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Remote Sensing of Vertical Profiles of Clouds and In-cloud Humidity Using a Combined Platform of Radar and Sub-Millimeter Microwave Radiometers

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TWICE, CloudCube, ENTICE

To provide coincident vertical profiles of hydrometeor particle size, ice water content, and in-cloud humidity and temperature by using a combined platform of low-cost multi-frequency sub-mm microwave radiometers and radar.

TWICE: Tropospheric Water and Cloud ICE (TWICE)

- PI S. Reising of CSU and Co-Is P. Kangaslahti of JPL and W. Deal of Northrop Grumman Corporation (NGC).
- Low-cost multi-frequency InP HEMT monolithic millimeter-wave integrated circuit (MMIC)-based radiometers for CubeSat and Smallsat missions developed under extensive investment by NASA ESTO.
- 118, 183, 380 GHz temperature and water vapor sounding channels and 240, 310, and 650 GHz window channels for cloud ice detection, 5-15km resolution
- Technical level: TRL-6. All receivers built and tested, assembly of the instrument completed.
- Instrument capability simulations and retrievals (Jiang et al. 2017)

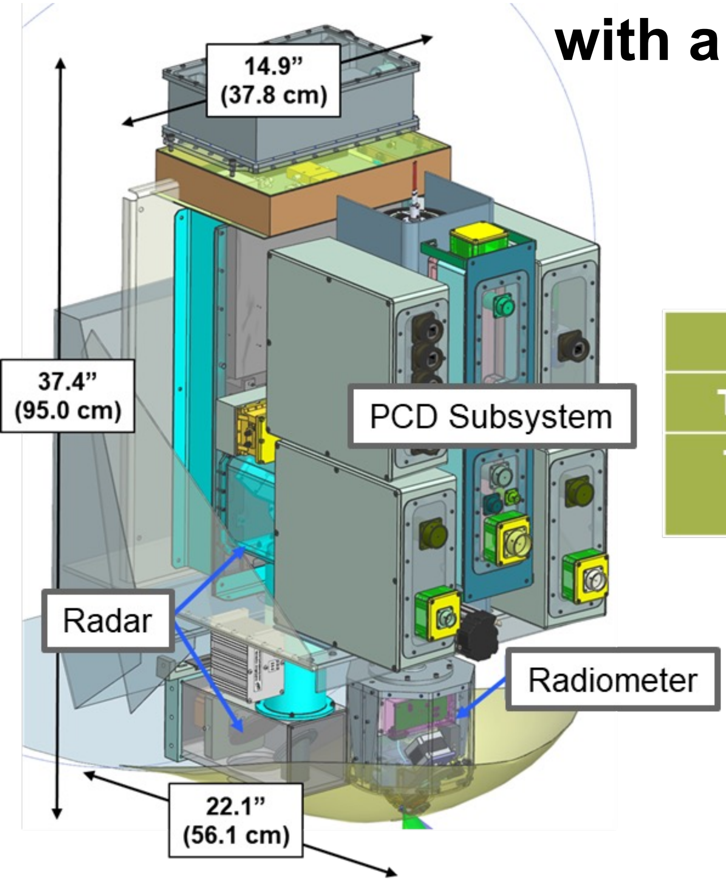
CloudCube: A compact multi-frequency mm-wave radar

- PI R. Rodriguez Monje of JPL, developed under ESTO IIP 2019 (Rodriguez Monje et al. 2021).
- Combines Ka-, W-, and G-band (35/94/239GHz) radar backscatter with Doppler velocity measurement capability at Ka-band.
- Modular design to allowing for selection of radar frequencies to meet targeted mission observables and budget.
- TRL-6.
- Space, aircraft, and ground-based.

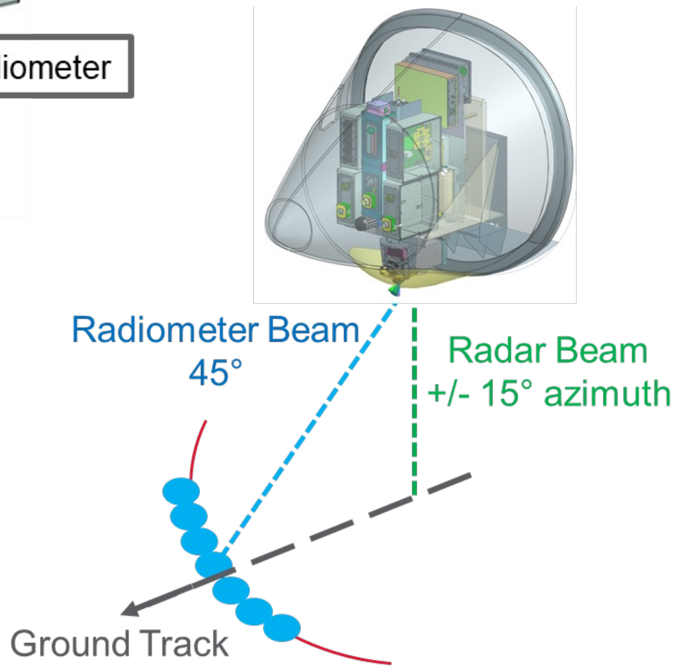
ENTICE: Earth's NexT-generation ICE mission concept

- Adding 850 GHz window channel to enhance sensitivity to cloud top and thin cirrus.
- Combining with a compact millimeter-wave radar for cloud or precipitation as CloudCube.
- Instrument simulation and retrievals (Jiang et al. 2019, Yue et al. 2020).
- Orbital sampling simulations (Johnson et al. 2021)

SMart Ice Cloud Sensing (SMICES) with a SmallSat Active/Passive Terahertz Instrument



Total Size	38 cm x 95 cm x 56 cm
Total Weight	80 kg
Total Power with AI	60 W



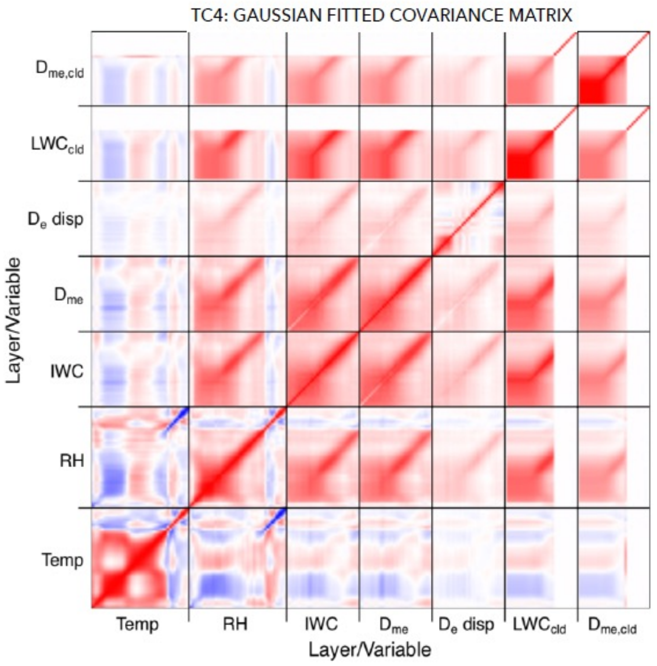
The instrument will be demonstrated airborne, paving the way to future SmallSat missions

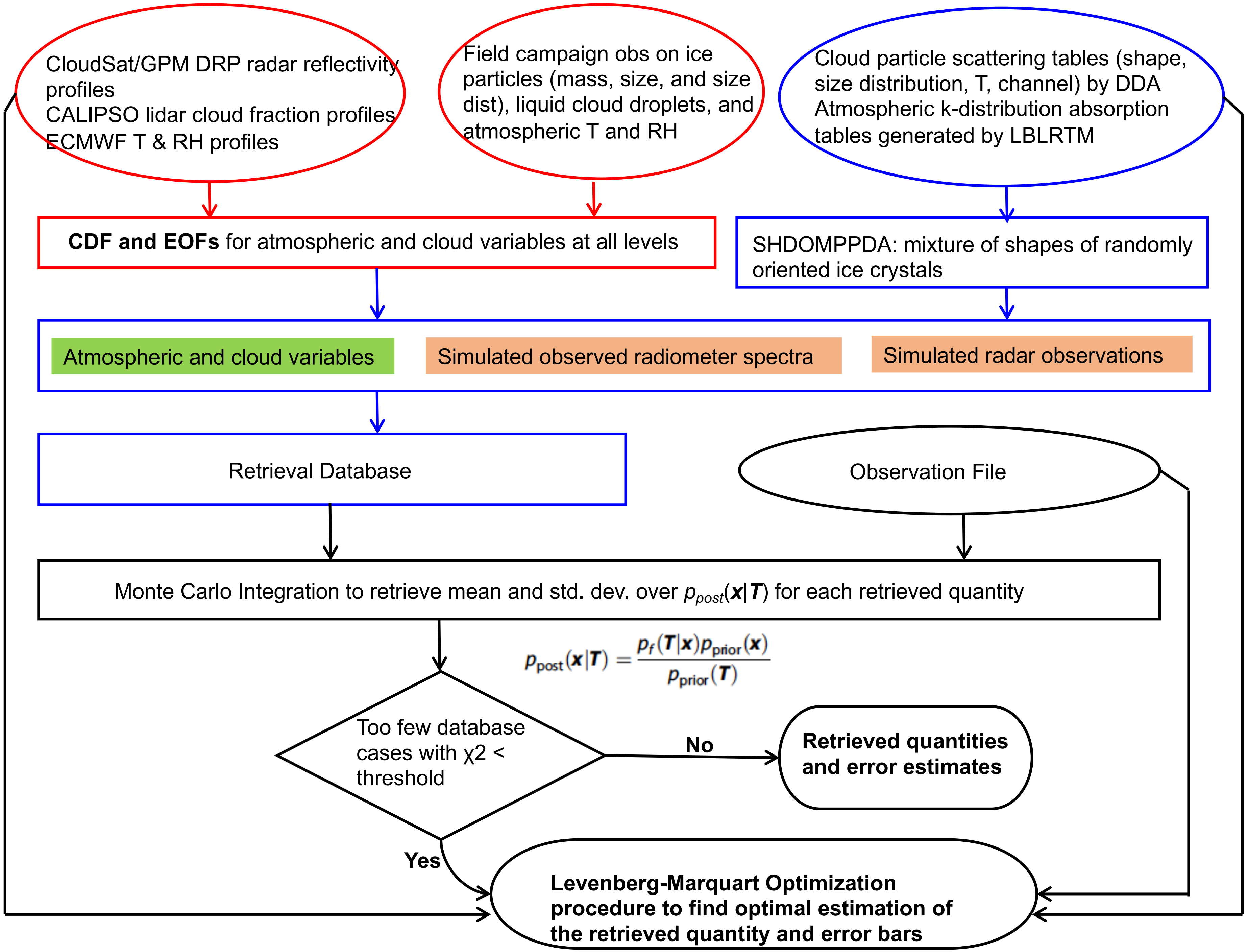
NASA ESTO IIP.

SMICES comprises:

- 239 GHz radar
- 250 GHz, 310 GHz and 670 GHz radiometers
- 380 GHz sounder
- On-board artificial intelligence (AI) controller detects radiometric features to intelligently control the radar turn-on and pointing.

JPL Sub-millimeter Microwave Simulation and Retrieval Package





Evans et al. 2005, 2012
Jiang et al. 2017, 2019
Yue et al. 2020

Hydrometer and Atmospheric Variables

Ice cloud:
Rain (melted ice cloud):

→ Vertical profiles of IWC, D_e, $D_{e,disp}$, shape, and vertically integrated parameters

Super cooled liquid water:
Liquid cloud cloud

→ Vertical profiles of LWC, De, and vertically integrated parameters

Atmospheric States:

→ temperature, water vapor mixing ratio, relative humidity

Table 2. Ice Particle Shapes Used in the Simulation and Their Applied Ranges of D_{me}

Particle Shape	Min D_{me} (μm)	Max D_{me} (μm)
Plate aggregates	6.310	398.1
Sphere aggregates	5.012	1584.9
Snow aggregates	63.10	1584.9
Solid sphere	398.1	3162.3

Shapes are allowed to vary among mixtures of realistic ice particle shapes in order to better simulate the actual ensemble of particles.

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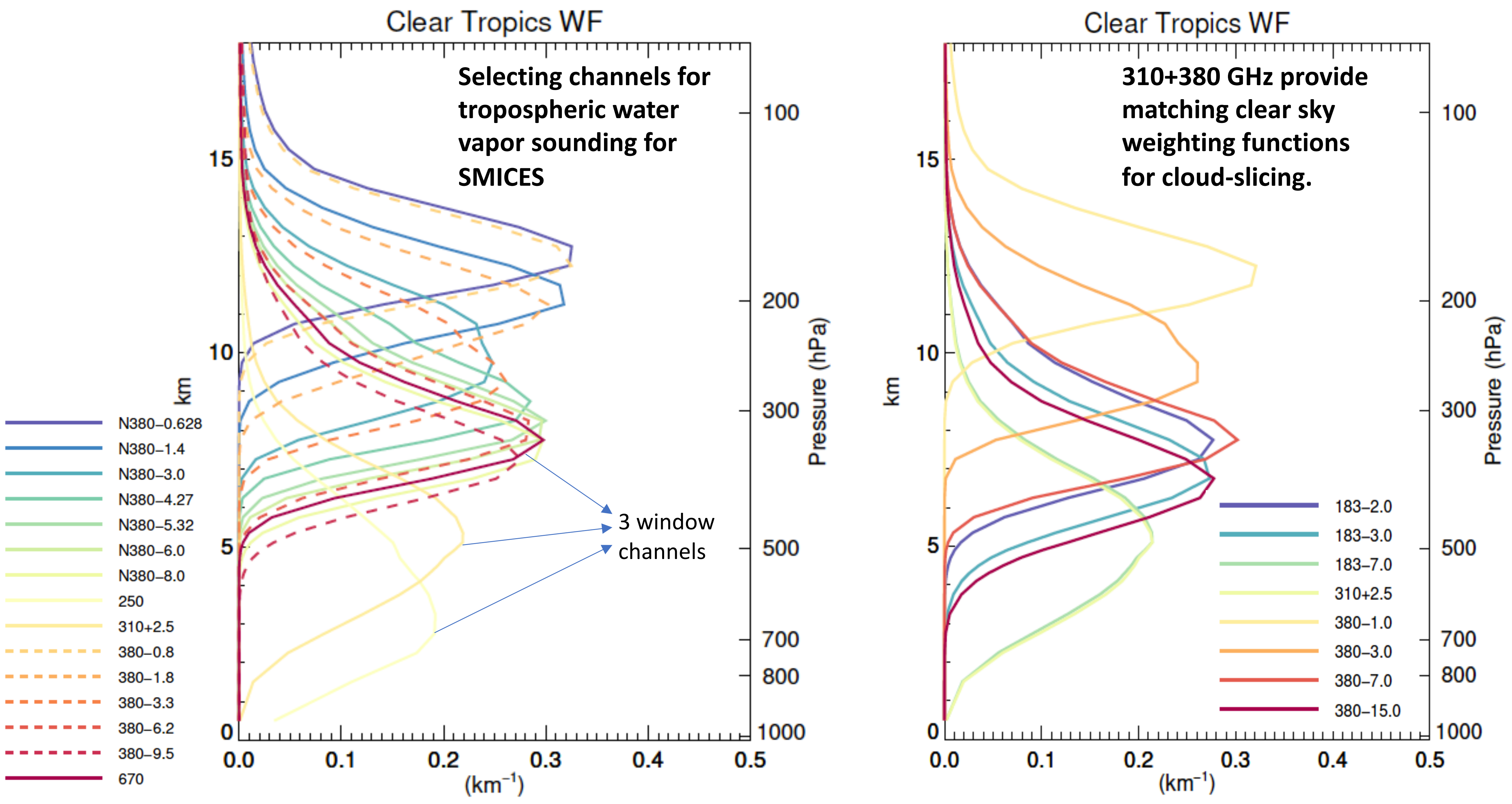
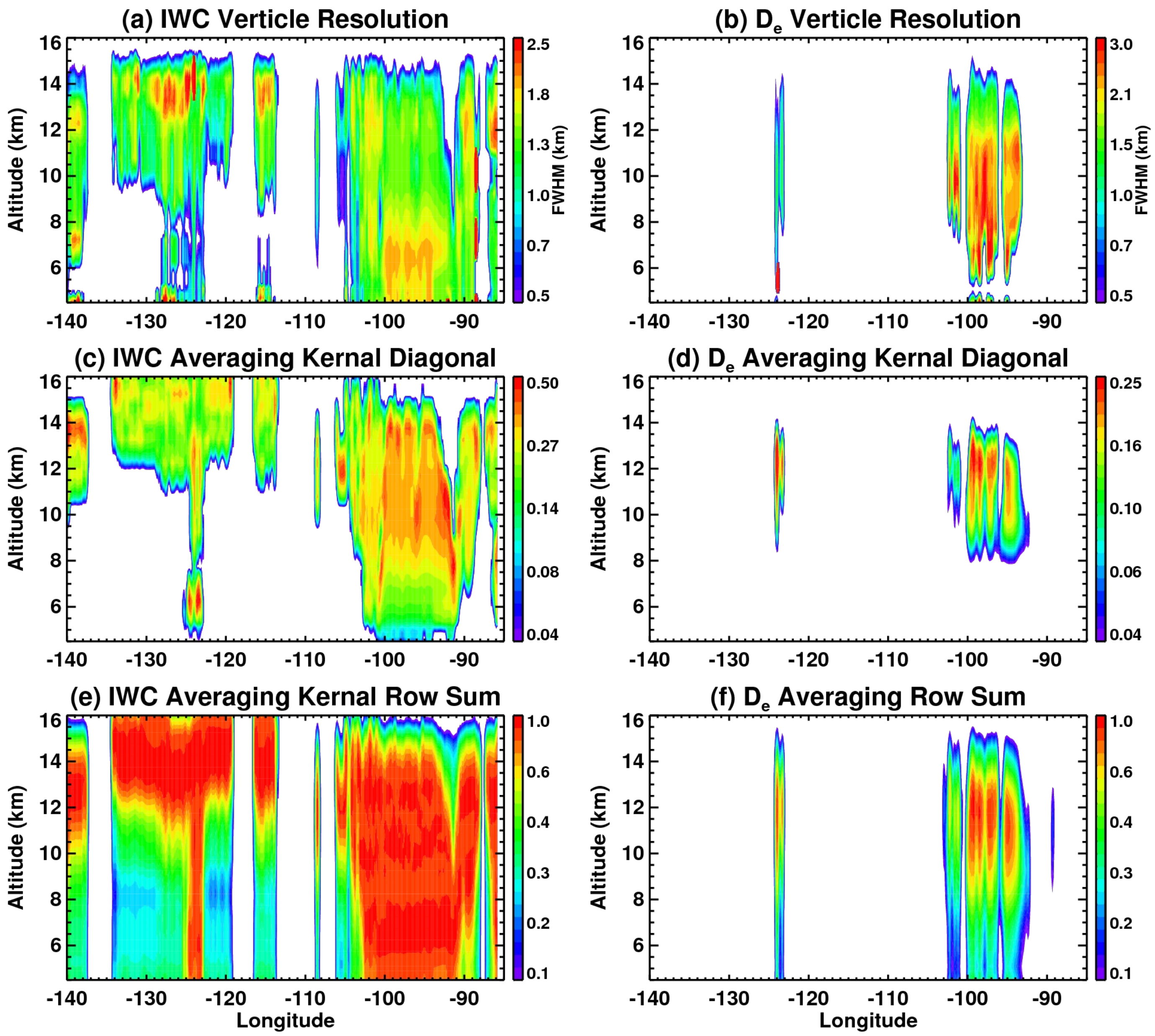
Scattering tables and Absorption tables as a function of atmospheric states and hydrometer properties

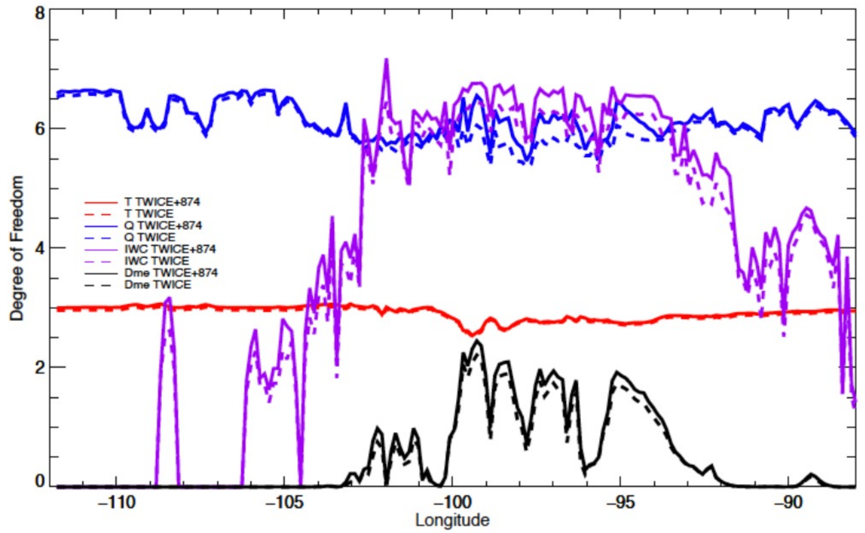
Water Vapor Sounding with 380 GHz Channels



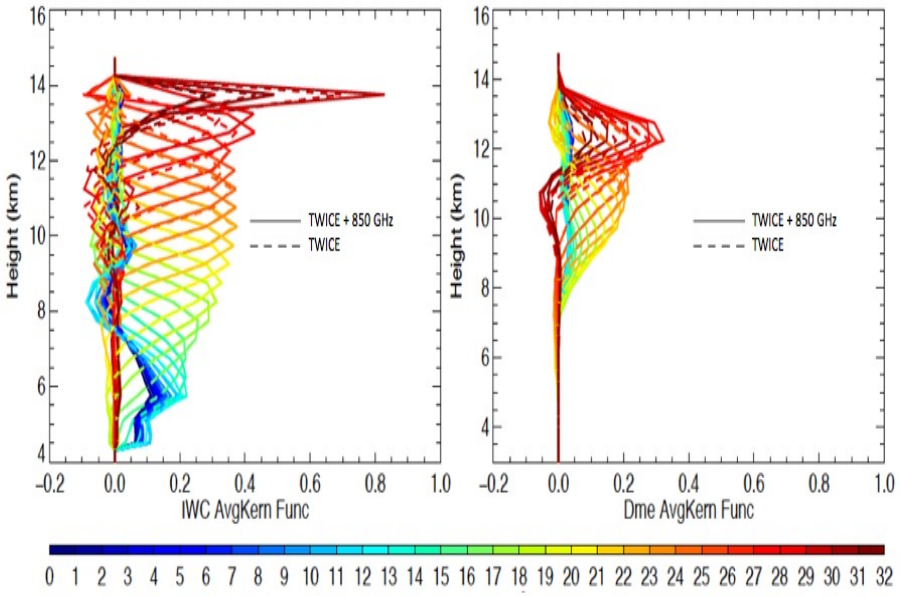
Information Content Analysis For Passive Radiometers Only: TWICE-Alone



Degree of Freedom

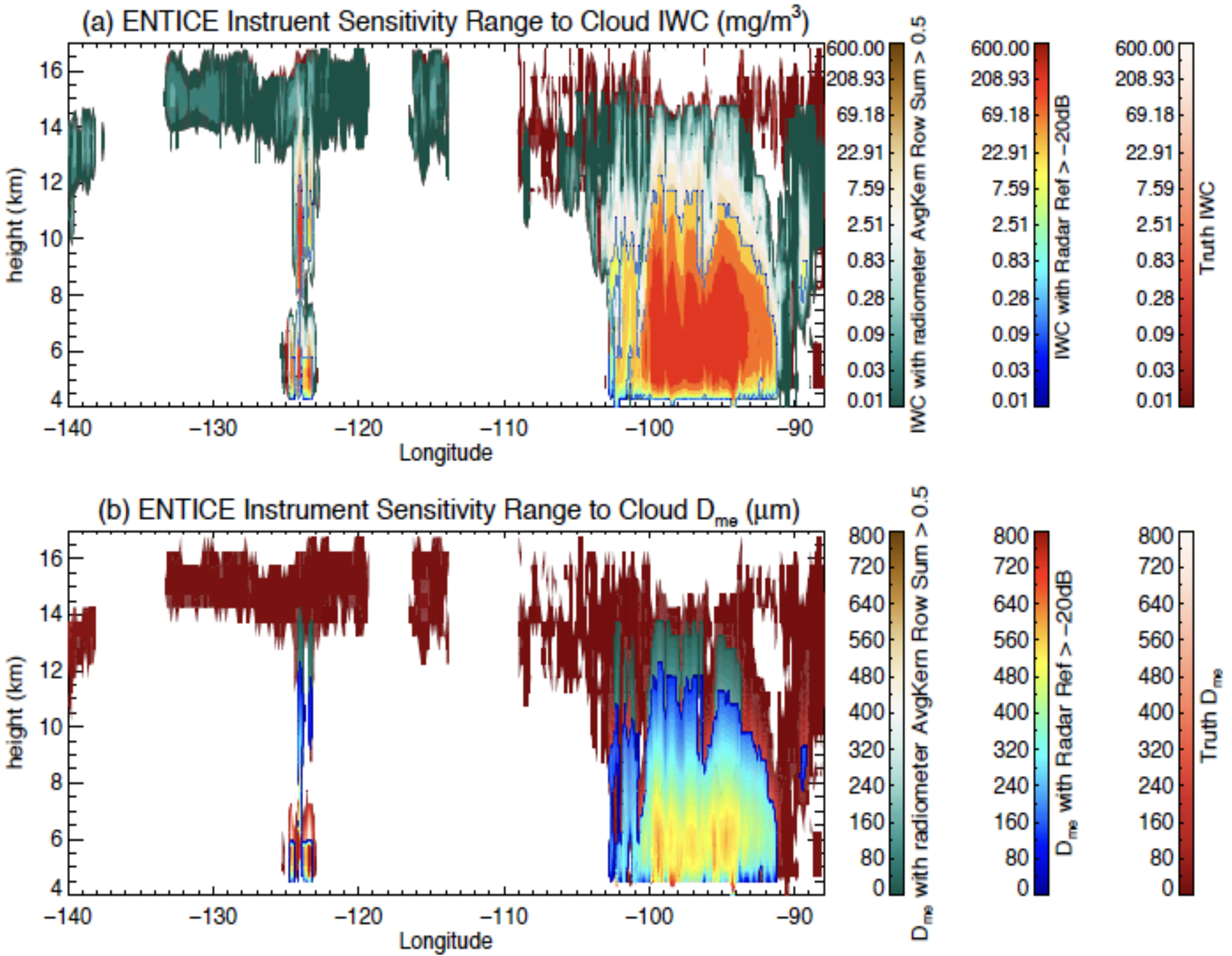


Avg Kern. Of a Single Case



Combine radar and radiometer to produce high vertical resolution profiles of both IWC and particle size to better resolve key processes controlling anvil clouds

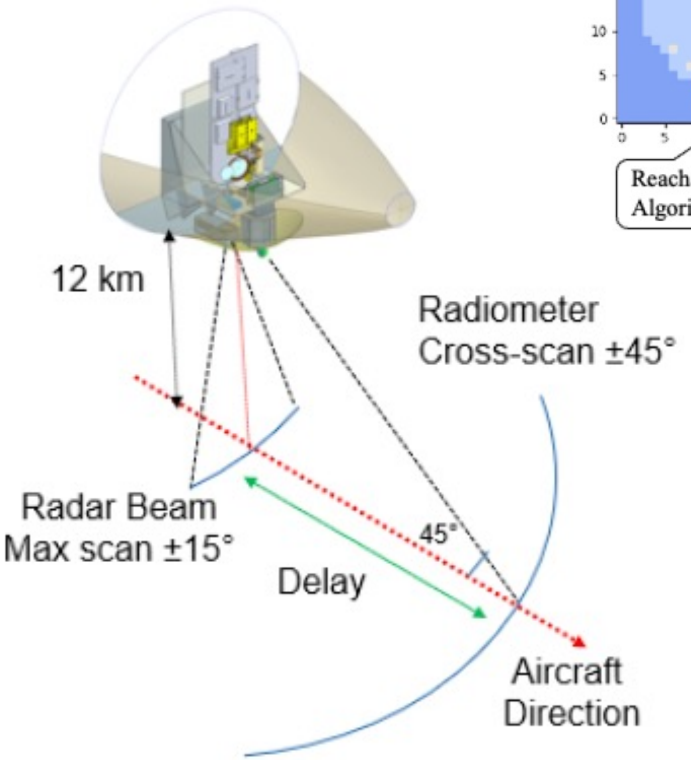
- Enhanced vertical resolution(*Radar: 500m; Radiometers: 1~3km)*
- Obtaining vertical profiles of cloud ice microphysics through convective clouds
    - *Radiometers are only sensitive to De above 8km, but have higher sensitivity to cloud top and IWC of thin cirrus.*
    - *Radar deeper penetration to the convective clouds.* Single piece of information from radar on the sensitivity to particle size distribution below 8km in the deep convective cloud
- Missing the thin cirrus and the very top of the deep convective cloud, especially for particle size retrieval -> importance of program of record observations, such as IR sounding, and visible/IR imaging.

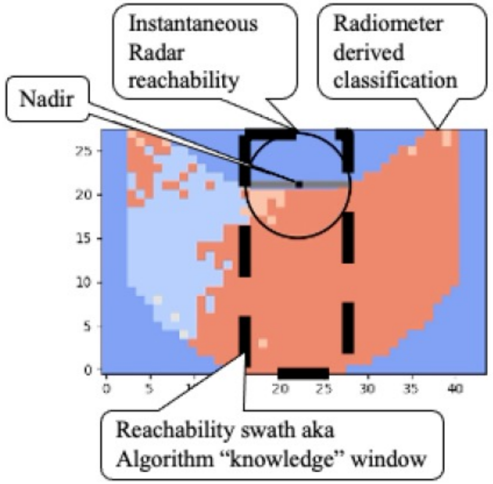


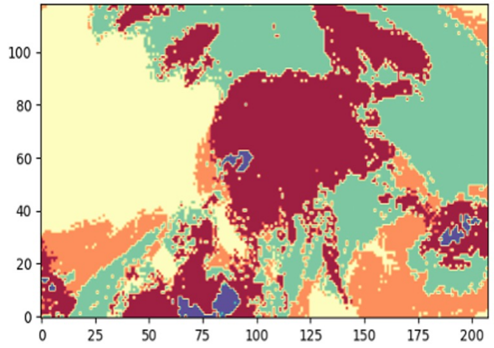
Connecting Science with AI-Labeling of Observing Targets

Combined conventional swath and AI-Smart observation approach provides more detailed observations on objects of high science interests together with information of the entire cloud system

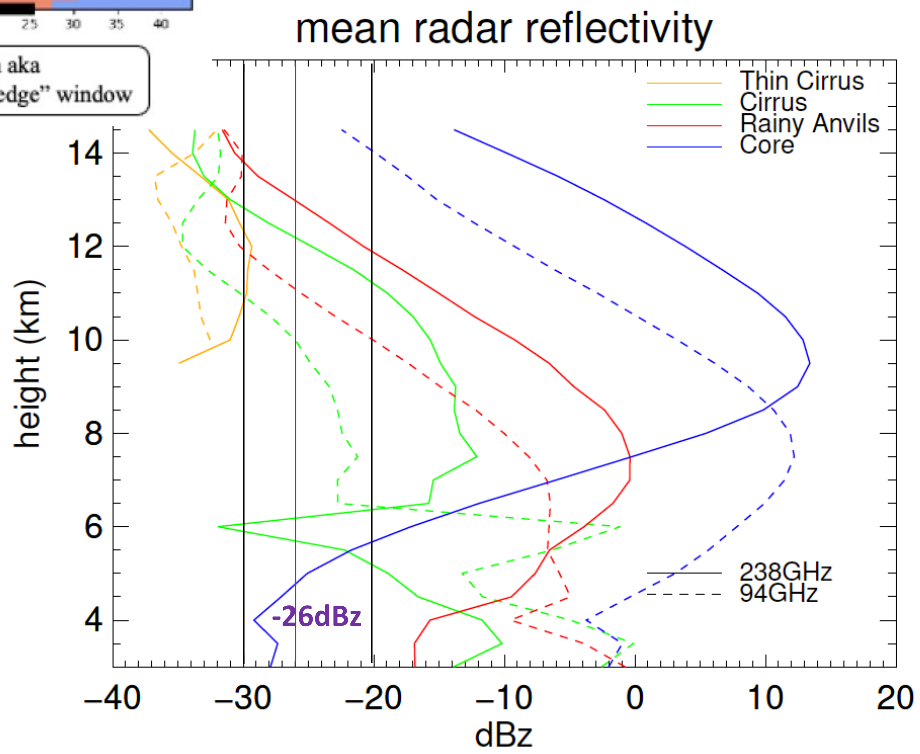
SMICES

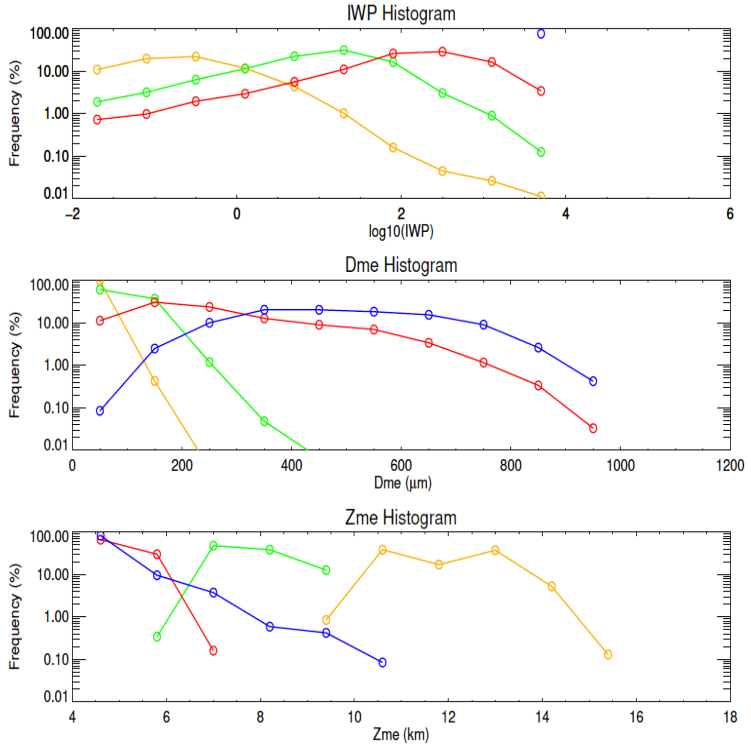






AI-identified clusters from cloud variables:
- Convective Core
- Thick Anvils
- Anvil Cirrus
- Thin Cirrus
- Clear Sky





M. Ogut, *et al.*, 2022
J. Swope et al. 2021
X. Bosch-Lluis *et al.*, 2022.

Summary

- A combined platform of radar and multi-frequency passive microwave sub-millimeter radiometers is recommended by the 2017 Decadal Survey as a candidate measurement approach for the Clouds, Convection and Precipitation (CCP) Designated mission.
- Multiple instruments have been developed with support from NASA's ESTO, that are technically ready for airborne, CubeSat and Smallsat missions.
- This study presents the JPL Sub-millimeter Microwave Simulation and Retrieval Package [Jiang et al. 2017, 2019, Yue et al., 2020] which provides a quantitative analysis on the capability of such measurements. The package is computationally efficient and simulates a wide range of microwave frequencies. It includes a Bayesian retrieval retrieval package with the a priori PDF including both the CDF of single parameter at a given level and the EOFs describing the relationships between variables and levels/layers.
- This study further demonstrates a smart observing scheme in which a radar targets the deep convective clouds based on information collected by lookahead radiometers [Swope et al. 2021].
- Together, our study shows a pathway towards a better quantification of ice cloud radiative effects to constrain model simulations of ice cloud feedbacks and associated hydrological processes.

Multiple Frequencies for Vertical Profiles of Clouds and In-Cloud Atmospheric States

Passive radiometer suite: window channels and T/Q sounding channels

- Sub-mm channels for instrument capability study with different channel specifications

Feature	Water Vapor Lines	Oxygen Lines	Window
Center [GHz]	183 325 380 448 620	118 425 487	220 243 310 640 683 850, 870

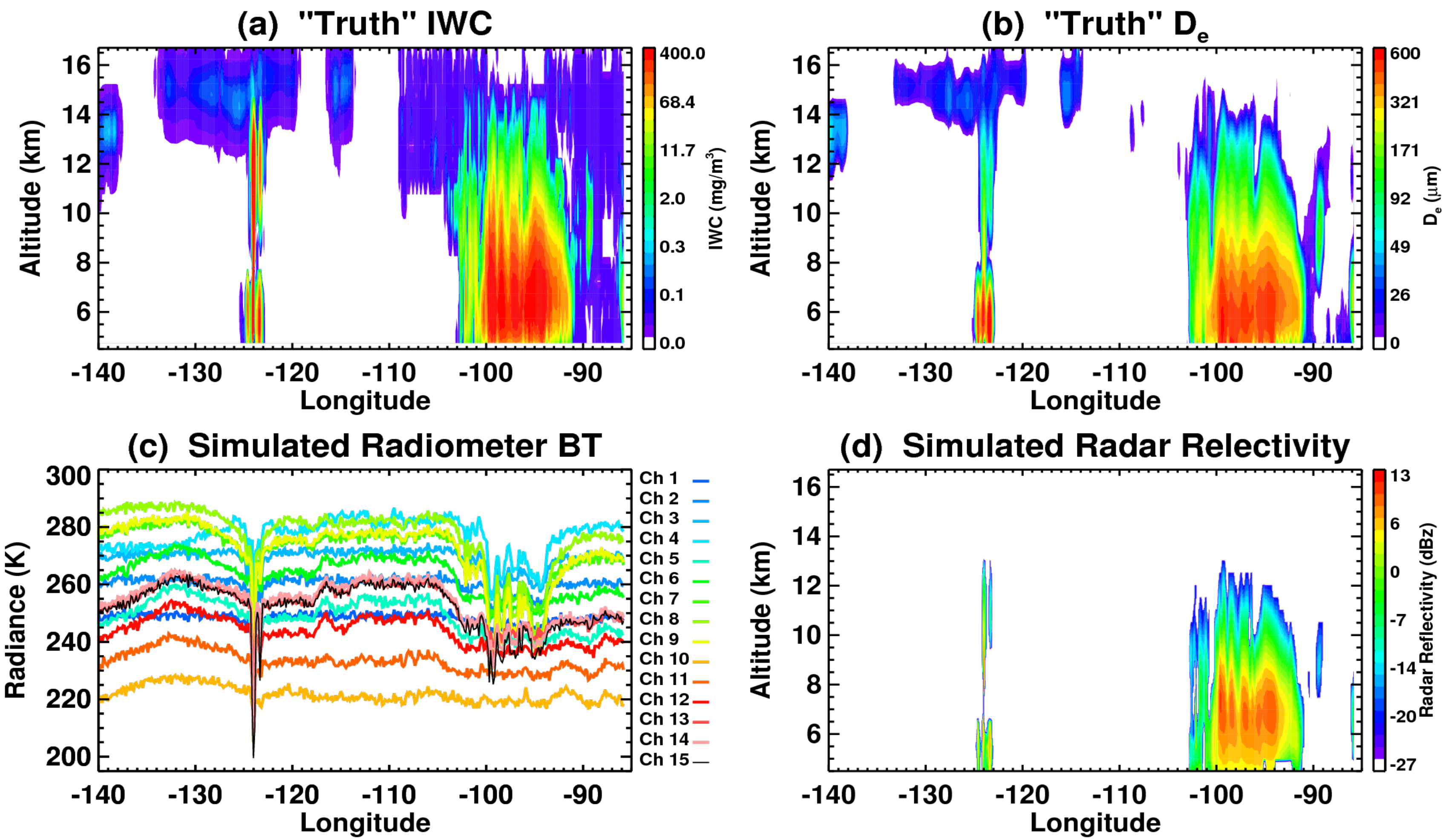
- ATMS and GMI channels

Active radar reflectivity:

- W-Band 94 GHz cloud radar
- G-Band 239 GHz cloud radar
- Capability to simulate more frequencies: GPM DPR

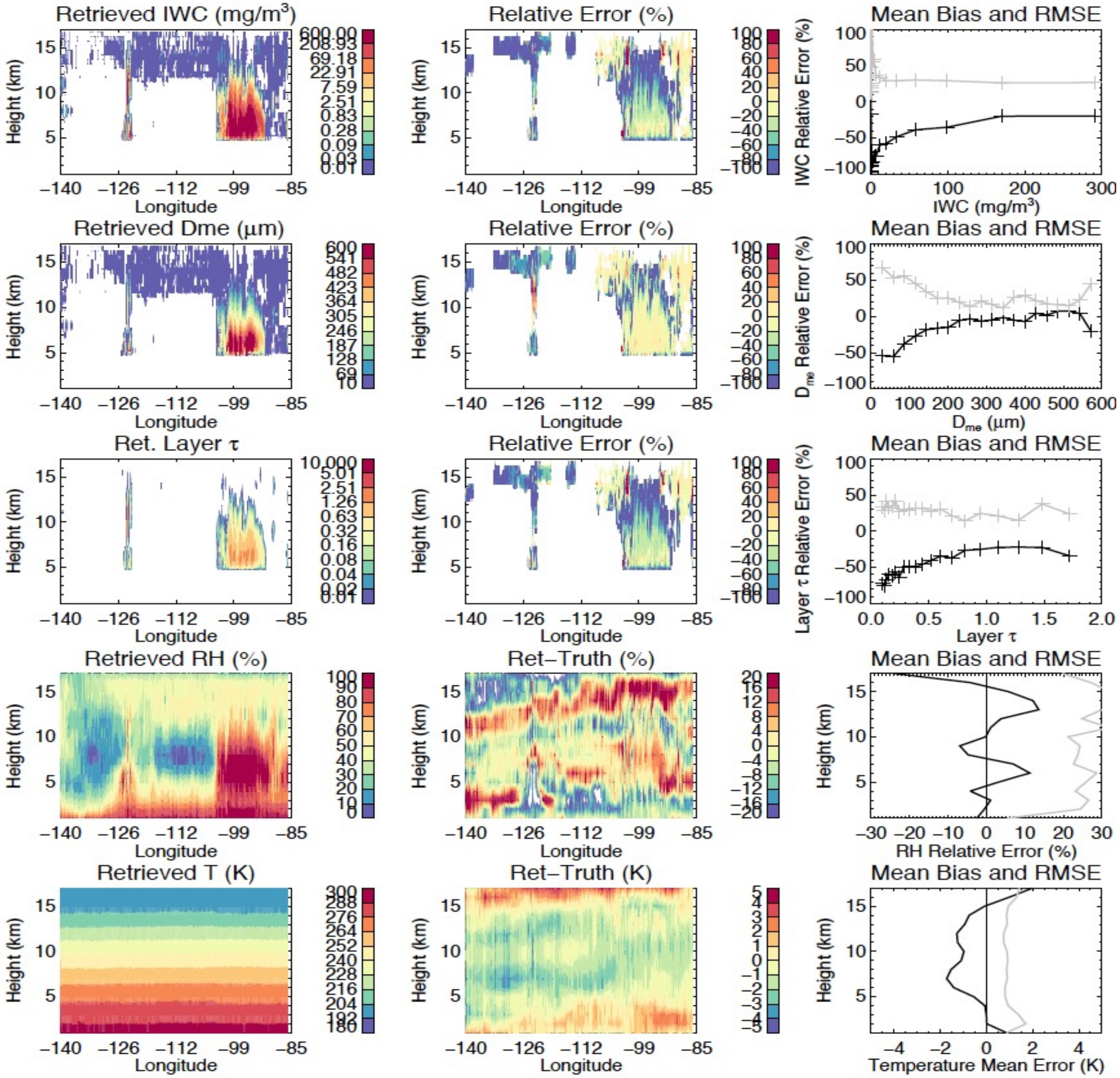
Simulated ENTICE (TWICE+94GHz Radar) Observations Using WRF Simulated Atmosphere and Cloud

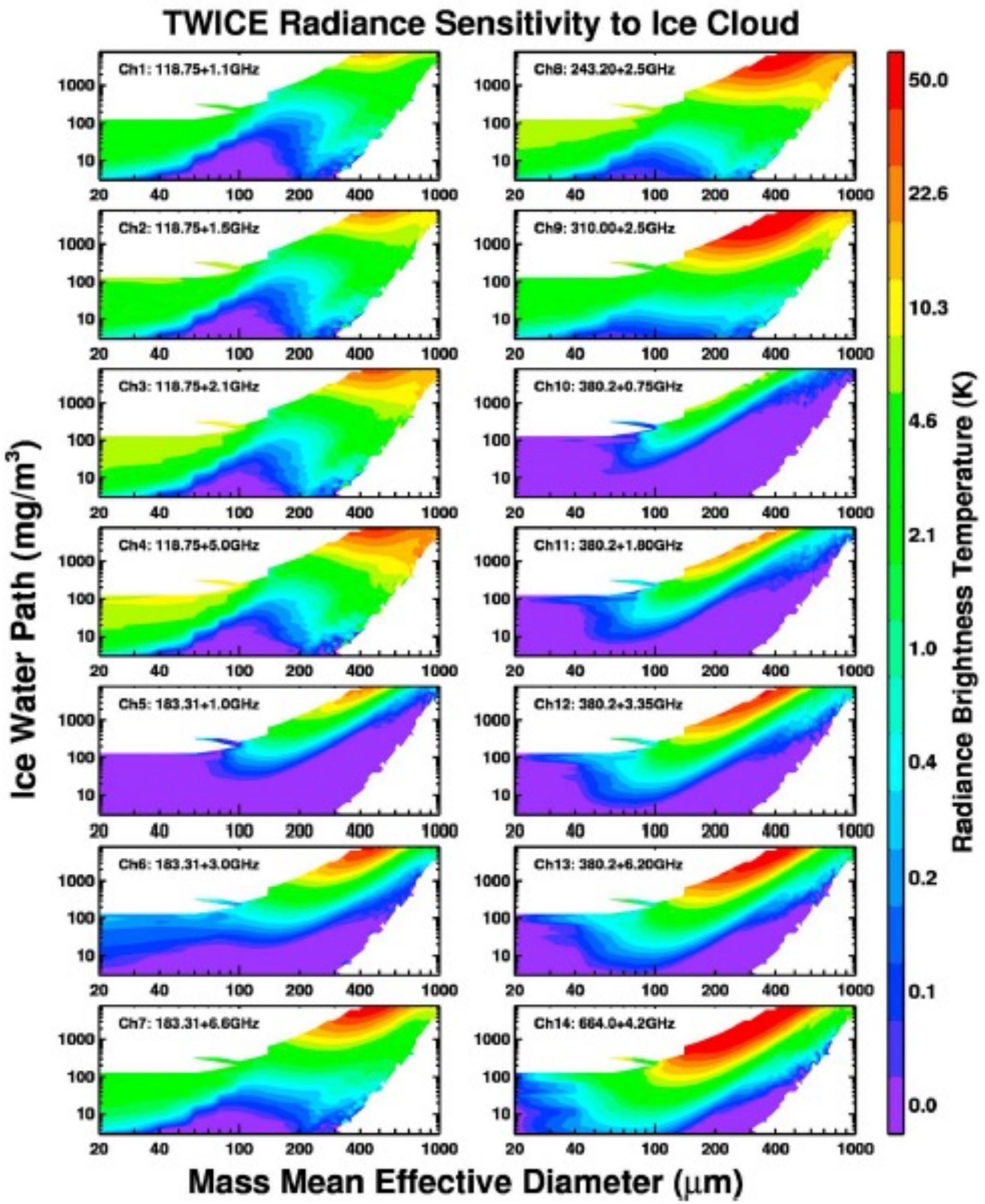
- PNNL-updated WRF V3.5.1
- Resolution 0.2° at 50 levels in the vertical
- **Ice: cloud ice + snow + graupel**
- **Liquid cloud**
- **Rain: simply treated as melted ice water -> high uncertainties in the retrievals when there is rain**
- Cross-section in WRF along 10°S between 140ºW and 85ºW longitude



ENTICE Simulated Retrieval and Retrieval Errors

1. Less than 50% bias (**25%**) for IWC>0.02 (**1**) g/m^3 and De> 50 (**120**) μm and optical depth >0.3 (**1**).
2. Less than 20% bias for RH and 2K for T.
3. Underestimate or completely miss thin ice cloud and cloud top.





- Results based on 10^6 simulations. Brightness temperature difference between cloud-free and cloudy calculations as a function of IWP and Dme.
- Prefer channels to be spaced evenly to have sensitivity to a range of particle sizes
- Sensitivity at channels far from the absorption line centers.

A Bayesian Algorithm

$$p_{\text{post}}(\boldsymbol{x}|\boldsymbol{T}) = \frac{p_f(\boldsymbol{T}|\boldsymbol{x})\,p_{\text{prior}}(\boldsymbol{x})}{p_{\text{prior}}(\boldsymbol{T})}$$

- ***x***: cloud and atmospheric parameters
- ***T***: measured radiances or brightness temperatures
- $P_{prior}(\boldsymbol{x})$, $P_{prior}(\boldsymbol{T})$: the prior probability distribution function of ***x*** and ***T***, respectively
- $P_f(\boldsymbol{T}|\boldsymbol{x})$: conditional PDF of ***T*** for a given ***x*** -> forward radiative transfer
- $P_{post}(\boldsymbol{x}|\boldsymbol{T})$: posterior PDF, probability distribution of ***x*** given the measurements ***T***