Cloud-based Arctic radiation management in idealized CESM simulations

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Cloud seeding as a proposed strategy for Earth radiation management

- **Warm / liquid clouds** --------→ - **Marine Cloud Brightening (MCB)**

  Mimic ship-track-induced cloud brightening by seeding aerosols into marine low clouds to increase cloud droplet number and thus cloud albedo (Twomey effect) (e.g., Latham, 1990, 2002)

- **Cold / ice clouds** --------→ - **Cirrus Cloud Thinning (CCT)**

  Reduce the heat-trapping efficiency by seeding INPs into high-level cirrus to stimulate early ice nucleation and thus cloud thinning (e.g., Mitchell & Finnegan, 2009)

- **Mixed-phase clouds** --------→ - **Mixed-phase Cloud Thinning (MCT)**

  Reduce the heat-trapping efficiency by seeding INPs into mixed-phase clouds to enhance glaciation and thus cloud thinning (e.g., Villanueva et al., 2023)

Arctic radiation management via cloud seeding

shortwave-focused (summer)

MCB, CCT

longwave-focused (winter)

MCT, CCT

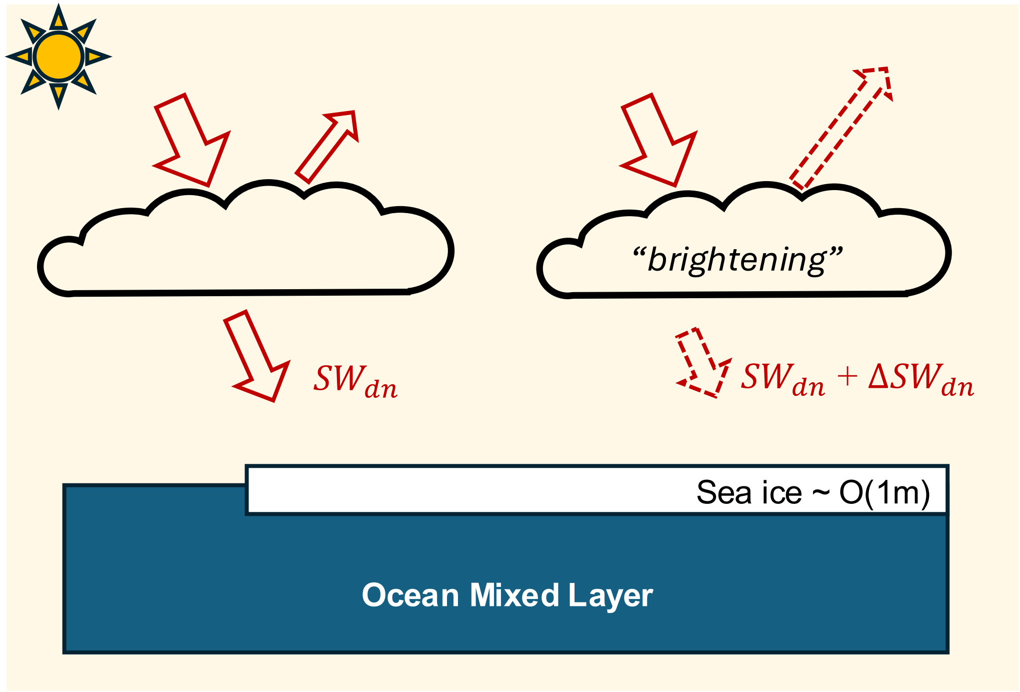
How do these two contrasting cloud-based strategies (MCB vs. MCT) compare in stabilizing sea ice and mitigating Arctic amplification?

A simplified representation of “cloud seeding” effects in CESM

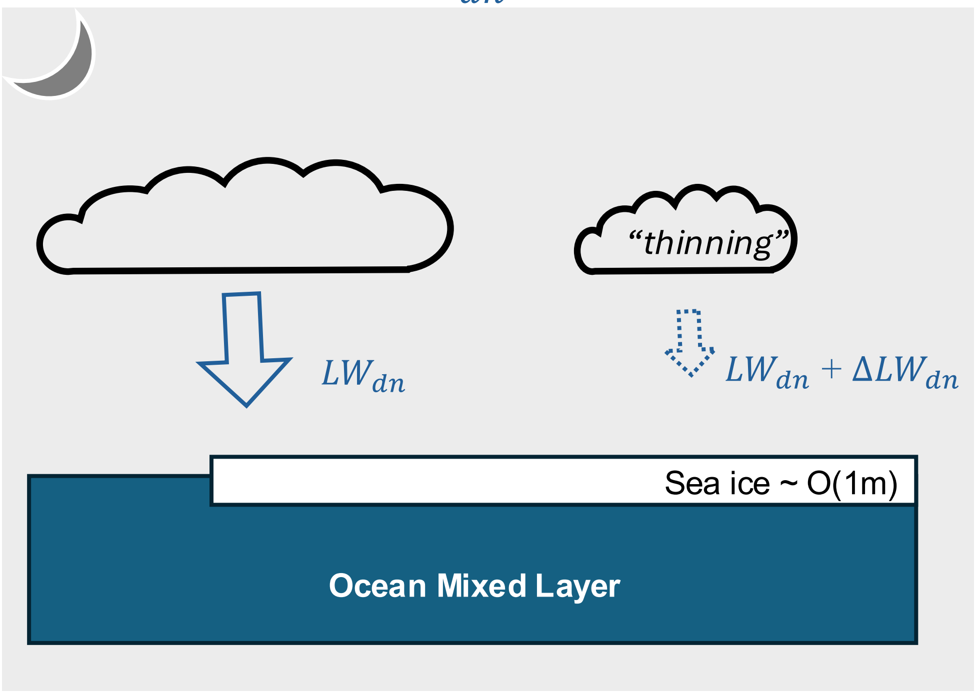
$$\frac{dT}{dt} \propto F_{net} = SHF + LHF + (1 - \alpha_s)\, SW_{dn} + LW_{dn} - LW_{up} + F_q \text{ (over ocean)}$$

$$\frac{dT}{dt} \propto F_{net} = SHF + LHF + (1 - \alpha_s)\, SW_{dn} + LW_{dn} - LW_{up} + F_{cond} \text{ (over sea ice, no melting, top model layer of the sea ice)}$$

MCB: $\Delta SW_{dn} = -10\ \text{W m}^{-2}$

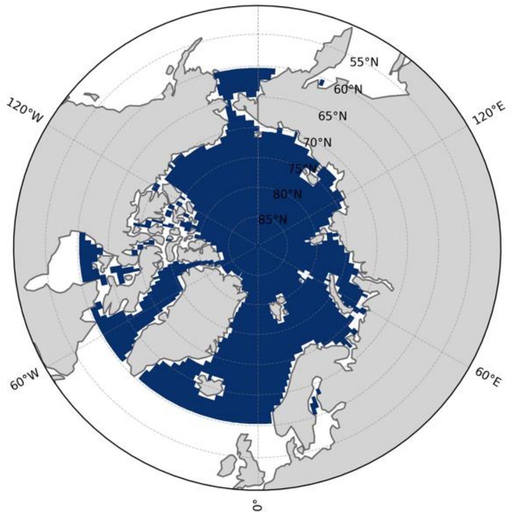


MCT: $\Delta LW_{dn} = -10\ \text{W m}^{-2}$



CESM experiments with idealized surface downwelling radiative forcing (surface ghost flux)

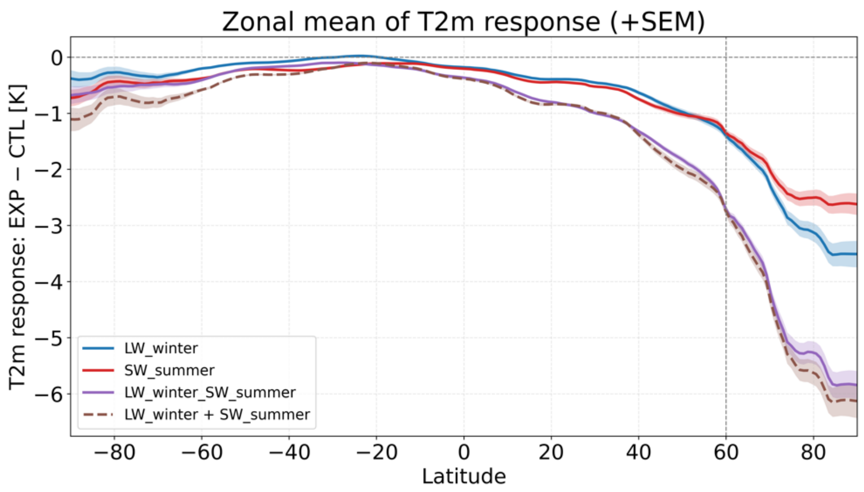
EXP	Forcing magnitude & time-window	Real-world analogy	Forcing domain
CTL	No forcing CESM2 with SOM		
EXP1: **LW_winter**	winter = Nov–Feb lw_dn_sfc = –10 W m^{-2}	MCT	North of 60N (non-land)
EXP2: **SW_summer**	summer = May–Aug sw_dn_sfc = –10 W m^{-2} (Direct UV = –4 W m^{-2}) (Direct IR = –6 W m^{-2})	MCB	North of 60N (non-land)
EXP3: **LW_winter_SW_summer**	lw_dn_sfc = –10 W m^{-2} (Nov-Feb) + sw_dn_sfc = –10 W m^{-2} (May-Aug)	MCT + MCB	North of 60N (non-land)

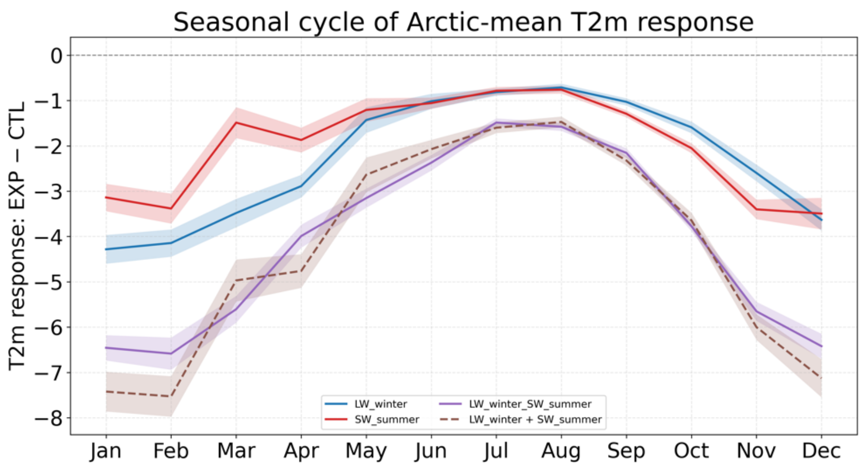


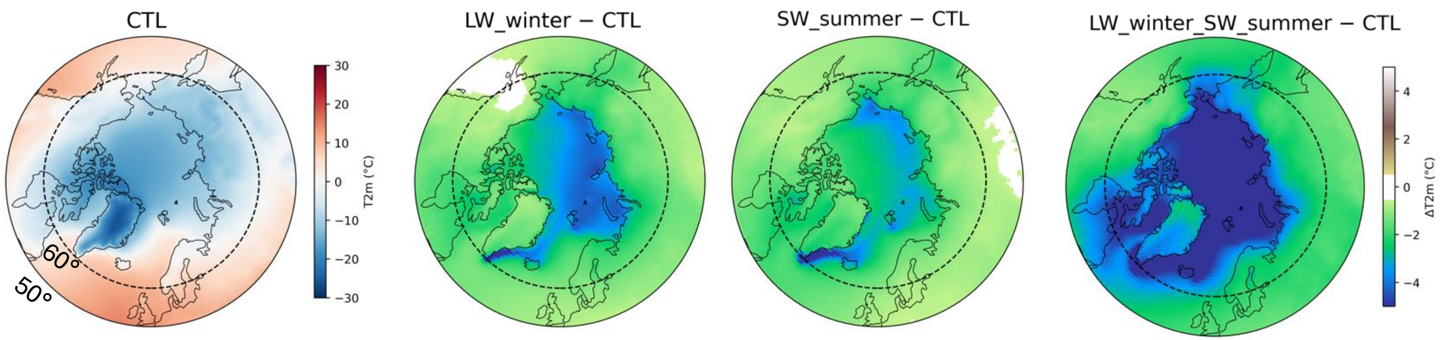
CESM2 coupled to a slab ocean and an interactive sea ice model

All experiments were run for 60 years, and the outputs from the final 30 years (equilibrium) were used for analysis

Amplified Arctic temperature response with the strongest cooling in winter

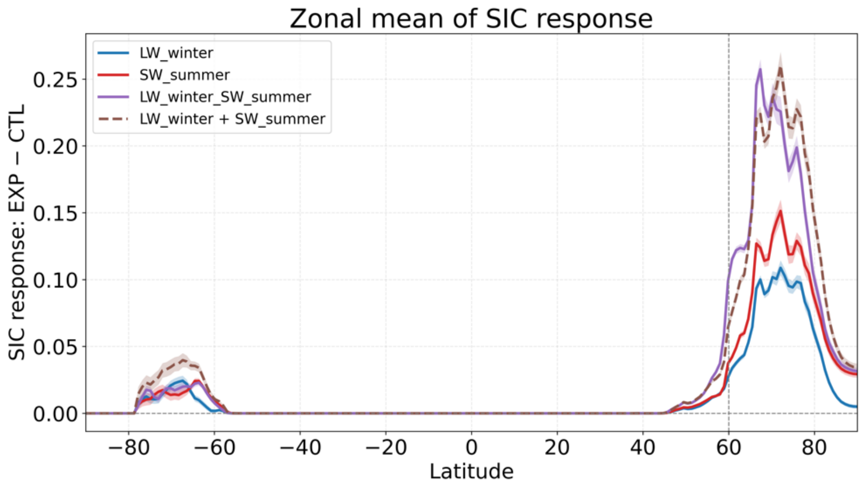


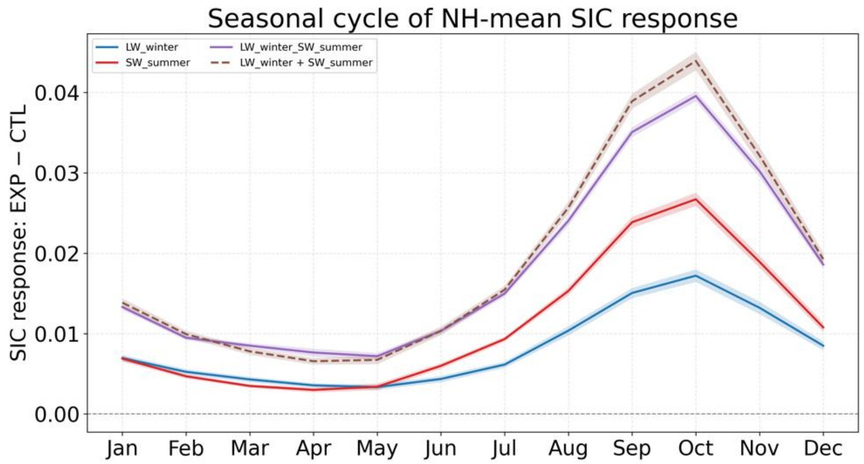


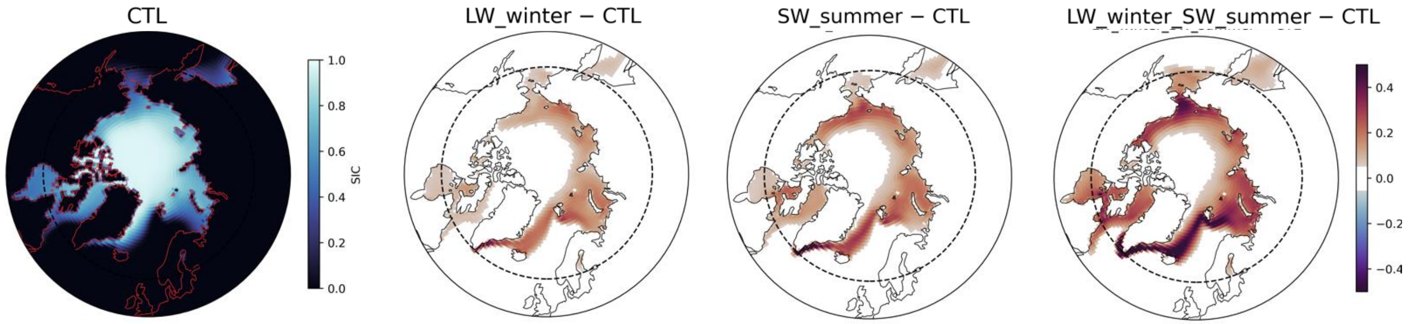


- T2m response from *LW_winter* is slightly stronger than from *SW_summer*, especially in wintertime Arctic
- Seasonal cycle of T2m response is independent from the applied forcing type and season
- T2m response is roughly linear (combined ≅ sum of individual response)

Arctic-confined SIC response with the strongest sea ice restoration in fall

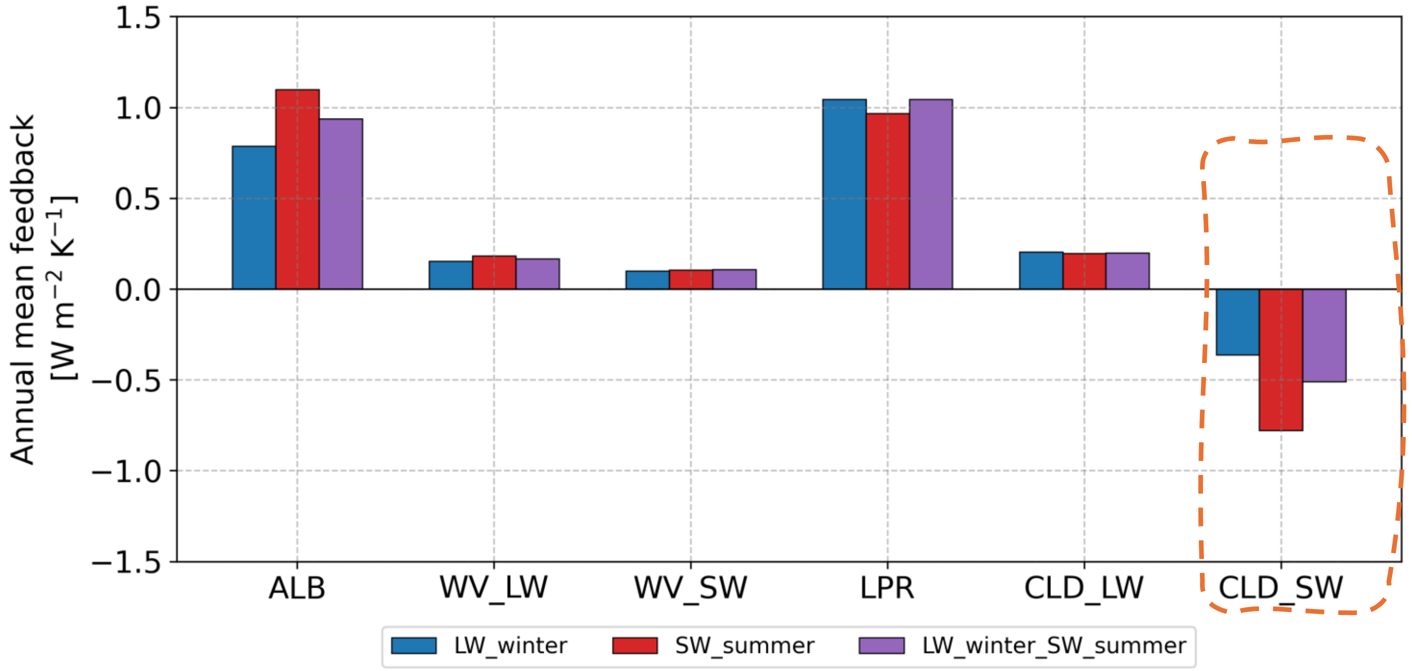






- *SW_summer* leads to slightly more sea ice restoration than *LW_winter,* especially in summertime Arctic
- Similar to T2m response, the seasonal cycle of SIC response is independent from the applied forcing type and season
- Different from T2m response, SIC response peaks in fall

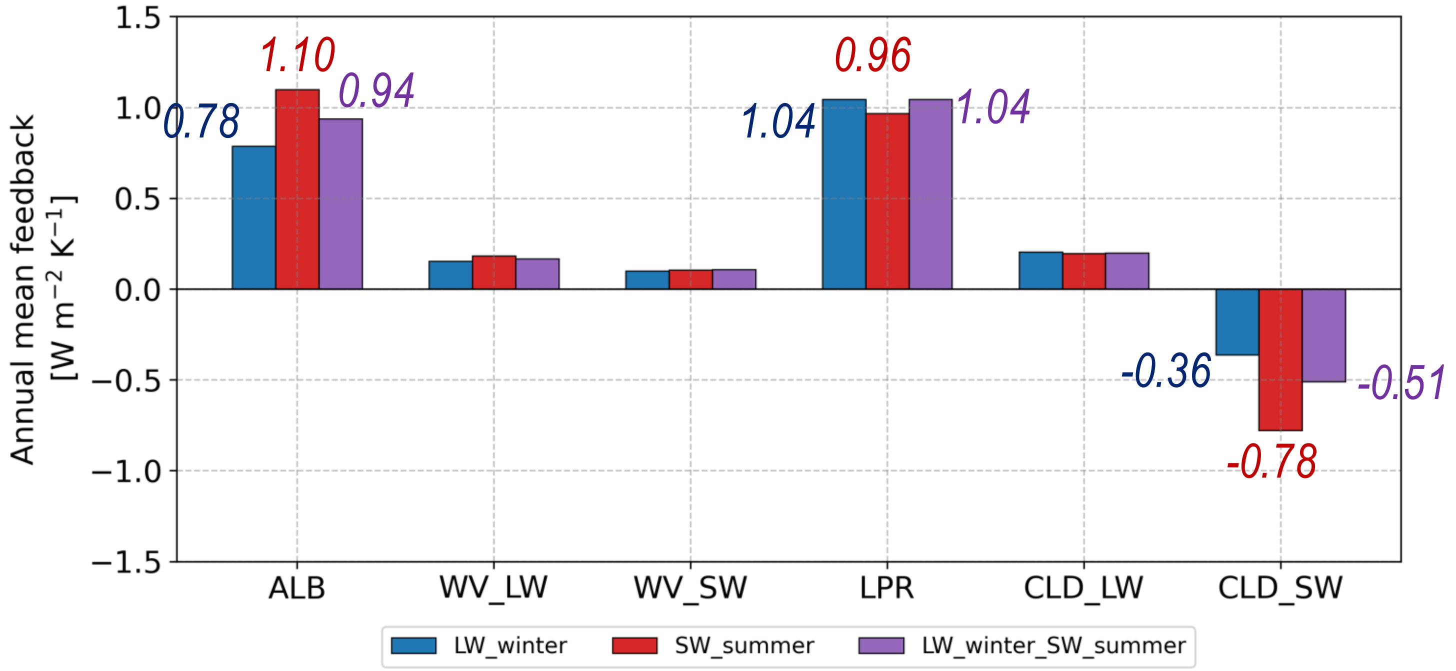
Albedo and lapse rate feedbacks jointly amplify the system cooling, while cloud shortwave feedback partially offsets the cooling



w/o Planck

- **Sea ice recovery–induced** albedo feedback accounts for ~half of the total positive feedback
- **Enhanced surface inversion–induced** lapse-rate feedback contributes the remaining half
- **Cloud shortwave feedback** becomes negative, primarily due **cloud thinning**, thereby damping the system cooling

Albedo and lapse rate feedbacks jointly amplify the system cooling, while cloud shortwave feedback partially offsets the cooling

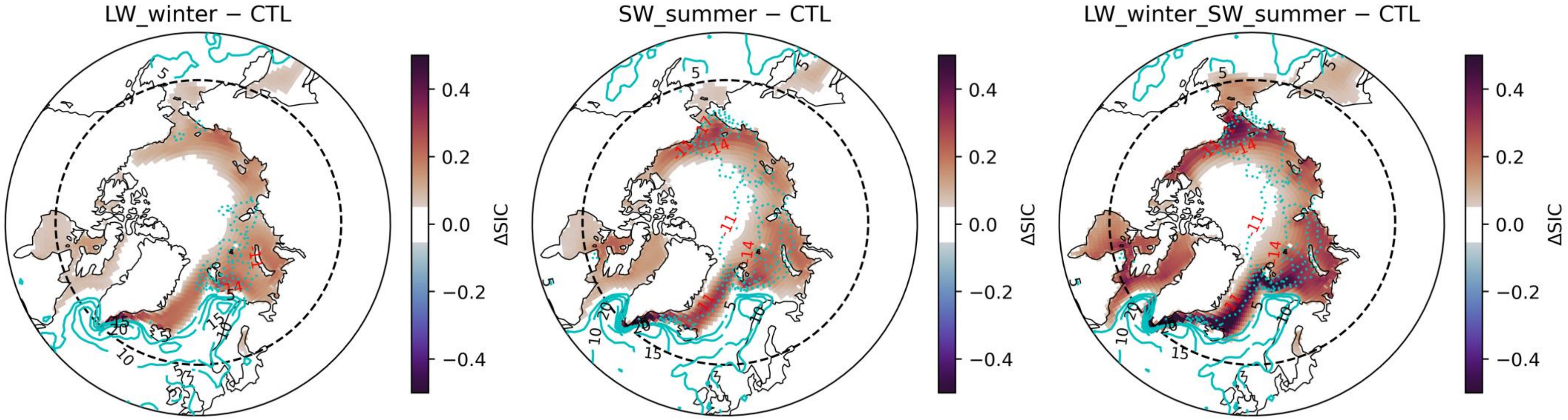


w/o Planck

Arctic domain mean feedbacks	all	positive	negative
LW_winter	+1.923	+2.287	-0.364
SW_summer	+1.770.	+2.549	-0.779
LW_winter_SW_summer	+1.942	+2.453	-0.511

Doubled shortwave cloud feedback in SW_summer compared to LW_winter

Cloud fraction has limited response, yet cloud liquid water path decreases and is spatially co-located with sea ice response



Cyan contour: LWP change
Shadding: SIC change

- Up to 20 g m^{-2} reduction in LWP is found over the sea ice recovery region in the *SW_summer* case

Cooling suppresses the hydrological cycle, leading to cloud thinning

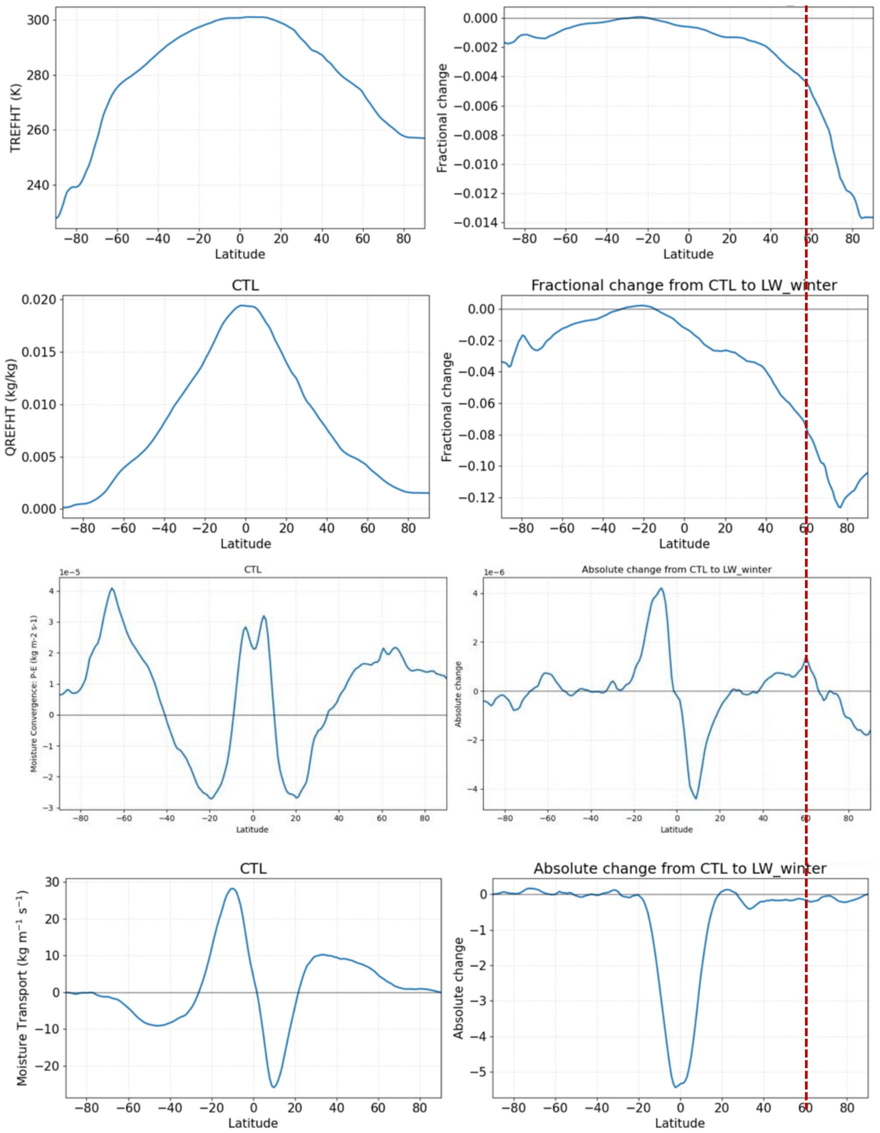
Near-surface Temperature

Near-surface specific humidity

P – E: Moisture convergence

Meridional moisture transport

CTL | **EXP – CTL**



Arctic (>60N)

Cooling ↓

Less moisture-holding capacity ↓

Less surface evaporation and much less precipitation ↓

Less moisture transport ↓

Key message

- Idealized simulations indicate that winter LW-focused radiation management produces slightly stronger Arctic cooling but slightly weaker sea ice recovery than summer SW-focused radiation management under equivalent surface downwelling perturbation

- The cooling difference arises from (1) partial reflection of downwelling SW forcing by sea ice, which reduces the effective forcing, and (2) the emergence of a negative SW cloud feedback, driven by a weakened hydrological cycle and cloud thinning, which partially offsets the cooling

- The identified negative SW cloud feedback suggests a potential hidden pathway that may have implications for Arctic radiation management strategies, including MCB and MCT