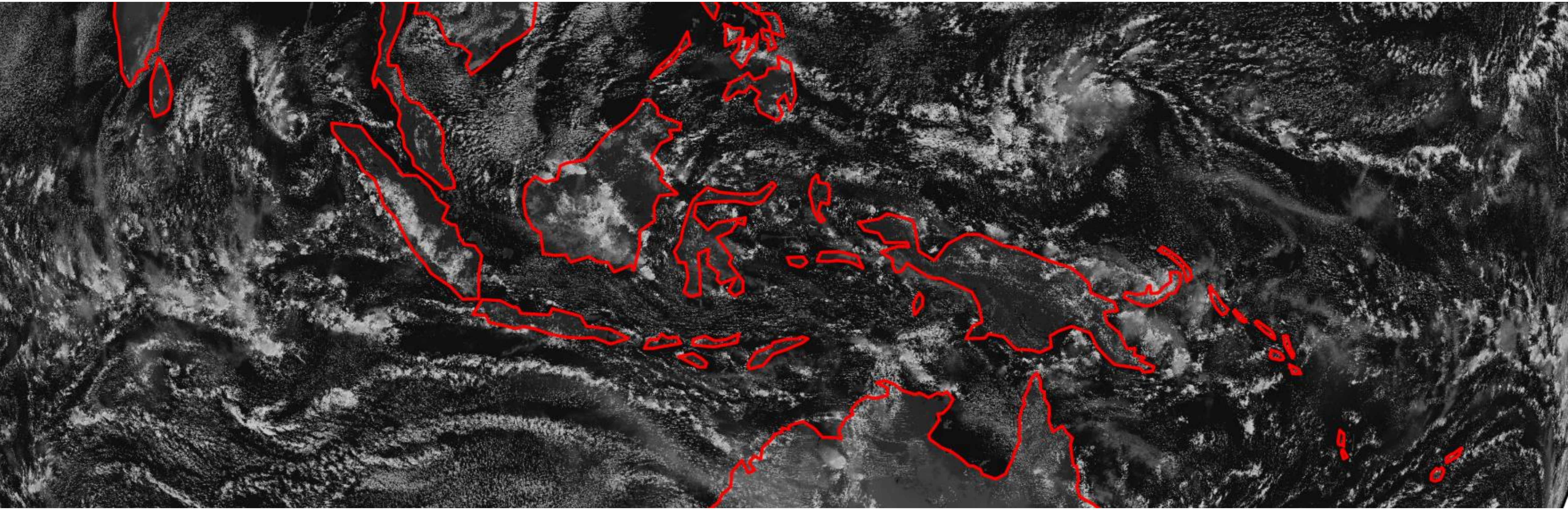
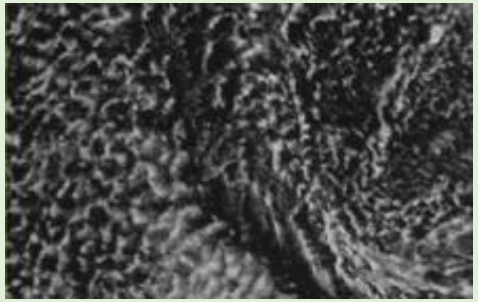
Evaluating clouds and vertical winds in global storm-resolving models with observations from satellite and aircraft



Rachel Atlas ◦ Chris Bretherton ◦ Marat Khairoutdinov ◦ Peter Blossey ◦ Adam Sokol

1) Southern Ocean Low Clouds



Atlas et al. 2022, AGU ADVANCES

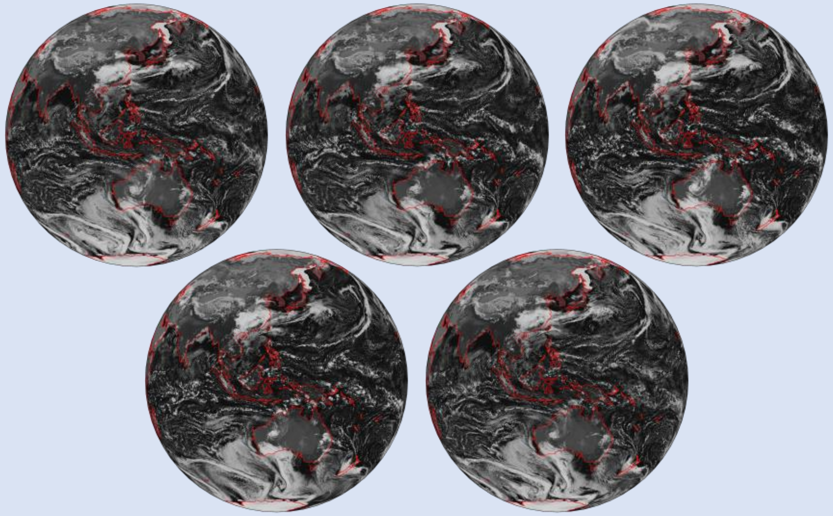
2) Tropical High Clouds

In review for GRL

3) Small-scale gravity waves

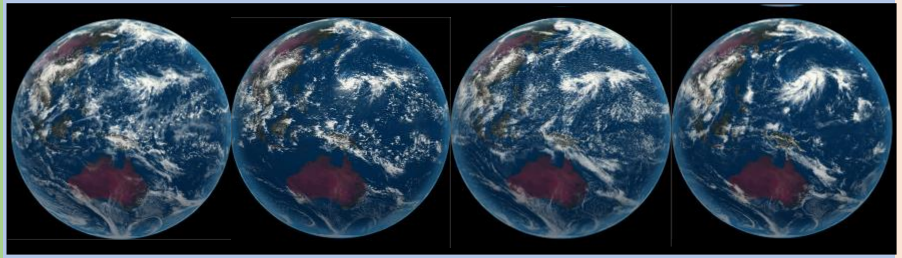
Atlas and Bretherton 2023, ACP

Five nudged simulations from one model with different microphysics



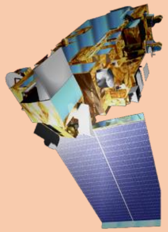
- Useful for microphysics sensitivity tests
- Allows for comparison with coincident observations

DYAMOND-1: Four free-running simulations from multiple models

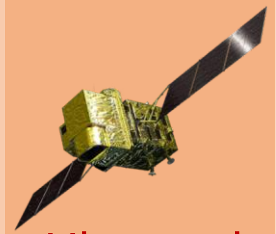


Useful for evaluating the state of GSRMs

Aircraft



Ceres

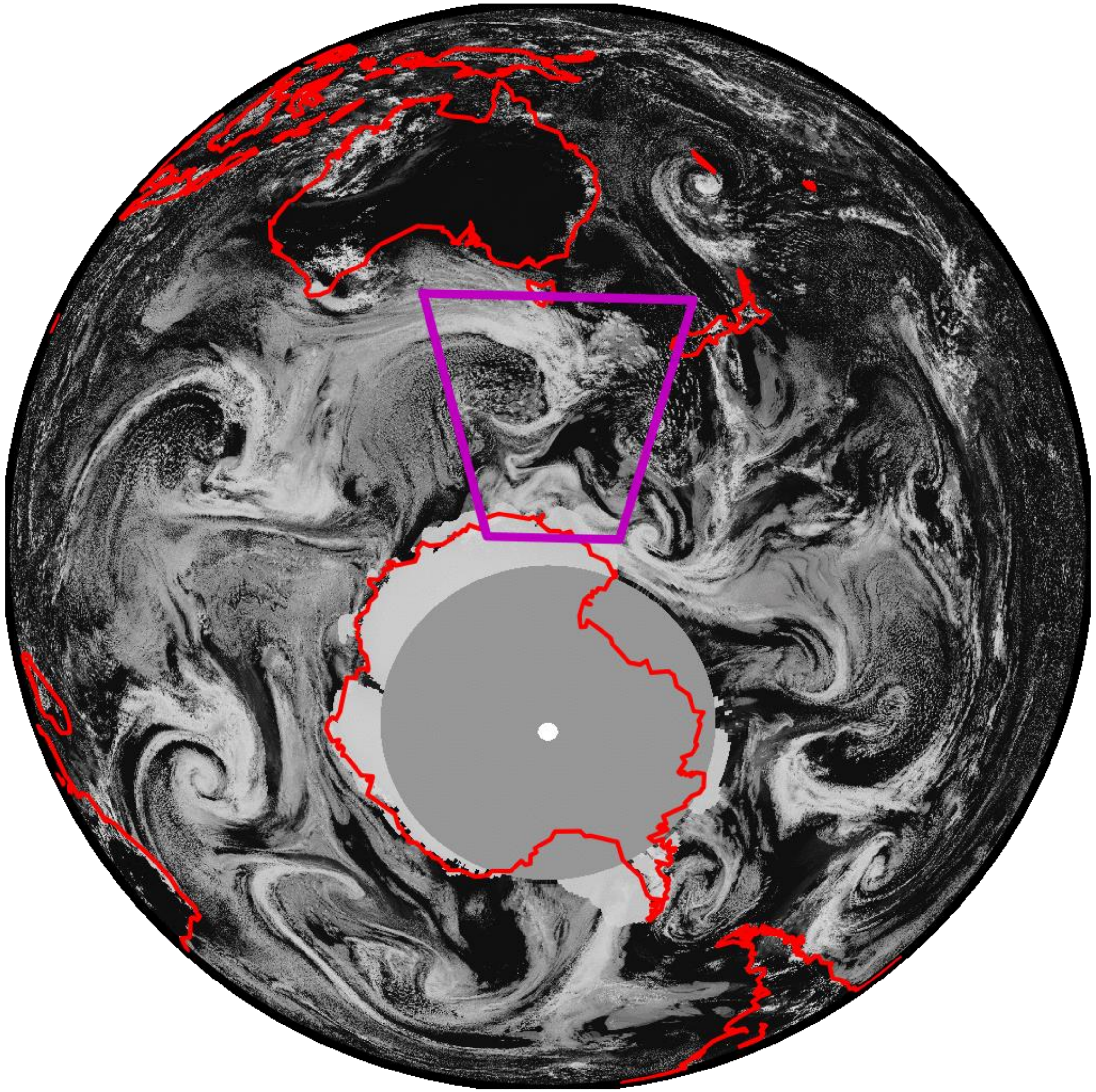


Himawari

DARDAR
2C-Ice

Five simulations from the global System for Atmospheric Modelling (gSAM)

- 4608 x 9216 x 74 grid (2-4 km horizontal resolution)
- Otherwise identical simulations are run with different microphysics schemes.
- Temperature and horizontal winds (but not moisture) are nudged to ERA5 with a 24-hour timescale
- Five day duration (February 15th - 20th 2018)

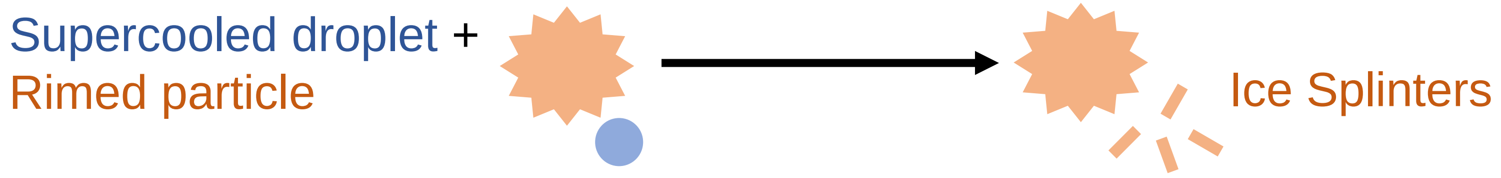


How does ice form in low mixed-phase clouds?

Primary ice production: heterogeneous nucleation

The number of ice particles produced by primary ice production is limited by the number of ice nucleating particles in the atmosphere

Secondary ice production: ice forms from other ice



This cartoon depicts just one of many secondary ice production processes

Microphysics scheme [number of prognostic variables]

Only primary ice production

Primary + secondary ice production

Complexity

M2005 [10]

M2005 MOD [10]

Identical except that M2005 MOD allows secondary ice production in low clouds

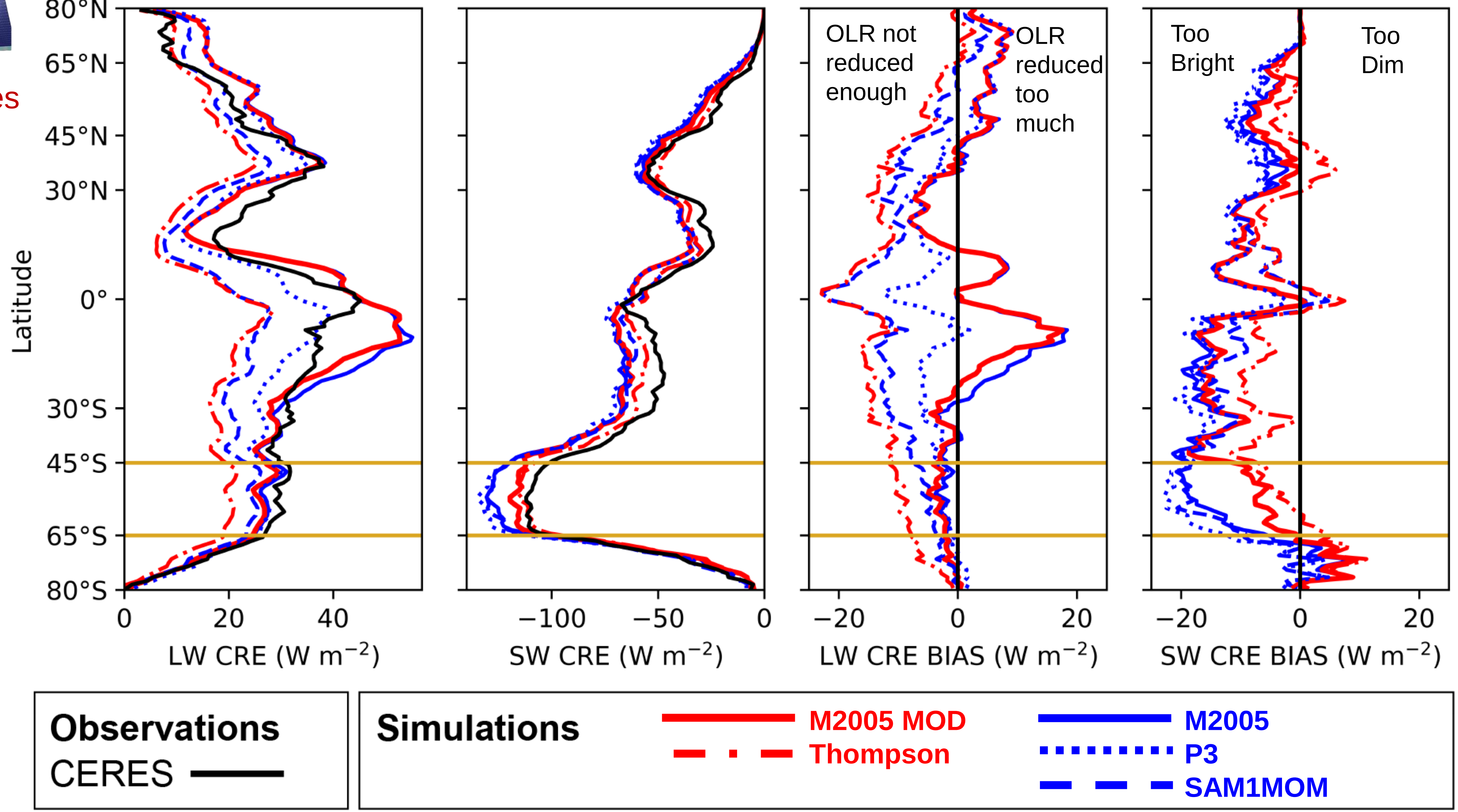
P3 [7]

Thompson [7]

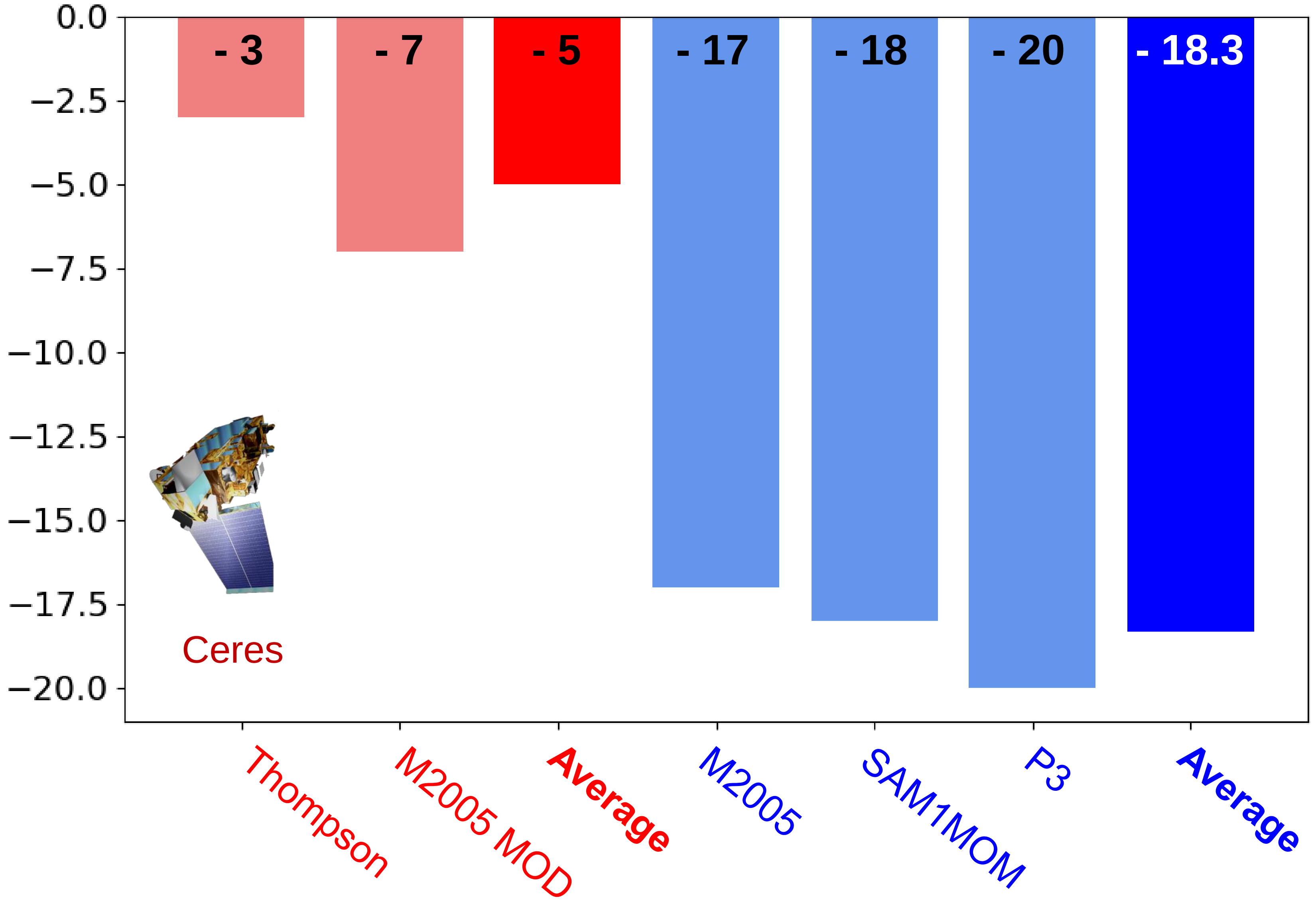
SAM1MOM [2]

Zonally averaged cloud radiative effects (CREs) and biases

Ceres

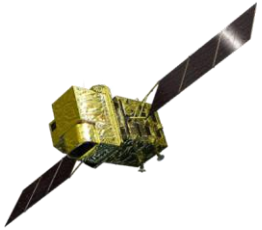


Mean bias in shortwave cloud radiative effects (W m^{-2})



Mean biases are computed over 45°S – 65°S and days 1-4 of the simulations

Red simulations (small cumulus cloud fraction) are **3.5 times** less biased than the blue simulations (large cumulus cloud fraction) on average

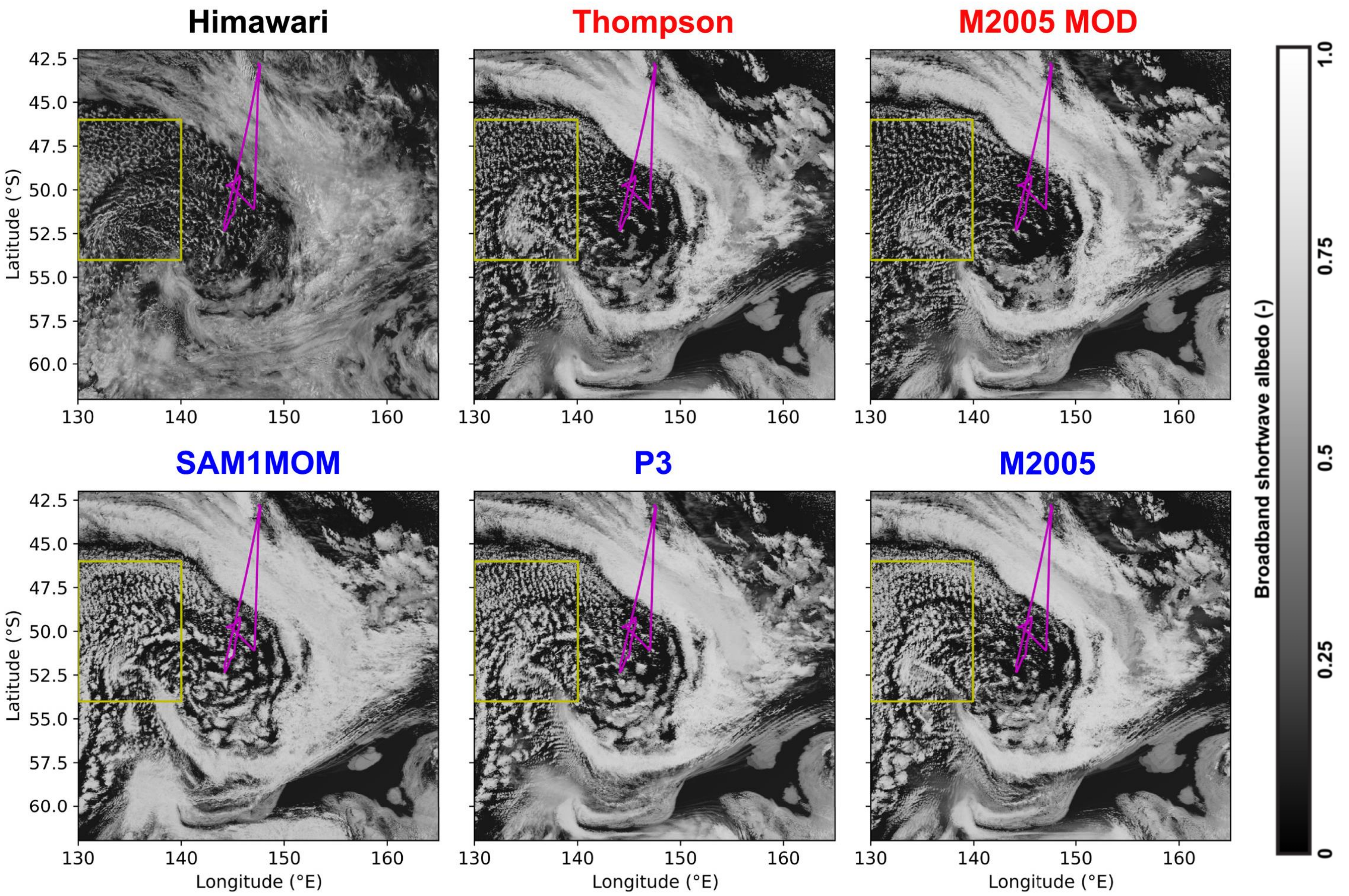


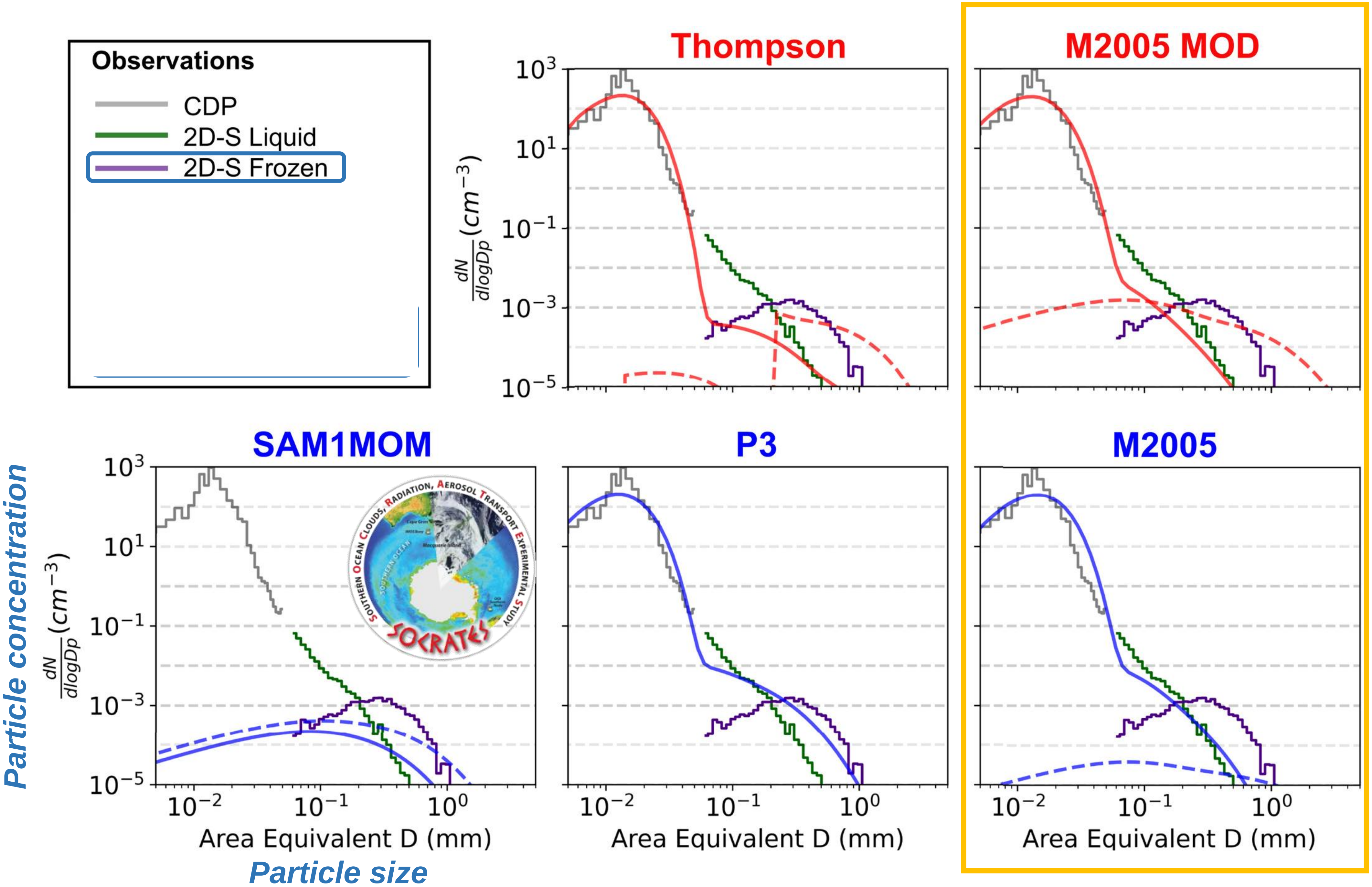
Himawari

Himawari satellite and two simulations have small cumulus cloud fraction

Three simulations have large cumulus cloud fraction

Shortwave Albedo with SOCRATES flight tracks (February 17th 2018 4 UTC)



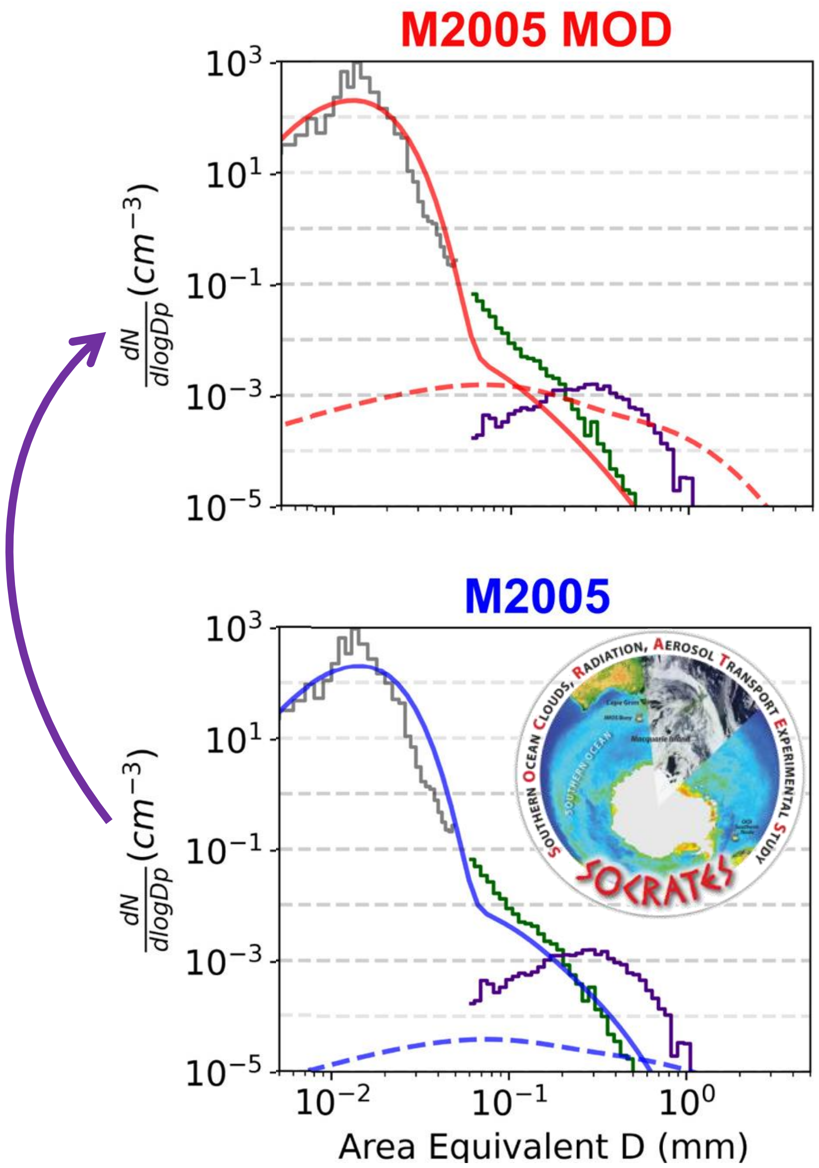


Red simulations (small cumulus cloud fraction) have more ice particles and are closer to the observations

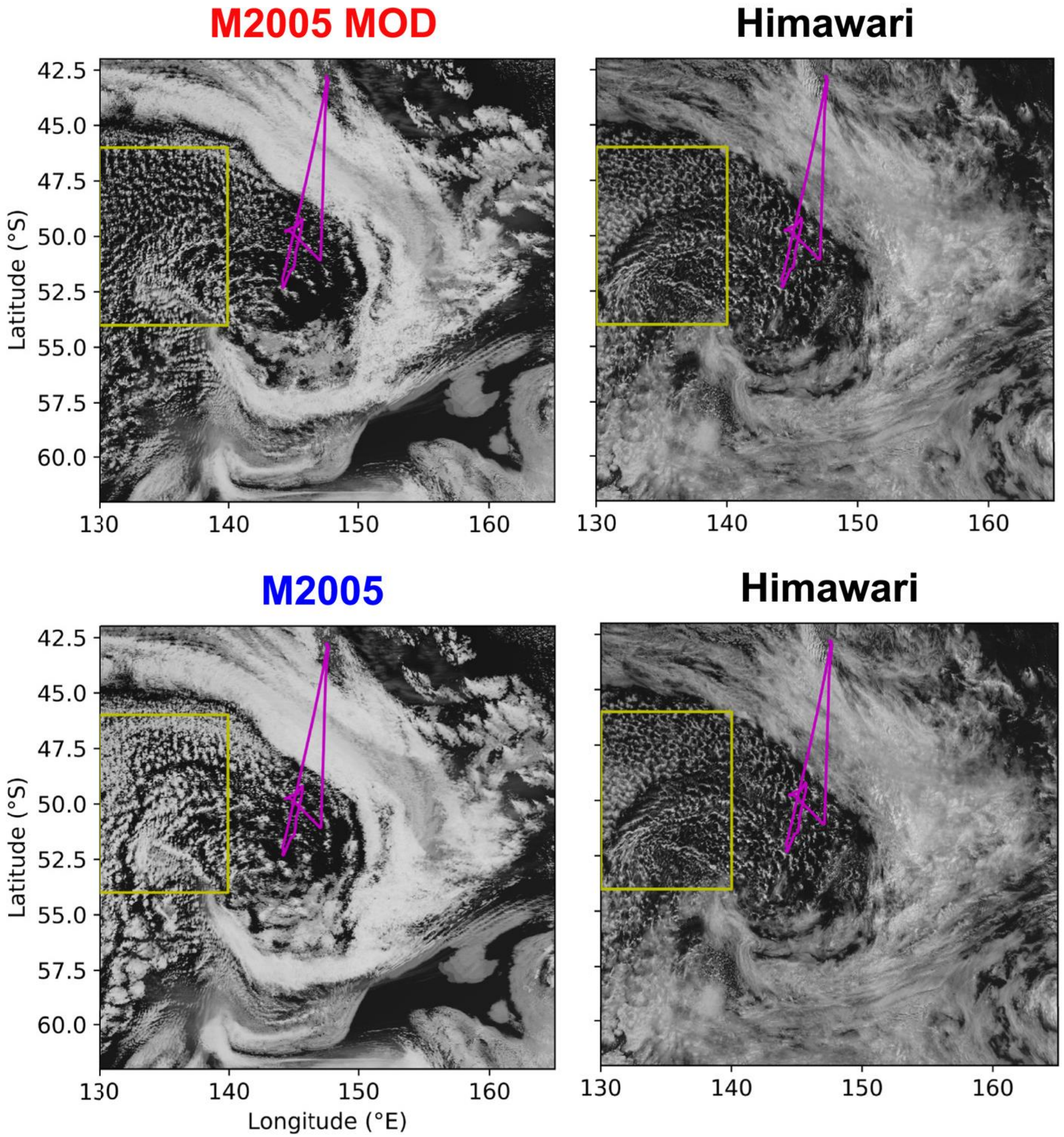
Blue simulations (large cumulus cloud fraction) have fewer ice particles

Turn on secondary ice production

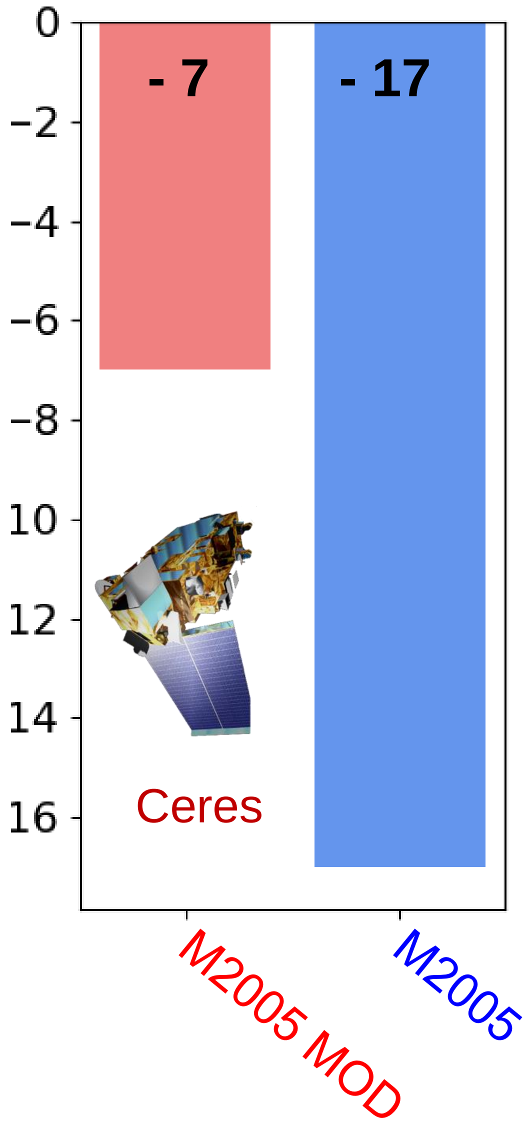
More Ice crystals



Less cumulus cloud



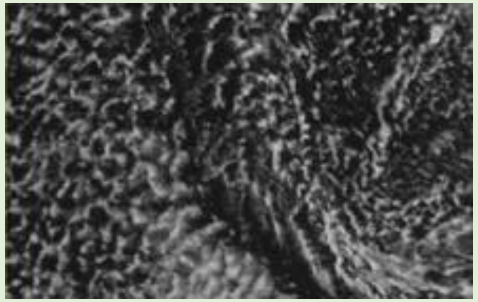
Smaller SW CRE bias



Take-aways

- Secondary ice production is important for Southern Ocean low clouds and shortwave cloud radiative effects
- Good demonstration of the usefulness of nudged simulations for studying specific microphysical processes
- Global storm-resolving models permit qualitative comparisons of cloud morphology with satellite imagery

1) Southern Ocean Low Clouds



Atlas et al. 2022, AGU ADVANCES

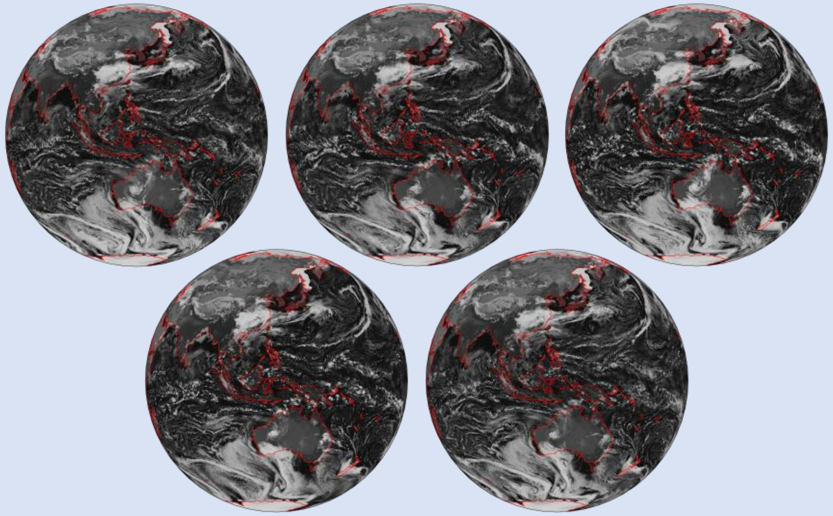
2) Tropical High Clouds

In review for GRL

3) Small-scale gravity waves

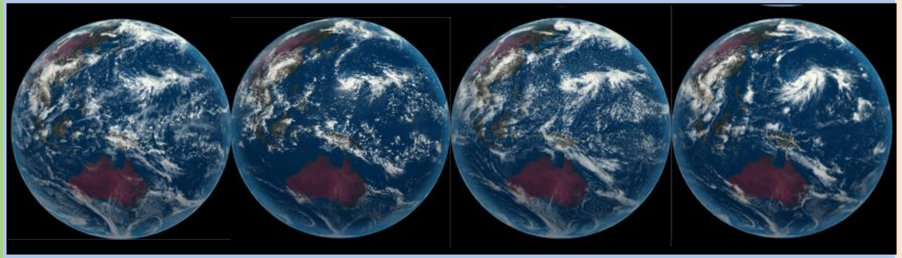
Atlas and Bretherton 2023, ACP

Five nudged simulations from one model with different microphysics



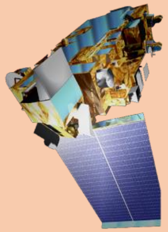
- Useful for microphysics sensitivity tests
- Allows for comparison with coincident observations

DYAMOND-1: Four free-running simulations from multiple models

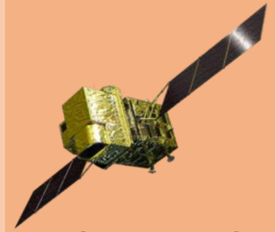


Useful for evaluating the state of GSRMs

Aircraft



Ceres

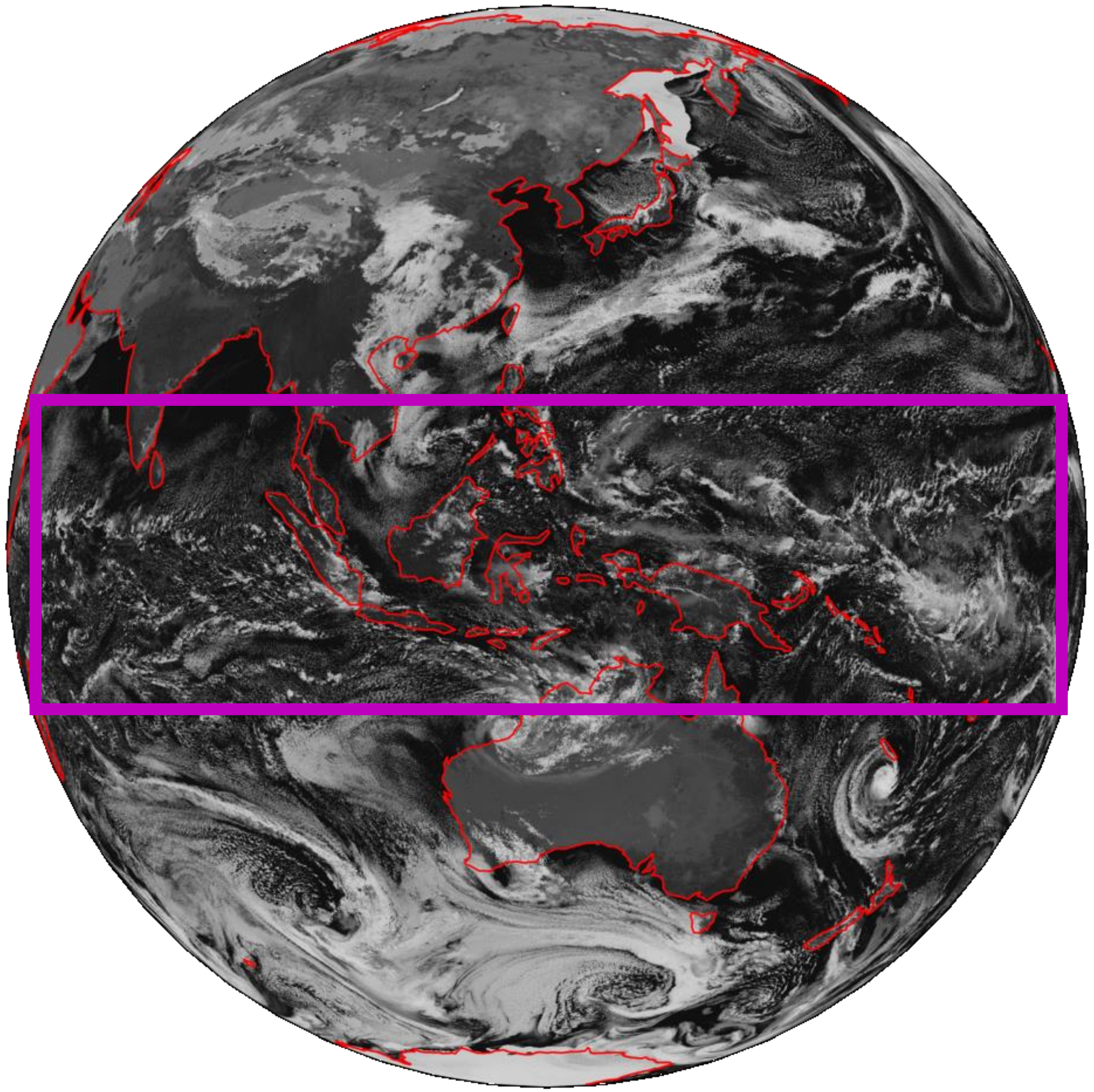


Himawari

DARDAR
2C-Ice

Five simulations from the global System for Atmospheric Modelling (gSAM)

- 4608 x 9216 x 74 grid (2-4 km horizontal resolution)
- Otherwise identical simulations are run with different microphysics schemes.
- Temperature and horizontal winds (but not moisture) are nudged to ERA5 with a 24-hour timescale
- Five day duration (February 15th - 20th 2018)



Microphysics scheme [number of prognostic variables]

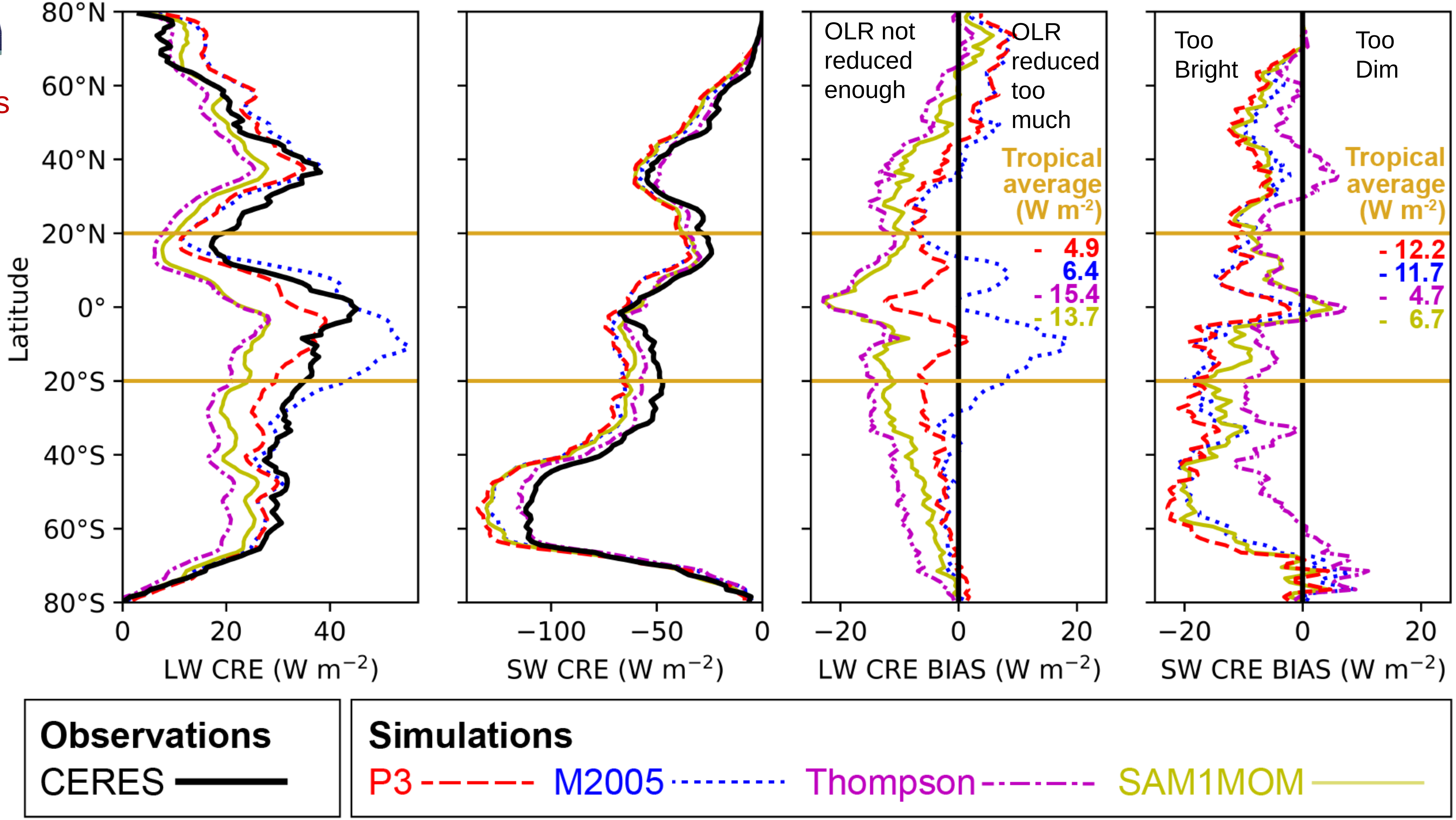
Complexity

M2005 [10]

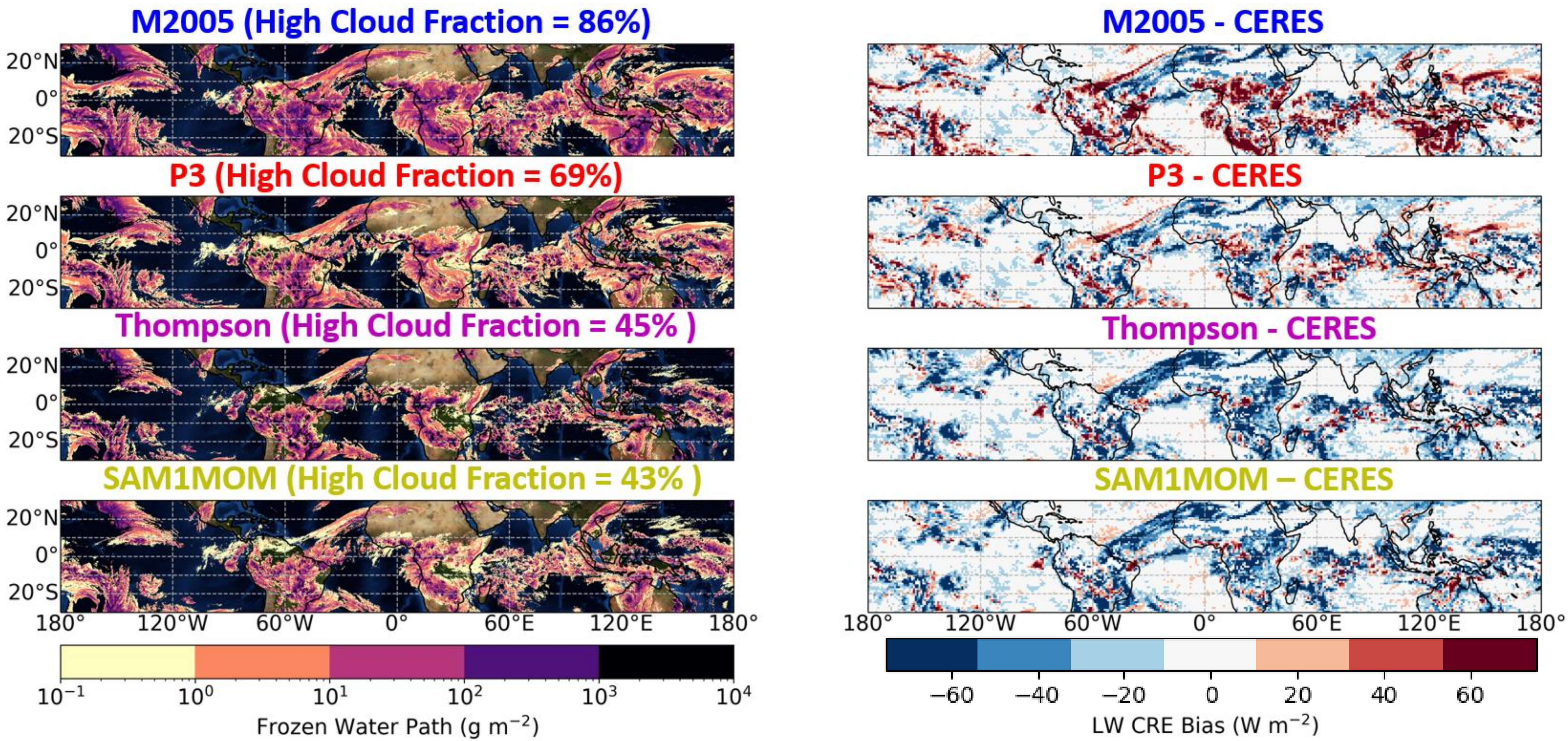
P3 [7] Thompson [7]

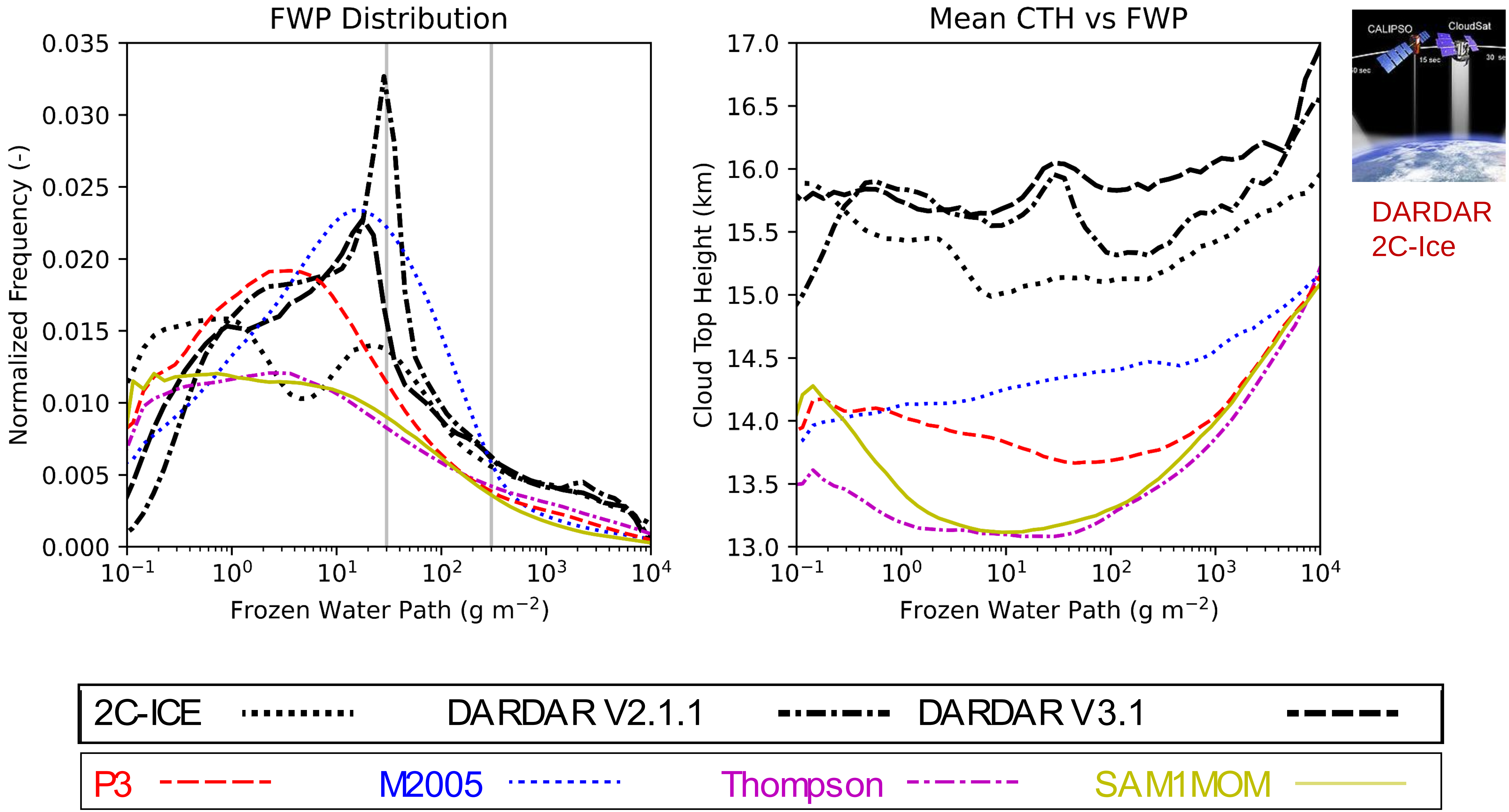
SAM1MOM [2]

Zonally averaged cloud radiative effects (CREs) and biases

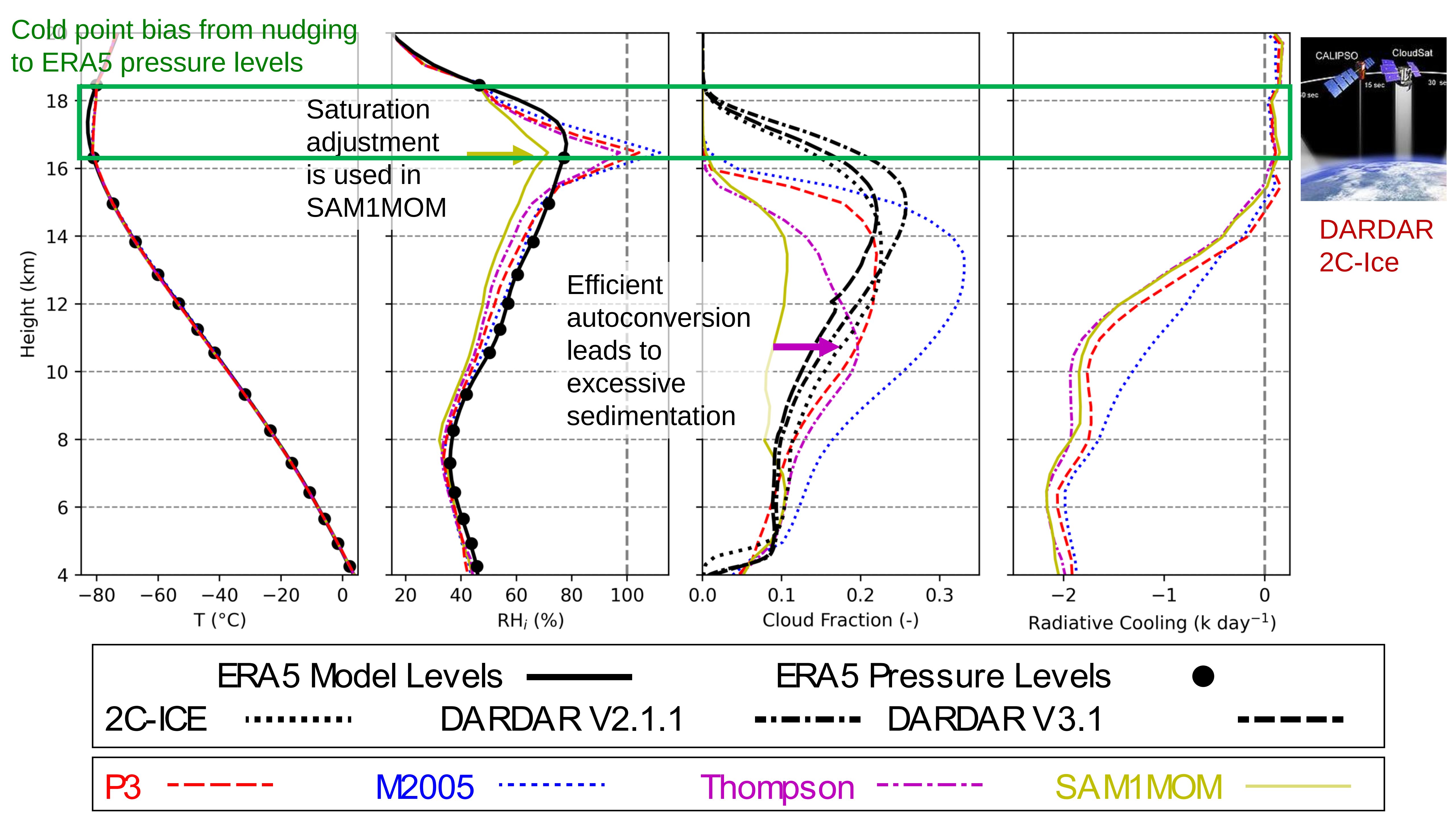


Large LW biases coincide with regions of anvil outflow





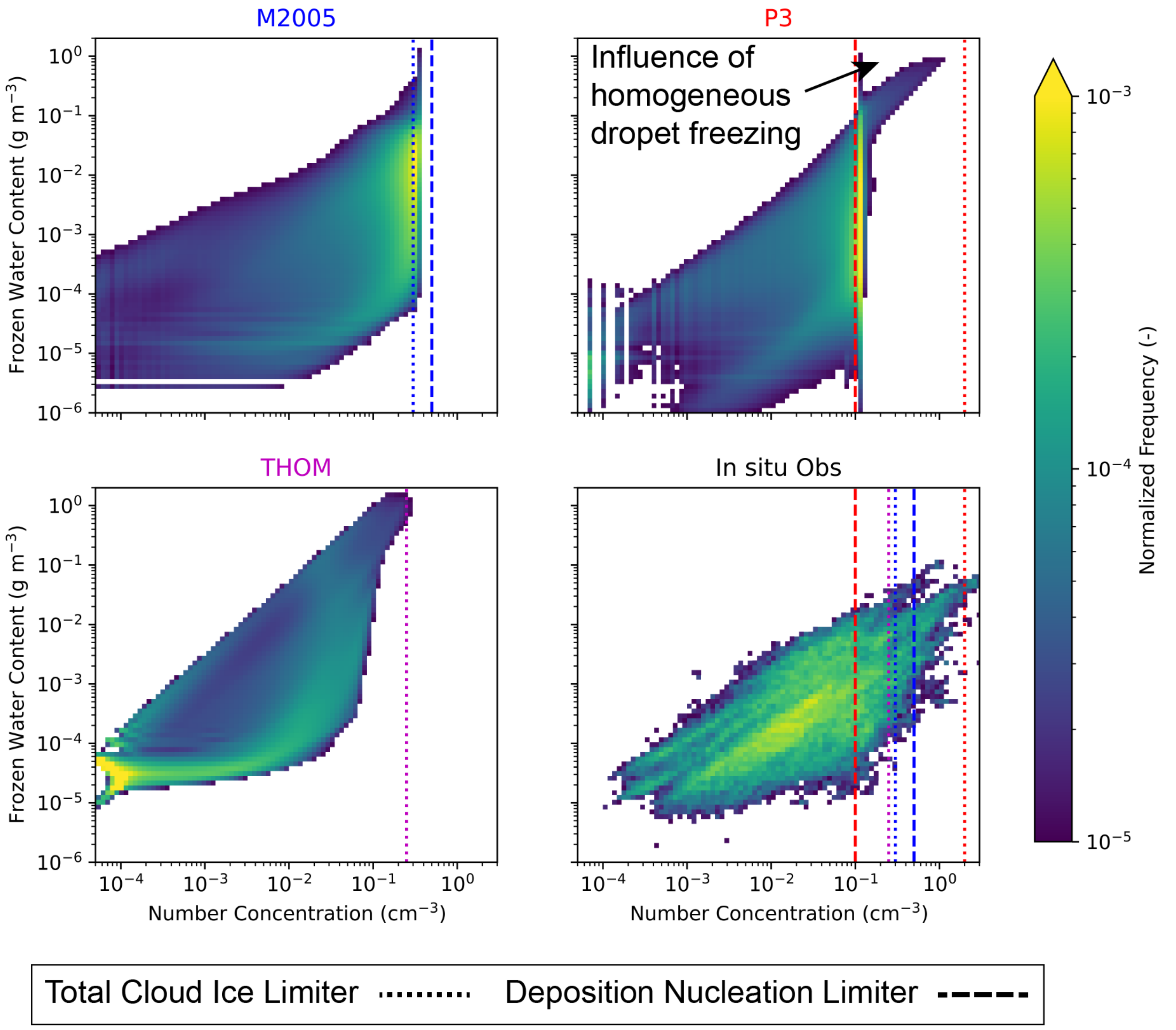
FWP Distribution
Normalized Frequency (-)
Frozen Water Path (g m^{-2})
Mean CTH vs FWP
Cloud Top Height (km)
Frozen Water Path (g m^{-2})
CALIPSO
CloudSat
DARDAR
2C-Ice
2C-ICE
DARDAR V2.1.1
DARDAR V3.1
P3
M2005
Thompson
SAM1MOM



Cold point bias from nudging to ERA5 pressure levels
Saturation adjustment is used in SAM1MOM
Efficient autoconversion leads to excessive sedimentation
Height (km)
T (°C)
RH$_i$ (%)
Cloud Fraction (-)
Radiative Cooling (k day^{-1})
CALIPSO
CloudSat
DARDAR
2C-Ice
ERA5 Model Levels
ERA5 Pressure Levels
2C-ICE
DARDAR V2.1.1
DARDAR V3.1
P3
M2005
Thompson
SAM1MOM

- Observations have typically have ice crystal number concentrations less than 0.1 cm^{-3} with a clear dependence on ice water content
- M2005 and P3 have ice crystal number concentrations that are too high and lack the dependence on ice water content
- M2005 has larger ice crystal number concentrations than P3
- Thompson has primarily tiny ice water contents and ice crystal number concentrations- these are likely what is left over after the larger particles have sedimented out

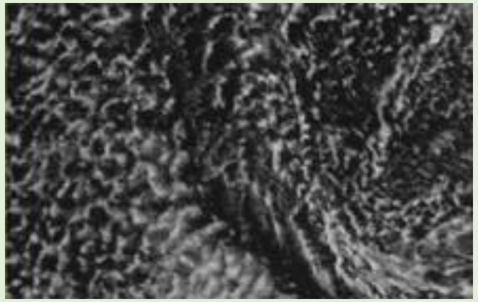
Aircraft data compiled by Martina Krämer in the “Microphysical guide to Cirrus” (Krämer et al. 2020)



Take-aways

- P3 and M2005 outperform SAM1MOM and Thompson
- Saturation adjustment and overly efficient autoconversion from cloud ice to snow likely lead to deficient high cloud cover in SAM1MOM and Thompson, respectively
- Ice crystal number concentrations are overly constrained by limiters in M2005 and P3
  - differences in limiters may be largely responsible for differences in anvil cirrus
- Nudging to a dataset with lower vertical resolution than the GSRM can cause unphysical behaviour

1) Southern Ocean Low Clouds



Atlas et al. 2022, AGU ADVANCES

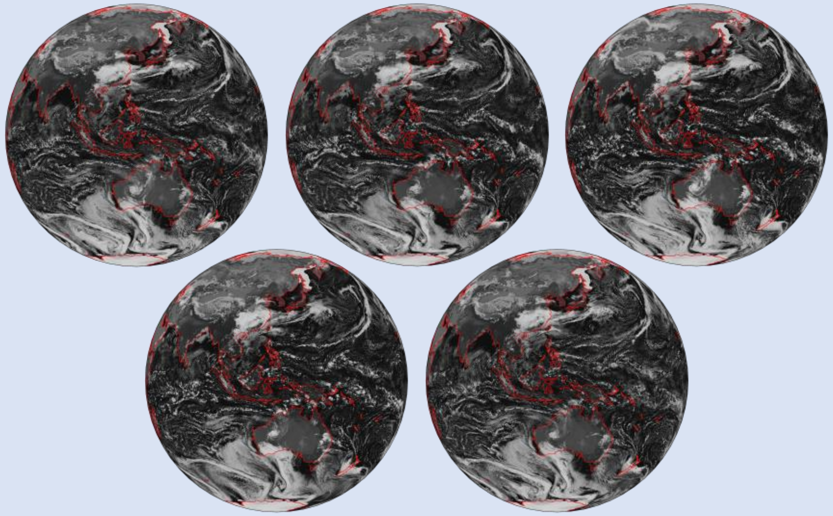
2) Tropical High Clouds

In review for GRL

3) Small-scale gravity waves

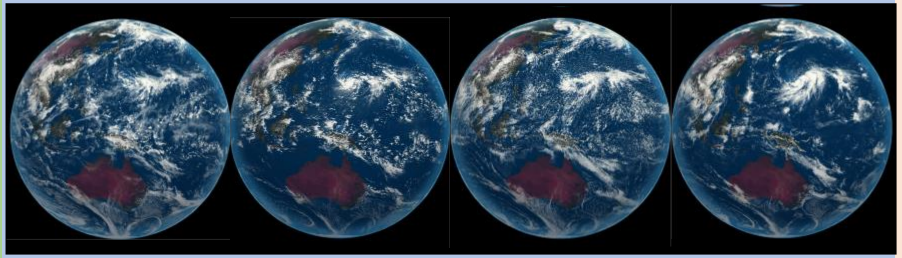
Atlas and Bretherton 2023, ACP

Five nudged simulations from one model with different microphysics



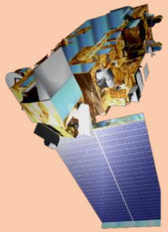
- Useful for microphysics sensitivity tests
- Allows for comparison with coincident observations

DYAMOND-1: Four free-running simulations from multiple models

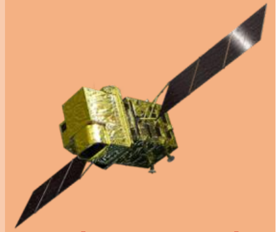


Useful for evaluating the state of GSRMs

Aircraft



Ceres



Himawari

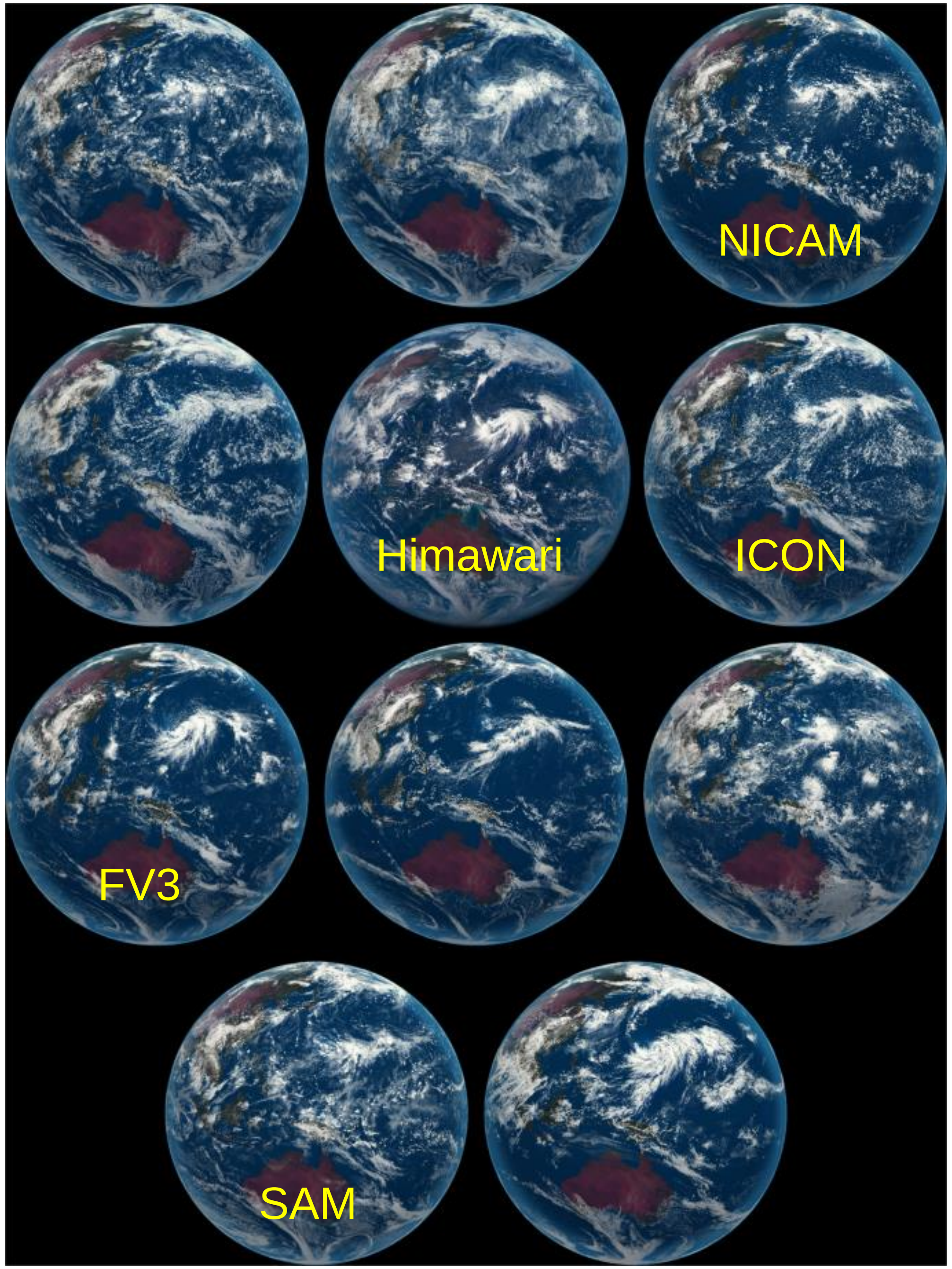
DARDAR
2C-Ice

DYAMOND-1 Experiment

- Forty day simulations initialized on August 1 2016
- 10 models
- Horizontal grid spacing of 5 km or less

I focus on:

- Four models: NICAM, ICON, FV3 and SAM
- tropical West Pacific
- lower tropical tropopause layer (TTL), height of 14.2 km

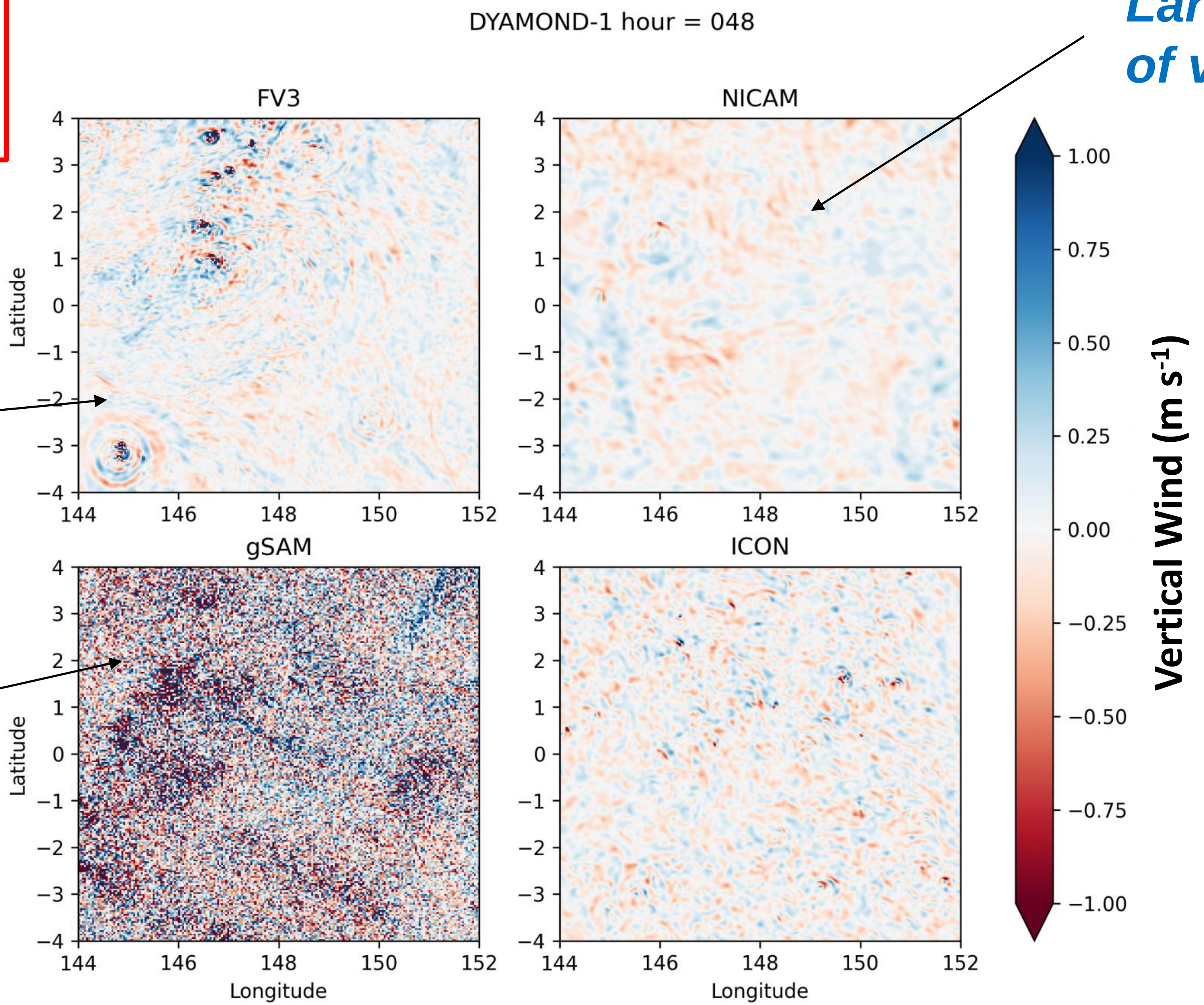


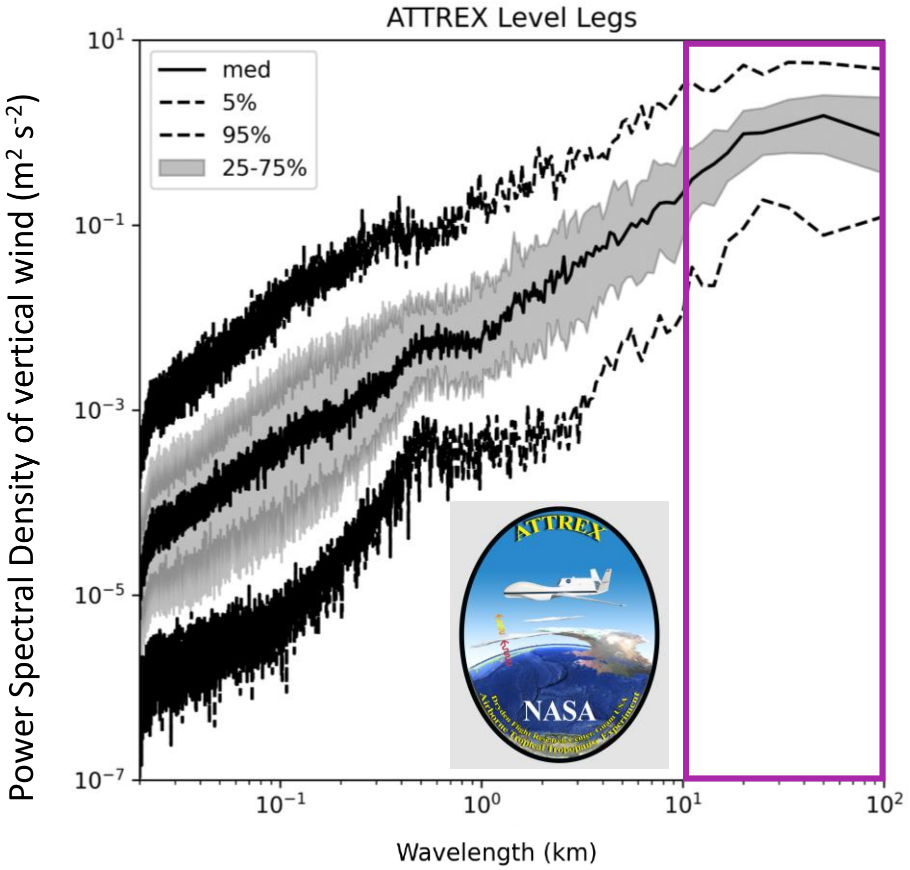
Simulated vertical winds at ~14.2 km over the tropical West Pacific

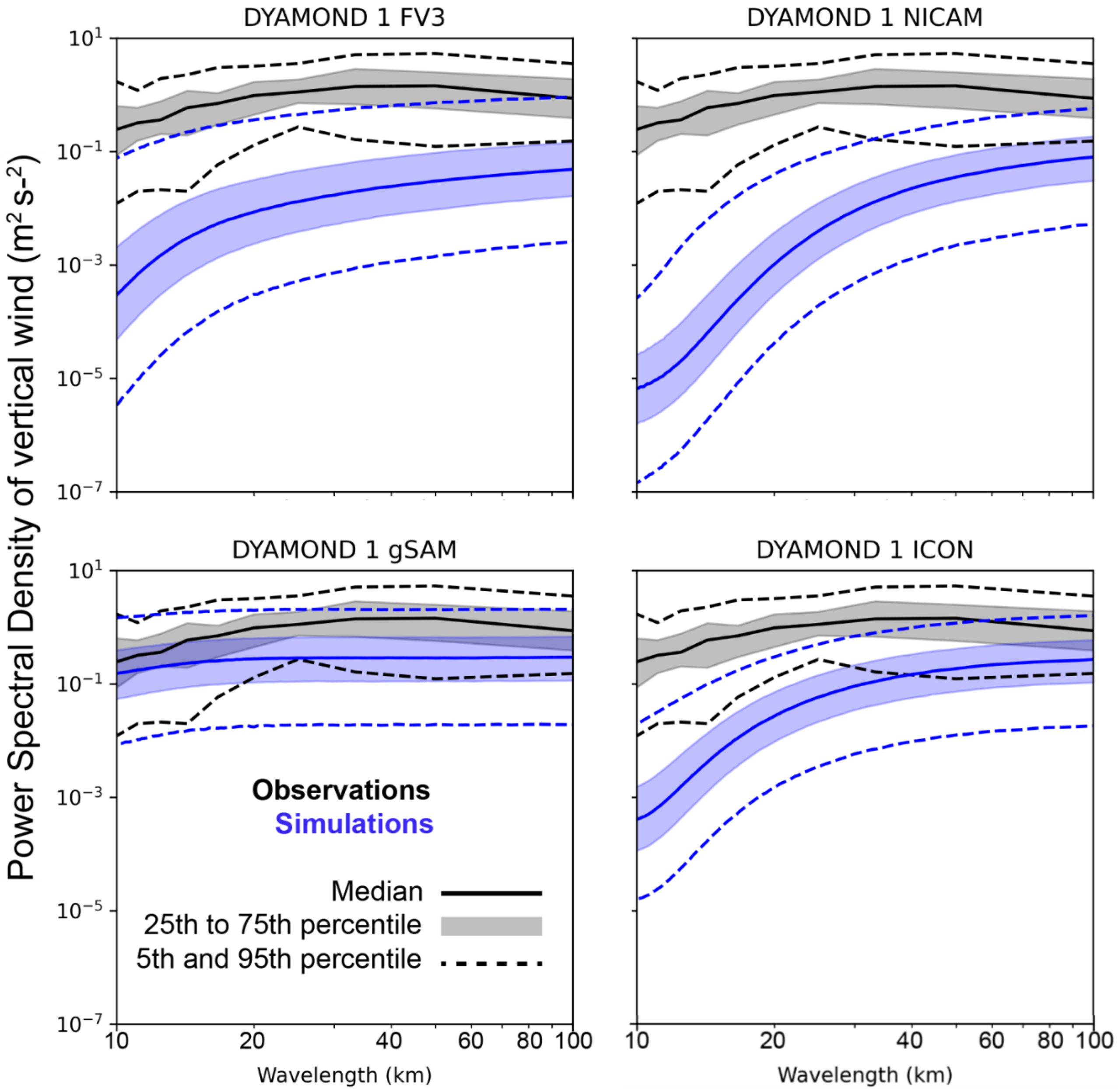
Larger scales of variability

Strong gravity waves around deep convection

Lots of grid scale variability



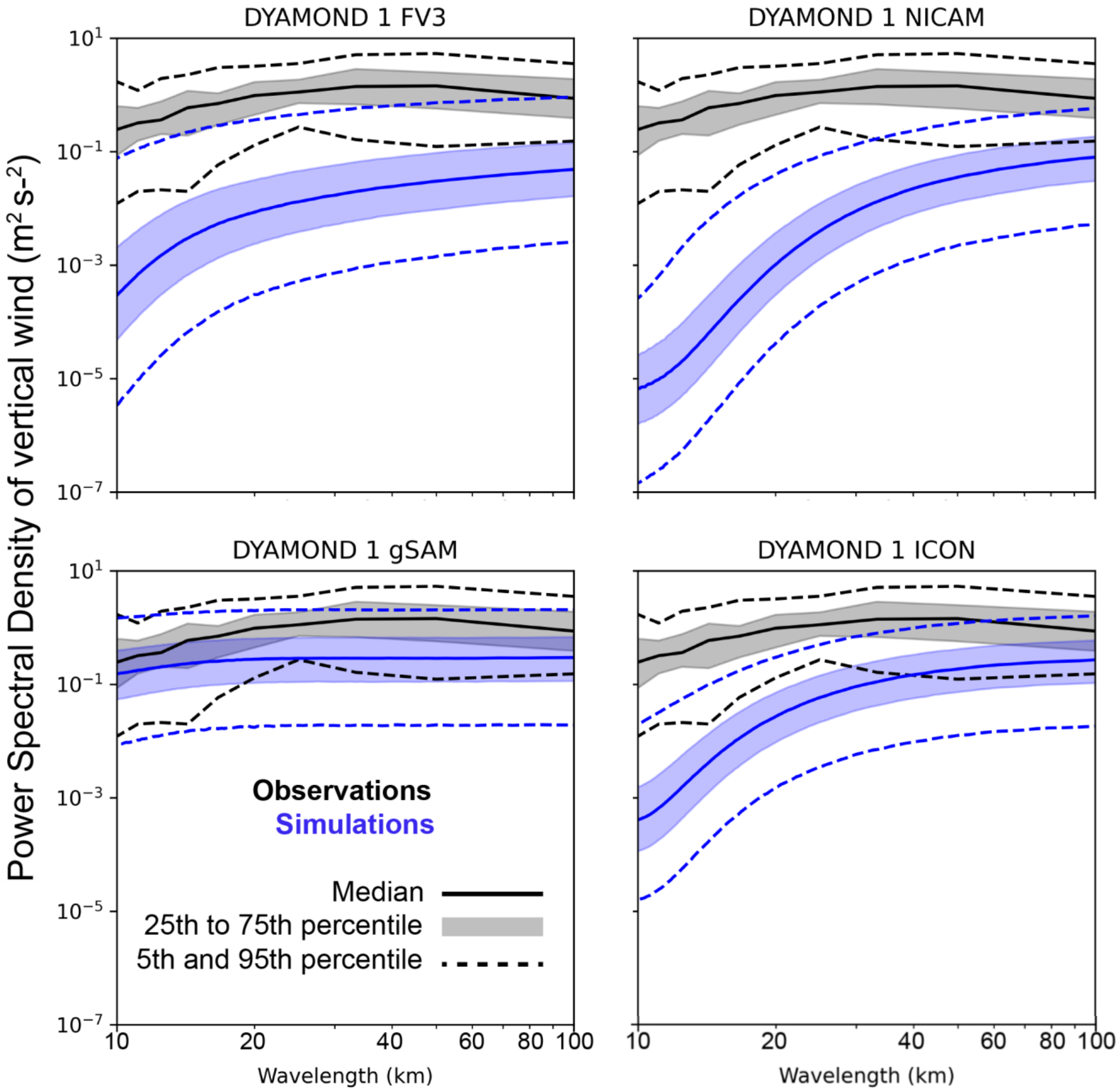

ATTREX Level Legs
med
5%
95%
25-75%
Power Spectral Density of vertical wind (m² s⁻²)
Wavelength (km)
ATTREX
NASA


DYAMOND 1 FV3
DYAMOND 1 NICAM
DYAMOND 1 gSAM
DYAMOND 1 ICON
Power Spectral Density of vertical wind (m² s⁻²)
Observations
Simulations
Median
25th to 75th percentile
5th and 95th percentile
Wavelength (km)
Wavelength (km)

Model	Horizontal grid spacing	Vertical grid spacing
SAM	4 km	500 m
NICAM	3.25 km	400 m
ICON	2.5 km	500 m
FV3	3.25 km	500 m

The effective resolution (the minimum length scale that is resolved) for GSRMs might be six times the grid spacing (Caldwell et al. 2021) which is 15-24 km here

Vertical grid spacing must be 200 m or less to adequately resolve upper tropospheric dynamics (Kuang and Bretherton 2014, Skamarock et al. 2019)



Next steps

1) Can small-scale gravity waves be better represented with decreased vertical and/or horizontal grid spacing?

Currently, I am using radiosonde data to investigate the frequency of turbulence in the upper troposphere/lower stratosphere, as a function of region and distance from deep convection

2) Does the frequency of turbulence in GSRMs match radiosonde observations?

*ICON is a good candidates for future studies