Ice Ice Maybe?

CAM6 Ice Formation in Southern Ocean Mixed Phase Clouds

Christina S. McCluskey, Andrew Gettelman, Jesse Nusbaumer, Cecile Hannay, Laura Riihimaki, Greg McFarquhar

ASR Atmospheric System Research

U.S. DEPARTMENT OF ENERGY | Office of Science

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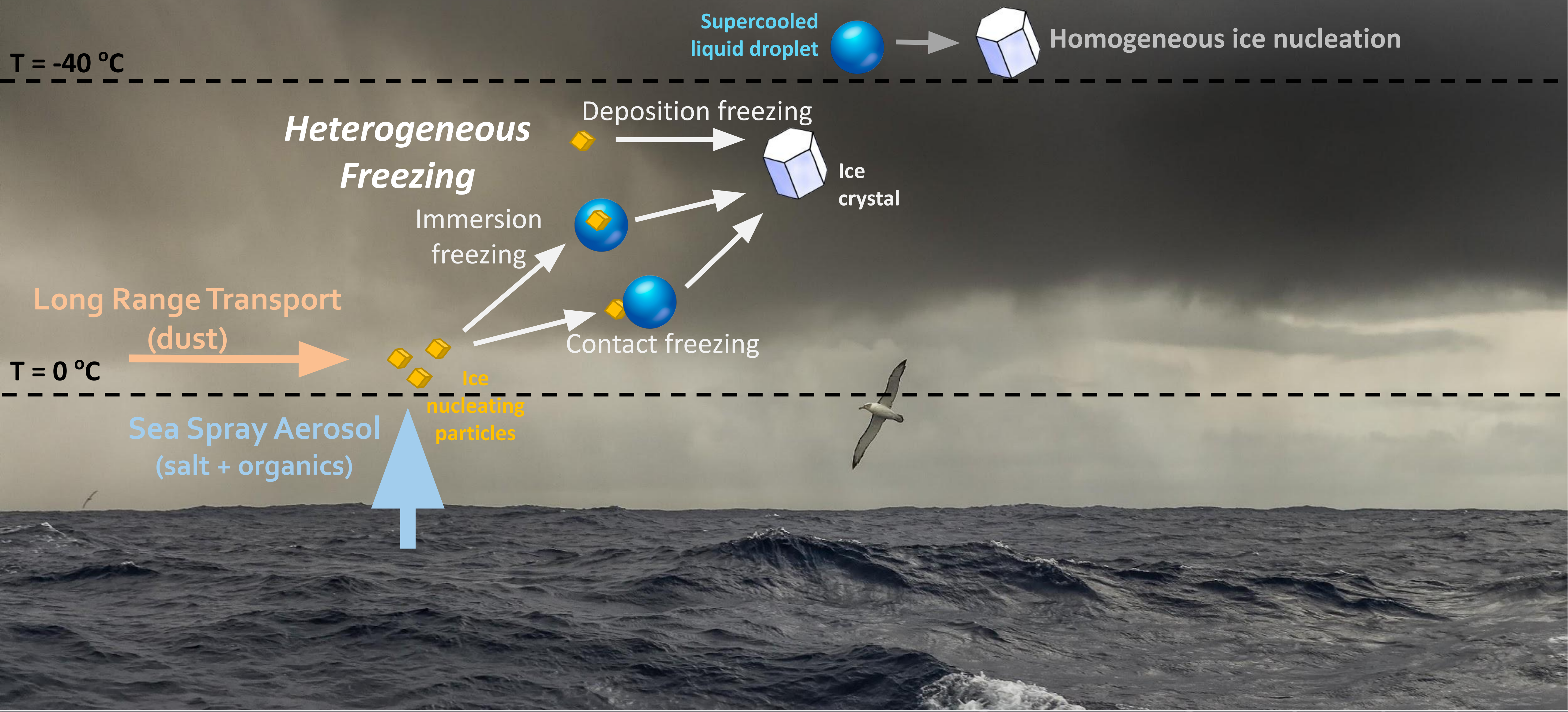
Heterogeneous freezing of rain & rime-splintering dominate ice production in CAM6 Southern Ocean mixed phase clouds; this (unrealistically) masks sensitivities to in aerosol-ice interactions in CAM/CESM.

The Southern Ocean is pristine and covered with optically thick mixed phase stratocumulus clouds

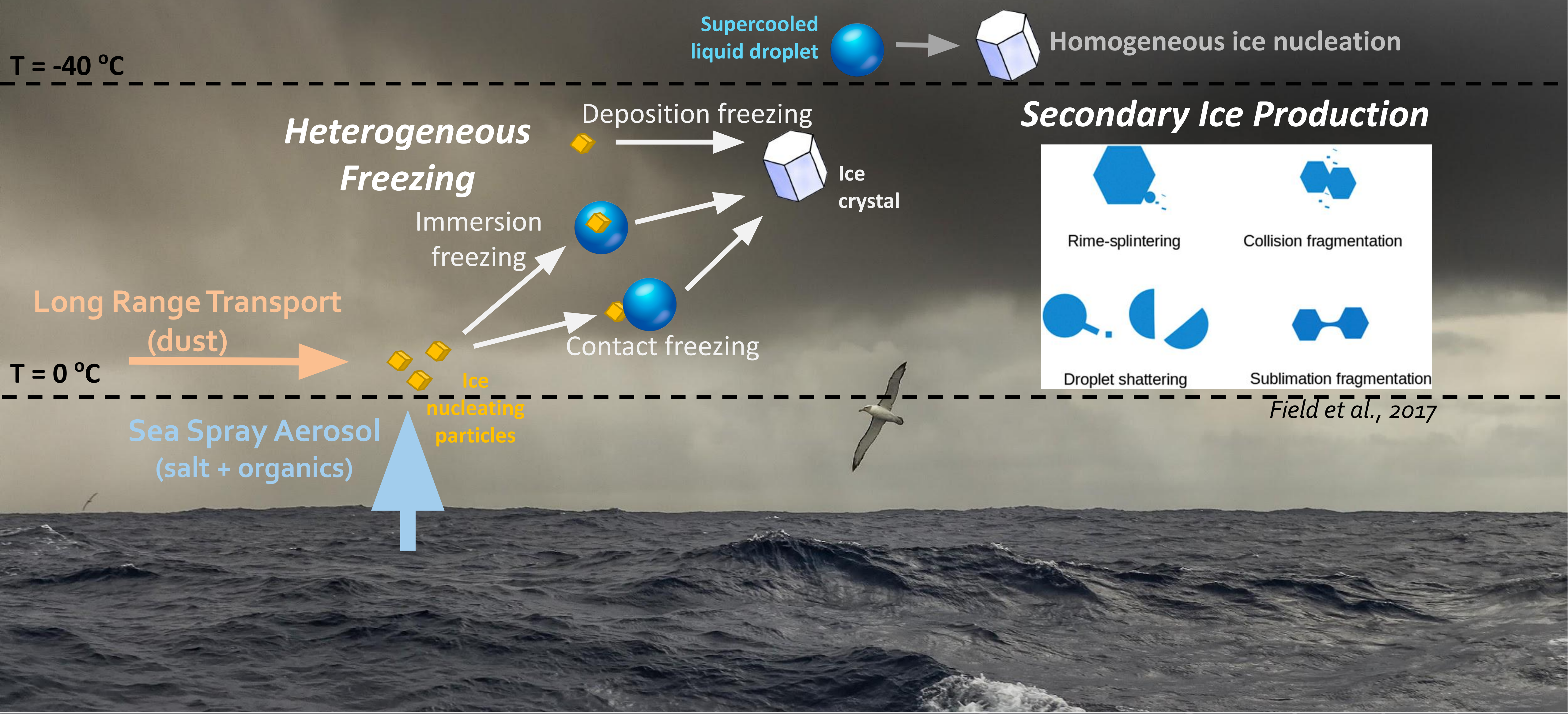
>80% cloud cover; up to 80% of clouds are low-level clouds and 50% are mixed-phase

Southern Ocean ice-phase aerosol-cloud interactions

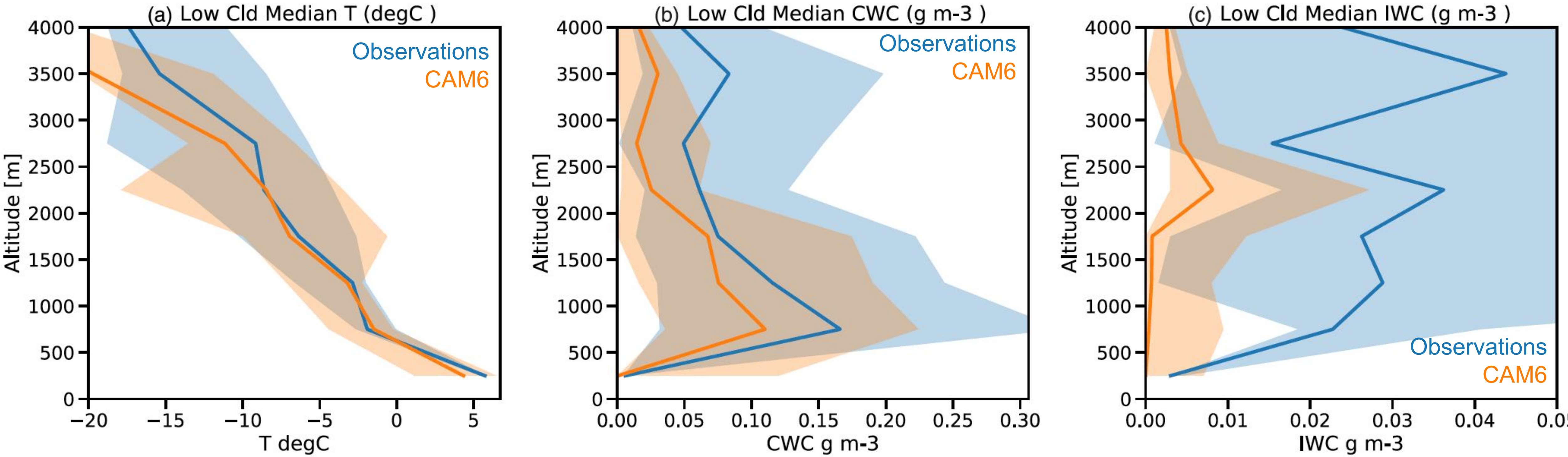
Southern Ocean ice-phase aerosol-cloud interactions



Southern Ocean ice-phase aerosol-cloud interactions



CAM6 underestimates ice in Southern Ocean low-level clouds
SOCRATES



Gettelman et al. (2020)

Hypothesis: *Marine INPs are responsible for the onset of ice formation in Southern Ocean low-level clouds*

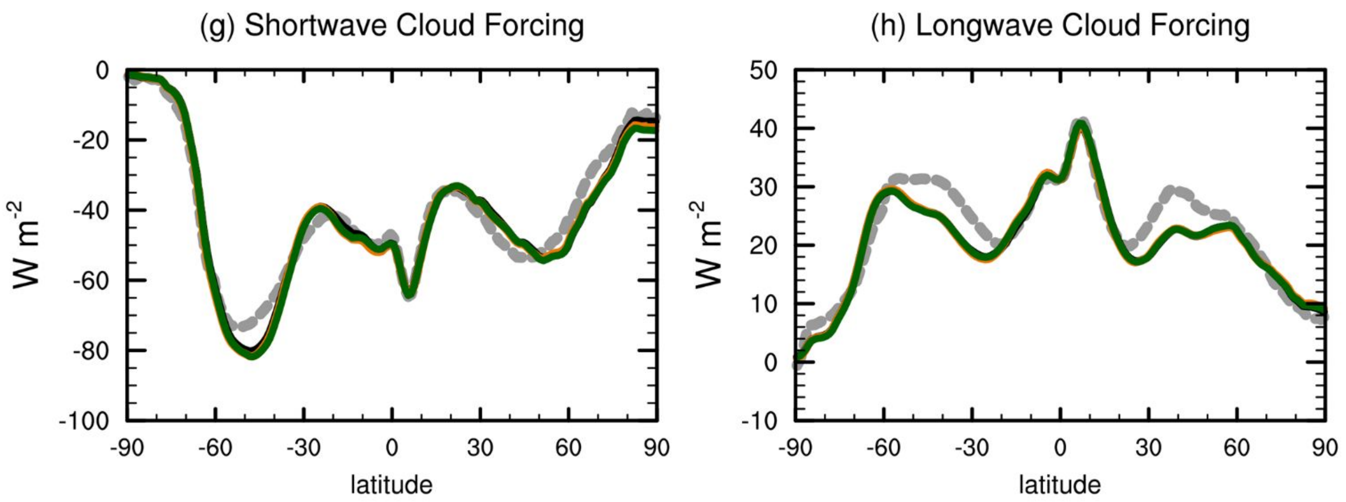
1. **Test and implement INP heterogeneous ice nucleation scheme for marine and dust aerosol**

   Christina S. McCluskey, et al., **Southern Ocean Aerosol and Ice Nucleating Particles in the Community Earth System Model Version 2**, Under Review at *J. Geophys. Res. Atmos.*

2. **Determine impact of marine INPs on Southern Ocean cloud properties**

   Southern Ocean low-level cloud radiative properties are sensitive to representation of dust and marine immersion freezing ice nucleation *Vergara-Temprado* et al., 2018

   Or are they?



Zhao et al., 2021

This Study: **Why are Southern Ocean clouds in CESM2 insensitive to heterogeneous freezing of cloud droplet?**

Model configuration:

- cam6_3_063
- 2˚ latitude x 2˚ longitude
- 32 levels to ~1 hPa (100-1200 m vertical resolution)
- 30 minute time step (10 min sub-step)
- F2000climo compset
- CAM6 default physics (MAM4, CLUBB, RRTMG)
- MG2 cloud microphysics (cam_dev) with modified **heterogeneous freezing ice nucleation**

What controls Ice Formation in CAM6?

CAM6 Mixed-Phase Cloud Ice Processes:

1. **Heterogeneous Freezing of Cloud Droplets** →

D15M18

Mineral Dust INPs: DeMott et al. 2015 (D15)

$$n_{INPs}(T) = f(T, \boldsymbol{n_{500nm,dust}})$$

Marine INPs: McCluskey et al. 2018 (M18)

IN-active molecules

$$n_{INPs}(T) = f(T, \boldsymbol{S_{seaspray}})$$

$$S_{seaspray} \approx \boldsymbol{S_{sea\ salt}}$$

1. Immersion Freezing of Cloud Droplets
   - **CAM6:** Stochastic Dust (Hoose et al., 2010)
   - **CAM5:** Bigg T-dependent (Bigg, 1953)
   - **NEW: Deterministic Marine and Dust (D15M18)**
2. Deposition Freezing of Cloud Droplets
   - **CAM6:** Stochastic Dust (Hoose et al., 2010)
   - **CAM5:** Meyers T-dependent (Meyers, 1992)
3. Contact Freezing of Cloud Droplets
   - **CAM6:** Stochastic Dust (Hoose et al., 2010)
   - **CAM5:** Young T-dependent (Young, 1974)

What controls Ice Formation in CAM6?

CAM6 Mixed-Phase Cloud Ice Processes:

1. **Heterogeneous Freezing of Cloud Droplets**
2. Heterogeneous Freezing of Rain to Ice (Bigg,1953)
3. Ice Multiplication from Rime-Splintering (Cotton, 1986)
4. Accretion of Cloud Ice to Snow
5. Autoconversion of Cloud Ice to Snow
6. Cloud Ice Sedimentation

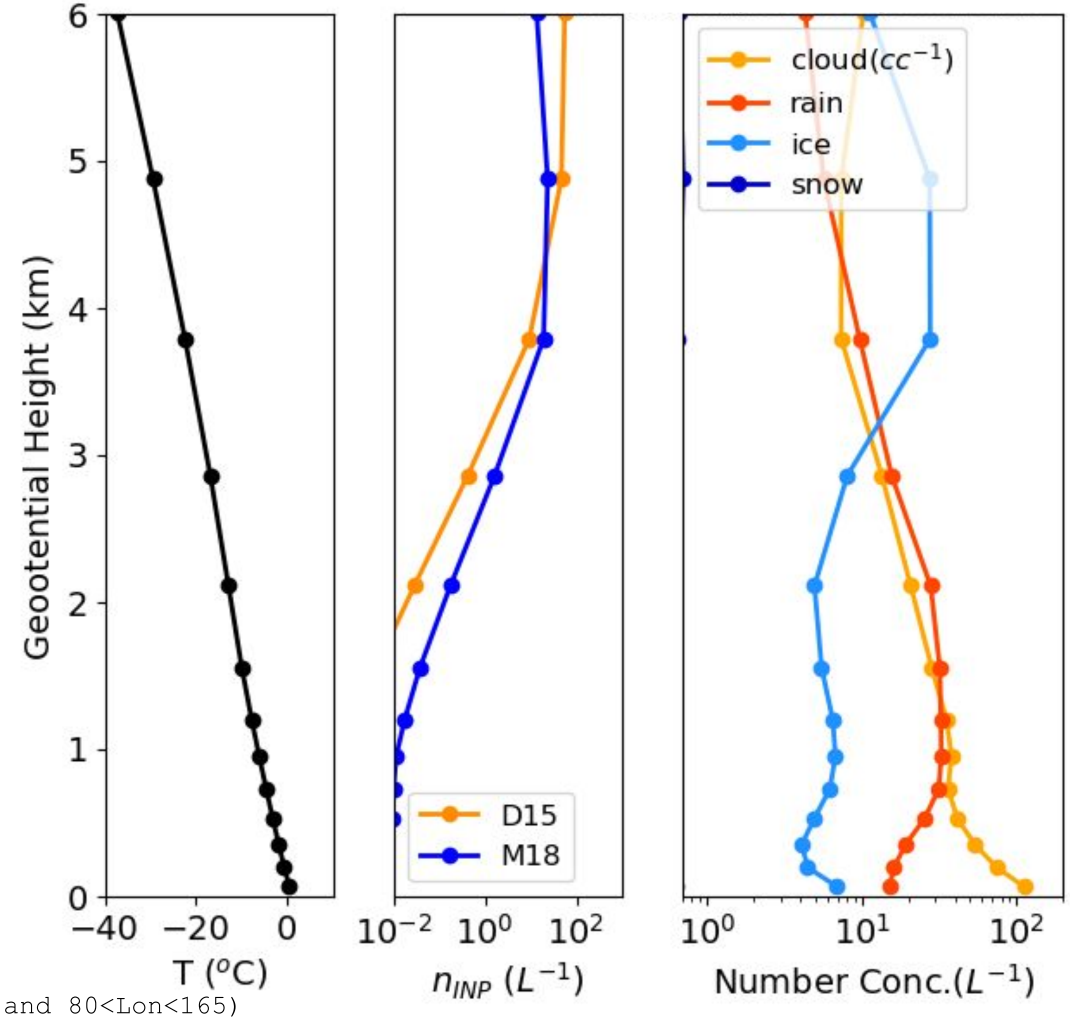
Number tendencies added to MG2/MG3/PUMAS

PROCESS	mass tendency grid-box avg	output name	number tendency grid-box avg name	output name
Cloud Droplet Activation				
cloud droplet activation?				
Primary Ice formation				
[cloud ice] Immersion freezing of cloud water	mnuccctot	MNUCCCO	nnuccctot	NNUCCCO
[cloud ice] Contact freezing of cloud water	mnuccttot	MNUCCTO	nnuccttot	NNUCCTO
[cloud ice] Homogeneous and heterogeneous nucleation from vapor	mnuccdtot	MNUCCDO	nnuccdtot	NNUCCDO
[cloud ice] Deposition Nucleation	mnudeptot	MNUDEPO	nnudeptot	NNUDEPO
[cloud ice] Homogeneous freezing of cloud water	homotot	HOMOO	nhomotot	NHOMOO
Heterogeneous freezing of rain to snow	mnuccrtot	MNUCCRO	nnuccrtot	NNUCCRO
Heterogeneous freezing of rain to ice	mnuccritot	MNUCCRIO	nnuccritot	NNUCCRIO
[cloud ice] Heterogeneous nucleation from vapor	*mnuccdohet*	*MNUCCDOhe*	*ignore in number tendencies*	
Secondary Ice formation				
Conversion of cloud water [to cloud ice] from rime-splintering	msacwitot	MSACWIO	nsacwitot	NSACWIO
Q change due to ice mult droplets/graupel	qmultgtot	QMULTGO	nmultgtot	NMULTGO
Q change due to ice mult rain/graupel	qmultrgtot	QMULTRGO	nmultrgtot	NMULTRGO
Accretion				
Accretion of cloud water by rain	pratot	PRAO	npratot	NPRAO
Accretion of cloud water by snow	psacwstot	PSACWSO	npsacwstot	NPSACWSO
Accretion of cloud ice to snow	praitot	PRAIO	npraitot	NPRAIO
Accretion of rain by snow	pracstot	PRACSO	npracstot	NPRACSO
Autoconversion				
Autoconversion of cloud water [to rain]	prctot	PRCO	nprctot	NPRCO
Autoconversion of cloud ice to snow	prcitot	PRCIO	nprcitot	NPRCIO
Collision/Collection				
Change in q collection rain by graupel	pracgtot	PRACGO	npracgtot	NPRACGO
Change in q collection droplets by graupel	psacwgtot	PSACWGO	npsacwgtot	NPSACWGO
Q conversion to graupel due to collection droplets by snow	pgsacwtot	PGSACWO	nscngtot	NSCNGO
Q conversion to graupel due to collection rain by snow	pgracstot	PGRACSO	ngracstot	NGRACSO
Collisions between rain & snow (Graupel collecting snow)	psacrtot	PSACRO	REVISIT – USED IN MG3 CODE C	
Sedimentation				
Cloud water mixing ratio tendency from sedimentation	qcsedten	QCSEDTEN	ncsedten	NCSEDTEN
Cloud ice mixing ratio tendency from sedimentation	qisedten	QISEDTEN	nisedten	NISEDTEN
Rain mixing ratio tendency from sedimentation	qrsedten	QRSEDTEN	nrsedten	NRSEDTEN
Snow mixing ratio tendency from sedimentation	qssedten	QSSEDTEN	nssedten	NSSEDTEN
Graupel/Hail mixing ratio tendency from sedimentation	qgsedten	QGSEDTEN	ngsedten	NGSEDTEN
Melting				
Melting of cloud ice	melttot	MELTO	nmelttot	NMELTO
Melting of snow	meltstot	MELTSTOT	nmeltstot	NMELTSTOT
Melting of graupel	meltgtot	MELTGTOT	nmeltgtot	NMETLGTOT

Special thanks to Kate Thayer-Calder & Cheryl Craig!

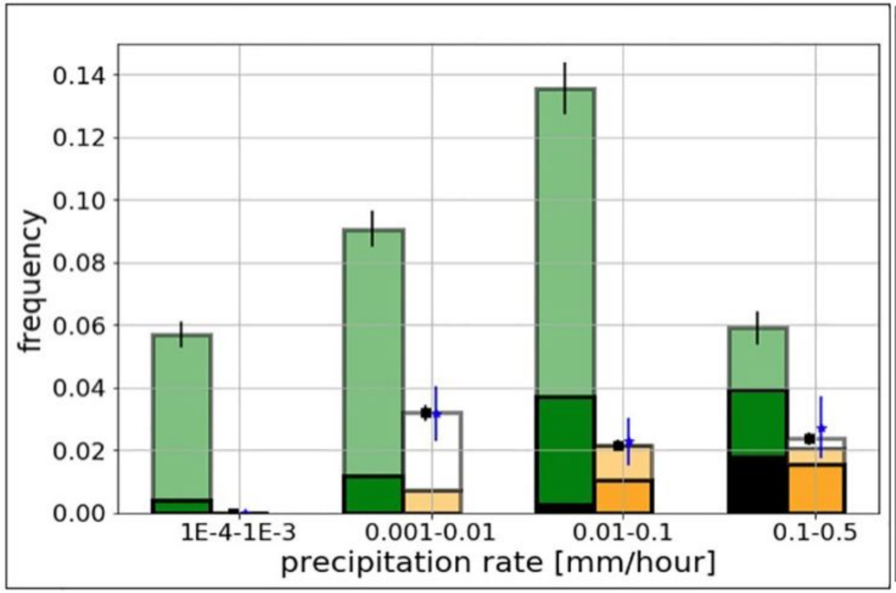
Heterogeneous Freezing of Rain & Ice Multiplication from Rime-Splintering dominate ice number production

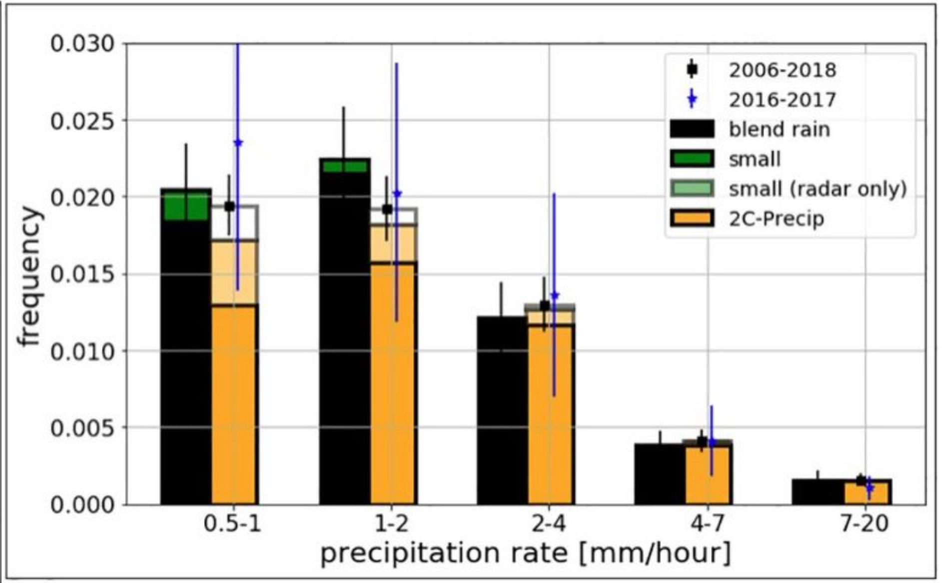
Similar results over the Arctic



SO region (-65<Lat<-50 and 80<Lon<165)

Observational context: Light precipitation/drizzle observed at Macquarie Island & McMurdo Station





Tansey et al., 2022

JGR Atmospheres

RESEARCH ARTICLE
10.1029/2019JD030882

Key Points:
- Drizzle was observed over McMurdo at cloud *T* <-25 degrees celsius for more than 7.5 hr in the presence of ice nucleation and growth

Persistent Supercooled Drizzle at Temperatures Below −25 °C Observed at McMurdo Station, Antarctica

Israel Silber[1], Ann M. Fridlind[2], Johannes Verlinde[1], Andrew S. Ackerman[2], Yao-Sheng Chen[3,4], David H. Bromwich[5,6], Sheng-Hung Wang[5], Maria Cadeddu[7], and Edwin W. Eloranta[8]

CAM5

T-dependent Immersion Freezing of cloud droplets (Bigg, 1953)

Over active **heterogeneous ice nucleation of cloud droplets** results in over-glaciated clouds

CAM6

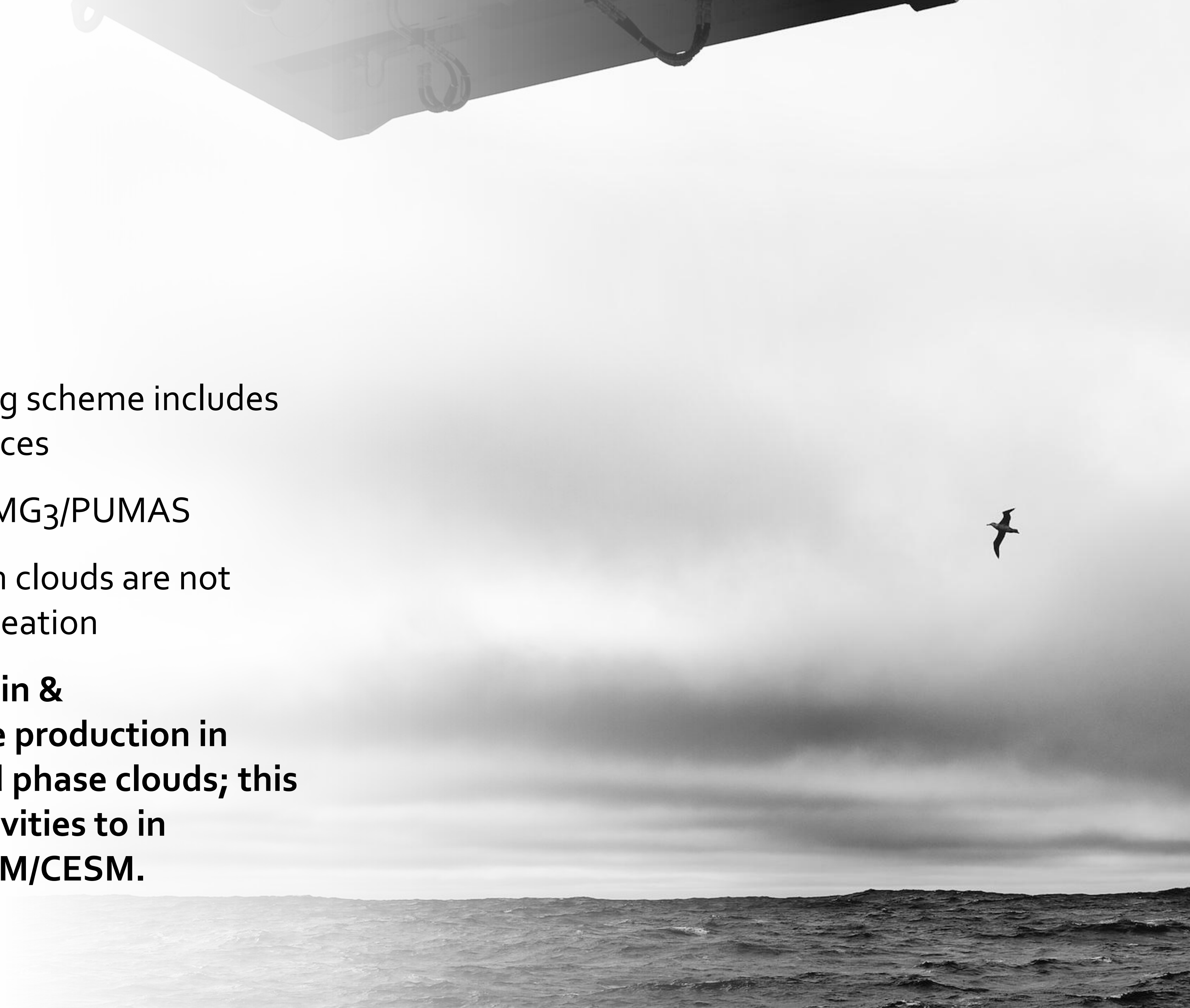
Dust Stochastic Immersion Freezing of cloud droplets (Hoose et al., 2010)

T-dependent Immersion Freezing of rain (Bigg, 1953)

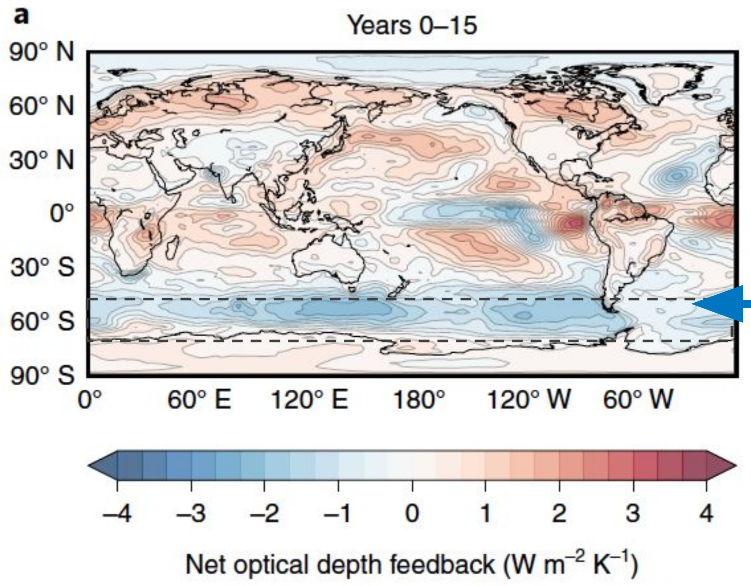
Reduction in **heterogeneous ice nucleation of cloud droplets** results in supercooled rain production, which is not maintained with CAM6 microphysics

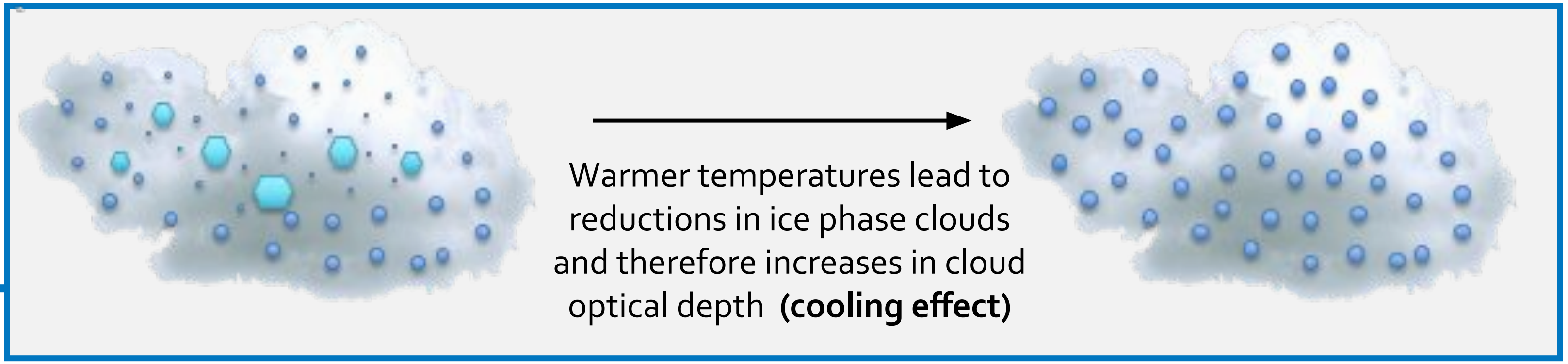
Summary

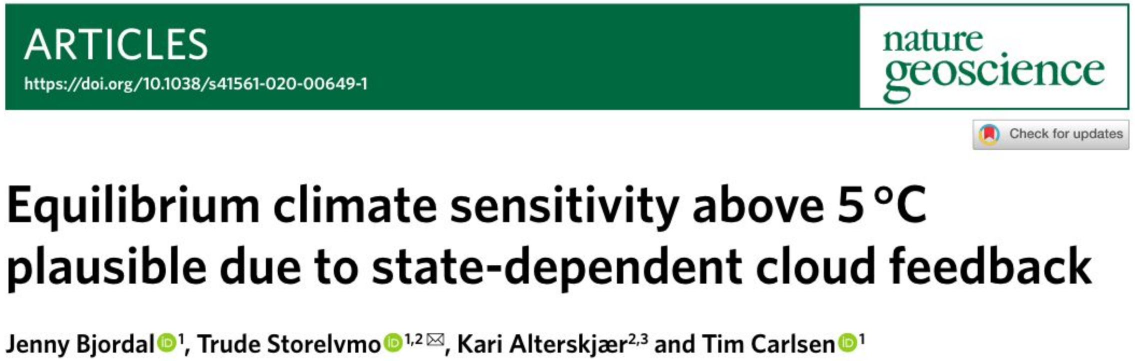
- New simple immersion freezing scheme includes both dust and marine INP sources
- Number tendencies added to MG3/PUMAS
- CAM6/CESM2 Southern Ocean clouds are not sensitive to changes in ice nucleation
- **Heterogeneous freezing of rain & rime-splintering dominate ice production in CAM6 Southern Ocean mixed phase clouds; this (unrealistically) masks sensitivities to in aerosol-ice interactions in CAM/CESM.**



Southern Ocean Cloud Feedback: cloud-phase







ARTICLES
https://doi.org/10.1038/s41561-020-00649-1
nature geoscience

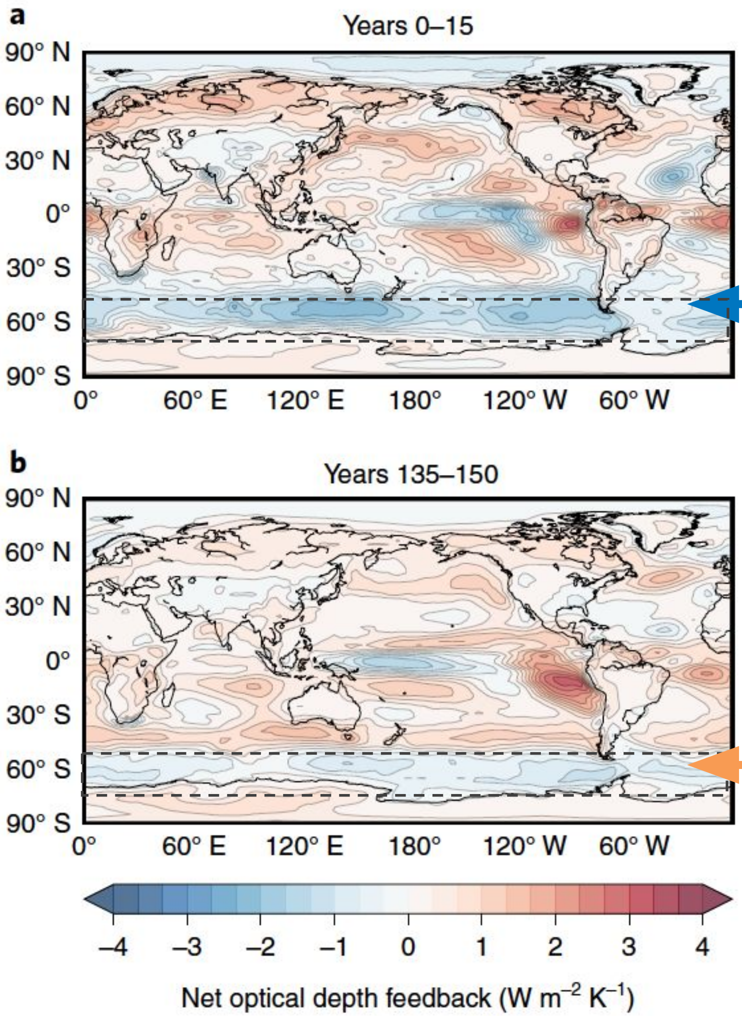
Check for updates

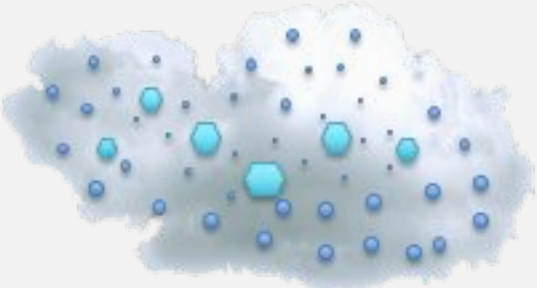
Equilibrium climate sensitivity above 5 °C plausible due to state-dependent cloud feedback

Jenny Bjordal[1], Trude Storelvmo[1,2], Kari Alterskjær[2,3] and Tim Carlsen[1]

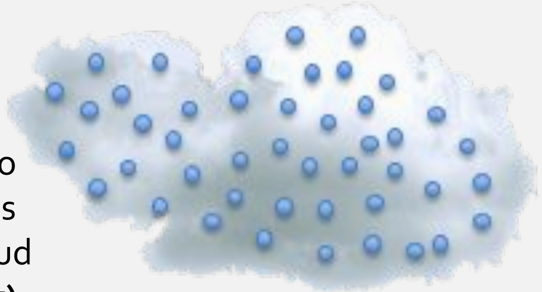
Bjordal et al., 2020

State-Dependent cloud-phase feedback

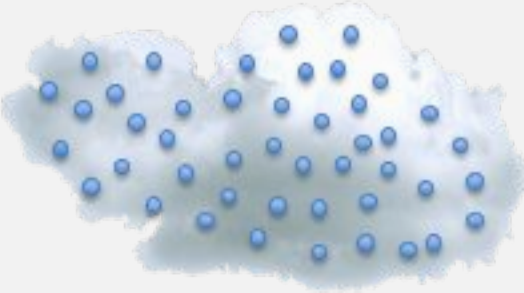




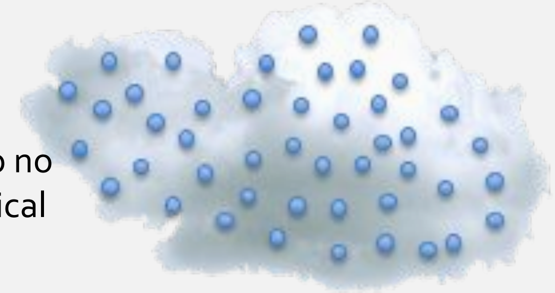
Warmer temperatures lead to reductions in ice phase clouds and therefore increases in cloud optical depth **(cooling effect)**



After some amount of warming, all clouds over southern ocean will be liquid, dampening the Southern Ocean negative cloud feedback.



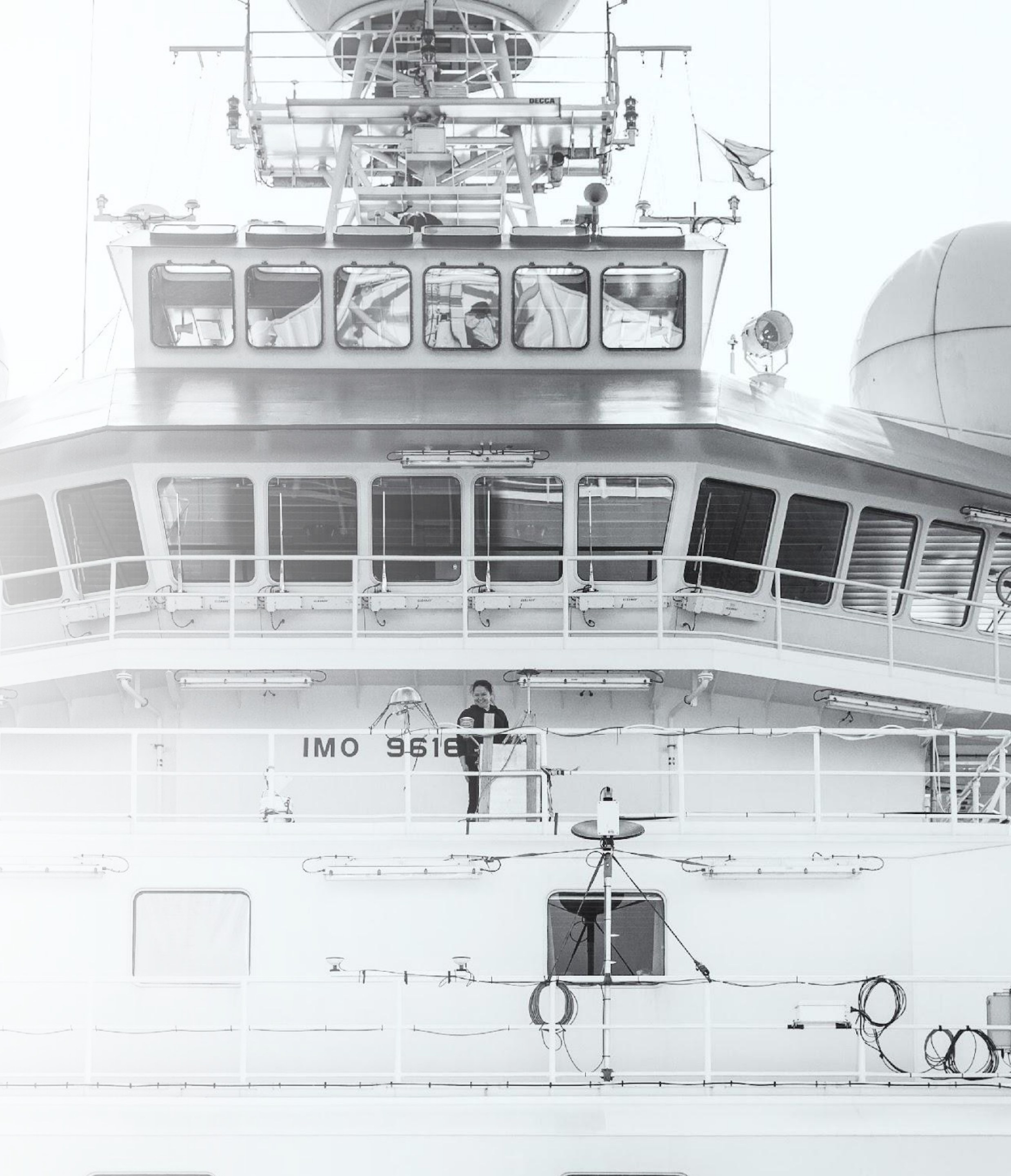
Warmer temperatures lead to no change in cloud phase or optical depth



Bjordal et al., 2020

Future Work

- Scale the Bigg 1953 Heterogeneous Freezing of Rain Parameterization – *not the full fix*
- Assess sensitivity to rain processes (e.g., rain autoconversion)
- Determine Southern Ocean Rain Biases and Budget
- Evaluate rain occurrence, phase, and rate against observations



Thank you!

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Deterministic Immersion Freezing Ice Nucleation:

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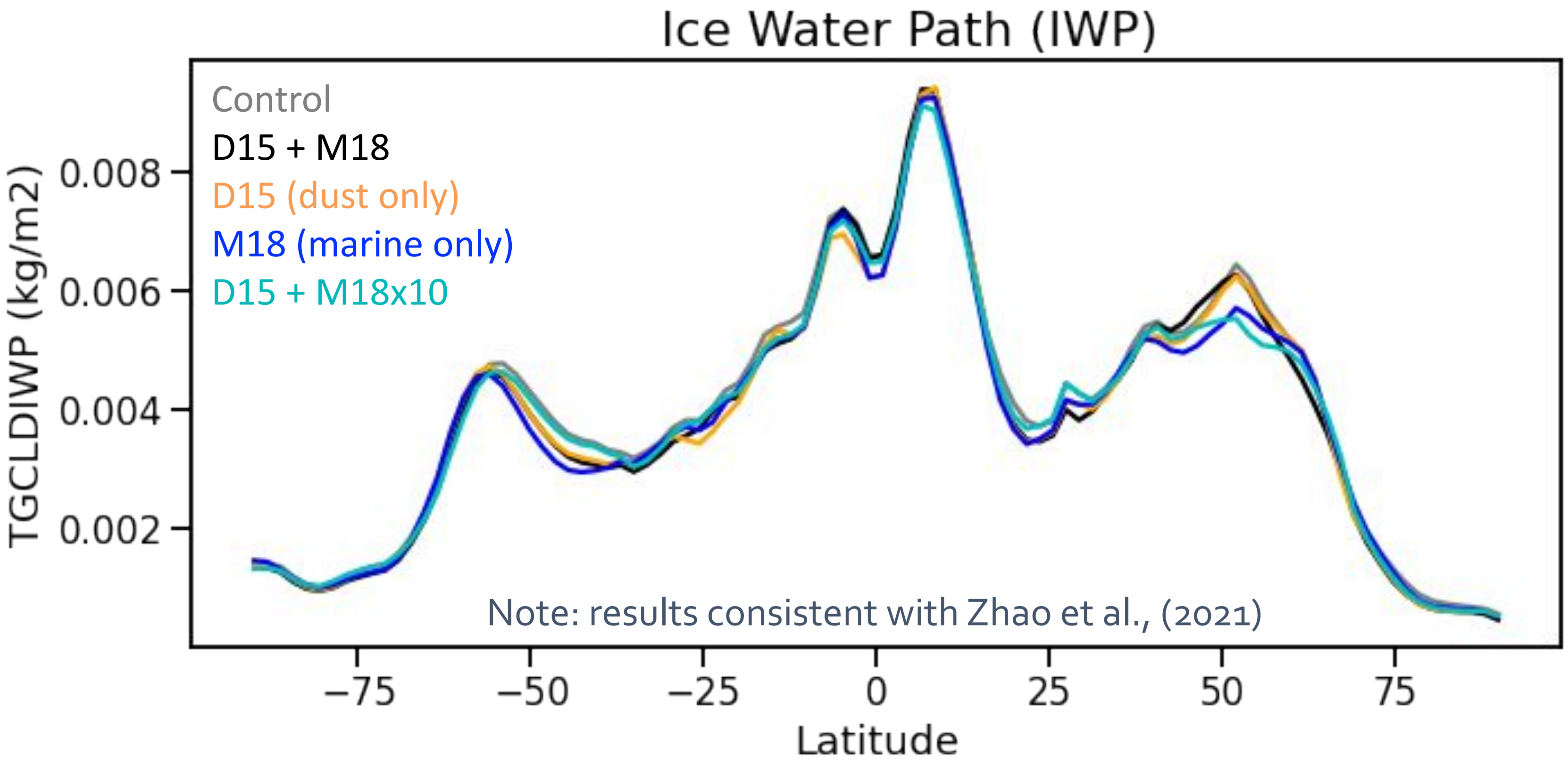
CAM6_3_63 Tests	Stochastic Dust (Hoose et al., 2010)	Deterministic Marine (McCluskey et al., 2018)	Deterministic Dust (DeMott et al., 2015)	Bigg T-dependent (Bigg, 1953)
Control	✅	❌	❌	❌
D15 + M18	❌	✅	✅	❌
D15 (dust only)	❌	❌	✅	❌
M18 (marine only)	❌	✅	❌	❌
D15 + M18x10	❌	✅ x10	✅	❌

Marine INPs minimally impacted cloud properties in CAM6



No simulated change in ice water path, shortwave or longwave cloud radiative effects due to ice nucleation modifications

Observational context: Light precipitation/drizzle observed at Macquarie Island

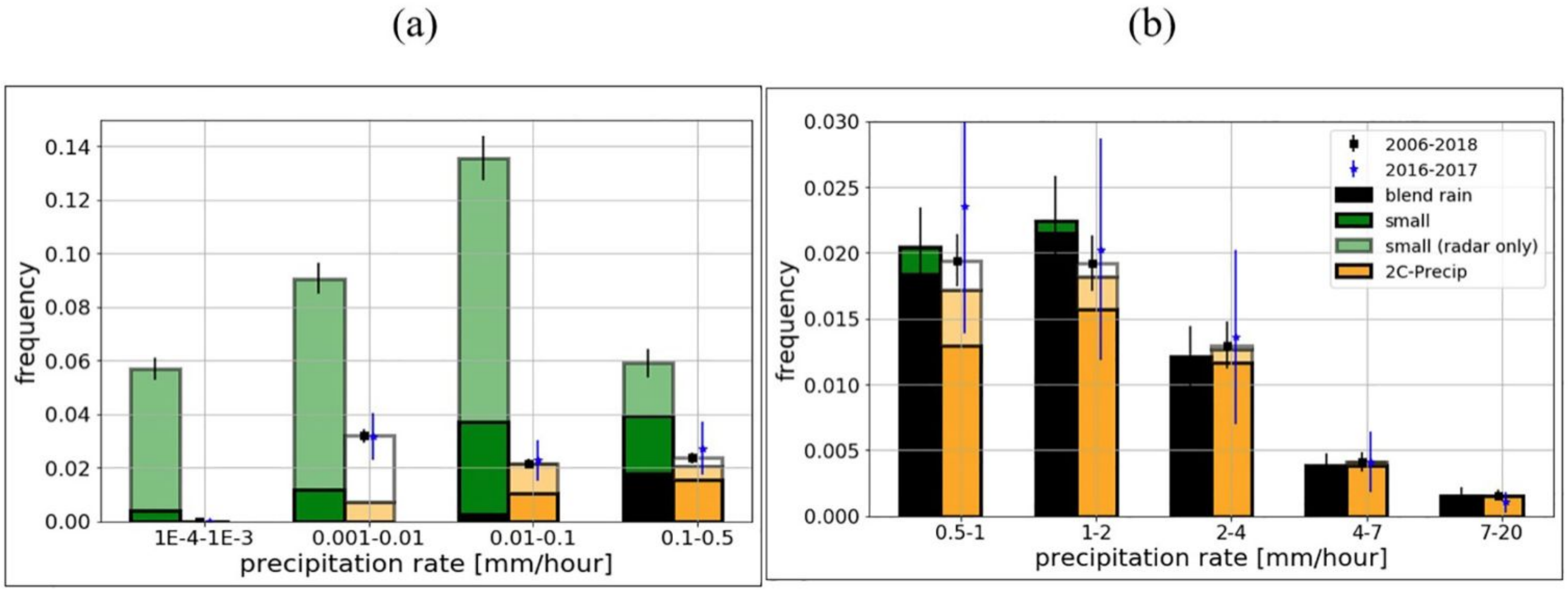


Figure 13. 2C-Precip and blend frequencies at (a) light rain rates and (b) moderate to heavy rain rates. Vertical axis gives the fraction of time that it rains at the rate specified. Black lines at the top of each colored bar show the sampling uncertainty, while blue stars and blue lines denote the CloudSat 2016–2017 (Macquarie Island Cloud and Radiation Experiment (MICRE) coincident period) mean and estimated sampling uncertainty. Black bars = blend rain (large particles). Dark green = blend drizzle (small particles) detected by both radar and disdrometer. Light green = blend drizzle (small particles) detected by radar only. Orange bars are CloudSat 2006–2017 averages, with dark orange bars = "rain certain," light orange = "rain probable," and white = "rain possible".

Tansey et al., 2022

Predicting Southern Ocean n_{INPs} in the marine boundary layer...

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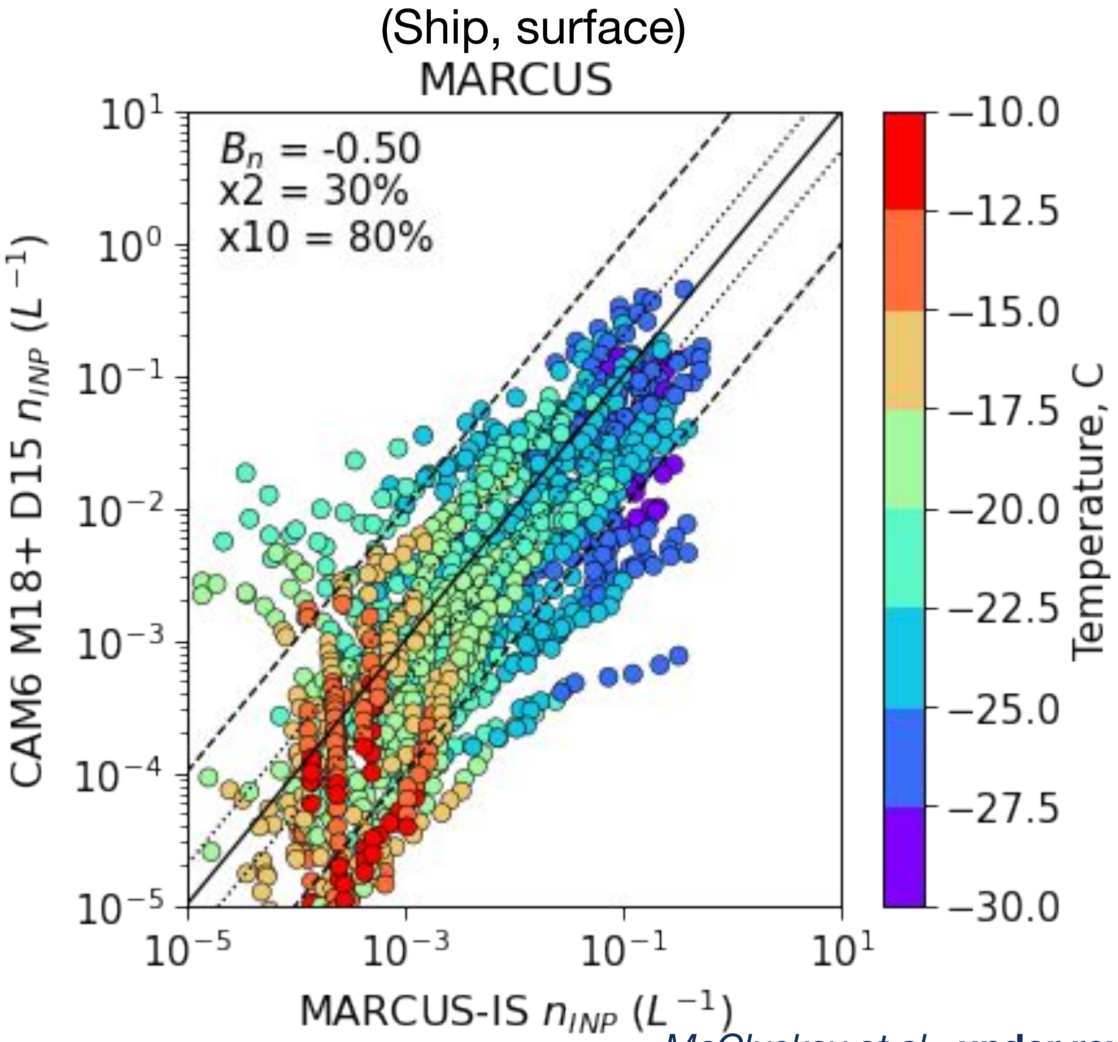
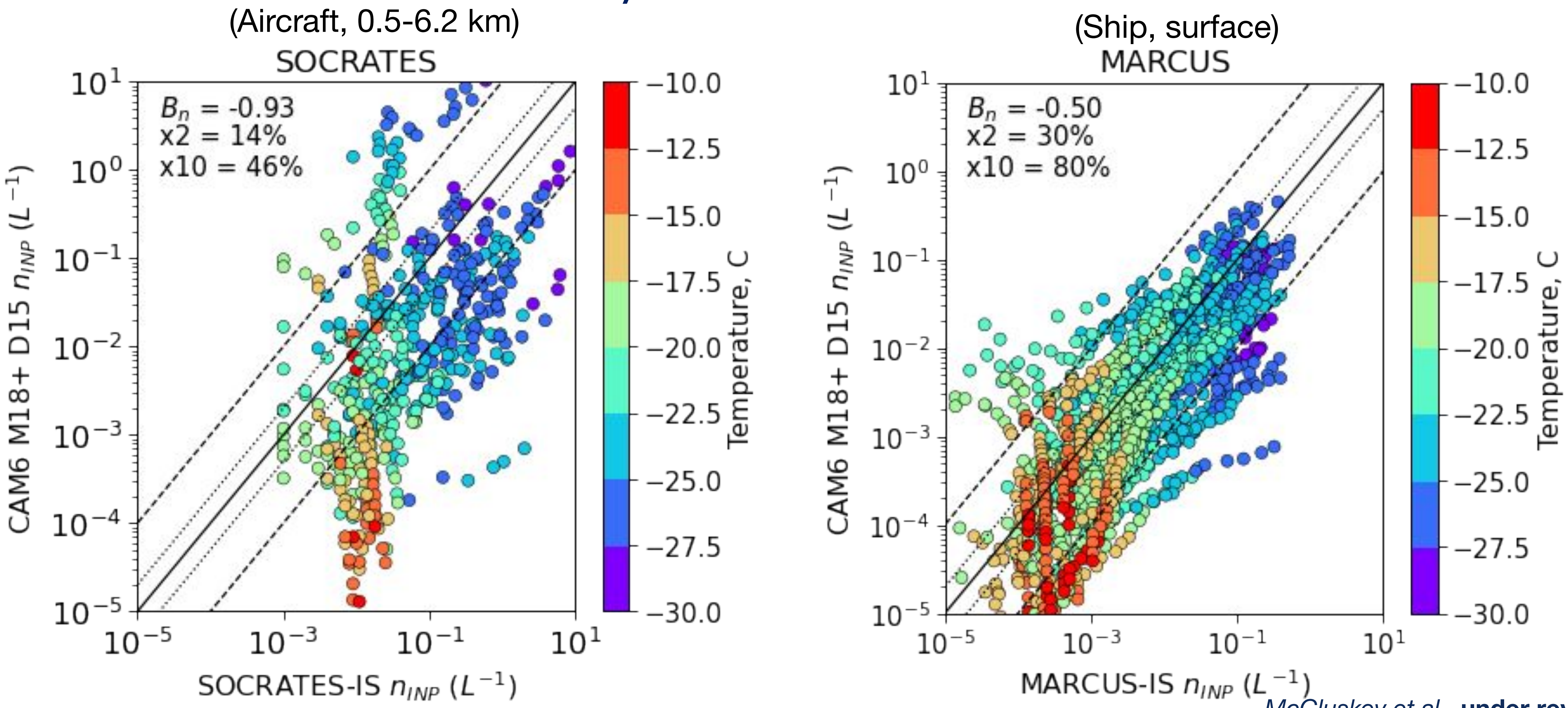
Modal Aerosol Model (MAM4)	
Black Carbon	
Dust *dynamic emissions*	n_{500nm}
Particulate Organic Matter	
Sea Salt *dynamic emissions*	$S_{seasalt}$
SO_4	
Secondary organic aerosol	



McCluskey et al., **under review**

Predicting Southern Ocean n_{INPs} in the marine boundary layer <u>is way easier than aloft!</u>



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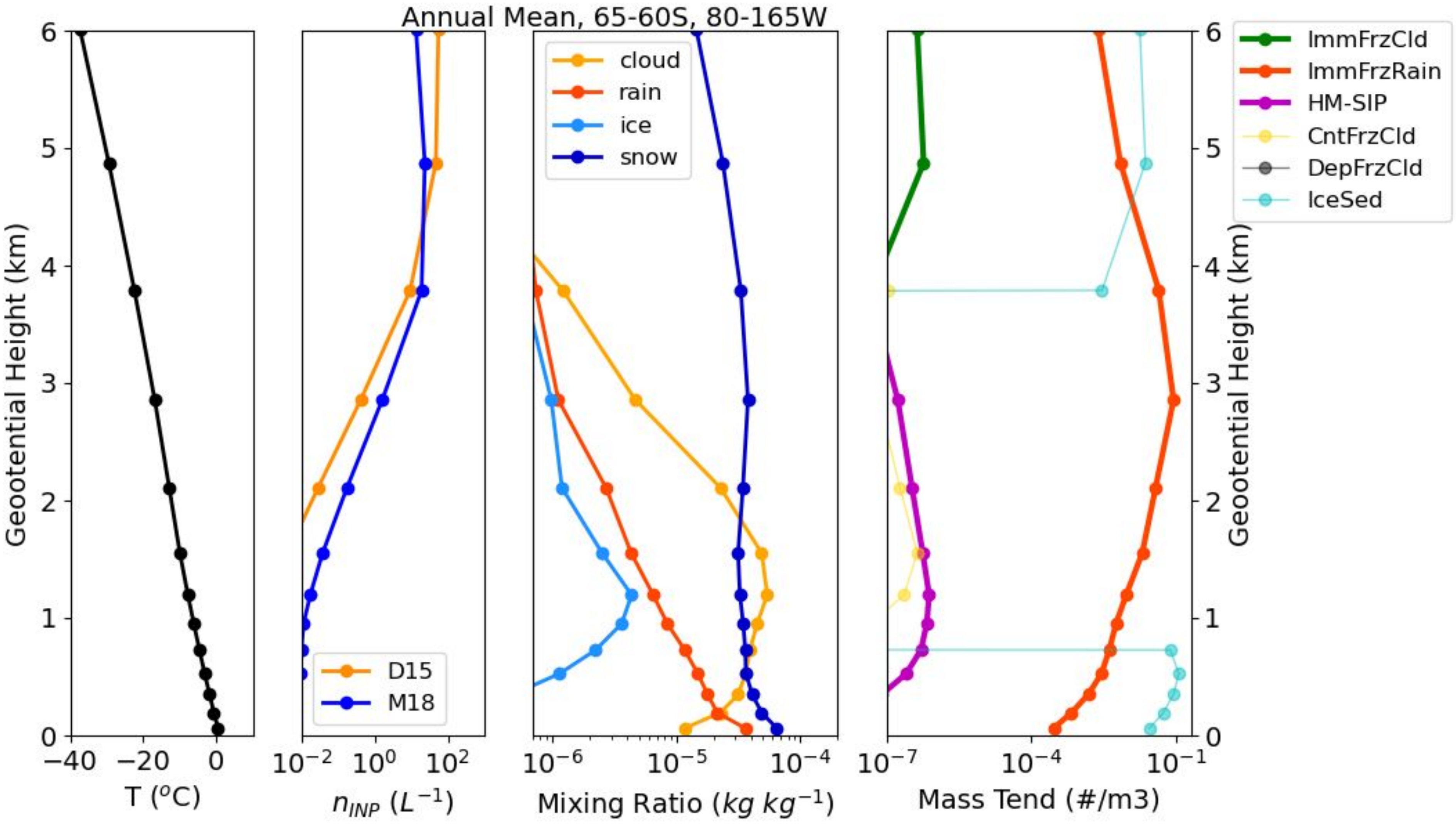
Annual Mean, 65-60S, 80-165W
Geootential Height (km)
T (°C)
n_{INP} (L^{-1})
D15
M18
Mixing Ratio ($kg\ kg^{-1}$)
cloud
rain
ice
snow
Mass Tend (#/m3)
ImmFrzCld
ImmFrzRain
HM-SIP
CntFrzCld
DepFrzCld
IceSed
Geootential Height (km)