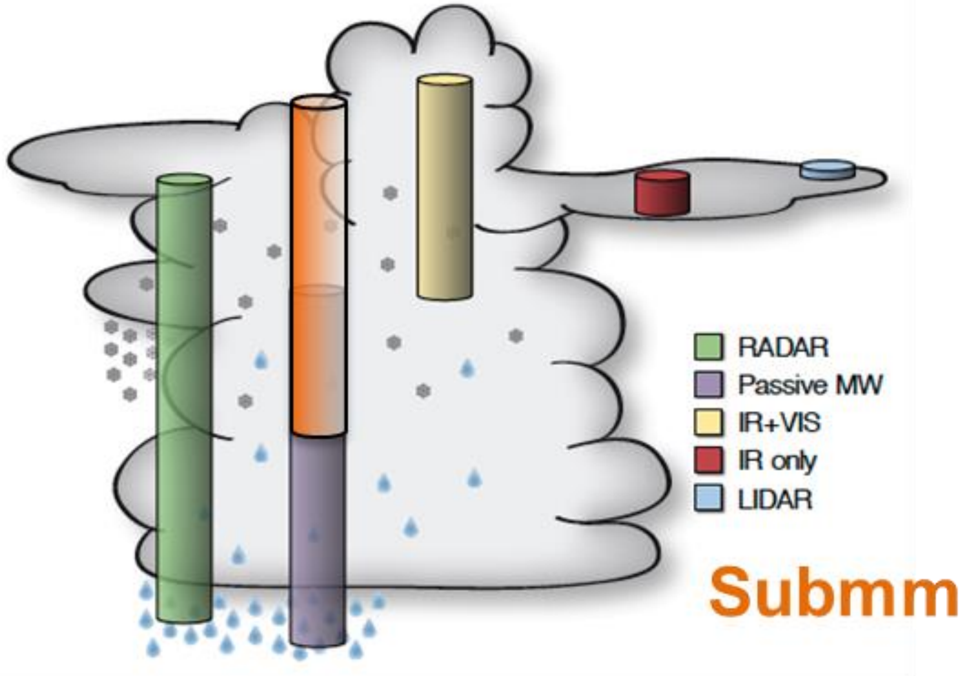
What new information on clouds and precipitation will become available rom ICI?

Susanne Crewell, Mario Mech, Stefan A. Bühler, Patrick Eriksson, Catherine Prigent, and many more

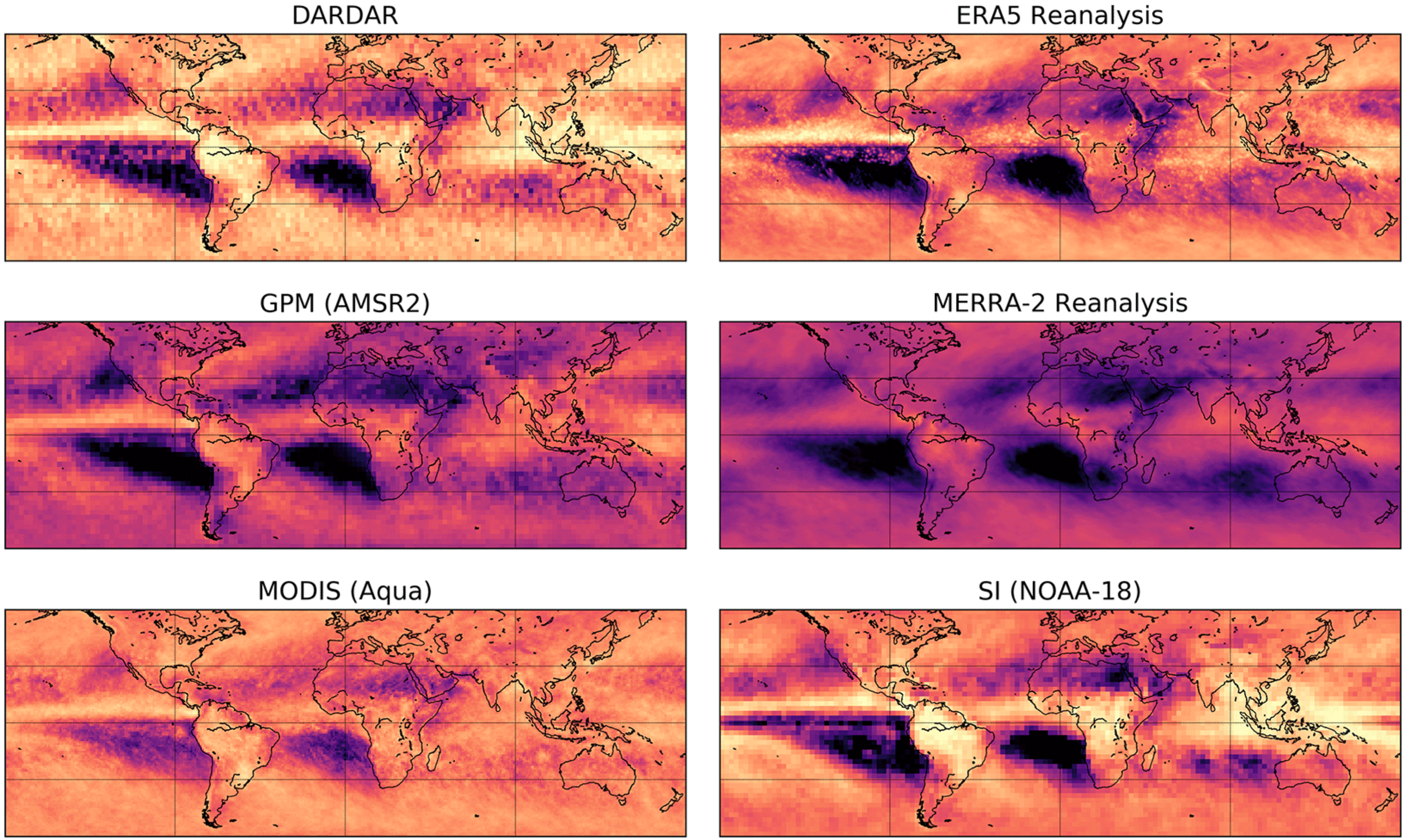
Content

- **Motivation**
- Exploiting ICI measurements
- Radiative Transfer
- Retrieval algorithms
- Conclusions and Outlook



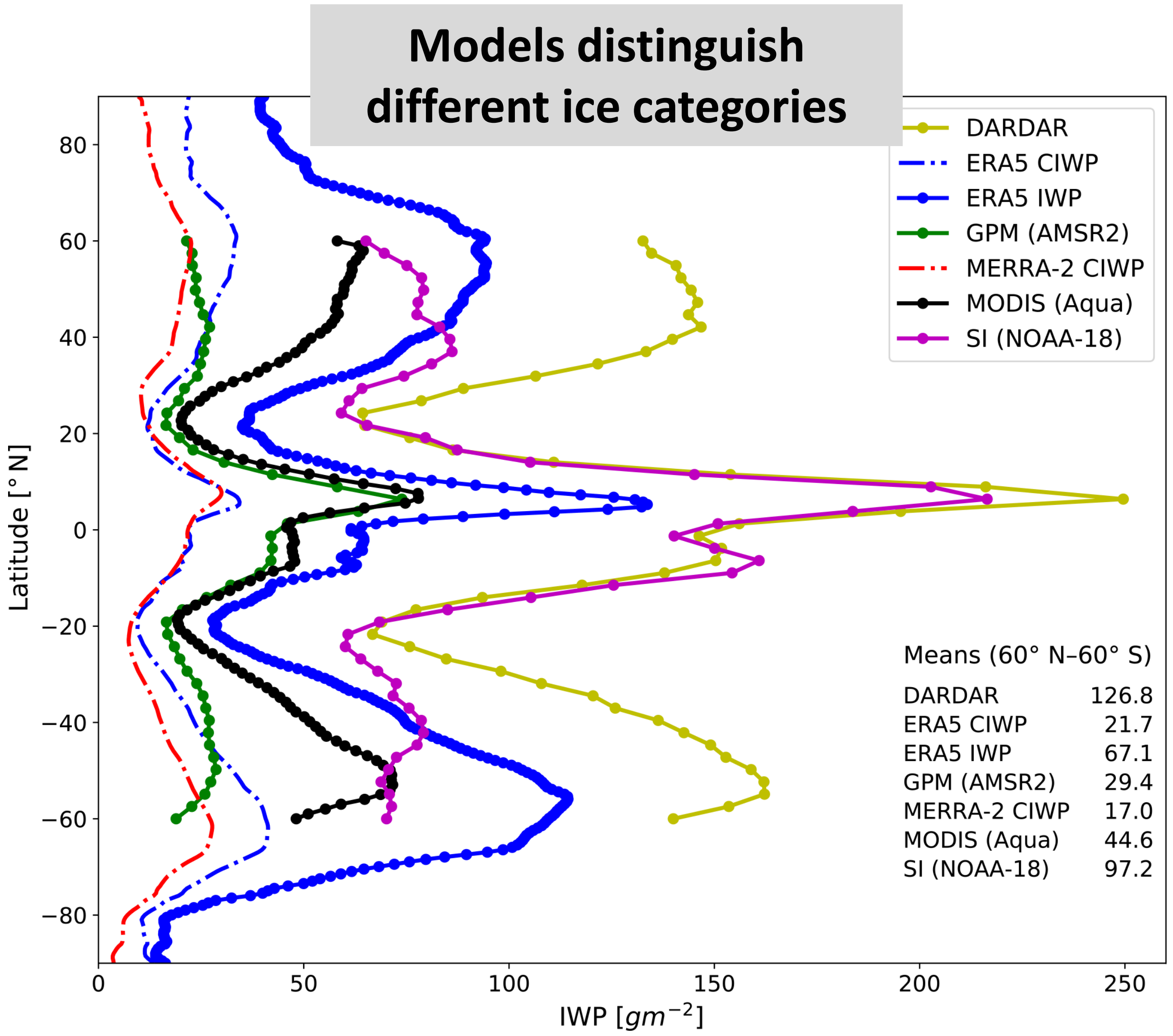
Adapted from
Eliasson et al., 2011

Global Atmospheric Ice Estimates



Duncan, D. I. and Eriksson, P.: An update on global atmospheric ice estimates from satellite observations and reanalyses, Atmos. Chem. Phys., 18, 11205–11219, 2018.

Global Atmospheric Ice Estimates



Ice water path (IWP)

=

Cloud Ice Water Path (CIWP)

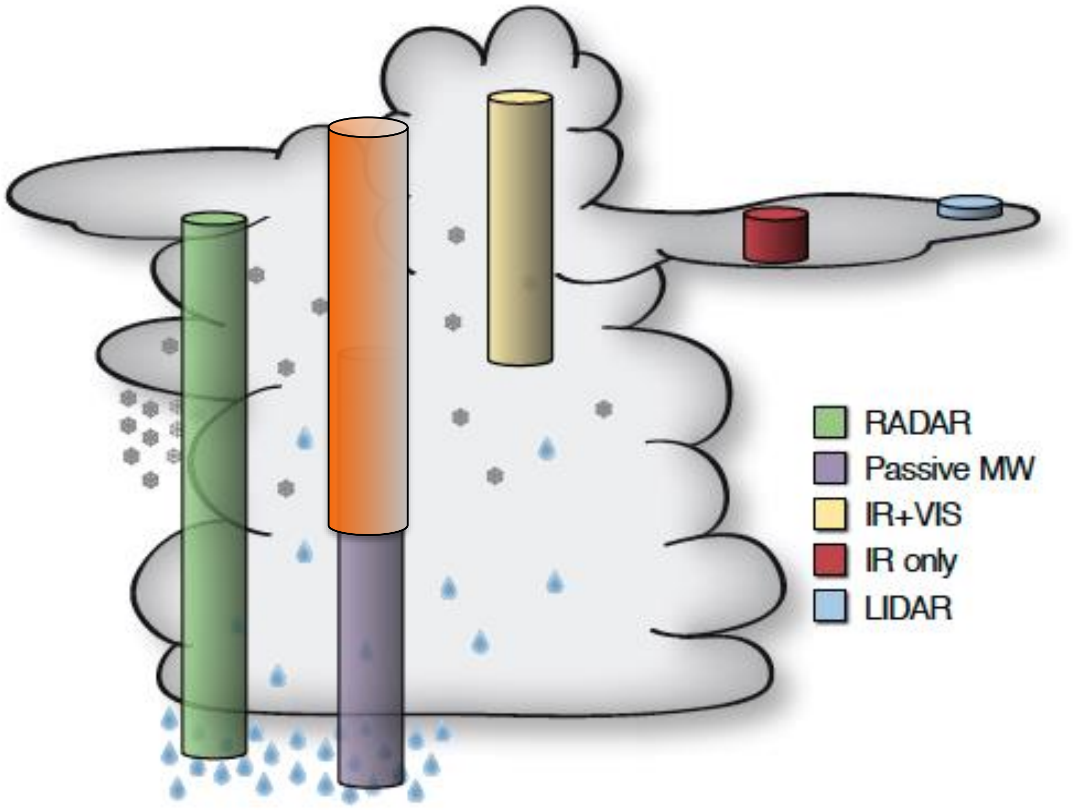
+

Snow Water Path (SWP)

Duncan, D. I. and Eriksson, P.: An update on global atmospheric ice estimates from satellite observations and reanalyses, Atmos. Chem. Phys., 18, 11205–11219, 2018.

Ice Cloud Remote Sensing

- **VIS / IR techniques**
  →only sense ice water path < 100 gm^{-2}
- **Lidars**
  →only sense optical depths < 3
- **Active microwaves (CloudSat CPR)**
  →poor spatial coverage
- **Passive microwaves**
  →only sense precipitating ice
  →used operationally for snowfall / rain rate retrievals
- **ICI submm channels**
  →sense different altitudes of cloud depending on wavelength
  →estimate ice mass and mean ice particle size



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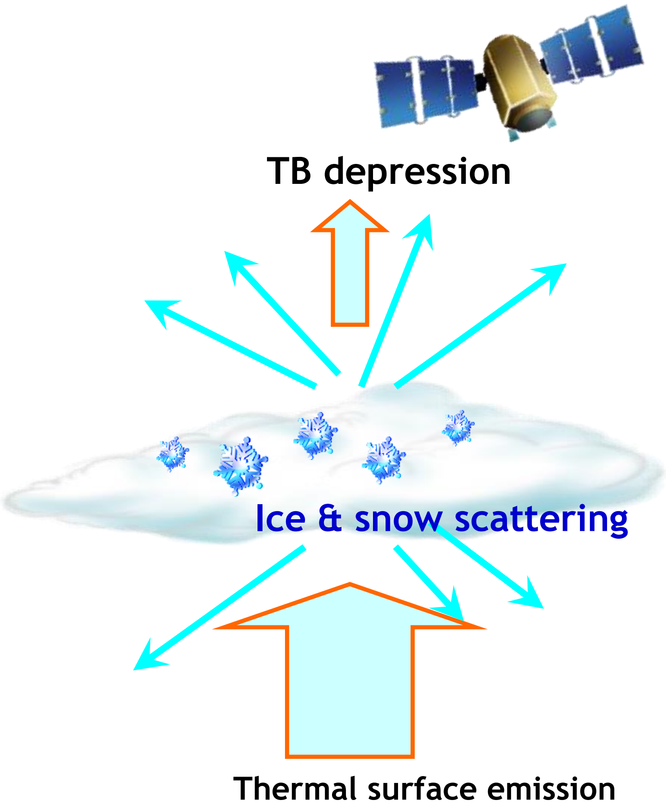
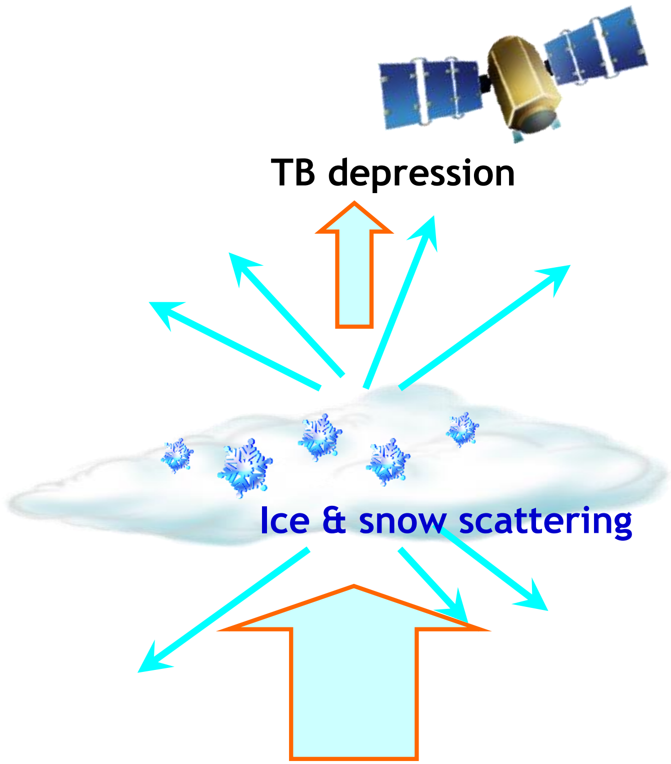
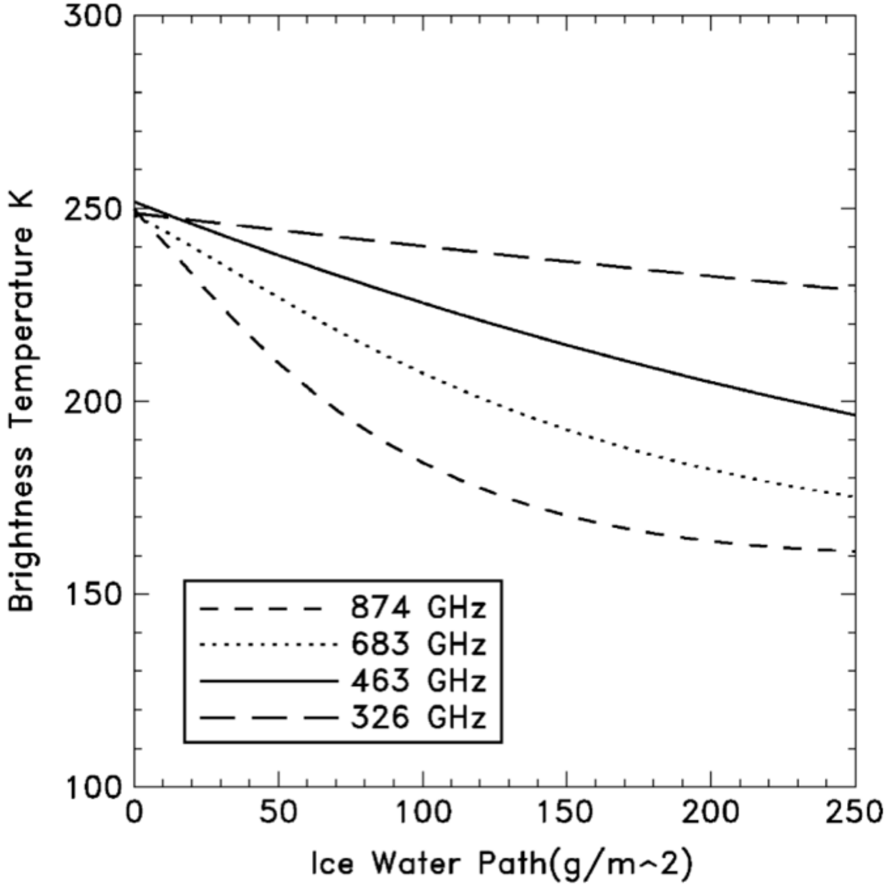


ICI measurement principle





Midlatitude-winter, spherical ice particles with D=200 µm. ARTS simulation. Figure from Buehler et al. 2007.

Bühler et al.: A concept for a satellite mission to measure cloud ice water path, ice particle size, and cloud altitude, Quarterly Journal of the Royal meteorological Society, 2017.

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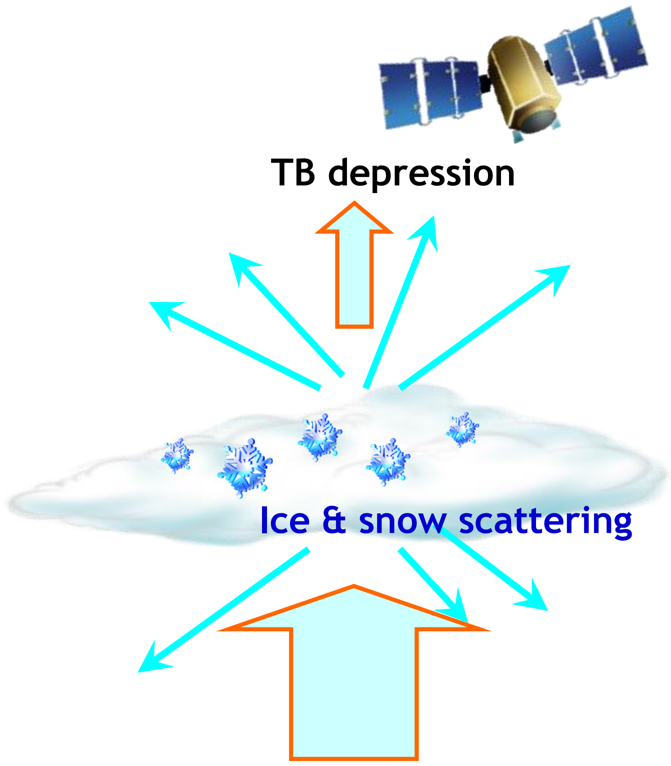
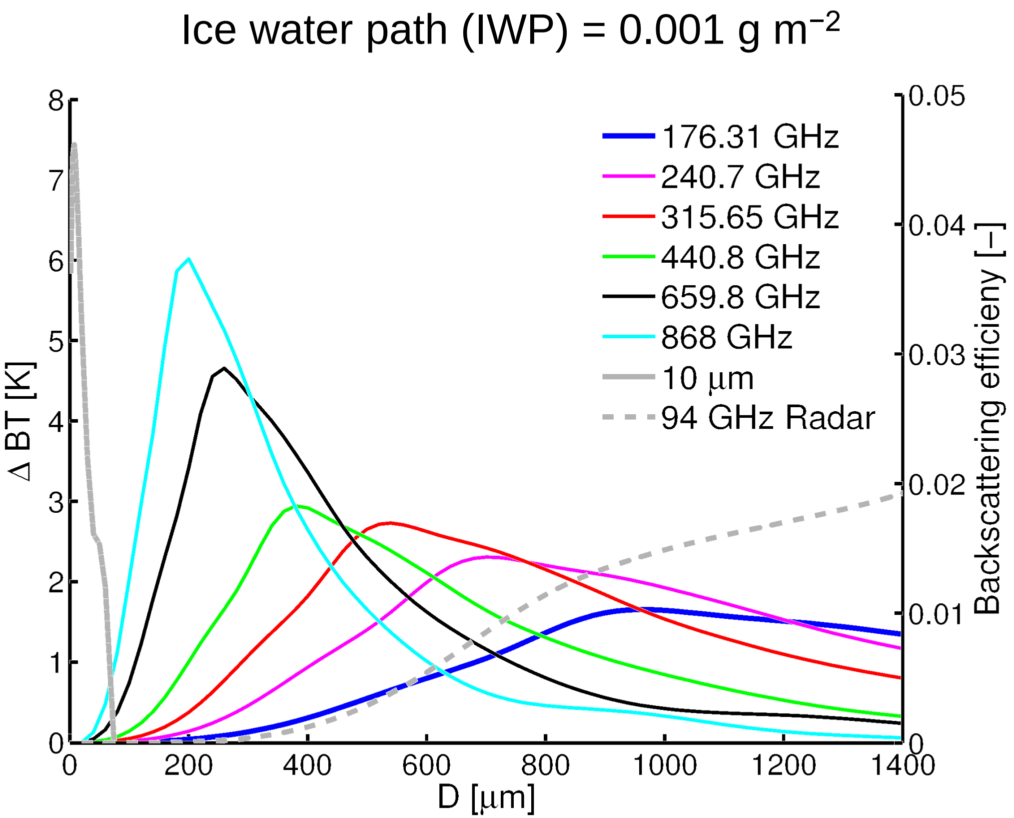




Buehler et al., 2007

Submm waves sense different particle sizes and fill the gap between IR and radar

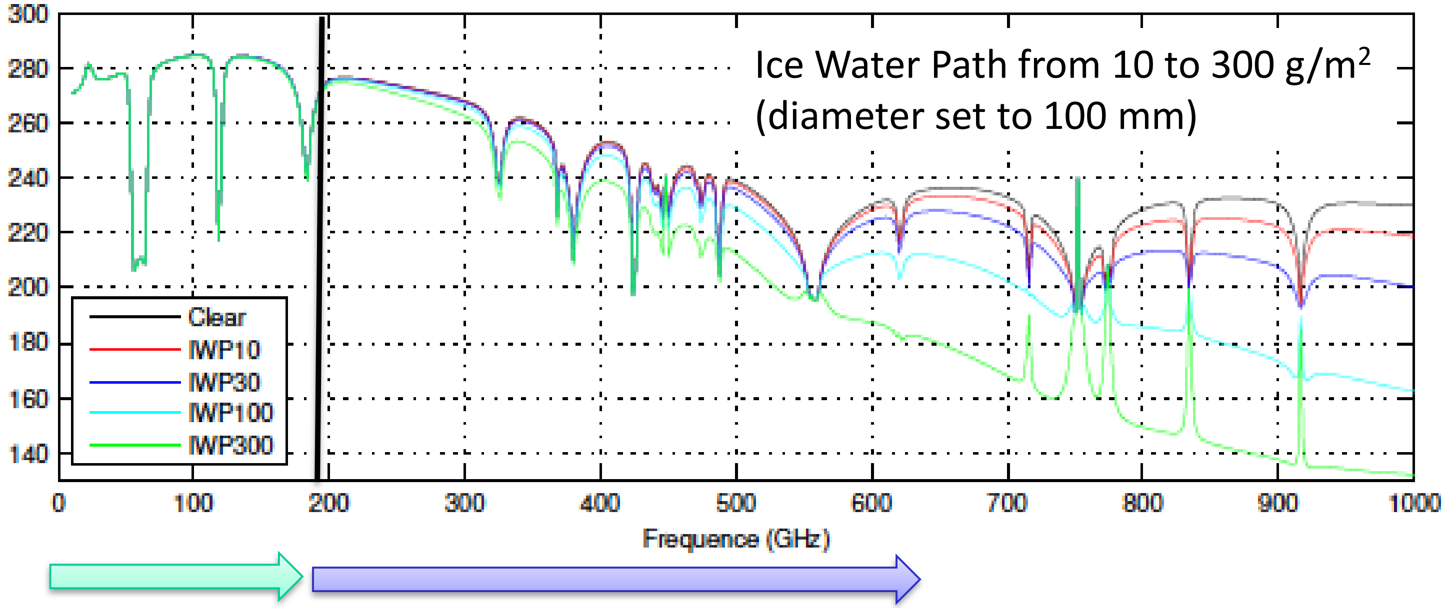
Bühler et al.: A concept for a satellite mission to measure cloud ice water path, ice particle size, and cloud altitude, Quarterly Journal of the Royal meteorological Society, 2017.

ICI applications

ICI's primary objectives are to support

- climate monitoring,
- validation of ice cloud models, and
- parameterisation of ice clouds in weather and climate models through the provision of ice cloud products.

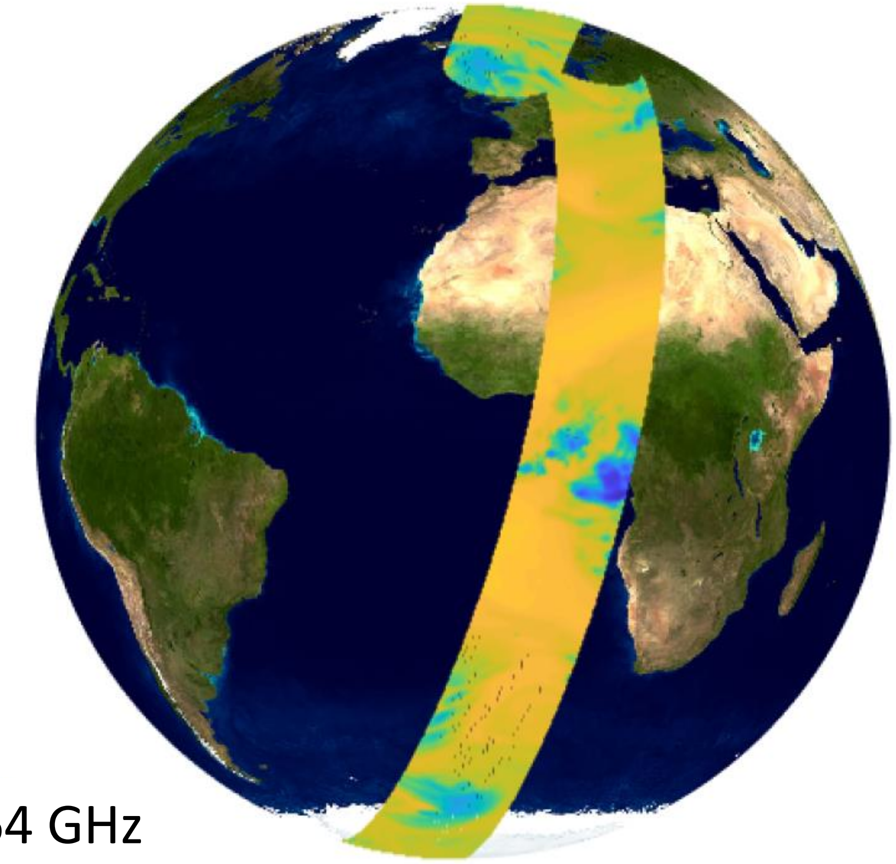
IWP available as MWI-ICI L2 products (see previous talk)



ICI applications

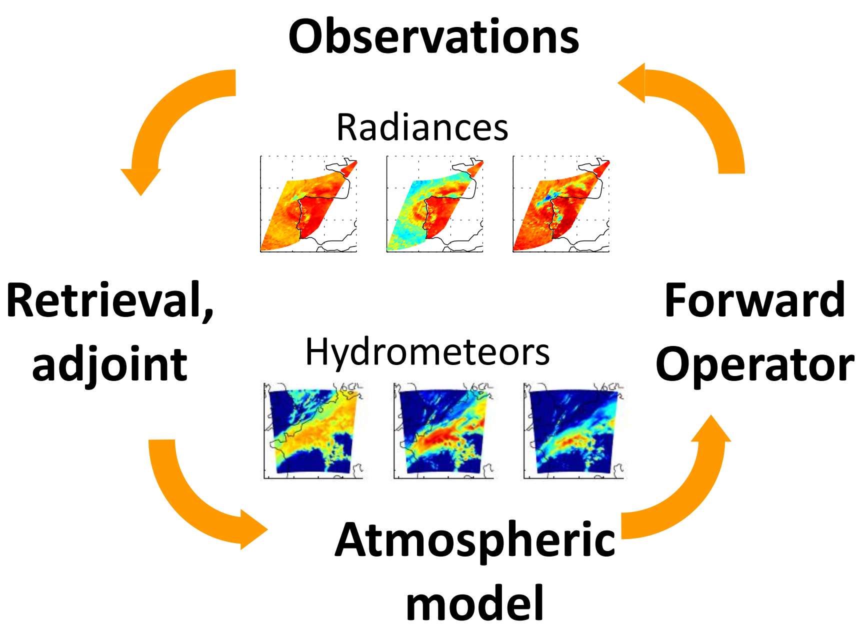
Further objectives:

- Measurement of snowfall distributions in support of numerical weather prediction and nowcasting
- Enhancement of the ability of NWP centres to initialise global and regional models with information on clouds
- Test suitability of submm to provide information on precipitation (towards GEO)


664 GHz

Novel „first time“ submm wave information might provide opportunities not expected ahead

Exploiting ICI measurements



- Direct **radiance assimilation** using fast parametrized radiative transfer model similar to todays microwave satellite data assimilation
- RTTOV (Radiative Transfer for TOVS; Sounders et al., 2018) from NWP-SAF is prepared for ICI channels to compute the tangent linear, adjoint and Jacobian matrix providing changes in radiances for profile variable perturbations

Saunders, R., Hocking, J., Turner, E., Rayer, P., Rundle, D., Brunel, P., Vidot, J., Roquet, P., Matricardi, M., Geer, A., Bormann, N., and Lupu, C.: An update on the RTTOV fast radiative transfer model (currently at version 12), Geosci. Model Dev., 11, 2717–2737, 2018.

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- **Radiative Transfer**
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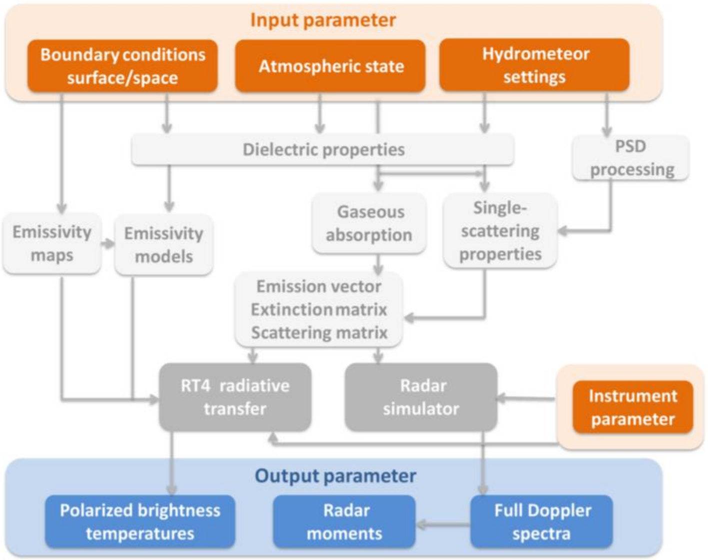
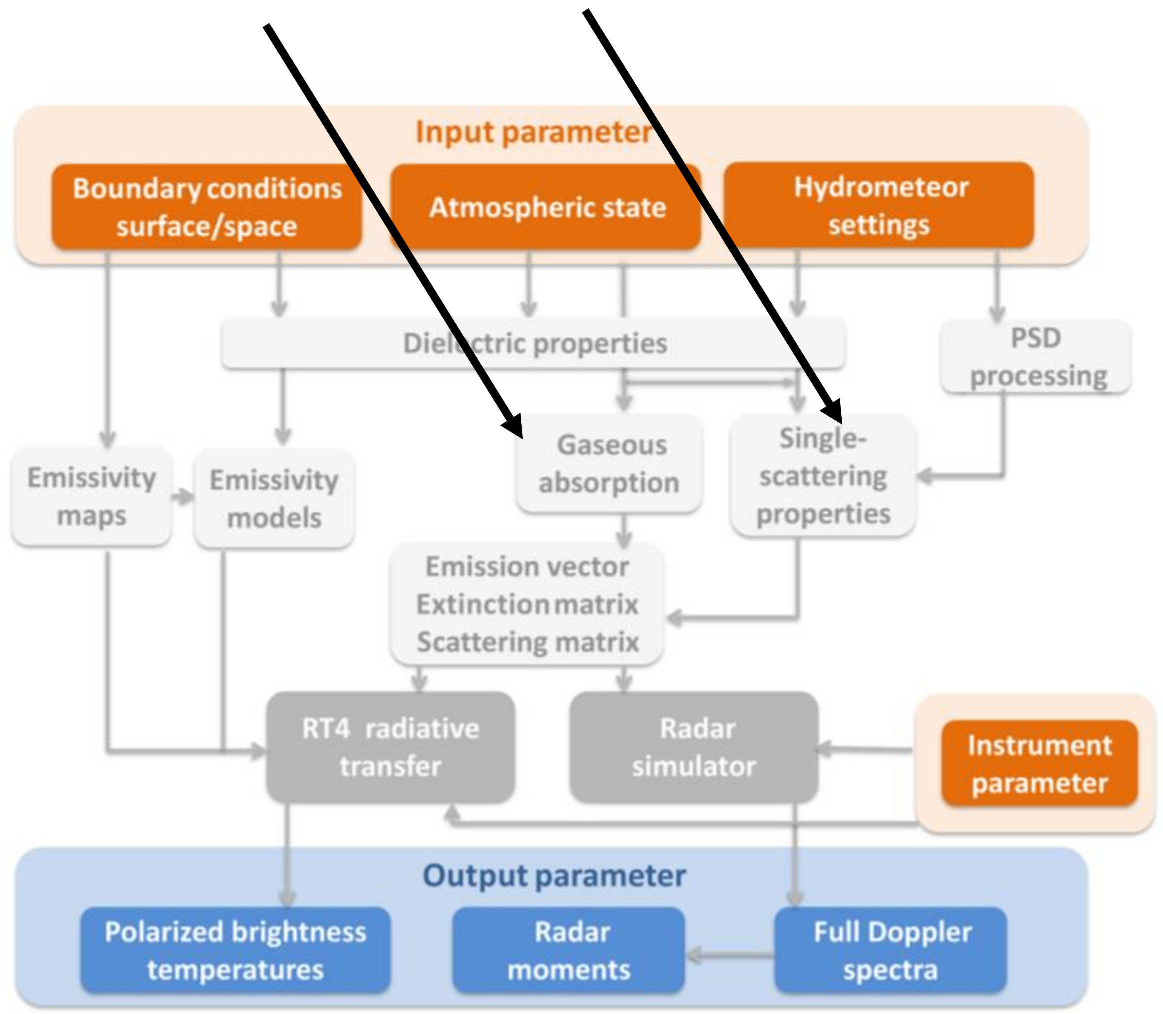


Radiative Transfer

- has been fundamental for developing ICI (ARTS, http://www.radiativetransfer.org/)
- is used in fast (parametrized) from in data assimilation (RTTOVS)
- has been used to generate test data sets (see previous talk) and is also basis for retrieval development
- is used for the interpretation of observed signals



Mech, M., M. Maahn, S. Kneifel, D. Ori, E. Orlandi, P. Kollias, V. Schemann, and S. Crewell, 2020: PAMTRA 1.0: A Passive and Active Microwave radiative TRAnsfer tool for simulating radiometer and radar measurements of the cloudy atmosphere, Geoscientific Model Development, 13, 4229-4251.

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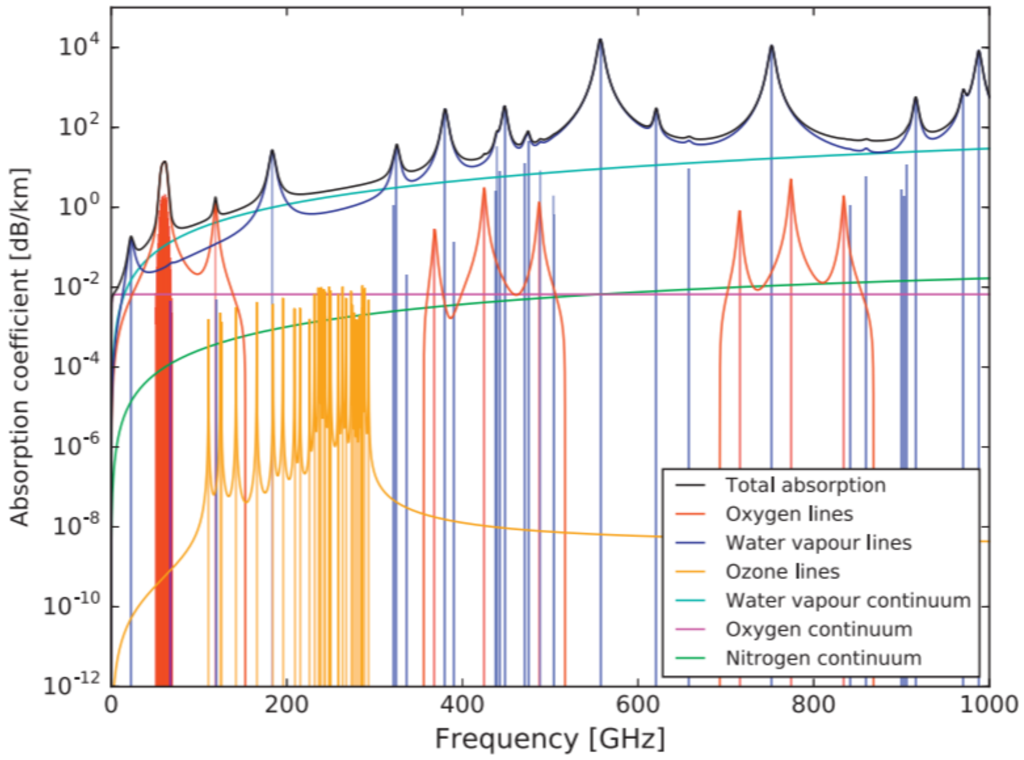
Radiative Transfer Challenges

Atmospheric gas absorption

- Submillimeter range includes many more lines than the currently used microwaves
- Water vapour continuum is less characterized

Need for validation using ground-based (astronomy) and airborne measurements
→ ongoing studies using ALMA observations



Turner et al., 2019

Mattioli, V. C. Accadia; C. Prigent; S. Crewell; A. Geer; P. Eriksson; S. Fox; J. R. Pardo-Carrión; E. Mlawer; M. Cadeddu; M. Bremer; C. De Breuck; A. Smette; D. Cimini; E. Turner; M. Mech; F. S. Marzano; P. Brunel; J. Vidot; R. Bennartz; T. Wehr; S. Di Michele; V. John: [Atmospheric Gas Absorption Knowledge in the Sub-Millimeter: Modeling, field measurements, and uncertainty quantification](), Bull. Amer. Meteor. Soc., 2019.

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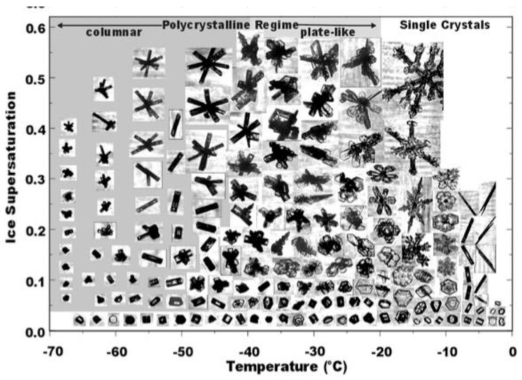
Radiative Transfer Challenges

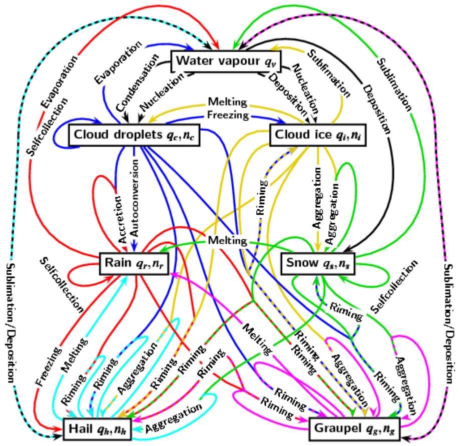
Challenges

- Complexity of ice particles in respect to size distribution, shape, density, orientation
- Atmospheric models include simplified assumption → ongoing development of microphysical schemes



Hydrometeor scattering

- forward model needs to handle multiple scattering of polarized radiation
- Detailed radiative transfer models available for assessment and used together with GMI observations as proxy

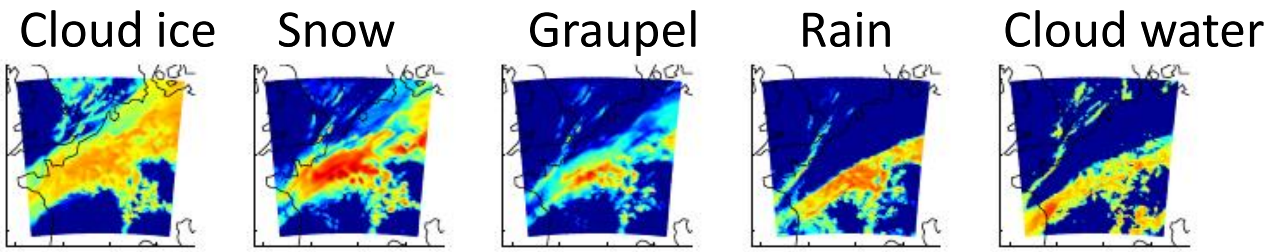


Bulk model hydrometeor properties need to be mapped to single scattering properties to feed radiative transfer model

Impact of microphysical schemes

Differences between different microphysical scheme for WRF simulations for a mid-latitude case

- Particle types (5 hydrometeor types in WRF)
- Particle size distributions; Particle density



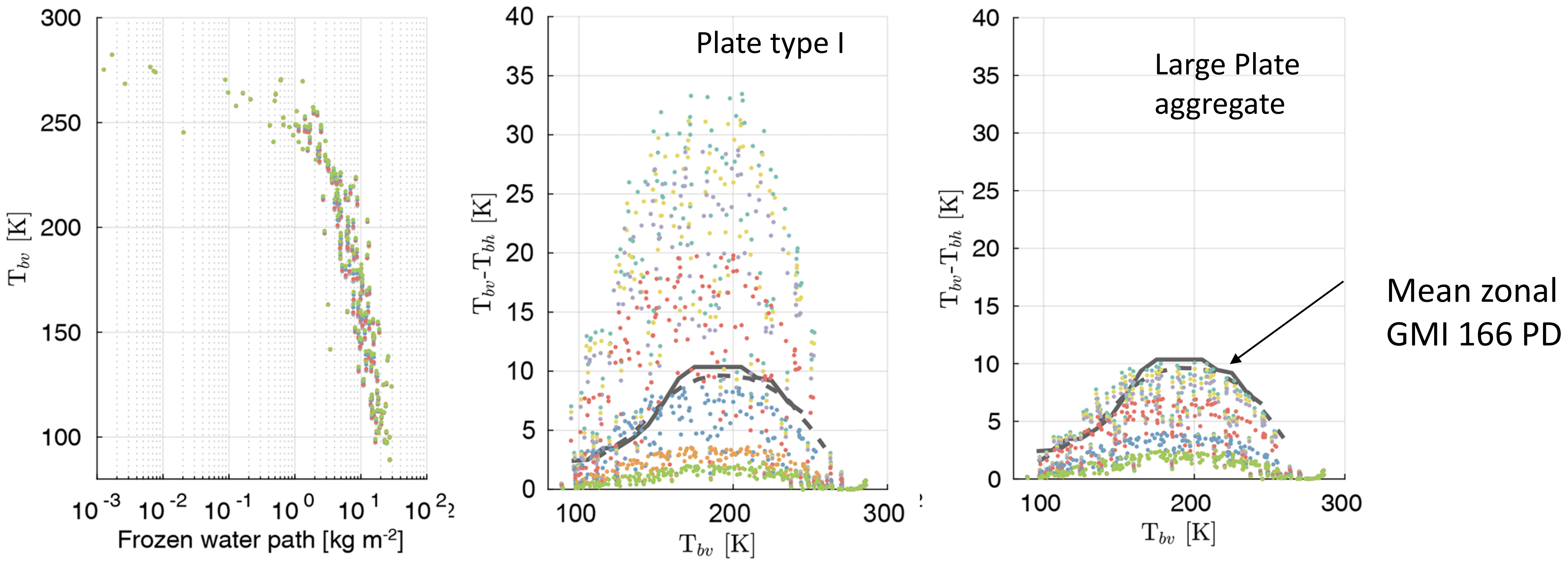
Can only be tested for existing measurements below 200 GHz

Wang, D. C. Prigent, F. Aires, C. Jiménez, 2016 : A statistical retrieval of cloud parameters for the millimeter wave Ice Cloud Imager on board MetOp-SG. IEEE, DOI: 10.1109/ACCESS.2016.2625742.

Log_{10} Integrated Water (kg/m^2)

Polarization information

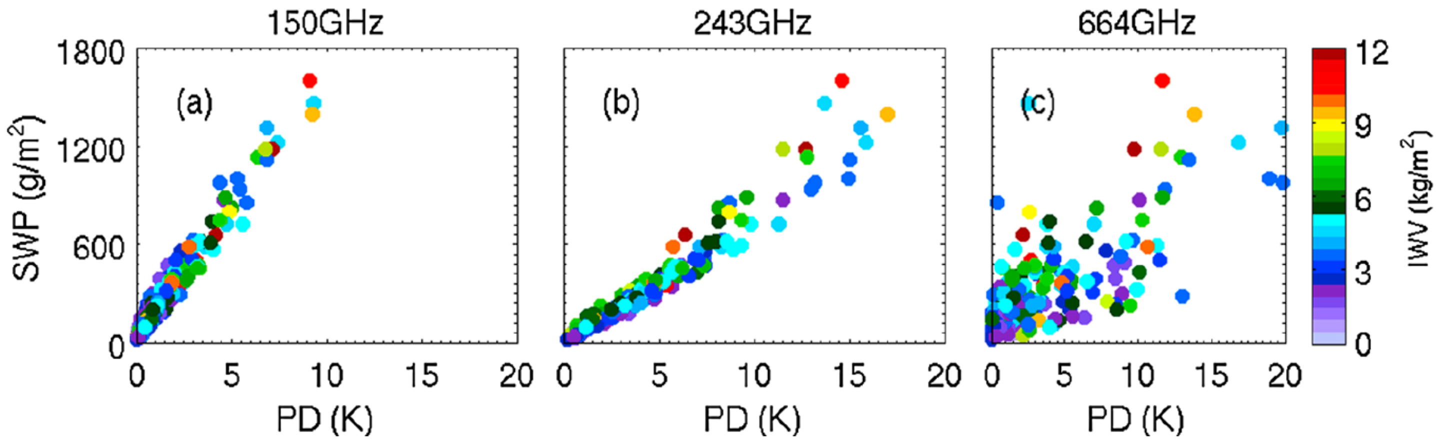
166 GHz – GMI frequency



Brath, M., Ekelund, R., Eriksson, P., Lemke, O., & Buehler, S. A. (2020). [Microwave and submillimeter wave scattering of oriented ice particles](). Atmospheric Measurement Techniques, 13(5), 2309-2333.

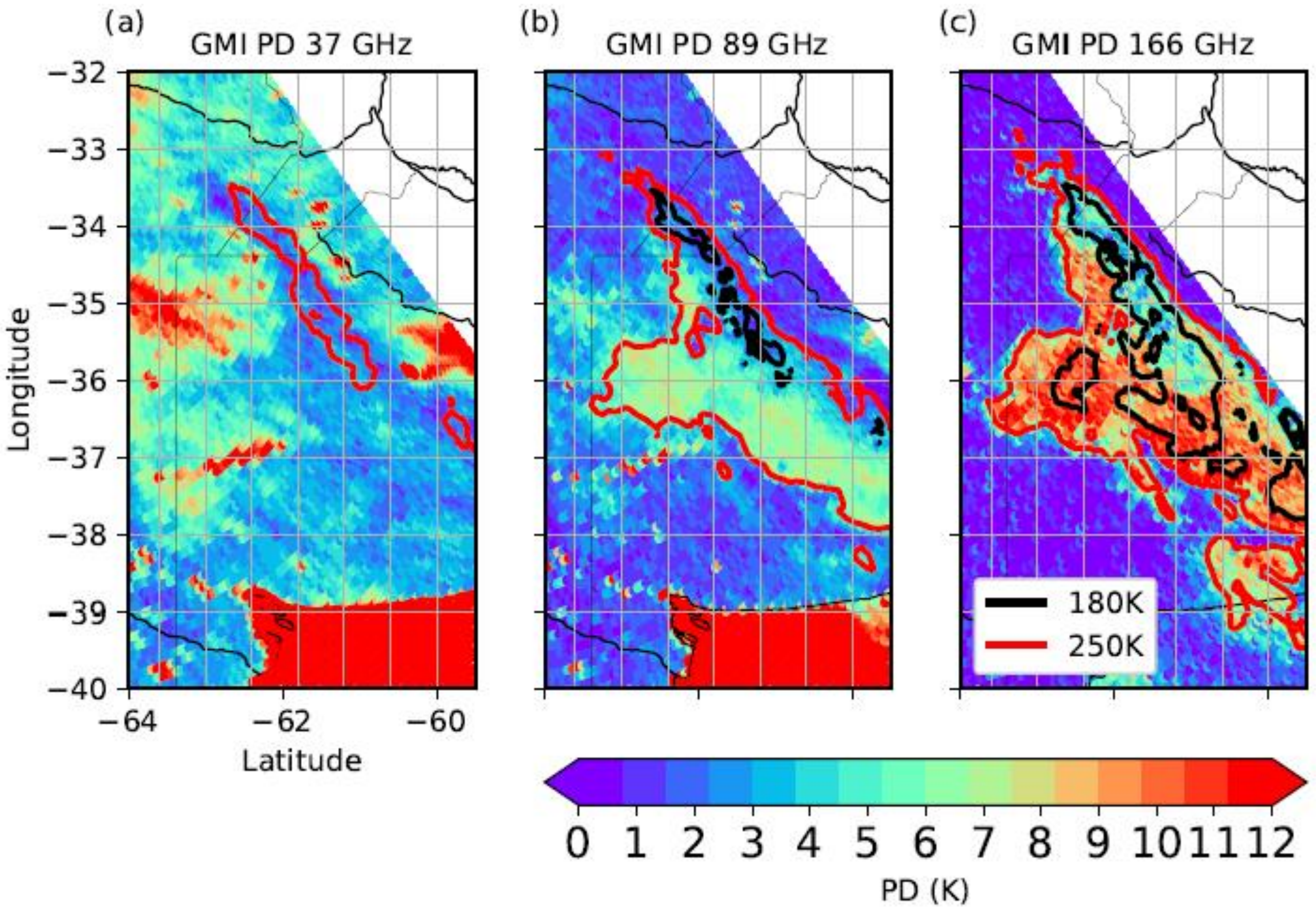
Polarization under absorbing conditions

Polarization difference (PD=TBV-TBH) caused by snow layer with varying snow water path (SWP)



Xie, X., S. Crewell, U. Löhnert, C. Simmer, J. Miao: Polarization Signatures and Brightness Temperatures Caused by Horizontally-Oriented Snow Particles at Microwave Bands: Effects of Atmospheric Absorption, J. Geophys. Res., 2015.

Exploiting polarization information



- polarized observations are linked to the orientation and shape of ice habits
- stratiform clouds show larger polarization differences (TBV-TBH) due to the presence of horizontally aligned snowflakes
- convective regions show smaller PD signals, as graupel and/or hail in the updraft tend to become randomly oriented

ICI will provide both polarizations at 243 and 664 GHz

Galligani, V. S., Wang, D., Corrales, P. B., & Prigent, C. , 2021: A Parameterization of the Cloud Scattering Polarization Signal Derived From GPM Observations for Microwave Fast Radative Transfer Models. *IEEE Transactions on Geoscience and Remote Sensing*.

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- Novel capabilities
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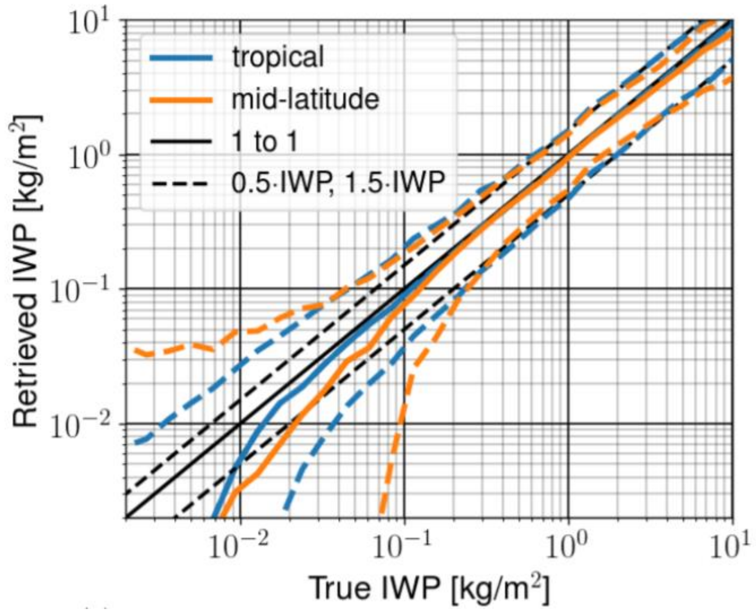
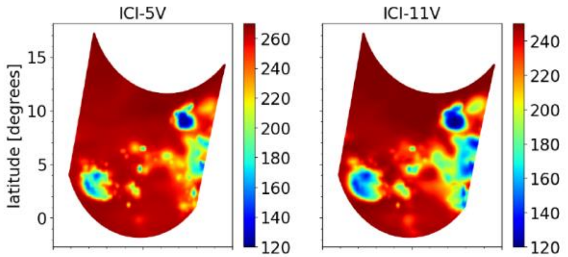
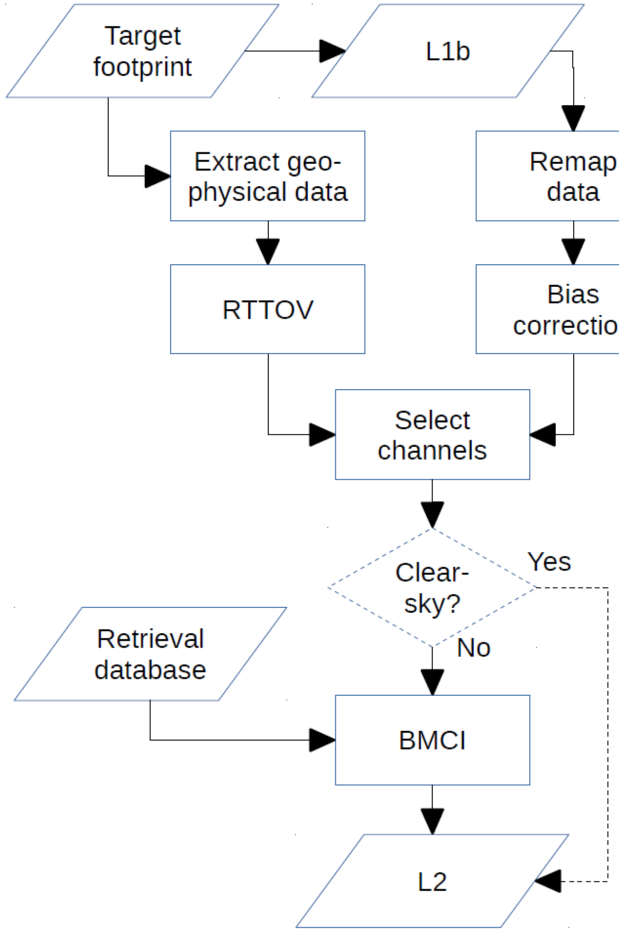


Operational ICI retrieval

- Toolbox for remapping of channels



- Retrieval data base providing atmospheric states and corresponding ICI measurements
  - CloudSat Scenes
  - microphyscial models
  - tests at existing frequencies
- Bayesian Monte Carlo Integration providing estimated posteriori distribution 5th, 16th, 50th, 84th and 95th percentiles



Eriksson, P., Rydberg, B., Mattioli, V., Thoss, A., Accadia, C., Klein, U., and Buehler, S. A.: Towards an operational Ice Cloud Imager (ICI) retrieval product, Atmos. Meas. Tech., 2020.

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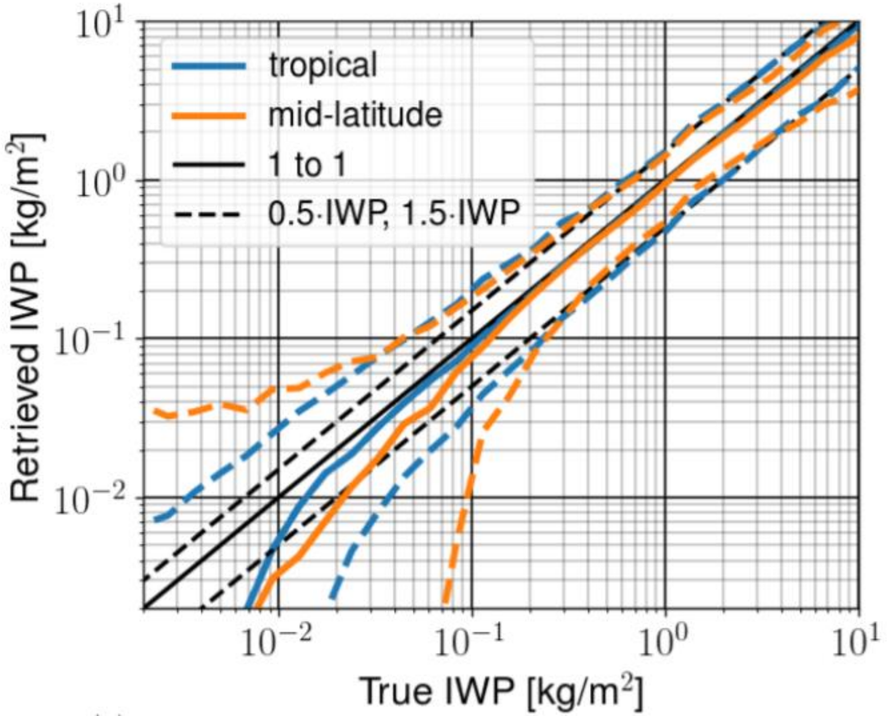
Operational ICI IWP product



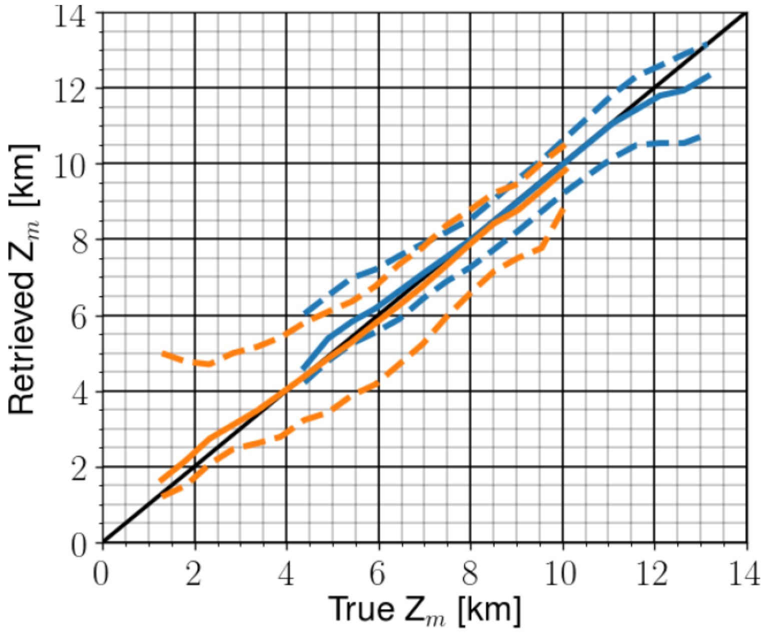
Dashed coloured lines match ±2σ

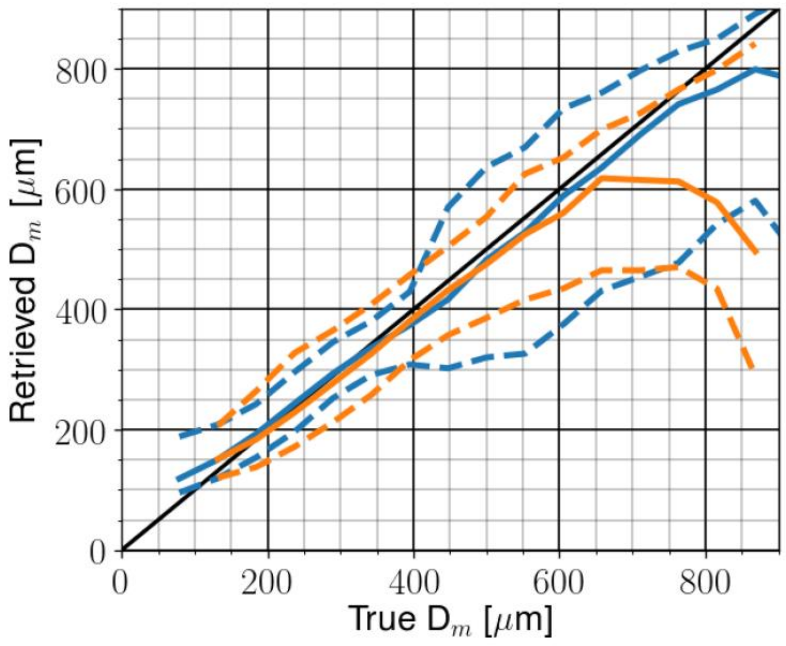
90% confidence at best inside 50% of IWP value

Good retrieval performance for Ice Water Paths higher than 0.1 kg/m^2

Eriksson, P., Rydberg, B., Mattioli, V., Thoss, A., Accadia, C., Klein, U., and Buehler, S. A.: [Towards an operational Ice Cloud Imager (ICI) retrieval product](), Atmos. Meas. Tech., 2020.

Additional retrieval products





Dashed coloured lines match ±2σ

Mean mass height (Z_m) and mean mass diameter (D_m) can be determined at best inside 700m and 50 µm, respectively.

Eriksson, P., Rydberg, B., Mattioli, V., Thoss, A., Accadia, C., Klein, U., and Buehler, S. A.: Towards an operational Ice Cloud Imager (ICI) retrieval product, Atmos. Meas. Tech., 2020.

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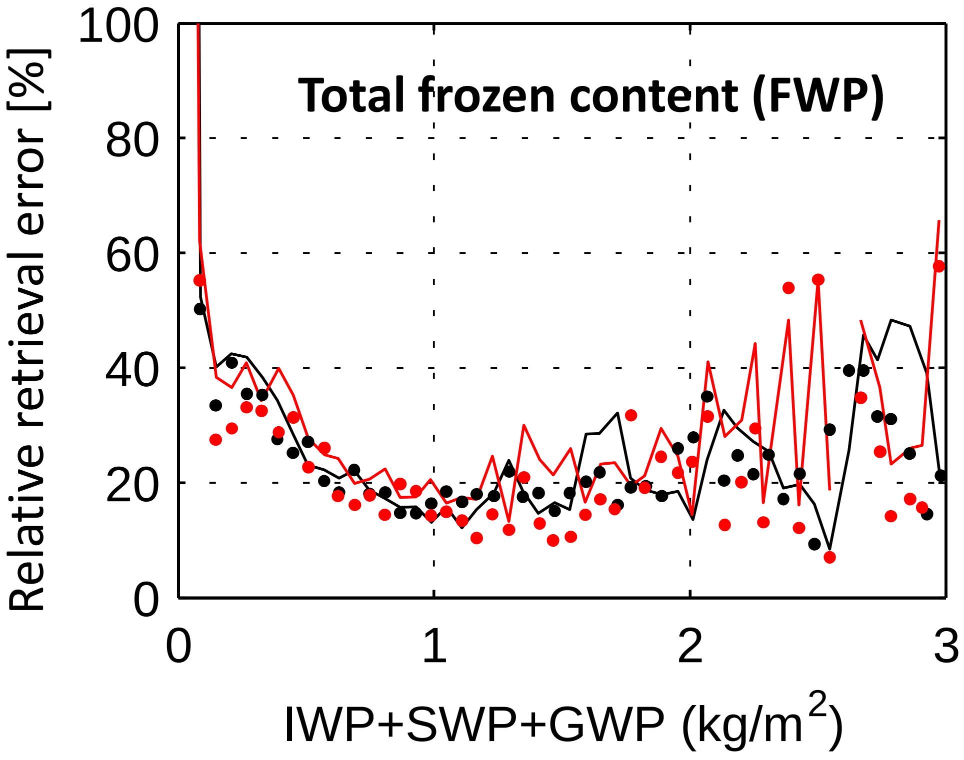
..a different approach



Neural network approach with prior hydrometeor type identification

- below 40 % relative error for 0.1 kg/m^2 < FWP < 0.5 kg/m^2
- below 20 % relative error for FWP > 0.5 kg/m^2

Land ICI   Sea ICI

Land ICI+MWI   Sea ICI+MWI

Wang, D. C. Prigent, F. Aires, C. Jiménez, 2016 : A statistical retrieval of cloud parameters for the millimeter wave Ice Cloud Imager on board MetOp-SG. IEEE, DOI: 10.1109/ACCESS.2016.2625742.

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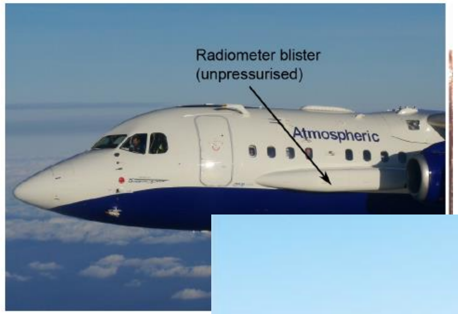

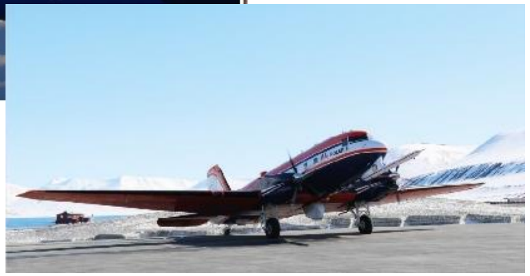

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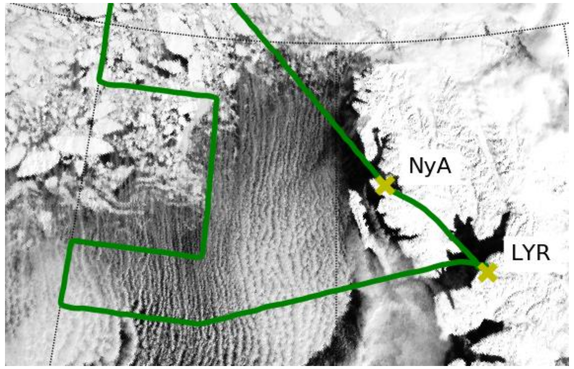
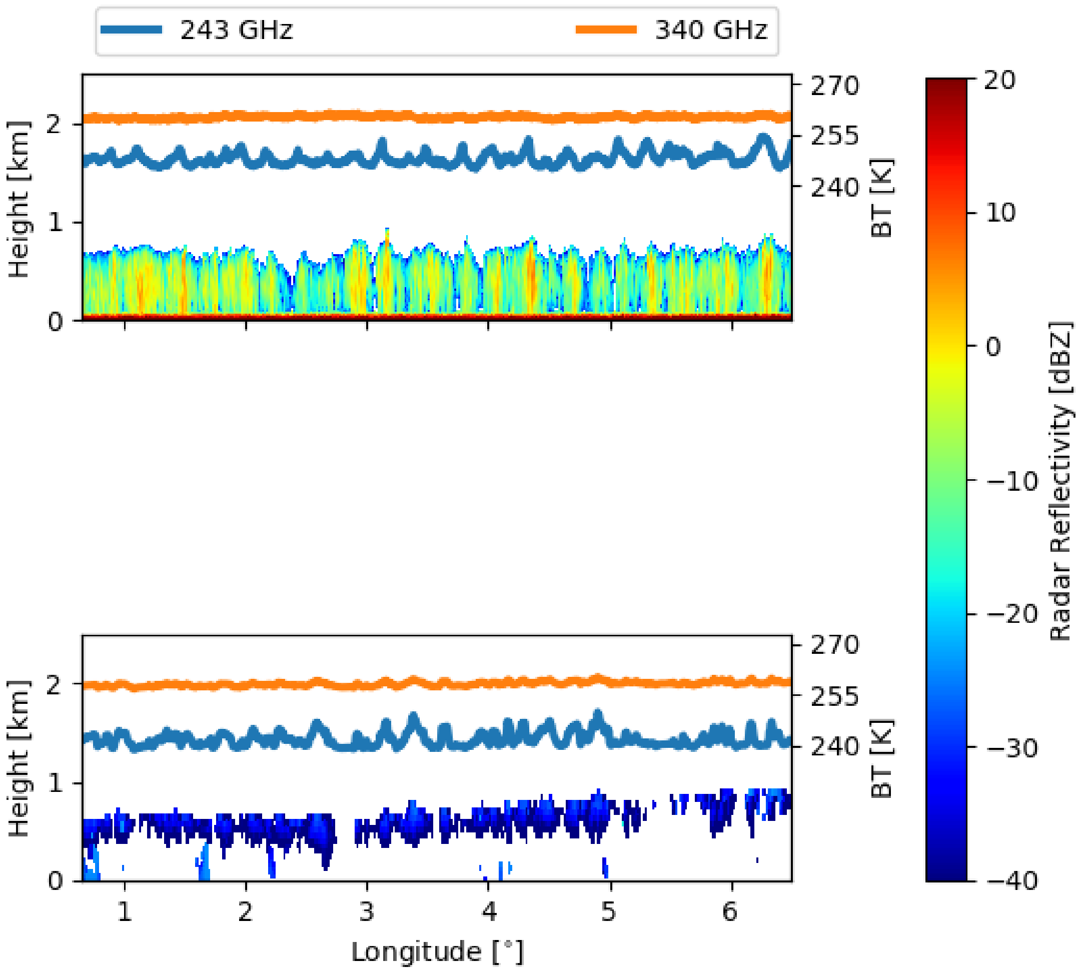
Airborne Active/passive measurements



Measurements

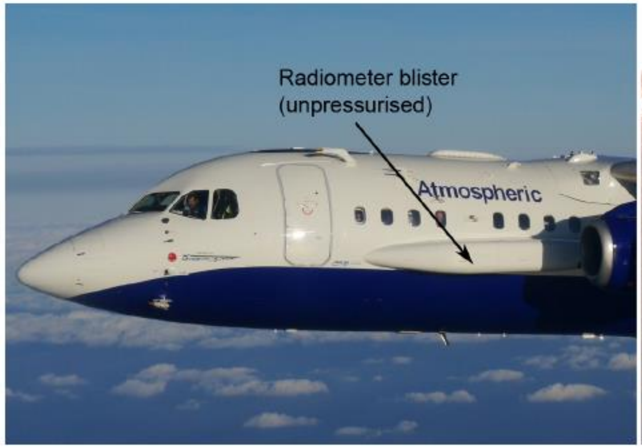
Standard microphysical scheme

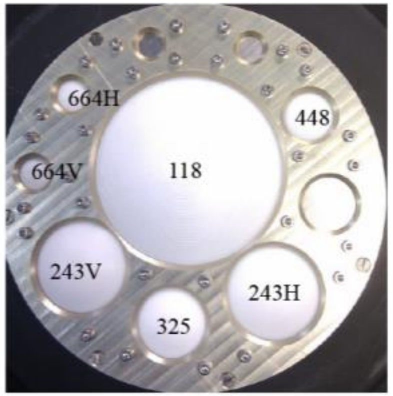
Testing of ICON 2-moment scheme



Airborne Demonstrator (ISMAR)

International Submillimetre Airborne Radiometer (**ISMAR**)



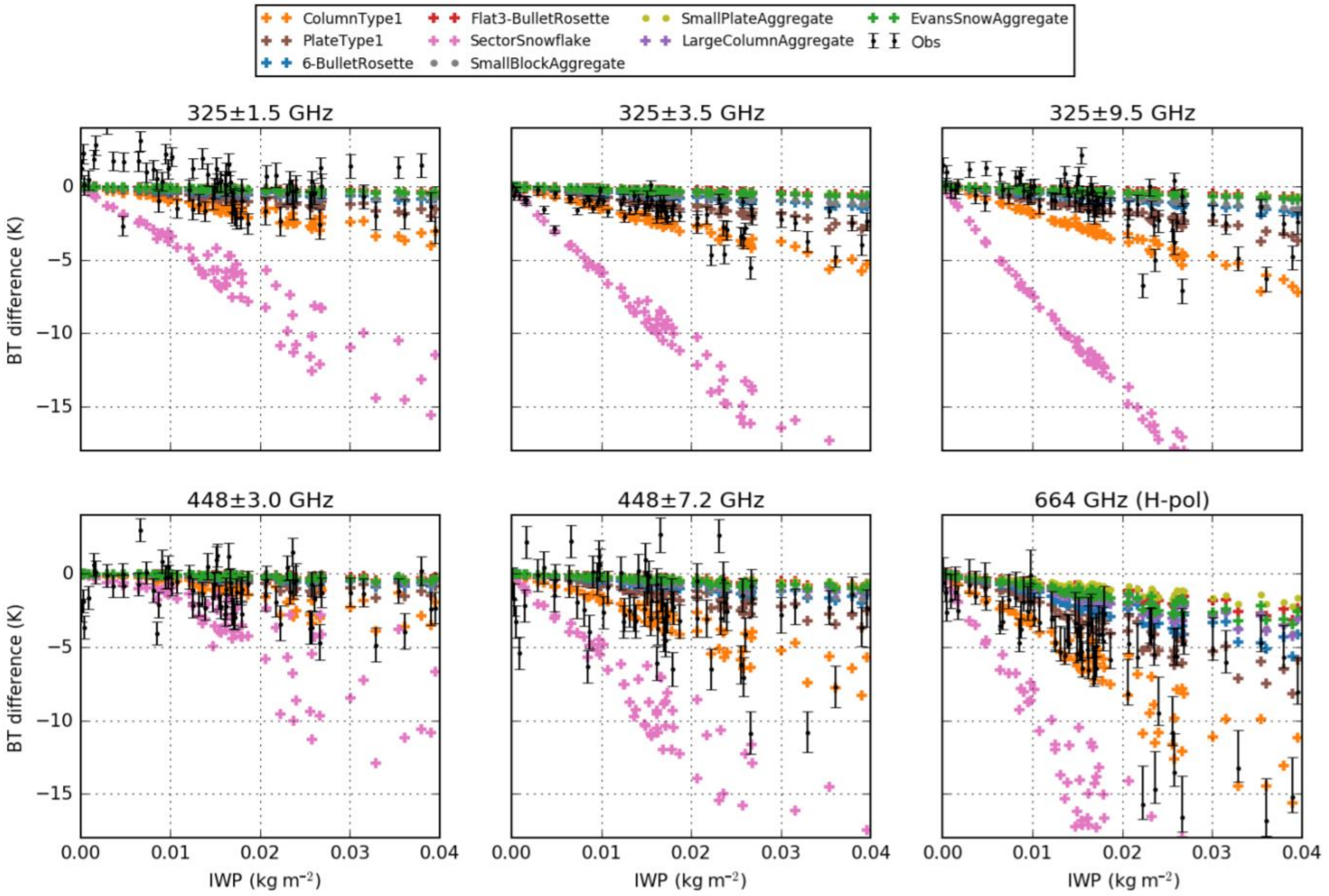


Front view of receiver array
showing PTFE lenses

- Ability to scan and provide upward and downward looking perspective
  → comparison of high-altitude zenith views with radiative-transfer simulations
- Bias in most channels is less than ±1 K and the NEΔT is less than 2 K, with many channels having an NE Δ T less than 1 K.

Fox, S., Lee, C., Moyna, B., Philipp, M., Rule, I., Rogers, S., King, R., Oldfield, M., Rea, S., Henry, M., Wang, H., and Harlow, R. C.: ISMAR: an airborne submillimetre radiometer, Atmos. Meas. Tech., 10, 477–490, 2017.

Airborne Demonstrator (ISMAR)



Fox, S., Mendrok, J., Eriksson, P., Ekelund, R., O'Shea, S. J., Bower, K. N., Baran, A. J., Harlow, R. C., and Pickering, J. C.: [Airborne validation of radiative transfer modelling of ice clouds at millimetre and sub-millimetre wavelengths](), Atmos. Meas. Tech., 12, 1599–1617, 2019.

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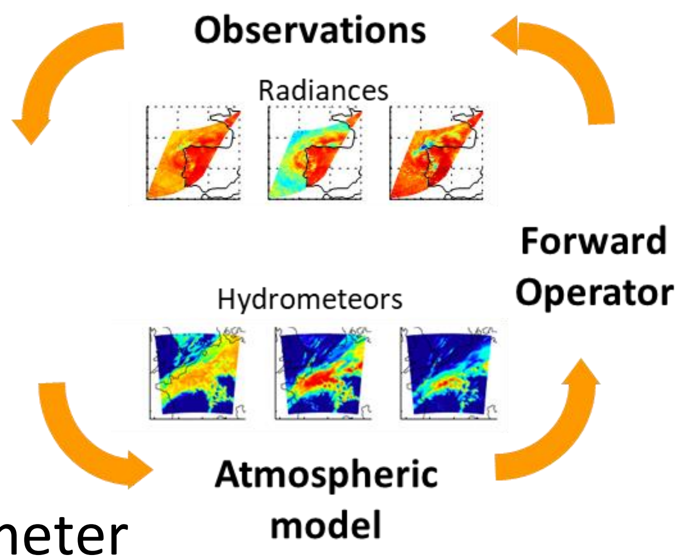
Conclusions

- **ICI** as a compact, low power, relatively low-cost mission will complement existing satellite measurements

- **ICI** impact to weather forecast via data assimilation
  → RTTOV (SCAT) fundamental
  → support development of
  microphysical parameterizations



- **ICI** retrieval ready for IWP, mean mass height and diameter

- **ICI** data will provide new opportunities for climate monitoring, nowcasting and reanalysis.
  → understanding of hydrometeor- radiation strongly increasing

Outlook

To fully prepare for ICI data

- development / validation of a **gas absorption** model using astronomical and airborne observations,
- further refining **single scattering** data bases,
- evaluation of ice **retrievals** with ISMAR and other aircraft data,
- investigation of **polarization** features, and
- **assimilation** tests in operational NWP environments

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