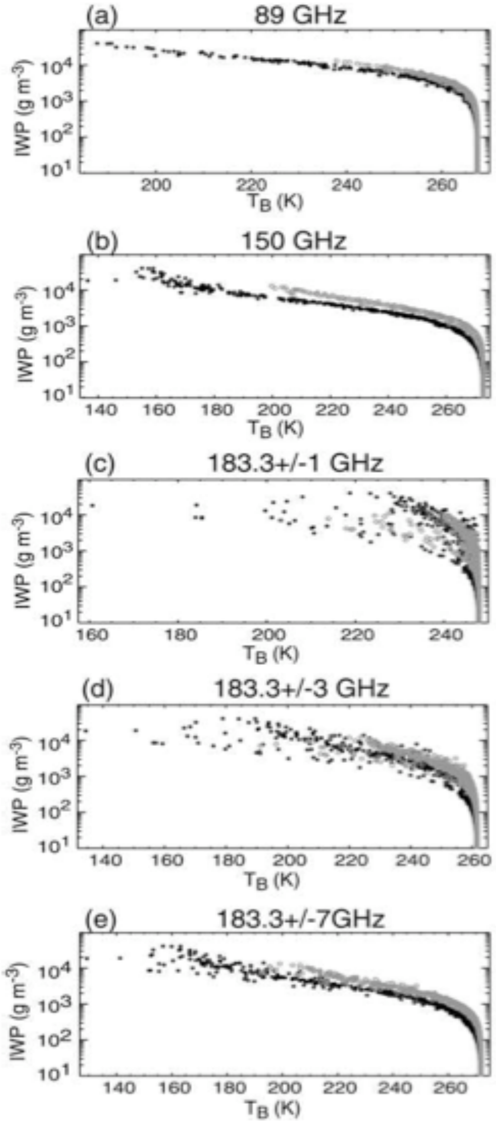
mm/sub-mm: simulations

- To make the scattering calculations tractable **shape simplifications** are required.





e.g. Simulations of brightness temperature as function of IWP assuming ice spheres (Mie theory) (grey dots) or more complex shapes (DDA) (black dots).

Courtesy of Seo and Liu (2005) Retrievals of cloud ice water path by combining ground cloud radar and satellite high-frequency microwave measurements near the ARM SGP site

mm/sub-mm: simulations

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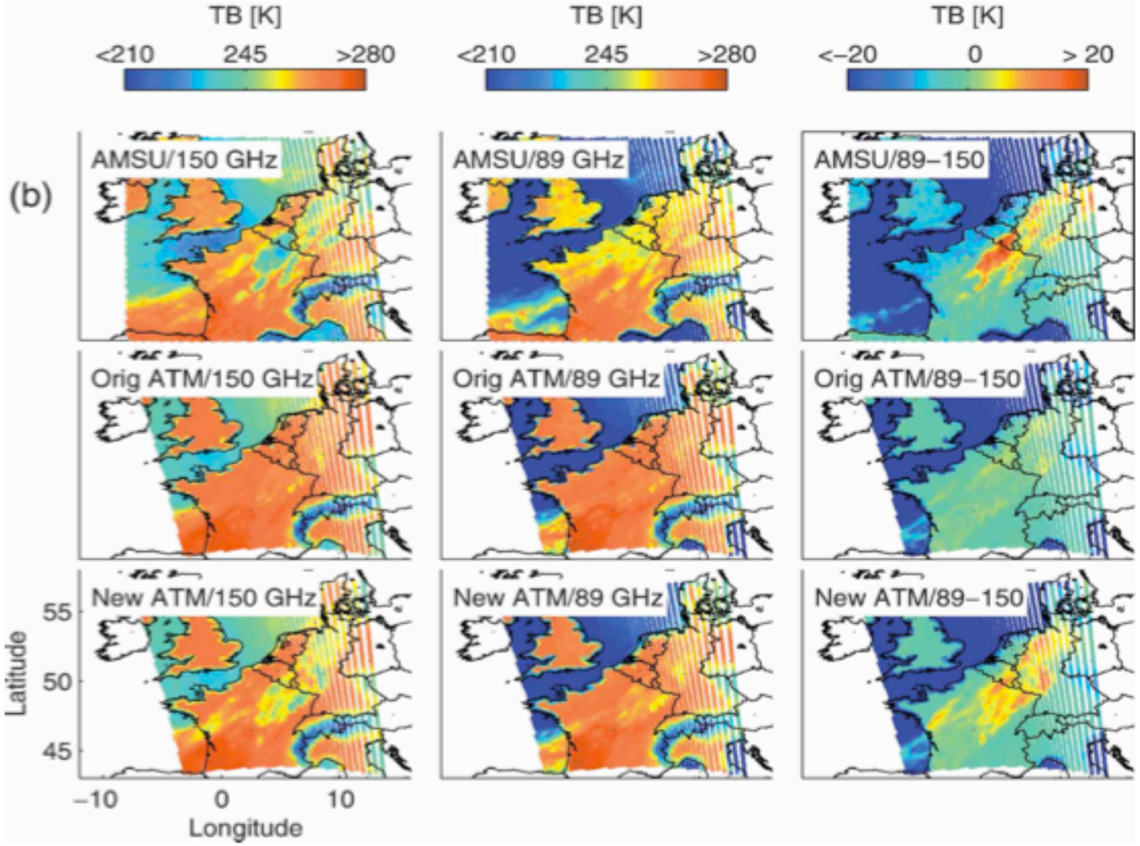
- Most ice particles are not solid and have a **density** different from solid ice.

e.g. Adding a cloud snow frequency dependant density improves notably the agreement between RT simulations (Meso-NH+ATM) and AMSU-B observations at mid latitudes.

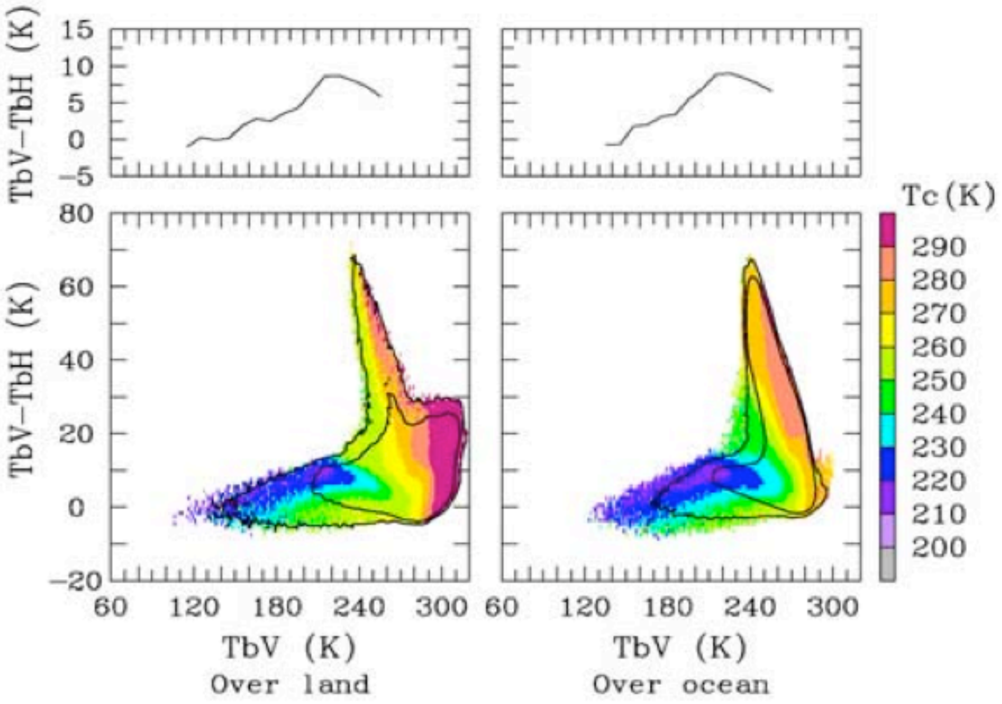


Courtesy of Meirold-Mautner et al. (2005) RT Simulations Using Mesoscale Cloud Model Outputs: Comparisons with Passive mm and IR Satellite Observations for Midlatitudes

mm/sub-mm: simulations

- Particles with a preferential **orientation** can generate polarized scattering signatures that can be replicated in the RT simulations.
- Large crystals can align **horizontally** when falling down, but **vertical** alignment can also be possible for cone-like particles (vertical symmetry axis) growing inside inside convective clouds with lighting activity.

e.g. Polarized scattering signatures at 85 GHz (TMI), where the negative polarization is explained by vertically aligned particles.



Courtesy of Prigent et al. (2005) Relations of polarized scattering signatures observed by the TRMM Microwave Instrument with electrical processes in cloud systems.

mm/sub-mm: potential

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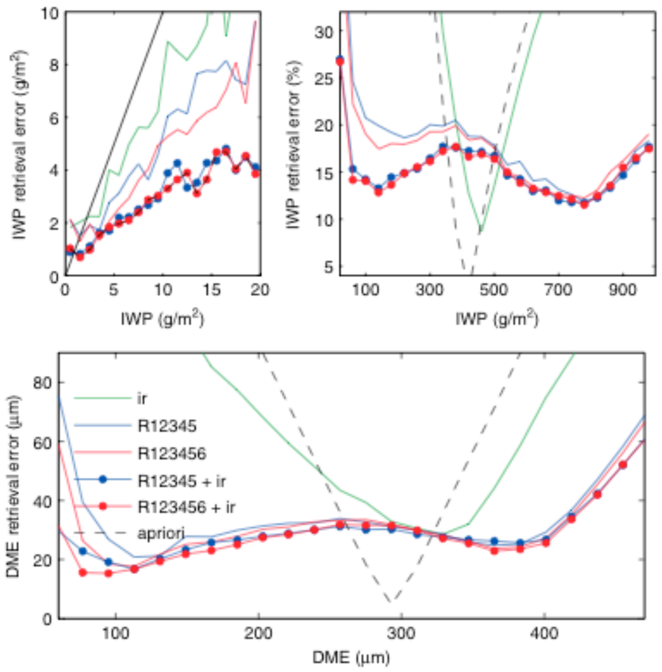
e.g. Performance simulations for the **CIWSIR** instrument proposal

Receiver	Channel	Frequency (GHz)	NEΔT (K)
R1	1	183.31 ± 1.5	0.6
	2	183.31 ± 3.5	0.5
	3	183.31 ± 7.0	0.4
R2	4	243.2 ± 2.5	0.5
R3	5	325.15 ± 1.5	0.8
	6	325.15 ± 3.5	0.7
	7	325.15 ± 9.5	0.6
R4	8	448.00 ± 1.4	1.3
	9	448.00 ± 3.0	1.0
	10	448.00 ± 7.2	0.7
R5	11	664.0 ± 4.2	1.4
R6	12	874.4 ± 4.5	2.3



from Jimenez et al. (2008) Performance simulations for a submillimetre-wave satellite instrument to measure cloud ice.

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Summary

- Ice clouds have a large **radiative impact** on the climate system. Their characterization will improve their representation in climate models and will contribute to a less uncertain climate predictions.

- Observations techniques in the **VIS-NIR, IR, mm** and **sub/mm** are available to characterize ice clouds, with different strengths and shortcomings.

- The **mm/sub-mm range** offers great potential to characterize cloud bulk properties such as IWP and effective particle size where there is still large discrepancies in the present available products.

- Realistic **radiative transfer simulations** of cloudy scenes are required to interpret the mm/sub-mm scattering signals and exploit this frequency range for ice cloud characterization.