Understanding seasonal asymmetry in Arctic climate change

Lily Hahn, Polar Amplification Workshop, January 17, 2024

Kyle Armour, David Battisti, Cecilia Bitz, Aaron Donohoe,
Ian Eisenman, Robert Fajber, Mark Zelinka

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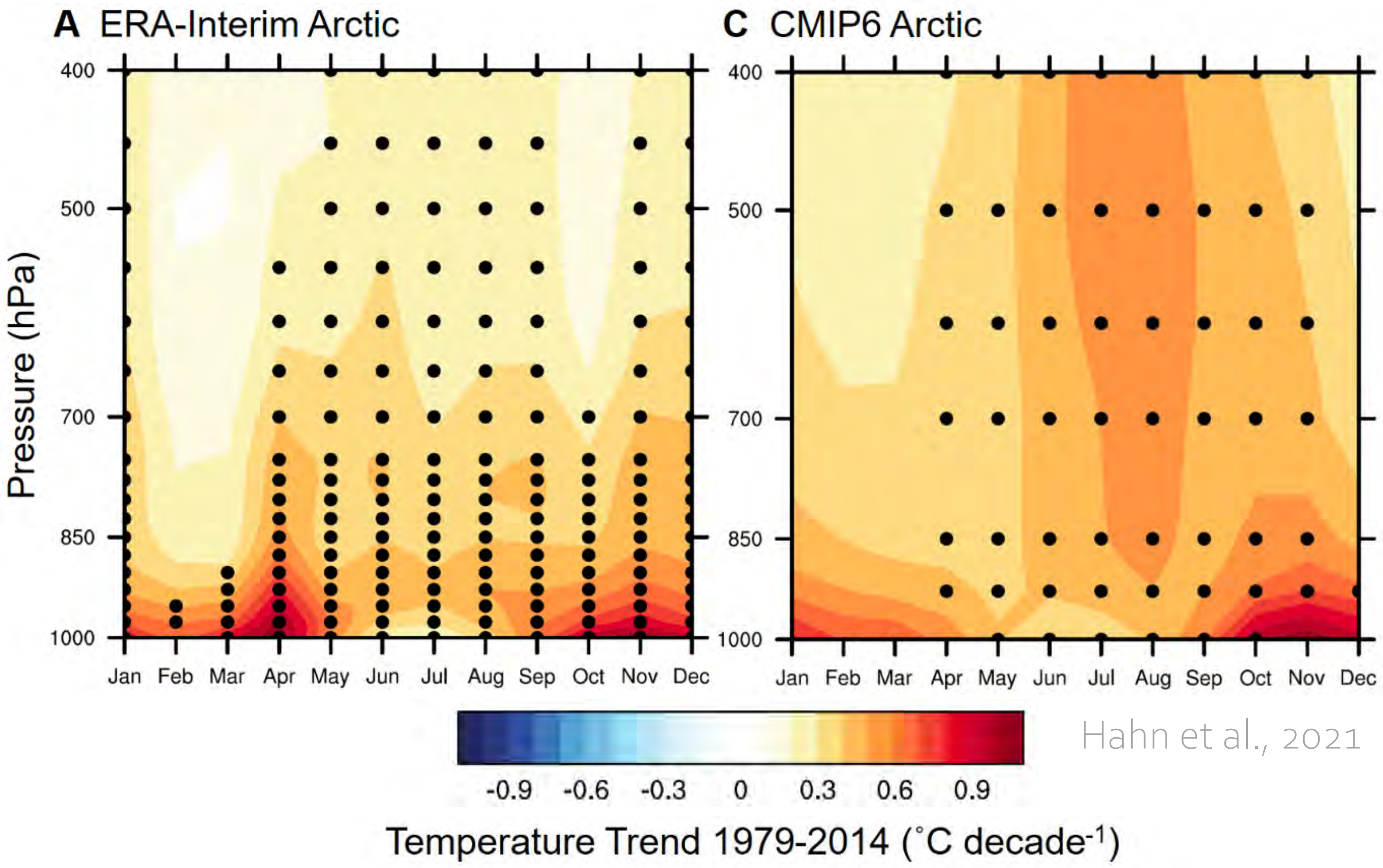
Photo: Vince Cooper, UW

Seasonal pattern of Arctic warming



Hahn et al., 2021

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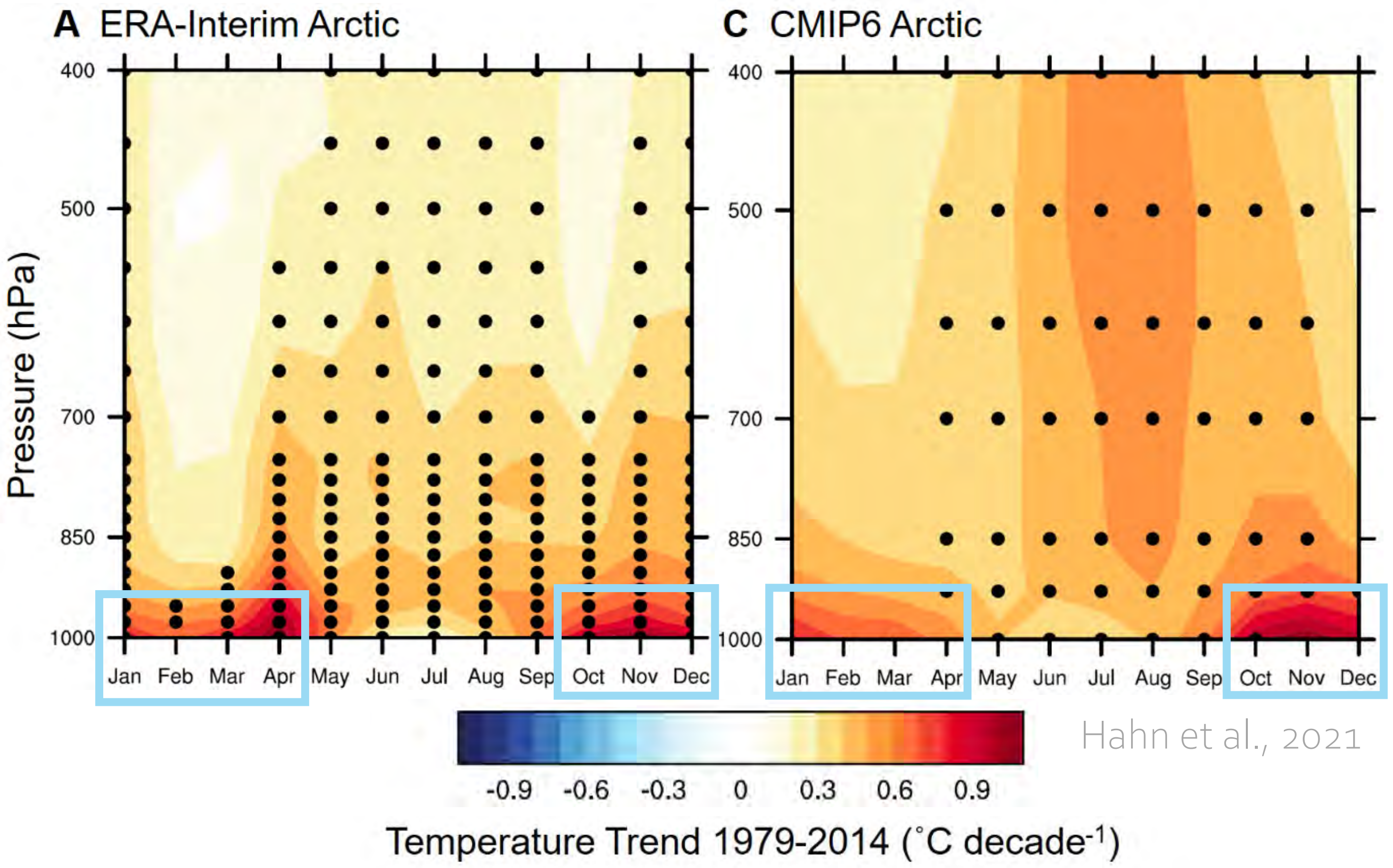
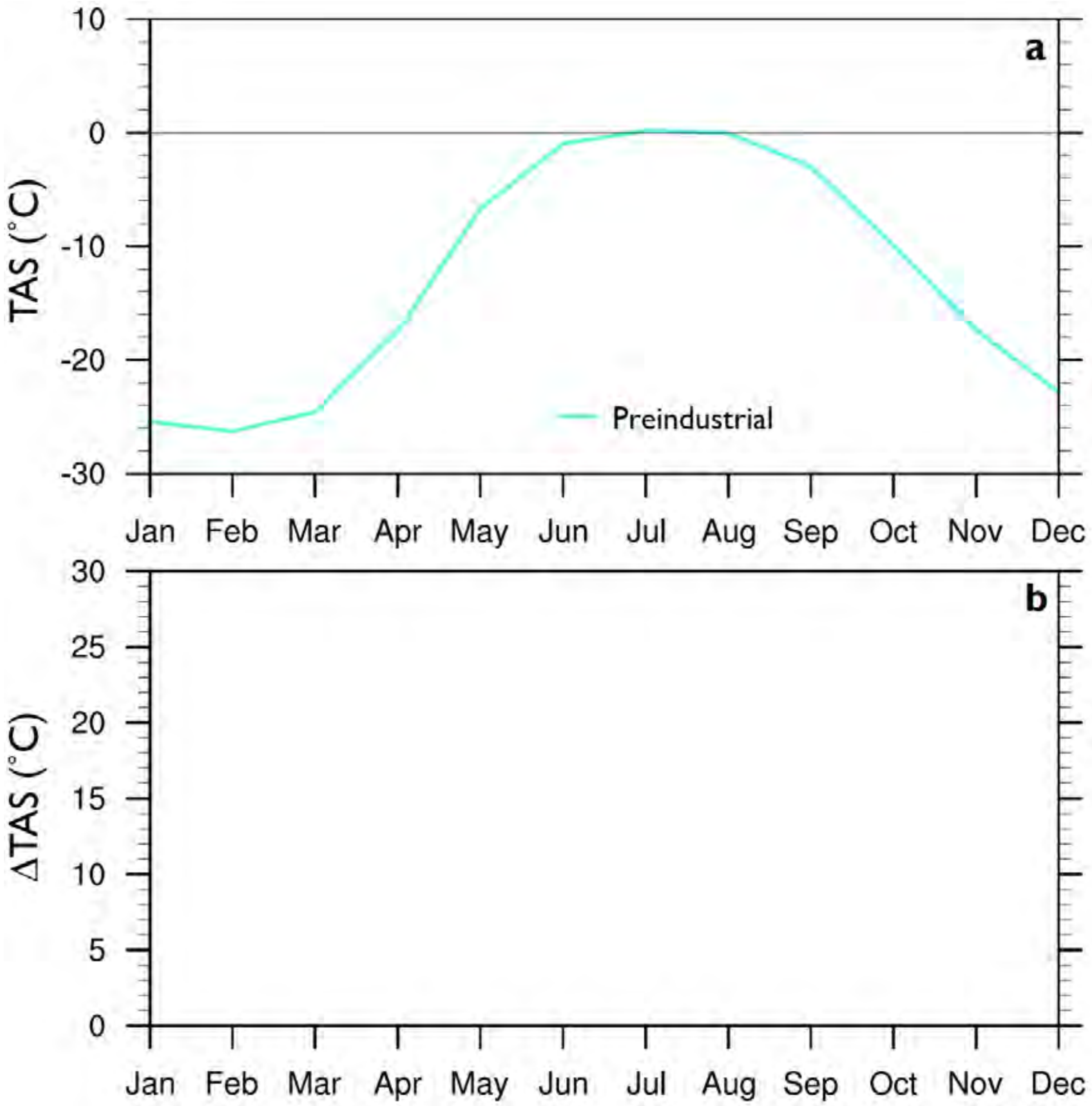


Hahn et al., 2021

1. What drives this winter peak in warming?
2. How is Arctic warming impacted by atmospheric heating in different seasons?

Key features of the seasonal warming pattern



Near-surface temperature over non-land surfaces for 70-90°N in CESM2 1pctCO2-4xext compared to a preindustrial control experiment

Hahn et al., 2022

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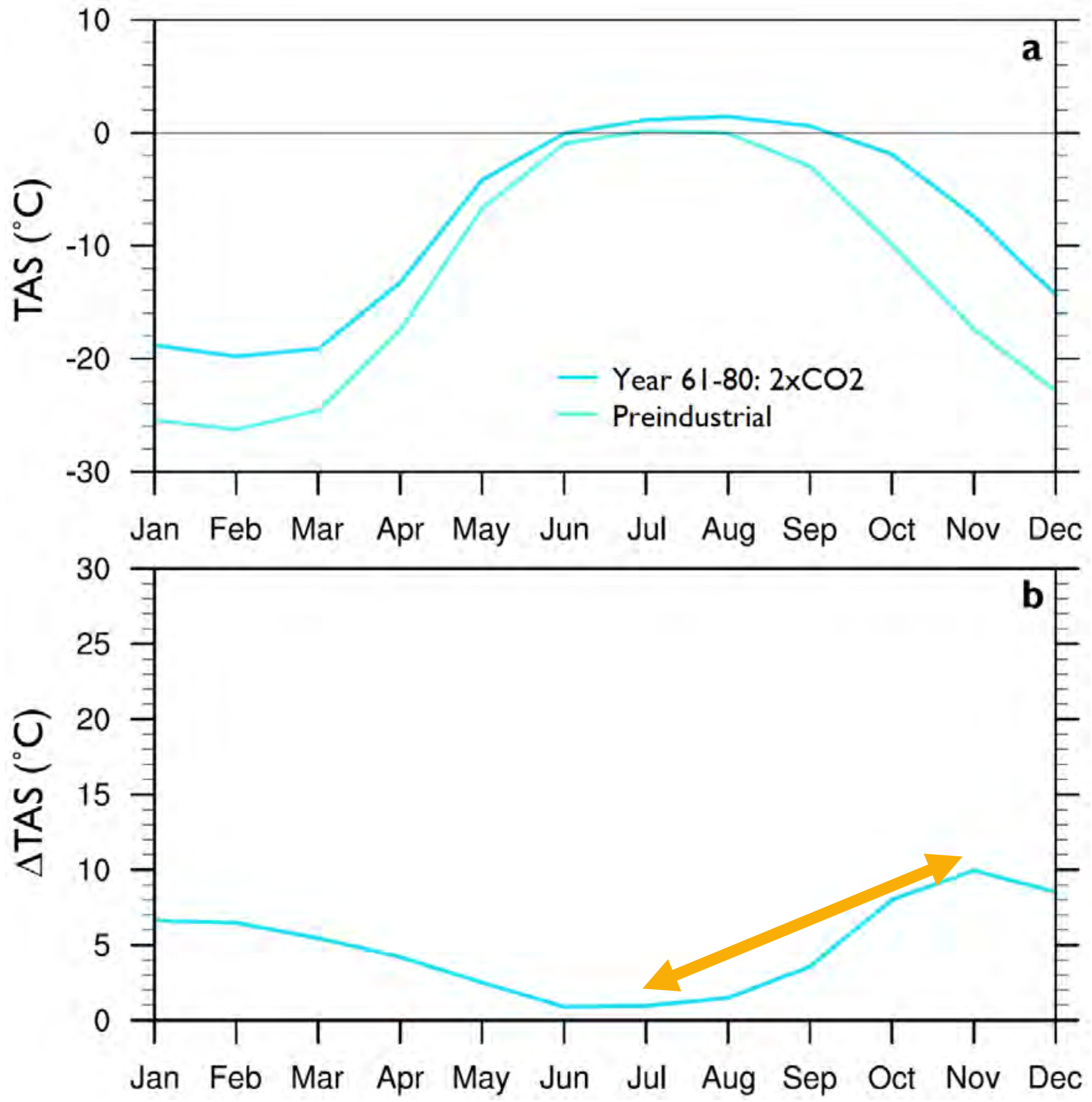

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Stronger warming in winter than summer

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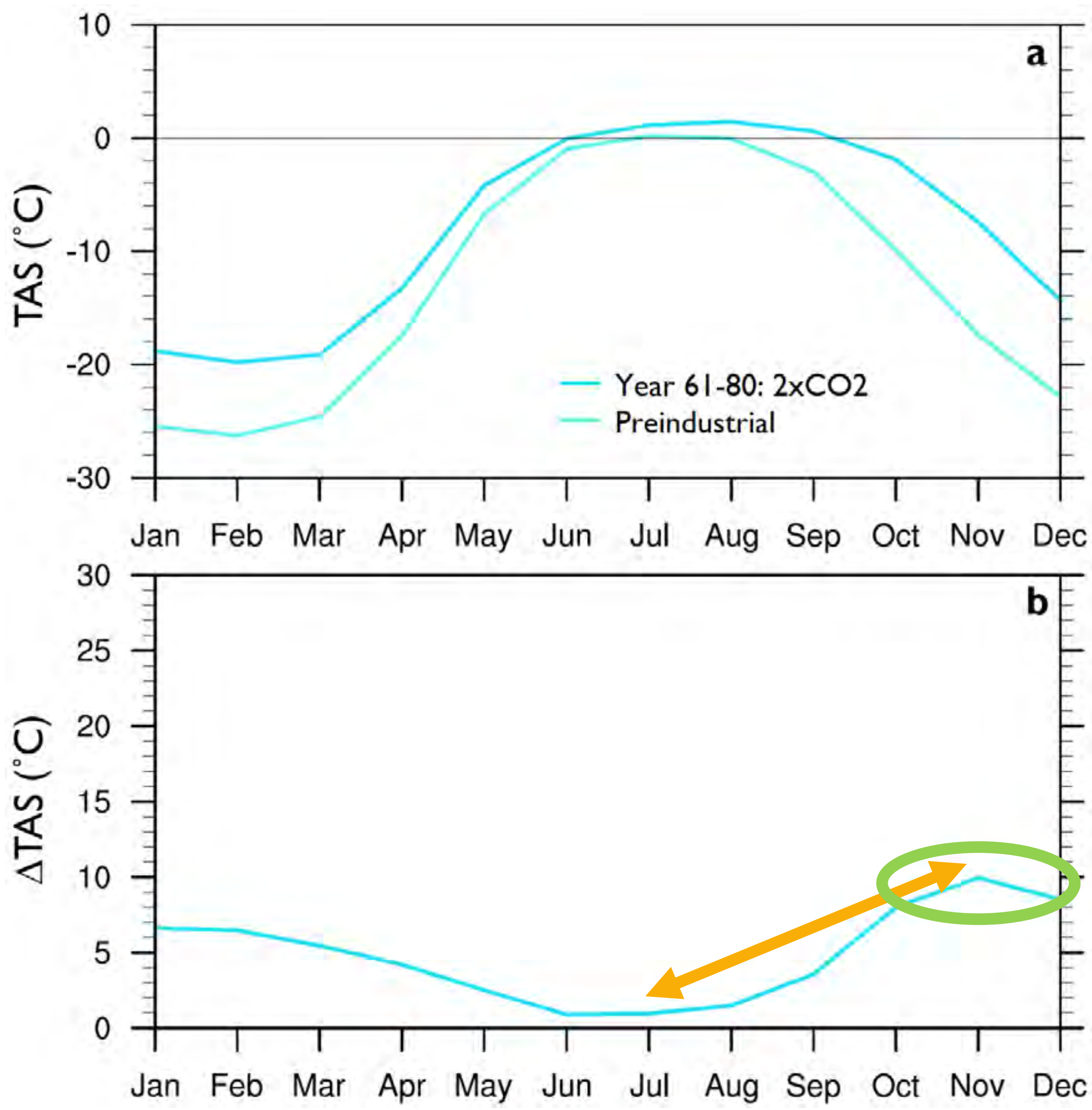

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Stronger warming in winter than summer

Peak warming in early winter

Hahn et al., 2022

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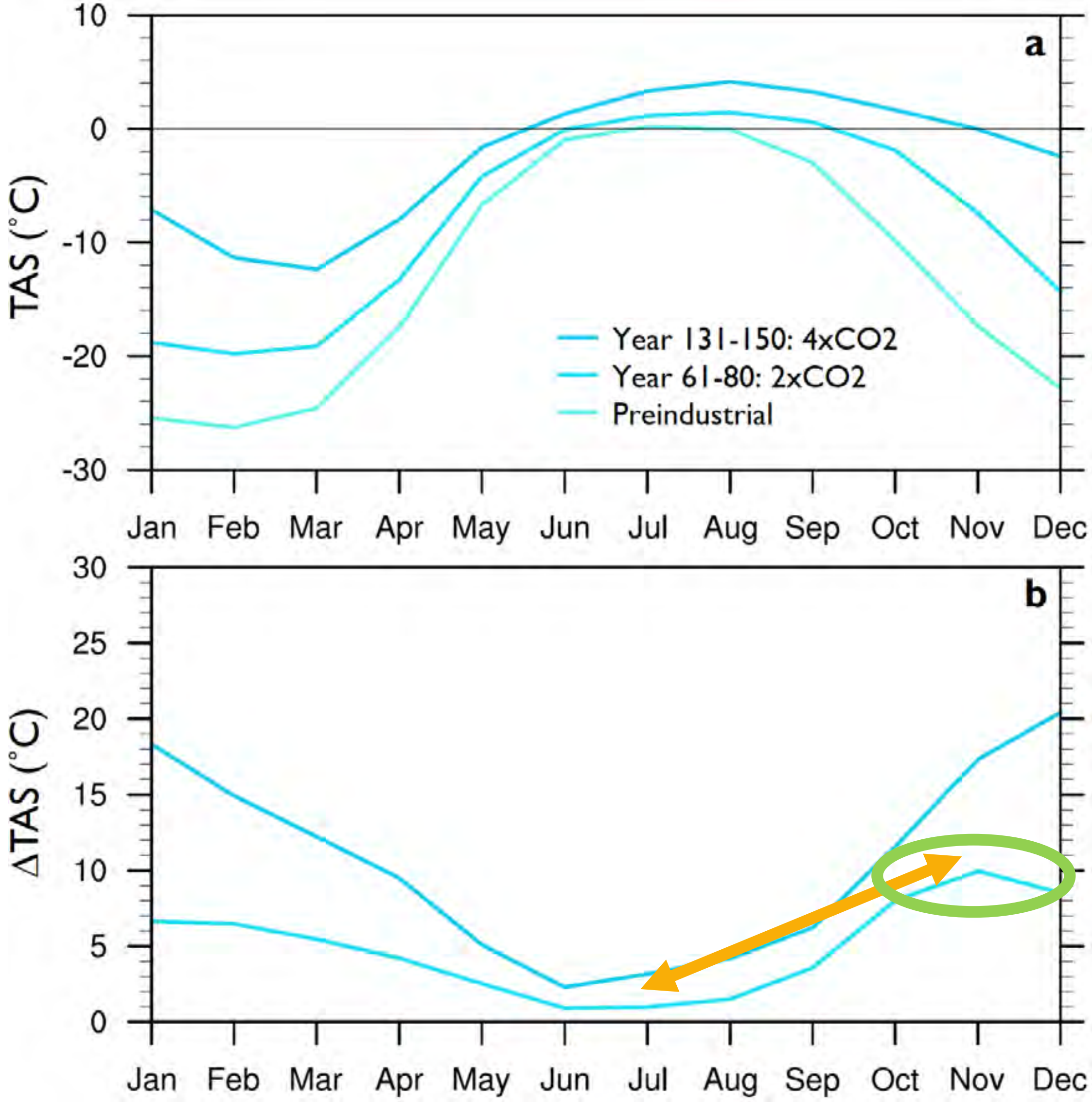

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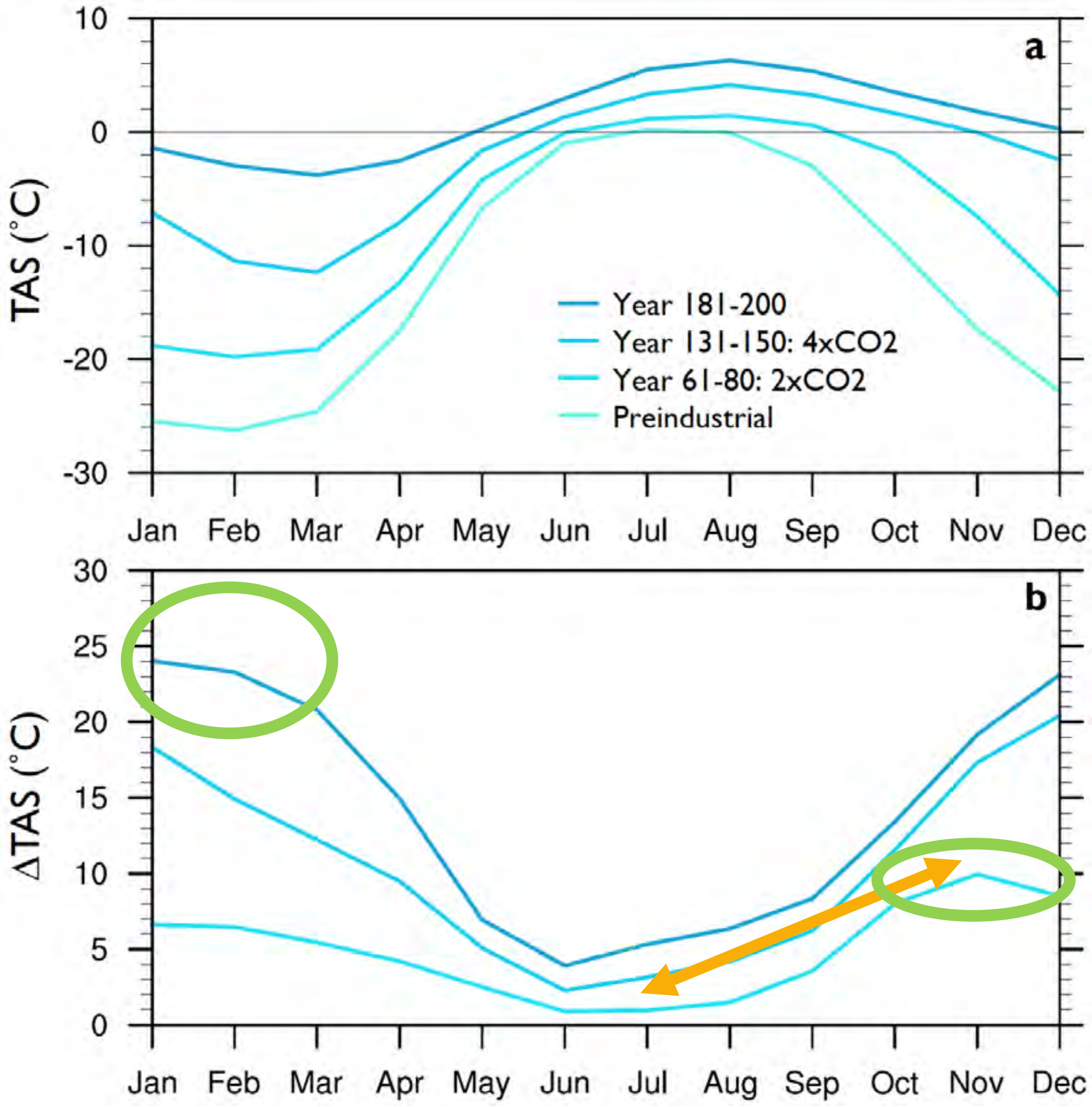

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Peak warming in early winter shifting to late winter with greater warming

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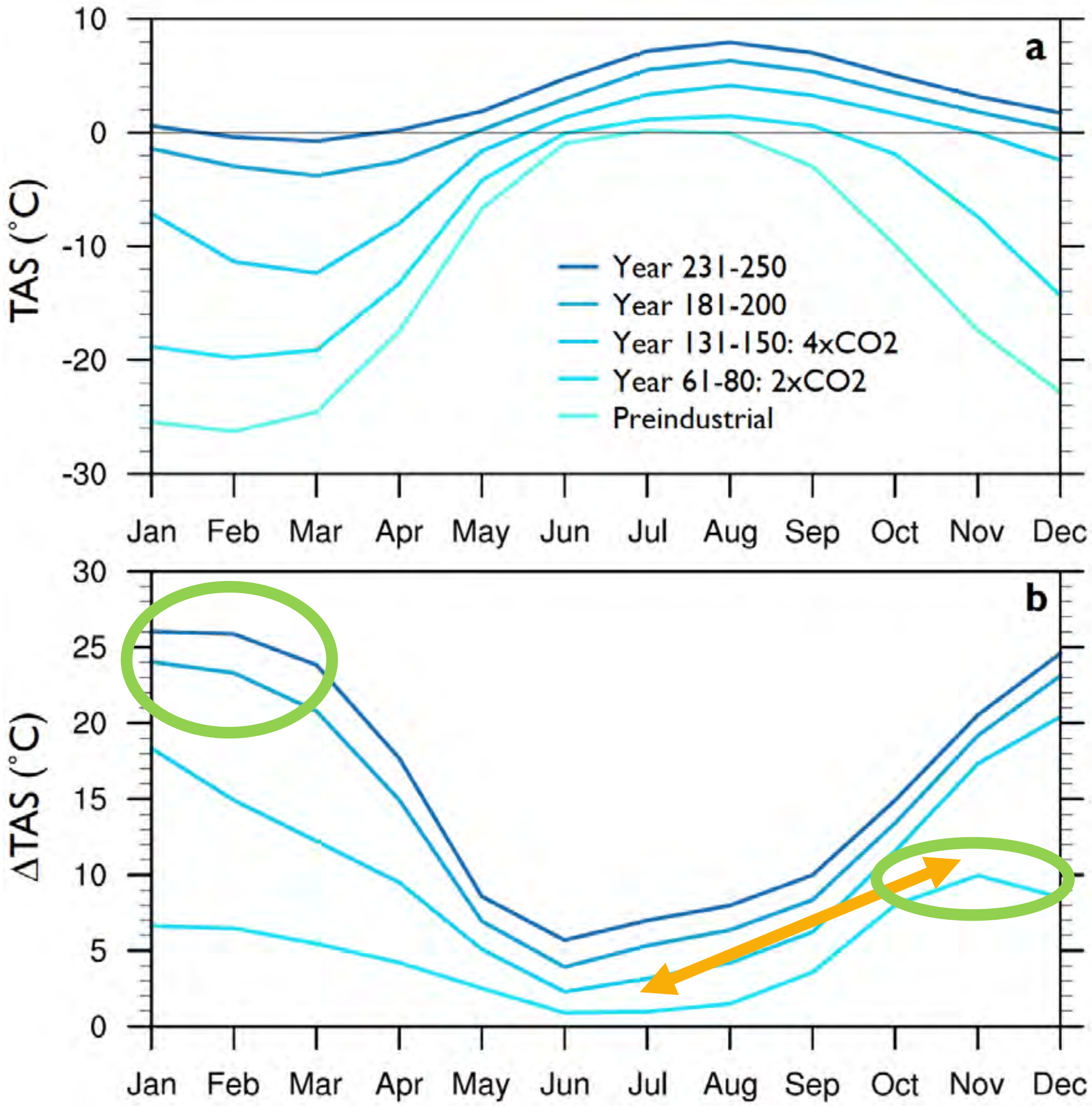

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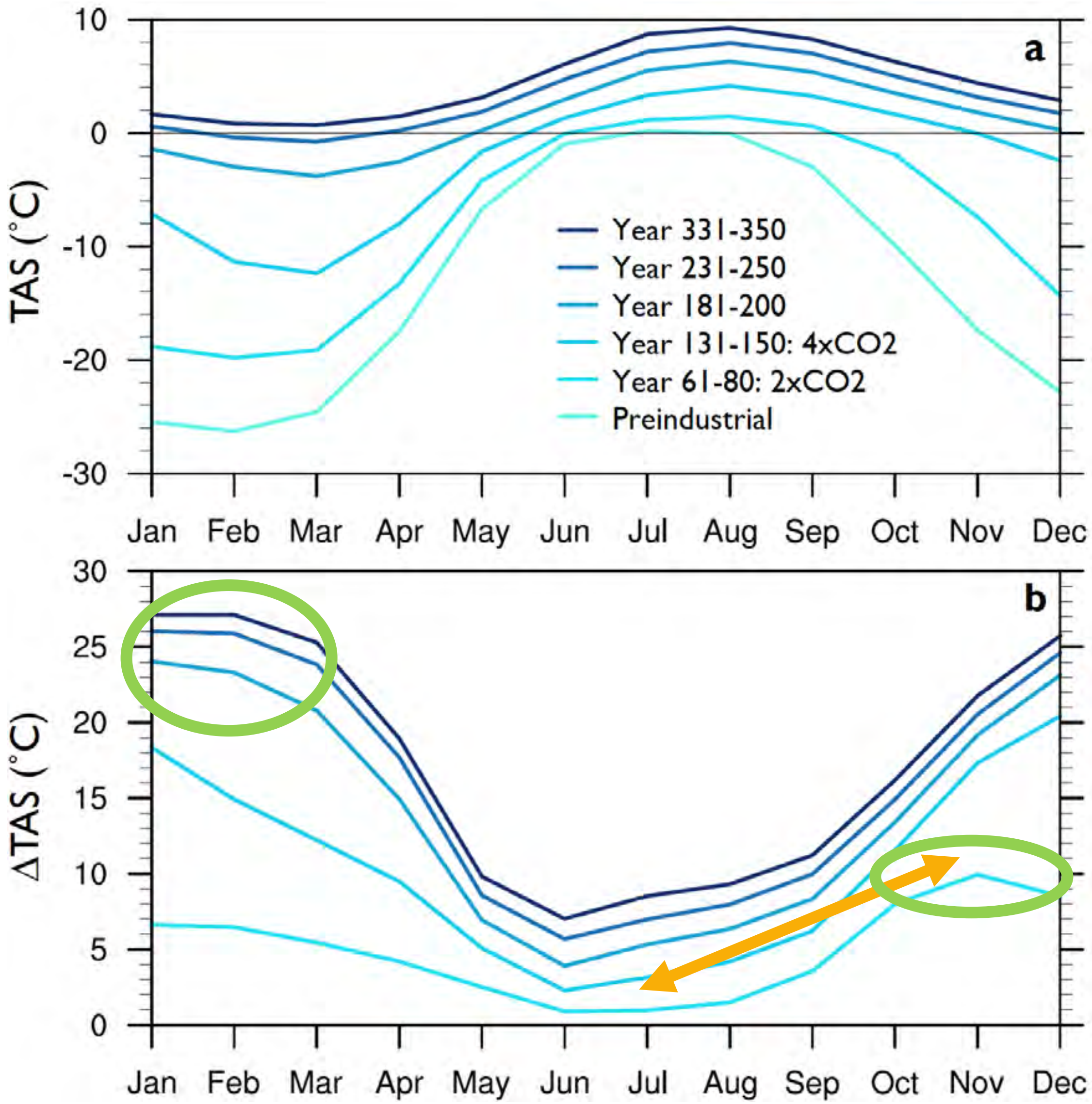

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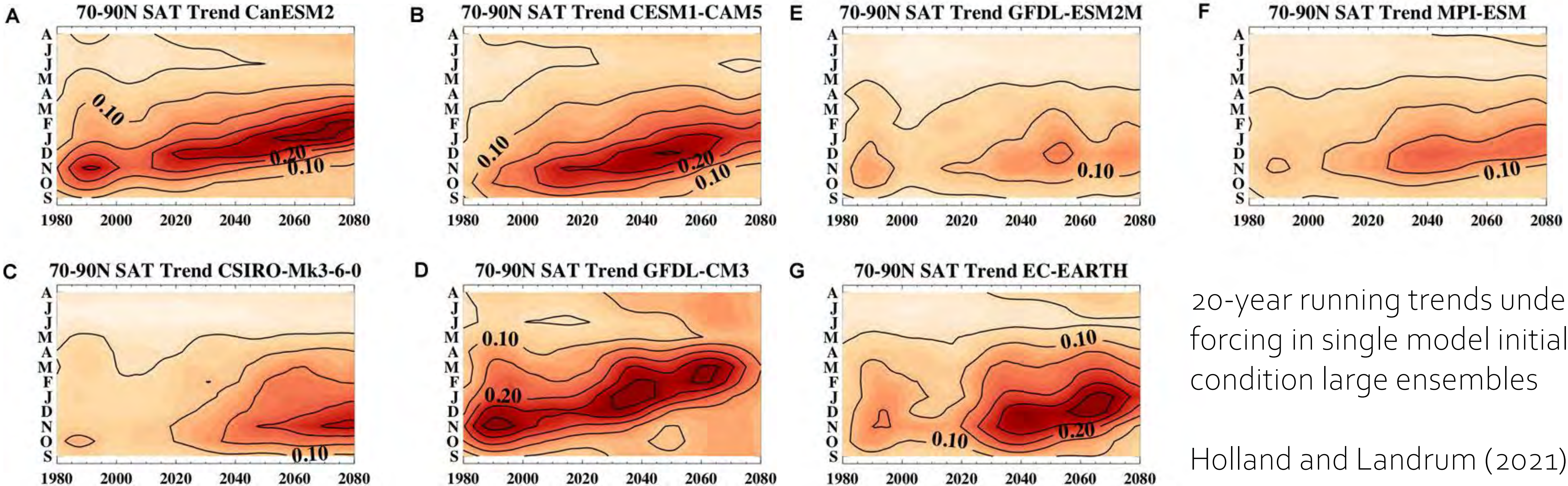
Hahn et al., 2022

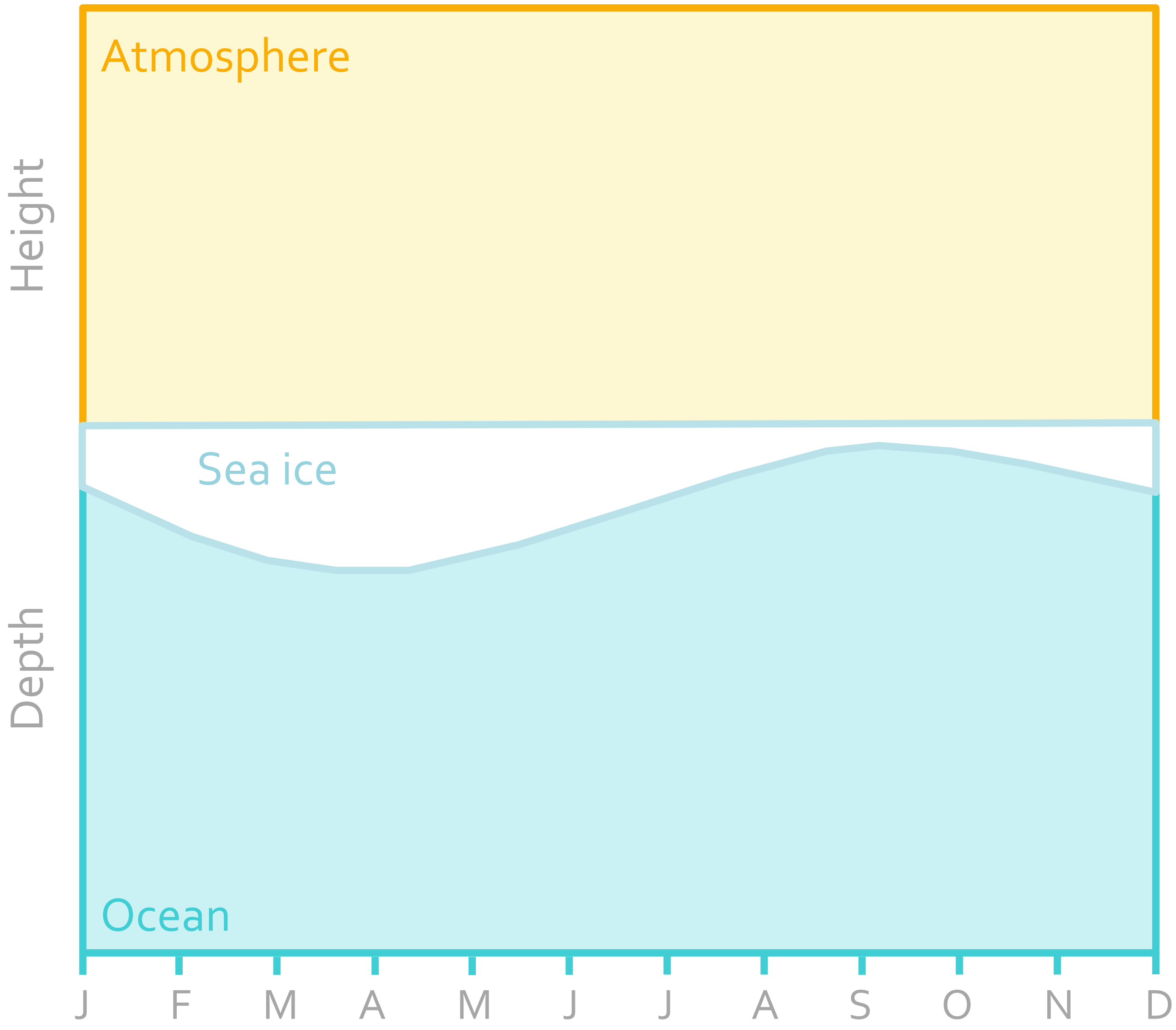
Seasonal migration of peak warming with increased forcing



20-year running trends under RCP8.5 forcing in single model initial-condition large ensembles

Holland and Landrum (2021),
Liang et al. (2022), Wu et al. (2023)

What drives seasonality in Arctic warming?



- Seasonal ocean heat storage

Dai et al., 2019; Deser et al., 2010; Dwyer et al., 2012; Henry and Vallis, 2021; Manabe and Stouffer, 1980; Pithan and Mauritsen, 2014; Robock, 1983; Screen and Simmonds, 2010; Yoshimori et al., 2014

Schematic adapted from Chung et al., 2020

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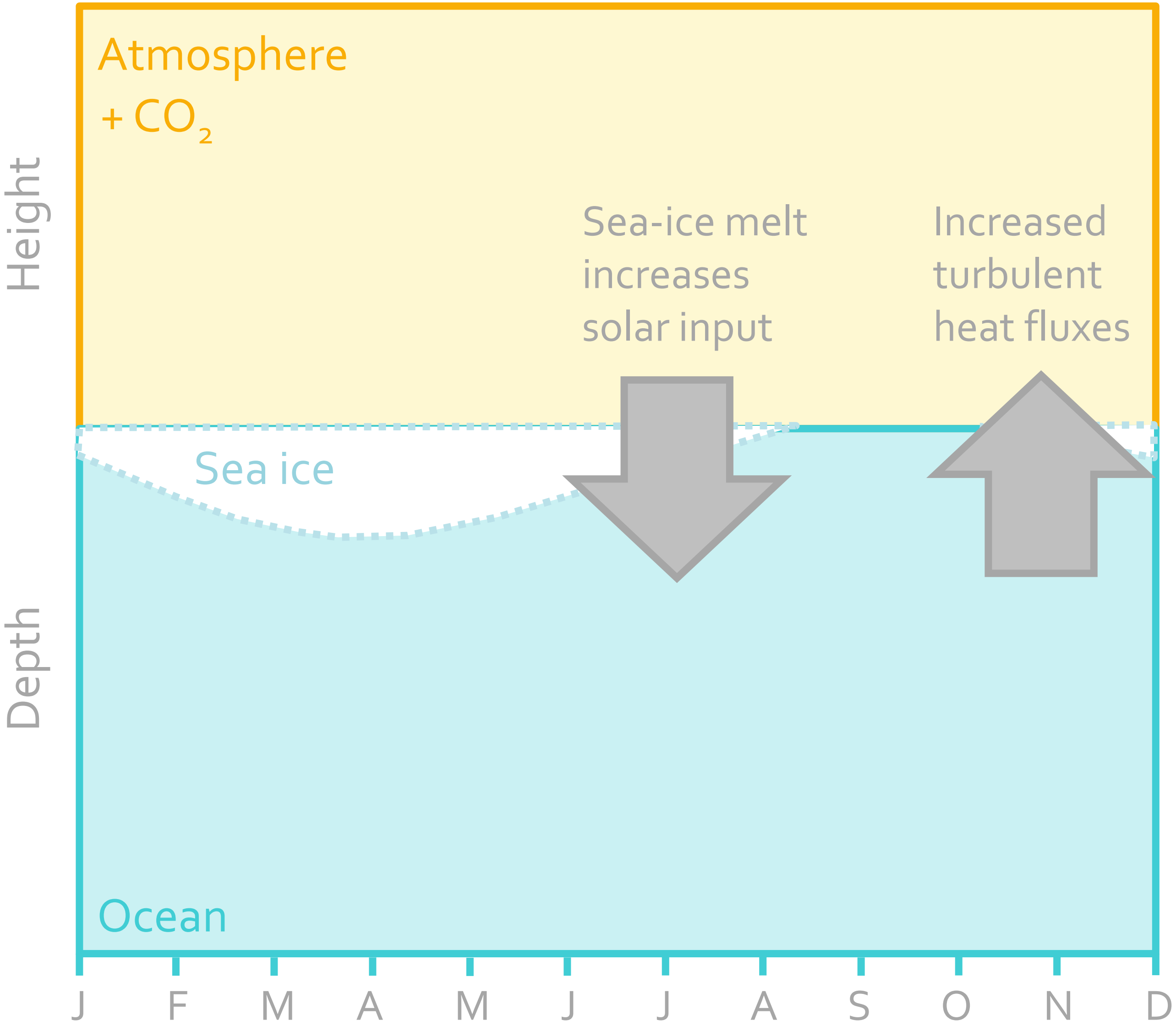

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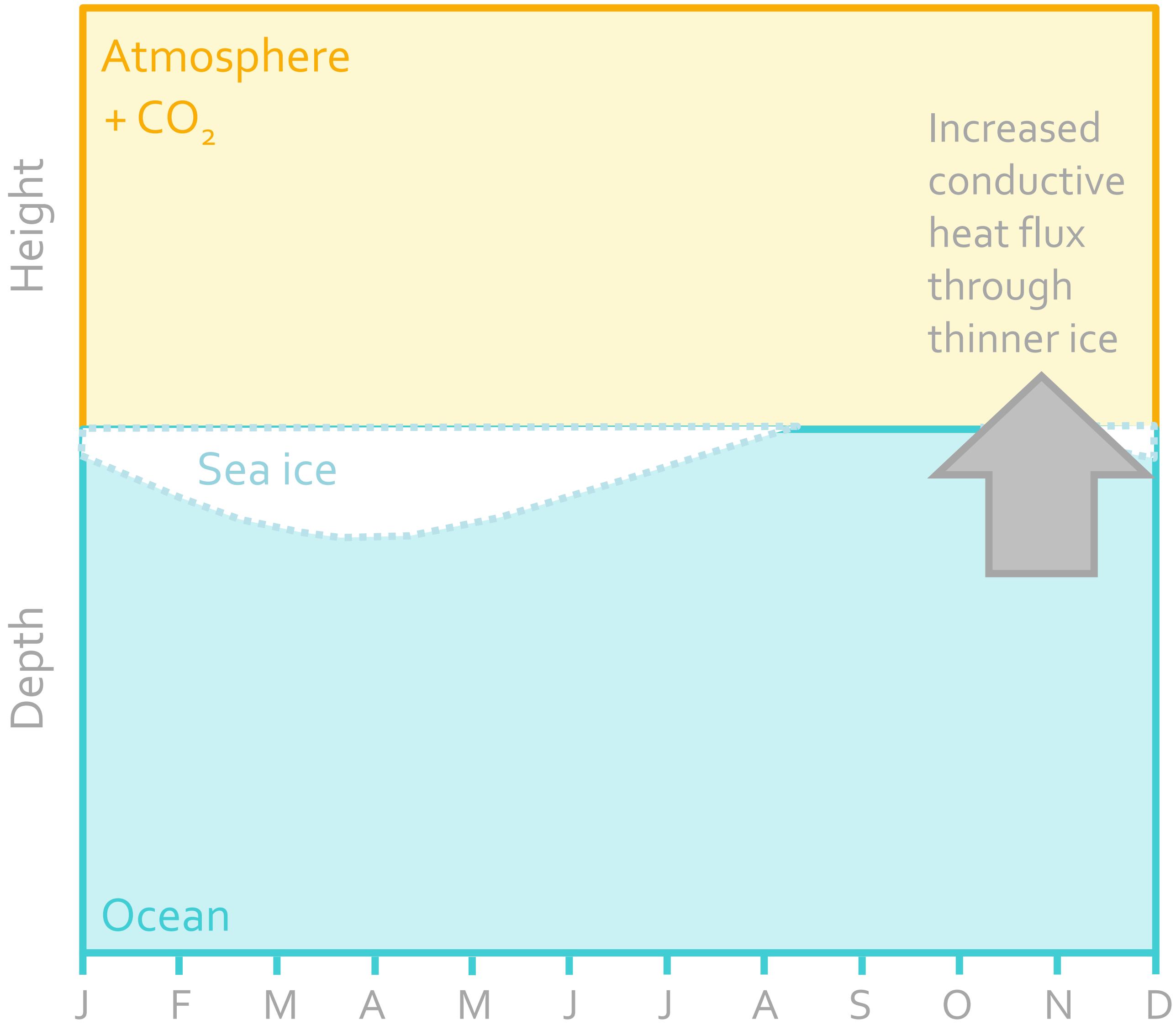

- Seasonal ocean heat storage
- Ice insulation effects

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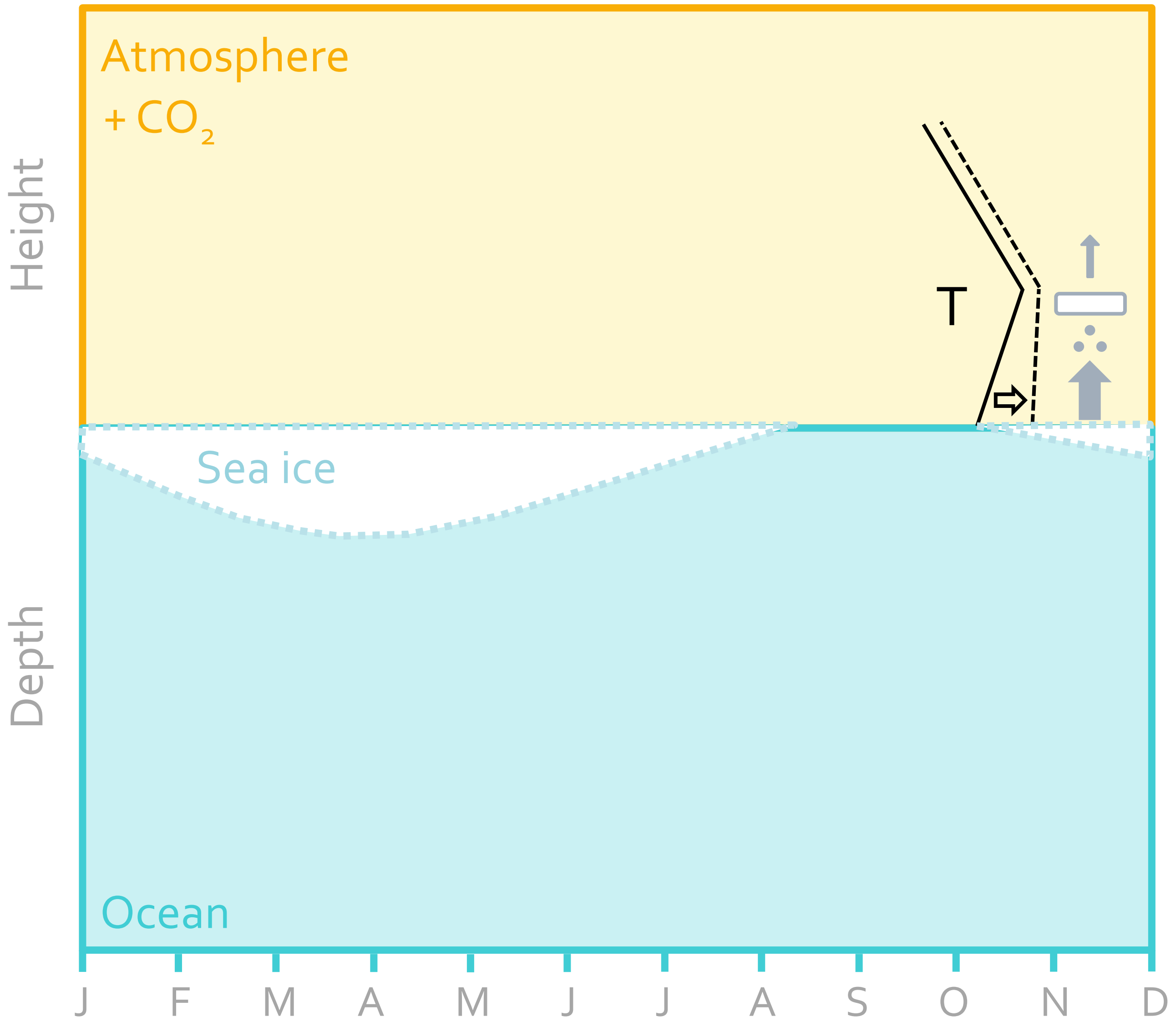

- Seasonal ocean heat storage
- Ice insulation effects
- Longwave cloud and temperature feedbacks

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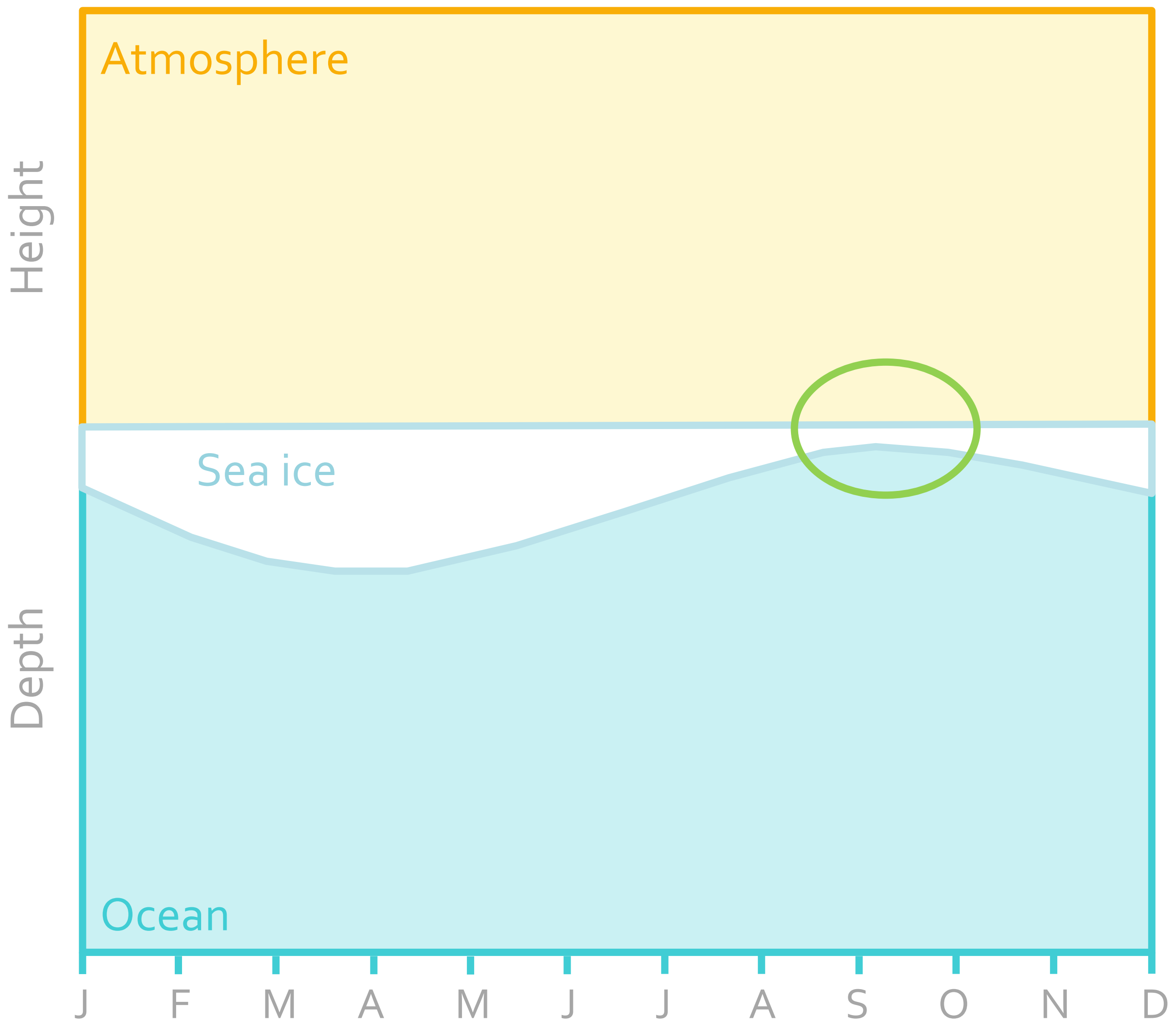

- Seasonal ocean heat storage
- Ice insulation effects
- Longwave cloud and temperature feedbacks
- Increasing effective heat capacity of the surface layer

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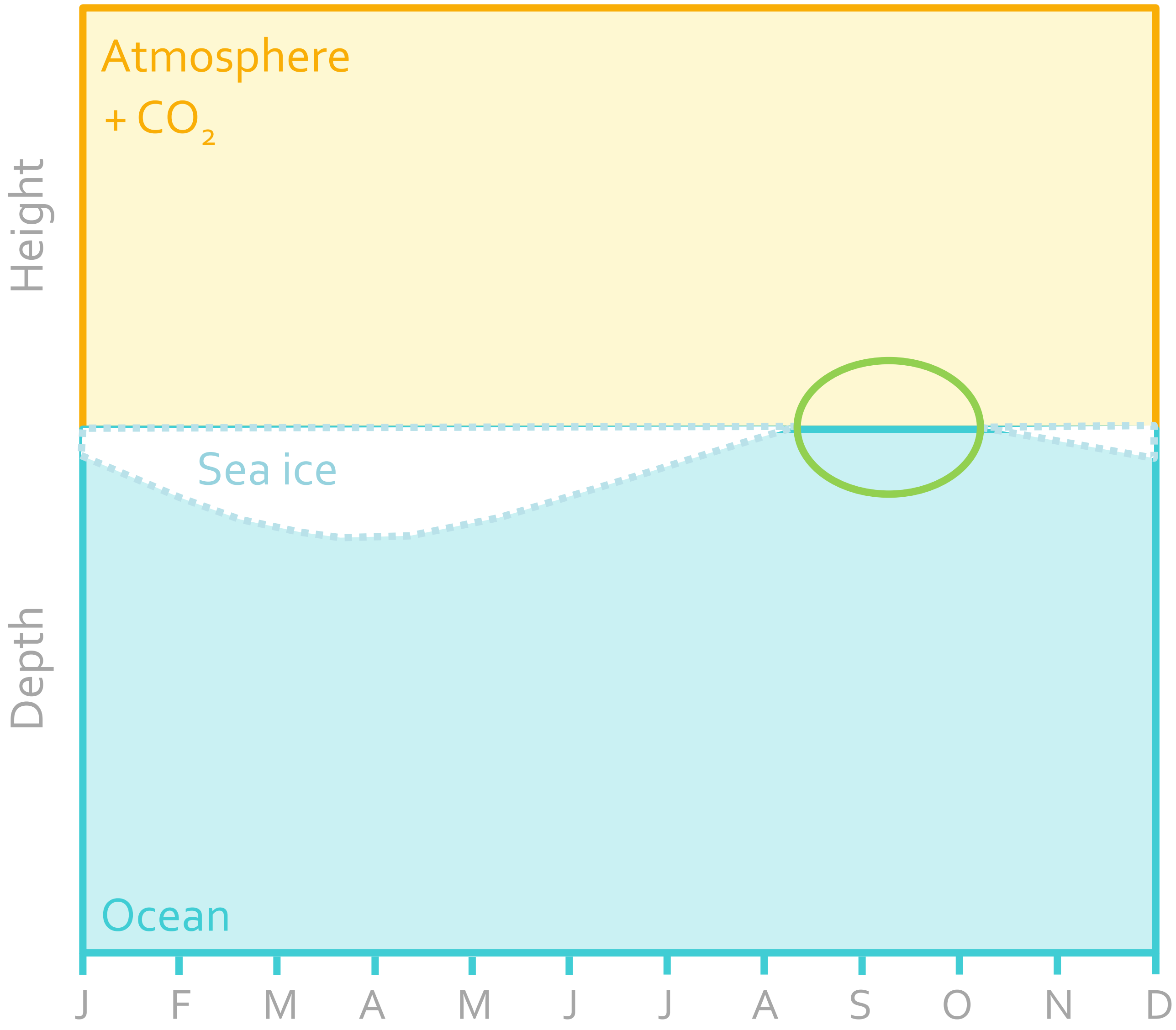

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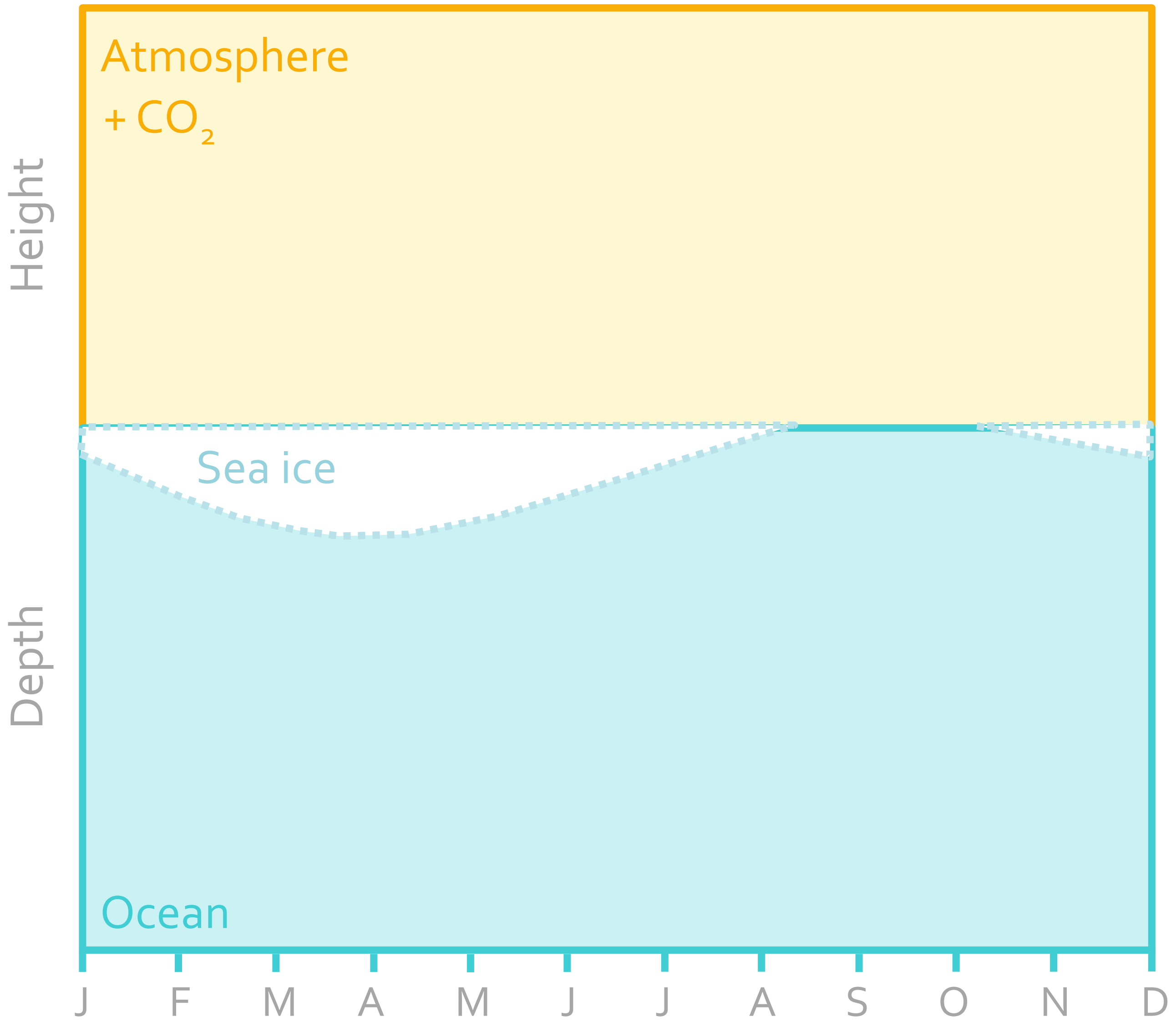

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- Ice insulation effects
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→ Use idealized experiments in a single-column sea-ice model to isolate different mechanisms

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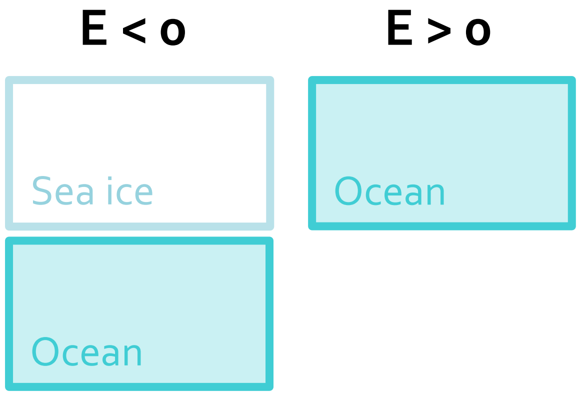
Single-column sea ice model (SCM; Eisenman and Wettlaufer 2009)

$$\underset{\substack{\uparrow\\ \text{surface enthalpy}}}{E} = \begin{cases} -L_i \overset{\substack{\text{sea-ice thickness}\\ \downarrow}}{H_i}, & E < 0 \ \ (sea\ ice) \\ c_{ml} \underset{\substack{\uparrow\\ 50\text{ m}}}{H_{ml}} \underset{\substack{\uparrow\\ \text{mixed-layer temperature (°C)}}}{T_{ml}}, & E > 0 \ \ (ocean) \end{cases}$$



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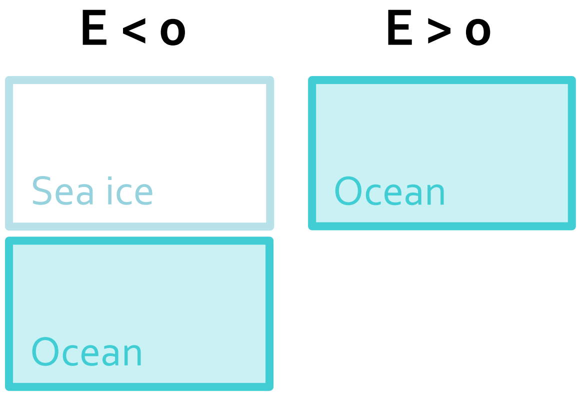
$$\frac{dE}{dt} = \underbrace{[1 - \alpha(E)]F_s(t)}_{\text{solar}} \underbrace{- F_0(t) \ - F_T(t)T(t,E)}_{\text{outgoing longwave radiation}} + \underbrace{F_B}_{\text{basal heat flux}} + \underbrace{v_0 R(-E)}_{\text{ice export}} + \underbrace{\Delta F_0}_{\text{forcing}}$$



E < 0

E > 0

Sea ice

Ocean

Ocean

Single-column sea ice model (SCM; Eisenman and Wettlaufer 2009)

sea-ice thickness

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surface enthalpy

50 m mixed-layer temperature (˚C)

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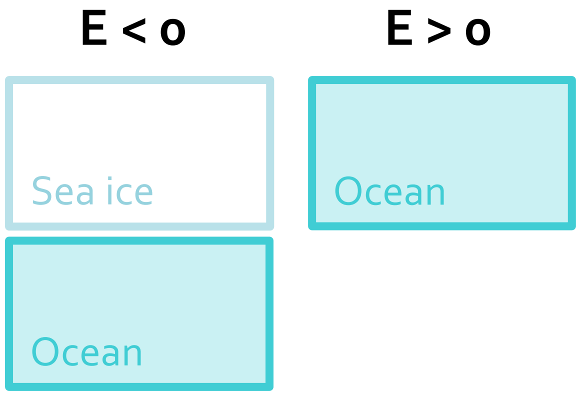
$$\alpha(E) = \frac{\alpha_{ml} + \alpha_i}{2} + \frac{\alpha_{ml} - \alpha_i}{2} \tanh\left(\frac{E}{L_i H_\alpha}\right)$$

albedo



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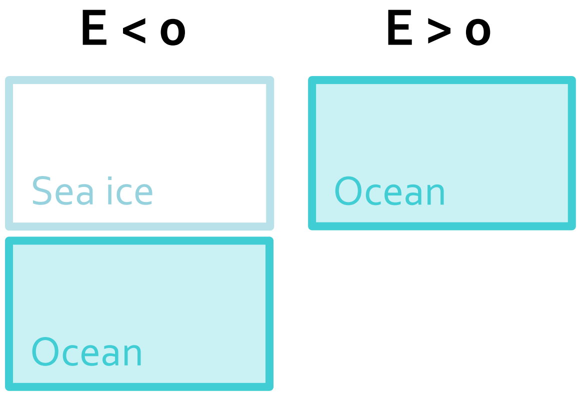
albedo

from balance of surface energy flux and conductive heat flux through ice

$$T(t,E) = \begin{cases} -\dfrac{(1-\alpha_i)F_s(t) - F_0(t) + \Delta F_0}{k_i L_i / E - F_T(t)}, & E < 0,\ T^* < 0 \ \ \text{(frozen ice)}, \\ 0, & E < 0,\ T^* > 0 \ \ \text{(melting ice)}, \\ \dfrac{E}{c_{ml} H_{ml}}, & E \geq 0 \qquad\qquad \text{(open ocean)}. \end{cases}$$

surface temperature (˚C)

effective heat capacity →



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Includes:

- Seasonally-varying Planck and surface albedo feedbacks
- Changes in ice insulation and conductive heat flux as sea ice thins
- Changes in surface effective heat capacity as sea ice melts and exposes open ocean

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surface temperature (˚C)

effective heat capacity →

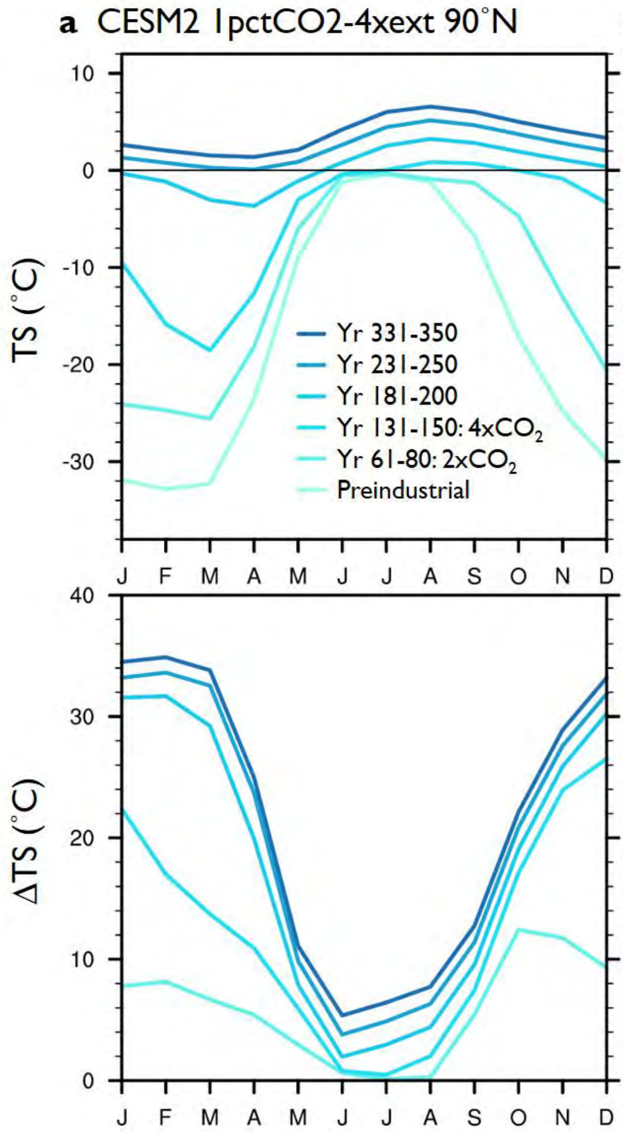
Includes:

- Seasonally-varying Planck and surface albedo feedbacks
- Changes in ice insulation and conductive heat flux as sea ice thins
- Changes in surface effective heat capacity as sea ice melts and exposes open ocean

Does not include:

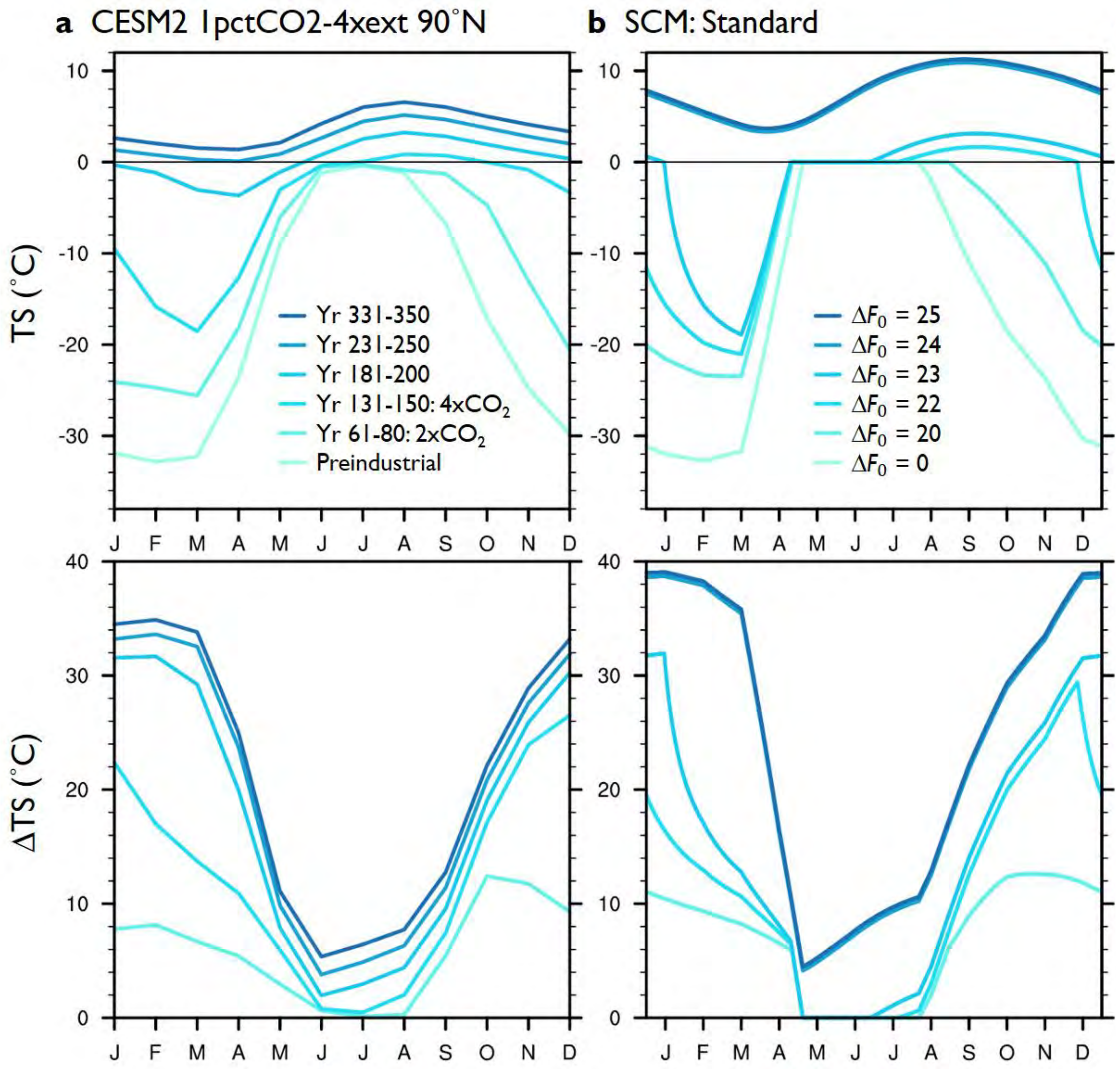
- Lapse-rate, cloud, and water-vapor feedbacks, changes in poleward heat transport

How does the SCM compare to a comprehensive climate model?



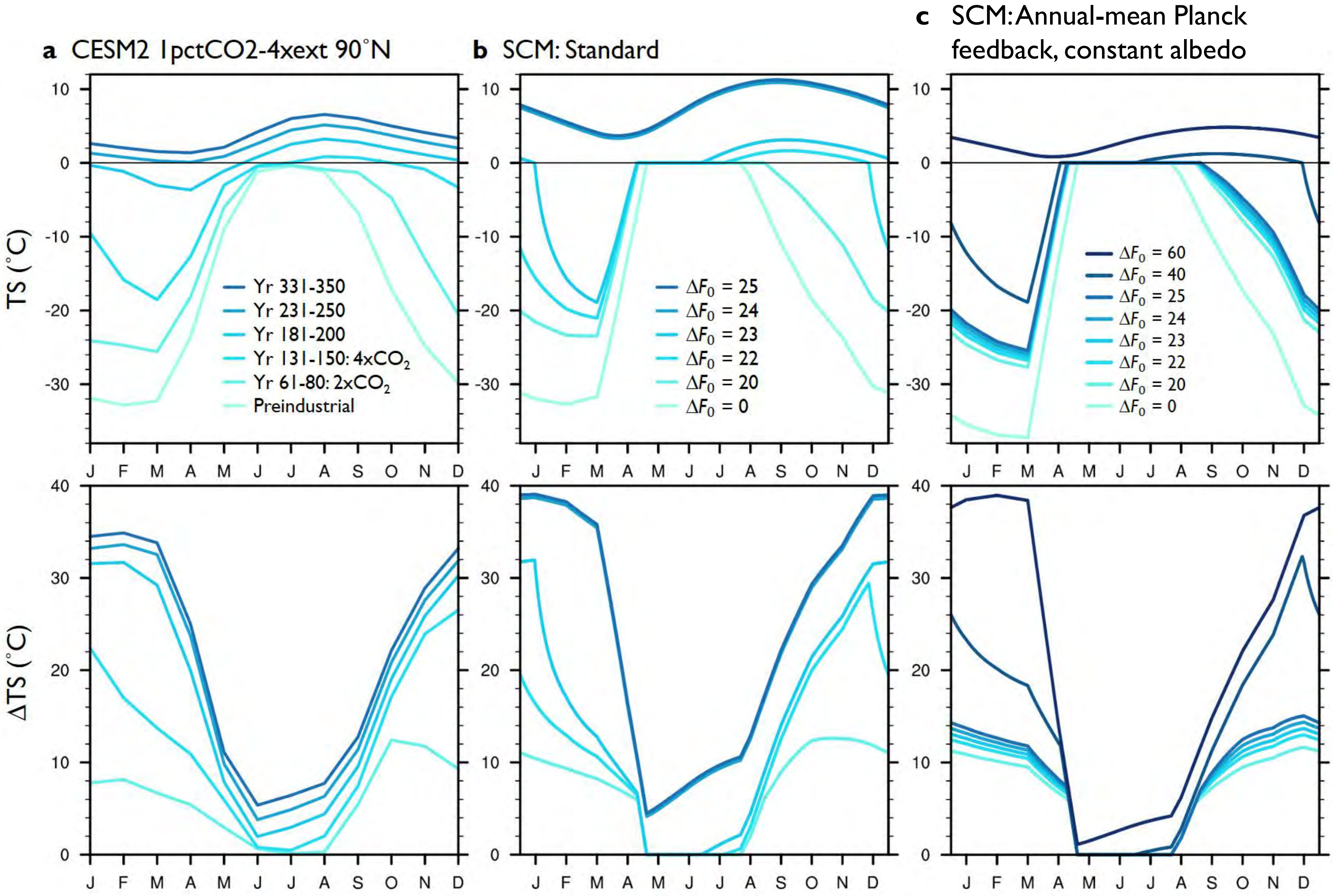
Hahn et al., 2022

Single-column model captures seasonal pattern of Arctic warming



Hahn et al., 2022 |

Seasonality in warming persists without seasonality in feedbacks



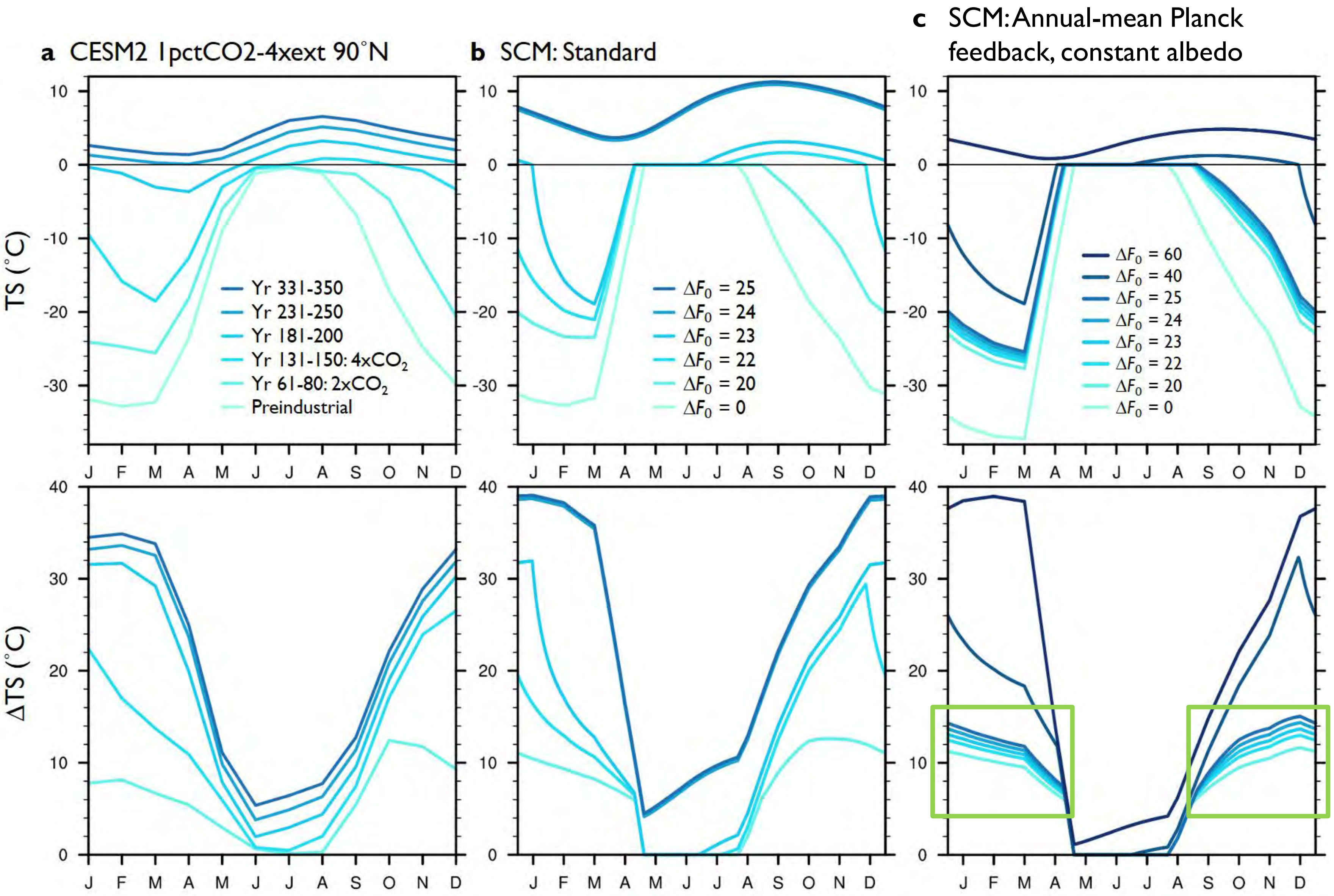
a CESM2 1pctCO2-4xext 90°N

b SCM: Standard

c SCM: Annual-mean Planck feedback, constant albedo

Hahn et al., 2022

Role of conductive heat flux?



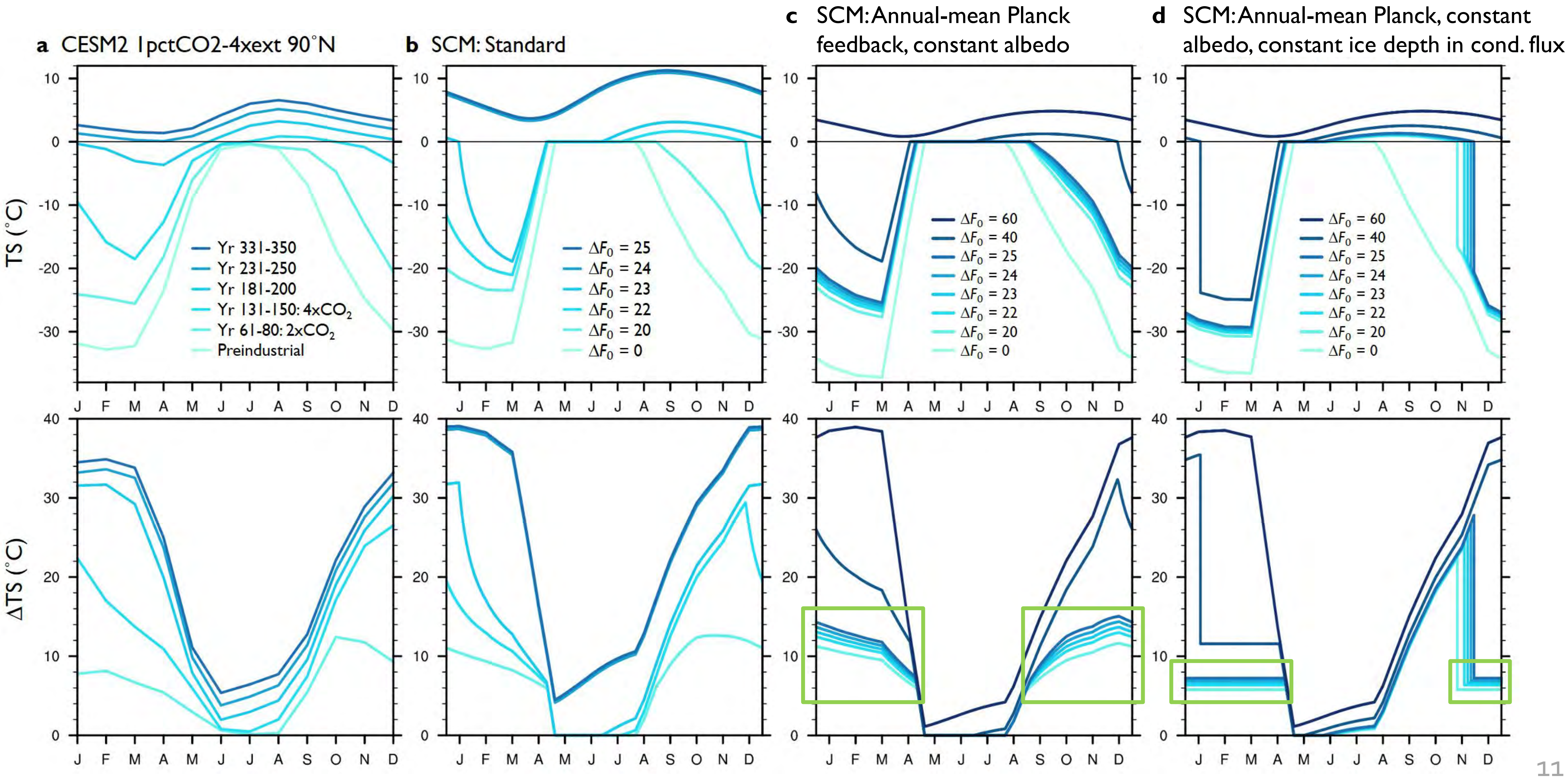
T > 0°C
Open ocean

→ T = 0°C
Melting ice

T < 0°C
Frozen ice

Hahn et al., 2022 |

Conductive heat flux supports peak early winter warming over frozen ice



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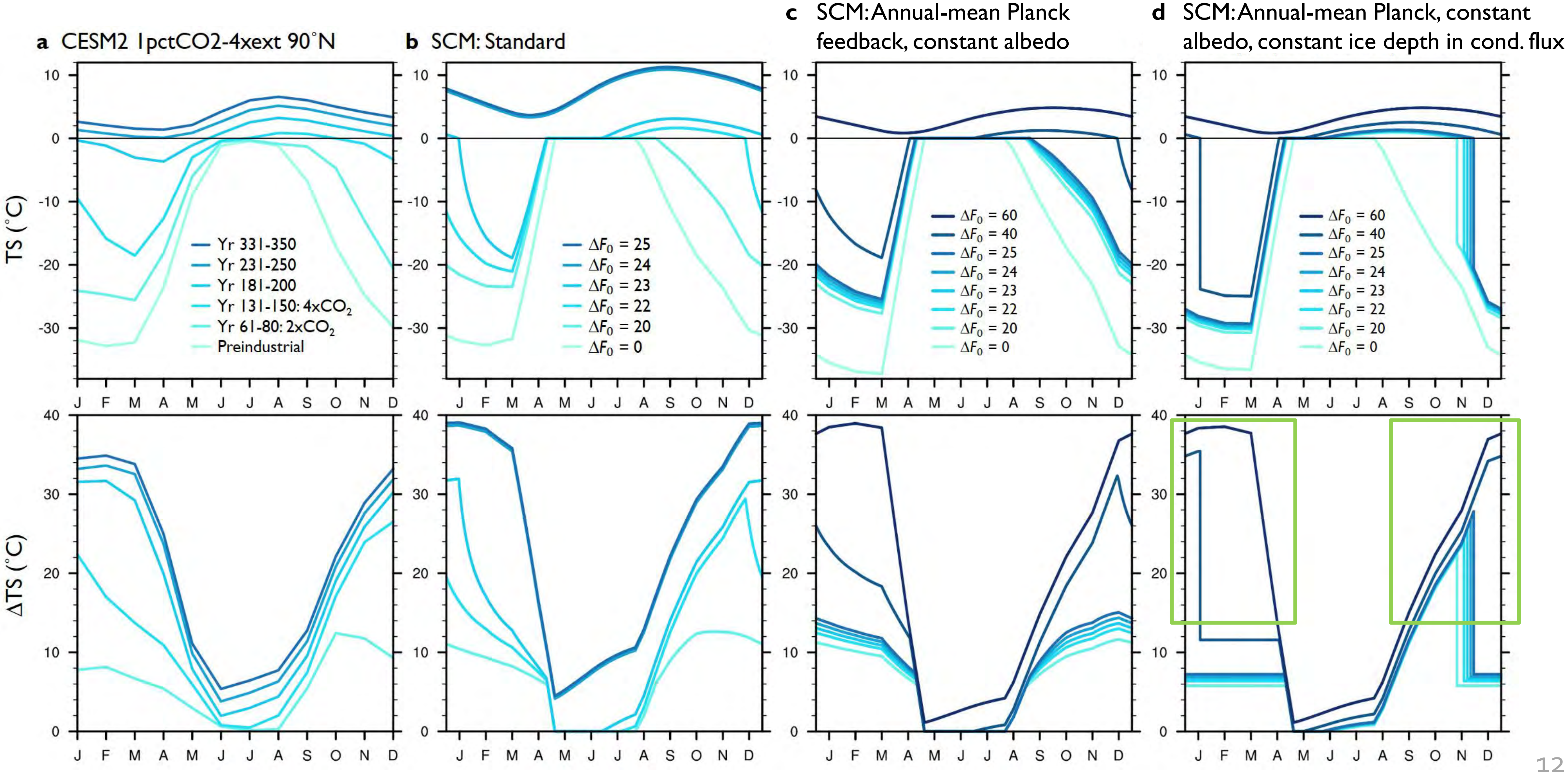
b SCM: Standard

c SCM: Annual-mean Planck feedback, constant albedo

d SCM: Annual-mean Planck, constant albedo, constant ice depth in cond. flux

Even with constant warming over frozen ice, the transition from ice to open ocean produces peak warming in early (shifting to late) winter



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Explicitly model changes in effective heat capacity

Single-column model with no ice, only an ocean mixed layer: $$\underset{\uparrow \atop \text{surface temperature}}{T(t,E)} = \frac{E}{c_{ml}H_{ml}} \quad \begin{matrix} \leftarrow \text{enthalpy} \\ \leftarrow \text{effective heat capacity} \end{matrix}$$

Explicitly model changes in effective heat capacity

Single-column model with no ice, only an ocean mixed layer: $T(t, E) = \dfrac{E}{c_{ml} H_{ml}}$

enthalpy

effective heat capacity

surface temperature

Annual-mean Planck feedback, a constant ice albedo α_i, no conductive heat flux

Explicitly model changes in effective heat capacity

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Annual-mean Planck feedback, a constant ice albedo α_i, no conductive heat flux

Experiments:

1) $H_{ml} = 1$ m - represents small effective heat capacity of frozen ice

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enthalpy

effective heat capacity

surface temperature

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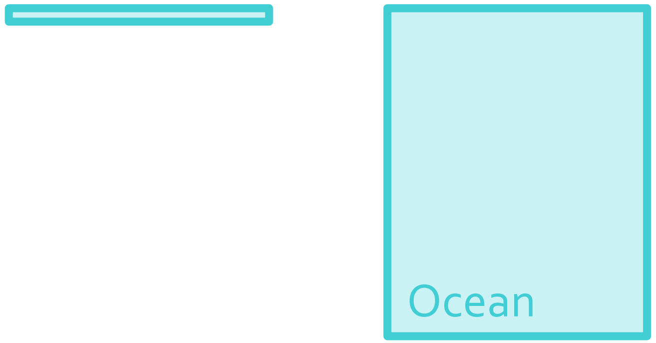
Experiments:

1) $H_{ml} = 1$ m - represents small effective heat capacity of frozen ice

2) $H_{ml} = 50$ m - represents large effective heat capacity of open ocean



Explicitly model changes in effective heat capacity

Single-column model with no ice, only an ocean mixed layer: $T(t,E) = \frac{E}{c_{ml}H_{ml}}$

← enthalpy

← effective heat capacity

↑ surface temperature

Annual-mean Planck feedback, a constant ice albedo α_i, no conductive heat flux

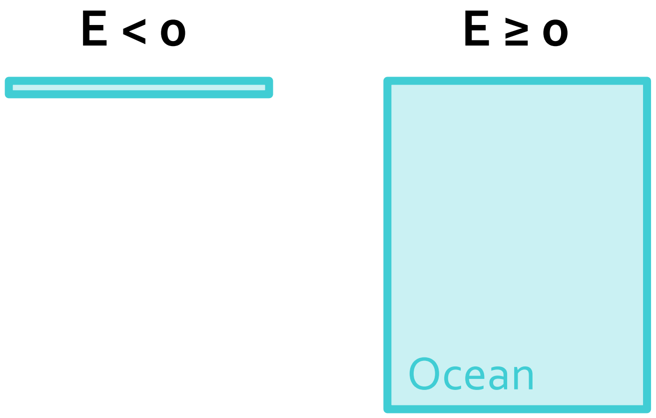
Experiments:

1) H_{ml} = 1 m - represents small effective heat capacity of frozen ice

2) H_{ml} = 50 m - represents large effective heat capacity of open ocean

3) H_{ml} = 1 m for $E < 0$, H_{ml} = 50 m for $E \geq 0$

- represents transition from frozen ice to open ocean



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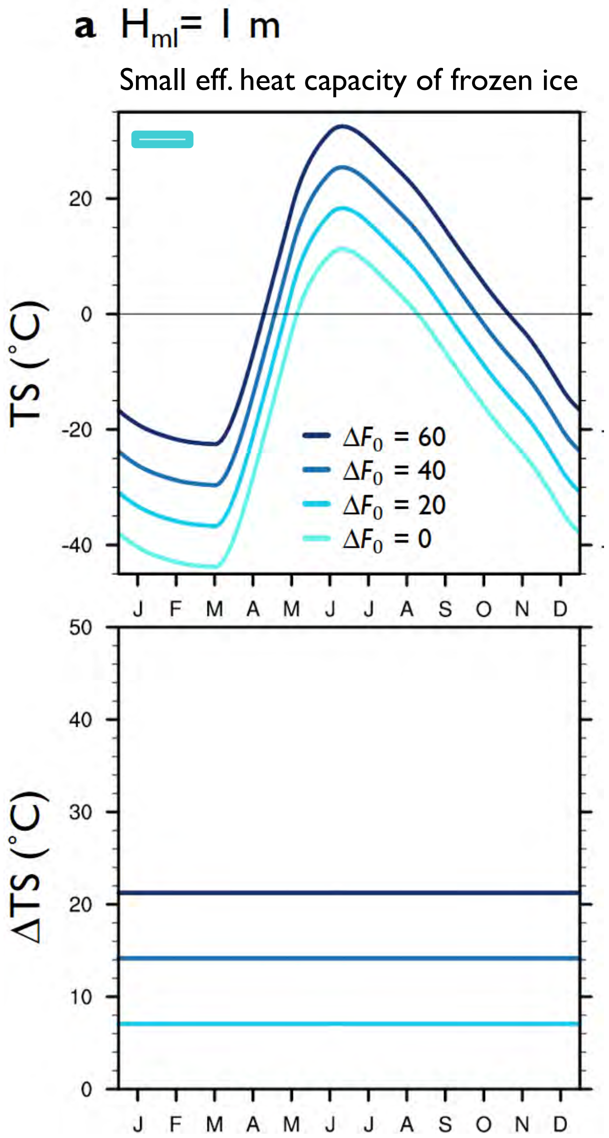

Hahn et al., 2022

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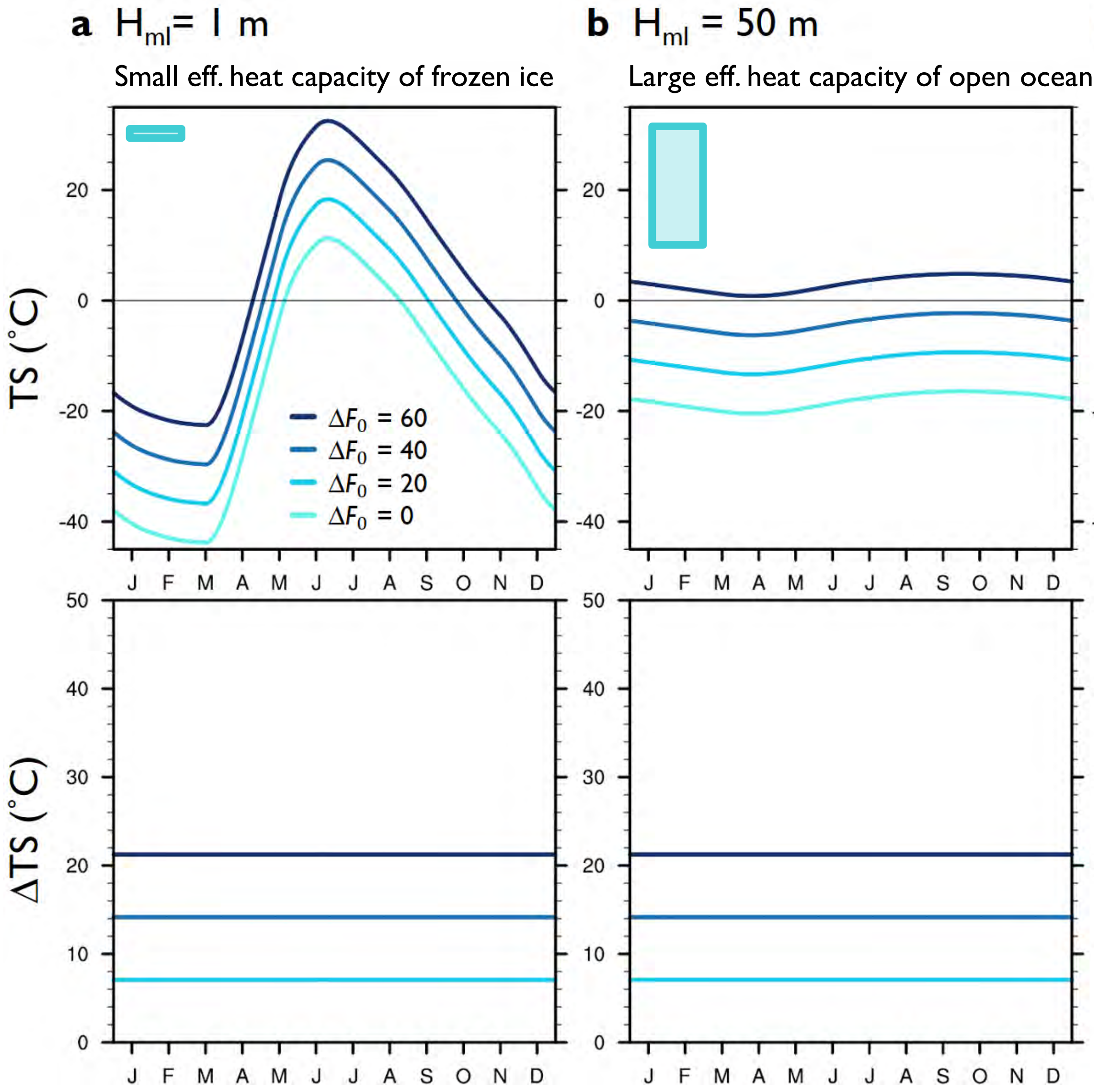

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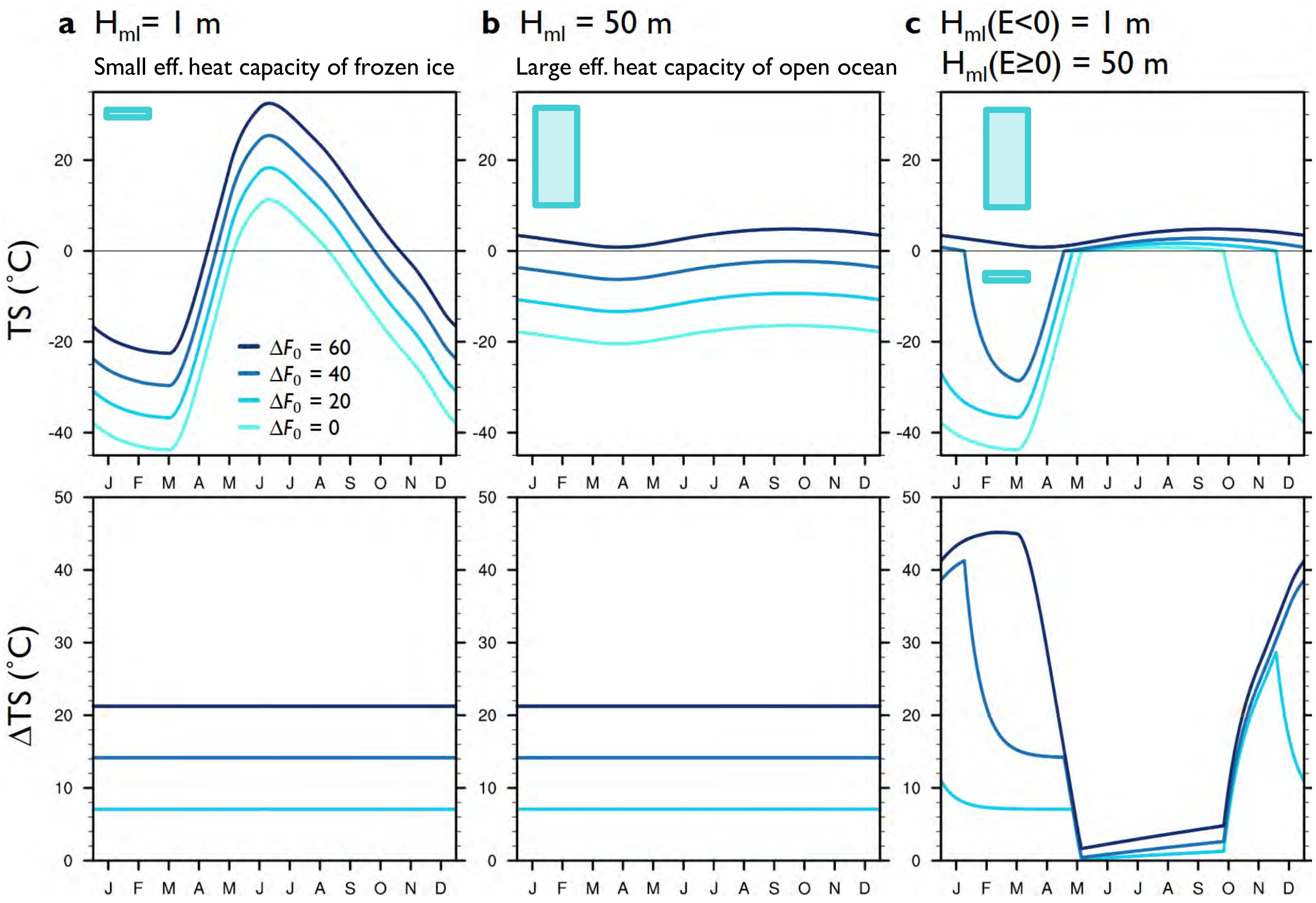
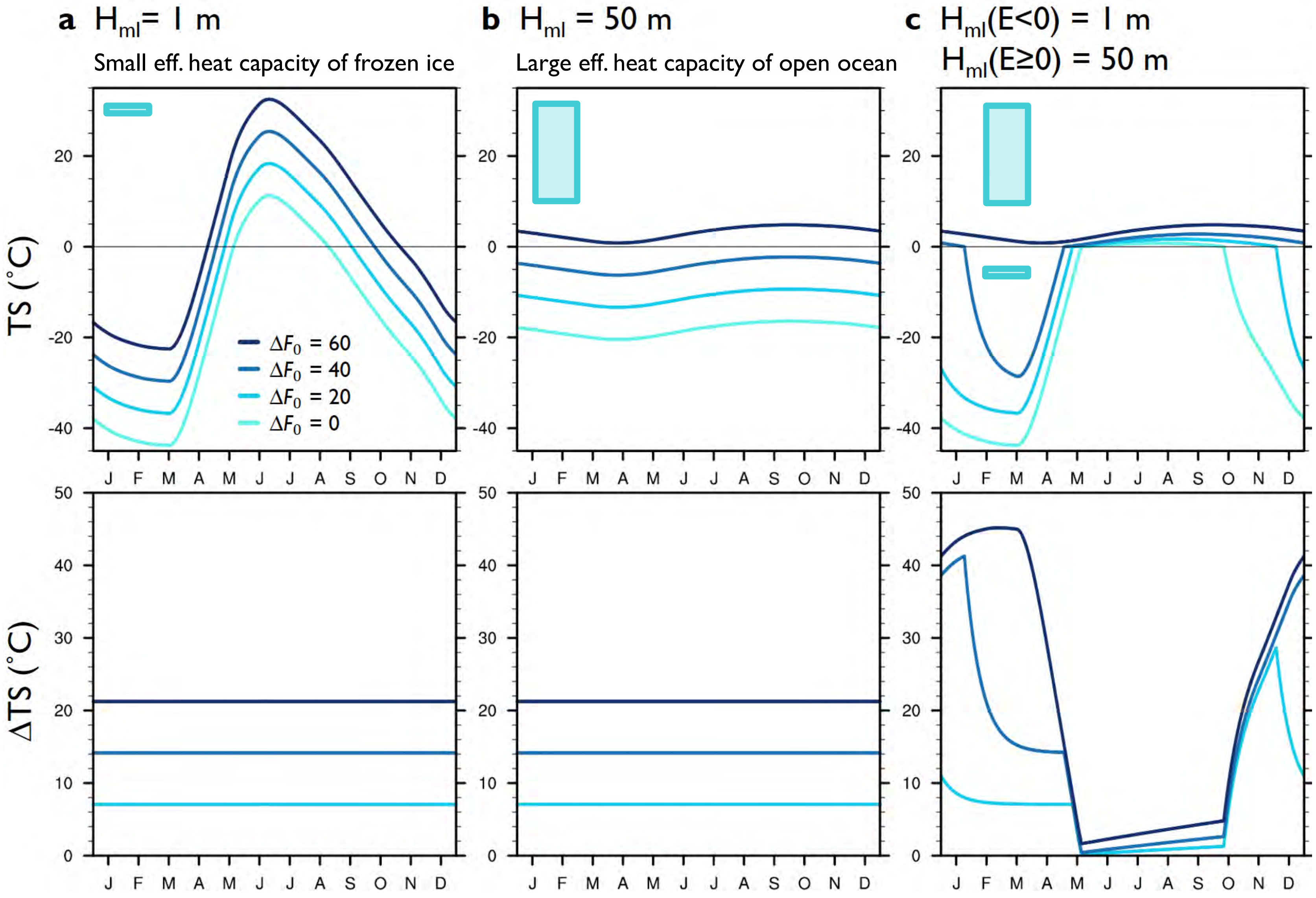


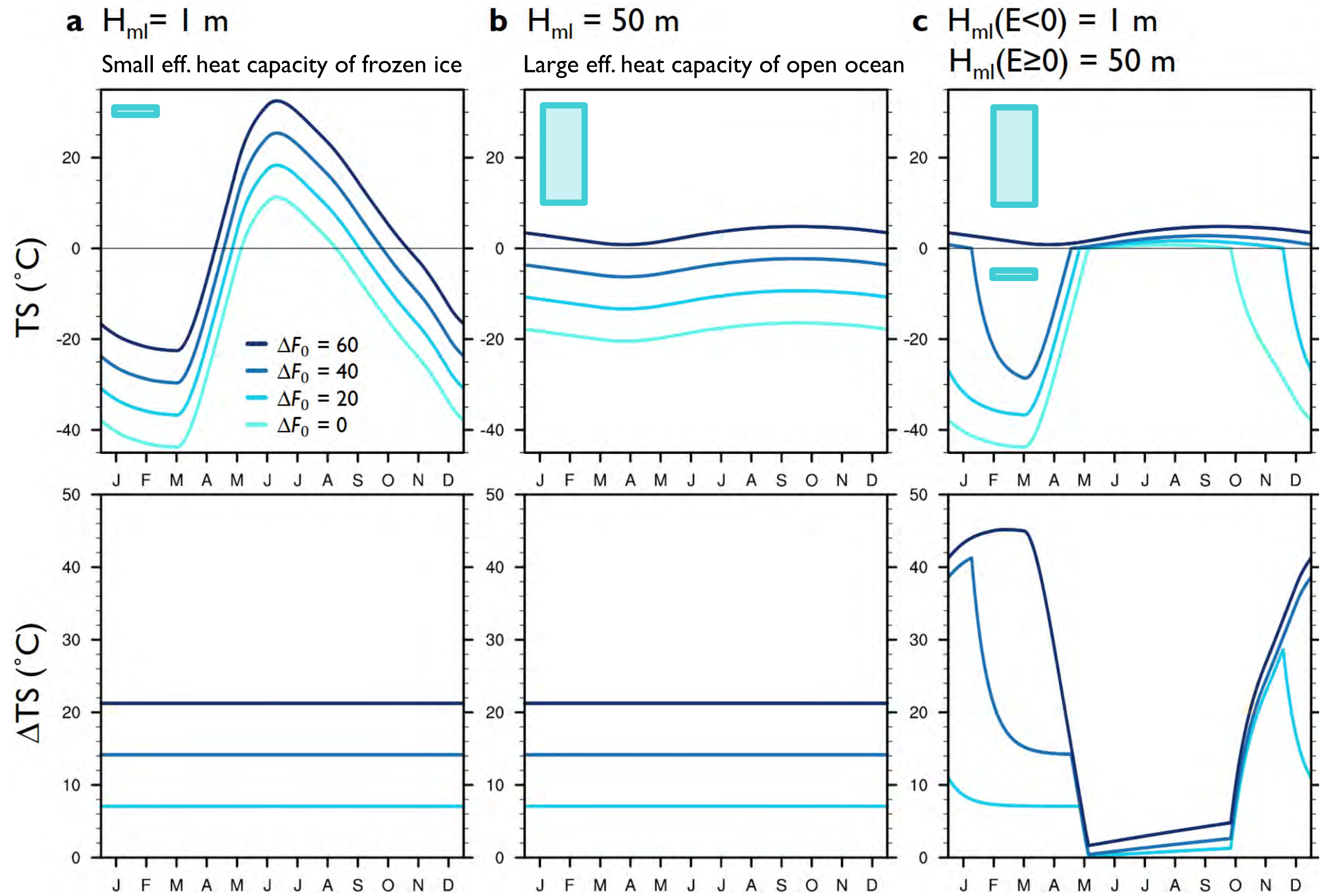
Explicitly model changes in effective heat capacity



Effective heat capacity changes alone can produce the seasonal pattern of Arctic warming

Hahn et al., 2022

Explicitly model changes in effective heat capacity



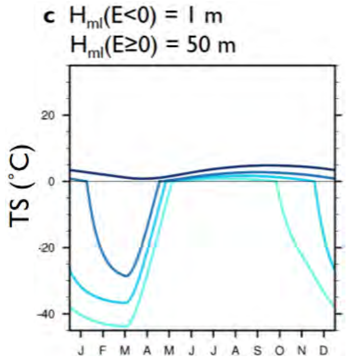
Effective heat capacity changes alone can produce the seasonal pattern of Arctic warming

Consistent mechanism across fully-coupled CMIP5 models (Sejas and Taylor, 2023)

Hahn et al., 2022 |

Seasonal pattern of Arctic warming

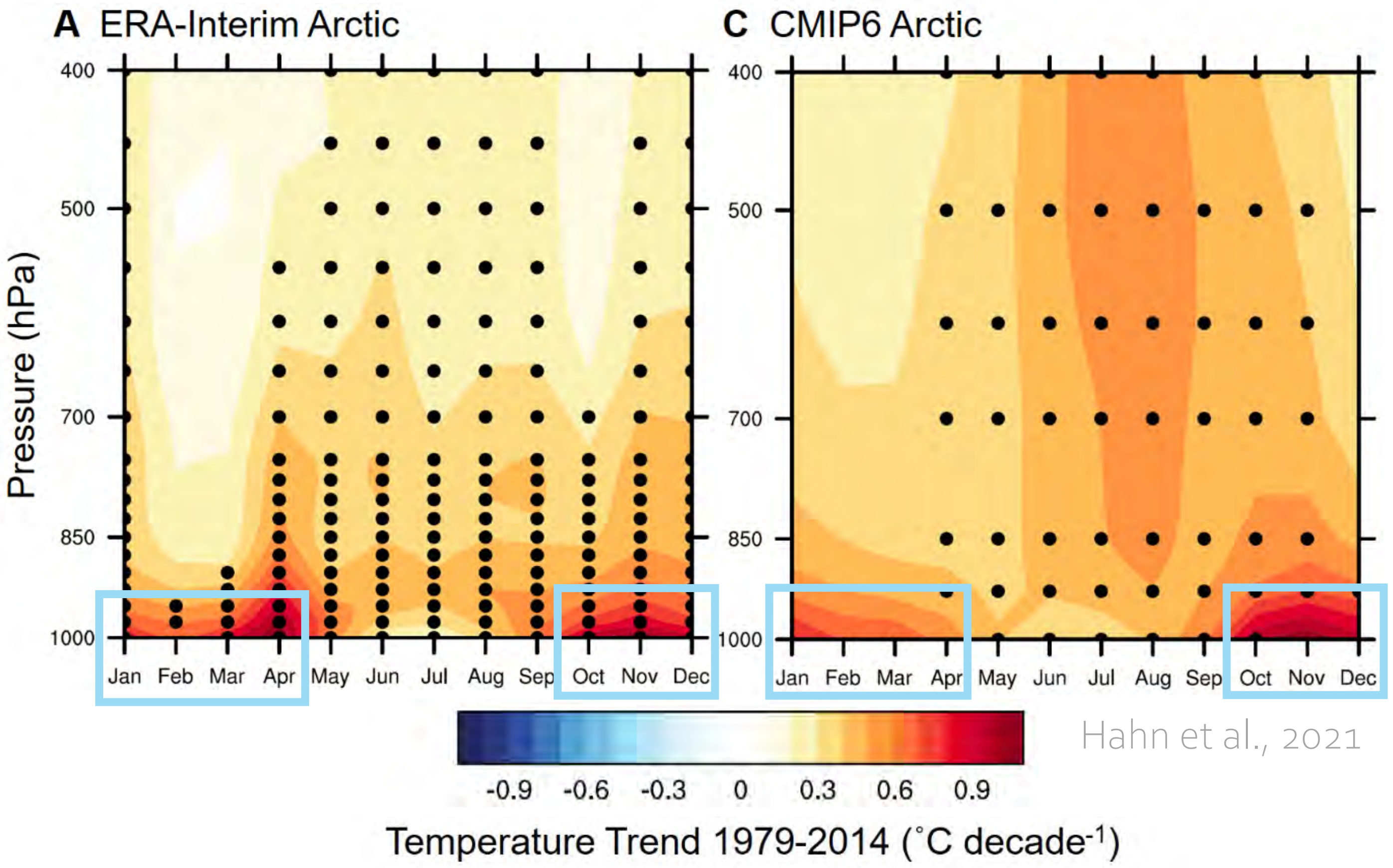
1. What drives the winter peak in Arctic warming?



Increasing effective heat capacity of the surface layer alone can produce this pattern; winter warming is also amplified by increasing conductive heat flux through thinning ice and the lapse-rate feedback

2. How is Arctic warming impacted by atmospheric heating in different seasons?

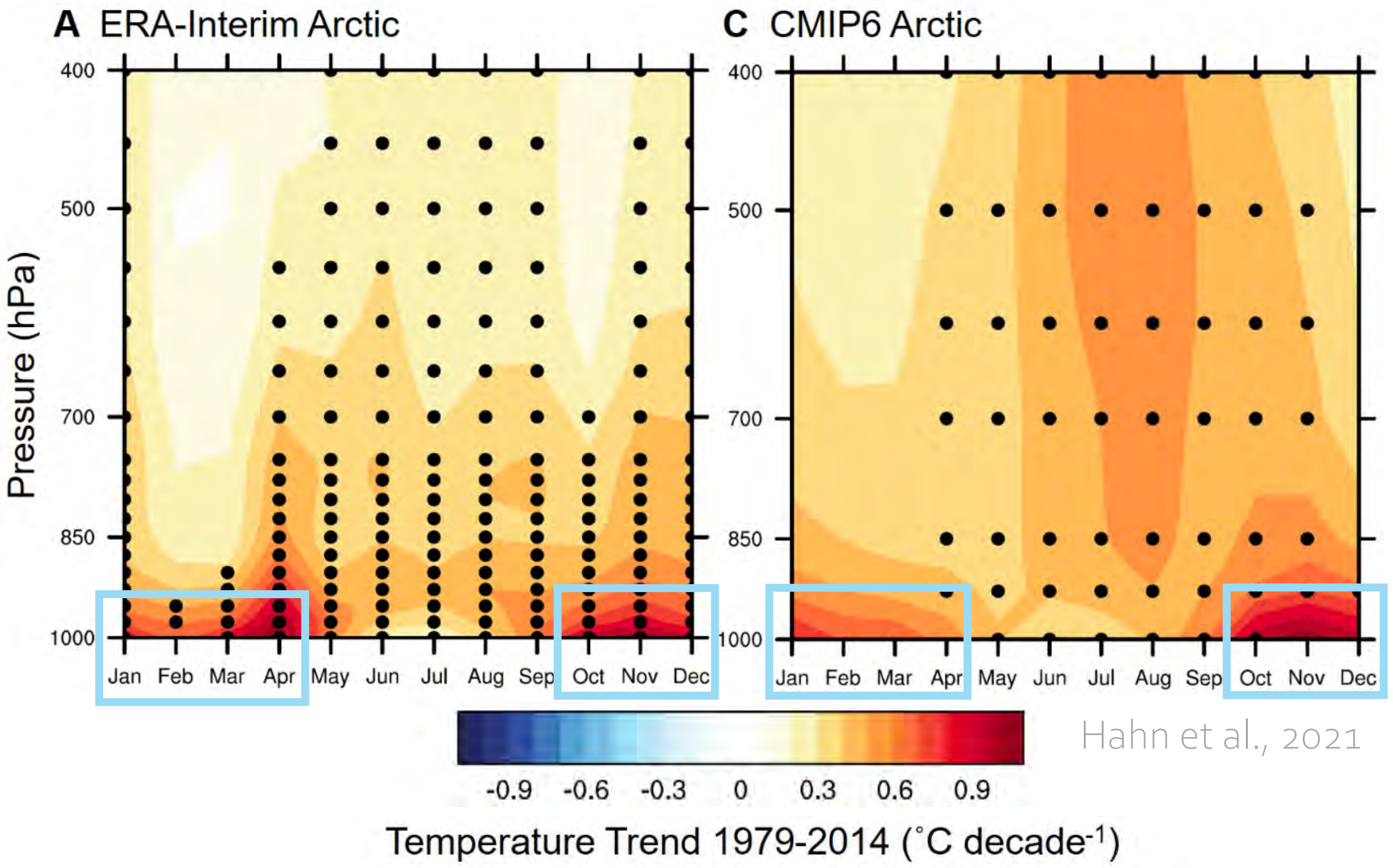
Seasonal contributions to Arctic warming



Hahn et al., 2021

- Many studies focus on winter mechanisms that increase Arctic warming

Seasonal contributions to Arctic warming

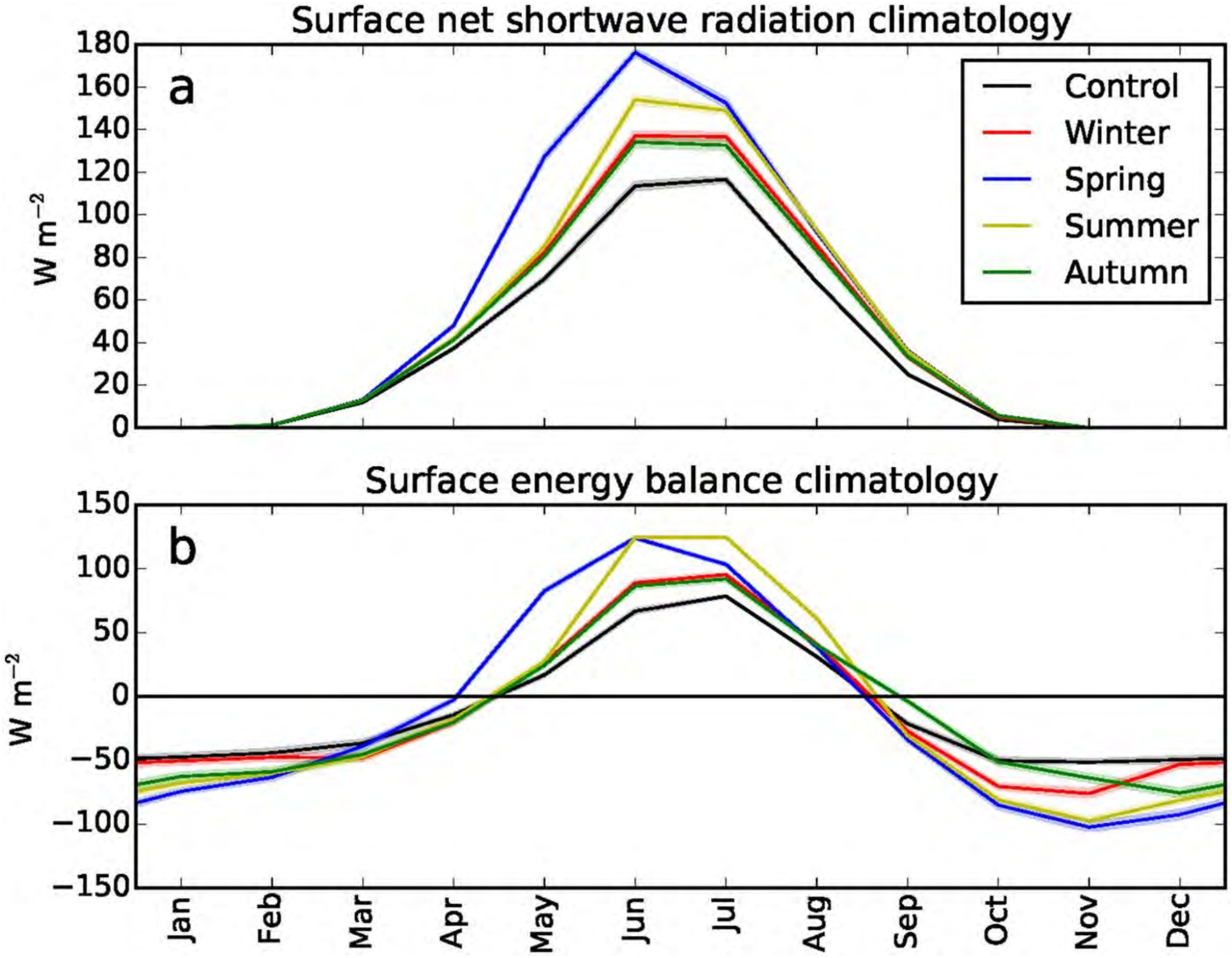


Hahn et al., 2021

- Many studies focus on winter mechanisms that increase Arctic warming
- Also expect summer atmospheric heating to drive winter warming by melting sea ice and supporting a transition to open ocean in early winter

How does seasonal radiative heating impact warming in other seasons and annually?

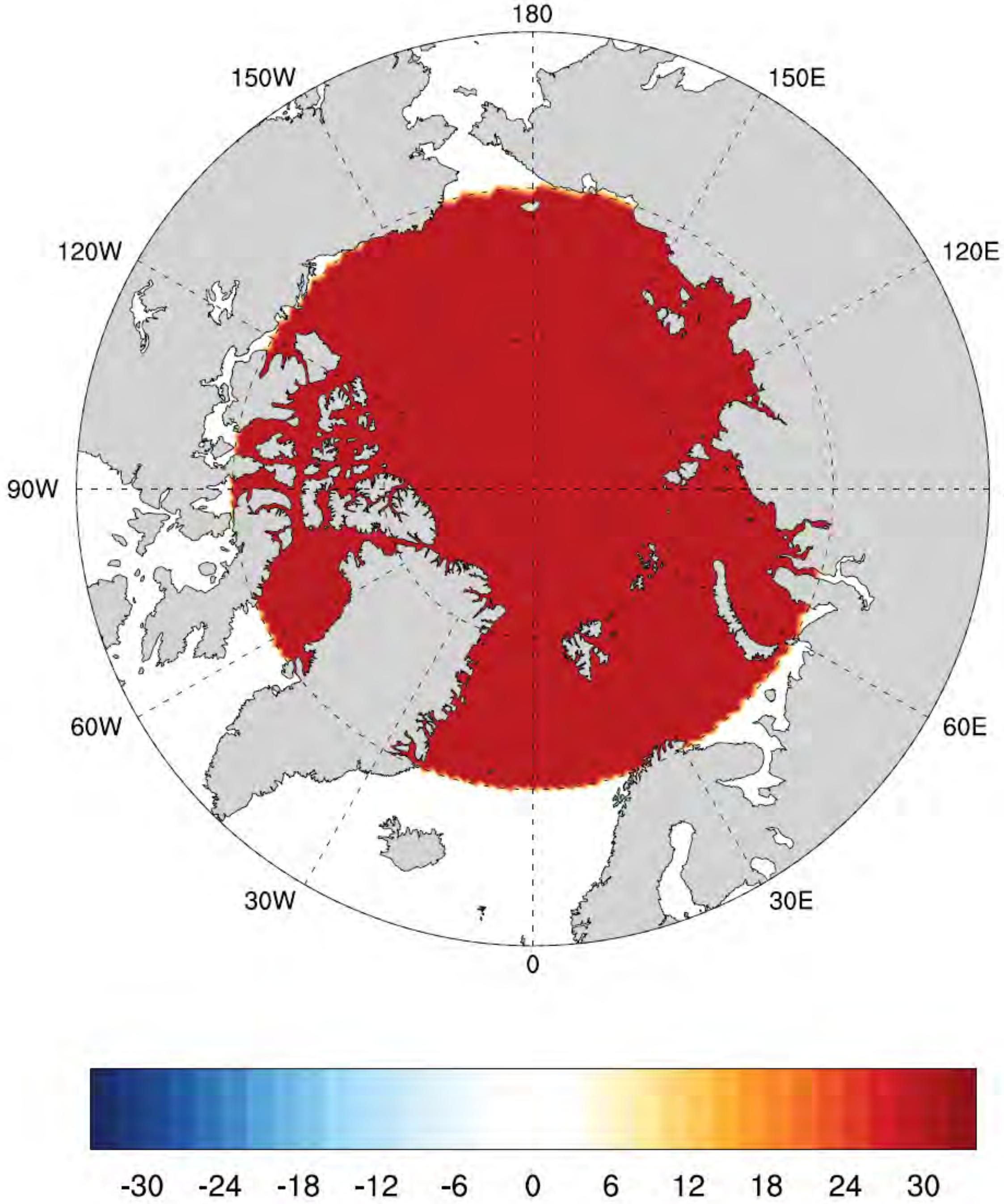
How does seasonal radiative heating impact warming in other seasons and annually?



- Bintanja and Krikken (2016) apply a 30 W m^{-2} artificial longwave forcing to Arctic surfaces in each season
- Spring and summer forcing produce the largest annual warming via a strong ice-albedo feedback and seasonal ocean heat storage

Methods

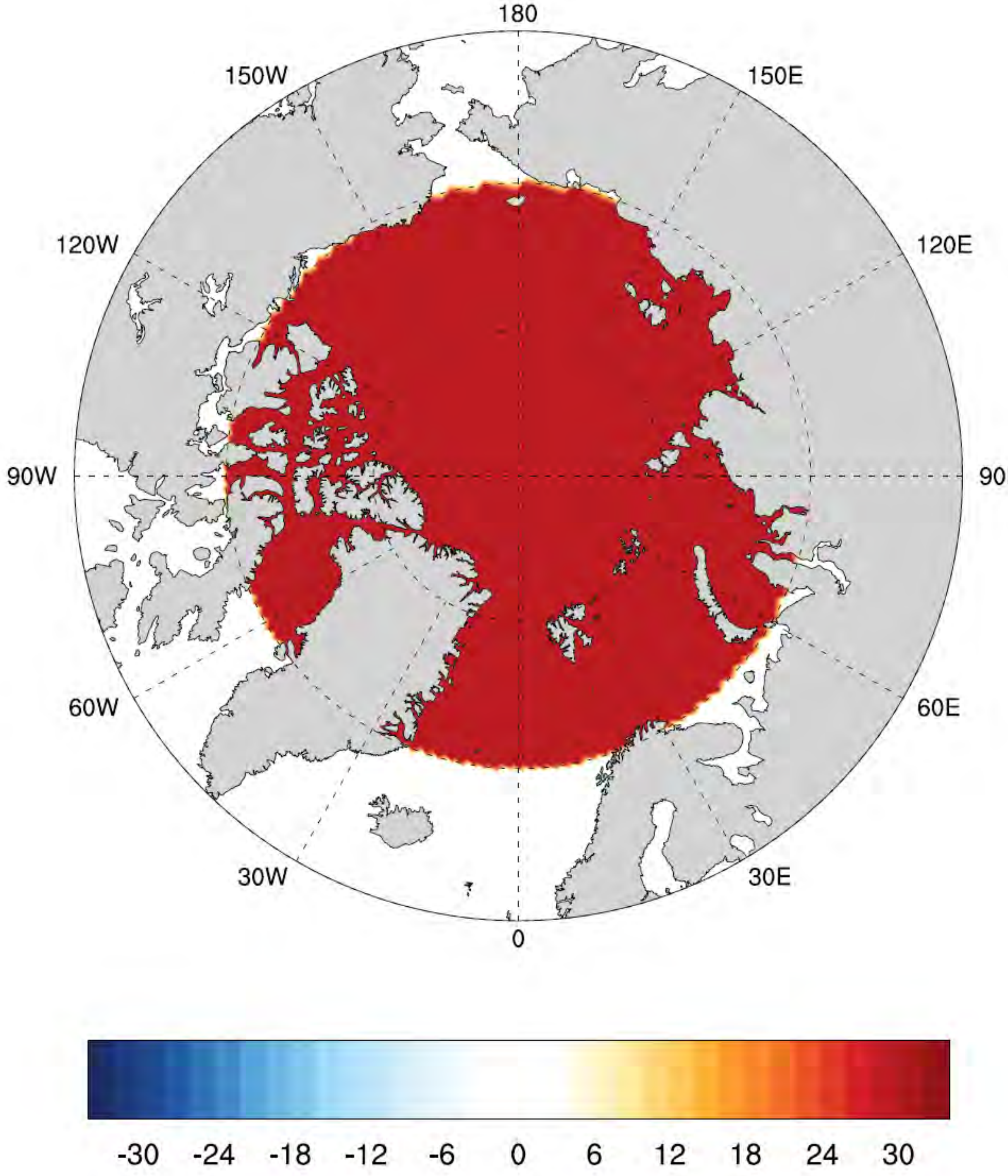
- Apply a 30 W m^{-2} longwave forcing to non-land surfaces north of 70°N in each month using the CESM1 (CAM4) slab-ocean model



Methods

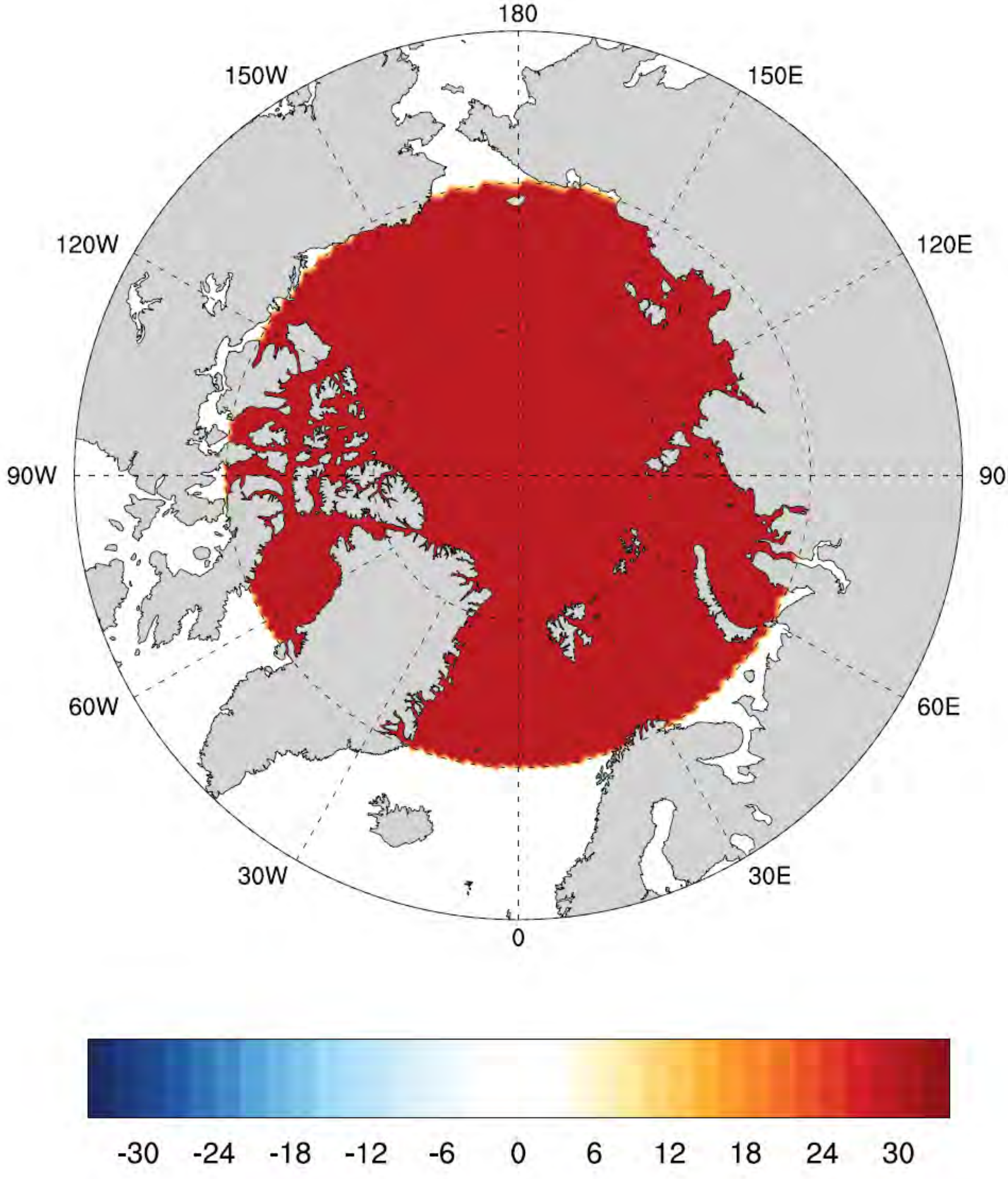
- Apply a 30 W m^{-2} longwave forcing to non-land surfaces north of 70°N in each month using the CESM1 (CAM4) slab-ocean model

- Sensitivity to mean-state climate (1850 or 2XCO2) and sign of forcing

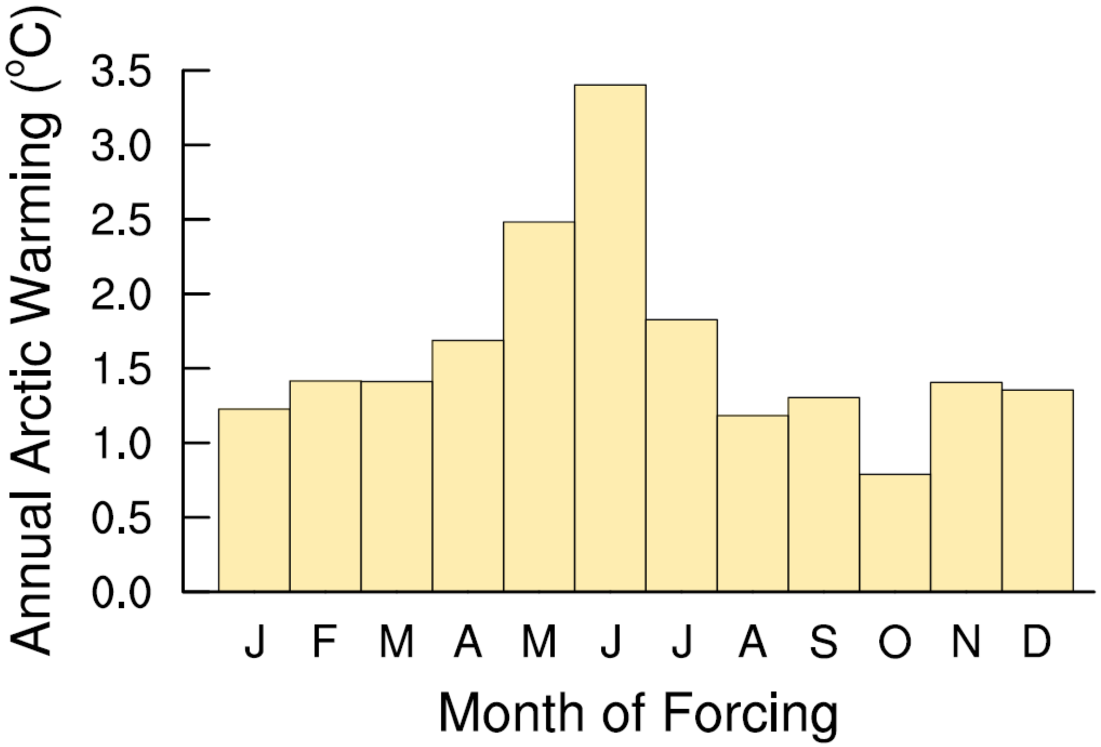


Methods

- Apply a 30 W m^{-2} longwave forcing to non-land surfaces north of 70°N in each month using the CESM1 (CAM4) slab-ocean model
- Sensitivity to mean-state climate (1850 or 2XCO2) and sign of forcing
- Complement with simpler models

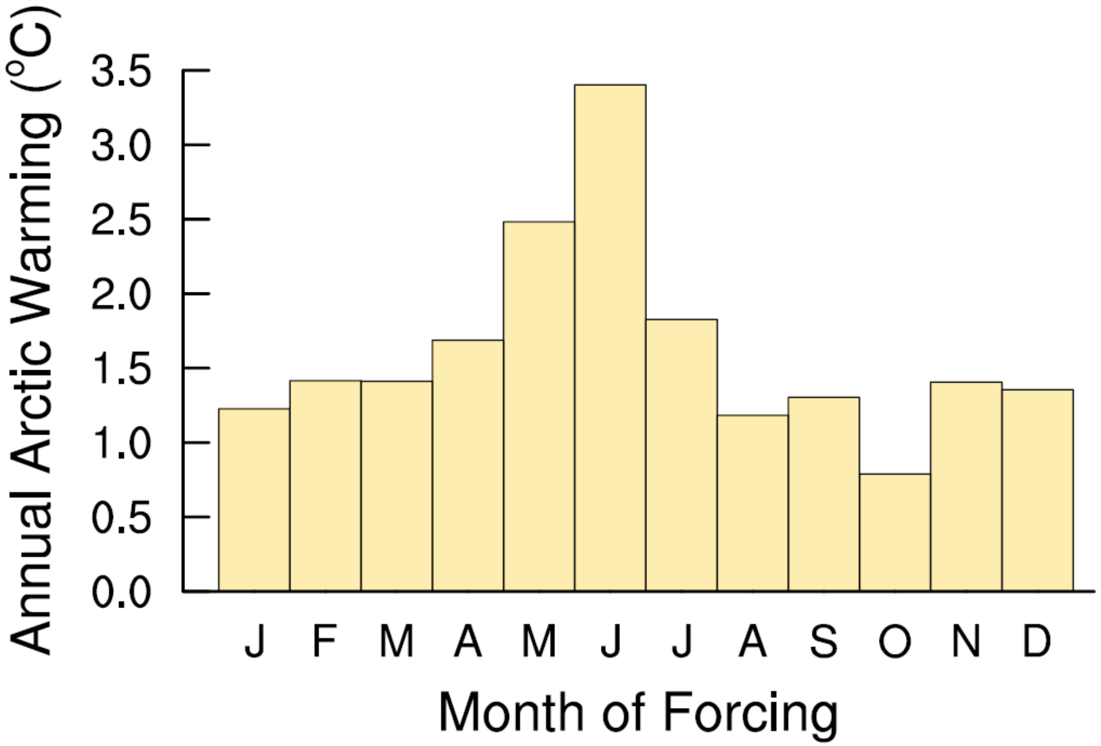


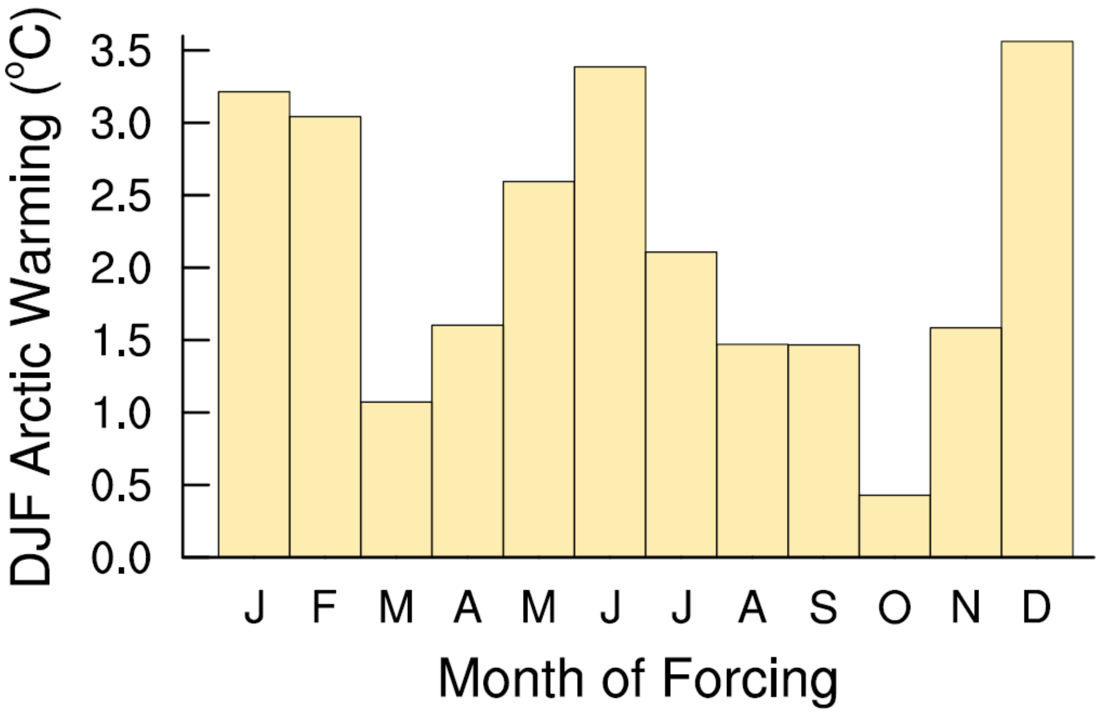
Early summer forcing produces the largest annual-mean warming



Hahn at al., in prep

Early summer forcing produces the largest annual-mean warming and comparable winter warming to winter forcing

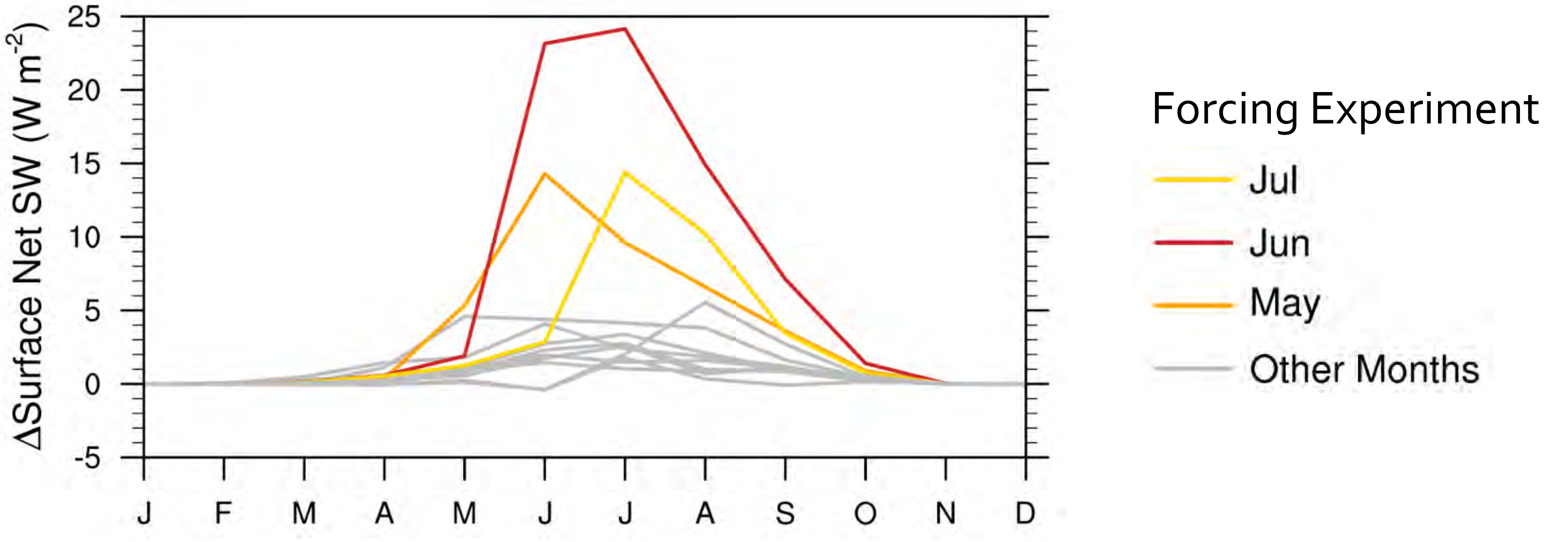




Hahn at al., in prep

Why does June forcing produce the largest annual Arctic warming?

Peak insolation gives largest increase in absorbed shortwave radiation



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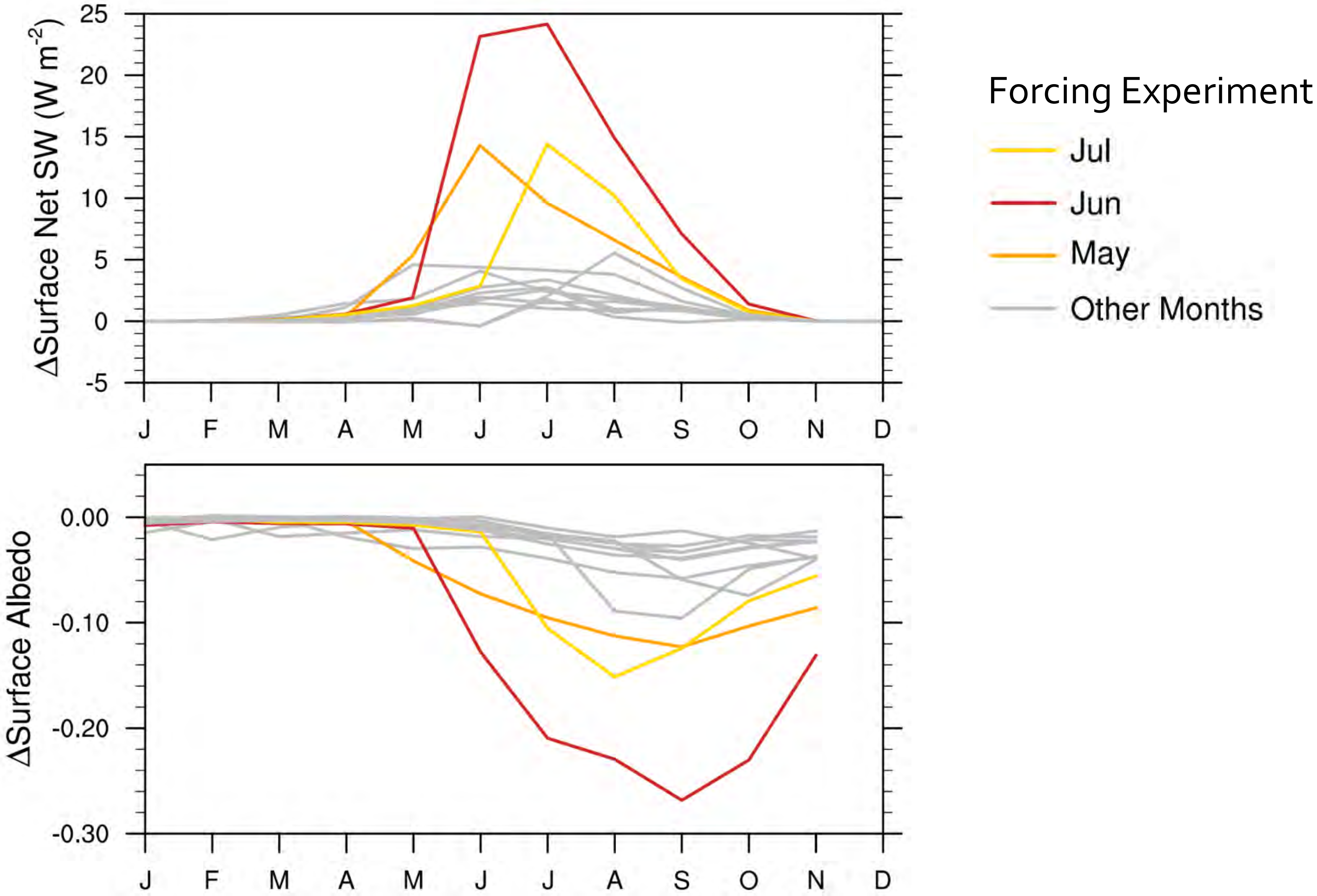

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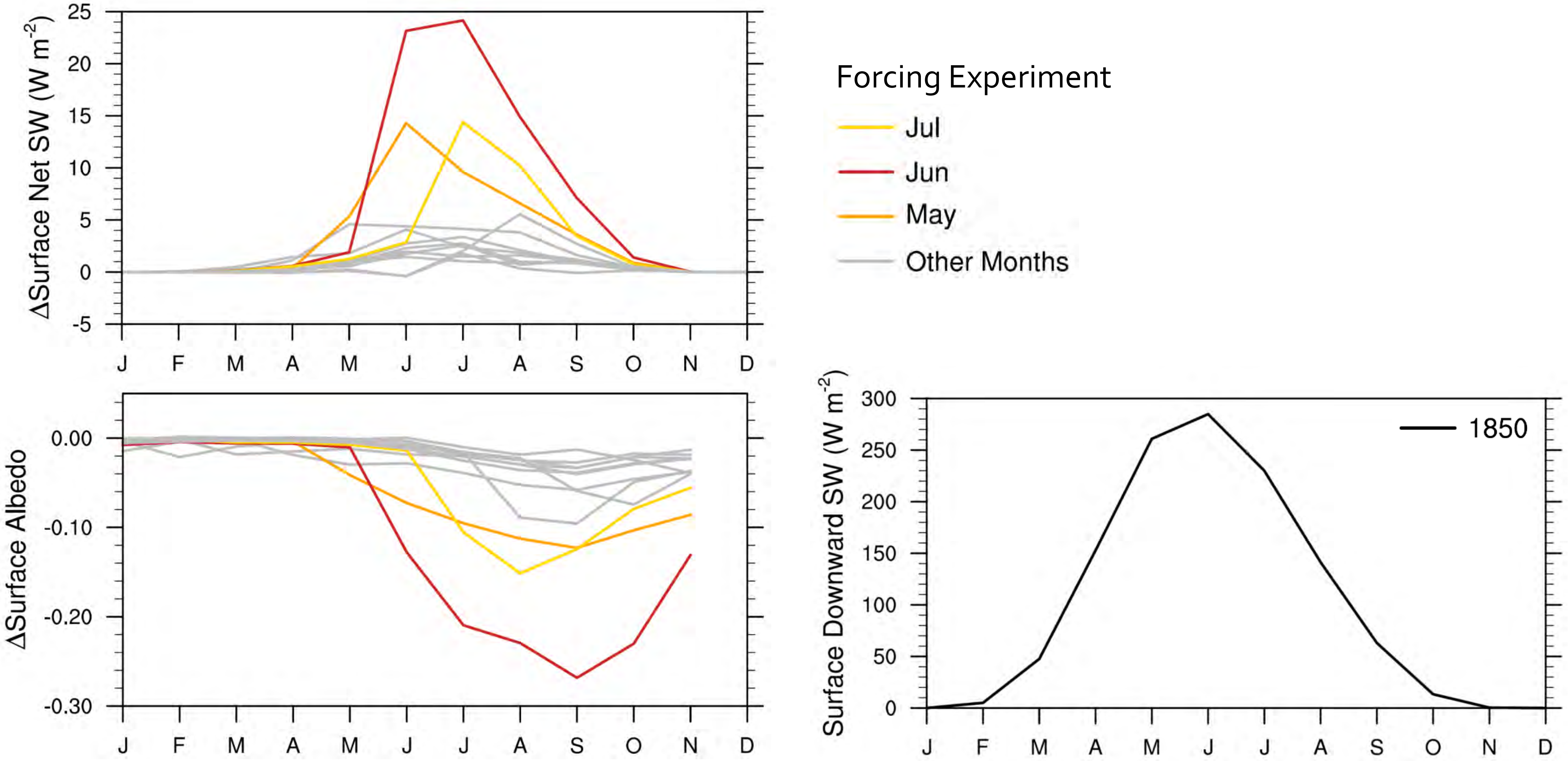
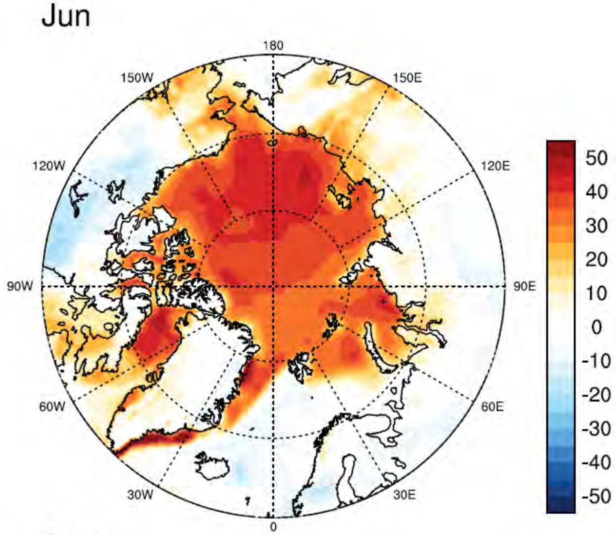
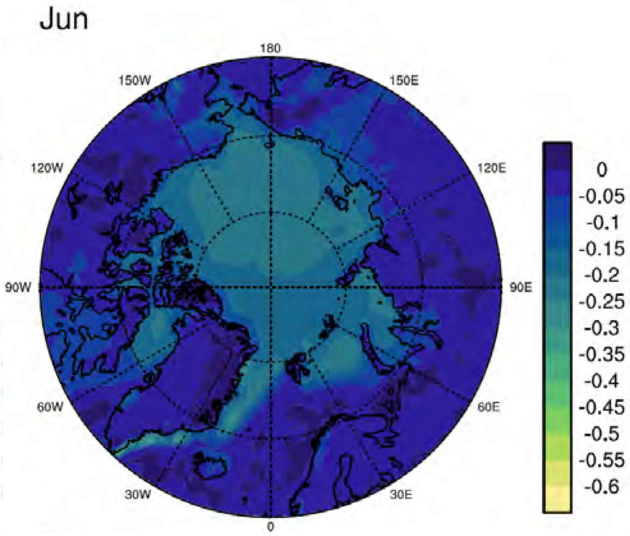


Snow melt increases early absorbed sunlight in June experiment

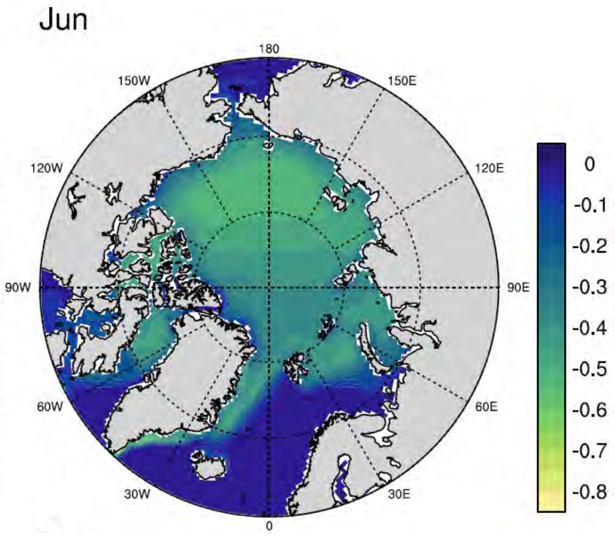
Δ Surface Net SW (W m^{-2})



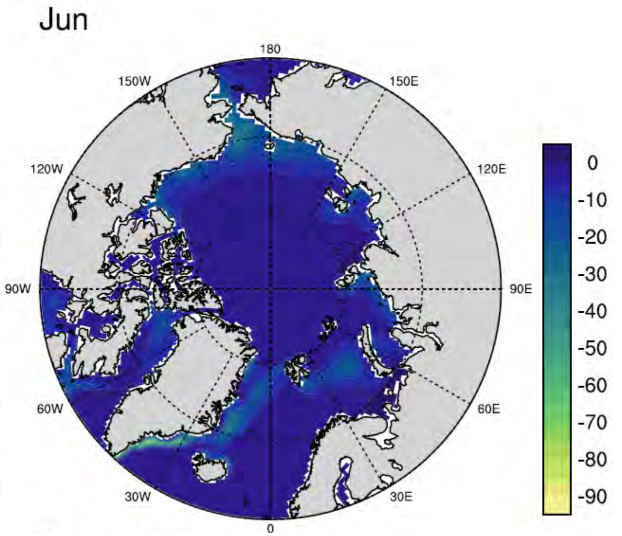
Δ Surface Albedo



Δ Snow Fraction



Δ Sea ice area (%)



Hahn at al., in prep

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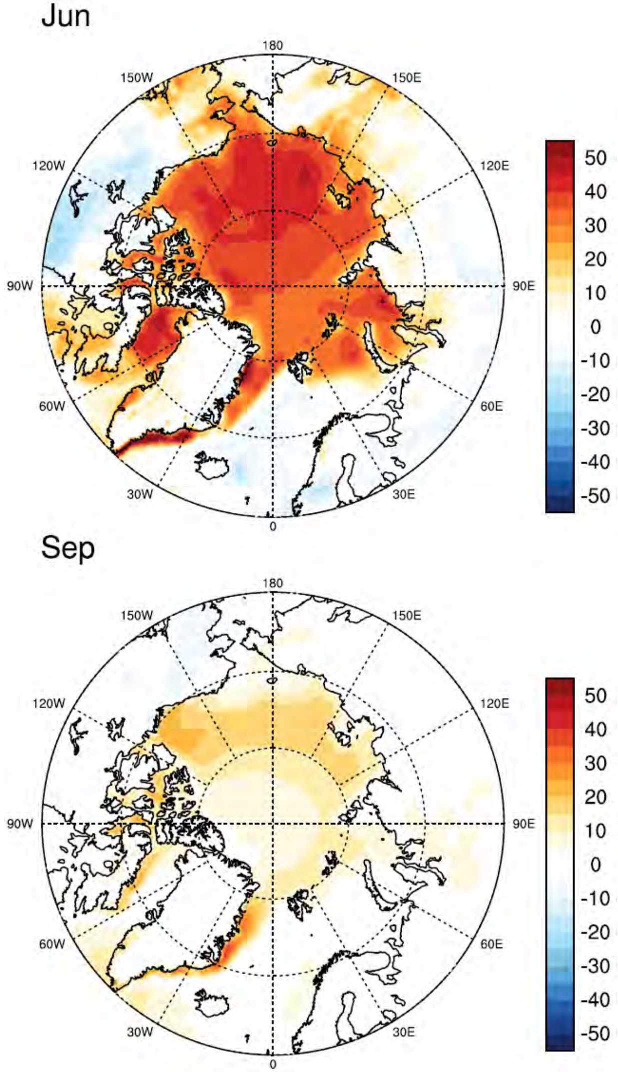

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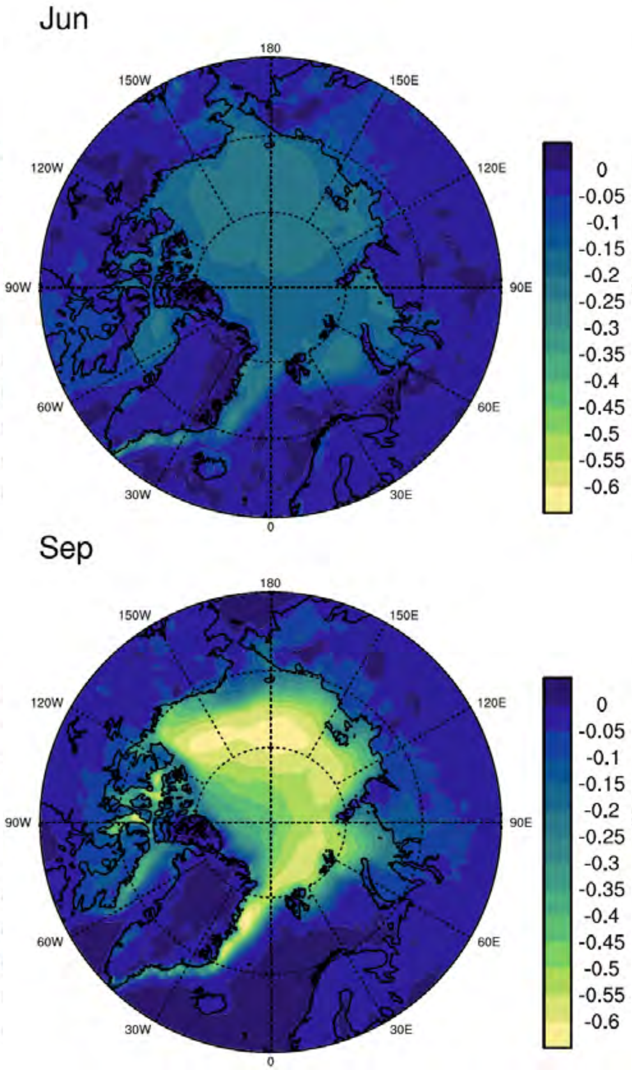

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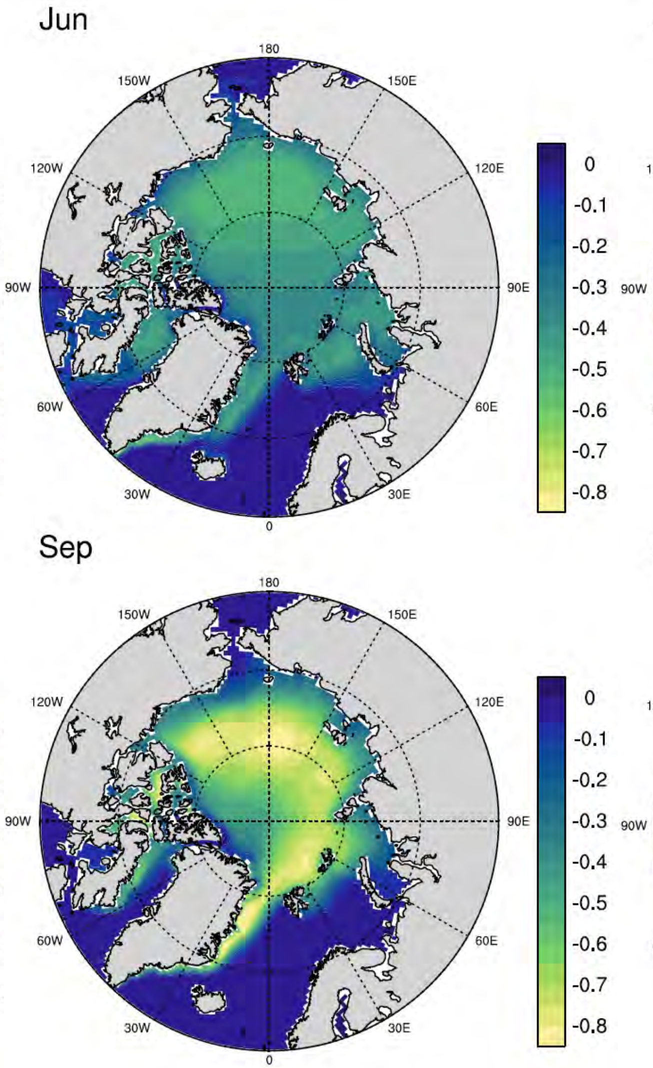

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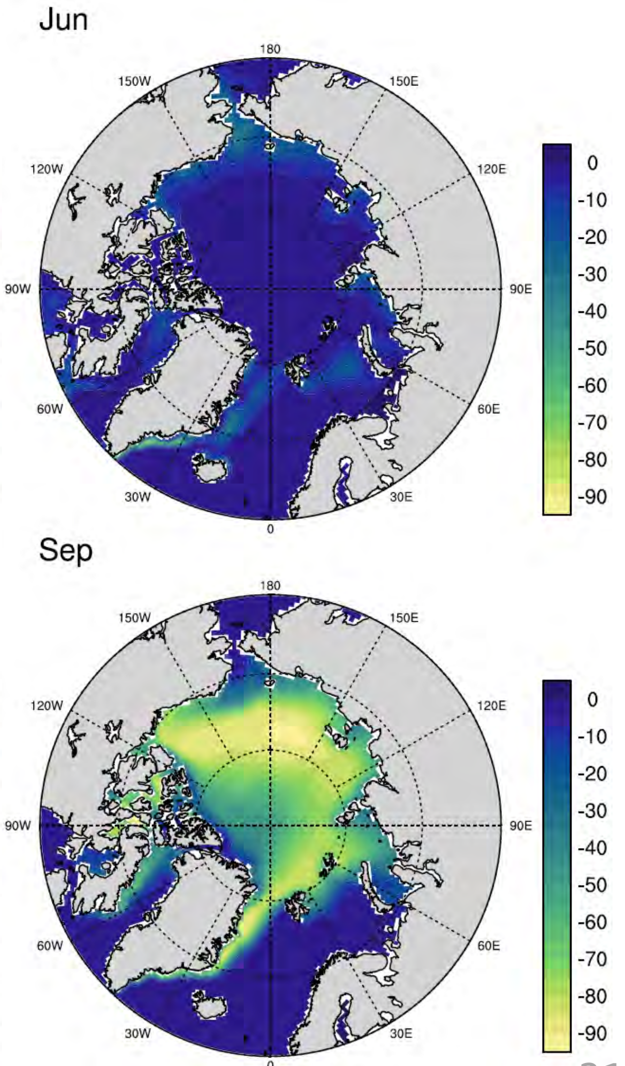
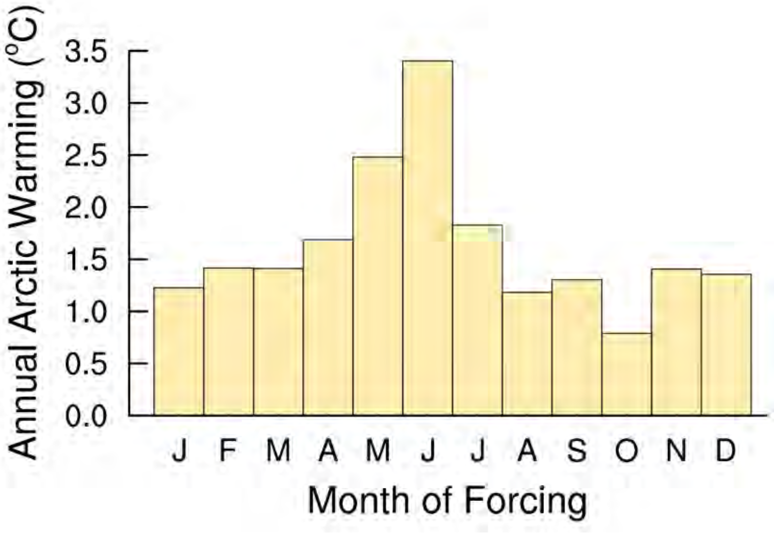


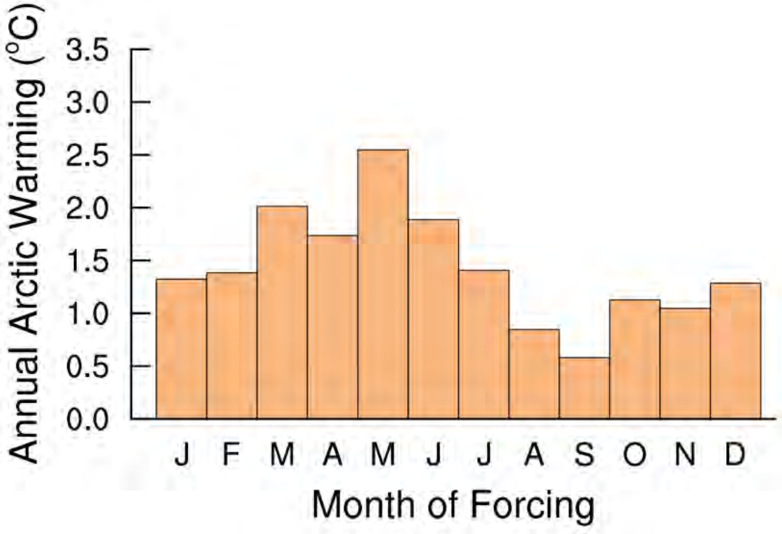
Summer forcing has a smaller impact in a warmer climate

Positive forcing

1850 base-state



2xCO2 base-state



Hahn at al., in prep |

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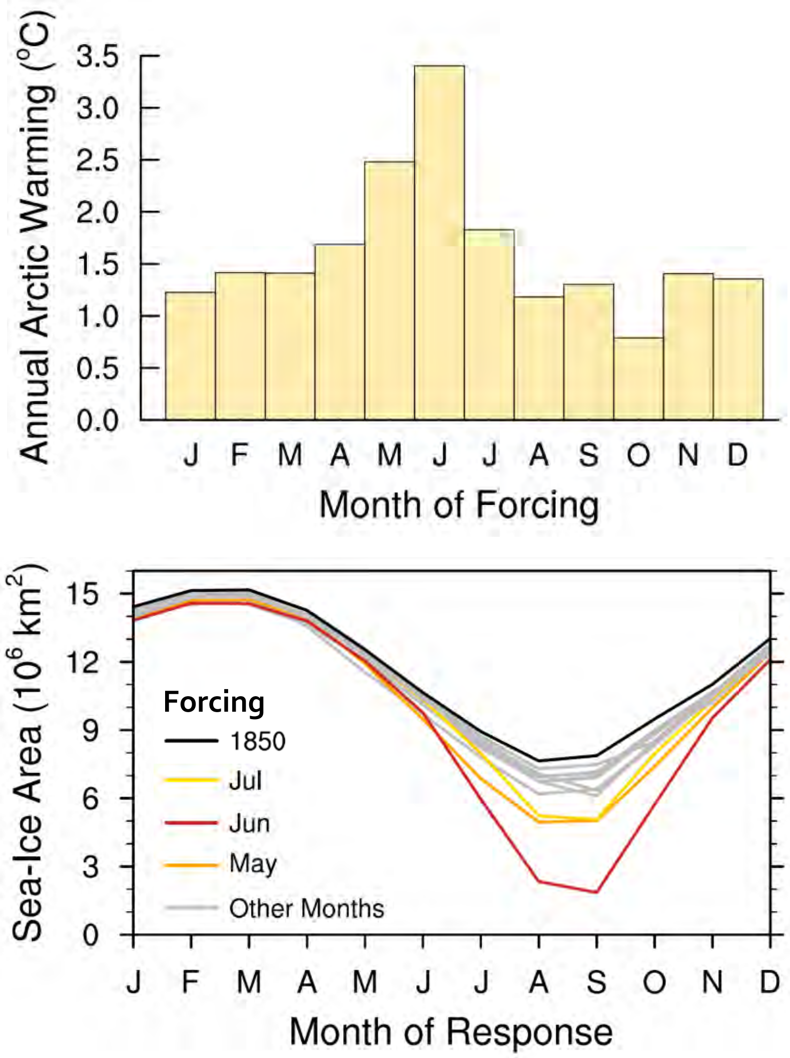
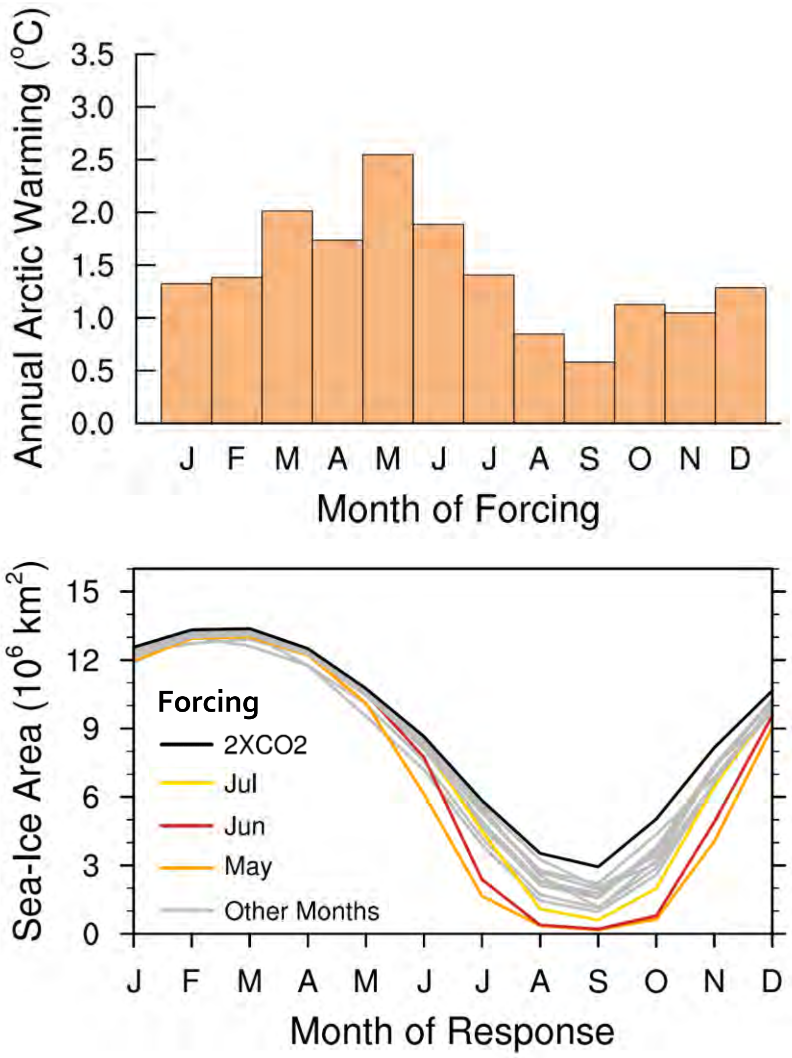


2xCO2 base-state



Hahn at al., in prep

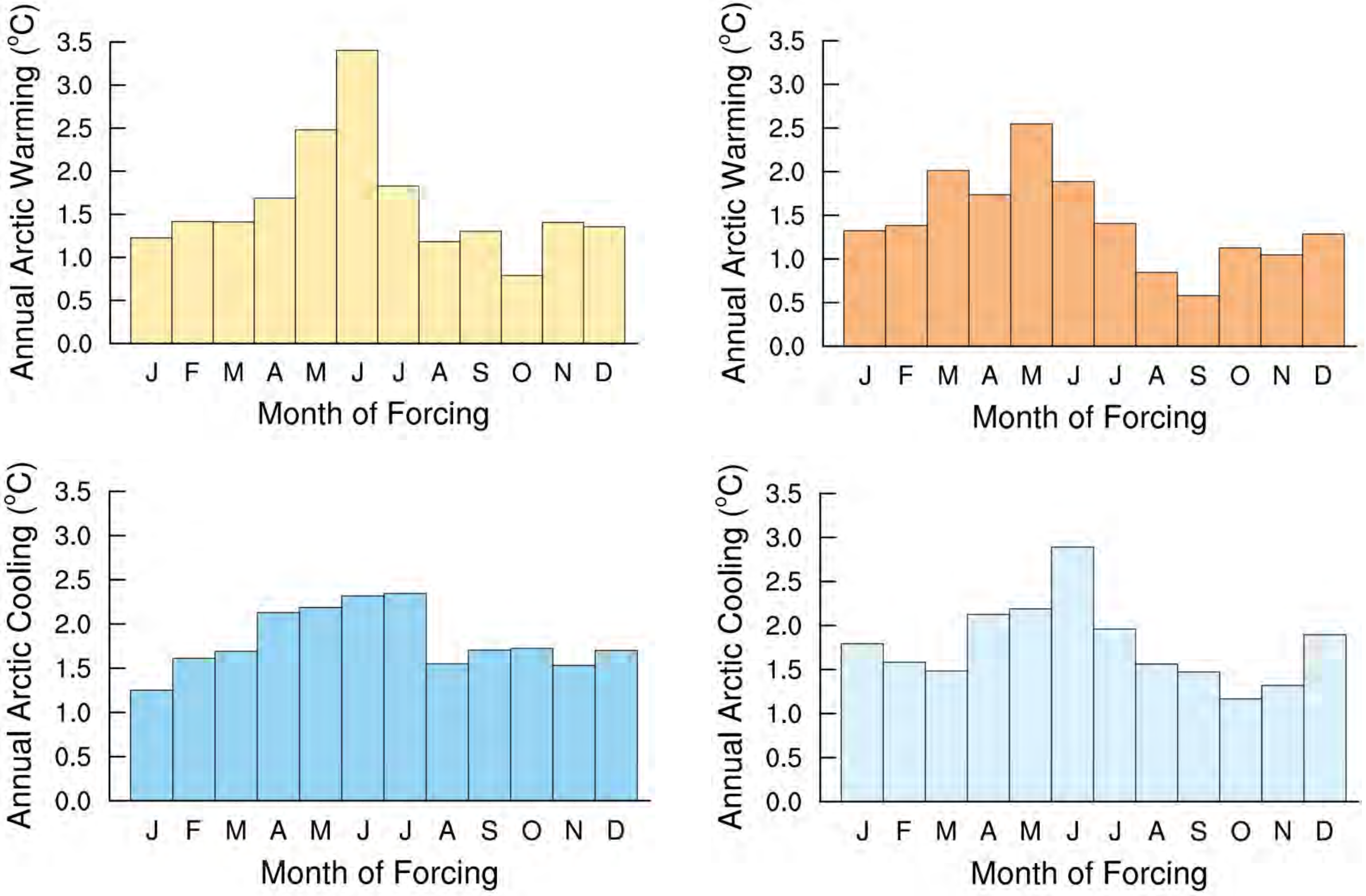
Sensitivity to sign of forcing depends on base-state climate

1850 base-state

2xCO2 base-state

Positive forcing

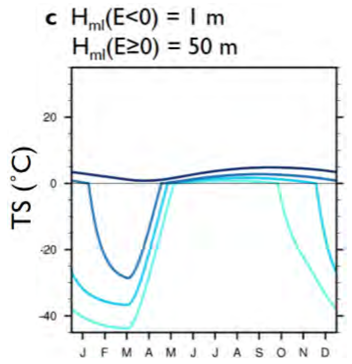
Negative forcing



Hahn at al., in prep

Seasonal pattern of Arctic warming

1. What drives the winter peak in Arctic warming?



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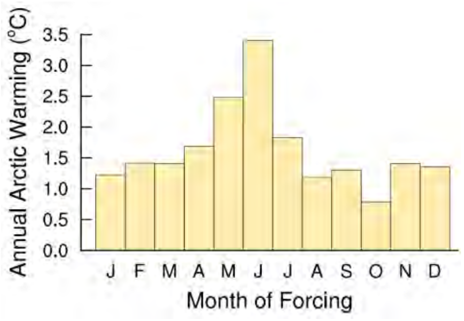

Early summer radiative heating produces the largest annual-mean Arctic warming and comparable winter warming to winter radiative heating

Seasonal pattern of Arctic warming

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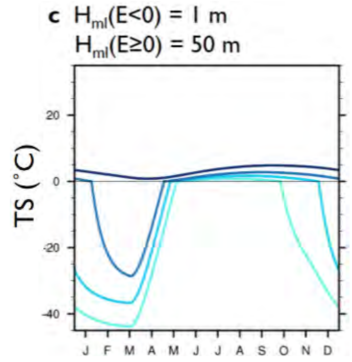

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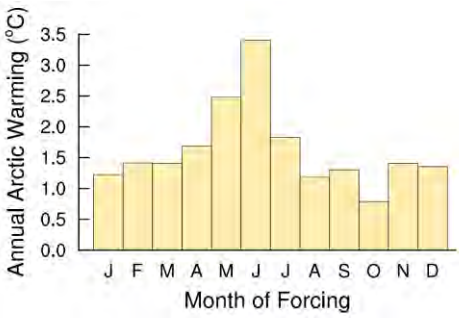

Early summer radiative heating produces the largest annual-mean Arctic warming and comparable winter warming to winter radiative heating

Early summer processes are particularly important for future study; expect important impacts of non-winter heat transport, forcing, and feedbacks on winter warming

Diagnostic analysis of winter feedback contributions in climate models excludes:

- Any physical process that does not appear in a radiative budget (like changes in surface effective heat capacity)

- Interactions between mechanisms in different seasons (like summer feedbacks that impact winter warming)

➡ Importance of alternative frameworks, simpler models, and idealized experiments to understand and predict polar climate change