Ice and Mixed-Phase Cloud Characteristics over the Southern Ocean and Antarctica based on Observations and NCAR Community Atmosphere Model

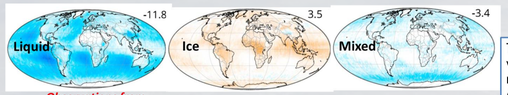
Minghui Diao[1], Ching An Yang[1], Jackson Yip[1], Ryan Patnaude[1], Kathryn Steinmann, John D'Alessandro[2], Andrew Gettelman[3], Israel Silber[4], Xiaohong Liu[5], Chenglai Wu[6]

[1]Department of Meteorology and Climate Science, San Jose State University, [2]University of Oklahoma, [3]National Center for Atmospheric Research, [4]Penn State University, [5]University of Wyoming, [6]Chinese Academy of Sciences

Motivation

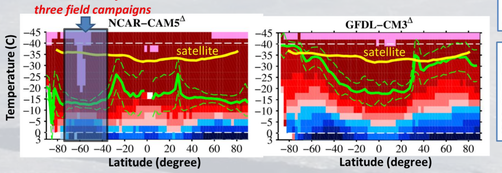
- Mixed-phase clouds are thermodynamically unstable, yet they have extensive distributions over the Southern Ocean and Antarctica.
- Using satellite observations, the validation of global climate models (GCM)s shows that the models often overlook supercooled liquid water over the Southern Ocean.
- Two highlights of this study: (1) we developed a scale-aware comparison between observations and simulations across scales from hundreds of meters to hundreds of kilometers; (2) evaluation of NCAR Community Atmosphere Model (CAM) is conducted for three cloud phases separately.

Impacts of Southern Ocean and Antarctic 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)*

Observations from three field 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. How do we conduct scare-aware comparisons between observations and GCM simulations?
2. What are the typical cloud characteristics that the NCAR CAM model misrepresent?
3. What are the lessons we learned for validating GCM cloud parameterization?

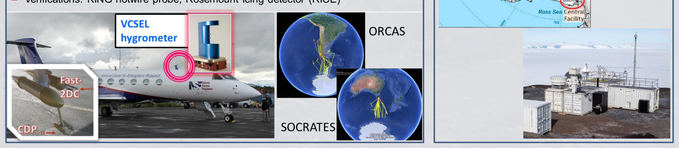
Three Field Campaigns and Instrumentations

NSF O_2/N_2 Ratio and CO_2 Airborne Southern Ocean (ORCAS) Study	NSF Southern Ocean Cloud, 20 Radiation, Aerosol Transport Experimental Study (SOCRATES)	DOE/NSF Atmospheric Radiation Measurement (ARM) West Antarctic Radiation Experiment (AWARE Campaign)
Jan 15–Feb 28 2016, Punta Arenas	Jan 15 – Feb 24 2018; Hobart, Australia	December 2015 – January 2017, McMurdo St.
In-situ observations on NSF G-V aircraft	In-situ observations on NSF G-V aircraft	Ground-based obs and sounding by ARM AMF

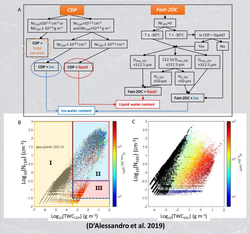
Vertical Cavity Surface Emitting Laser (VCSEL) hygrometer
- Near infrared; 25 Hz -> 1 Hz; Accuracy ≤ 6%; Precision ≤ 1% (Zondlo *et al.* 2010)
- Combine with ±0.3 K temperature uncertainties, **RHice and RHliq** uncertainties are **7.5%–6.5%** and **10.4%–6.4%** for -69°–0°C, respectively.

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

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



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

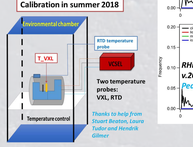


(D'Alessandro et al. 2019)

Continuous Work: Laboratory Calibration of the Airborne Hygrometer

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

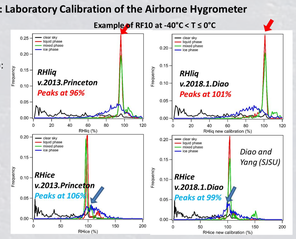
Calibration in summer 2018



Two temperature probes: VXL, RTD

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

Example of RF10 at -40°C < T ≤ 0°C



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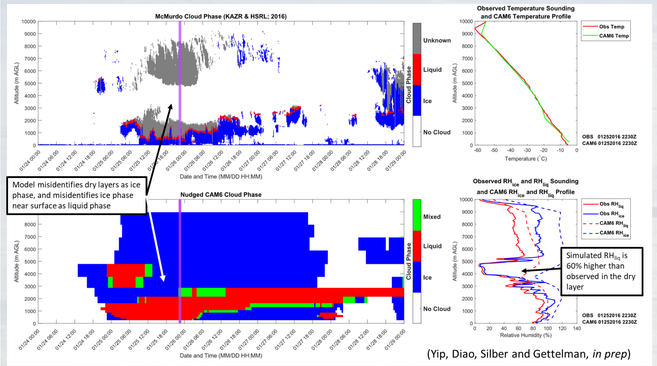
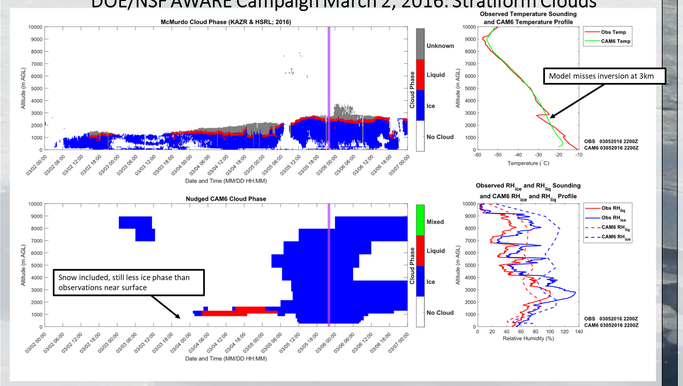
Clouds over the Antarctica

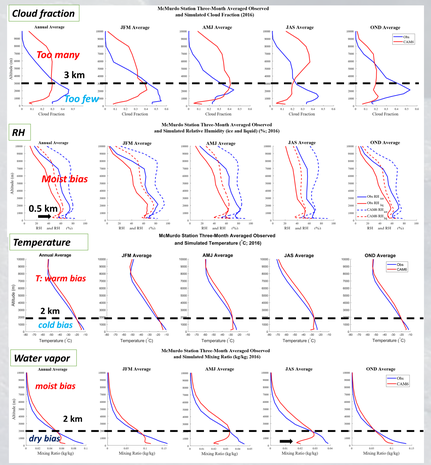
DOE/NSF AWARE Campaign January 24, 2016: Multi-layer Clouds



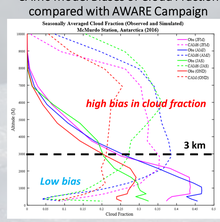
(Yip, Diao, Silber and Gettelman, *in prep*)

DOE/NSF AWARE Campaign March 2, 2016: Stratiform Clouds





CAM6 Model Biases of Cloud Fraction compared with AWARE Campaign



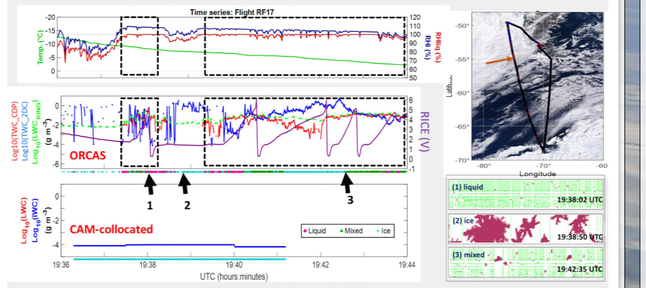
It is challenging to represent complex topography around the McMurdo Station, which often produce katabatic wind.

Based on the analysis of an entire year in 2016, the CAM6 simulation nudged towards reanalysis data overestimates cloud fraction > 3 km, and underestimate cloud fraction < 3 km.

Thermodynamic conditions in the model show warm and moist biases > 3 km, and cold and dry biases < 3 km. This result indicates that the biases in water vapor and temperature may hold the key to improve model simulations of ice and mixed-phase clouds at this region.

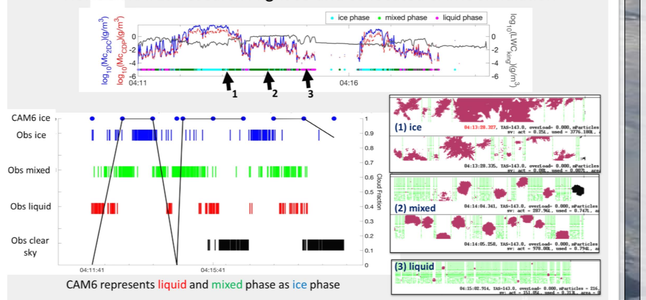
Clouds over the Southern Ocean

NSF ORCAS campaign Research Flight 17 compared with National Center for Atmospheric Center (NCAR) Community Atmosphere Model Version 5 (CAM5) simulation



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

NSF SOCRATES Research Flight 09 and collocated CAM6 simulation

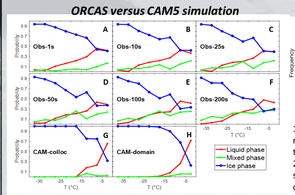


CAM6 represents liquid and mixed phase as ice phase

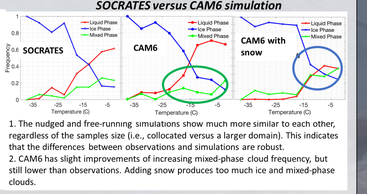
Comparisons of cloud phase frequency distribution in observations and simulations

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", "NUMLIC", "NUMICE"

ORCAS versus CAM5 simulation



SOCRATES versus CAM6 simulation



1. The nudged and free-running simulations show much more similar to each other, regardless of the samples size (i.e., collocated versus a larger domain). This indicates that the differences between observations and simulations are robust.
2. CAM6 has slight improvements of increasing mixed-phase cloud frequency, but still lower than observations. Adding snow produces too much ice and mixed-phase clouds.

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-colloc ated	-10°≤T<0°C	60%	3%	37%
	-20°≤T<-10°C	53%	1%	46%
	-30°≤T<-20°C	0%	0%	100%
	-40°≤T<-30°C	0%	0%	100%
CAM-doma in	-10°≤T<0°C	70%	4%	25%
	-20°≤T<-10°C	29%	1%	70%
	-30°≤T<-20°C	1%	<1%	99%
	-40°≤T<-30°C	0%	0%	100%

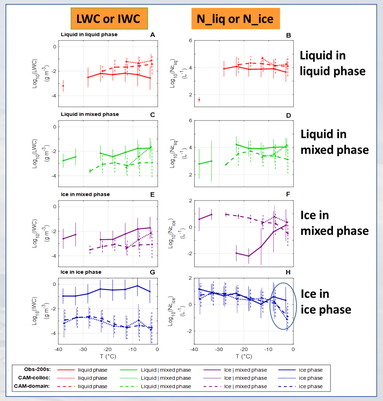
All data are restricted to cloud water content (TWC) ≥ 0.01 g m-3

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

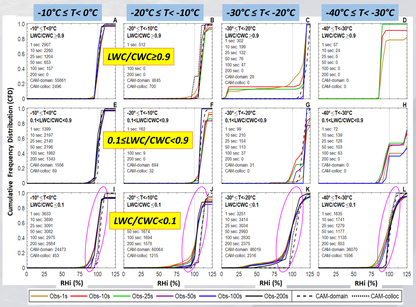
At -40°C≤T<-20°C: CAM5 underestimates liquid and mixed phase clouds

It is possible that satellite observations have biases towards observing cloud top, which is often liquid phase dominated. Thus it is important to use in-situ and ground-based observations as alternative observations approach to validate GCM simulations, which will complement spaceborne remote sensing observations for their limitation.

Cloud microphysical properties in three cloud phases



Liquid saturation assumption in GCMs



- *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…

Conclusions

1. **We developed a scale-aware comparison between aircraft observations and GCM simulations** (D'Alessandro et al. 2019).
2. **Nudged, collocated and free-running simulations show mostly similar results** for cloud phase frequency, LWC, IWC, N_{ice}, N_{liq}.
3. **Common mistakes in CAM5 and CAM6**
   CAM6 has small increase of mixed-phase cloud frequency comp. with CAM5
   Southern Ocean: spatially heterogeneous mixed-phase clouds => ice clouds
   Antarctica: cld frct high (low) bias > (≤) 2 km; multi-layer clouds => one layer
4. **Implications on validating and improving GCM cloud parameterizations**
   Validations are recommended for specific cloud phases.
   Thermodynamic condition, especially relative humidity, may hold the key to improve simulations of cloud phase and microphysical properties in NCAR CAM model.

Acknowledgement

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References

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3. Wu, C., X. Liu, M. Diao, K. Zhang, A. Gettelman, Z. Lu, J.E. Penner, and Z. Lin. Direct comparisons of ice cloud macro- and microphysical properties simulated by the Community Atmosphere Model version 5 with HIPPO aircraft observations, *Atmos. Chem. Phys.*, 2017.