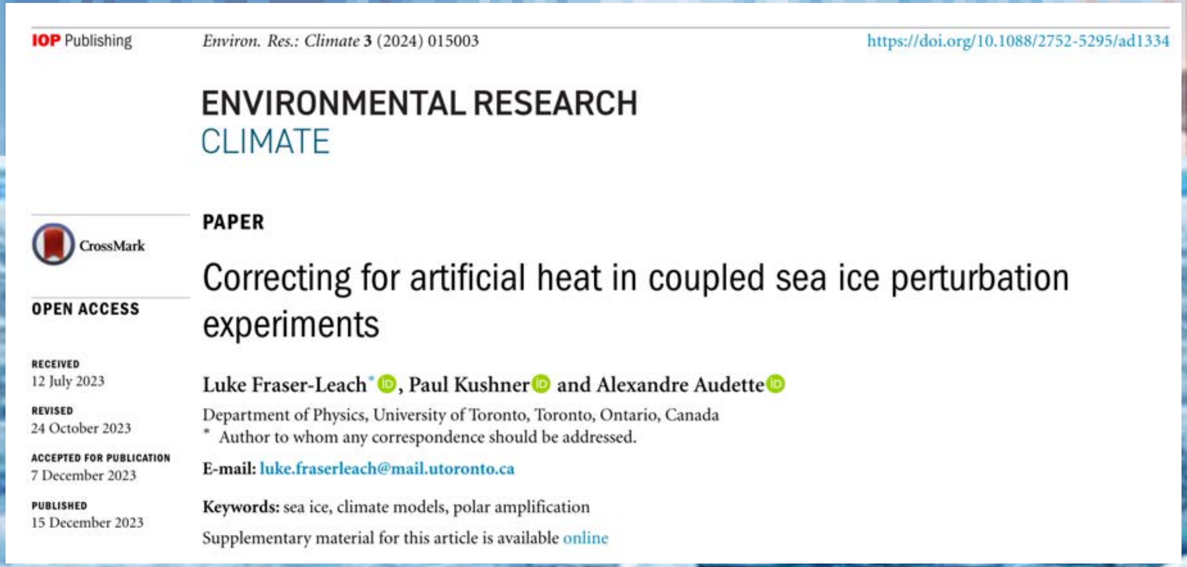
Applying, Justifying, and Extending Multi-parameter Pattern Scaling to Interpret Polar Amplification in Earth System Models



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PAPER

Correcting for artificial heat in coupled sea ice perturbation experiments

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Keywords: sea ice, climate models, polar amplification

Supplementary material for this article is available online

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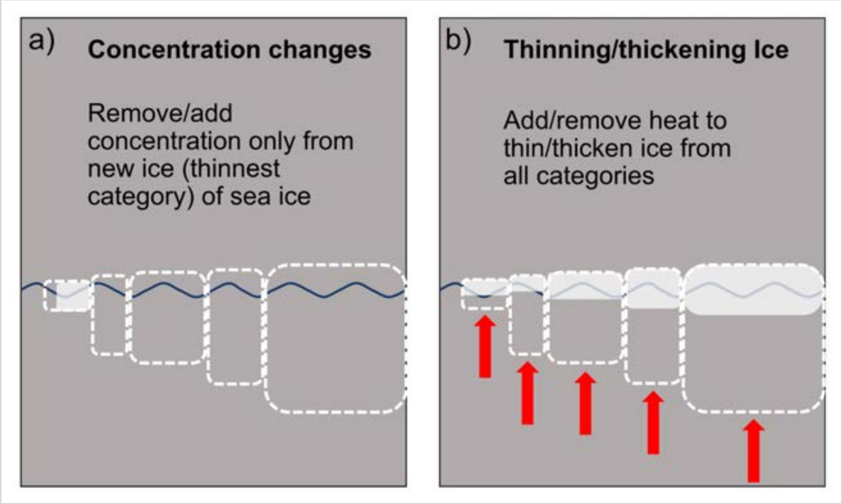
Alexandre Audette, *University of California, Santa Cruz*
Stephanie Hay, *University of Exeter*

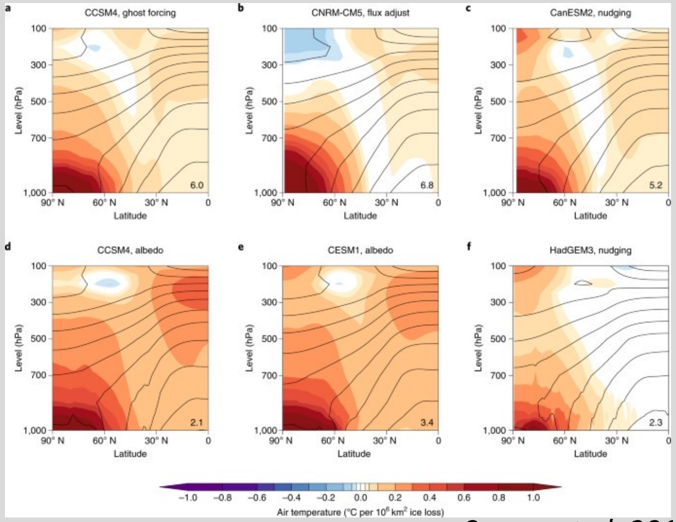
Dealing with artifacts in sea-ice perturbation experiments

Impose sea ice loss in a coupled model



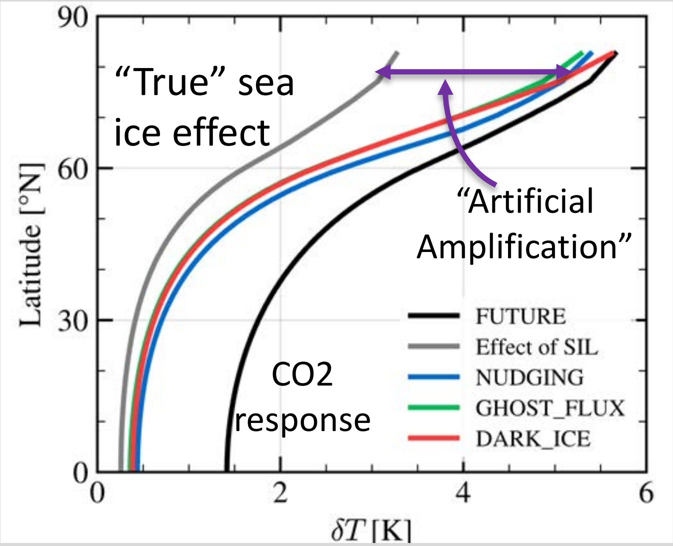
Audette & Kushner 2023

Response to imposed sea-ice loss in coupled models



Screen et al. 2018

Artificial heat in a moist EBM



England et al. 2022, Fraser-Leach et al. 2023

- Issues with coupled sea ice perturbation experiments:
  - Responses to sea ice depend on model and forcing method (Screen et al. 2018, Hay et al. 2022, Audette & Kushner 2022).
  - Constraining sea ice drives artificial Arctic warming and Arctic amplification (England et al. 2022, Fraser-Leach et al. 2023).
- To interpret and attribute causes and consequences of Arctic amplification, we have linearly combined greenhouse forcing and sea-ice forcing experiments, using *multi-parameter pattern scaling* (MPPS; Blackport & Kushner 2017, Hay et al. 2022, Zappa et al. 2018).
- Here, we extend MPPS to deal with artificial Arctic amplification and reinterpret the polar-tropical "tug of war" (Fraser-Leach et al. 2023).
- We examine alternate scalings based on sea-ice forcing and atmospheric lapse rates (Hay & Kushner, in review)

MPPS in a nutshell

Posit that response to external forcing depends on internal scaling parameters, like spatial mean temperature and sea-ice extent, independent of forcing.

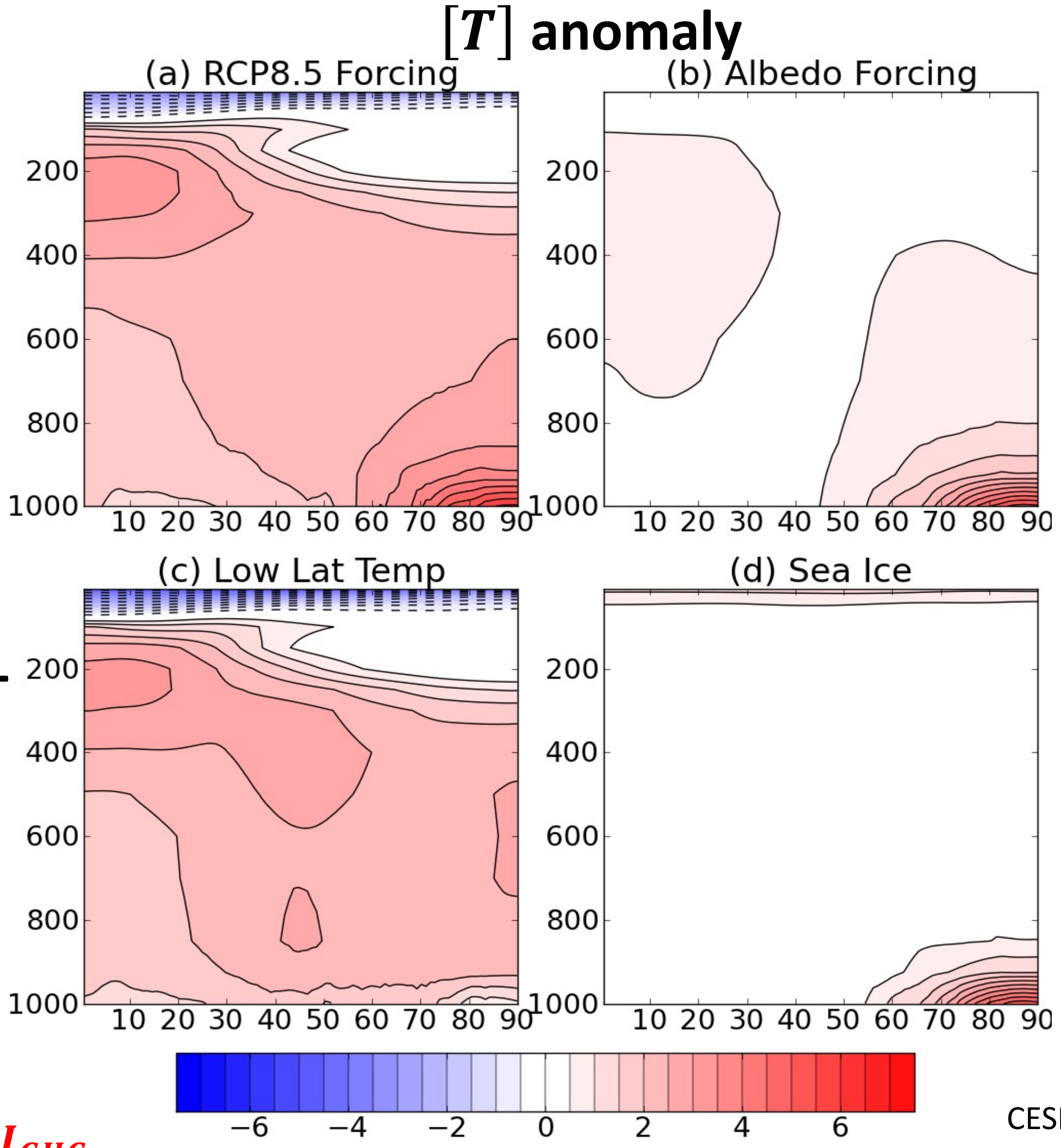
1. Diagnose pattern of response to *N* forcings (e.g. GHG or sea-ice forcing).	$\{\delta Z_m(\vec{x})\}, m = 1, \ldots, N$
2. Diagnose response of *N* scaling parameters to N forcings (e.g. tropical temperatures, sea-ice extent), assuming independence of responses.	$\{\delta s_{m,n}\}, m, n = 1, \ldots, N$
3. Infer underlying patterns of sensitivity to internal scaling variables.	$\delta Z_m(\vec{x}) = \sum_n \frac{\partial Z(\vec{x})}{\partial s_n} \delta s_{m,n}$ $\Rightarrow \frac{\partial Z(\vec{x})}{\partial s_n} = \sum_m \delta s^{-1}_{m,n} \delta Z_m(\vec{x})$

Blackport and Kushner 2017, Hay et al. 2022, Fraser-Leach et al. 2023, Hay and Kushner in review

E.g. MPPS for CESM LENS & Albedo-Forcing Experiments

Response **to greenhouse warming** $\delta[T]_{GHG}$

Response **to albedo change** $\delta[T]_{albedo}$



Partial response to low-latitude warming

$$\left(\frac{\partial[T]}{\partial T_l}\right)_I \delta T_{l,GHG}$$

Partial response to sea-ice loss

$$\left(\frac{\partial[T]}{\partial I}\right)_{T_l} \delta I_{GHG}$$

(a) = (c) + (d)

$$\delta[T]_{GHG} = \left(\frac{\partial[T]}{\partial T_l}\right)_I \delta T_{l,GHG} + \left(\frac{\partial[T]}{\partial I}\right)_{T_l} \delta I_{GHG}$$

CESM1 LENS & Albedo forcing experiments
Blackport and Kushner 2017

Sea-ice *extent* scaling implies a strong tug of war

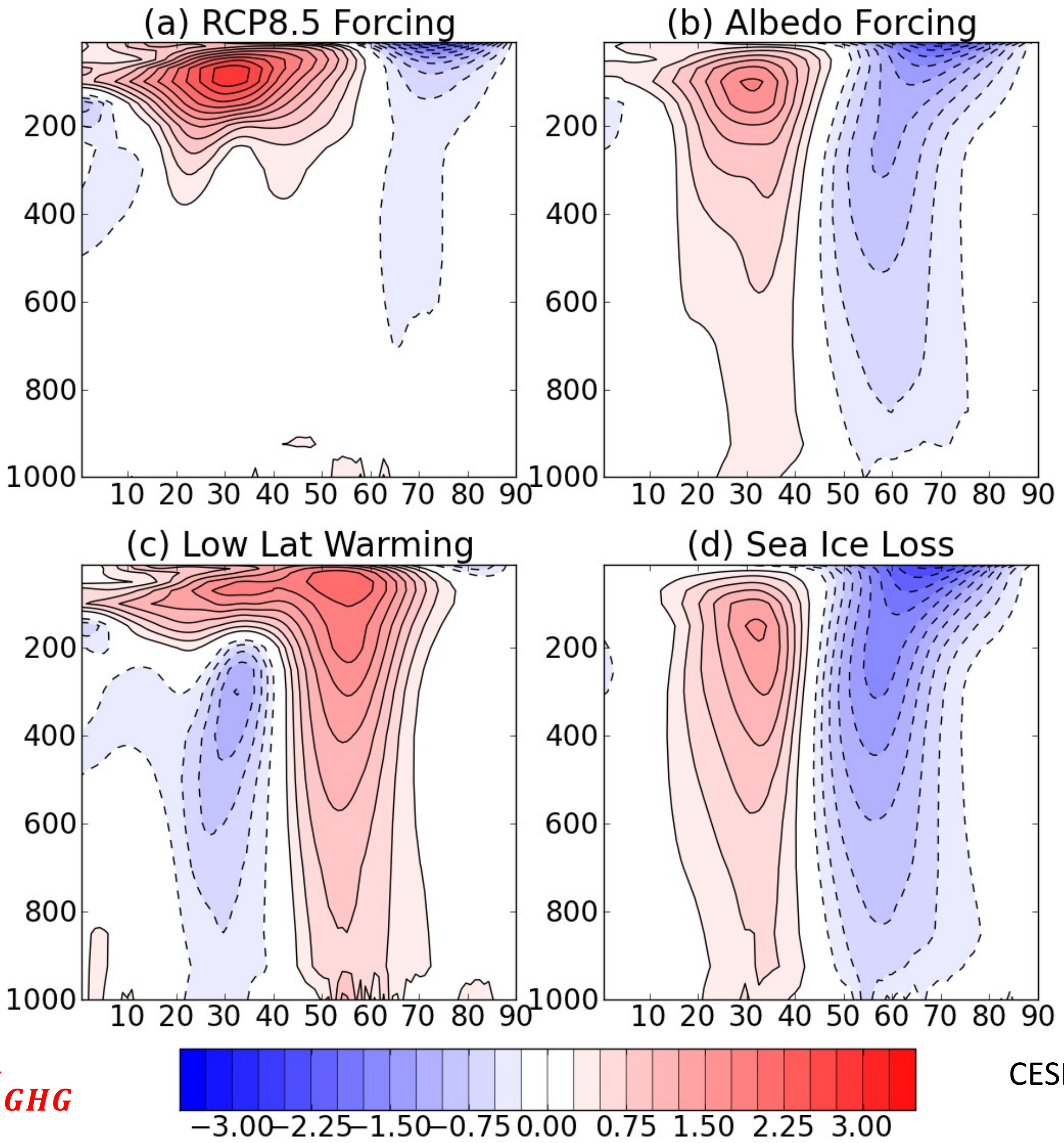
$[U]$ anomaly

Response **to greenhouse warming**

$$\delta[U]_{GHG}$$

Response **to albedo change**

$$\delta[U]_{albedo}$$



Partial response to low-latitude warming

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Partial response to sea-ice loss

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(a) = (c) + (d)

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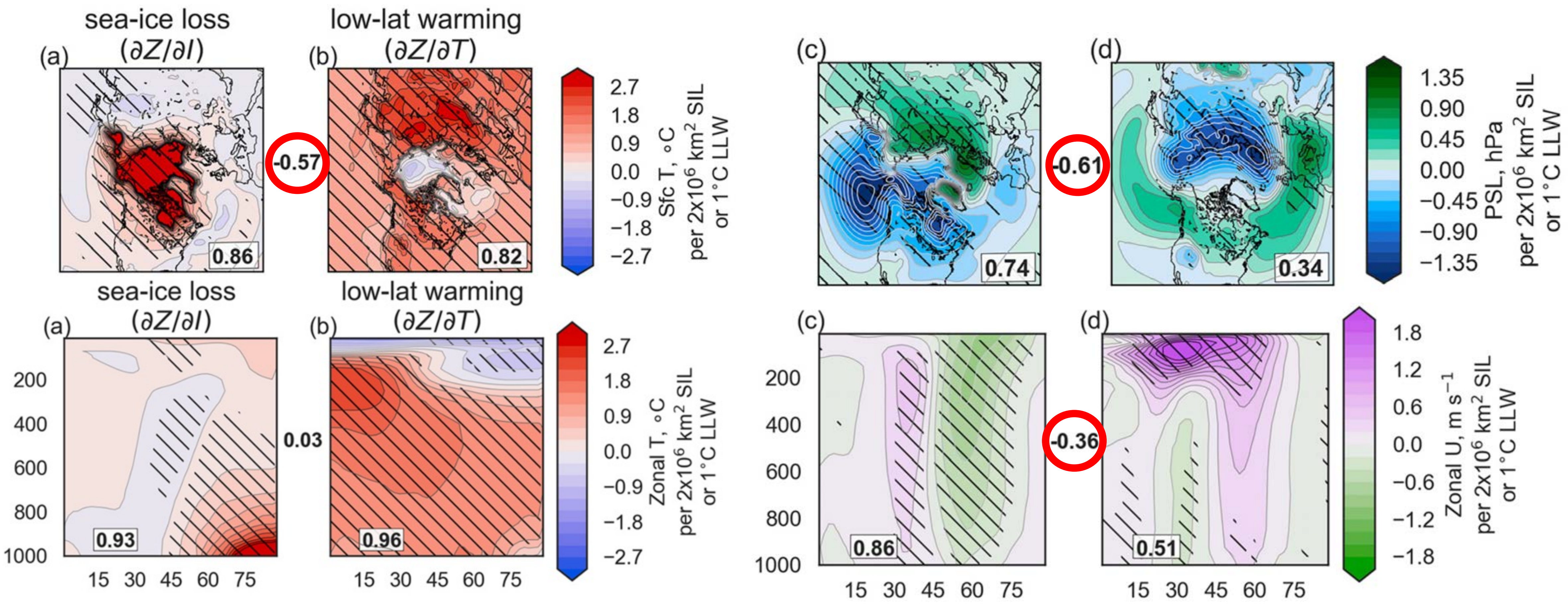
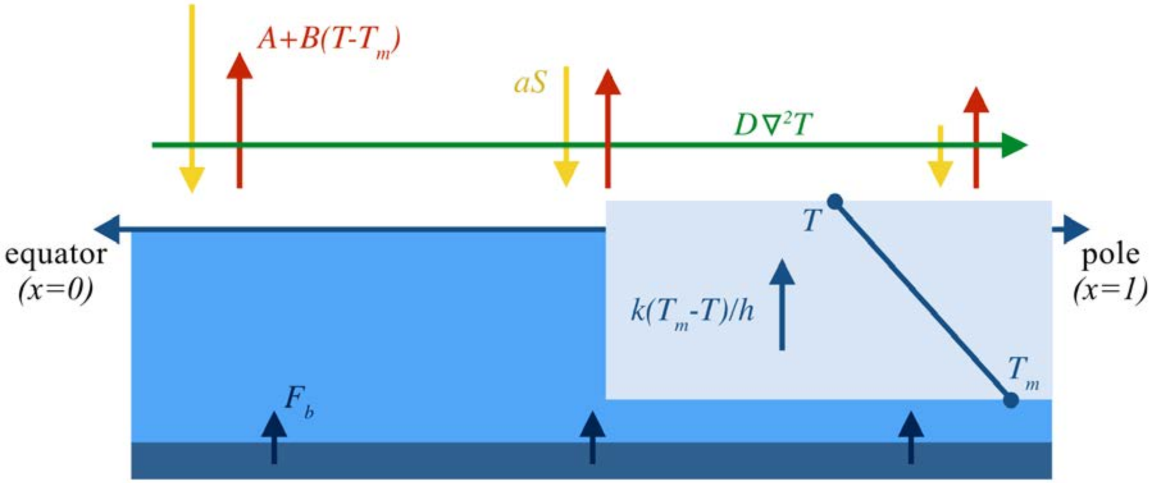
Sea-ice *extent* scaling implies strong tugs of war



Hay et al., 2022: mean of MPPS partial responses from sea ice perturbation experiments in 5 models.

Energy balance model (EBM)



$$\frac{\partial E}{\partial t} = \underbrace{aS}_{\text{solar}} - \underbrace{L}_{\text{OLR}} + \underbrace{D\nabla^2 T}_{\text{transport}} + \underbrace{F_b}_{\text{ocean heating}} + \underbrace{F}_{\text{forcing}}$$

$$\boldsymbol{B\delta\langle\overline{T}\rangle_{GHG} = \delta\langle\overline{aS}\rangle_{GHG} + \delta F_{GHG}}$$

$\overline{\boldsymbol{x}}$ = annual mean

$\langle\boldsymbol{x}\rangle$ = global mean

True effect of SIL:

$$\boldsymbol{B\delta\langle\overline{T}\rangle_{SIL,\,true} = \delta\langle\overline{aS}\rangle_{GHG}}$$

Wagner & Eisenman, 2015

England et al. 2022

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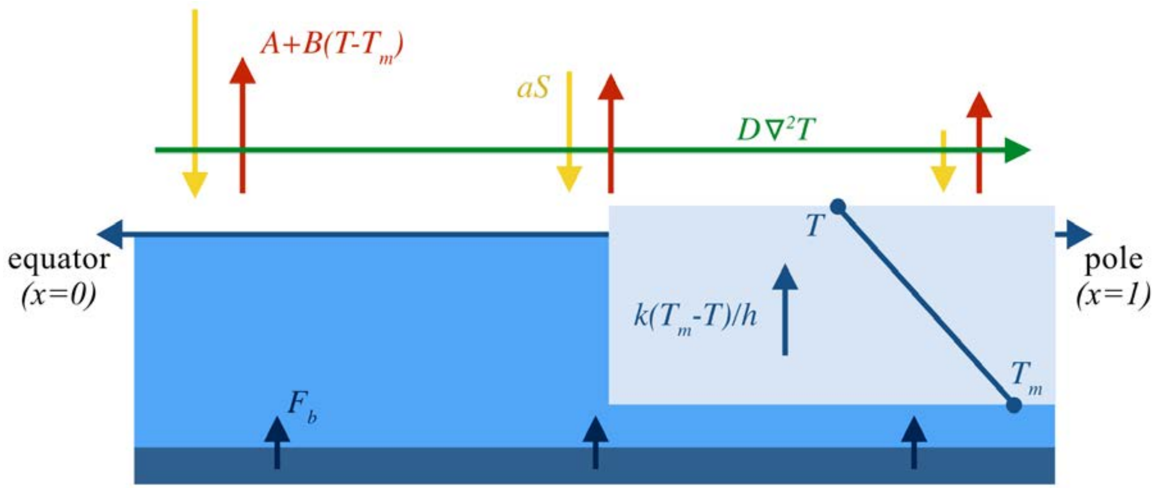

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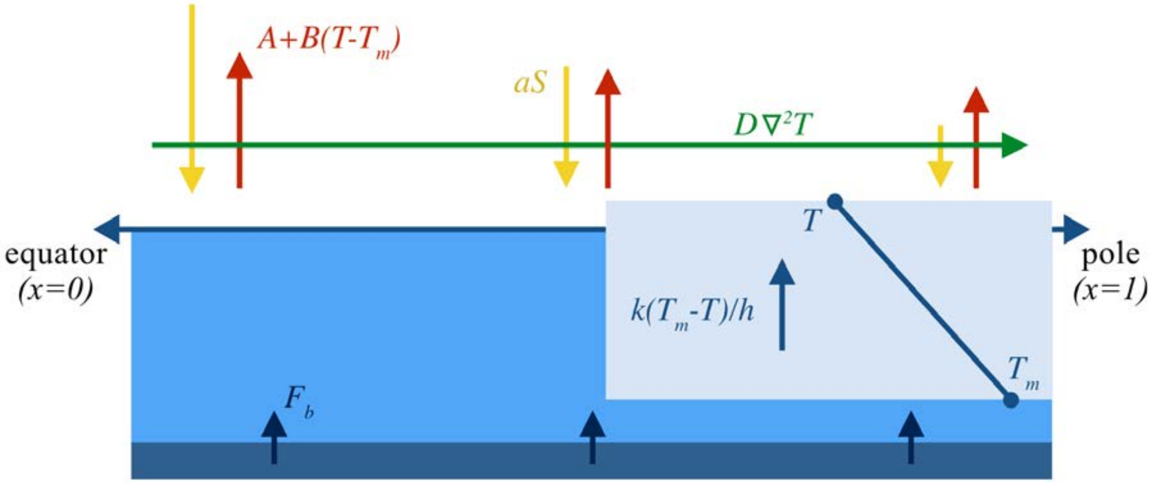

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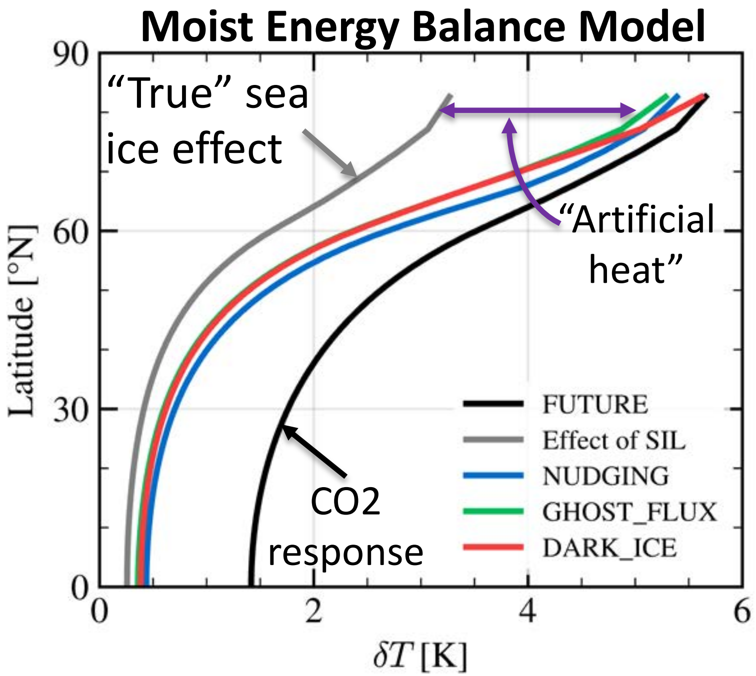
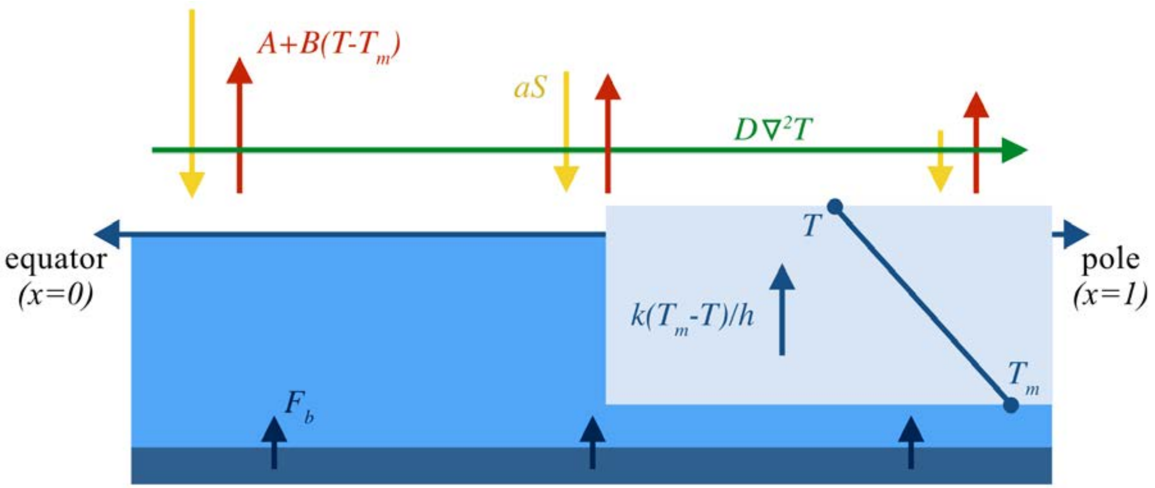
Perturbation experiments:



England et al. 2022

Energy balance model (EBM)



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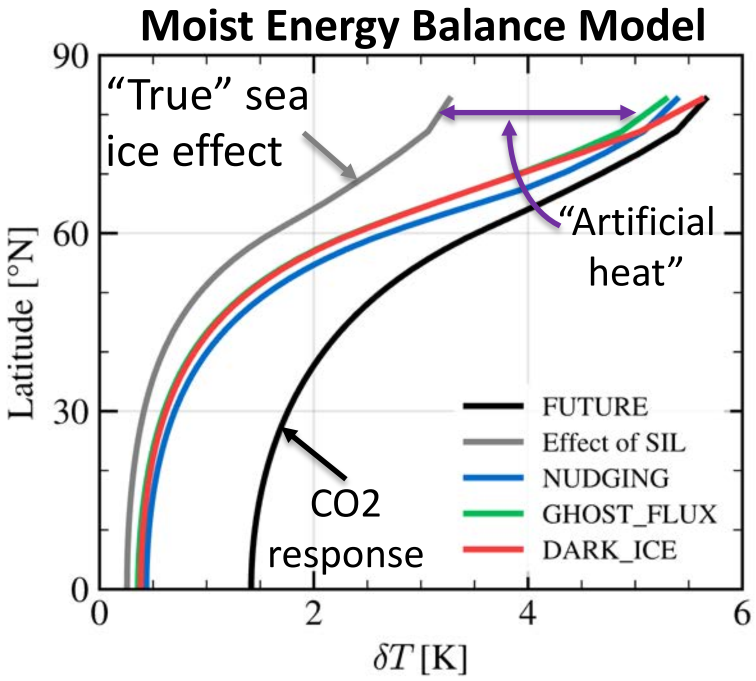
$$B\delta\langle\overline{T}\rangle_{SIL,\,true} = \delta\langle\overline{aS}\rangle_{GHG}$$

Perturbation experiments:

$$B\delta\langle\overline{T}\rangle_{GHOST} = \delta\langle\overline{aS}\rangle_{GHG} + F_{GHOST}$$



England et al. 2022, Fraser-Leach et al., 2023

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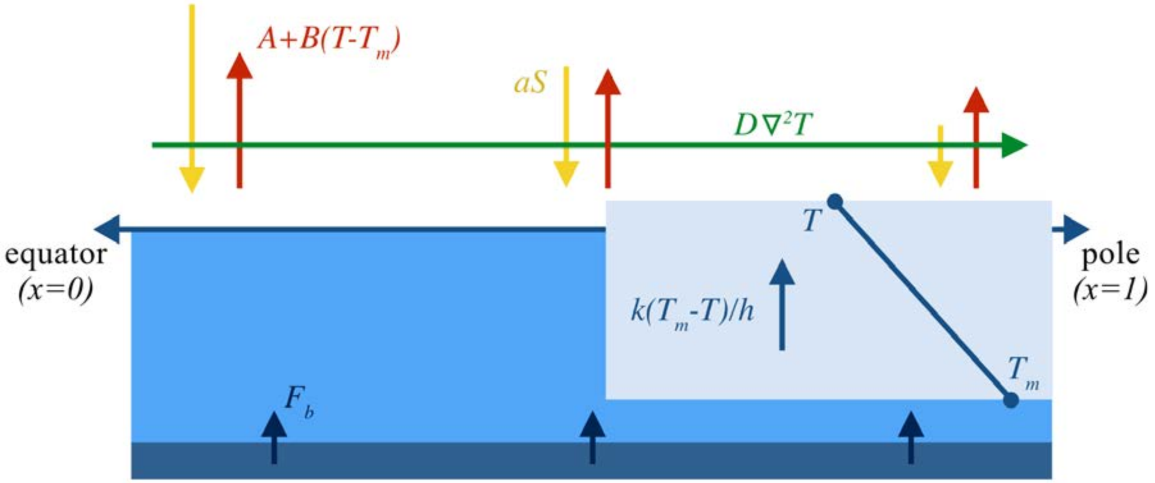

$$\frac{\partial E}{\partial t} = \underbrace{aS}_{\text{solar}} - \underbrace{L}_{\text{OLR}} + \underbrace{D\nabla^2 T}_{\text{transport}} + \underbrace{F_b}_{\text{ocean heating}} + \underbrace{F}_{\text{forcing}}$$

$$B\delta\langle\overline{T}\rangle_{GHG} = \delta\langle\overline{aS}\rangle_{GHG} + \delta F_{GHG}$$

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Wagner & Eisenman, 2015

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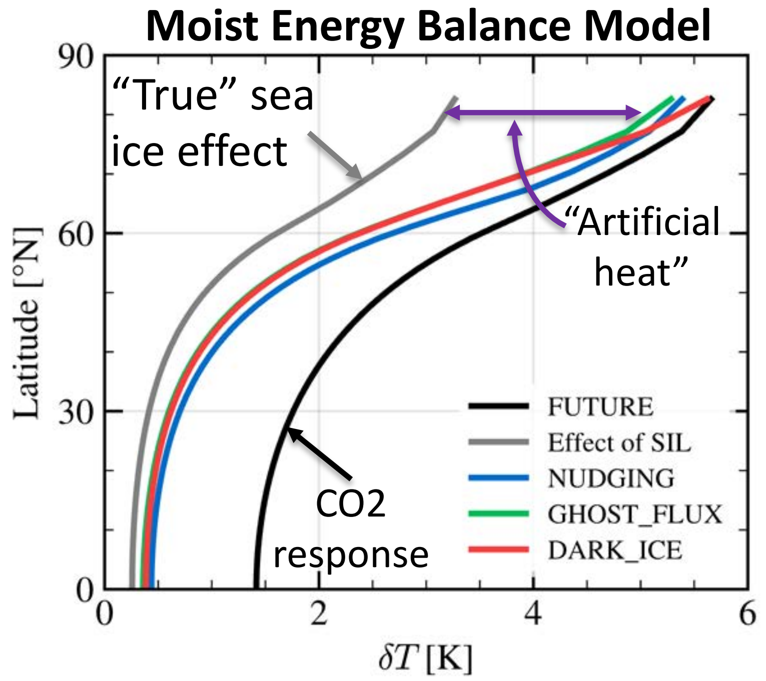
Perturbation experiments:

$$B\delta\langle\overline{T}\rangle_{GHOST} = \delta\langle\overline{aS}\rangle_{GHG} + F_{GHOST}$$
$$B\delta\langle\overline{T}\rangle_{NUDGING} = \delta\langle\overline{aS}\rangle_{GHG} + F_{NUDGING}$$



England et al. 2022, Fraser-Leach et al., 2023

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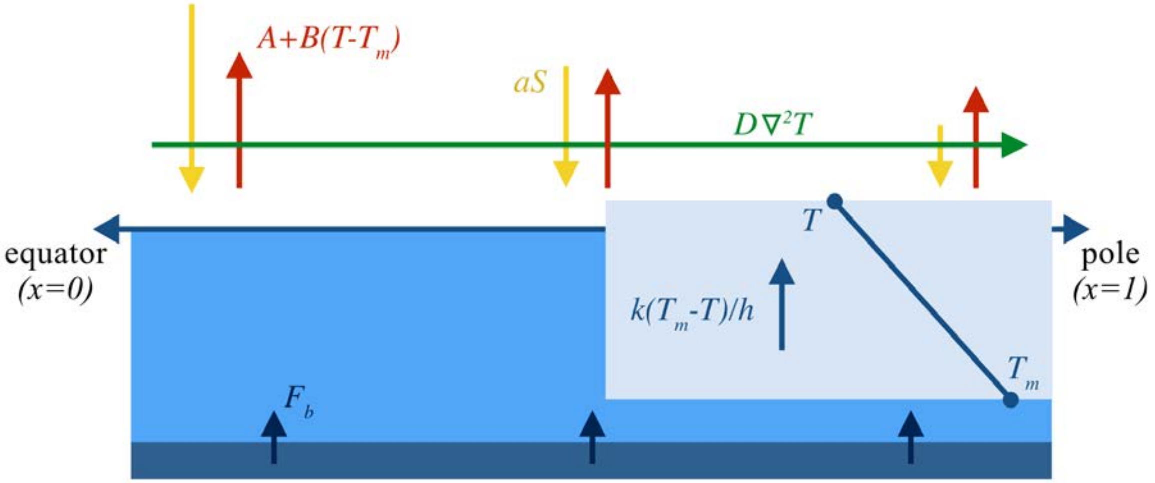

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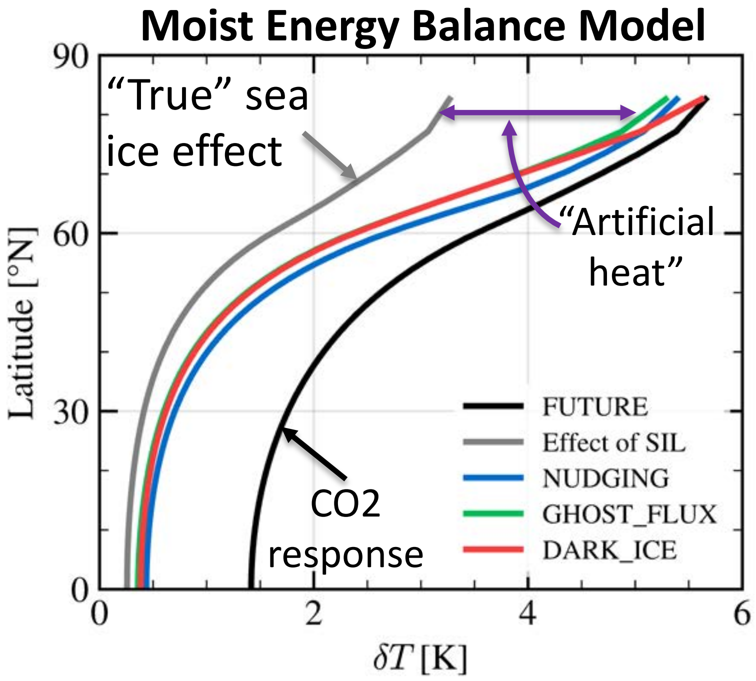
$$B\delta\langle\overline{T}\rangle_{DARK\_ICE} = \delta\langle\overline{aS}\rangle_{GHG} + \delta\langle\overline{aS}\rangle_{artificial}$$



England et al. 2022, Fraser-Leach et al., 2023

Sea-ice *forcing* scaling corrects for the artificial heat

Original sensitivities misattribute artificial warming to SIL:

$$\frac{\partial\langle\overline{T}\rangle}{\partial T_l} \approx \frac{B^{-1}\left(F_{ghg} - \langle\overline{F_{pert}}\rangle\right)}{\delta T_{l,F}}$$

$$\frac{\partial\langle\overline{T}\rangle}{\partial I} \approx \frac{B^{-1}\left(\delta\langle\overline{aS}\rangle + \langle\overline{F_{pert}}\rangle\right)}{\delta I}$$

Scale by $\boldsymbol{F_{ice} = \delta\langle aS\rangle + \langle F_{pert}\rangle}$ instead:

$$\frac{\partial\langle\overline{T}\rangle}{\partial F_{ghg}} = \frac{B^{-1}F_{ghg}}{F_{ghg}} = \frac{1}{B}$$

$$\frac{\partial\langle\overline{T}\rangle}{\partial F_{ice}} = \frac{B^{-1}(F_{pert} + \delta aS)}{F_{pert} + \delta aS} = \frac{1}{B}$$

Sea-ice *forcing* scaling corrects for the artificial heat

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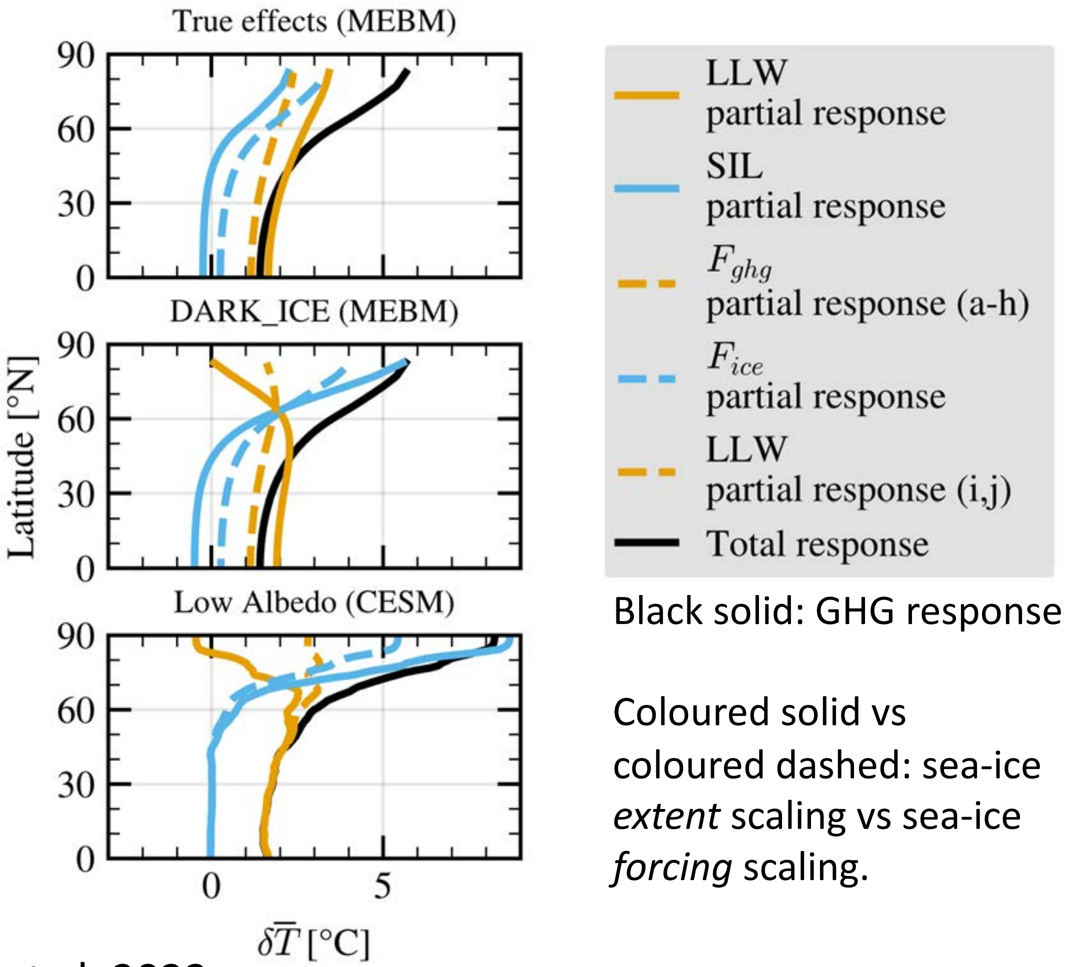
EBM experiments: "True" albedo & GHG

EBM experiments: Artificial albedo & GHG

ESM experiments: Artificial albedo & GHG



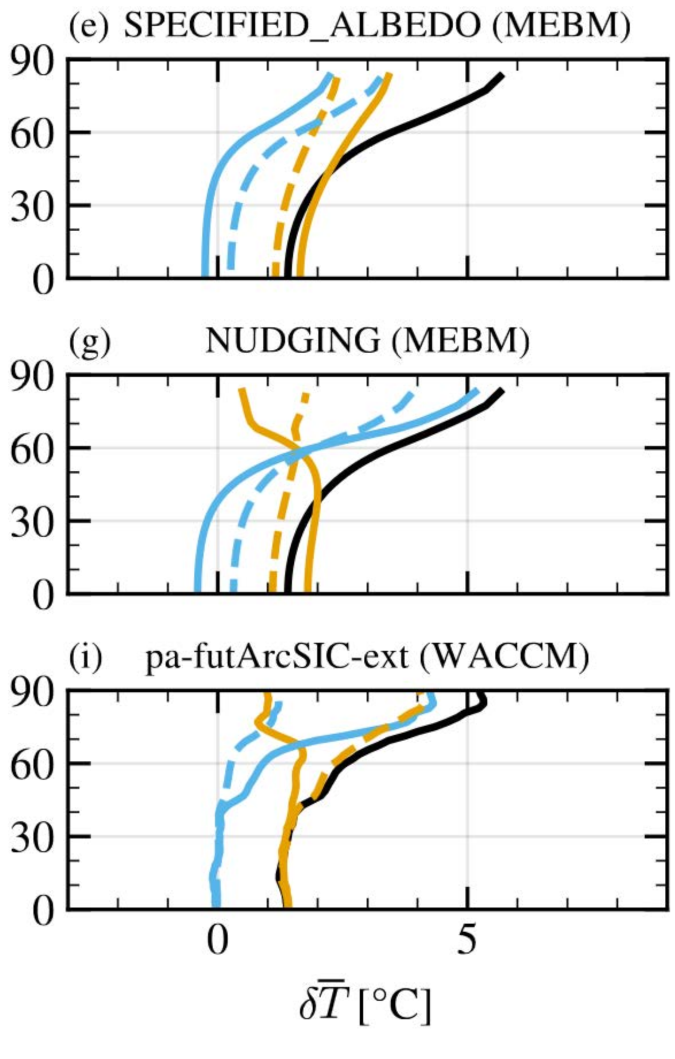
Black solid: GHG response

Coloured solid vs coloured dashed: sea-ice *extent* scaling vs sea-ice *forcing* scaling.

Fraser-Leach et al. 2023

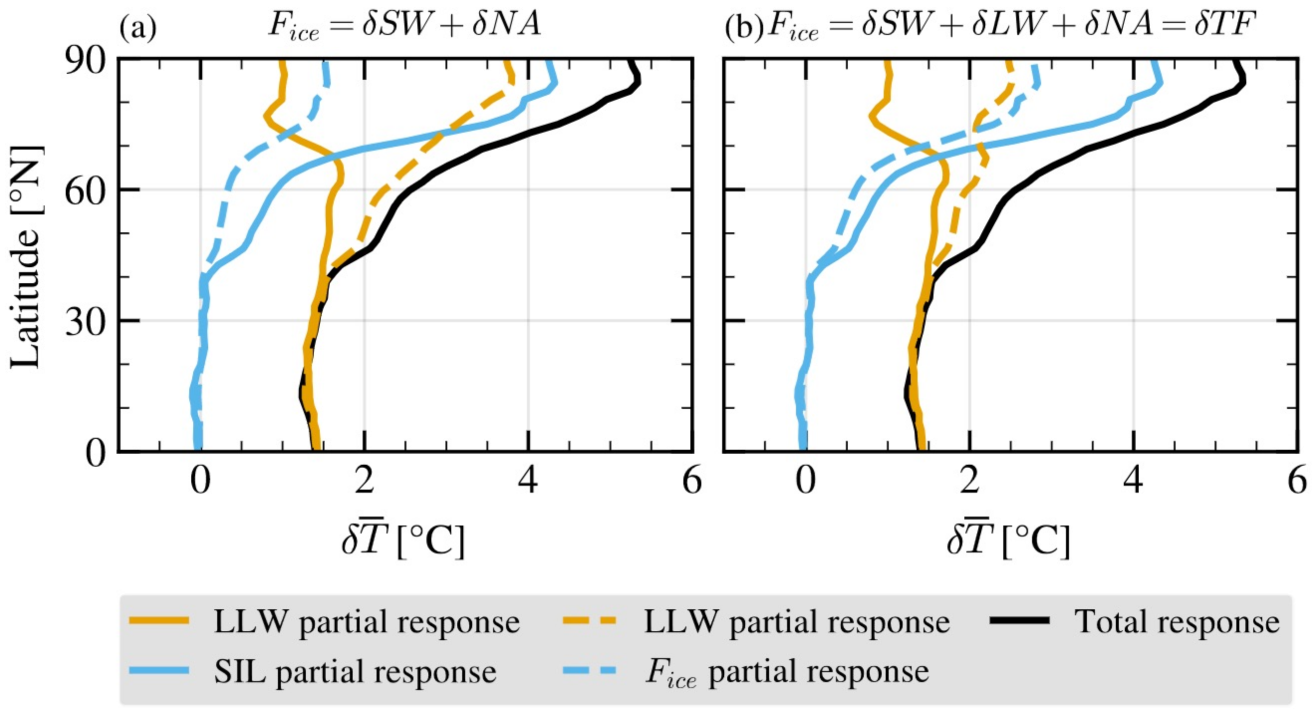
- **Accounts for spurious Arctic amplification.**
- **Eliminates tropical amplification in LLW partial response.**
- **Highlights role of latent heat transport in Arctic amplification (e.g. Merlis and Henry 2018).**

Not obvious how to determine sea ice forcing scaling in ESMs in general



Doesn't make sense to add ghost flux to TOA radiative flux

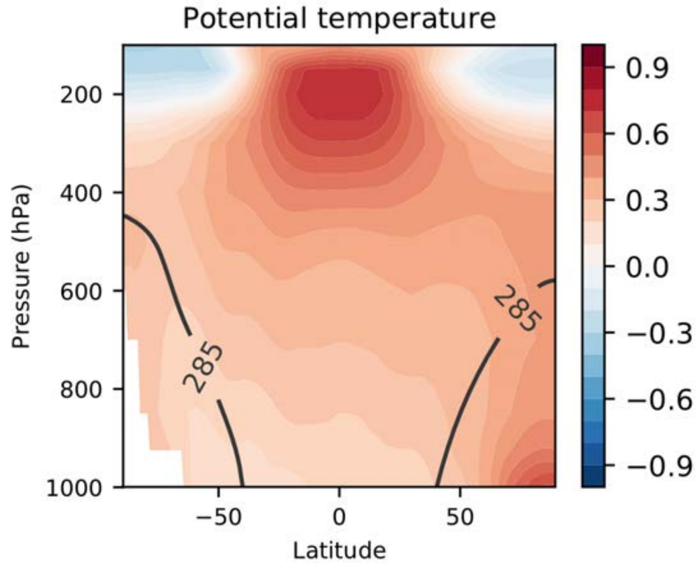
Try different scaling parameters based on surface energy budget (e.g. change in turbulent heat flux)



Fraser-Leach et al. 2023

Using lapse rate as a scaling variable

- Sea-ice *forcing* scaling parameters are forcing method dependent and subjective (Fraser-Leach et al. 2023).
- In multi-model ensembles, polar responses scale with Arctic lower-tropospheric lapse rate (Feldl et al. 2020).
- So let's try lapse-rate scaling alongside the sea-ice scalings (Hay and Kushner in review) ...



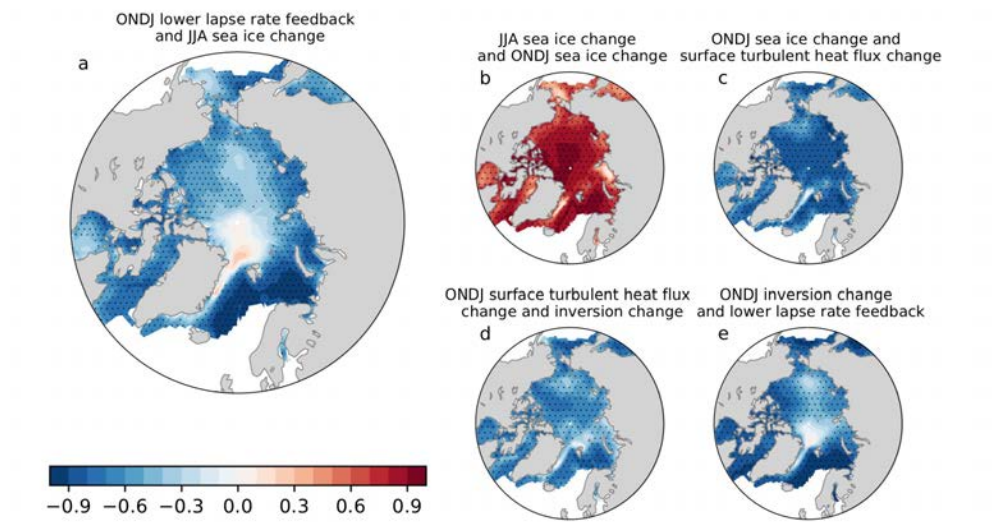


Fig. 4 Map of Pearson correlation coefficient across models between winter lower lapse rate feedback and change in surface and boundary-layer properties in the Arctic. Correlation coefficient between a early fall/late winter (ONDJ; October through January) lower lapse

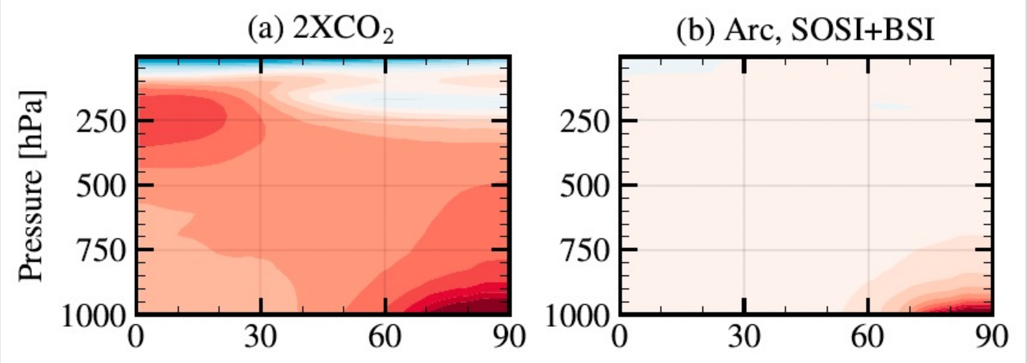
Feldl et al. 2020

Modified albedo (CESM-CAM5)

- Sea-ice forcing scaling and lapse-rate scaling yield similar results:
  - Shallow Arctic amplification that scales with Arctic lapse rate changes/sea ice forcing.
  - Deep Arctic amplification that scales with tropical lapse rate changes
  - Avoids tropical amplification/polar amplification tug-of-war.

Greenhouse and sea-ice forcing responses

δT_{2XCO2} δT_{Albedo}

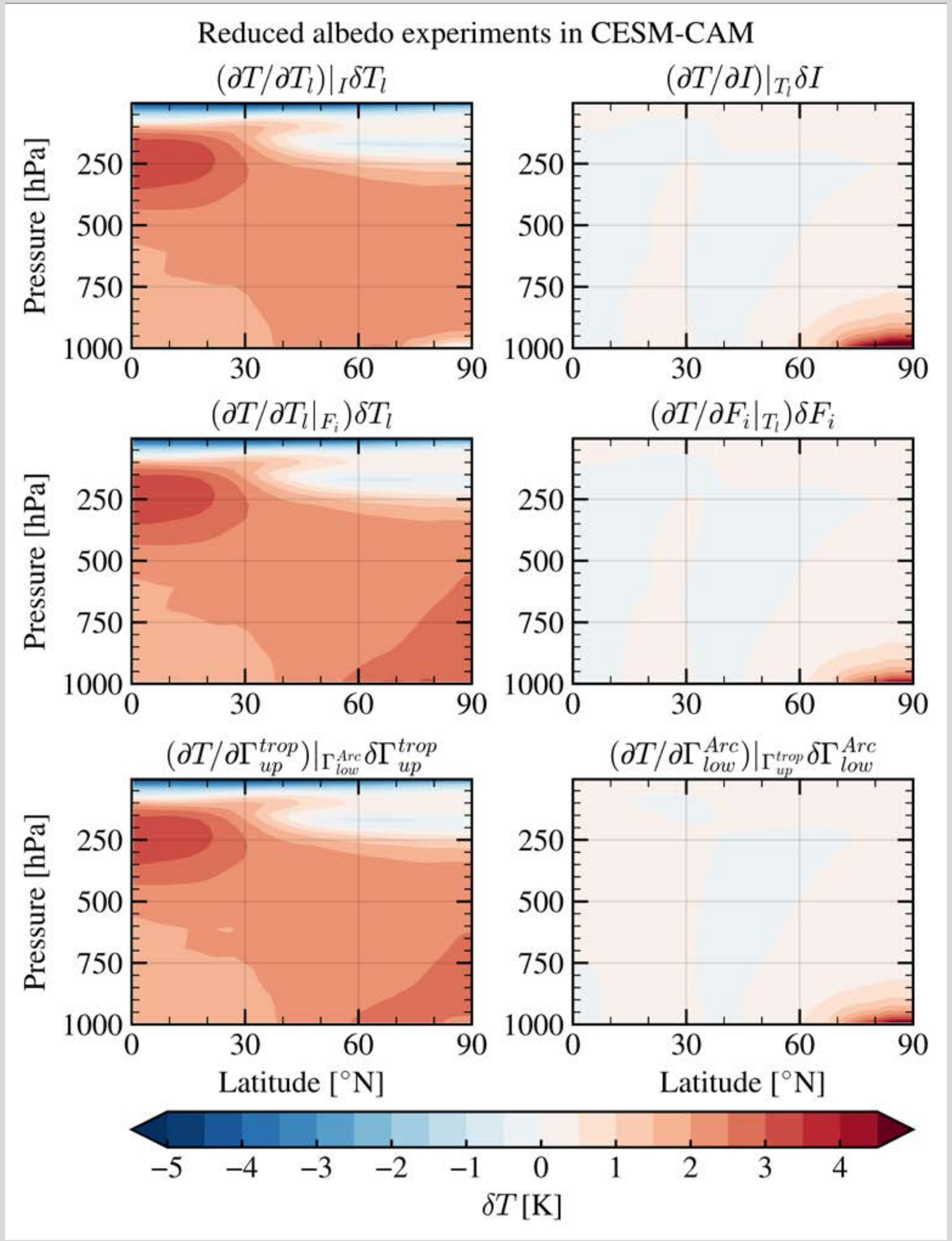


MPPS decompositions

Sea ice *extent* scaling

Sea ice *forcing* scaling (with TOA Arctic SW)

Lapse-rate scaling

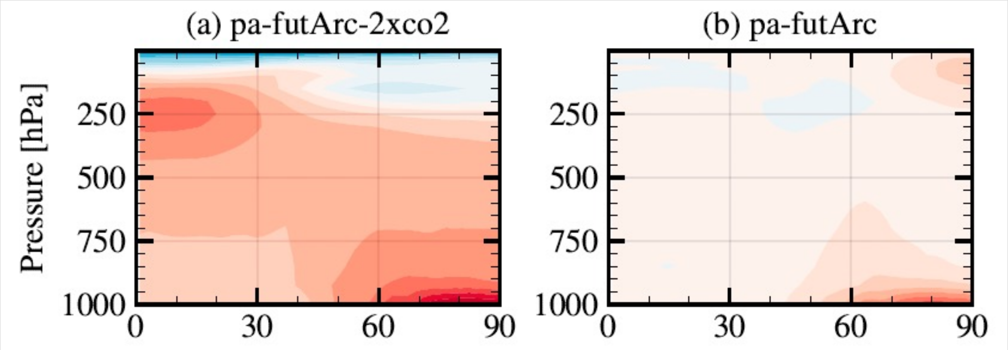


PAMIP hybrid nudging (WACCM-SPCAM4)

- We get similar results with a different ESM and sea-ice forcing technique.

Greenhouse and sea-ice forcing responses

δT_{2XCO2} $\delta T_{Nudging}$

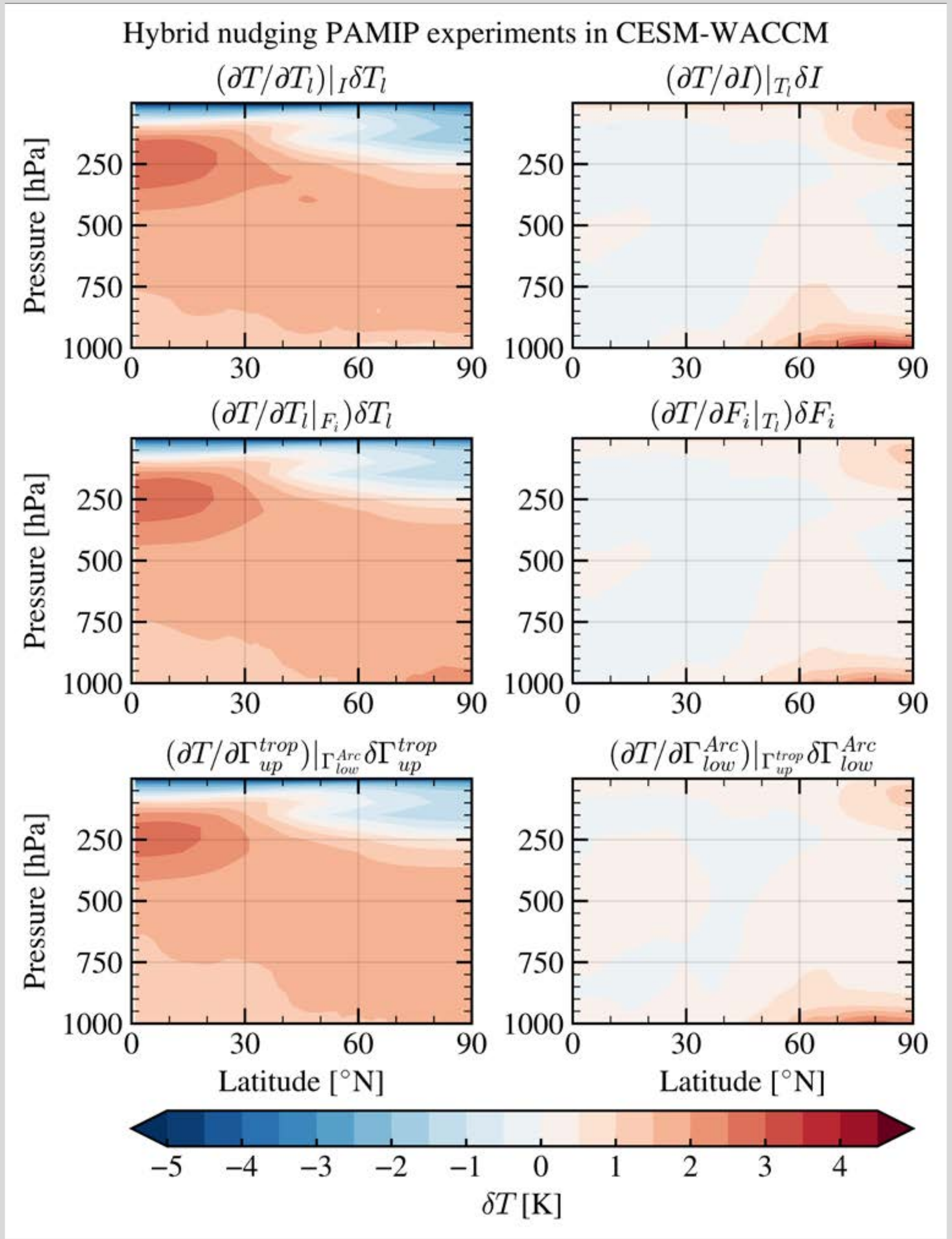


MPPS decompositions

Sea ice *extent* scaling

Sea ice *forcing* scaling (with Arctic surface heat flux)

Lapse-rate scaling

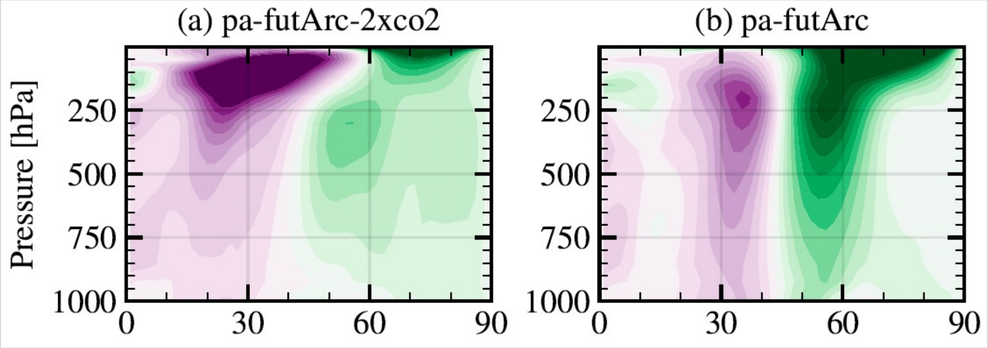


PAMIP hybrid nudging (WACCM-SPCAM4)

- Accounting for artificial heat reduces the tug of war over the midlatitude jet

Greenhouse and sea-ice forcing responses

δT_{2XCO2} $\delta T_{Nudging}$

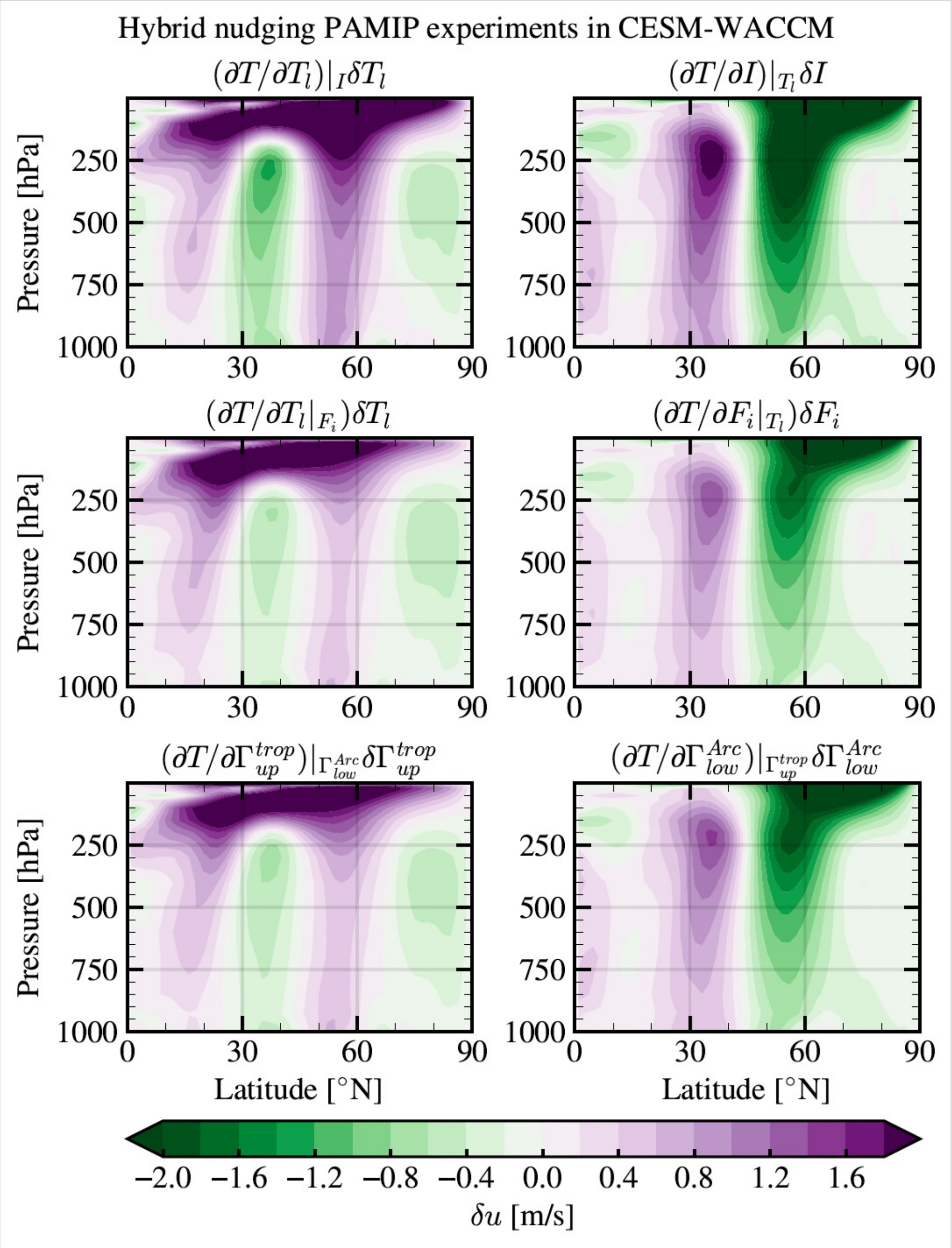


MPPS decompositions

Sea ice *extent* scaling

Sea ice *forcing* scaling (with Arctic surface heat flux)

Lapse-rate scaling



Correcting for artificial heat with MPPS

- MPPS with sea ice forcing scaling recovers the true partial response in a moist energy balance model, and similar results are found in a comprehensive model.
- Sea ice forcing is difficult to justify in ESMs.
- Lapse rate scaling is physically motivated, simple to calculate and gives similar results to sea ice forcing scaling.
- All correction methods reveal that sea ice perturbation experiments overestimate the response to sea ice loss and exaggerate tugs-of-war between low latitude warming and sea ice loss.