Cloud phase and relative humidity distributions over the Southern Ocean in austral summer based on in situ observations, CAM5 and CAM6 simulations

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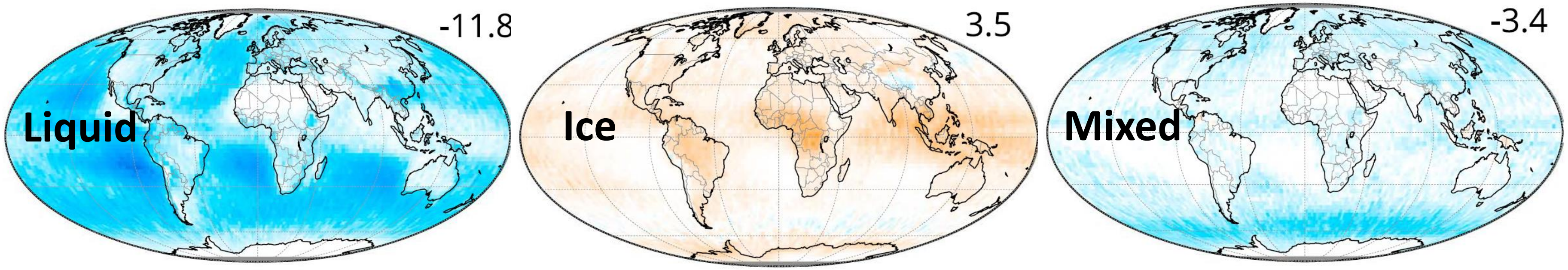
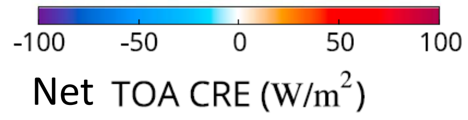
NSF ORCAS, SOCRATES campaign science team

CESM Atmosphere Working Group Meeting,
February 21, 2019, NCAR, Boulder

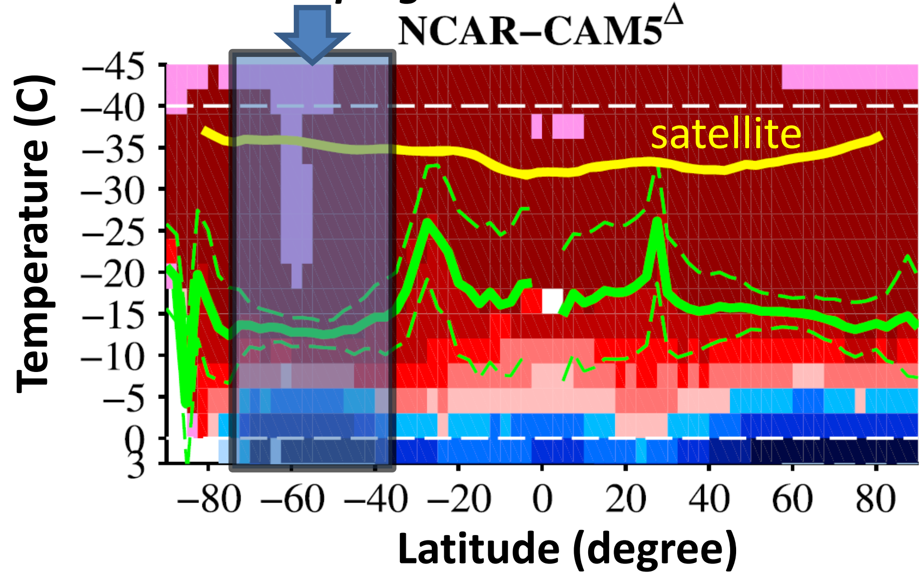
Impacts of Southern Ocean clouds on Earth's climate

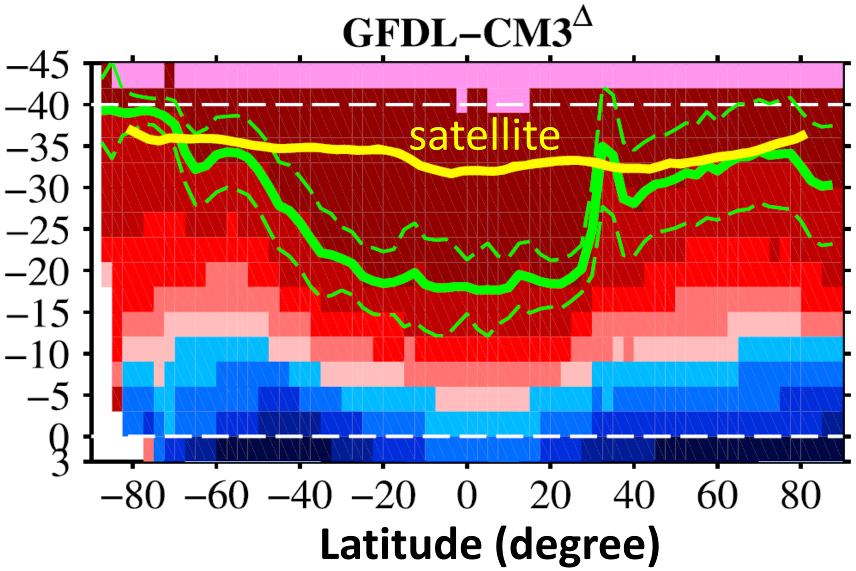




Three cloud phases show very different net TOA cloud radiative effects *(Matus and L'Ecuyer 2017, using CloudSat R05 2B-FLXHR-LIDAR)*

In-situ observations from two NSF campaigns





Discrepancies in the locations of 90% ice cloud phase ratio in climate model and satellite observations *(Cesana et al. 2015, using CALIPSO-GOCCP)*

1. What methods do we use to compare in-situ data with GCM simulations?

2. Do collocated, nudged simulations match better with observations than free-running ones?

3. What are the implications for cloud microphysics parameterization?

Data set and instrumentations

NSF O_2/N_2 Ratio and CO_2 Airborne Southern Ocean (ORCAS) Study

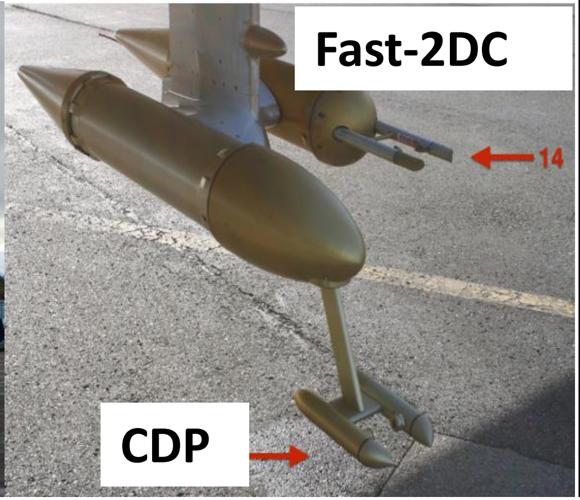
- Jan 15–Feb 28 2016, Punta Arenas; **50°W–92°W and 30°S–75°S**
- 18 flights; **~95 hr**; in-cloud **7.6 hr**, restricted to **T < 0°C**; Horizontal resolution: **~100 – 250 m**

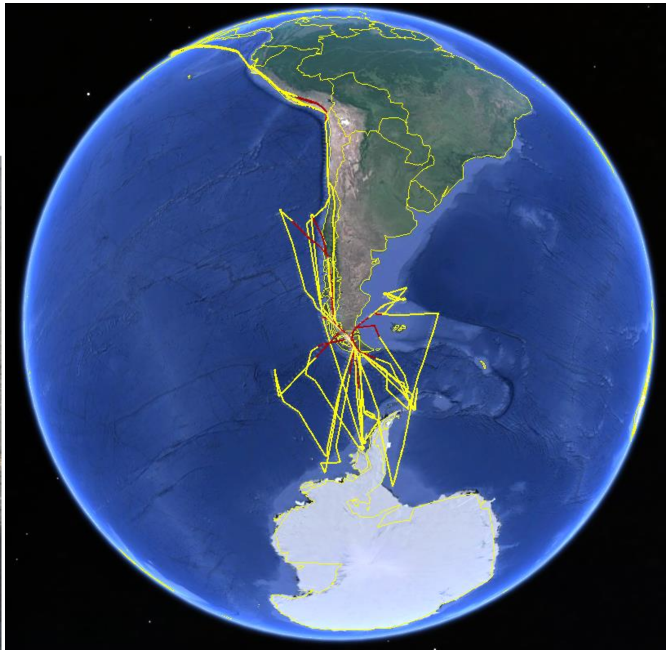
Vertical Cavity Surface Emitting Laser (VCSEL) hygrometer

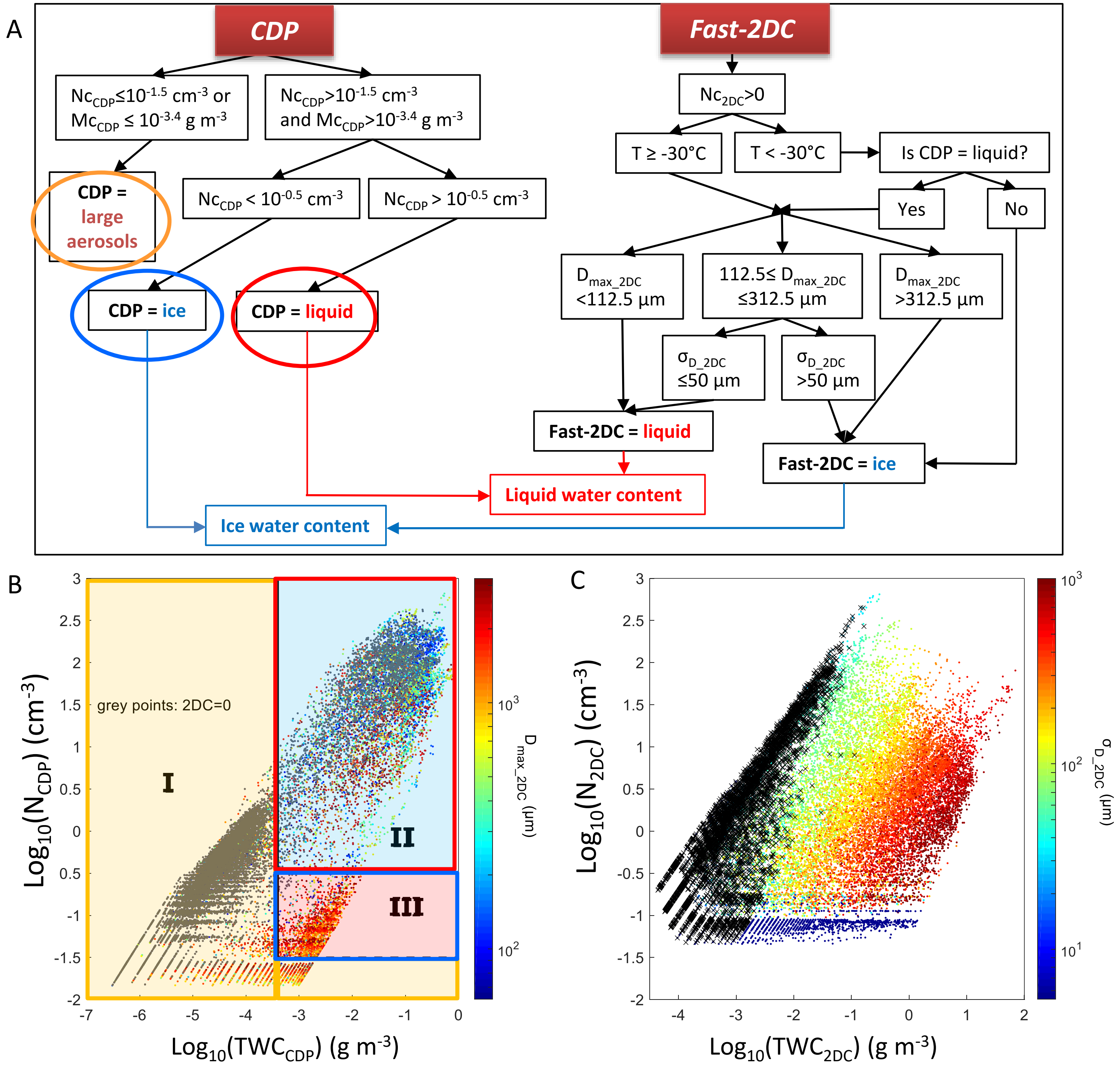
- Near infrared; use 1 Hz; Accuracy ≲ 6%; Precision ≲ 1% (Zondlo *et al*. 2010)
- Combine with ±0.3 K temperature uncertainties, **RHice and RHliq** uncertainties are **7.5%–6.5%** and **10.4%–6.4%** for -69°–0°C, respectively.

Cloud probes

- (1) Cloud droplet probe (**CDP**) (2–50 μm);
- (2) Fast-Two dimensional cloud (**Fast-2DC**) probe (67.5–1600 μm);
- Verifications: KING hotwire probe, Rosemount Icing detector (RICE)







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

Method is modified for GV observations in ORCAS, developed based on previous methods:

Korolev et al. (2003)

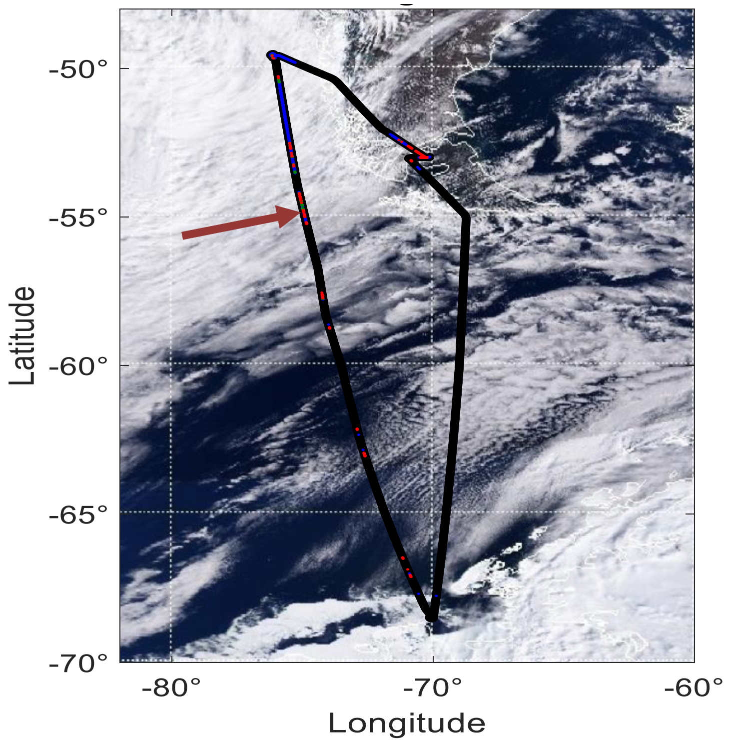
Cober et al. (2001)

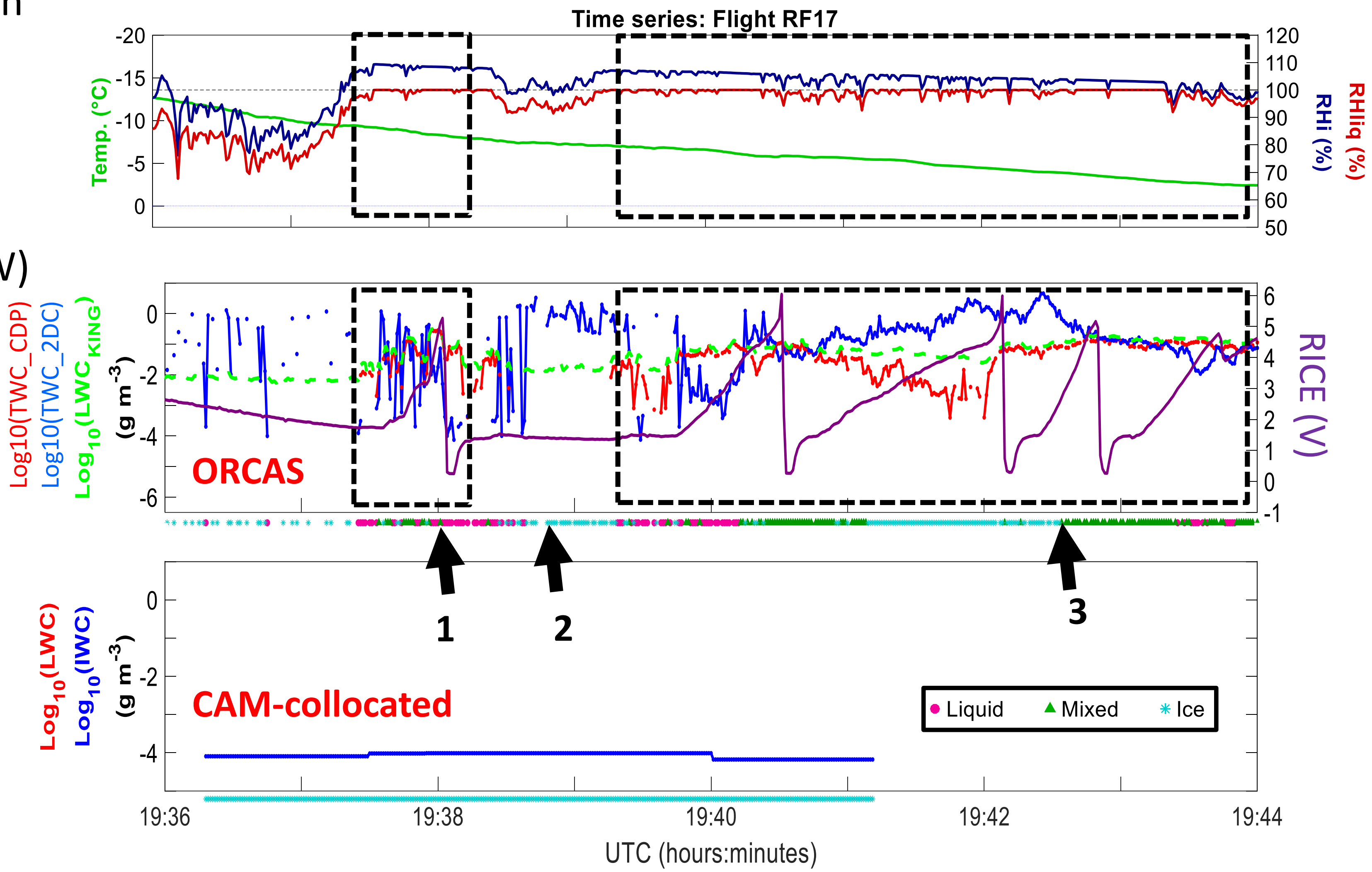
McFarquhar et al. (2007)

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*, *accepted*, *2019*.

Time series in RF17 with collocated CAM5 simulation output

- Phase separation correlates well with RICE indicator and is verified via Fast-2DC imagery
- CAM5 nudged simulation shows missing supercooled liquid water (SLW)





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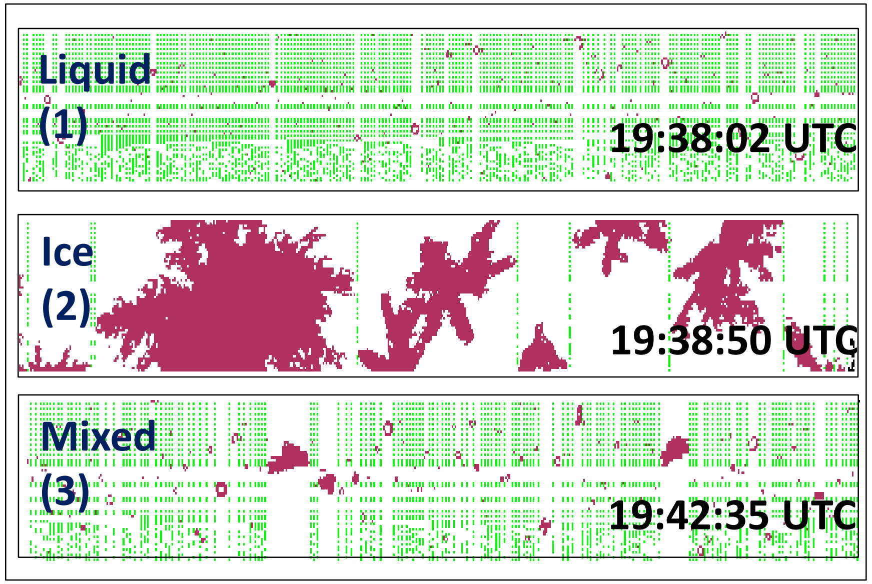
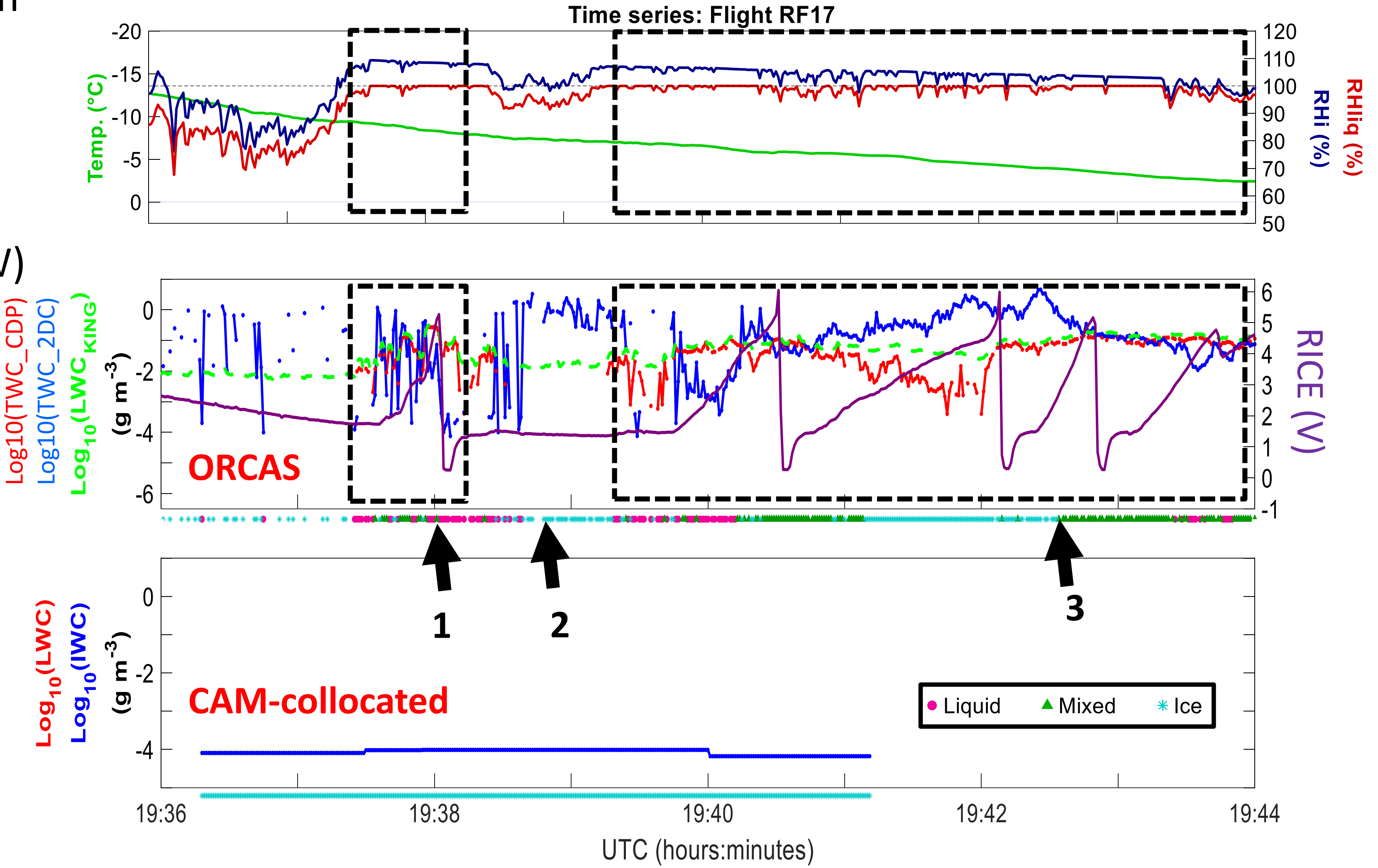
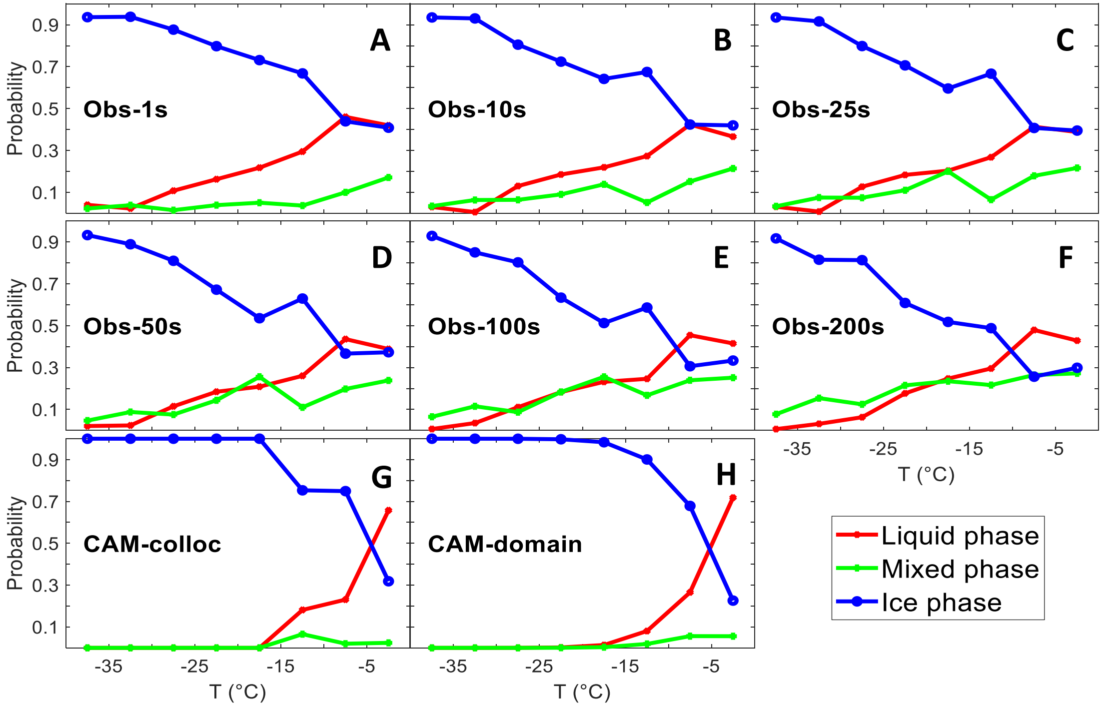


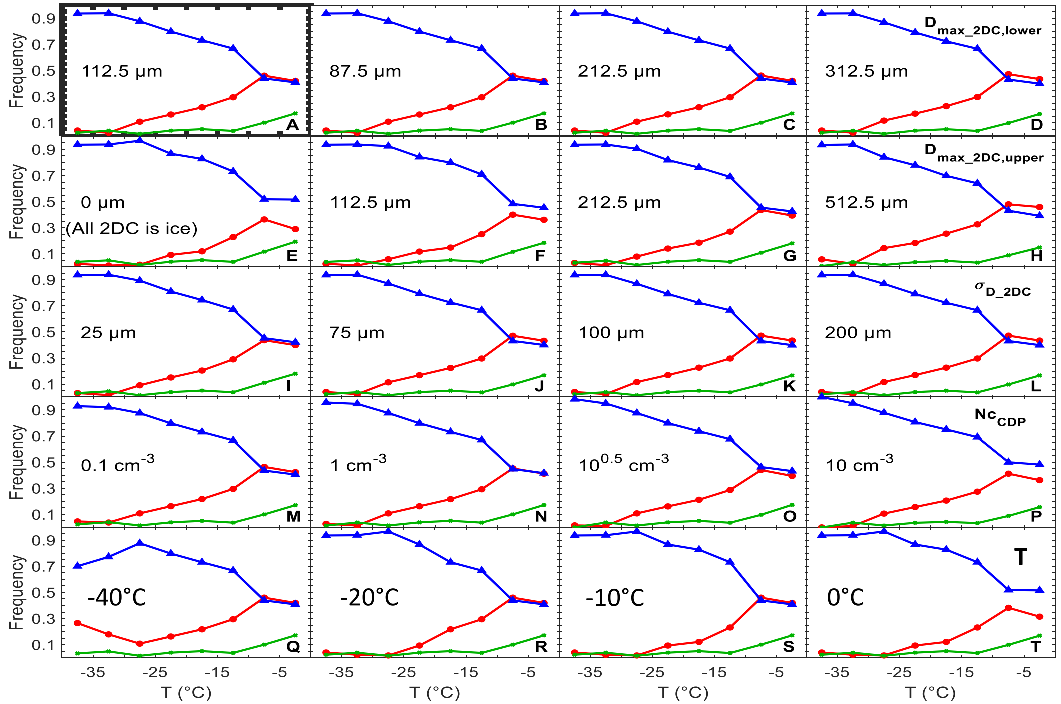


Comparisons of cloud phase frequency distribution in observations and simulations

Comparison set-up	"Scale-aware" comparison	Cloud phases: ratio of LWC / (LWC+IWC)	Cloud microphysics quantities
Observations in ORCAS campaign (1 – 200 s)	**0.1 – 0.25 km** to **20 – 50 km** from near surface to UT/LS	≤ 0.1 (ice) **0.1 – 0.9** (mixed-phase) ≥ 0.9 (liquid) (similar to Korolev et al. 2003)	Similar "grid-mean quantities"
CAM5 (nudged and free-running) (MG08, PB09, MAM3) 0.47°×0.63°	**14 – 70 km** at 30°S–75°S	The same	**Grid-mean quantities**: "LWC", "IWC", "NUMLIQ", "NUMICE"



Sensitivity tests to cloud phase id method



Cloud phase occurrence frequency comparison

		Liquid	Mixed	Ice
Obs-1s	-10°≤T<0°C	34%	17%	49%
	-20°≤T<-10°C	18%	5%	77%
	-30°≤T<-20°C	6%	3%	91%
	-40°≤T<-30°C	3%	4%	92%
Obs-200s	-10°≤T<0°C	27%	37%	36%
	-20°≤T<-10°C	16%	17%	67%
	-30°≤T<-20°C	5%	5%	90%
	-40°≤T<-30°C	0%	10%	90%

	Liquid	Mixed	Ice
CAM-collocated	60%	3%	37%
	53%	1%	46%
	0%	0%	100%
	0%	0%	100%
CAM-domain	70%	4%	25%
	29%	1%	70%
	1%	<1%	99%
	0%	0%	100%

-20°C≤T<0°C:
CAM5 has twice as many liquid phase clouds as observations and much fewer mixed phase clouds

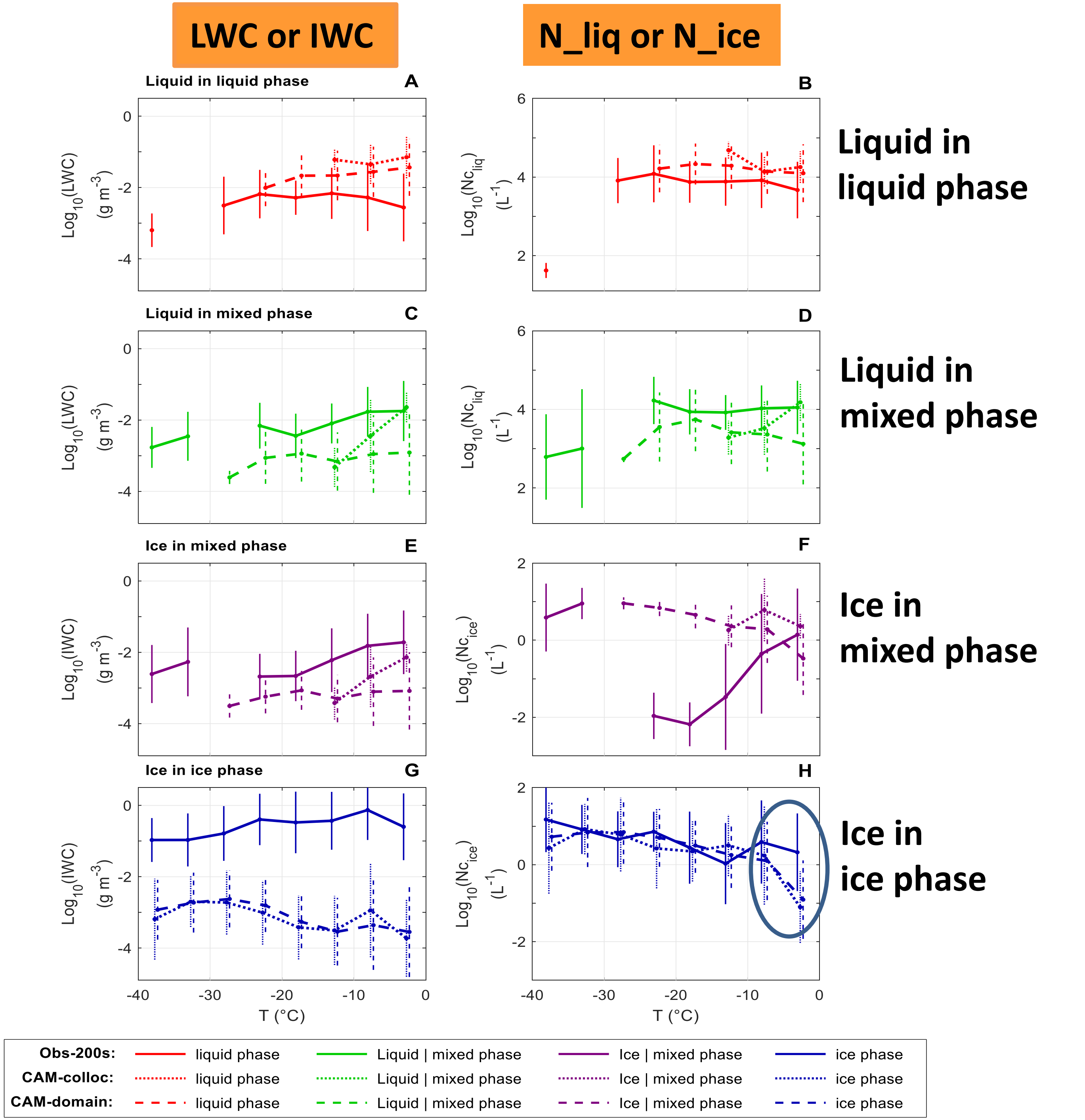
-40°C≤T<-20°C:
CAM5 underestimates liquid and mixed phase clouds

All data are restricted to CWC ≥ 0.01 g m-3

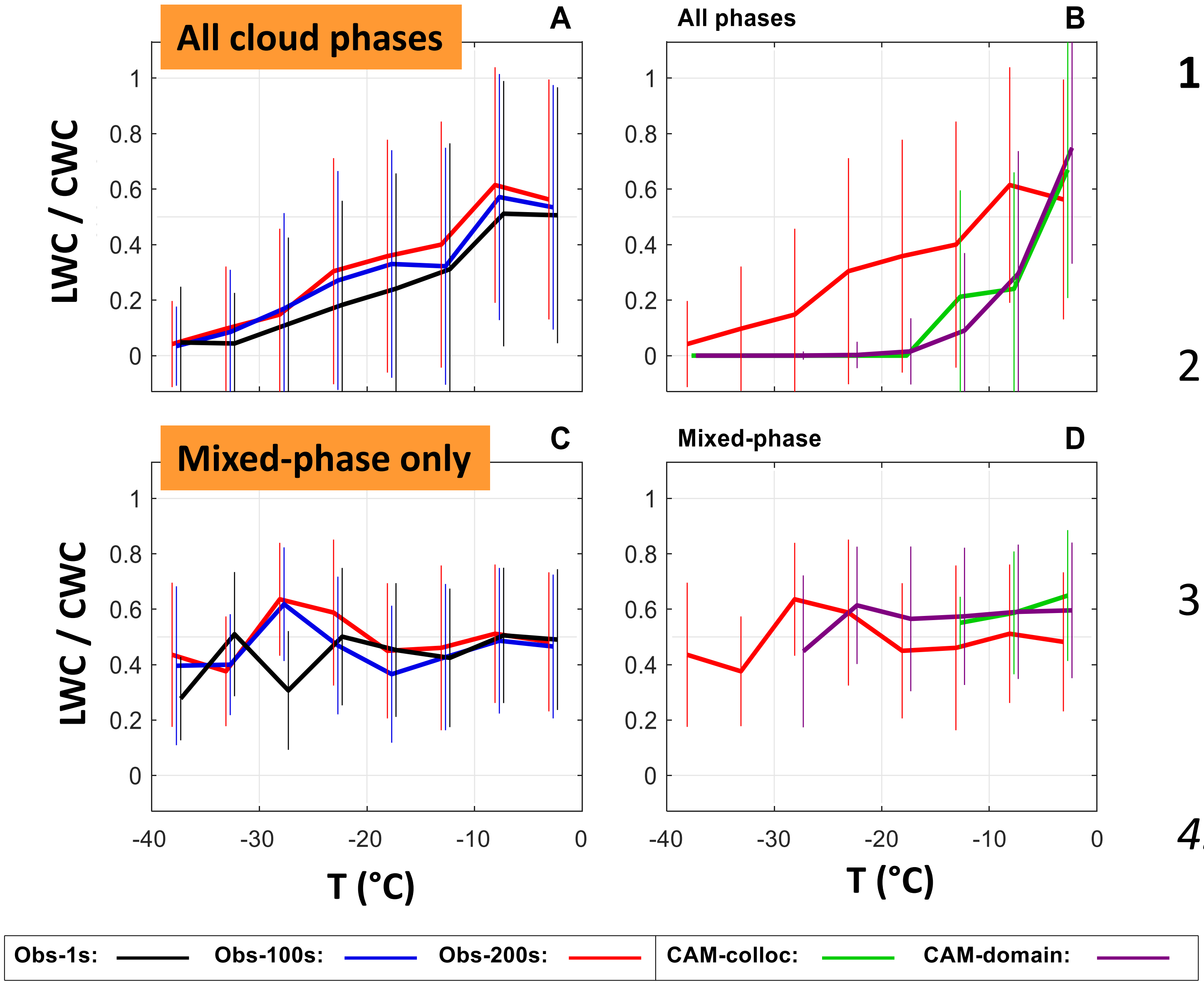
Comparisons of cloud microphysical properties

How well can CAM5 represent cloud microphysical properties in three cloud phases?

- **Liquid phase**:
  - overestimates LWC by 10 times
  - overestimates N_{liq} by 3 times
- **Mixed phase**:
  - underestimates LWC and N_{liq} by 10 times
  - underestimates IWC by 10 times and overestimates N_{ice} by 10-100 times, likely due to Meyers et al. (1992) parameterization
- **Ice phase**:
  - underestimates IWC by 100-1000 times
  - underestimates N_{ice} at T > -10°C by 10 times (possibly by lack of secondary ice production and/or less IN over this region)



Sensitivity of LWC / CWC to spatial scales and various cloud phases



1. **LWC/CWC ratios are similar (<0.1 difference) when averaging observations** from the scales of 100s of meters to 10s km (CWC = LWC+IWC)
2. When analyzing **all cloud phases** altogether, CAM5 simulations show **lower** LWC/CWC ratios than observations by 0.2-0.4.
3. When analyzing **mixed-phase clouds only**, CAM5 simulations show **higher** LWC/CWC ratios than observations by 0.2.
4. *Important to validate different cloud phases separately*

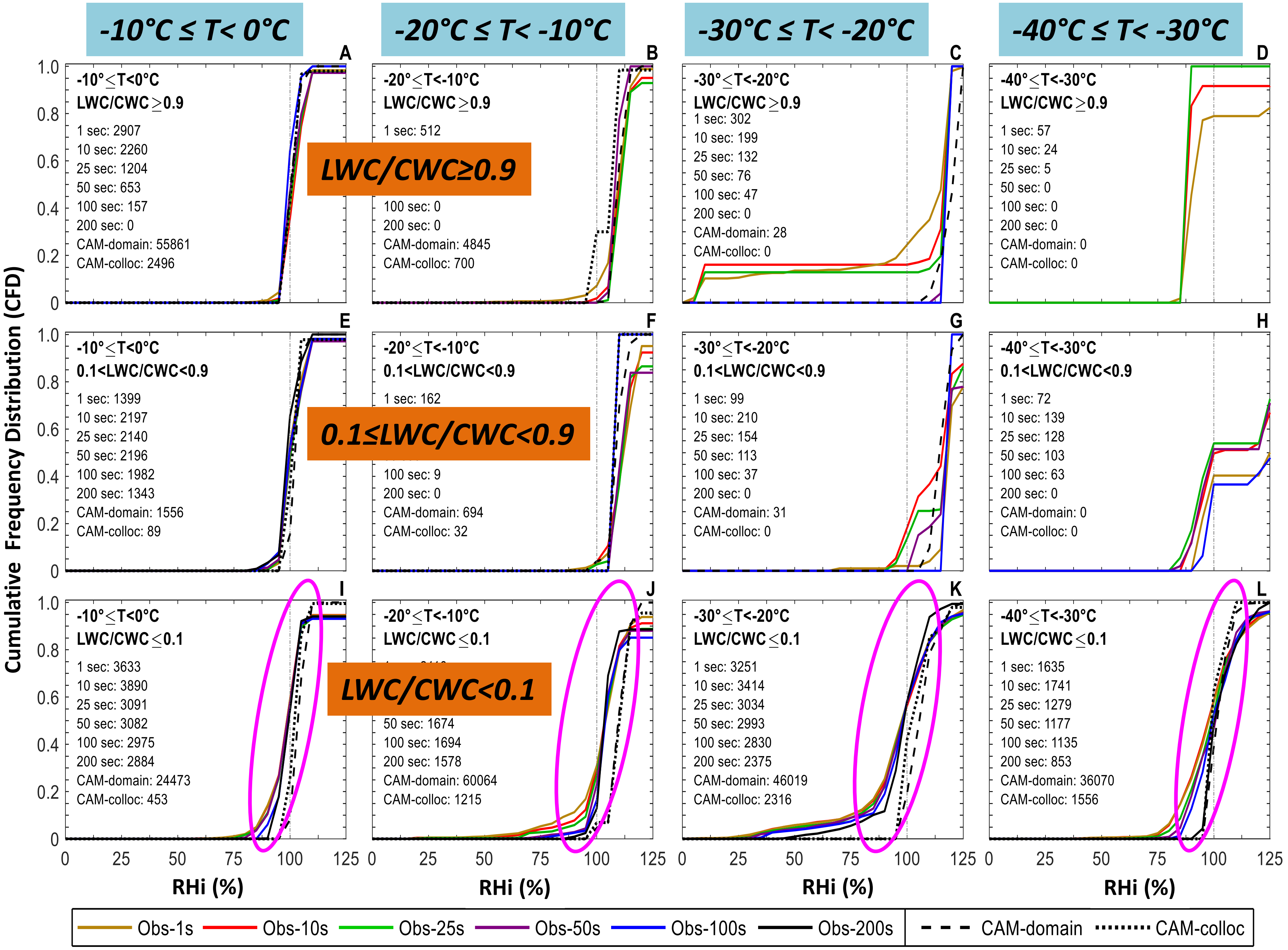
Liquid saturation assumption

- *For 0.1 ≤ LWC/CWC < 0.9*, 10 sec averaged obs show **98%, 90% and 64%** of RHliq>90% from 0°C to -30°C in 10°C bin. Consistent with previous obs (e.g., Korolev and Mazin 2003).
- *But for LWC/CWC ≤ 0.1*, **only 80%, 59% and 11%** of RHliq>90%, respectively.

- Rotstayn et al. (2000) assumes **RH = liquid saturation** when ice and liquid coexist in mixed phase clouds, regardless of the amount of liquid phase.

- Also used in CAM5 (Morrison and Gettelman 2008; Gettelman et al. 2010; Gettelman and Morrison 2015), ECMWF (Forbes and Ahlgrimm 2014), GFDL CM2 and CM3 (Anderson et al. 2004; Donner et al. 2011).

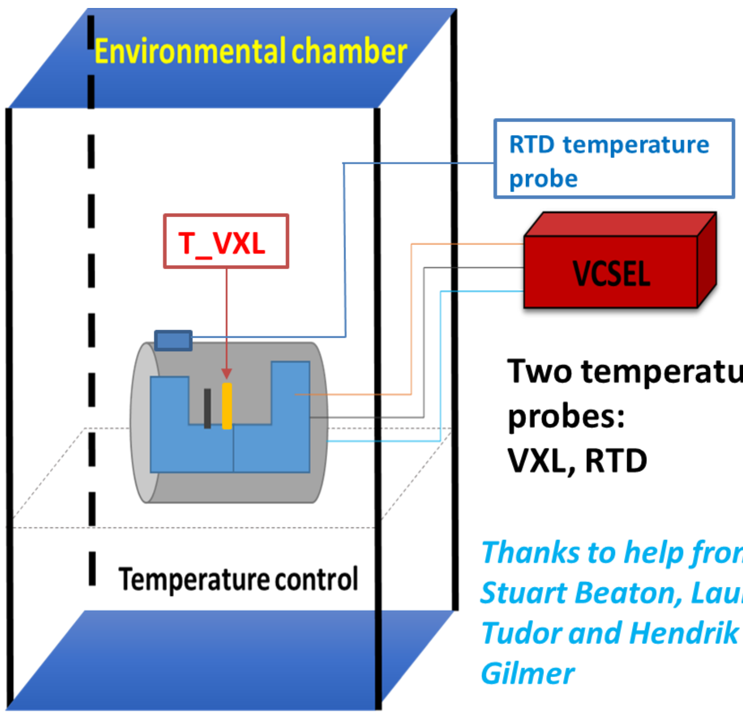
- More variability of RH may need to be allowed…



NSF SOCRATES campaign: RH distribution and new water vapor data calibrations

NSF Southern Ocean Clouds, Radiation, Aerosol Transport Experimental Study (SOCRATES): January 15 – February 24 2018, based at Hobart Australia

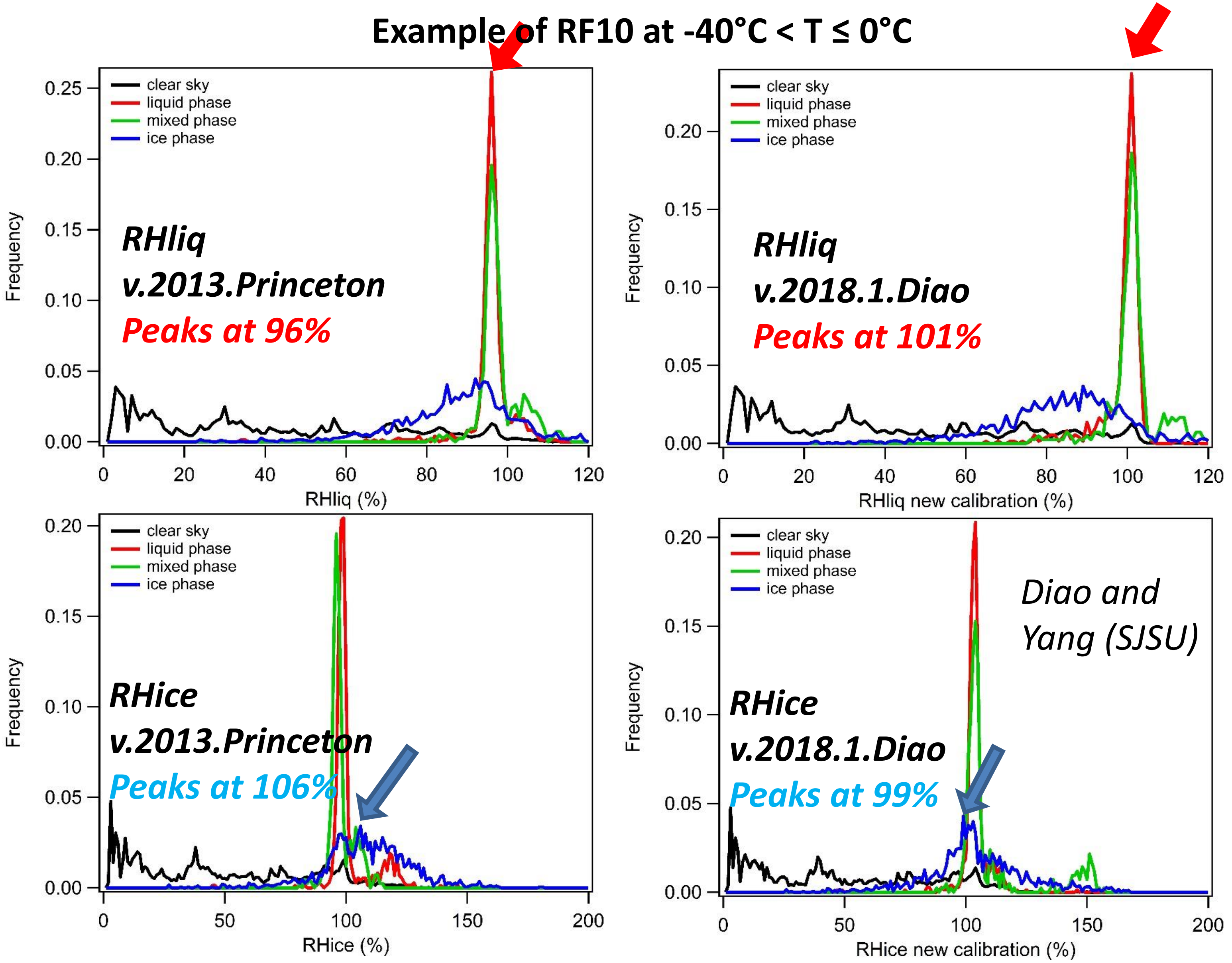
Calibration in summer 2018



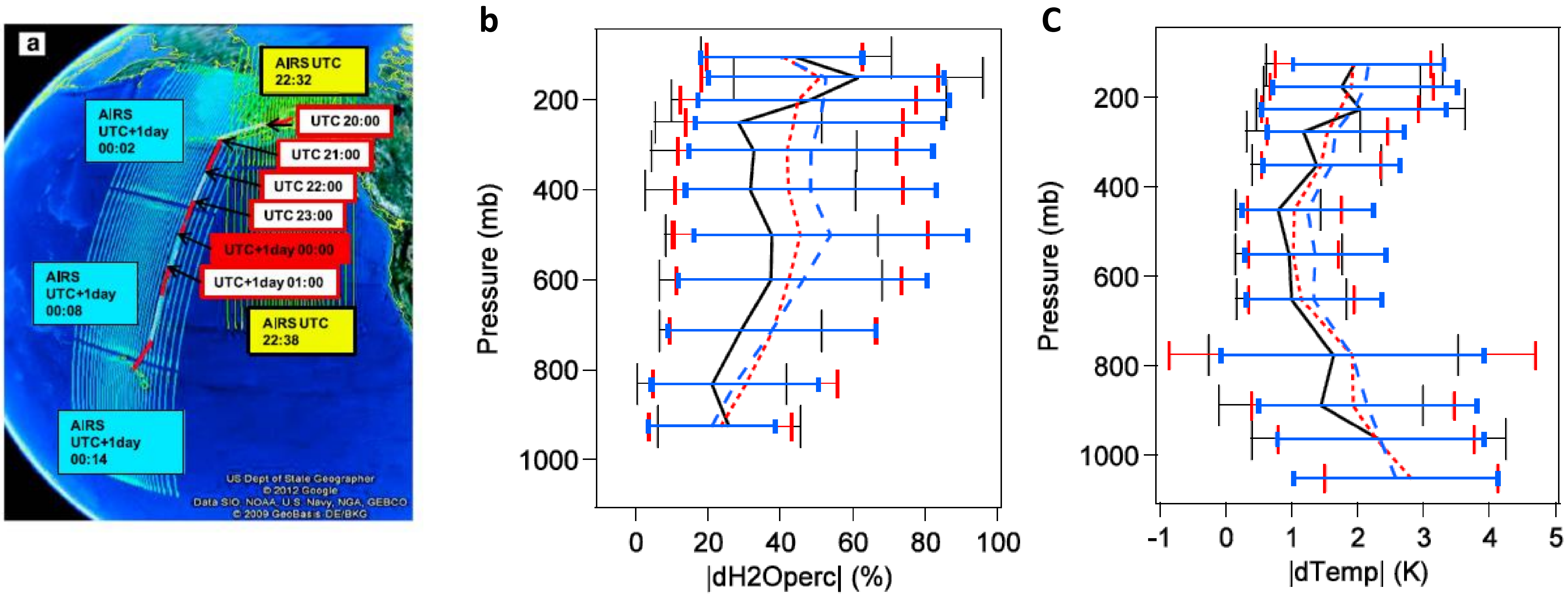
Two temperature probes: VXL, RTD

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

Example of RF10 at -40°C < T ≤ 0°C



Advantage of using in-situ observations for certain comparisons

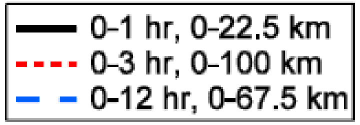


The RH difference between liquid saturation and ice saturation is ***only a few % to ~30%*** at 0°C to -30°C

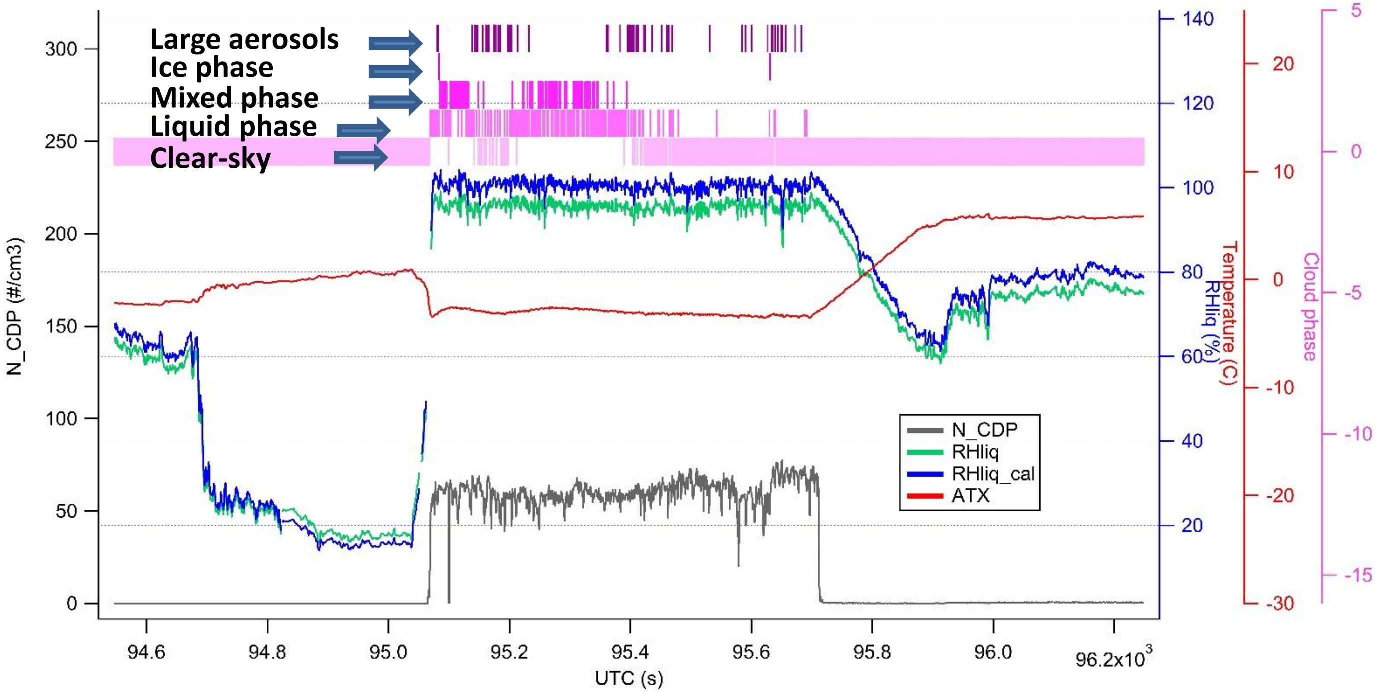
Validation of NASA AIRS water vapor and temperature using HIPPO campaign: **20%-40% H_2O difference, and 1–2 K Temp difference** from surface to UT/LS within 1 hr and 22.5 km collocation of AIRS and aircraft

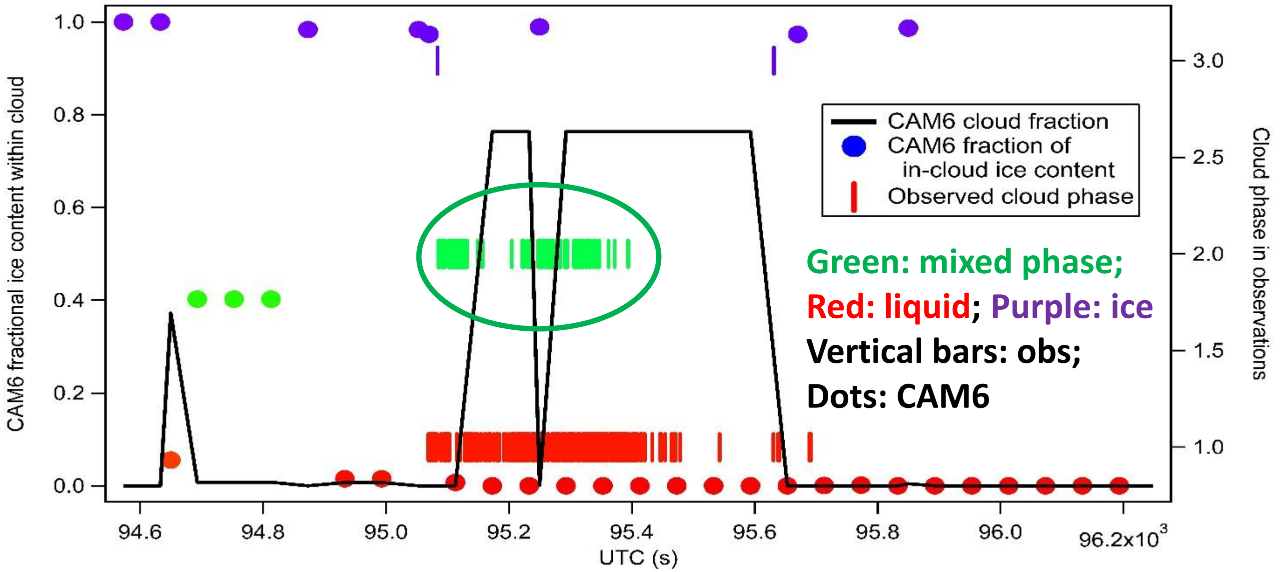
(Diao *et al*. 2013, JGR-Atmosphere)

Collocation of AIRS and aircraft



Ongoing: Cloud phase and cloud fraction in SOCRATES observations and CAM6





How well does CAM6 model represent cloud phase and fraction in segments with heterogeneous phase distributions?

- **CAM6 shows similar locations and cloud fraction for where clouds are observed** in the example for RF10
- **CAM6 captures the dominant phase – liquid phase**
- **CAM6 underestimates occurrence mixed phase cloud segments**
- More analyses to be conducted using the newly calibrated water vapor data to compare with nudged and free-running CAM6 simulations

Conclusions

1. **In-situ observations are very useful for evaluating GCM simulations**
2. **Scale-aware comparisons**
   dependent on scales: LWC, IWC, N_{ice}, N_{liq}, cloud phase freq
   independent on scales: LWC/IWC, N_{ice}/N_{liq}
3. **Nudged, collocated simulations show mostly similar comparison results as free-running simulations for analyses of cloud phase frequency, LWC, IWC, N_{ice}, N_{liq}**
4. **Implications on cloud microphysics parameterizations**
   Observation-based constraints are recommended for specific cloud phases

CAM5 results	Frequency	LWC or IWC	Nliq or Nice	LWC/CWC	Hor scales 0.1-10 km in obs
Mixed phase	Too low	10-100 times lower LWC and IWC	10 times lower Nliq, 10-100 times lower Nice	Ratio is 0.2 higher than obs	Increasing freq by 2-3 times
Liquid phase	Too high at T>-20°C	10 times higher LWC	3 times higher Nliq	For all clouds, ratio is 0.2-0.4 lower than obs	Decreasing freq
Ice phase	Similar	100-1000 times lower IWC	10 times lower Nice at T>10°C		Decreasing freq

Acknowledgement

- NSF OPP grant 1744965
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Future work

Ice supersaturation and mixed-phase clouds in CAM6, compared with SOCRATES and AWARE campaigns by Ching An Yang and Jackson Yip, collab. w/ Andrew Gettelman, Christina McCluskey, and Israel Silber

Cirrus clouds in CAM6 compared with 7 NSF flight campaigns by Ryan Patnaude, collab. w/ Xiaohong Liu

Thank you! Questions?

RHi frequency distribution at various T and cloud fraction

CAM5 has a lack of variability of RHi, particularly for partial cloud fraction (0.1 – 0.9)

Future work: test parameterizations of sub-grid variability of RHi based on PDFs of q and T.