Ice and Mixed-phase Cloud Characteristics in the High Southern Latitudes based on Observations and NCAR CESM2 Model

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- NSF Atmospheric Geospace Sciences grant 1642291
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- NCAR ASP Faculty Fellowships 2016, 2018

CESM Workshop, June 15, 2021

Image from NASA worldview

Mixed-Phase Clouds in Observations and Simulations

Mixed Cloud Definition in AMS Glossary

A cloud containing both water drops (supercooled at temperatures below 0°C) and ice crystals, hence a cloud with a composition between that of a water cloud and that of an ice-crystal cloud.

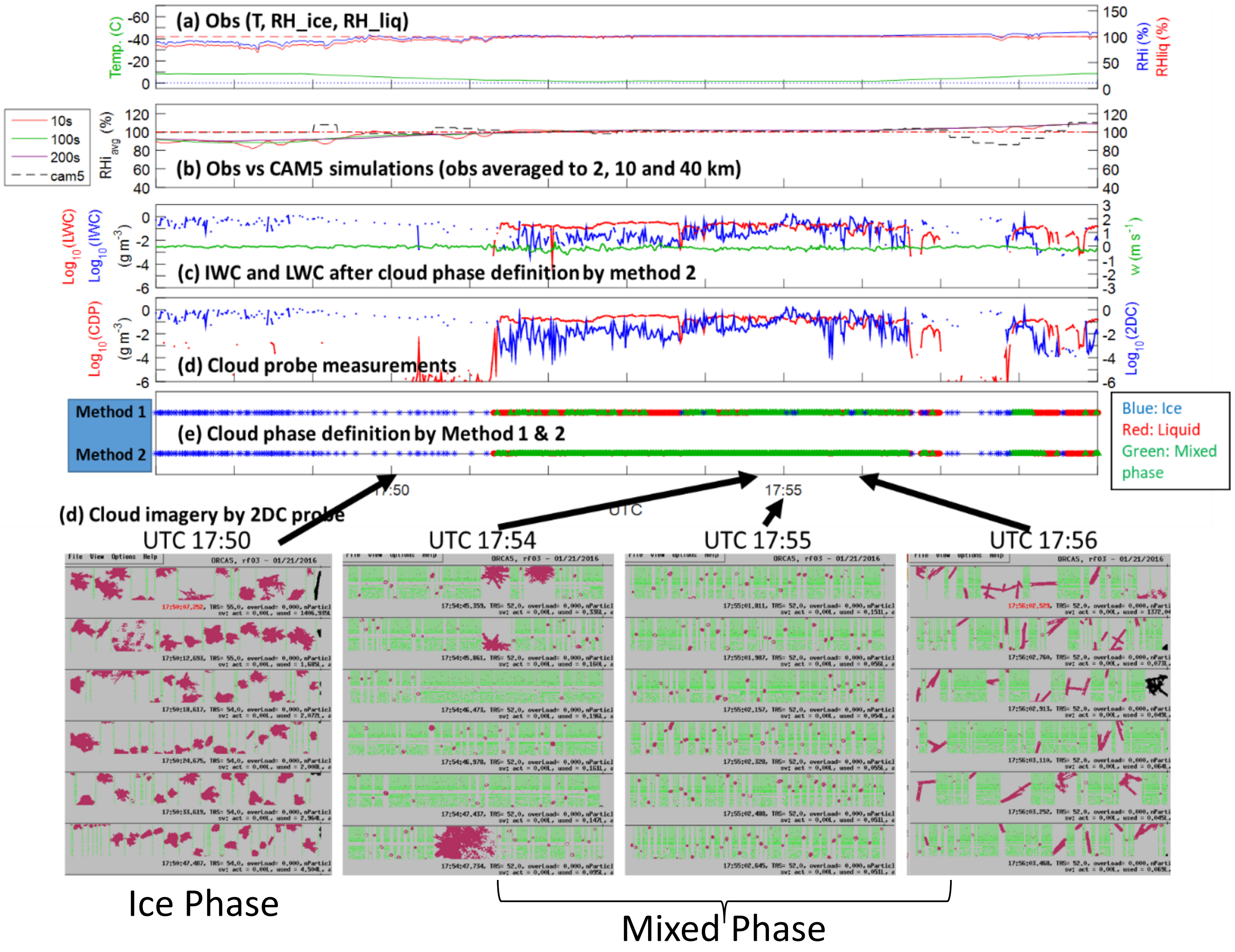
Questions:

(1) How frequently do three cloud phases occur over the Southern Ocean and Antarctica?

(2) How well do global climate models simulate three cloud phases and their microphysical properties?

(3) What are the aerosol indirect effects on ice and mixed-phase clouds?

Examples of ice and mixed-phase clouds in NSF ORCAS campaign



NSF SOCRATES Field Campaign and Instrumentations

NSF Southern Ocean Cloud, Radiation, Aerosol Transport Experimental Study (SOCRATES)
Jan 15 – Feb 24, 2018 in Hobart, Australia, onboard the NSF Gulfstream-V aircraft

Vertical Cavity Surface Emitting Laser (VCSEL) hygrometer

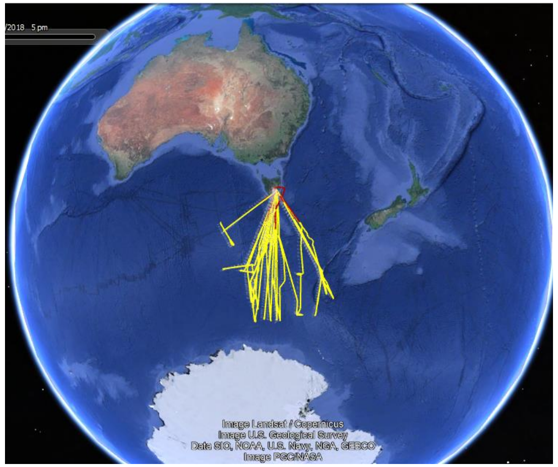
– Near infrared; 25 Hz -> 1 Hz; Accuracy $\lesssim$ 6%; Precision $\lesssim$ 1% (Zondlo *et al*. 2010)

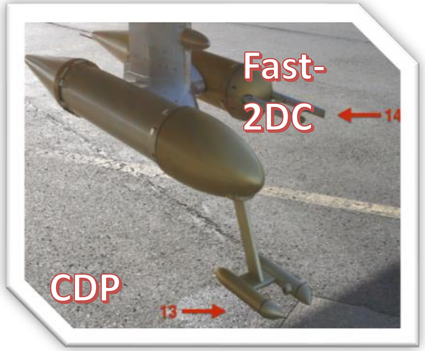
Cloud probes

– Cloud droplet probe (**CDP**) (2–50 μm)
– 2D-S Stereo Probe (**2DS**) (40 – 5000 μm)
– Fast Two-Dimensional Cloud (**Fast-2DC**) probe (62.5–1600 μm)
– King probe, RICE icing indicator

Aerosol probe

– Ultra-High Sensitivity Aerosol Spectrometer (UHSAS) (0.06 – 1 μm)

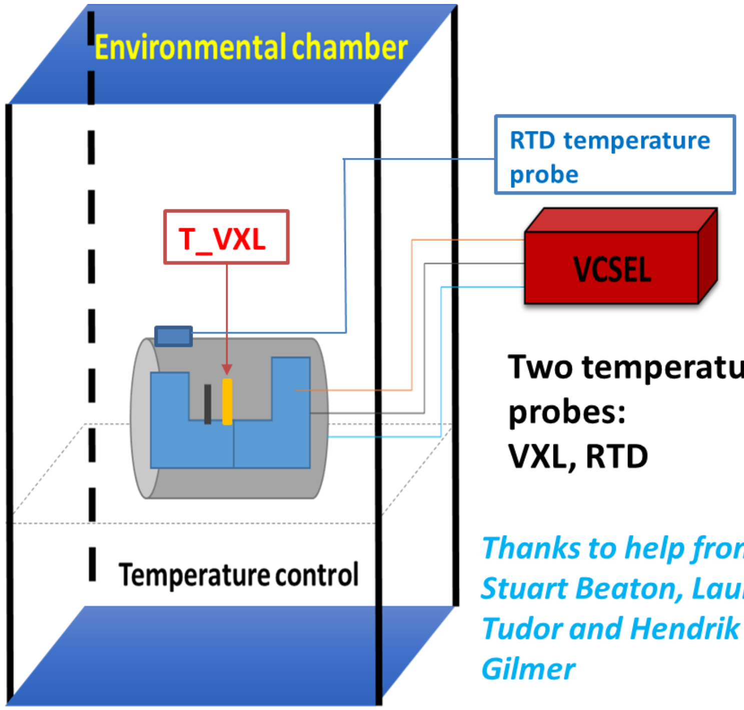




Laboratory Calibration of the VCSEL Hygrometer

RHice and RHliq uncertainties

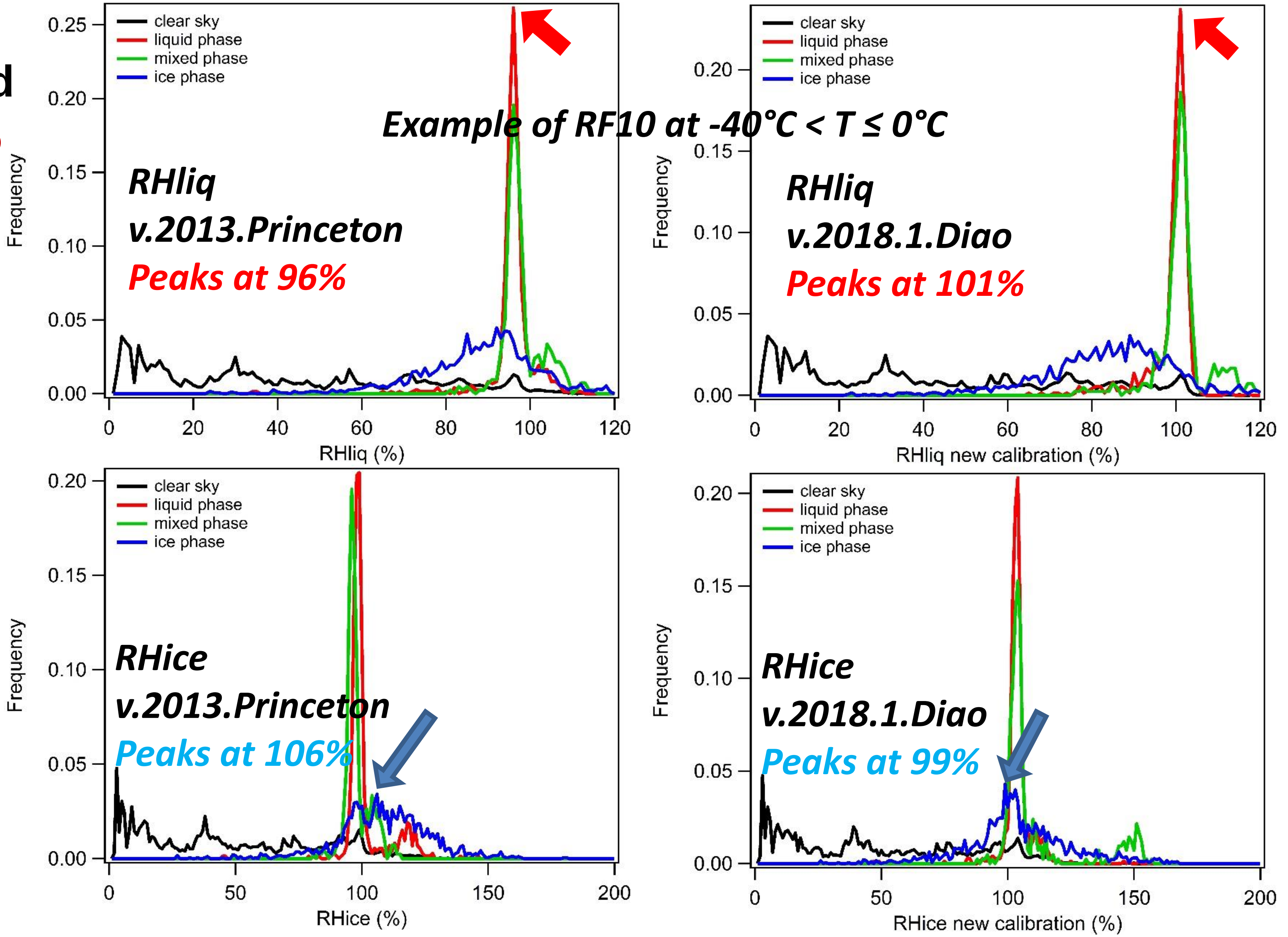
– Combine 6% water vapor mixing ratio uncertainty with ±0.3 K temperature uncertainty, **RHice and RHliq** uncertainties are **7.5%–6.5%** and **10.4%–6.4%** from -69° to 0°C, respectively.



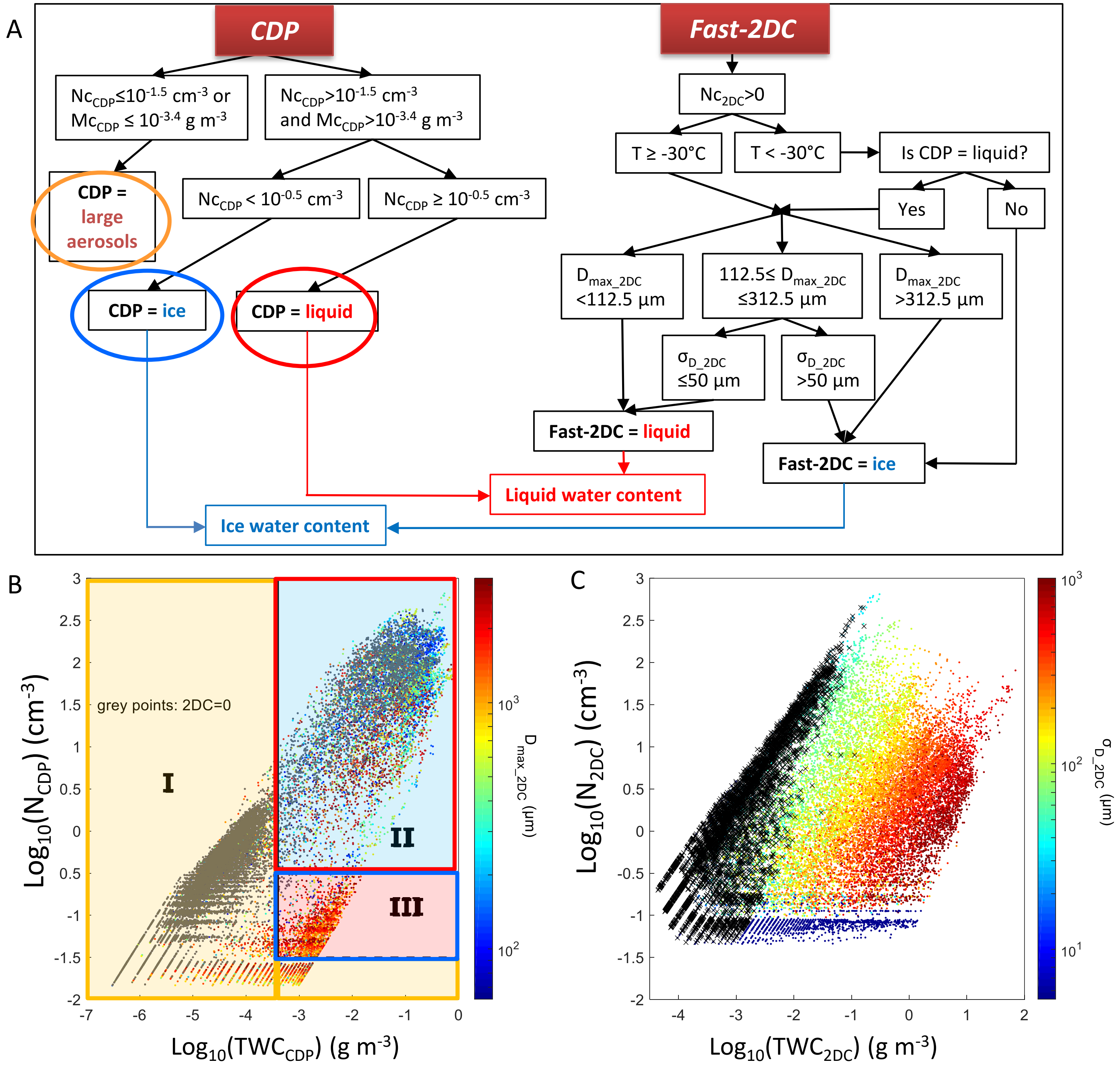
Two temperature probes: VXL, RTD

Thanks to help from Stuart Beaton, Laura Tudor and Hendrik Gilmer

[Diao, M. (2020). VCSEL 1 Hz Water Vapor Data. UCAR/NCAR - Earth Observing Laboratory. https://doi.org/10.26023/KFSD-Y8DQ-YC0D, https://data.eol.ucar.edu/dataset/552.051](https://data.eol.ucar.edu/dataset/552.051)



Cloud phase identification method based on in-situ aircraft-based observations



A cloud phase identification method was developed for GV observations using CDP and 2DC probes.
The development of this method has considered previous methods:
Korolev et al. (2003)
Cober et al. (2001)
McFarquhar et al. (2007)

D'Alessandro, J., M. Diao, C. Wu, X. Liu, B. Stephens, and J.B. Jensen, "**Cloud phase and relative humidity distribution over the Southern Ocean based on in-situ observations and global climate model simulations**", *Journal of Climate, 2019.*

NCAR CESM1 / CAM5

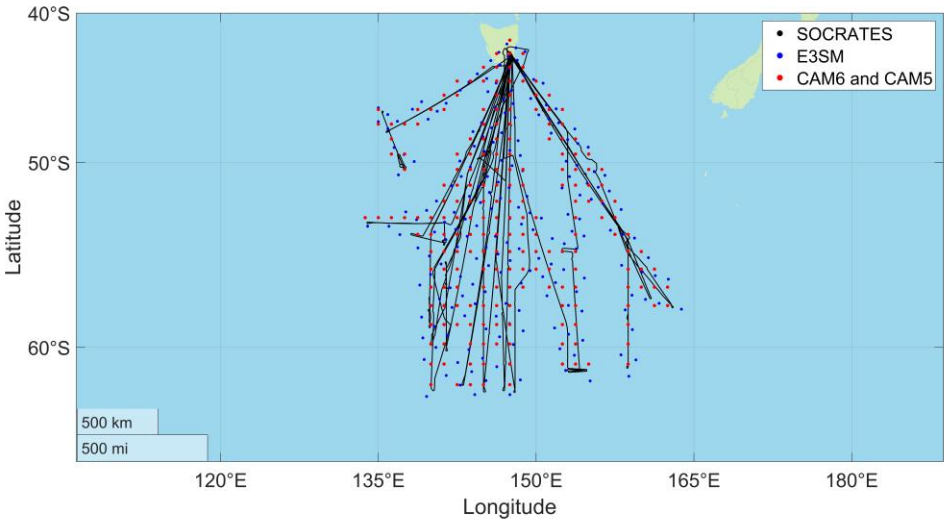
- Finite Volume Core
- 1° and 32 vertical levels
- Nudged towards MERRA-2
- Output to closest location for every 1-minute
- MG1 scheme (Morrison & Gettelman, 2008)
- MAM 3 (Liu et al., 2012)

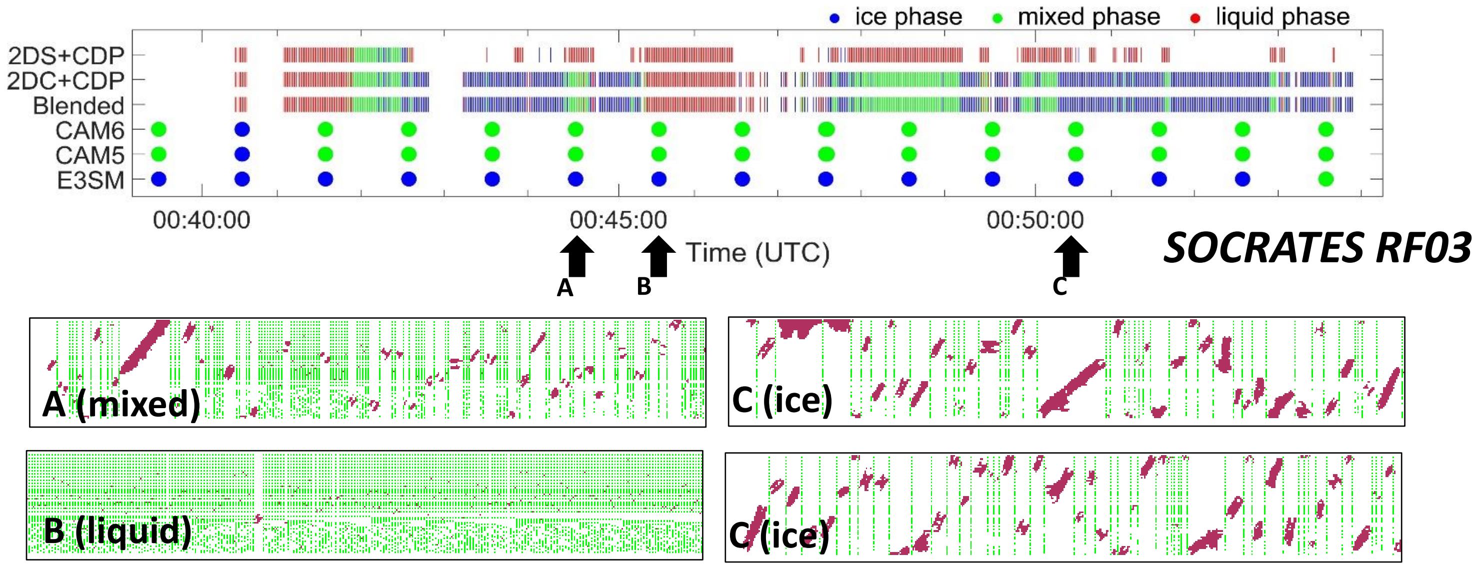
NCAR CESM2 / CAM6

- Finite Volume Core
- 1° and 32 vertical levels
- Nudged towards MERRA-2
- Output to closest location for every 1-minute
- MG2 scheme (Gettelman & Morrison, 2015)
- MAM 4 scheme (Liu et al., 2016)
- CLUBB for turbulence and shallow convection

DOE E3SM / EAM version 1

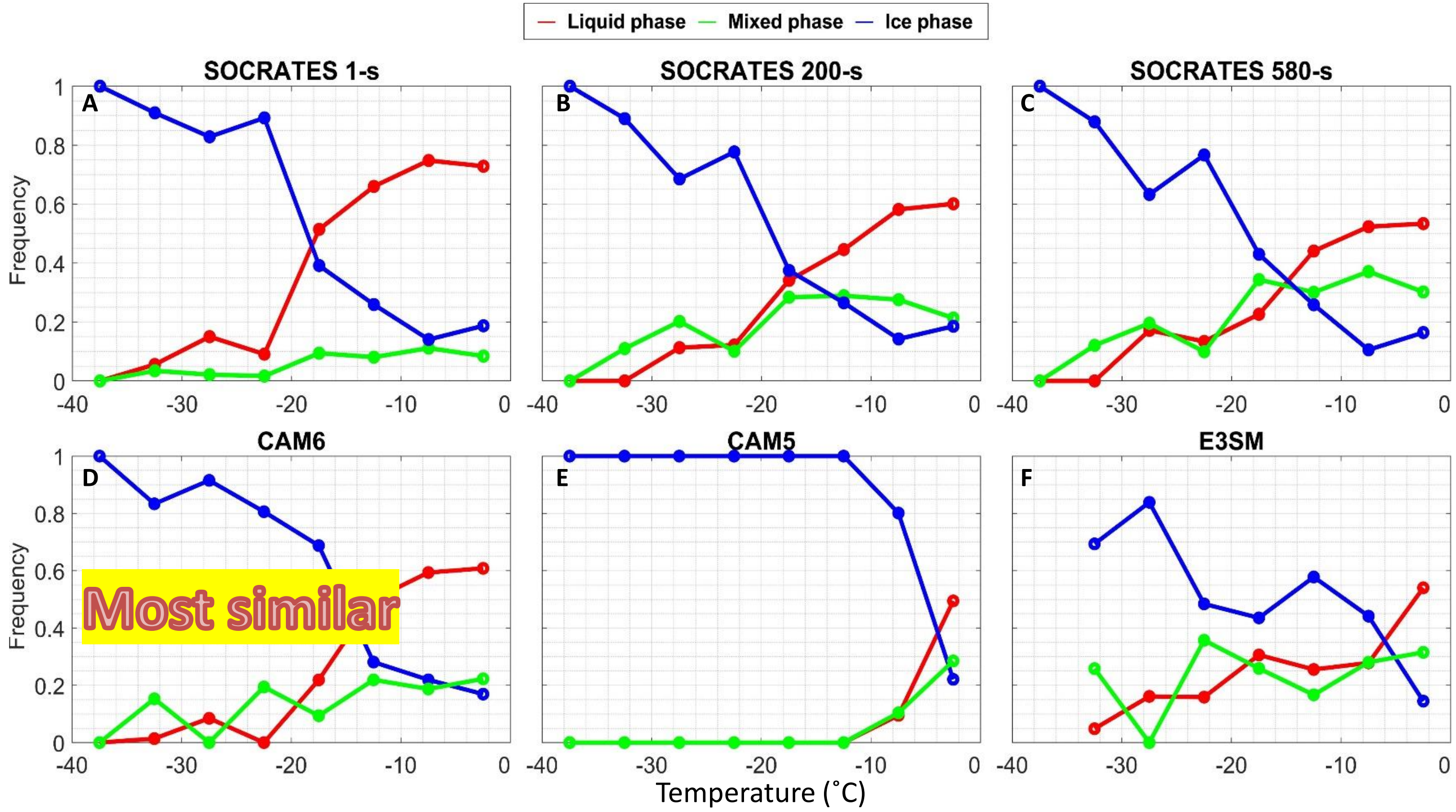
- Spectral element dynamical Core
- 1° and 73 vertical levels
- Nudged towards ERA5
- Output to closest location for every 1-minute
- MG2 scheme (Gettelman & Morrison, 2015)
- MAM 4 scheme (Liu et al., 2016)
- Detailed treatments of aerosol categories





Comparisons between in-situ observations and GCM simulations

Comparison set-up	"Scale-aware" comparison	Cloud phases: ratio of LWC / (LWC+IWC)	Cloud microphysics quantities
Aircraft Observations (averaged by 1 – 580 s)	**0.1 – 0.25 km** to **20 – 100 km** from near surface to UT/LS	≤ 0.1 (ice); ≥ 0.9 (liquid) **0.1 – 0.9** (mixed-phase) (D'Alessandro et al. 2019)	Similar "grid-mean quantities"
Climate Models **(1°, CAM6, CAM5, E3SM)**	**14 – 70 km** at 30°S–75°S	The same	**Grid-mean quantities**: "LWC", "IWC", "NUMLIQ", "NUMICE"



Cloud phase occurrence frequency

1. CAM6 shows the most similar results compared with observations on 100 km scale.
2. CAM5 does not allow supercooled liquid water below -10°C
3. E3SM underestimates (overestimates) ice phase below (above) -20°C

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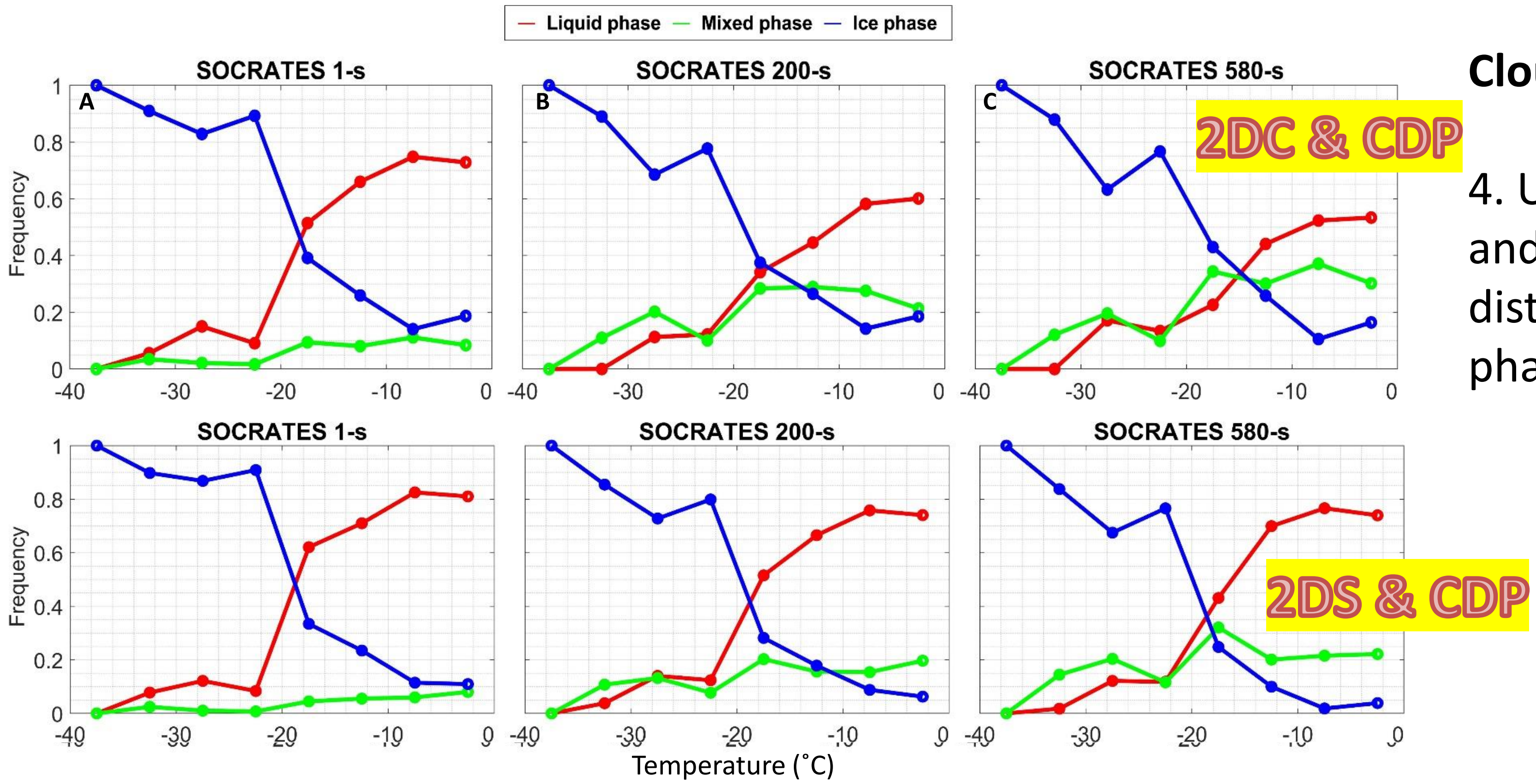


Cloud phase occurrence frequency

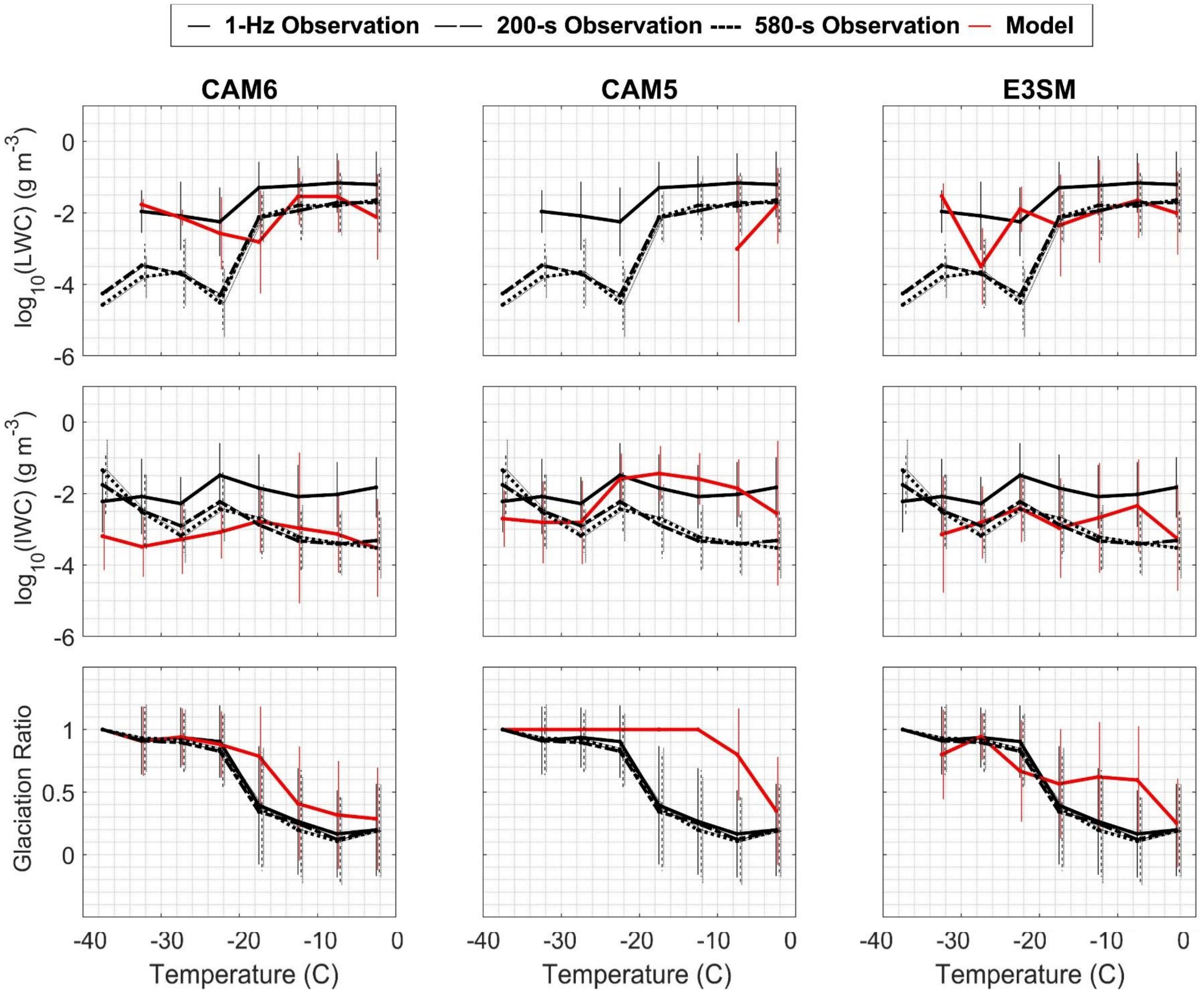
4. Using phase identification from 2DC and 2DS probes, similar frequency distributions are seen for three cloud phases.

Comparisons of LWC and IWC between Observations and Simulations

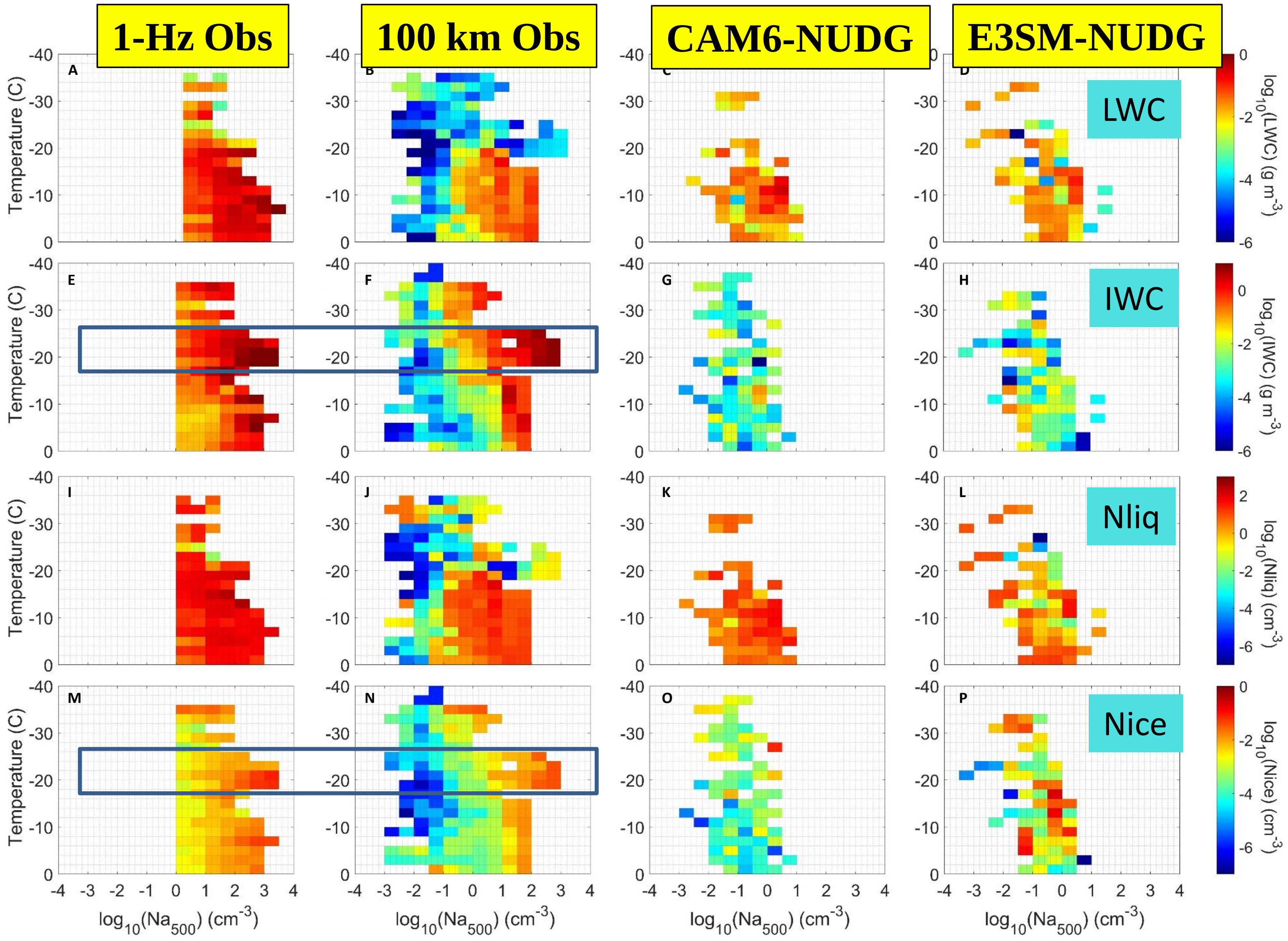
(1) Coarser-scale observations show lower LWC and IWC than finer-scale obs.

(2) CAM6 and E3SM show similar LWC to obs from -20^{o}C – 0^{o}C, but **overestimate LWC** by 0.5 – 2 orders of magnitude below -20^{o}C.

(3) CAM6 **underestimate IWC** by 0.5 – 1 order of magnitude below -20^{o}C.



Correlations with Aerosol Number Concentrations > 0.5 µm or > 0.1 µm



(1) Observations show higher LWC and Nliq with higher Na from -20 – 0ºC, and higher IWC and Nice with higher Na from -35 – 0ºC, indicating ***Twomey effects*** on liquid and ice.

(2) Higher IWC and Nice are correlated with lower LWC and Nliq at -18ºC to -25ºC, indicating Wegener–Bergeron–Findeisen process.

(3) CAM6 and E3SM show weak Twomey effect on LWC and Nliq, but no aerosol indirect effects on ice.

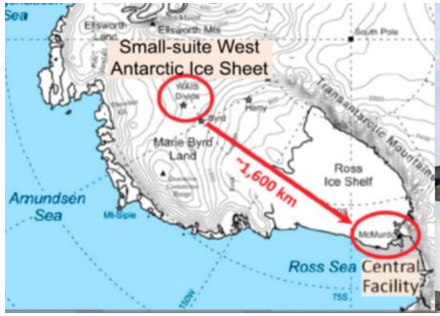
Evaluation A Climate Model Using Cloud Observations at McMurdo Station, Antarctica

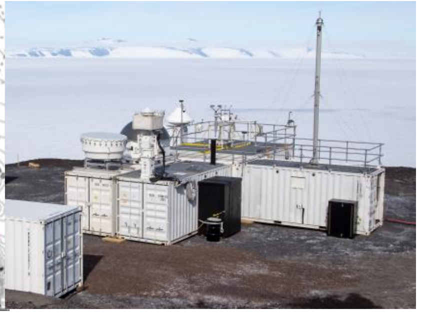
DOE/NSF Atmospheric Radiation Measurement (ARM) West Antarctic Radiation Experiment (AWARE Campaign)

December 2015 – January 2017, McMurdo St.

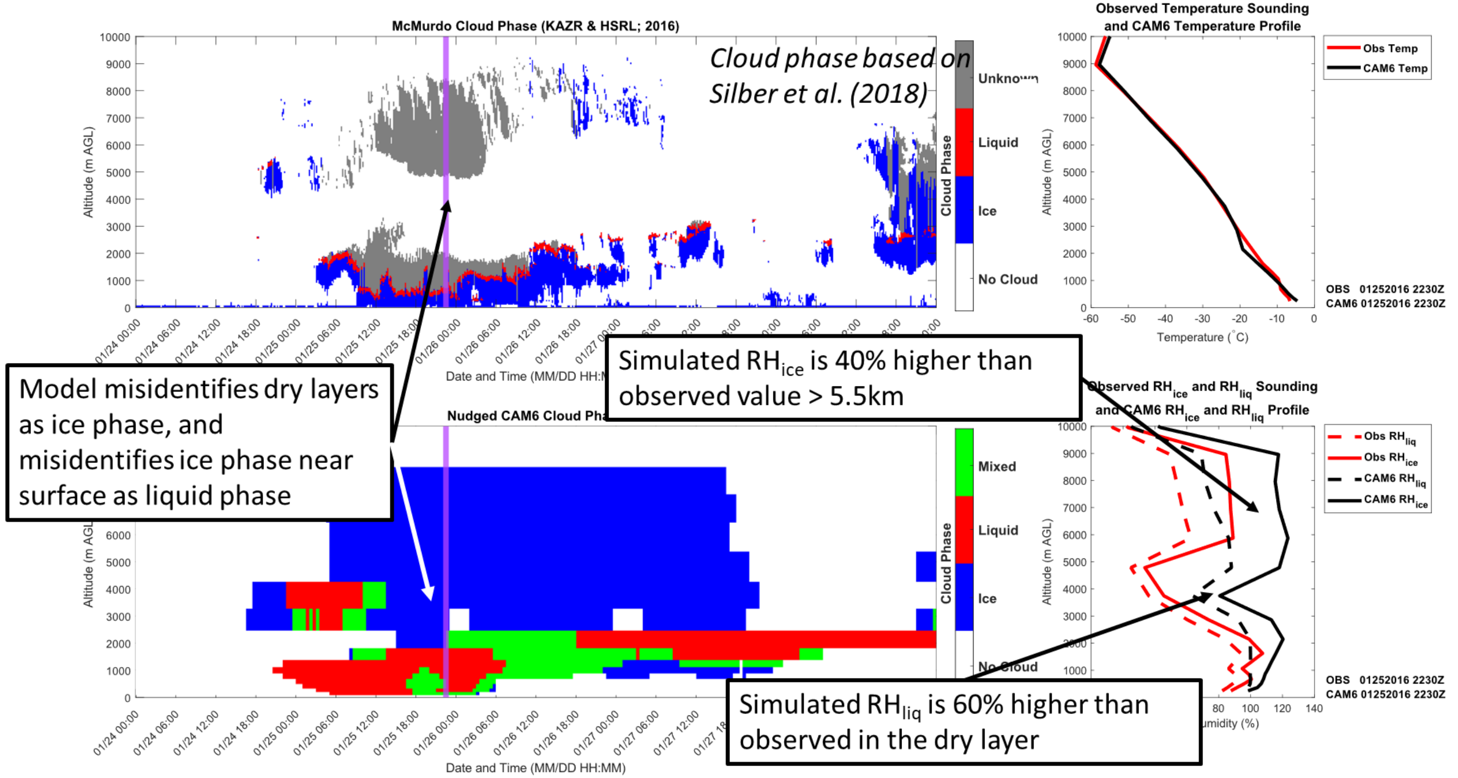
Ground-based obs and sounding by ARM AMF

High Spectral Resolution Lidar (**HSRL**), Ka-Band ARM Zenith Radar (**KAZR**) (Silber et al. 2018)





DOE/NSF AWARE Campaign January 24, 2016: Multi-layer Clouds



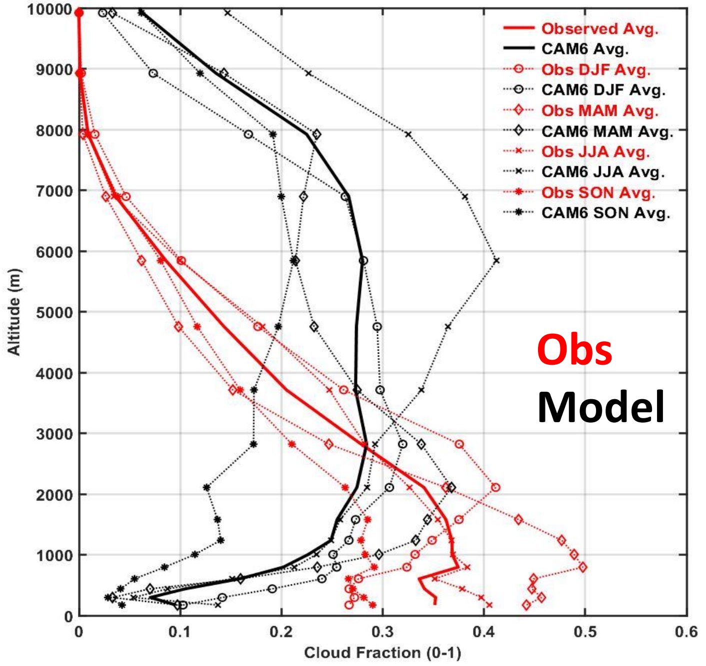
Key points:

1. Cloud phase, cloud fraction and thermodynamic conditions are compared between DOE AWARE campaign observations and the NCAR Community Earth System Model version 2 (CESM2) / Community Atmosphere Model version 6 (CAM6).
2. Case studies show biases of cloud fraction and cloud phase correlating with relative humidity biases.

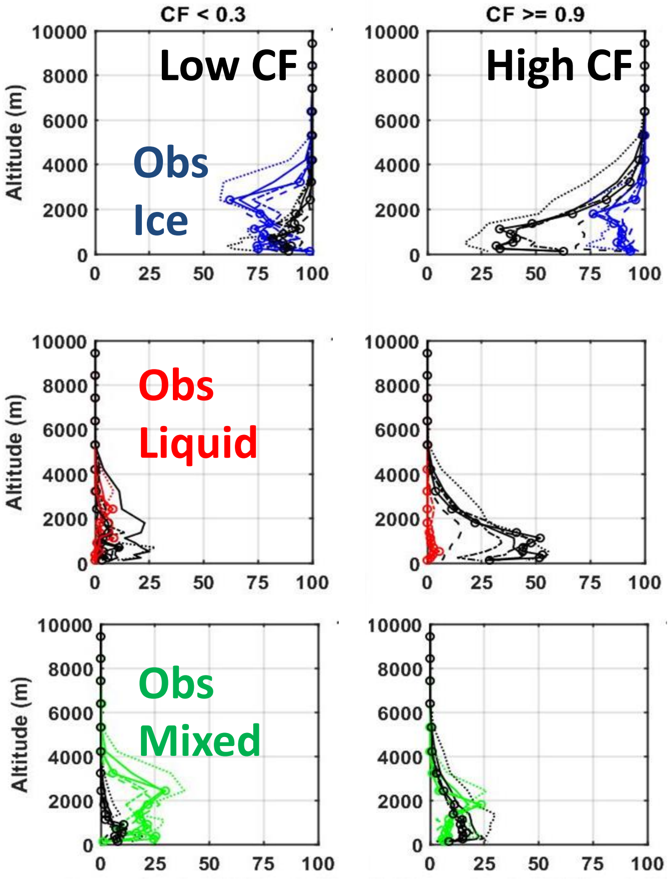
Yip, J., M. Diao, I. Silber, A. Gettelman, Evaluation of the CAM6 Climate Model Using Cloud Observations at McMurdo Station, Antarctica, JGR-Atmosphere, in revision.

Evaluation A Climate Model Using Cloud Observations at McMurdo Station, Antarctica

Seasonal Averages of Cloud Fraction Biases

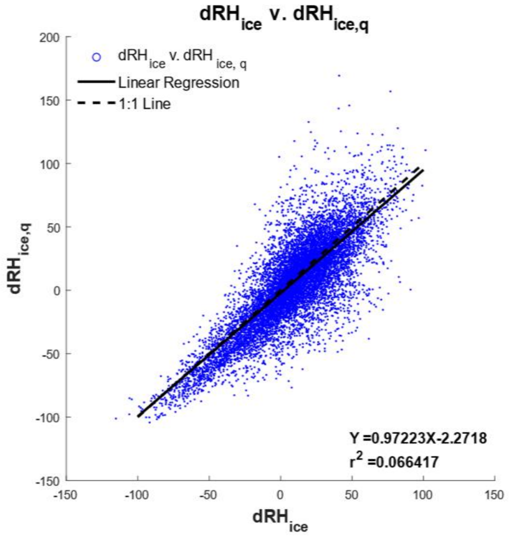


Cloud Phase Frequency Biases Correlated with Cloud Fraction



Percentage of Each Cloud Phase

Relative Humidity Bias Decomposition (Q vs T)



dRH_q v. dRH

Stronger correlation, nearly 1:1 regression slope (0.97)

Key points:

1. Cloud phase biases are correlated with cloud fraction (CF) and relative humidity. Relative humidity and cloud fraction biases are strongly correlated with **water vapor biases**.
2. CAM6 model overestimates cloud fraction above 3 km, underestimates CF below 3 km. The model underestimates ice phase frequency at high cloud fraction but overestimate it at low cloud fraction.

Conclusions

1. Development of methods to compare cloud phase and microphysical properties between in-situ observations and GCM simulations.

3. Cloud phase frequency distributions: CAM6 shows the most similar results to 100-km scale observations. E3SM model underestimates (overestimates) ice phase below (above) -20°C.

4. Microphysical properties: CAM6 and E3SM overestimate LWC by 0.5 – 2 orders of magnitude below -20ºC, and underestimate IWC by 0.5 – 1 order of magnitude below -20ºC.

5. Aerosol indirect effects: Observations show Twomey effects on ice and liquid phases, while only Twomey effects on liquid are seen in CAM6 and E3SM. Twomey effects are consistently seen regardless of analyzing clear-sky aerosols only or analyzing coarser-scale observations.

6. McMurdo Station, Antarctica: biases of cloud fraction and phase correlate with biases of RH, which is dominated by water vapor biases.

Yang, et al. Ice and Supercooled Liquid Water Distributions over the Southern Ocean based on In Situ Observations and Climate Model Simulation, in revision.

Yip, J., M. Diao, I. Silber, A. Gettelman, Evaluation of the CAM6 Climate Model Using Cloud Observations at McMurdo Station, Antarctica, JGR-Atmosphere, in revision.

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