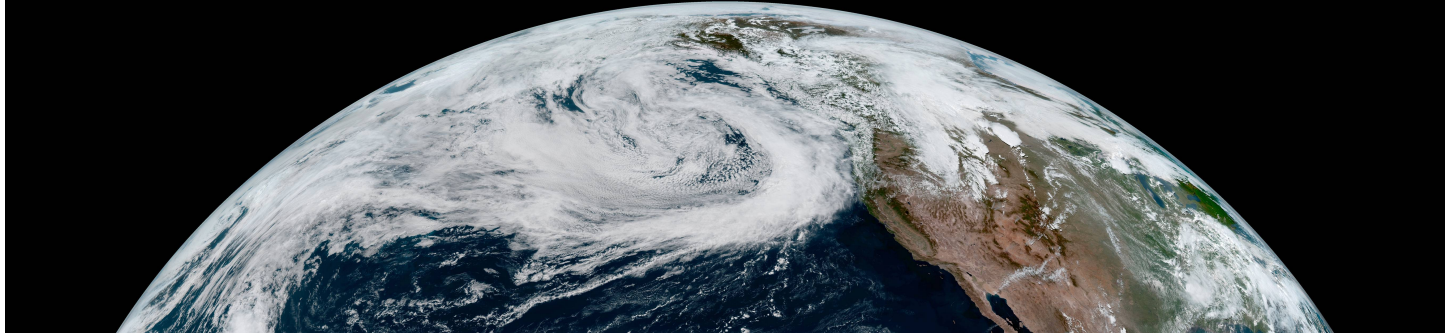
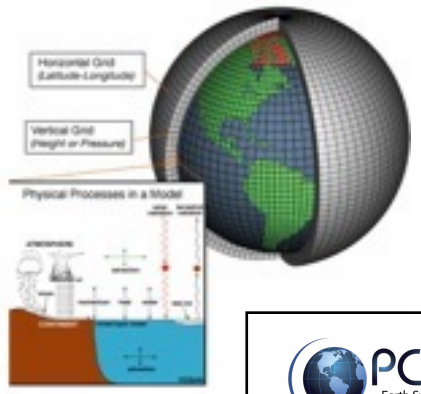


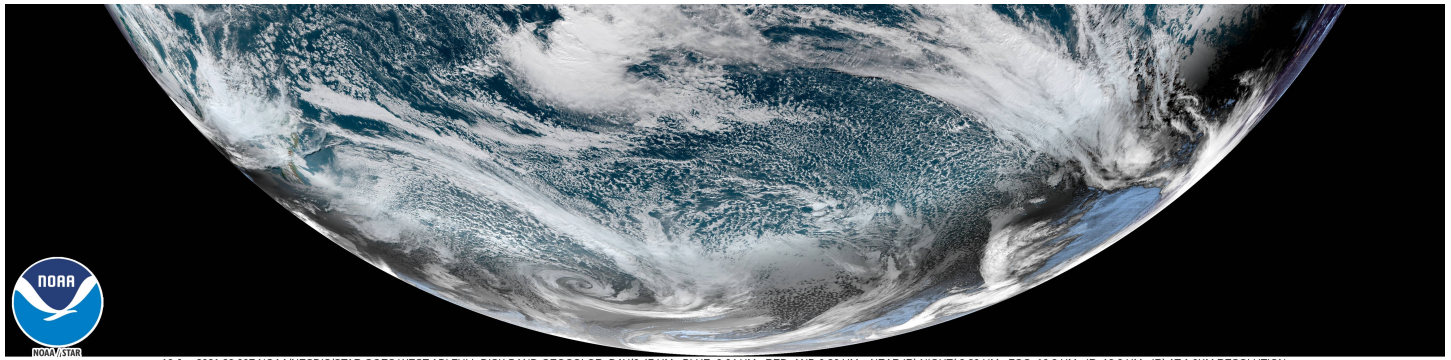
Extra-tropical Cloud Feedbacks in Climate Models

Steve Klein (PCMDI/LLNL)

ARM/ASR 2021 Virtual Joint Meeting

June 24, 2021





PCMDI Earth System Model Evaluation Project

U.S. DEPARTMENT OF ENERGY | Office of Science

ASR Atmospheric System Research

RGMA

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Security, LLC, Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-PRES-823808

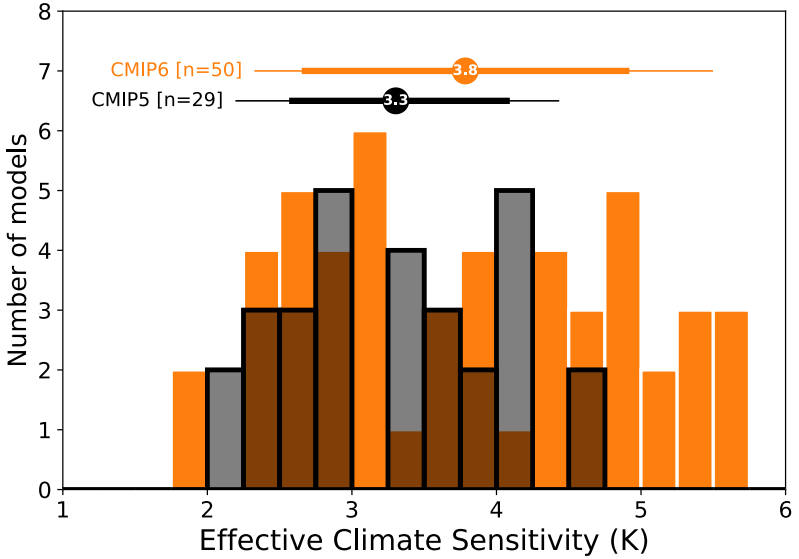
Extra-tropical Cloud Feedbacks and Climate Sensitivity

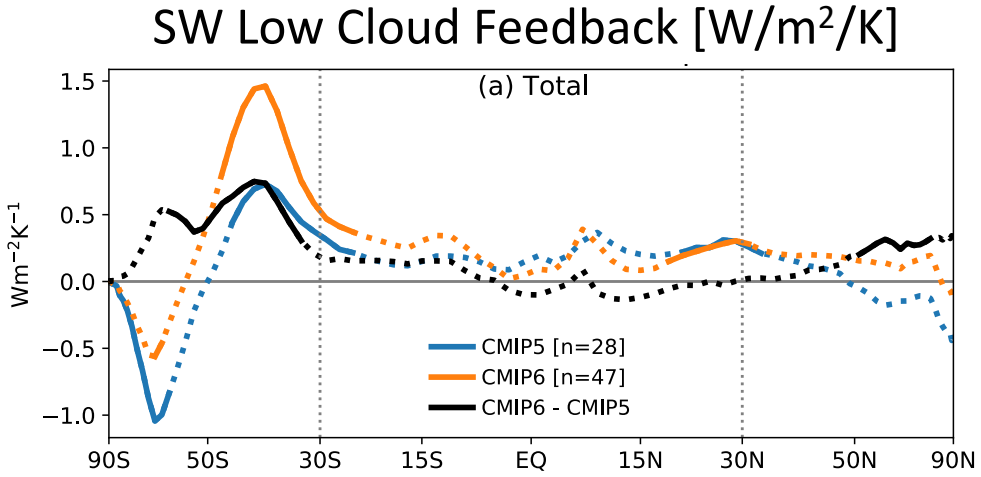
Cloud Feedback ≡ How Cloud Radiative Effects Change with Climate Warming

Climate Sensitivity ≡ How Much Warming Will Result from a Given Increase in Radiative Forcing (i.e., CO_2)

Latest Climate Models Have Increased Climate Sensitivity Which Is Due to an Increase in the Feedbacks from Extra-tropical Low Clouds

What do we believe about these changes in cloud feedbacks and climate sensitivity?





Zelinka et al. (2020)

Extra-tropical Cloud Feedbacks and Climate Sensitivity

Sherwood et al. (2020)

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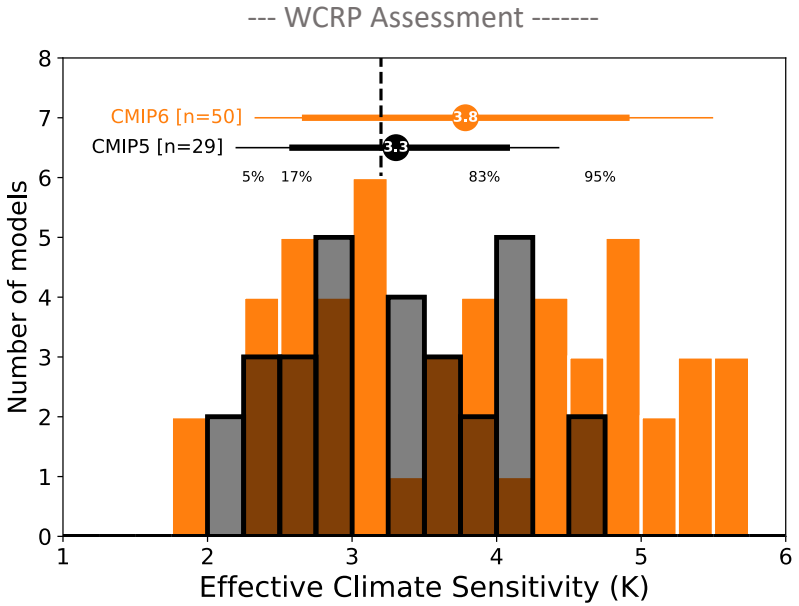
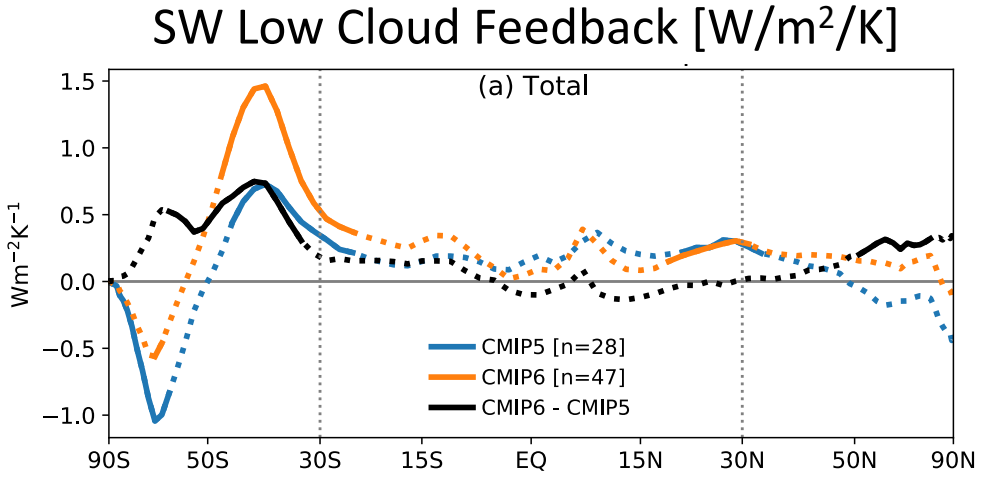




Zelinka et al. (2020)

Processes at Play in Extra-Tropical Cloud Feedbacks in Climate Models

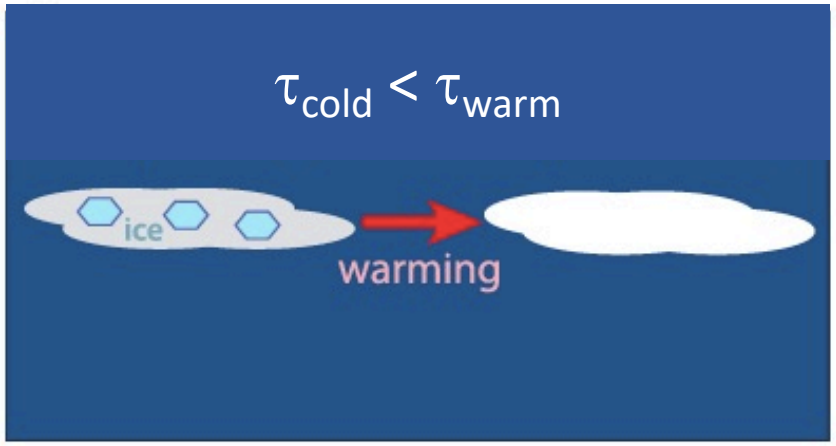
1. Extratropical Cloud Phase Feedback

2. Aerosol-mediated Cloud Feedback in the Southern Ocean

1. Extra-tropical Cloud Phase Feedback

Model 1 (~Older Models)

Less Supercooled Liquid and More Ice



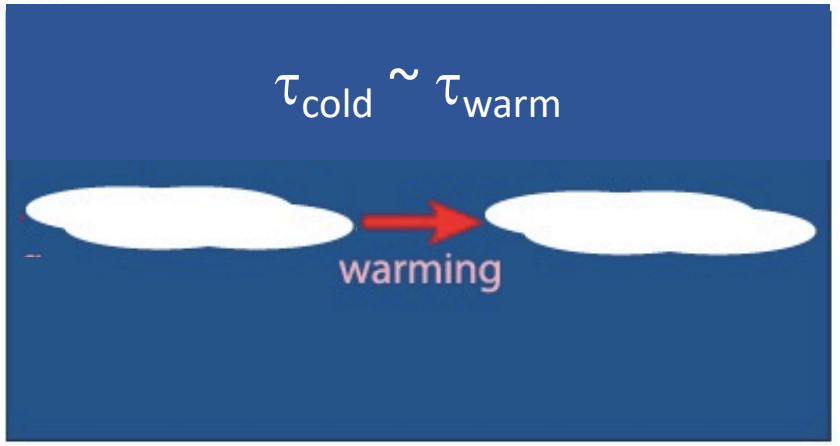
Clouds Get Brighter With Warming

More Reflection of Solar Radiation With Warming

Negative Cloud Feedback

Model 2 (~Newer Models)

Model With More Supercooled Liquid and Less Ice



Clouds Unchanged With Warming

Unchanged Reflection of Solar Radiation With Warming

Zero Cloud Feedback

Tan et al. 2016, Frey and Kay 2017, Bodas-Salcedo et al. 2019, Gettelman et al. 2019

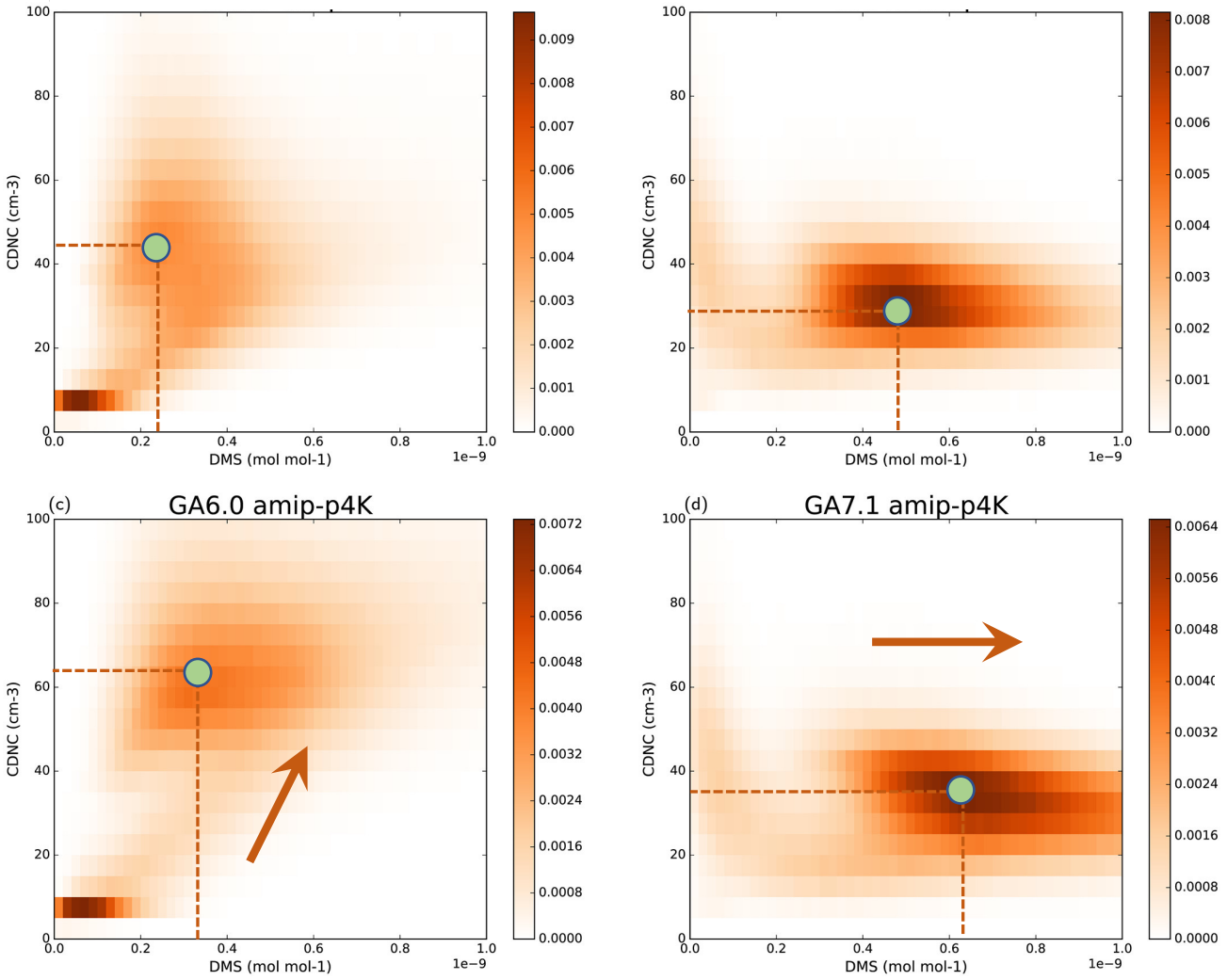
2. Aerosol-mediated Cloud Feedback in the Southern Ocean

Under climate warming, surface winds strengthen in the Southern Ocean driving increases in DMS concentrations. How do the clouds respond?

Old Aerosol Model → Newer Aerosol Model

Present Day ↓ Warmer World

Cloud Droplet Number Concentration



DiMethyl Sulfide Concentration

Joint PDF of DMS and Cloud Droplet Number Concentrations

Bodas-Salcedo et al. 2019 from the HadGEM model

Key Question

What processes determine the radiative properties (water paths and particle sizes of ice and liquid) of extra-tropical low clouds and how they change with warming?

- Cloud Microphysical Processes: ice processes influencing cloud phase (e.g., WBF[1] or SIP[2] processes), liquid-phase precipitation[3]
- Aerosol-Cloud Interactions: cloud droplet nucleation[4], ice nucleating particles[1,5])
- Radiative, Turbulent, and Convective Processes: cloud-top radiative cooling[6], entrainment, convection[7], boundary layer mixing
- Large-scale water-vapor convergence by extra-tropical cyclones[8]

[1]Tan et al. 2016, [2]Zhao et al. 2021, [3]Muhlmendstadt et al. 2021, [4]Bodas-Salcedo et al. 2019, [5]Morrison et al. 2005, [6]Field et al. 2014, Furtado et al. 2016, [7]Kay et al. 2016, [8]McCoy et al. 2020

How Can Observations Help? (just an incomplete list …)

Satellite observations

- What is the global extent of supercooled liquid clouds? (from Calipso observations) *(Hu et al. 2010)*
- How much precipitation occurs in warm and super-cooled clouds? (from Cloudsat observations) *(Haynes et al. 2009, McIlhattan et al. 2017)*
- How does cloud optical depth change with temperature? *(Gordon and Klein 2014, Terai et al. 2016)*

In-situ / Ground-based ARM data

- How much precipitation occurs in clouds with super-cooled liquid? *(Silber et al. 2021)*
- How do extra-tropical cloud properties (e.g., liquid and ice) vary with temperature and its fine structures as revealed by soundings? *(Terai et al. 2019)*

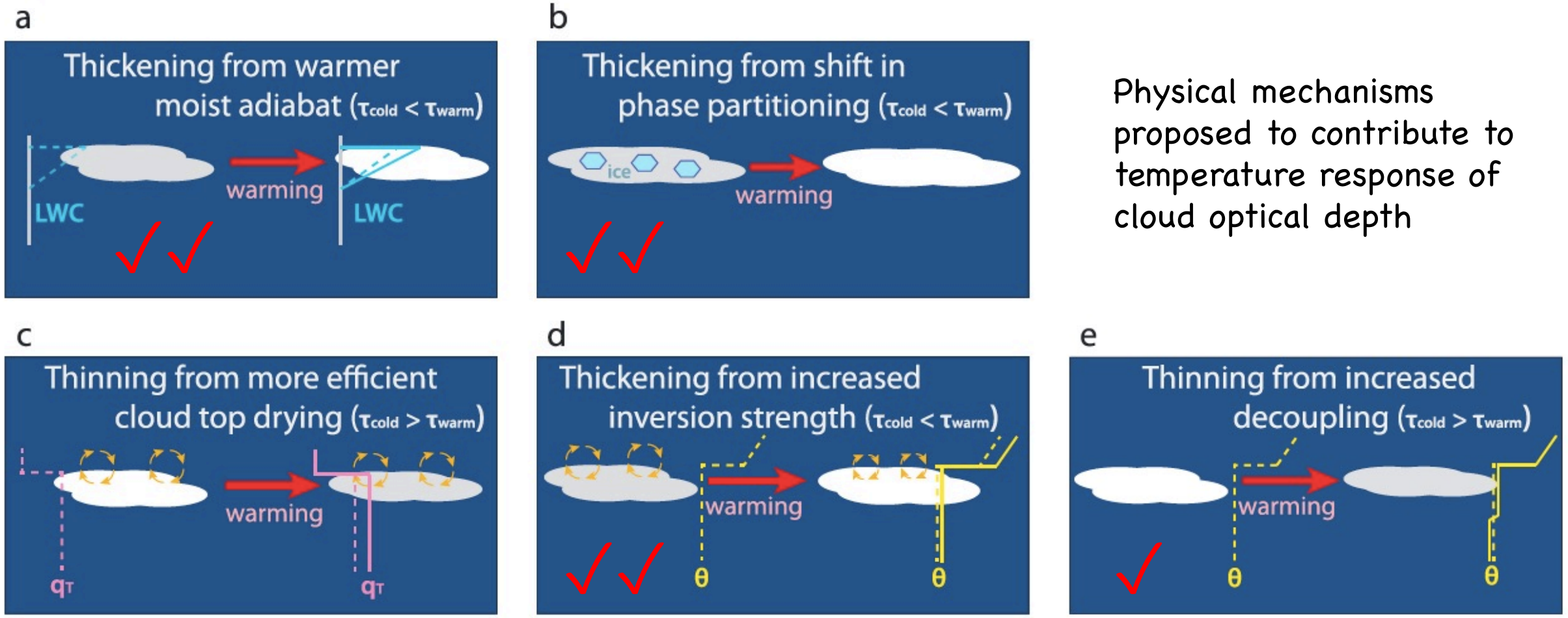
JGR Atmospheres

Mechanisms Behind the Extratropical Stratiform Low-Cloud Optical Depth Response to Temperature in ARM Site Observations

Terai et al. (2019)

From SGP, ENA, and NSA data

C. R. Terai[1], Y. Zhang[1], S. A. Klein[1], M. D. Zelinka[1], J. C. Chiu[2], and Q. Min[3]



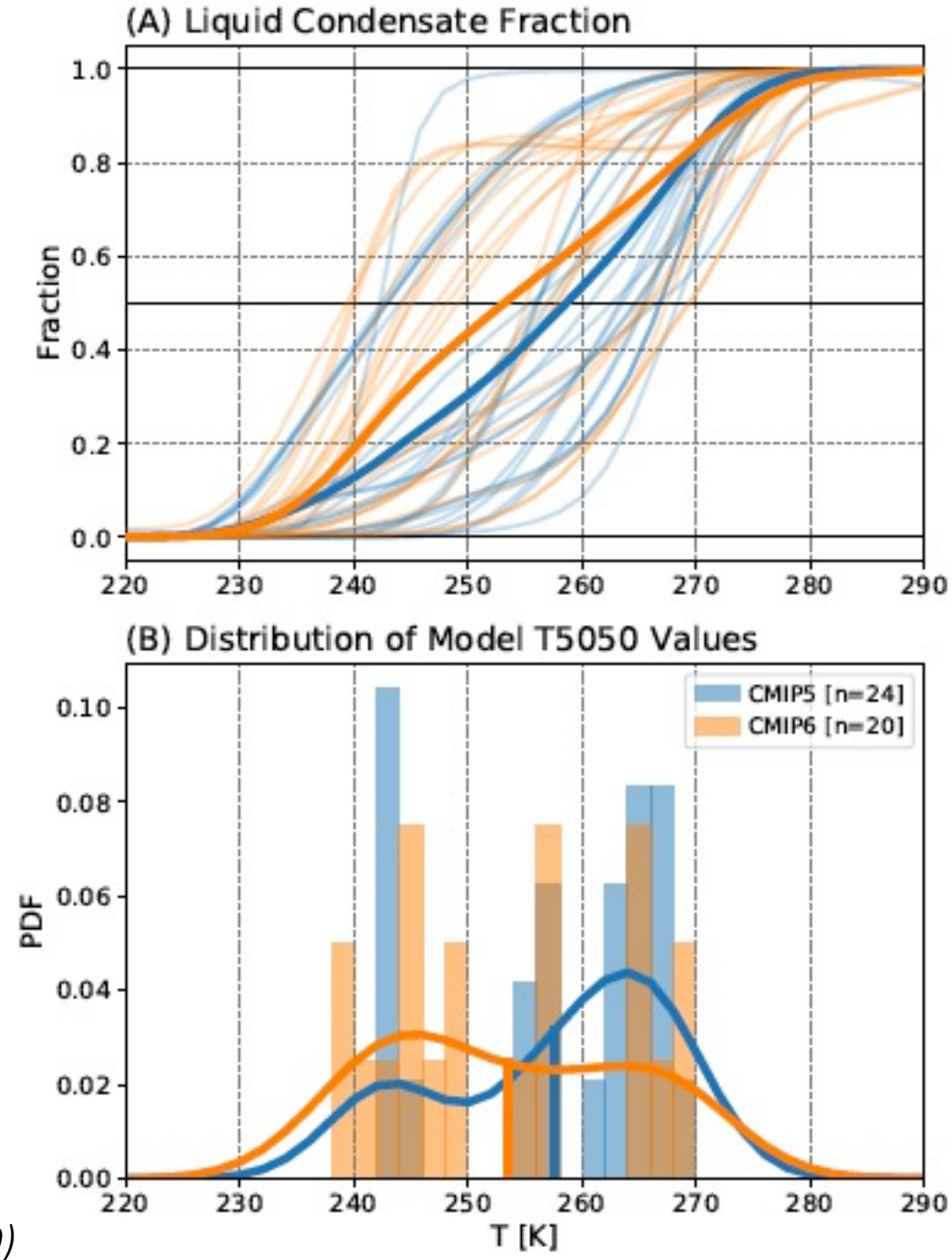
Physical mechanisms proposed to contribute to temperature response of cloud optical depth

What will the recent ARM campaigns (AWARE, MARCUS, MICRE, COMBLE) reveal about extra-tropical clouds and the processes governing them?

Extra Slides

Extra-tropical Cloud Phase in Climate Models

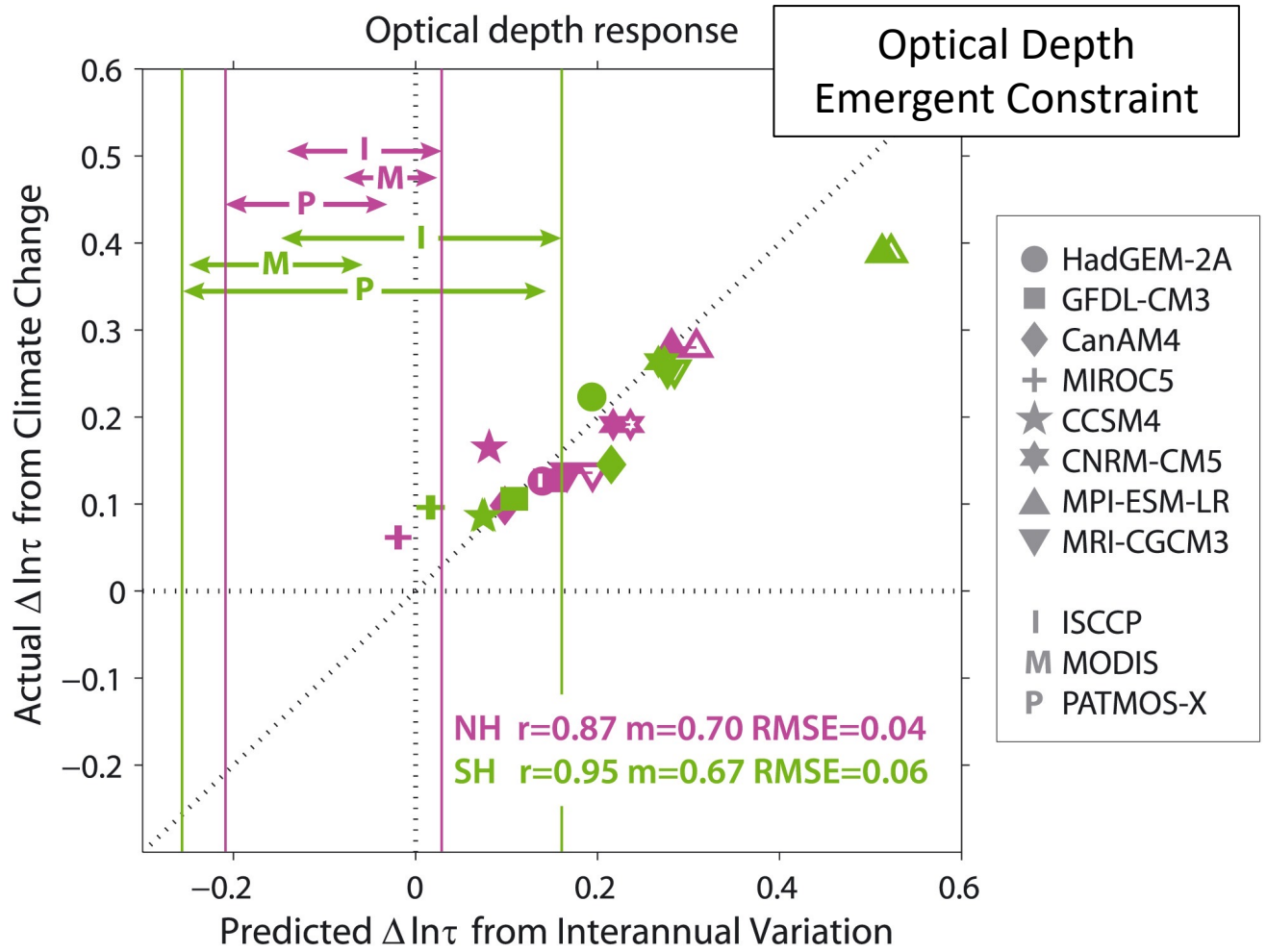
Newer models have more super-cooled liquid generally in better agreement with observations



Zelinka et al. (2020)

Using Satellite Observations to Constrain the Extratropical Cloud Optical Depth Feedbacks

Satellite observations suggest $\partial \ln(\tau)/\partial T \lesssim 0$ *, a property which models suggest is time-scale invariant*



Terai et al. (2016)