Observation-oriented CCN modification over the Southern Ocean using the CAM6

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Introduction: Radiation Bias and Southern Ocean (SO)

Southern Ocean Clouds are:

- Essential to global radiation
- But are poorly understood
- Limited available observations
- Model parameters are NH-oriented

Simulated Antarctic Clouds "bright" enough?

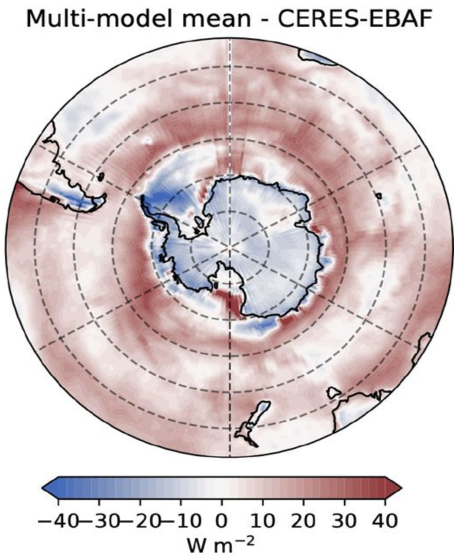


Fig 1. Bias of **surface incoming shortwave radiation** between mean of Coupled Model Intercomparison Project phase 6 (**CMIP6**) models and the **CERES-EBAF** satellite product during **Austral summertime**[1].

Introduction: Observation of Natural Marine Cloud Brightening

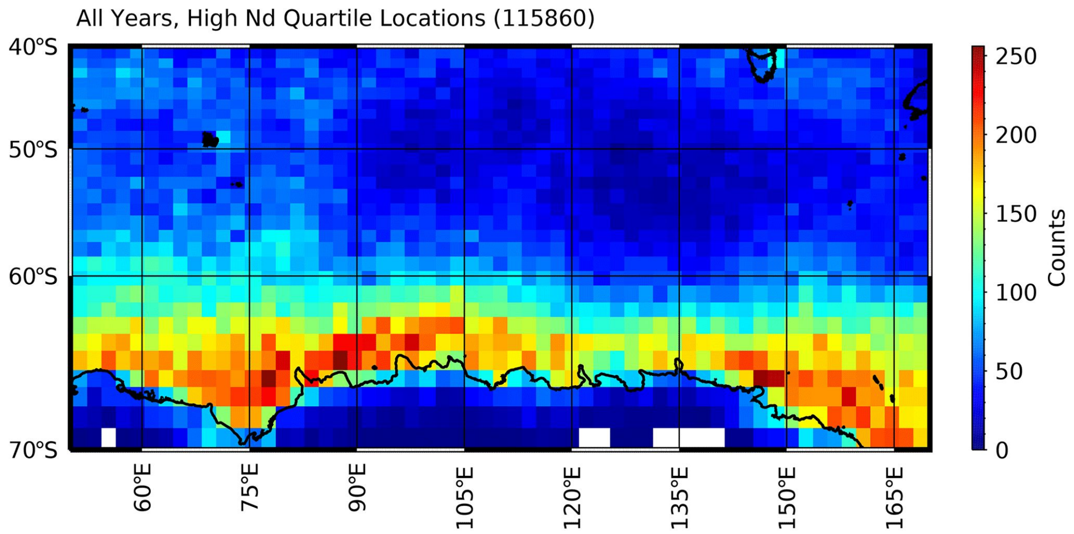
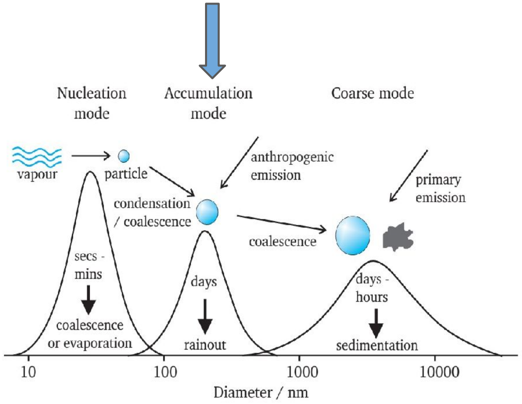


Fig 2. Geographic distribution of the high-Nd-quartile cloud scenes during **Austral summertime,** Mace et al., (2021)

- Seasonal cycle in cloud droplet number concentration (Nd)
- Along the MIZ
- Seasonal increases in CCN and biological activity

Introduction: Activation of cloud droplets in CAM6 – Abdul-Razzak and Ghan (2000)

a) Cloud Condensation Nuclei



* Courtesy of James Davies

$$\frac{dn}{da} = \sum_{i=1}^{I} \frac{N_i}{\sqrt{2\pi}\sigma_i} \exp\left(-\frac{1}{2}\frac{\ln^2(a/a_{mi})}{\ln^2 \sigma_i}\right)$$

b) the Maximum supersaturation (SS_{max})

$$\frac{dS}{dt} = Q_1 \frac{dz}{dt} - Q_2 \frac{d\chi}{dt}$$

+ : cooling in adiabatic ascent (f1)

- : condensation of water vapour on droplets (f2)

	Sea Salt	**Sulfate**	Secondary organic Aerosols (**SOA**)	Primary organic matter (**POA**)
Hygroscopicity kappa	1.16	0.507	0.14	0.1

SO clouds: Aerosol-limited OR updraft limited regime

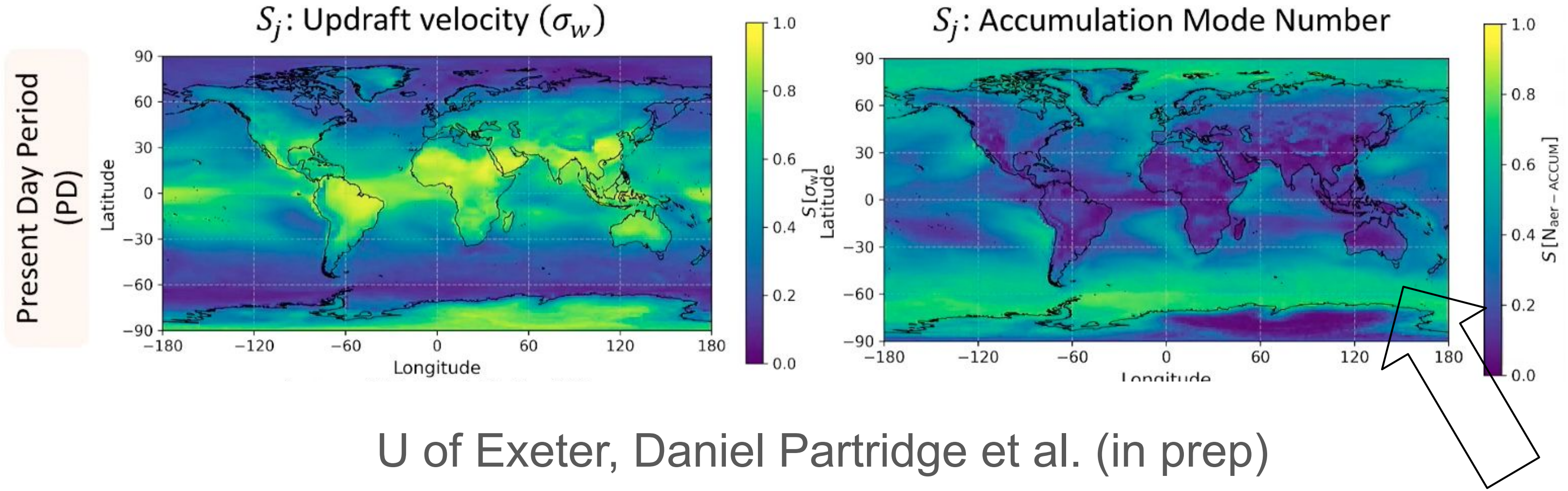
Introduction: SO clouds are **Aerosol-limited**

Sobol's index $S_j = \frac{V[E[Y|X_j]]}{V[Y]}$

partial variance of the response that can be attributed to model inputs

UKESM1

ECHAM6.3-HAM2.3



U of Exeter, Daniel Partridge et al. (in prep)

Introduction: High $N_{70\text{-}100}$ cause high N_{CCN} over summer SSO

Niu et al. 2024 JGR-A
(doi 10.1029/2023JD040396)

Observed polar-ward:

- increased $N_{70\text{-}100}$
- decreased $N_{700\text{-}1000}$

⇒ lead to increased N_{CCN} over the summer SSO

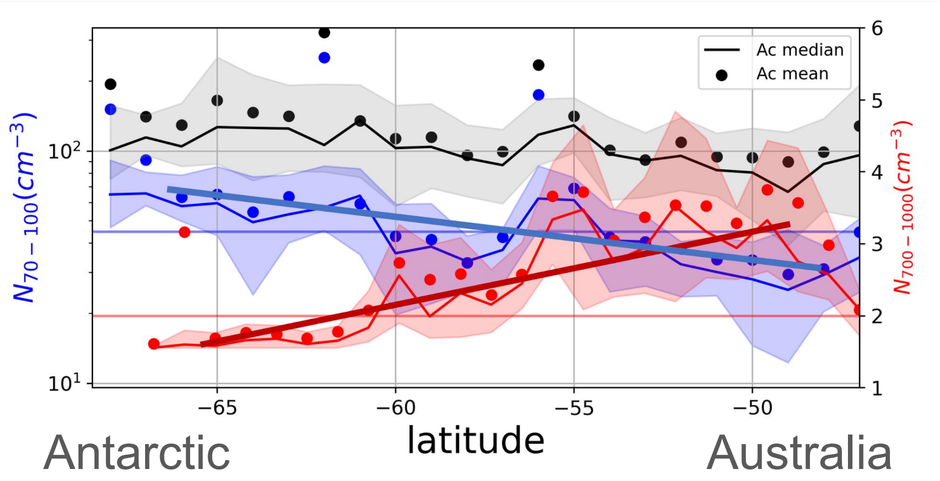


Fig 3. Latitudinal dependence of **Ac**cumulation-mode-aerosol **(70 nm < D < 1000 nm)** number concentration (**Ac**) from Ultra High Sensitivity Aerosol Spectrometer (UHSAS), particles with **70 nm < D < 100 nm**, and **700 nm < D < 1000 nm**

Methods

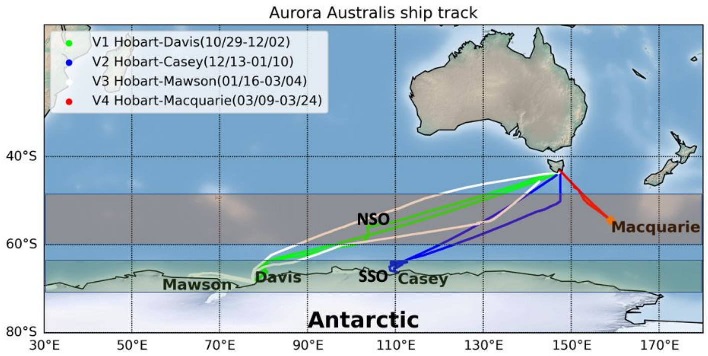
0.9° latitude x 1.25° longitude (~100 x 100 km at 50oS)

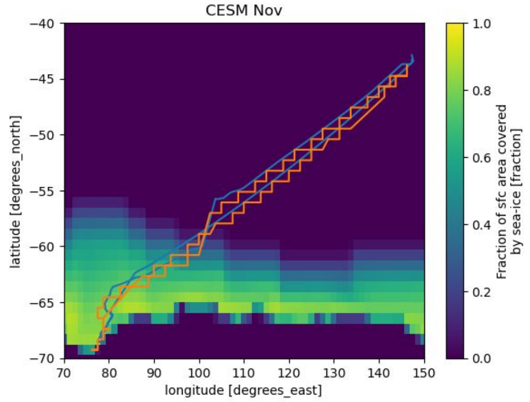
32 levels to ~1 hPa (100–1200 m vertical resolution)

30 minute time step (10 min sub–step)

Specified dynamics (nudged) U, V, T (MERRA–2, 24–hr)

Cloud Microphysics	MG2	Two Moment	Gettelman et al. (2019)
Aerosols	MAM4	Modal	Liu et al. (2016)
Boundary Layer, Shallow Convection, Cloud Macrophysics	CLUBB	High-order Moments	Bogenschutz et al. (2012), Golaz et al., 2002
Radiation	RRTMG	Correlated-k	Mlawer et al. (1997)
Surface emission	CMIP6 climatological profiles in 2000		Feng et al., (2020)
Sea Ice	CICE5	Monthly mean climatology	Hunke et al., (2015)



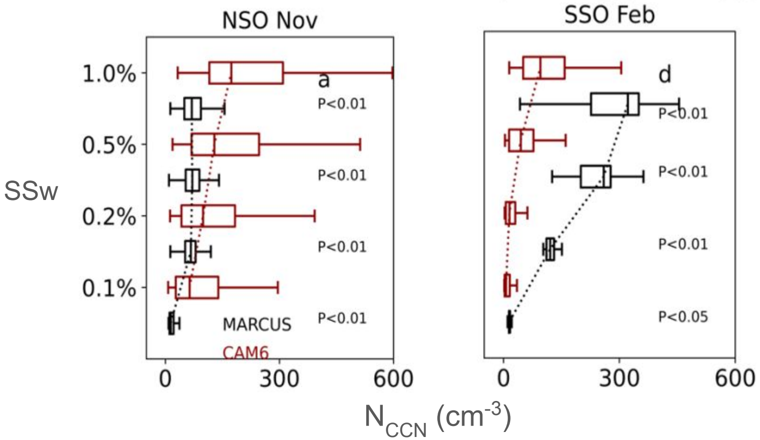


Co-location Method

Introduction: CAM6 CCN Bias

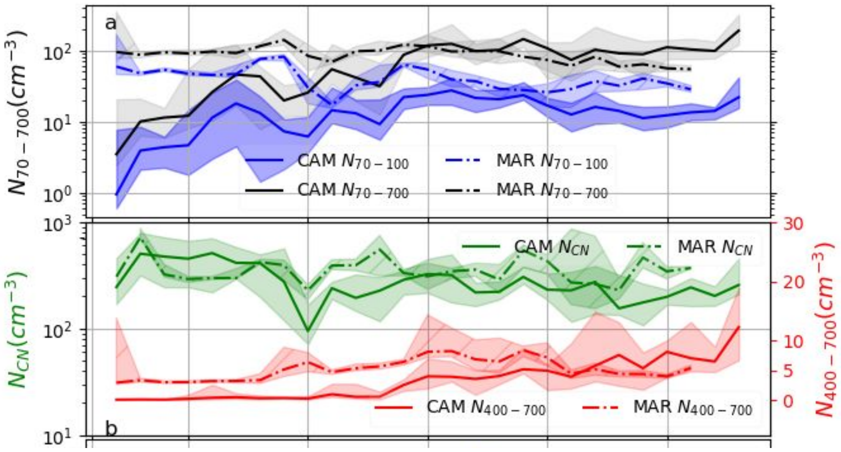
Niu et al. 2025 JGR-A:
[(doi 10.1029/2024JD042734)](https://doi.org/10.1029/2024JD042734)

A. CAM6 missing small sulfates
B. Sometimes overestimate sea salts



To do list:

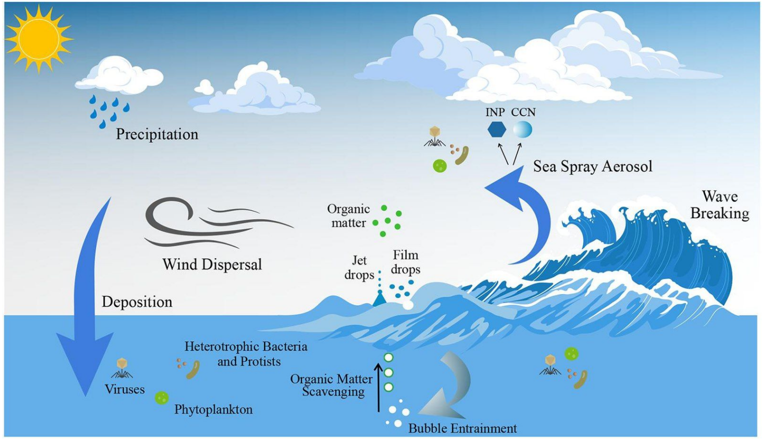
A. Tuning up sulfates ↑
B. Tuning down sea salts↓



Antarctic Australia

Fig 4. Latitudinal N_{Ac} comparison, CAM6 in solid and MARCUS in dashed line for N_{At}, $N_{large\ Ac}$, $N_{small\ Ac}$, N_{Ac}

A. Tuning down sea-salt emission scheme over the SO



Daniel C. O. Thornton & Sarah D. Brooks

${U_{10}}^{3.41}$ parametrization

(Monahan & Muircheartaigh, 1980; Gong, 1997, 2003; Clarke et al., 2006)

Over the SO:

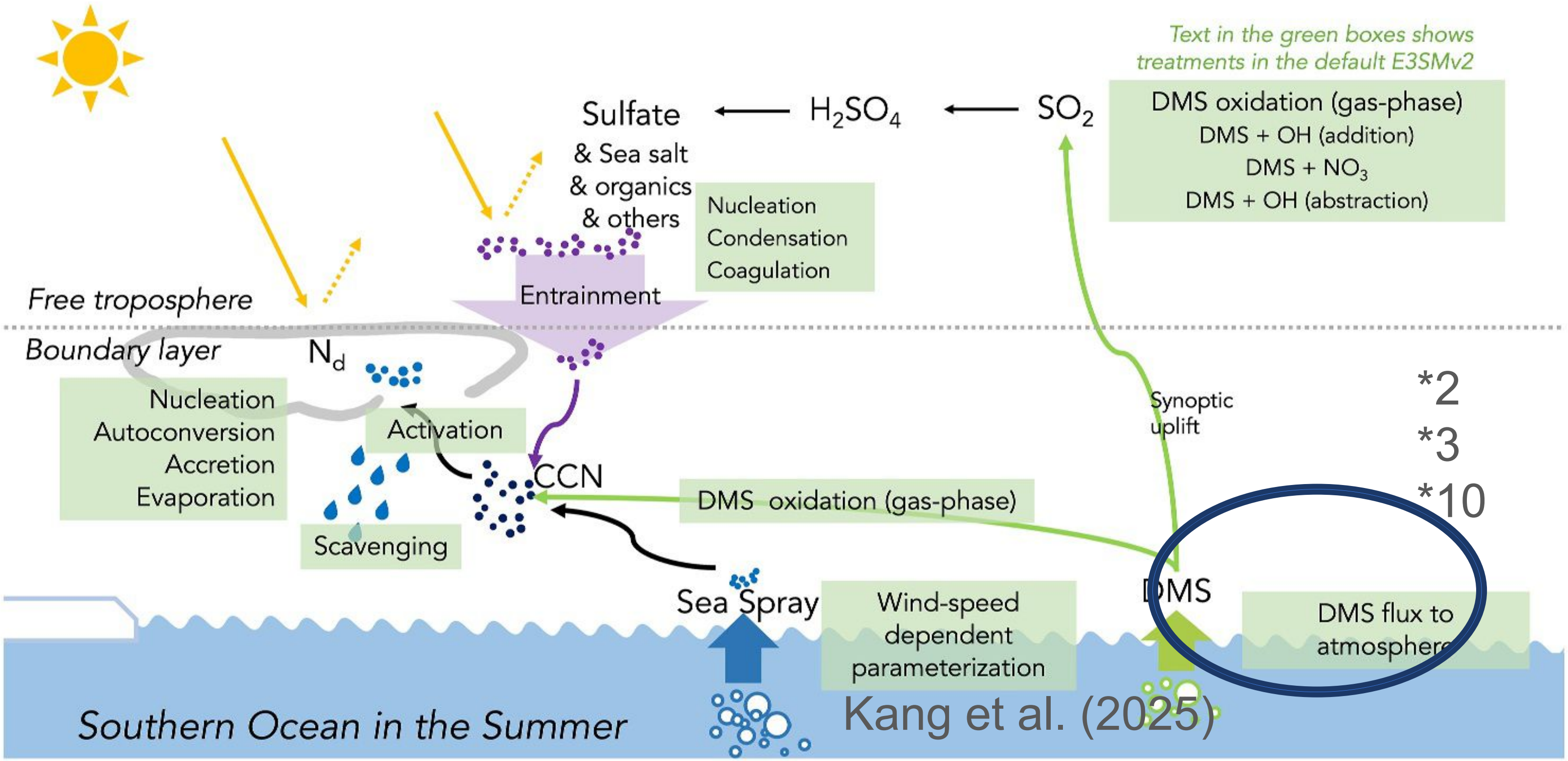
Reduced sensitivity of sea-salt emission flux to ${U_{10}}^{2.8}$

(Revell et al., 2019; Hartery et al., 2020; Kang et al., 2022)

B. Tuning up sulfates

DMS (dimethyl sulfide)

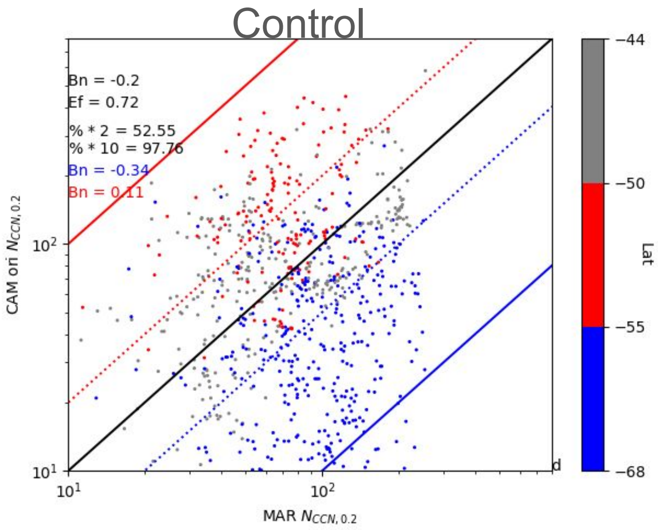
$$\mathbf{DMS \rightarrow SO_2 \rightarrow SO_4}$$

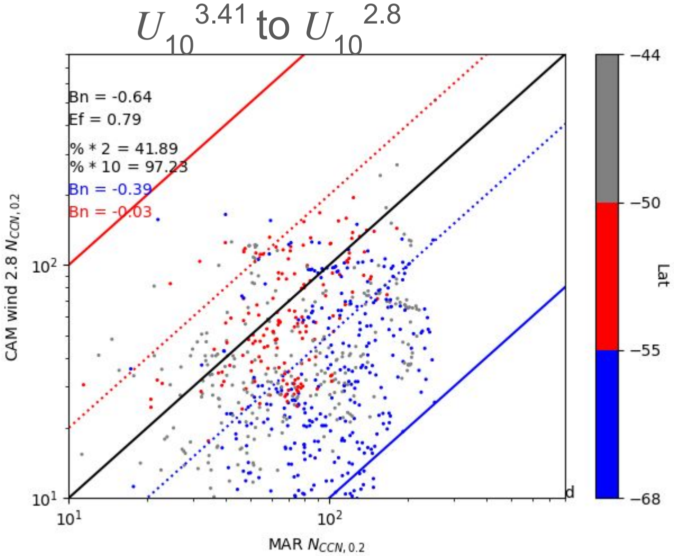


*2
*3
*10

Kang et al. (2025)

A. Tuning down sea-salt emission scheme over the SO



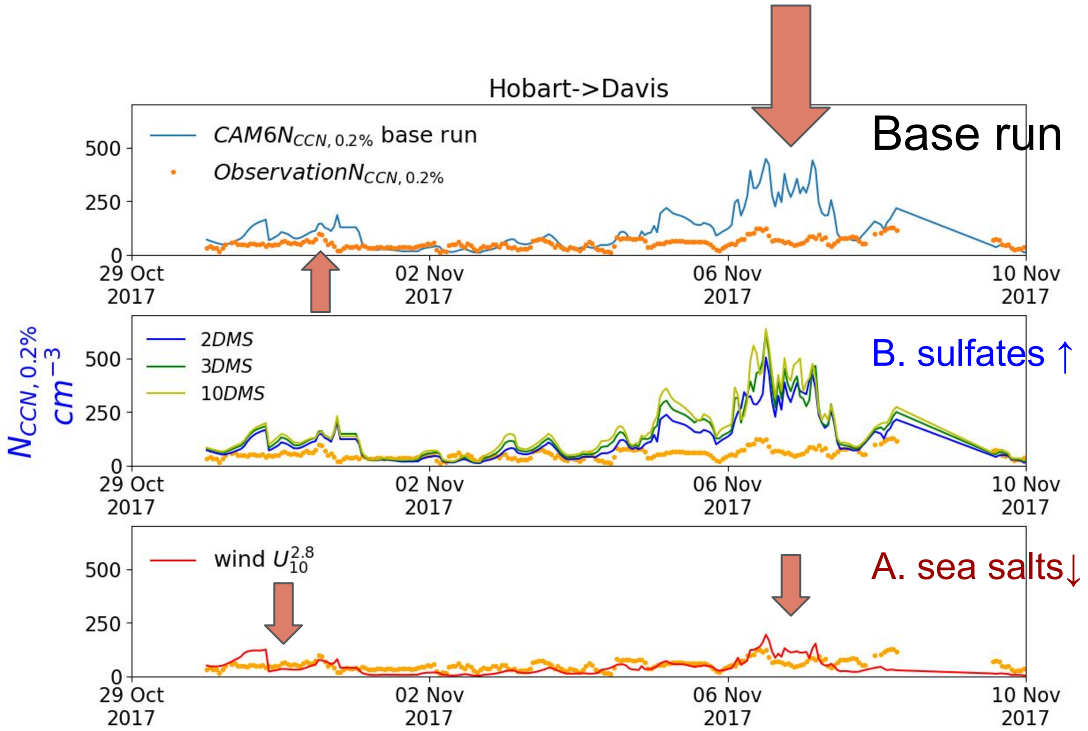


- ✅ Largely improve the N_{CCN} between 45°S -55°S (grey and red)
- ❌ Not for south of 55°S

- ⇒maybe caused by substantial SO_4 south of 55°S

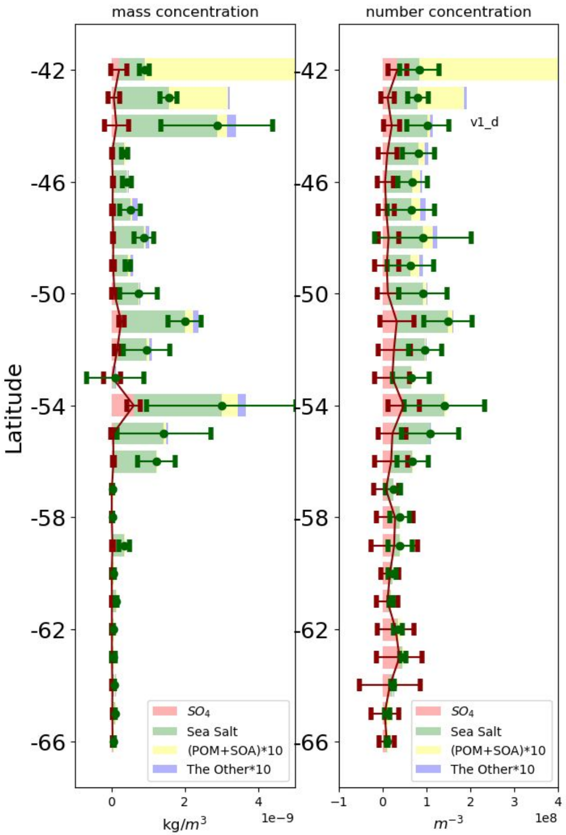
A. Sea salt case in Nov 2017

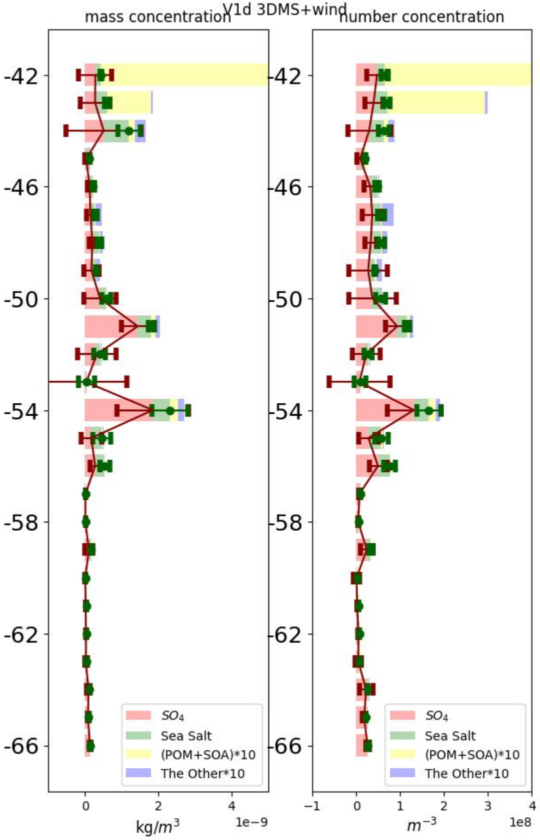
- Oct 30-Nov 9, 2017
- 42.5°S-60°S
- $U_{10}^{3.41} \rightarrow U_{10}^{2.8}$ solved the overestimation of N_{CCN}

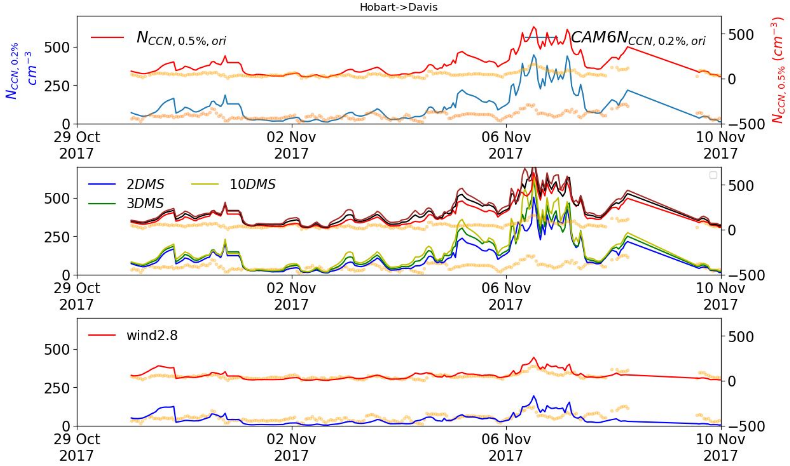


Base run

B. sulfates↑ + A. sea salts↓







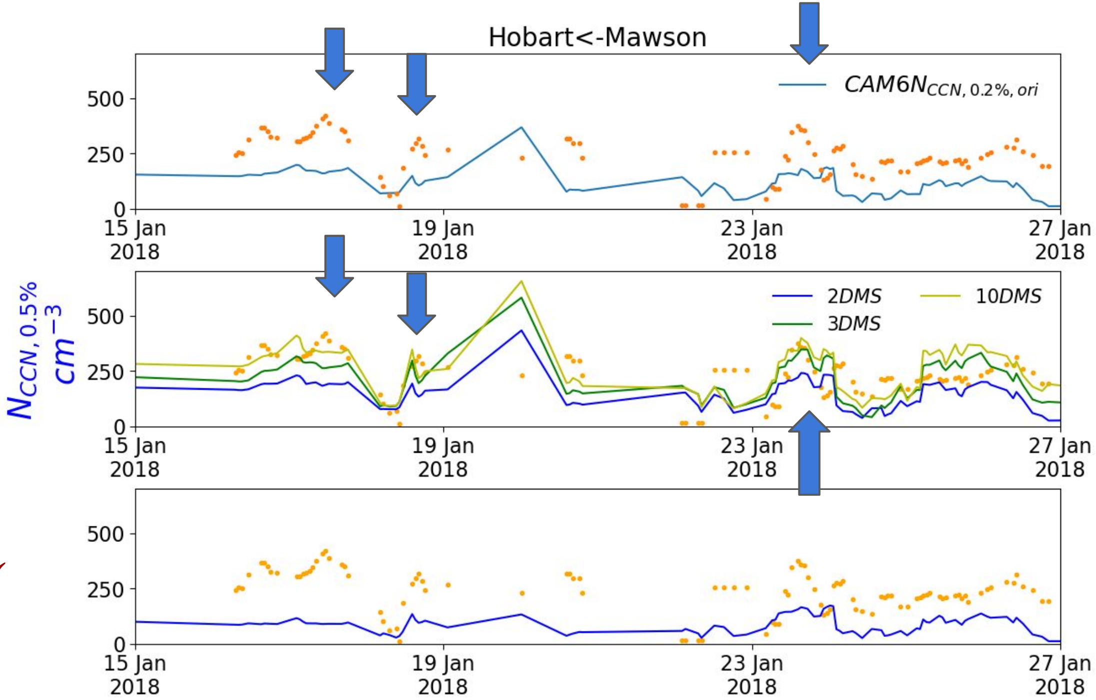
B. Sulfate case

- Jan 17-29, 2018
- 45 °S - 68 °S
- DMS * N improves the N_{CCN}

Base Run

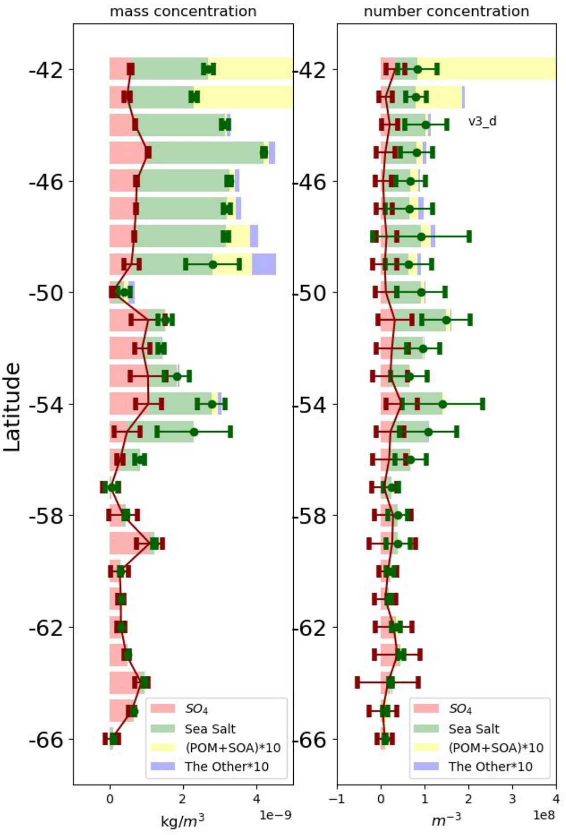
B. sulfates↑

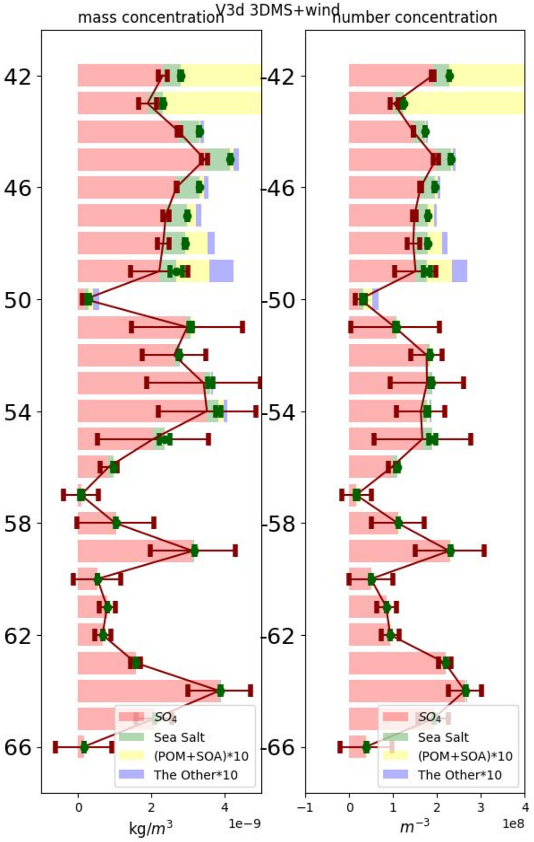
A. sea salts↓

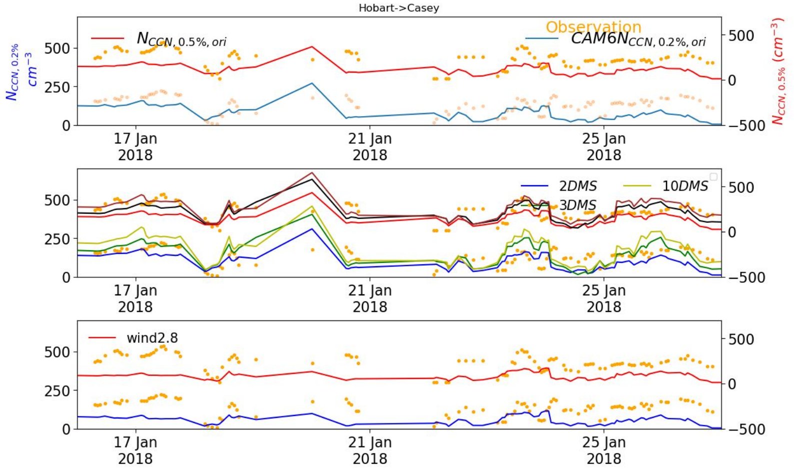


Base run

B. sulfates ↑ + A. sea salts↓







Take home message

1. MARCUS Seasonal + Regional → sea salt scenario + sulfate scenario
2. Both modifications improved the N_{CCN} over the SO
3. Sea salt emission power law can be regional dependent
4. Low bias of N_{CCN} in the summer SSO related to lack of **S**

Potential improve if:

1. Fully coupled ocean + atmosphere + chemistry
2. Adding aqueous-phase reactions of DMS oxidation intermediates (e.g. DMSO, MSIA, HPMTF); adding species such as MSA, BrO, MeSH
3. DMS climatology emission → current flux
4. Oxidation ratios of reactions..

Next Step:

- Lifetime of Ac sea salt and sulfates
- Influence from synoptic uplift and descend
- The following influence on clouds

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Institutions

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3. NSF National Center for Atmospheric Research (NCAR)
4. Pacific Northwest National Laboratory (PNNL)

Questions and Comments?