Marine Cloud Brightening Forcing and Response in CESM2 and E3SMv1

Haruki Hirasawa[1], Mingxuan Wu[2], Kyoungock Choi[3], Dipti Hingmire[1], Phil Rasch[3], Hailong Wang[2], Hansi Singh[1], Rob Wood[3], Sarah Doherty[3]

1 UVIC

2 PNNL

3 UNIVERSITY of WASHINGTON

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Marine Cloud Brightening (MCB)

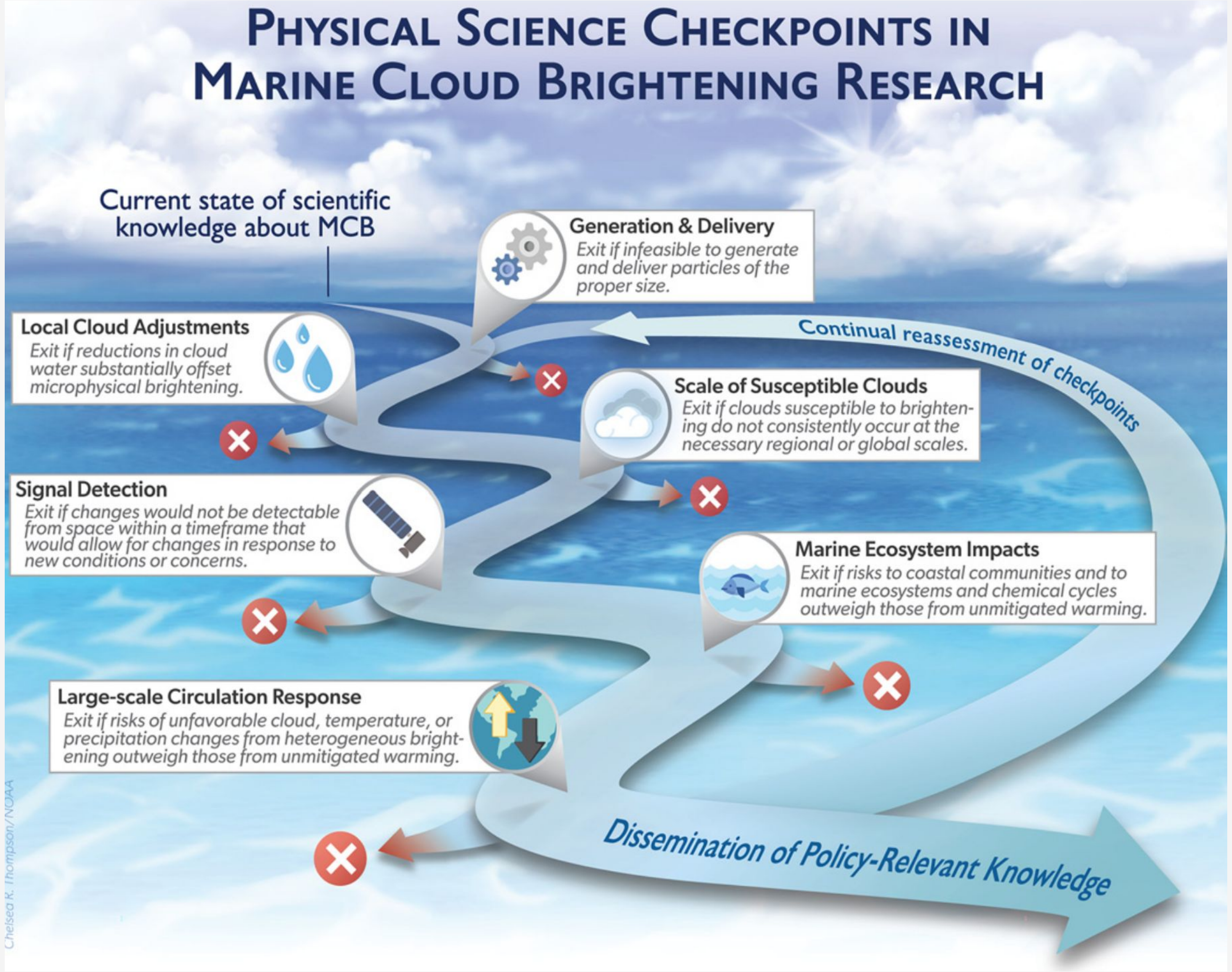
MCB is a proposed solar radiation management technique where:

1. Sea salt aerosol injected into low clouds
2. Cloud droplet number concentration increase
3. Cloud albedo increase
4. Local surface cooling

What can we learn about MCB from GCMs?

GCMs can be used to assess:

- Large scale cloud response to aerosol injection
- Radiative and carbon cycle feedbacks
- Local and remote climate impacts due to brightening

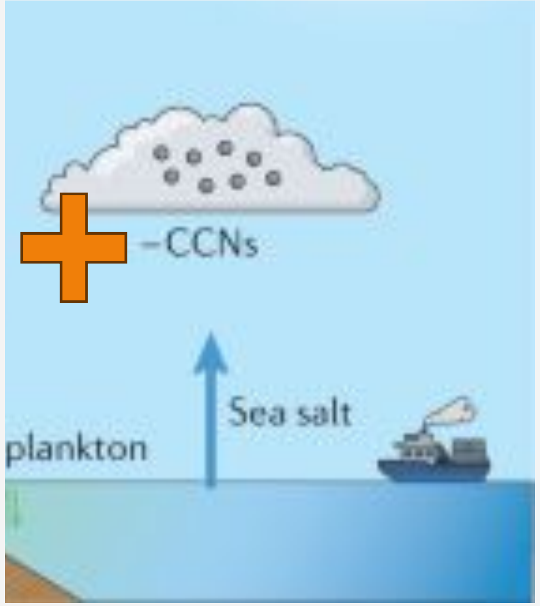


Diamond et al., 2022

Testing MCB in GCMs

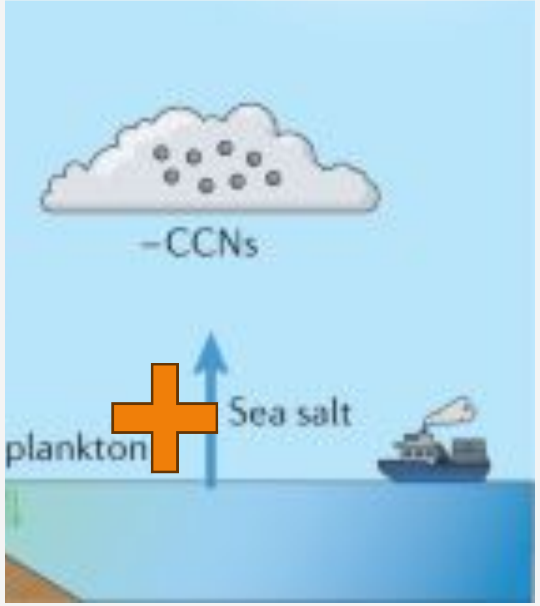
Prescribed Cloud Droplet Number Concentration (**CDNC**)

- Set in-cloud liquid CDNC to prescribed values in selected regions



Sea salt emissions (**SSE**)

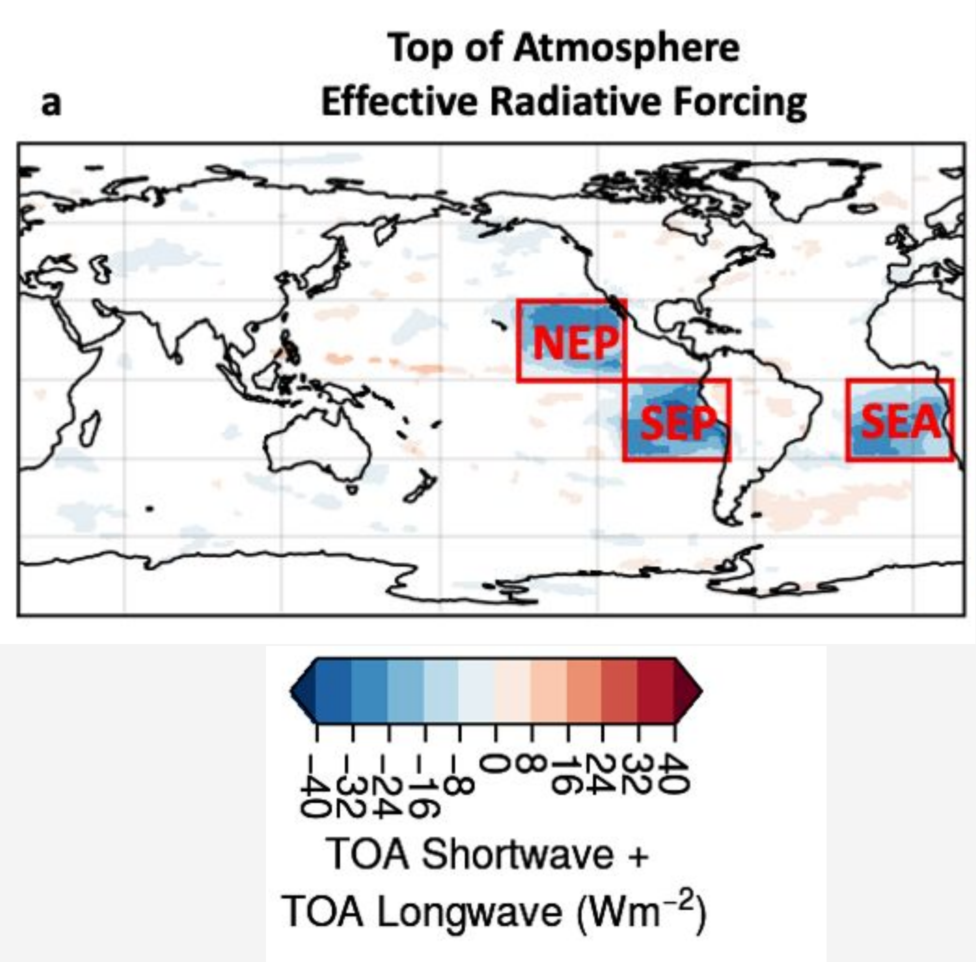
- Add accumulation mode (~0.1micron) aerosols to surface sea salt flux in selected regions



MCB Forcing Experiments

- We conduct CESM2 and E3SMv1 simulations
- Apply MCB perturbations three tropical regions with extensive low cloud (NEP, SEP, SEA)
- Vary MCB magnitude in Fixed SST simulations (targeting ERF = -1.8Wm^{-2})

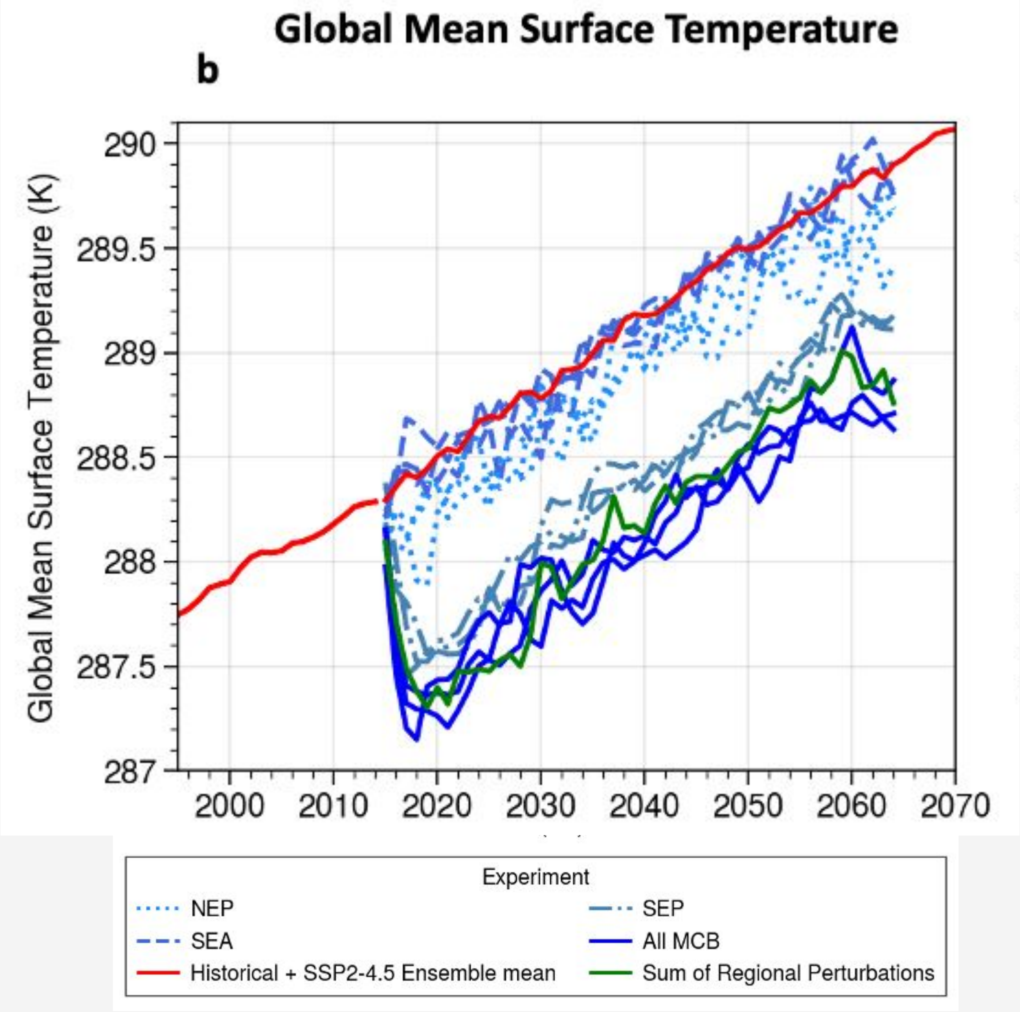
		CESM2	E3SMv1
CDNC	Tested range	375 to 675cm^{-3}	375 to 2000cm^{-3}
	-1.8Wm^{-2} value	600cm^{-3}	2000cm^{-3}
SSE	Tested range	4.3 to 250Tg/yr	14 to 150Tg/yr
	-1.8Wm^{-2} value	7Tg/yr	42.5Tg/yr



Coupled Experiments

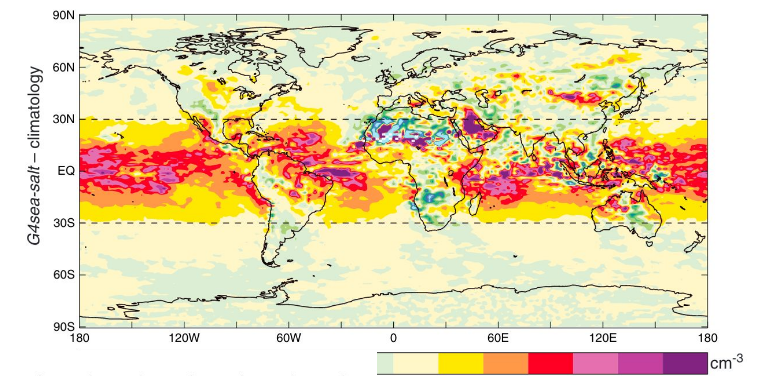
- CDNC and SSE perturbations are applied to coupled SSP2-4.5 simulations ("G4-like")
- -1.8Wm-2 forcing applied for 2015-2065 for NEP + SEP + SEA
- Three regions also tested separately

CESM2 annual mean GMST

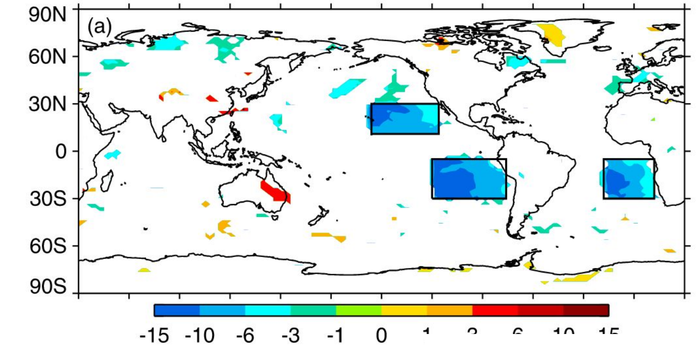


How do these simulations differ from past work?

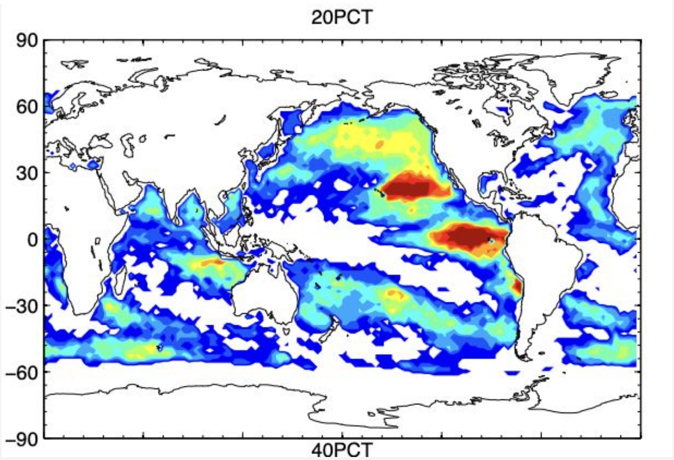
1. Perform a multi-model comparison of climate impact of MCB in regions with high cloud sensitivity
2. Specify based on **forcing** strength rather than CDNC/SSE increase
   - Separate forcing uncertainty from teleconnection uncertainty
3. Updated assessment in CMIP6 models



G4seasalt
Kravitz et al., 2013



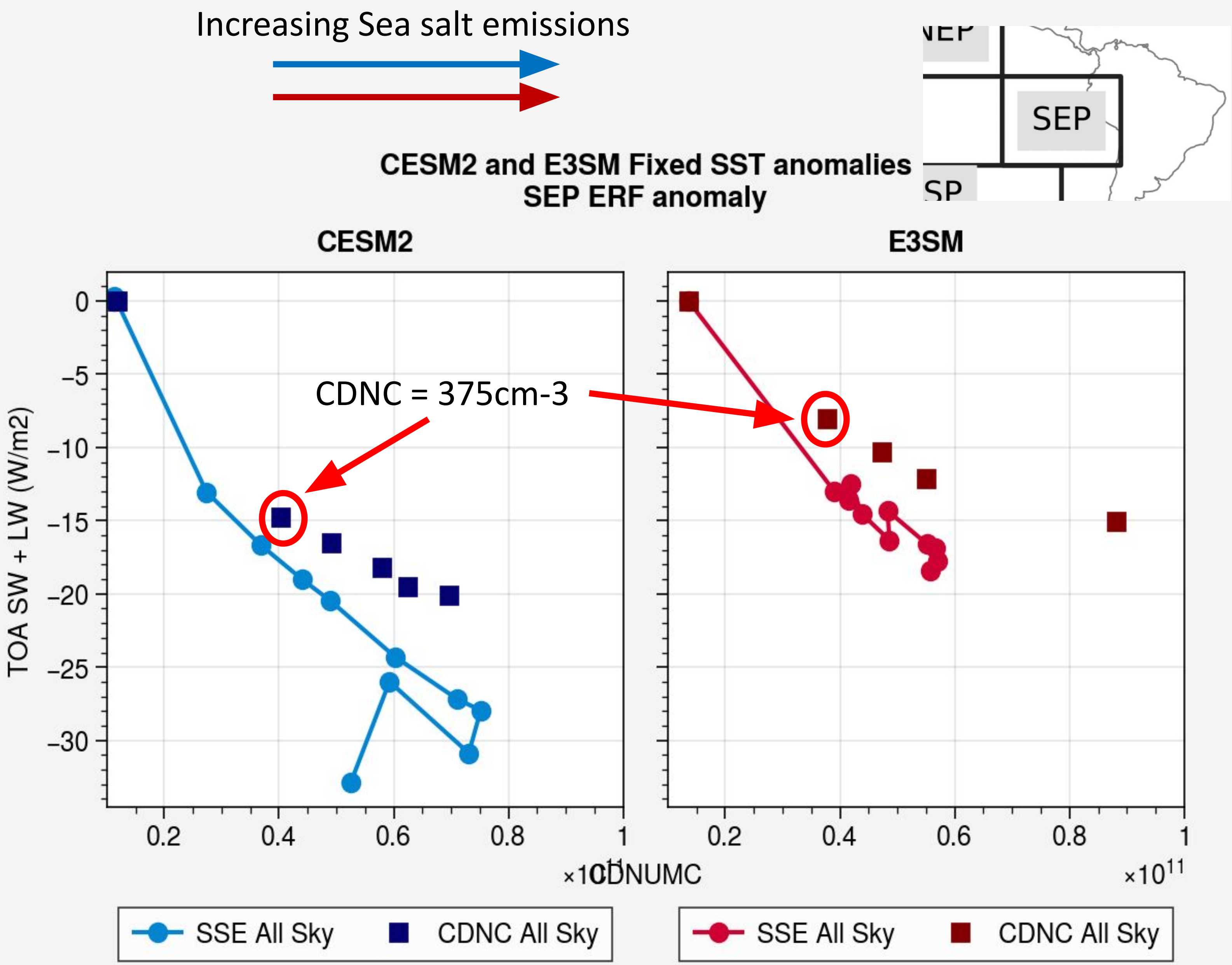
Hill and Ming, 2012



Rasch et al., 2008

How much does MCB brighten clouds?

- Aerosol-cloud interaction more sensitive in CESM2



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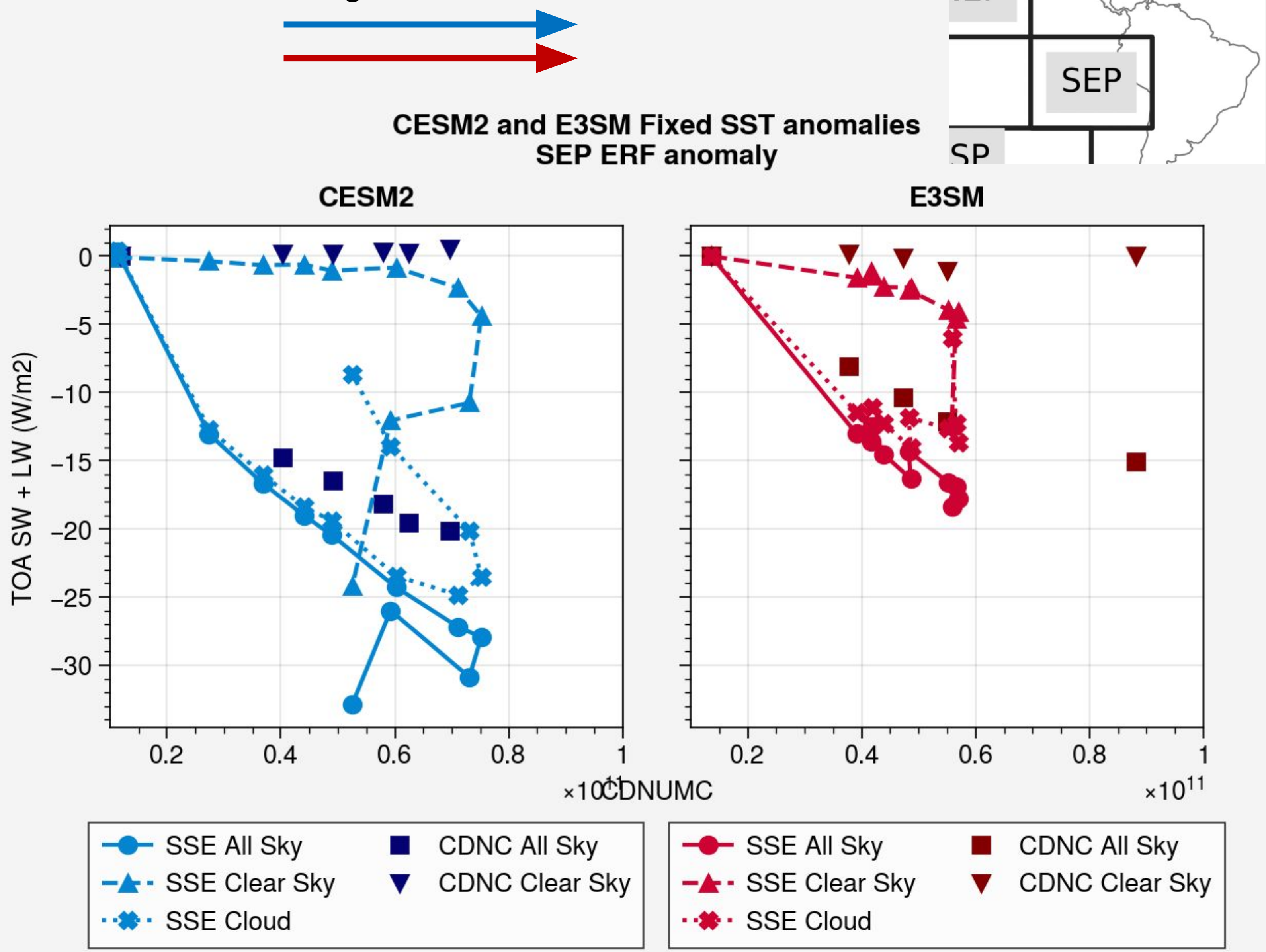
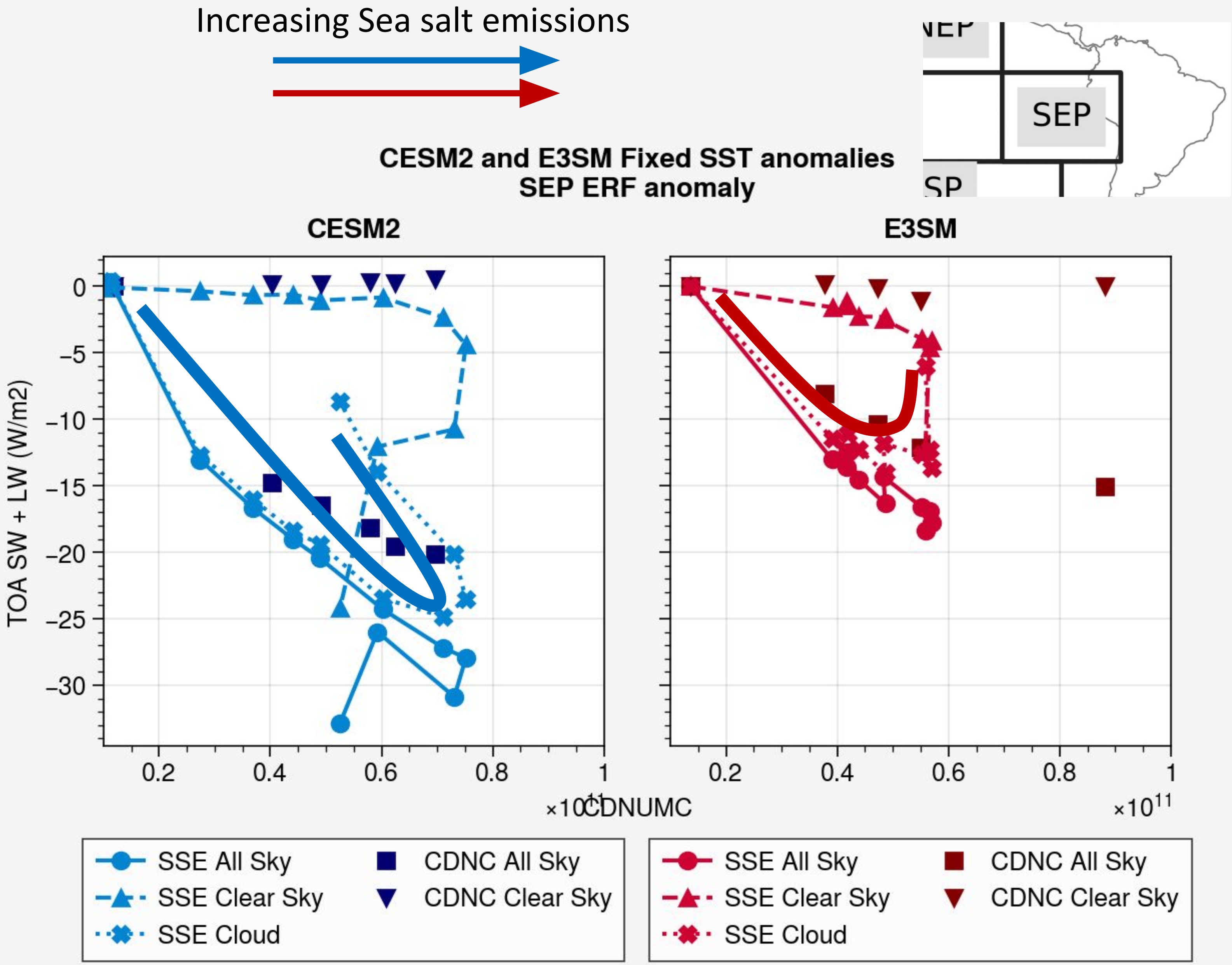
Increasing Sea salt emissions



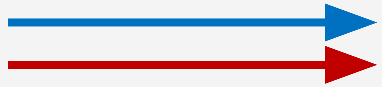
How much does MCB brighten clouds?

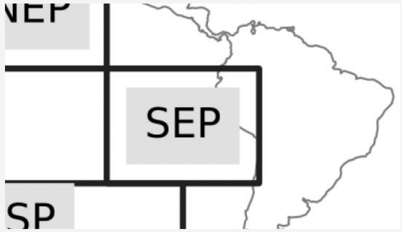
- Aerosol-cloud interaction more sensitive in CESM2
- At very high emission rates, additional SSE reduces ACI (>100Tg/yr globally)



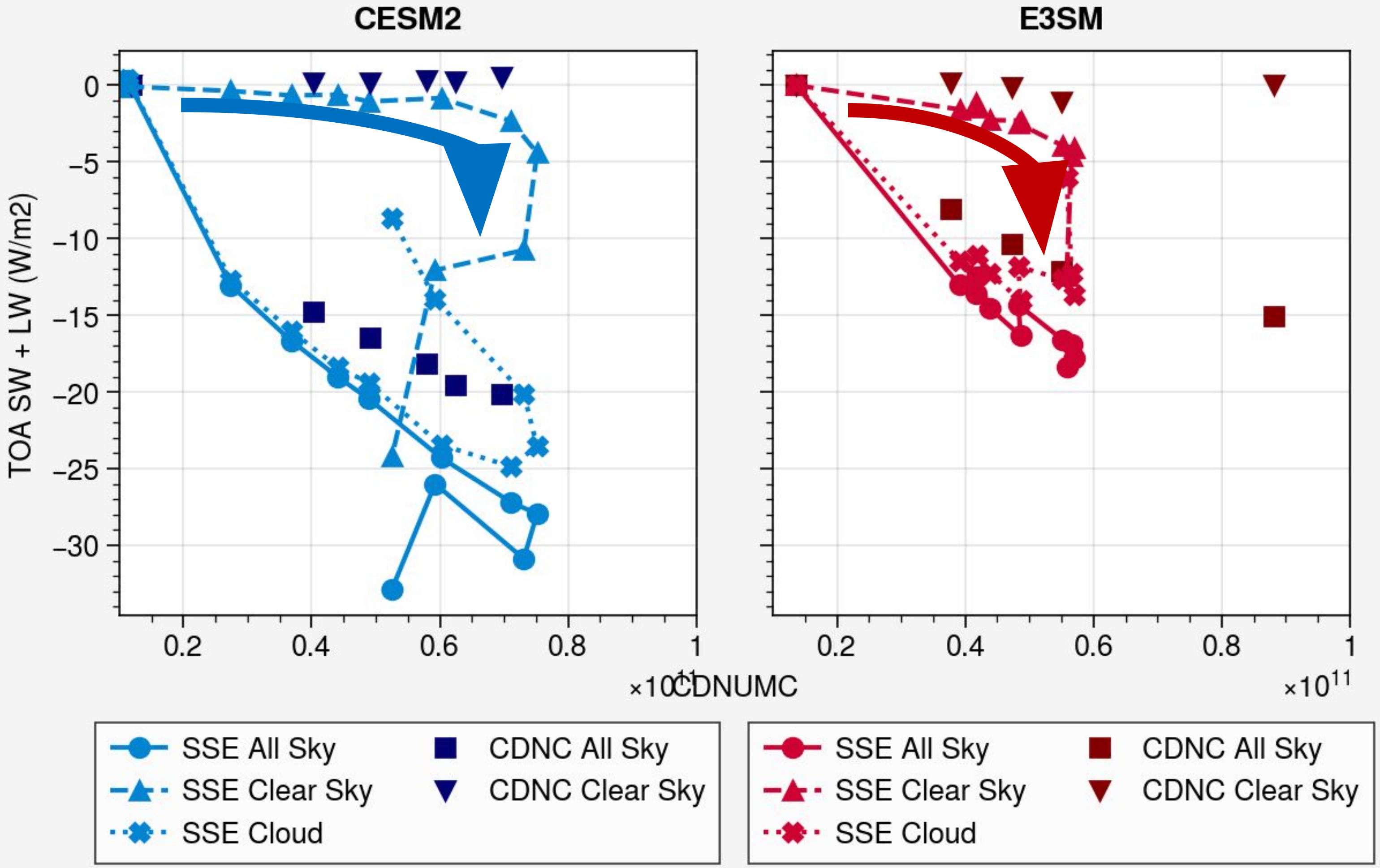
How much does MCB brighten clouds?

- Aerosol-cloud interaction more sensitive in CESM2
- At very high emission rates, additional SSE reduces ACI (>100Tg/yr globally)
- Globally, SSE forcing continues to increase due to direct aerosol forcing



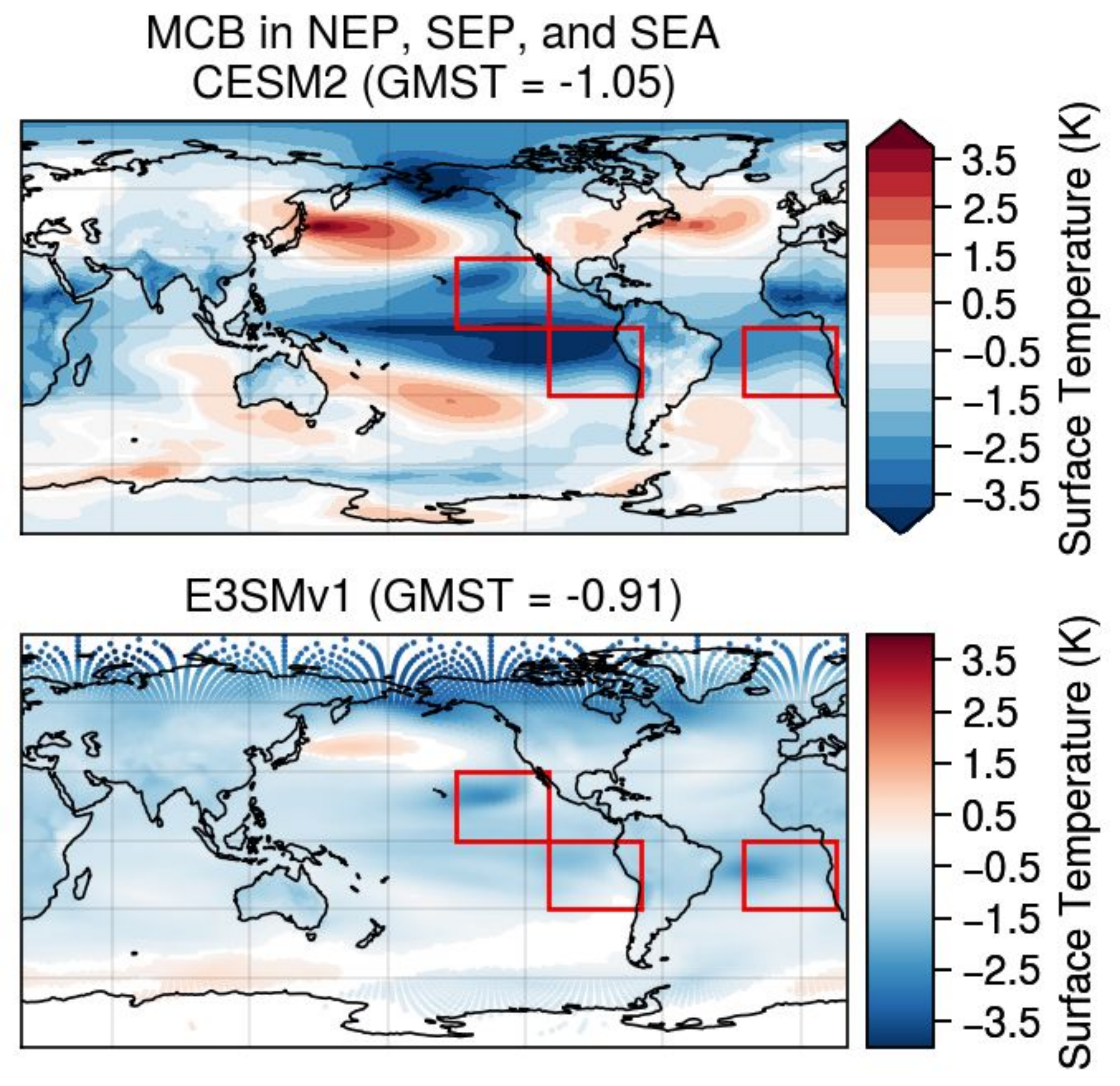


CESM2 and E3SM Fixed SST anomalies
SEP ERF anomaly



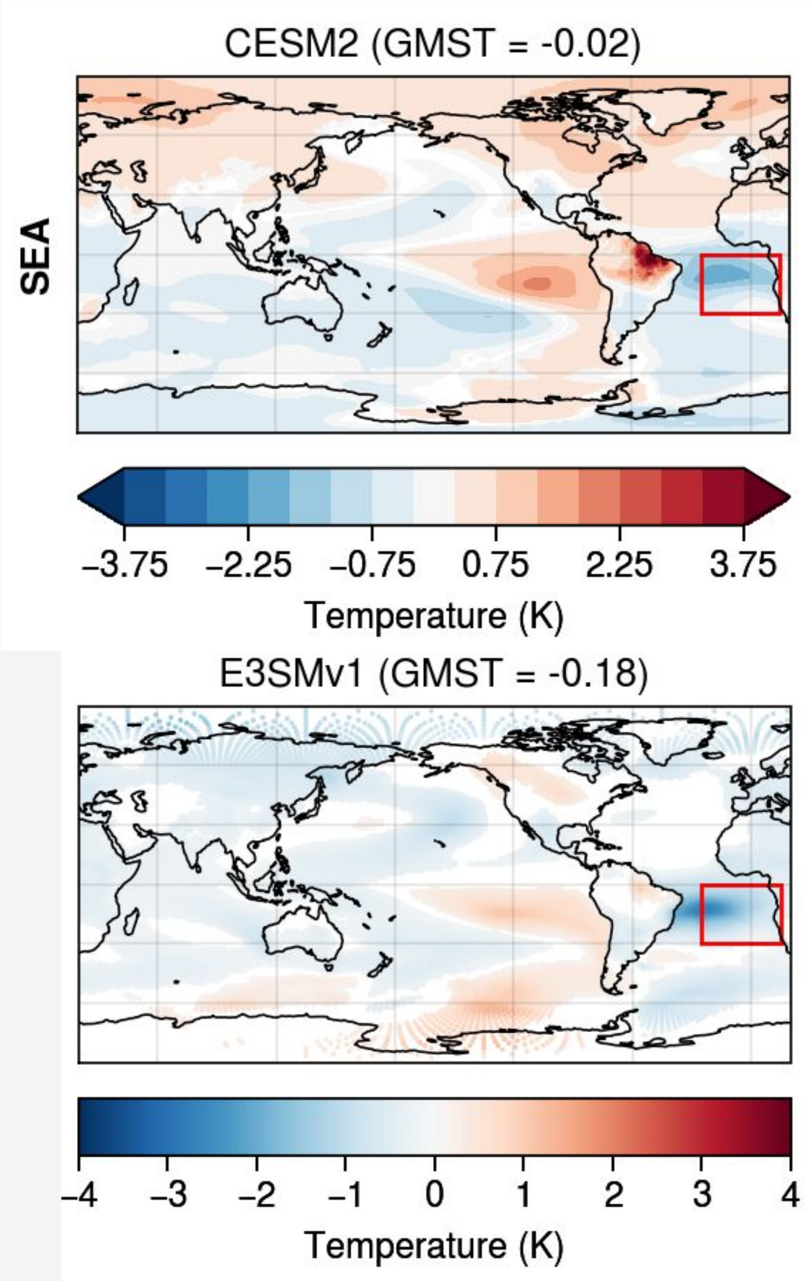
MCB temperature impact comparison (CDNC -> $-1.8 Wm^{-2}$)

- La Niña cooling pattern in both models
- <u>CESM2</u>:
  - Stronger tropical cooling
  - Offset by midlatitude warming
- <u>E3SM</u>:
  - Weaker Pacific cooling
  - Few regions of warming



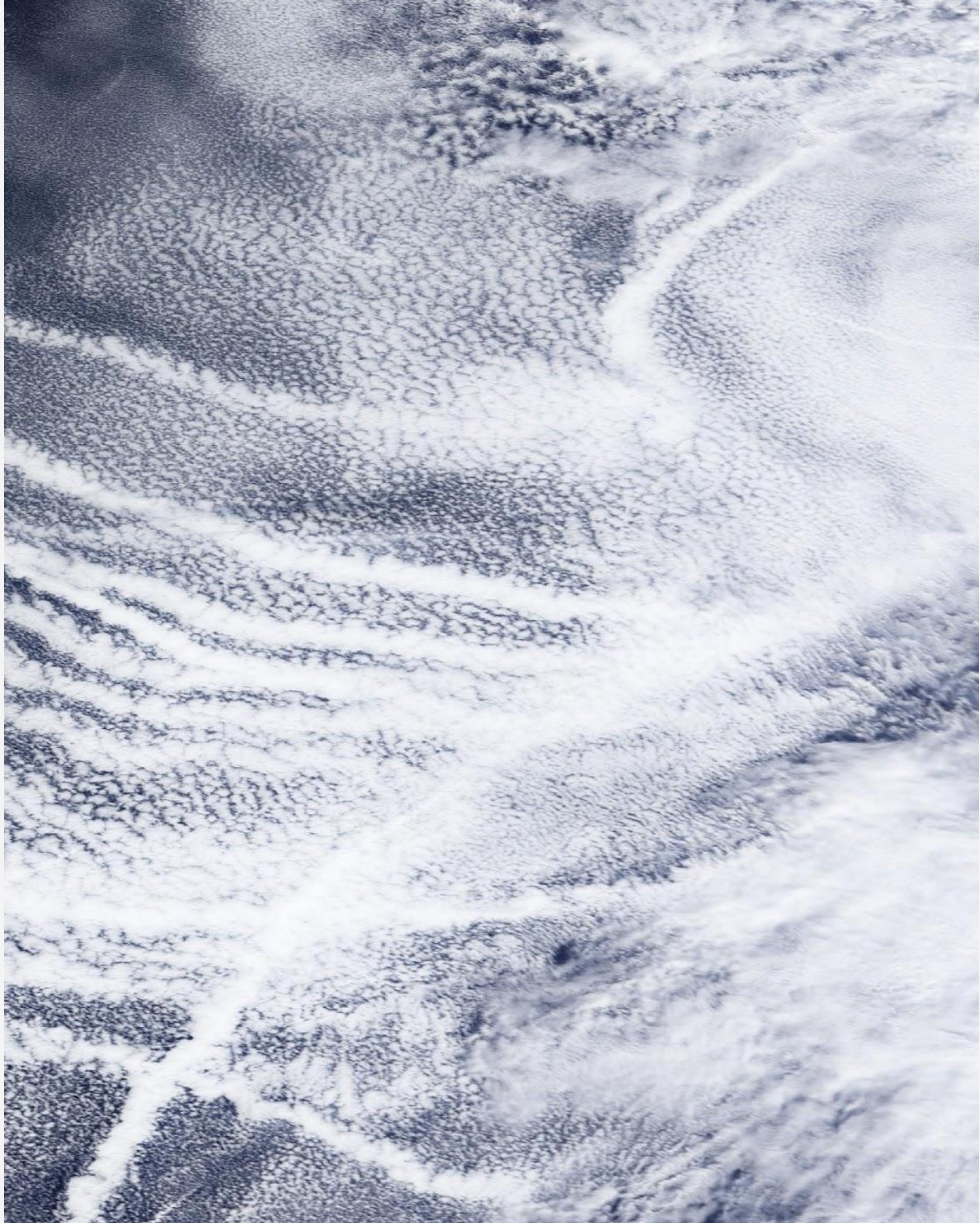
Large scale response uncertainty for SEA MCB

- We test the response to each of the three regions individually
- For example, SEA MCB induces a "Atlantic Nina" response
- CESM2 and E3SMv1 see opposite signed high NH latitude response



Conclusions

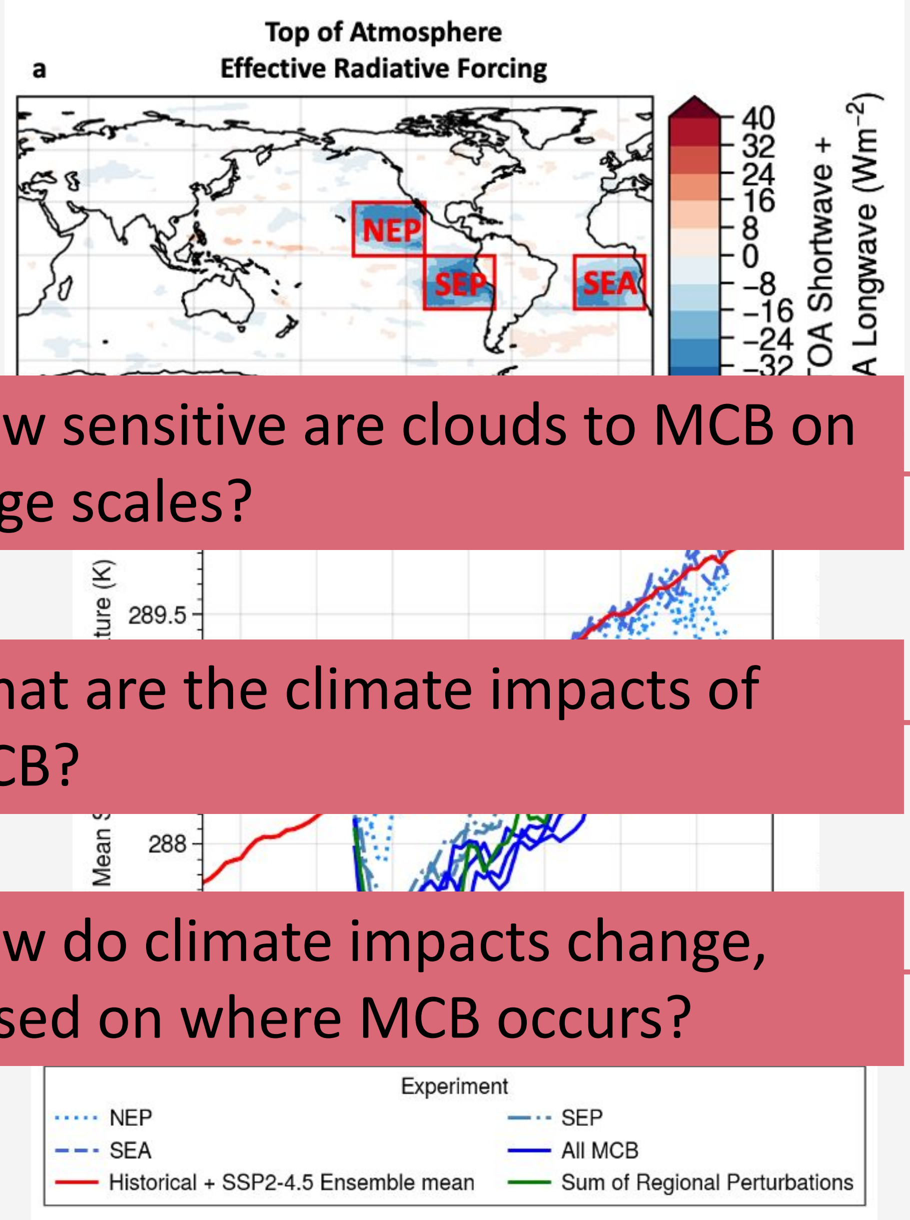
- CESM2 is substantially more sensitive to SSE and CDNC perturbations than E3SMv1
- Excessive SSE emissions reduces aerosol-cloud interaction efficacy
- Substantial role for direct aerosol forcing at high emission rates
- Difference in large-scale response, such as opposite signed effects between CESM2/E3SM in some regions



Experiments

We conduct CESM2 and E3SMv1 simulations :

1. Fixed SST simulations at a range of CDNC and SSE perturbations to find target forcing (-1.8Wm-2)
2. Apply chosen CDNC to NEP, SEP, and SEA in coupled SSP2-4.5 simulations (G4-like)
3. Apply chosen CDNC to each region individually in coupled SSP2-4.5 simulations



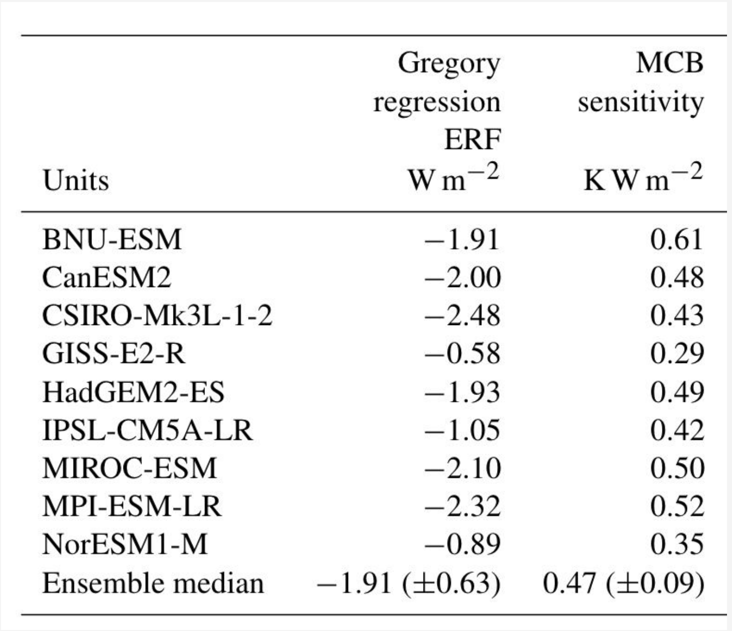
How sensitive are clouds to MCB on large scales?

What are the climate impacts of MCB?

How do climate impacts change, based on where MCB occurs?

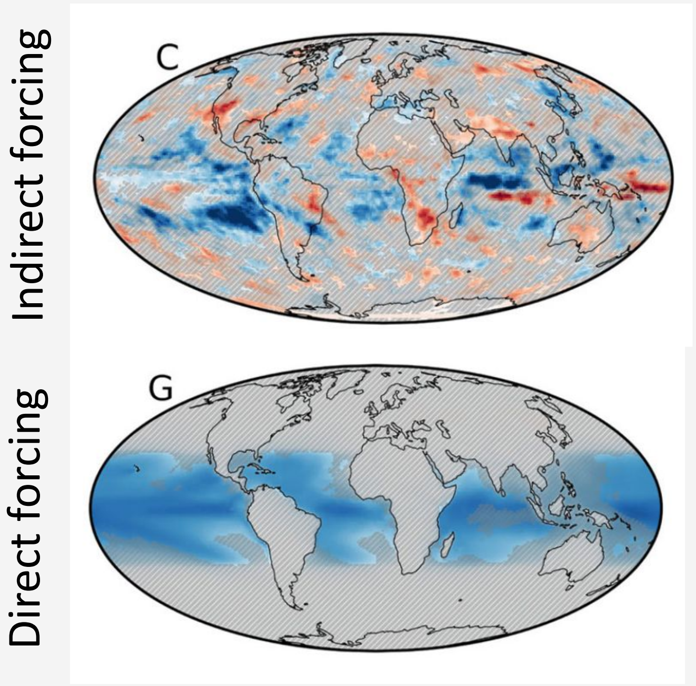
GCM uncertainty in MCB impacts

- MCB depends on aerosol-cloud interactions, which have large uncertainties across GCMs



Units	Gregory regression ERF W m^{-2}	MCB sensitivity K W m^{-2}
BNU-ESM	−1.91	0.61
CanESM2	−2.00	0.48
CSIRO-Mk3L-1-2	−2.48	0.43
GISS-E2-R	−0.58	0.29
HadGEM2-ES	−1.93	0.49
IPSL-CM5A-LR	−1.05	0.42
MIROC-ESM	−2.10	0.50
MPI-ESM-LR	−2.32	0.52
NorESM1-M	−0.89	0.35
Ensemble median	−1.91 (±0.63)	0.47 (±0.09)

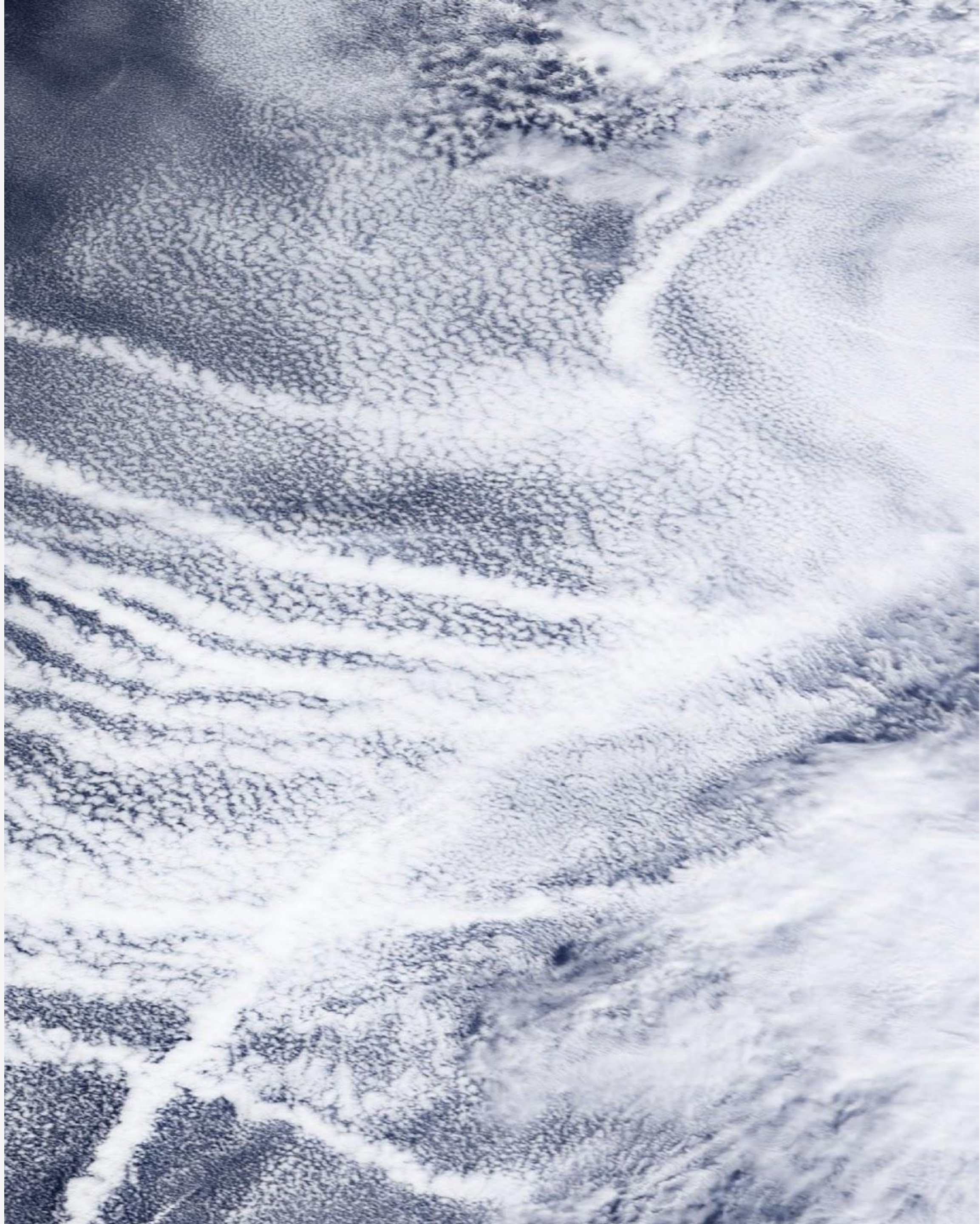
G4cdnc forcing (50% cdnc increase)
Stjern et al., 2018

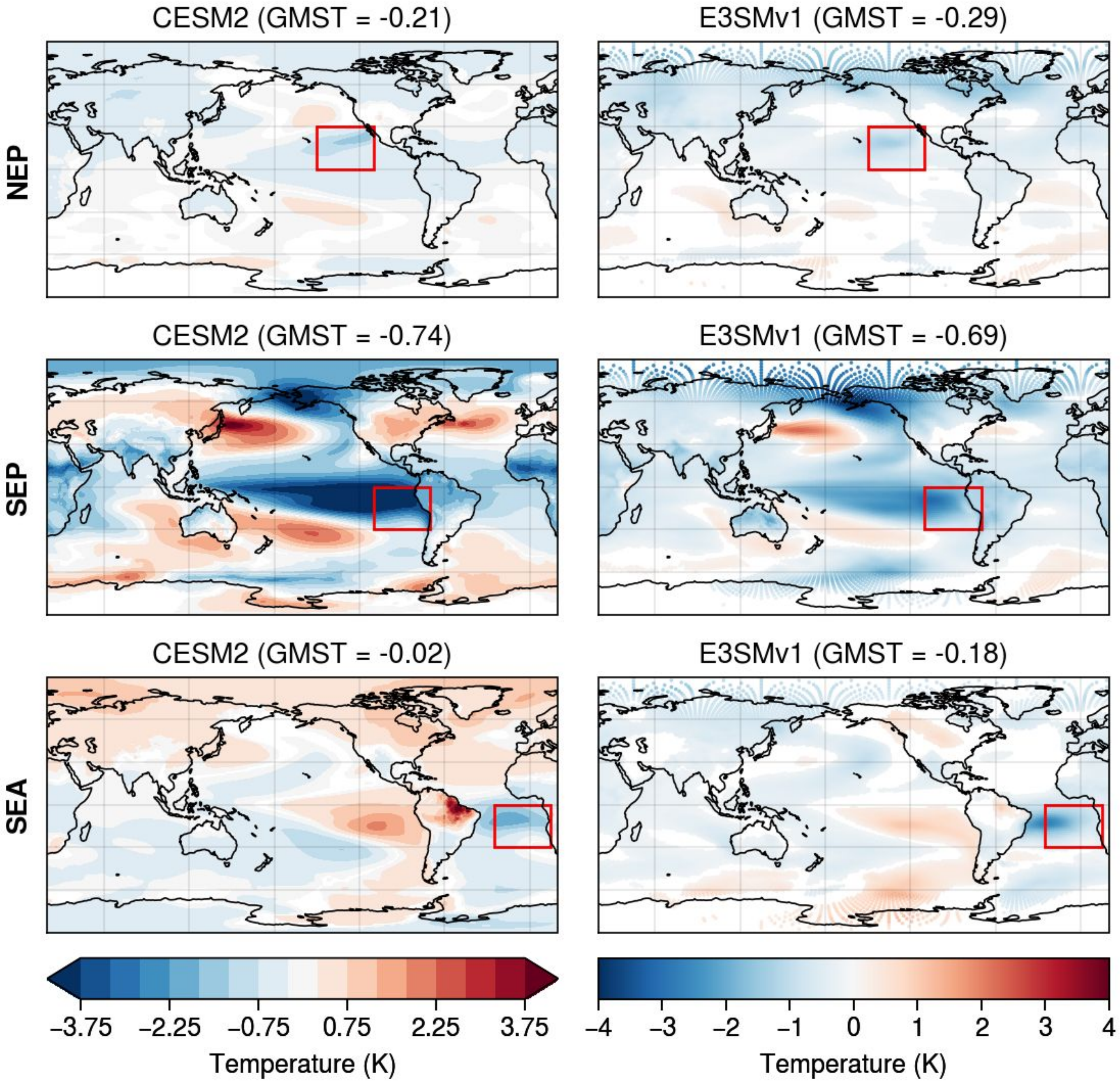


GFDL G4seasalt forcing
Mahfouz et al., 2023

What can we learn about MCB from ESMs?

- How sensitive are clouds to MCB on large scales?
- What are the climate impacts of MCB?
- How do climate impacts change, based on where MCB occurs?




CESM2 (GMST = -0.21)
E3SMv1 (GMST = -0.29)
NEP
CESM2 (GMST = -0.74)
E3SMv1 (GMST = -0.69)
SEP
CESM2 (GMST = -0.02)
E3SMv1 (GMST = -0.18)
SEA
–3.75
–2.25
–0.75
0.75
2.25
3.75
Temperature (K)
–4
–3
–2
–1
0
1
2
3
4
Temperature (K)

Cloud, forcing impacts

Cloud, forcing impacts

CDNC vs. SSE – does it change the response?

- The climate response to CDNC vs. SSE are very similar when ERFs are similar
- Modest, but statistically significant differences:
    - CDNC causes more cooling + drying within forcing regions and less outside of them

CESM2 Annual mean Temperature and Precipitation response