Which burners heat up the Arctic atmosphere?

Paul Kushner

Professor, Department of Physics, University of Toronto

Sabbatical activities:

Invited participant for BL18 @ KITP/UCSB,

Visiting Scientist @ Paul G. Allen Philanthropies (Vulcan), Seattle WA

Mackenzie Delta flyover, 3/2018

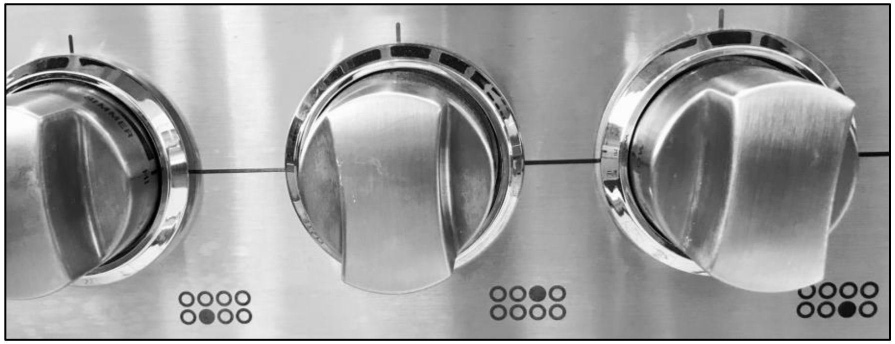
Collaborators in Toronto . . .
Robert Fajber, Stephanie Hay, Thomas Oudar,
. . . and external collaborators . . .
Russell Blackport and James Screen (Exeter), Frederic Laliberté (Squarepoint), Kelly McCusker (Rhodium), Clara Deser (NCAR), John Fyfe (CCCma)

If you join us at the Munger Residence for our Tuesday potluck dinners,

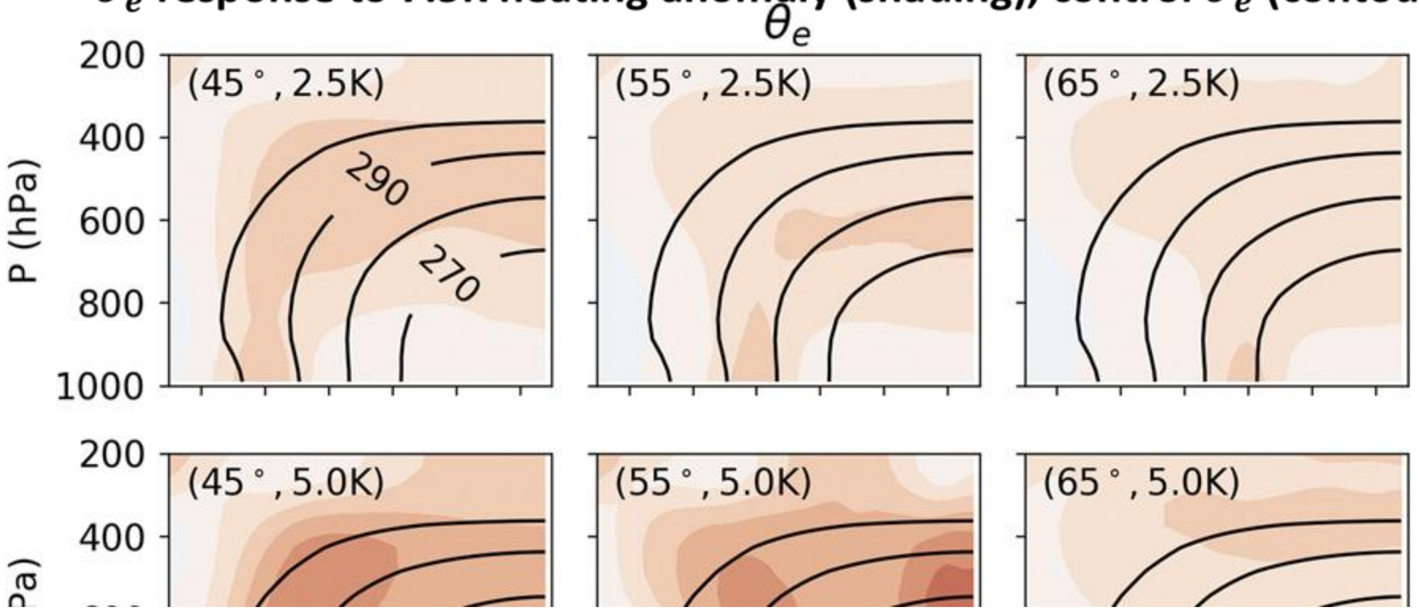
you will find a magnificent contraption in the kitchen . . .

The stove is an impressive device.

But study is required to map burner knobs to heating elements.



- Let’s peek at another cooking contraption: Dargan and Tapio’s simplified moist atmospheric general circulation model.
- Slow cooking over a midlatitude surface burner for a couple of weeks ventilates the Arctic atmosphere with warm moist air.



θ_e response to 7.5K heating anomaly (shading), control θ_e (contours)

100 realization ensemble- and time-mean, for days 10-20 after switch-on.

The further equatorward the burner, the higher (and stronger) the Arctic warming response.

Fajber, R., P. J. Kushner, and F. Laliberté, 2018: Influence of Midlatitude Surface Thermal Anomalies on the Polar Midtroposphere in an Idealized Moist Model. *J. Atmos. Sci.*, **75**, 1089–1104, doi:10.1175/JAS-D-17-0283.1.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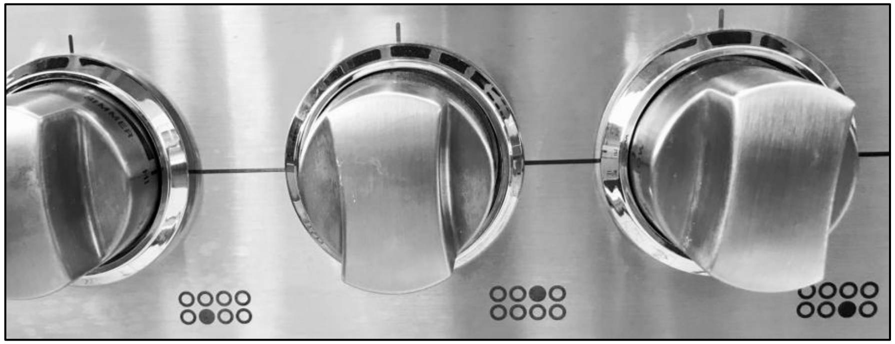
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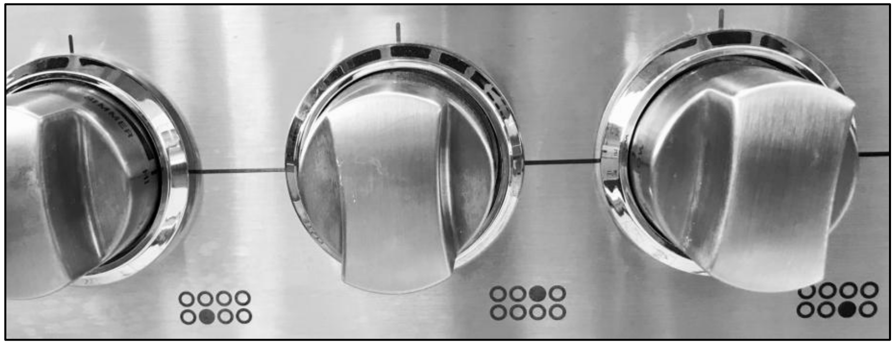
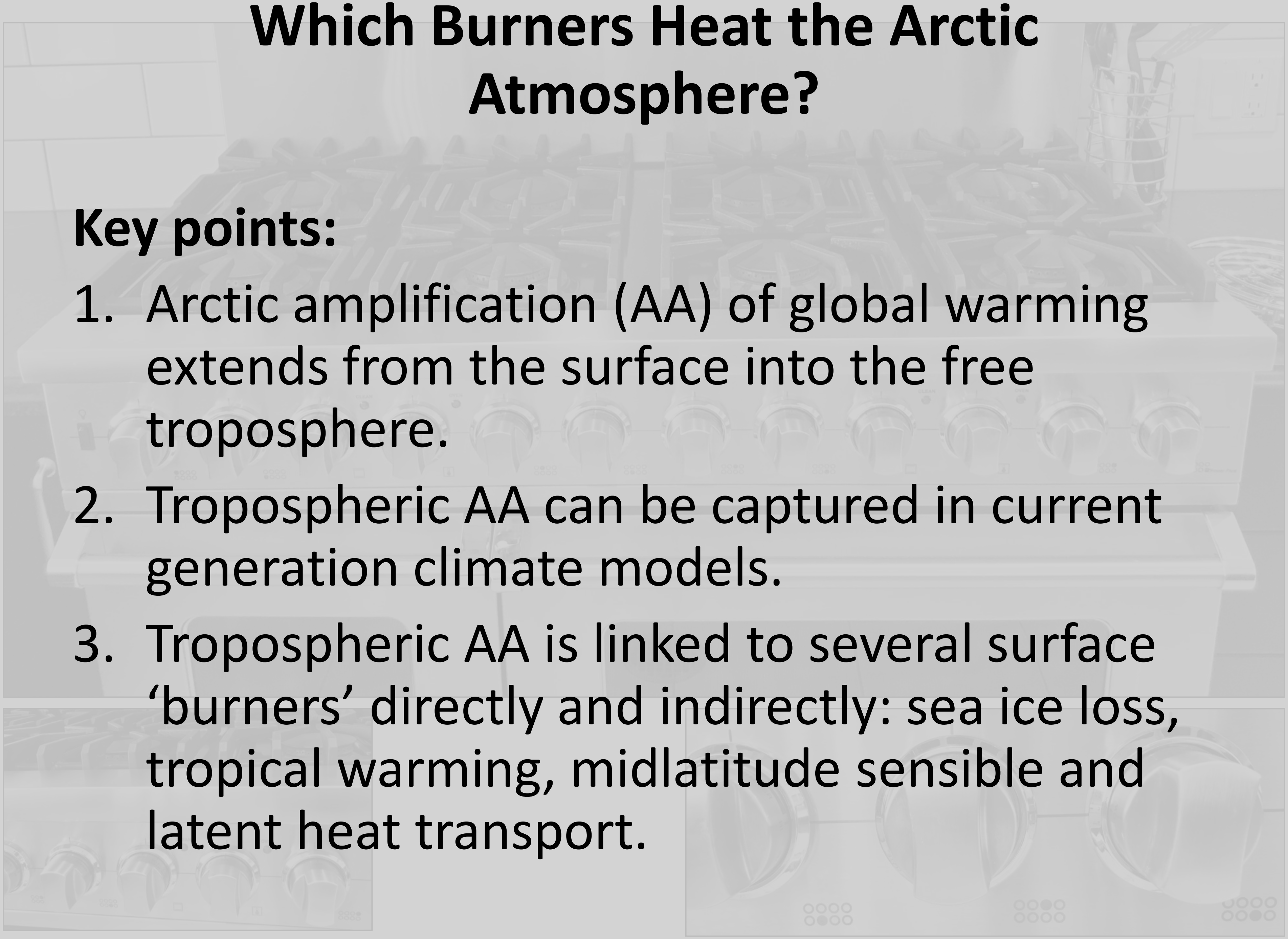
Which Burners Heat the Arctic Atmosphere?



Which Burners Heat the Arctic Atmosphere?



Key points:

1. Arctic amplification (AA) of global warming extends from the surface into the free troposphere.
2. Tropospheric AA can be captured in current generation climate models.
3. Tropospheric AA is linked to several surface ‘burners’ directly and indirectly: sea ice loss, tropical warming, midlatitude sensible and latent heat transport.

- The vertical structure of Arctic warming was controversial a decade ago.
- There's now more agreement that Arctic amplification extends to the free troposphere.

Letter

Vertical structure of recent Arctic warming

Rune G. Graversen, Thorsten Mauritsen, Michael Tjernström, Erland Källén & Gunilla Svensson

Nature **451**, 53–56 (03 January 2008)
doi:10.1038/nature06502
Download Citation

Received: 28 March 2007
Accepted: 29 November 2007
Published: 03 January 2008

Abstract

Near-surface warming in the Arctic has been almost twice as large as the global average over recent decades[1,2,3,4,5]—a phenomenon that is known as the 'Arctic amplification'. The underlying causes of this temperature amplification remain uncertain. The reduction in snow and ice cover that has occurred over recent decades[6,7] may have played a role[5,8]. Climate model experiments indicate that when global temperature rises, Arctic snow and ice cover retreats, causing excessive

Editorial Summary

Warming with altitude

Some of the most pronounced signs of climate change have been seen in the Arctic, for example, near-surface warming there has been... show more

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Arctic warming aloft is data set dependent
Cecilia M. Bitz & Qiang Fu

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Peter W. Thorne

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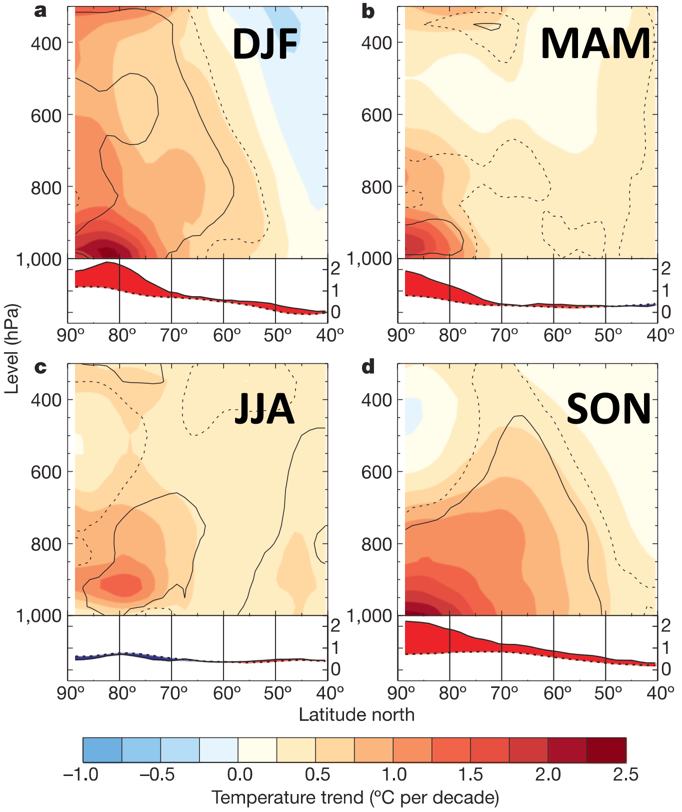
Recent Arctic warming vertical structure contested
A. N. Grant, S. Brönnimann & L. Haimberger

Zonal Mean Temperature Trends ERA-Interim, 1989-2008



Screen, J. A., and I. Simmonds, 2010: The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature*, **464**, 1334–1337, doi:10.1038/nature09051.

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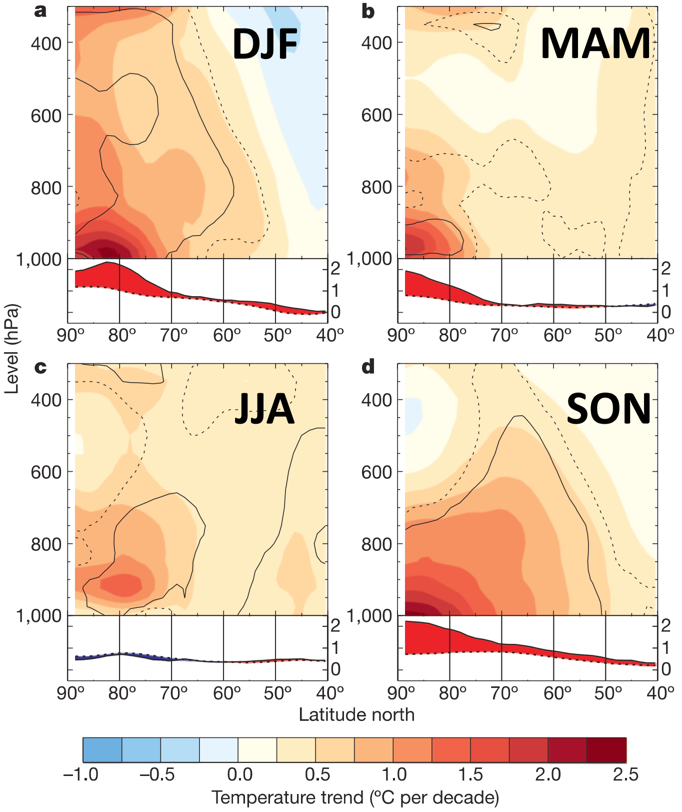
My boys, Santa Barbara, 2008
KITP’s first climate program!

Screen, J. A., and I. Simmonds, 2010: The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature*, **464**, 1334–1337, doi:10.1038/nature09051.

Zonal Mean Temperature Trends
ERA-Interim, 1989-2008



The vertical structure of Arctic warming was controve

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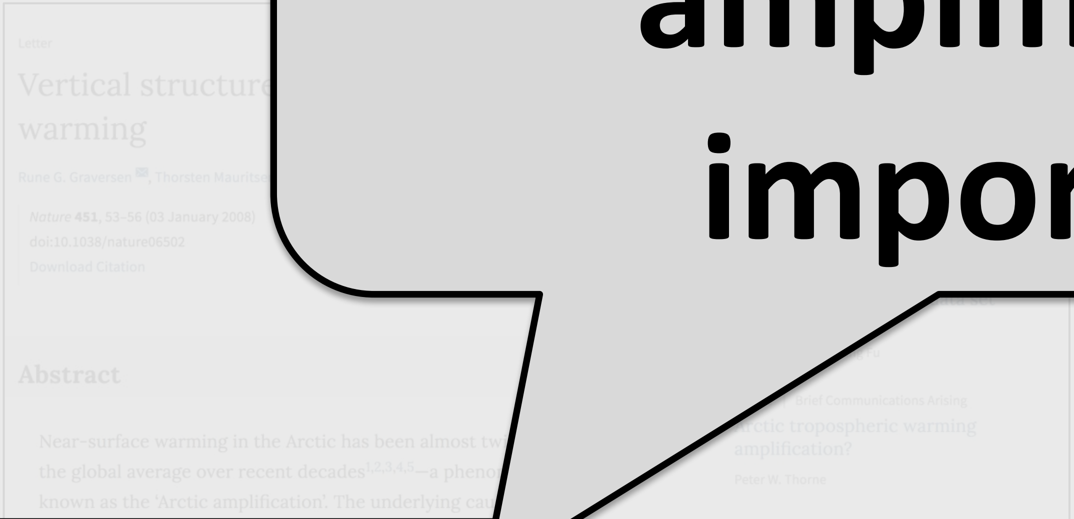
Is tropospheric Arctic amplification important?



Letter

Vertical structure

warming

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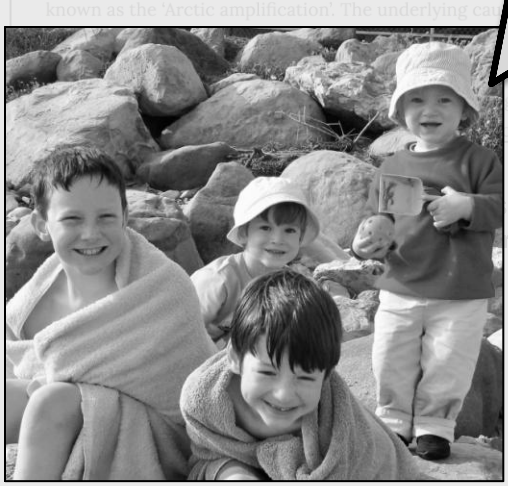

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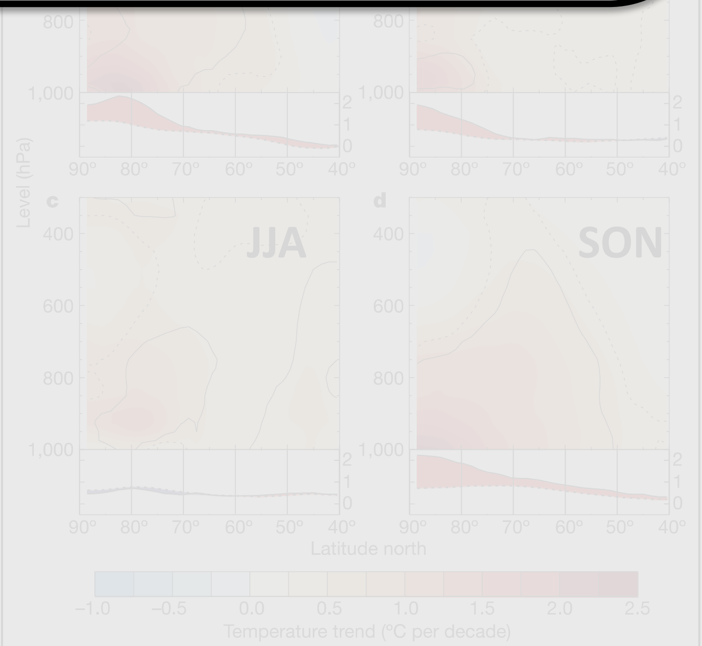
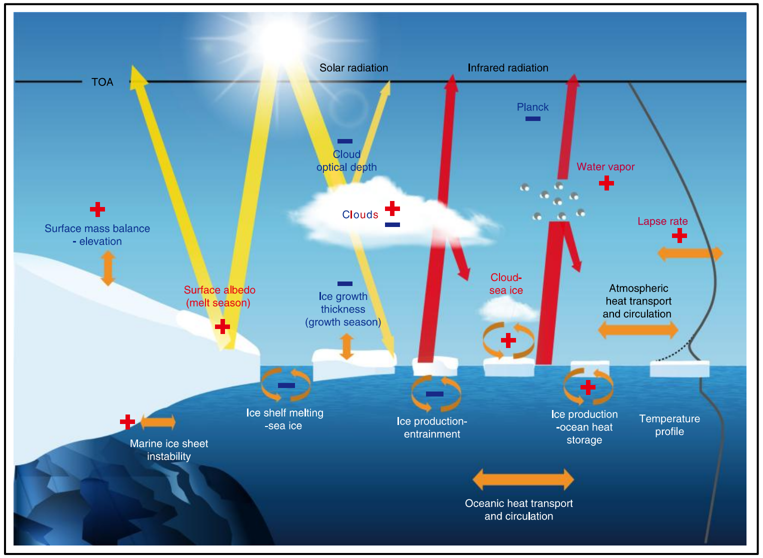


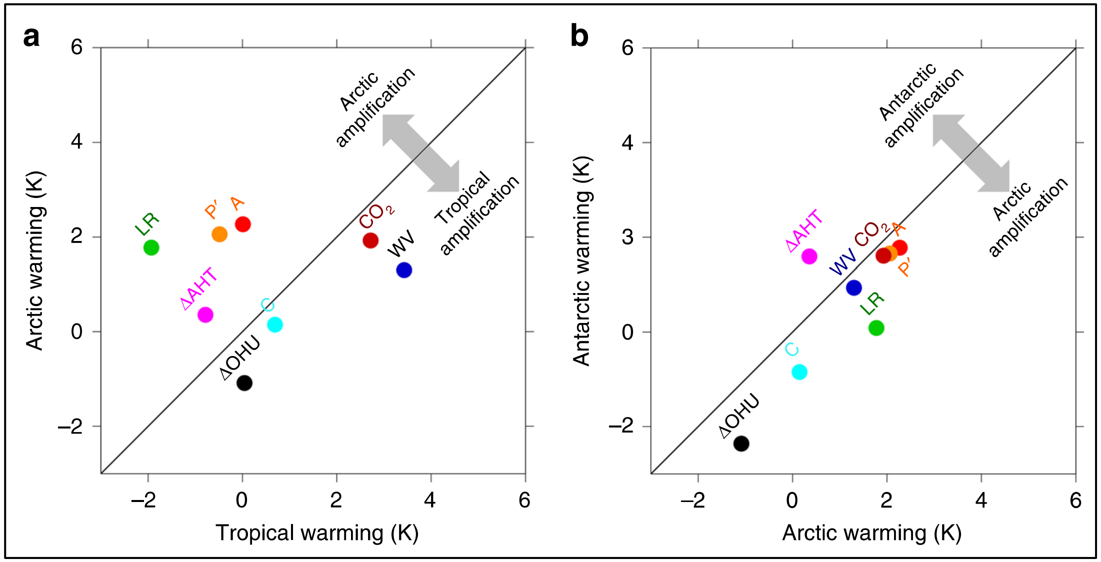
Yes! Tropospheric AA Is Important . . .

- For understanding how the Arctic's stratification, clouds, and composition respond to climate change.
- For constraining the Arctic lapse rate which feedback.
- For influencing lower latitude circulation and weather.

Radiative and Other Feedbacks in Polar Regions



Feedback contributions to Arctic, Tropical, and Antarctic Amplification



Goosse, H., J. E. Kay, K. C. Armour, A. Bodas-Salcedo, H. Chepfer, D. Docquier, A. Jonko, P. J. Kushner, O. Lecomte, F. Massonnet, H.-S. Park, F. Pithan, G. Svensson, and M. Vancoppenolle, 2018: Quantifying climate feedbacks in polar regions. *Nature Communications*, **9**, 1919, doi:10.1038/s41467-018-04173-0.

Scientific Significance of Tropospheric AA

- We'd like to understand what sets the stratification, cloud structure, and composition of the Arctic atmosphere within the general circulation.
- We want to constrain the response of the Arctic lapse rate $\Gamma = -dT_{Arctic}(z)/dz$, which is a positive feedback in the climate response to greenhouse warming.
  - $\Delta\Gamma < 0$ in the tropics and $\Delta\Gamma > 0$ in the Arctic.

Radiative and Other Feedbacks in Polar Regions

Feedback Contributions to Arctic, Tropical, and Antarctic Amplification

Goosse, H., J. E. Kay, K. C. Armour, A. Bodas-Salcedo, H. Chepfer, D. Docquier, A. Jonko, P. J. Kushner, O. Lecomte, F. Massonnet, H.-S. Park, F. Pithan, G. Svensson, and M. Vancoppenolle, 2018: Quantifying climate feedbacks in polar regions. *Nature Communications*, **9**, 1919, doi:10.1038/s41467-018-04173-0.

Fine . . . so what *causes* tropospheric Arctic amplification??

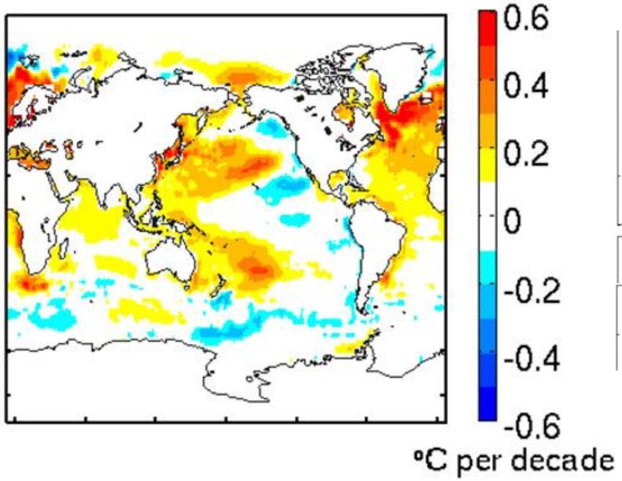
Model Results - Preview

Mackenzie Delta flyover, 3/2018

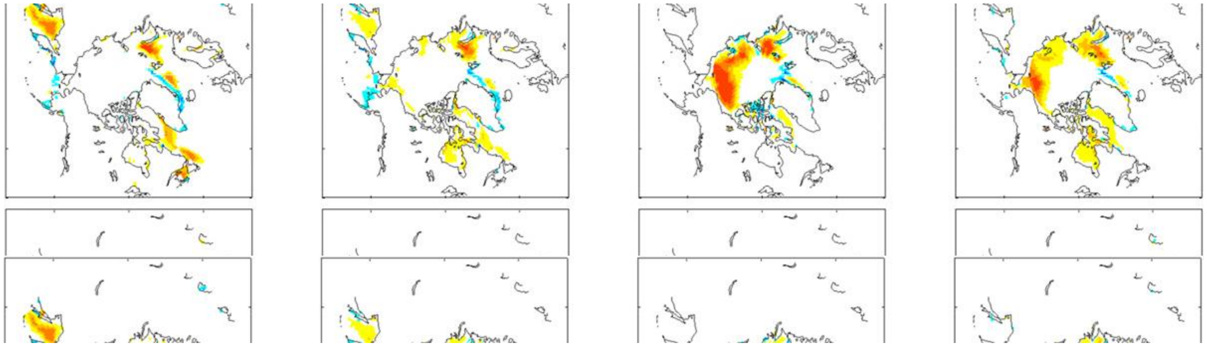
- Turning on *all* the surface burners, climate models can capture observed tropospheric AA.
- Coupling to the ocean is critical to tropospheric AA.
- We can separate a robust response to sea ice loss from “the remainder” of greenhouse warming.

Technical Background: AMIP Protocol

- Prescribe observed ocean surface and sea ice conditions for atmosphere/land general circulation model.
- This leads to realistic atmospheric/land responses to such forcing, even without observed external forcing.



Hurrell SST Trends, 1980-2010

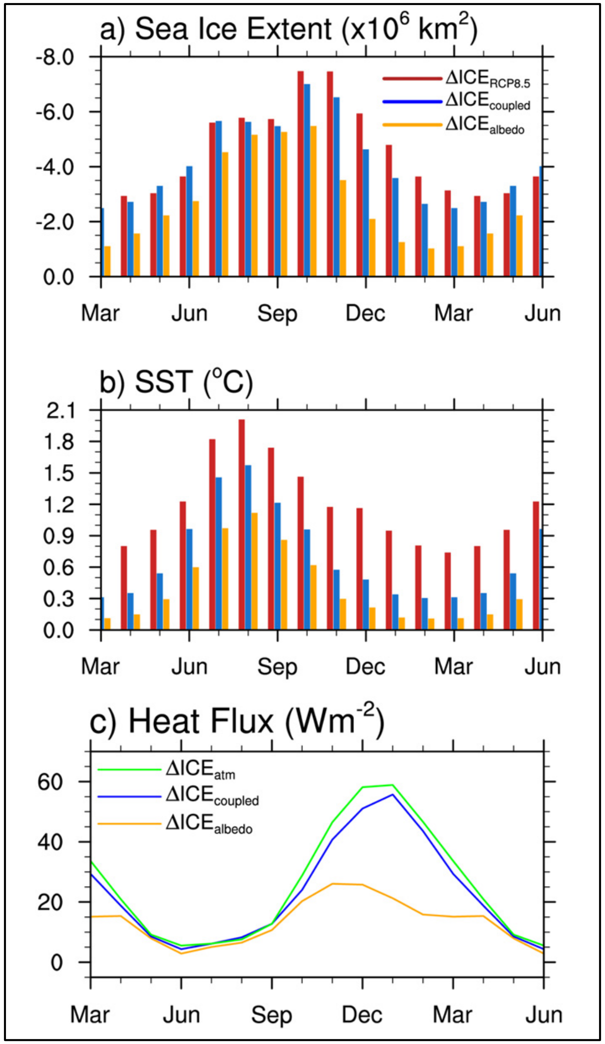


Hurrell Sea Ice Concentration Trends, 1980-2010

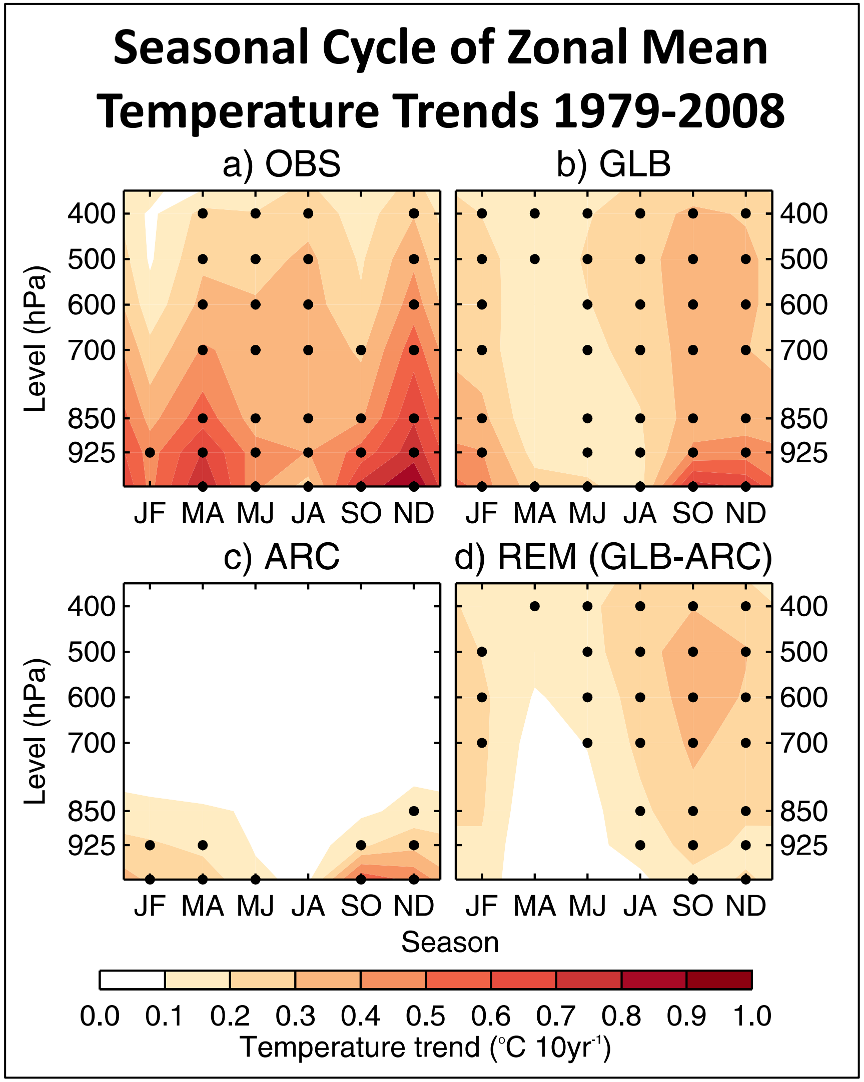
Bichet, A., P. J. Kushner, and L. Mudryk, 2016: Estimating the Continental Response to Global Warming Using Pattern-Scaled Sea Surface Temperatures and Sea Ice. *J. Climate*, **29**, 9125–9139, doi:10.1175/JCLI-D-16-0032.1.

Direct Impact of Sea Ice Loss

- Sea ice loss can be forced in AMIP simulations or in coupled (dynamical) ocean-atmosphere model simulations.
- Projected sea ice loss changes the Arctic leads to 30-50 Wm^{-2} heat flux into the atmosphere.
- The response peaks in winter and lags the fall sea ice melt.
- The winter response is dominated by turbulent fluxes of heat and moisture.



Deser, C., R. A. Tomas, and L. Sun, 2014: The Role of Ocean–Atmosphere Coupling in the Zonal-Mean Atmospheric Response to Arctic Sea Ice Loss. *J. Climate*, **28**, 2168–2186, doi:10.1175/JCLI-D-14-00325.1.



a) OBS: Reanalysis mean

b) GLB: AMIP simulation with global observed sea ice and SST

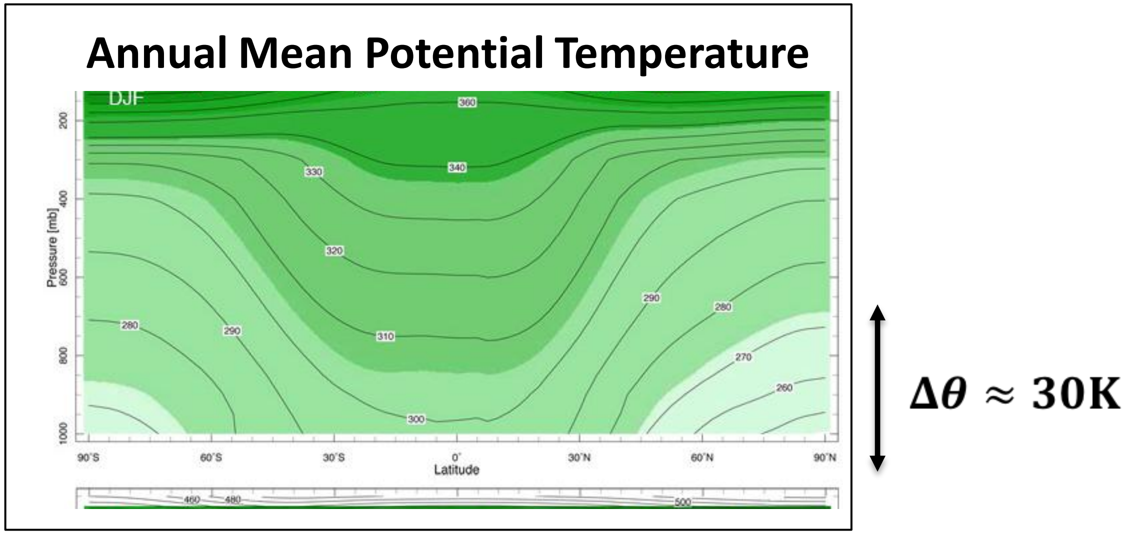
c) ARC: AMIP simulation with Arctic sea ice and SST

d) REM: Remote effects, GLB-ARC

Screen J. A., Deser C., and Simmonds I., 2012: Local and remote controls on observed Arctic warming. *Geophysical Research Letters*, **39**, doi:10.1029/2012GL051598.

- Arctic winter tropospheric warming can be approximately captured when observed boundary conditions are prescribed.
- Sea ice loss has less influence than warming from lower latitudes.

Entropy Perspective


Annual Mean Potential Temperature

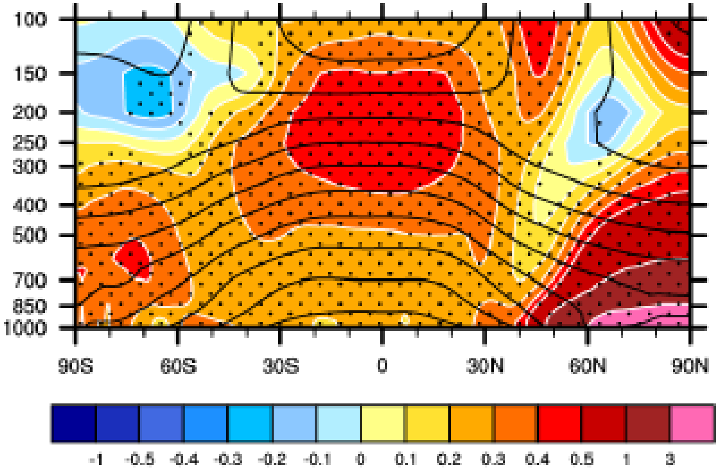
$\Delta\theta \approx 30\mathrm{K}$

http://paoc.mit.edu/labweb/notes/chap5.pdf

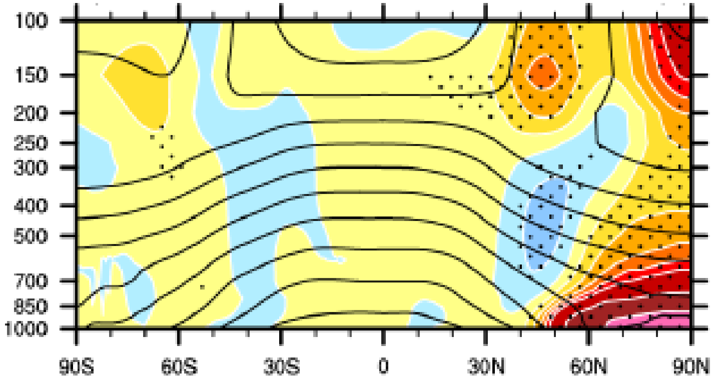
- The Arctic is strongly stably stratified.
- This traps, near the surface, the buoyancy source exposed by sea ice removal, absent other adjustments.

Coupling Strengthens Tropospheric AA

- Response to Induced Sea Ice Loss, DJF T
- Coupled CCSM4



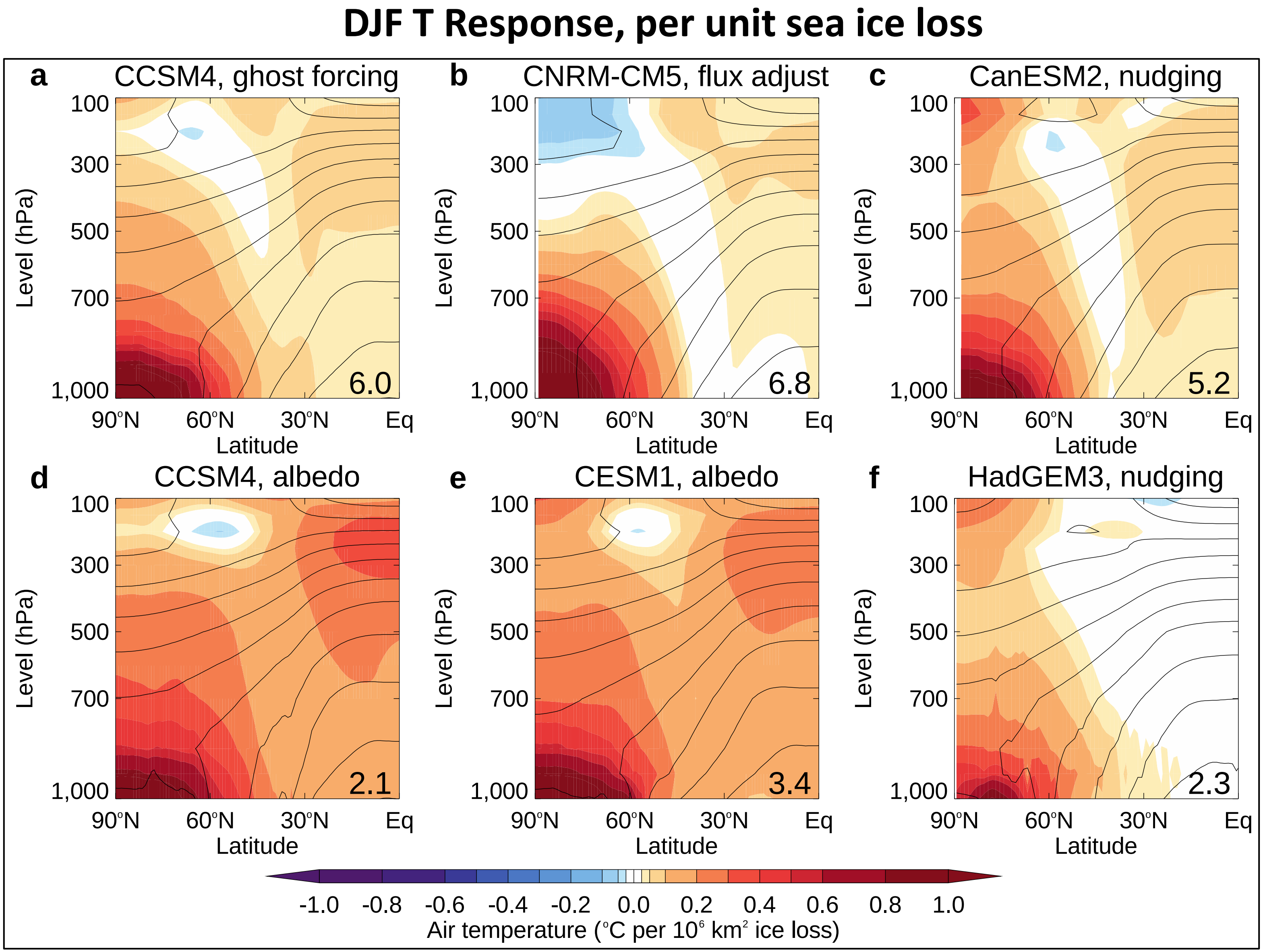
- Response to Imposed Sea Ice Loss from the above sea ice.
- AGCM CAM4



- Coupled response to sea ice loss:
  - ‘mini’ global warming
  - Tropospheric AA
- We’ll try to reconcile this with Screen et al.’s Arctic/remote picture.
- First, a couple of other points to make . . .

Deser, C., R. A. Tomas, and L. Sun, 2015: The Role of Ocean–Atmosphere Coupling in the Zonal-Mean Atmospheric Response to Arctic Sea Ice Loss. *J. Climate*, **28**, 2168–2186, doi:10.1175/JCLI-D-14-00325.1.

The response to sea-ice loss in coupled models is robust



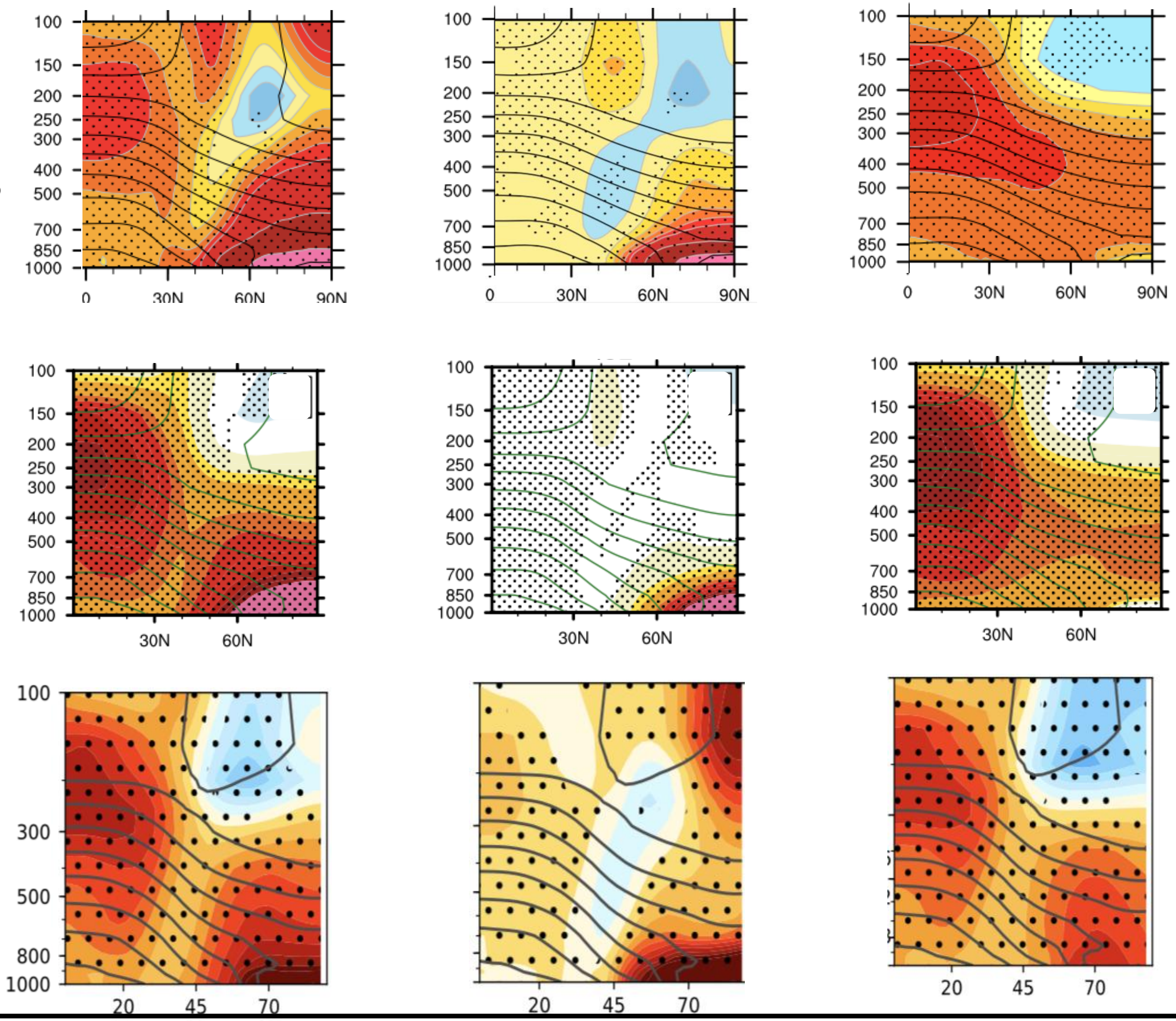
Screen, J. A., C. Deser, D. M. Smith, X. Zhang, R. Blackport, P. J. Kushner, T. Oudar, K. E. McCusker, and L. Sun, 2018: Consistency and discrepancy in the atmospheric response to Arctic sea-ice loss across climate models. *Nature Geoscience*, **11**, 155–163, doi:10.1038/s41561-018-0059-y.

Separating Ice Loss Response from the Rest of Global Warming

GHG Forcing

Ice Loss

GHG Forcing without Ice Loss

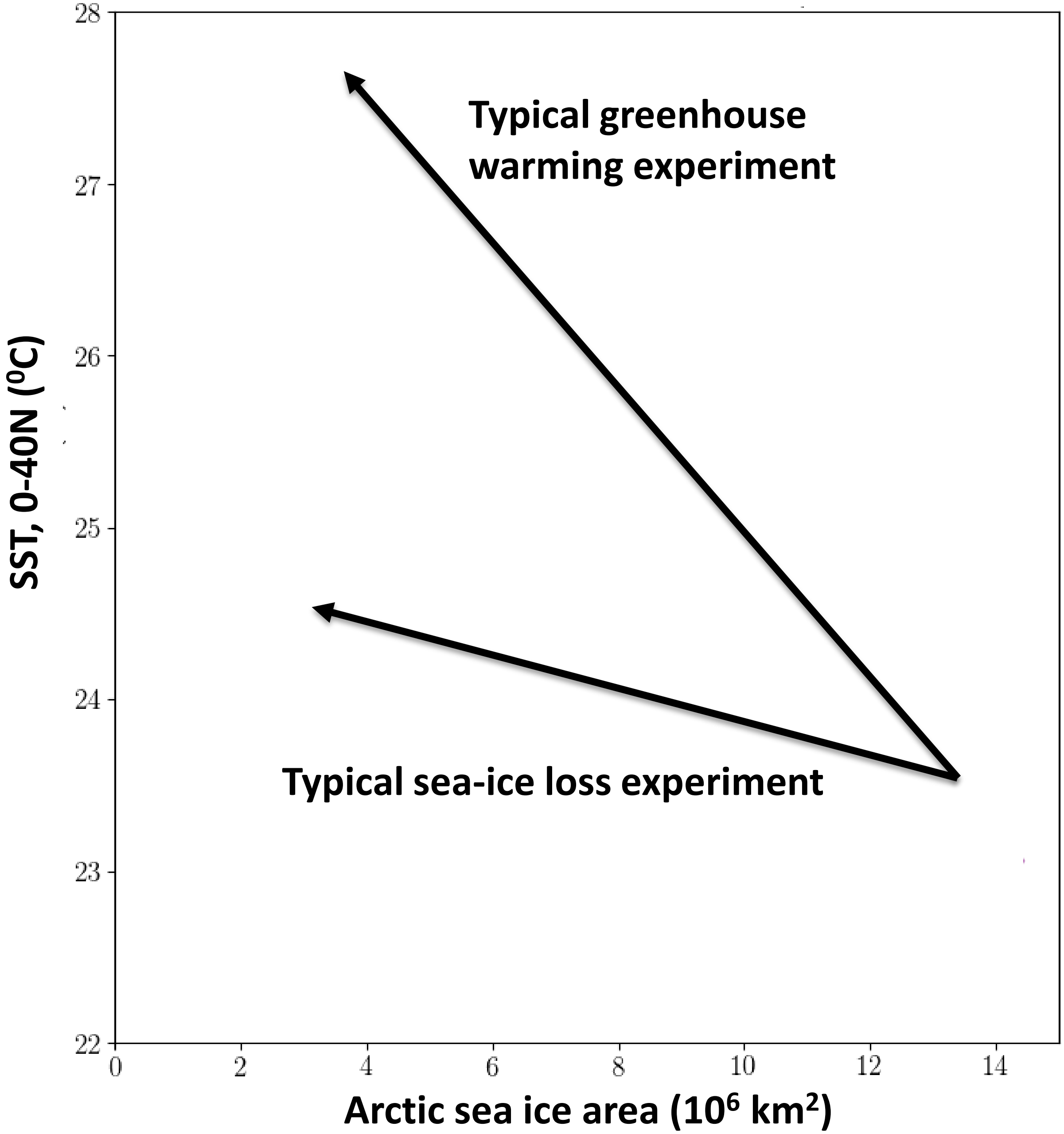


- Annual mean
- CCSM4
- Deser et al. 2015

- DJF mean
- CNRM-GAME
- Oudar et al. 2017

- DJF mean
- CanESM2
- McCusker et al. 2017

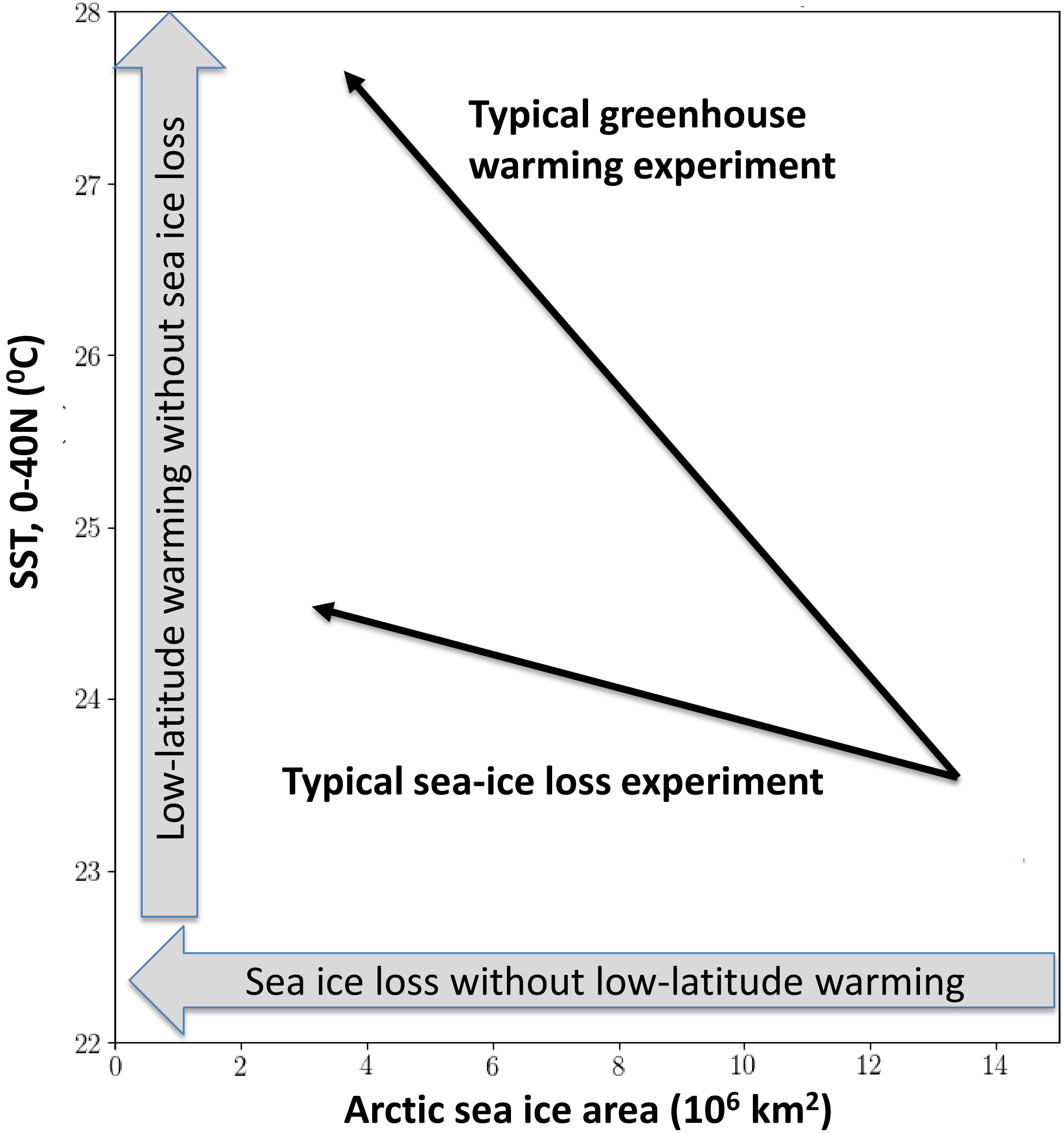
Arctic and Tropical Change Are Entangled



In coupled ocean-atmosphere models:

- Global warming drives sea-ice loss.
- Induced sea-ice loss drives 'mini' global warming (Deser et al. 2015).

Arctic and Tropical Change Are Entangled



To disentangle these effects, we have developed a two-parameter pattern scaling technique (Blackport and Kushner 2017; Hay et al. in press and in prep.)

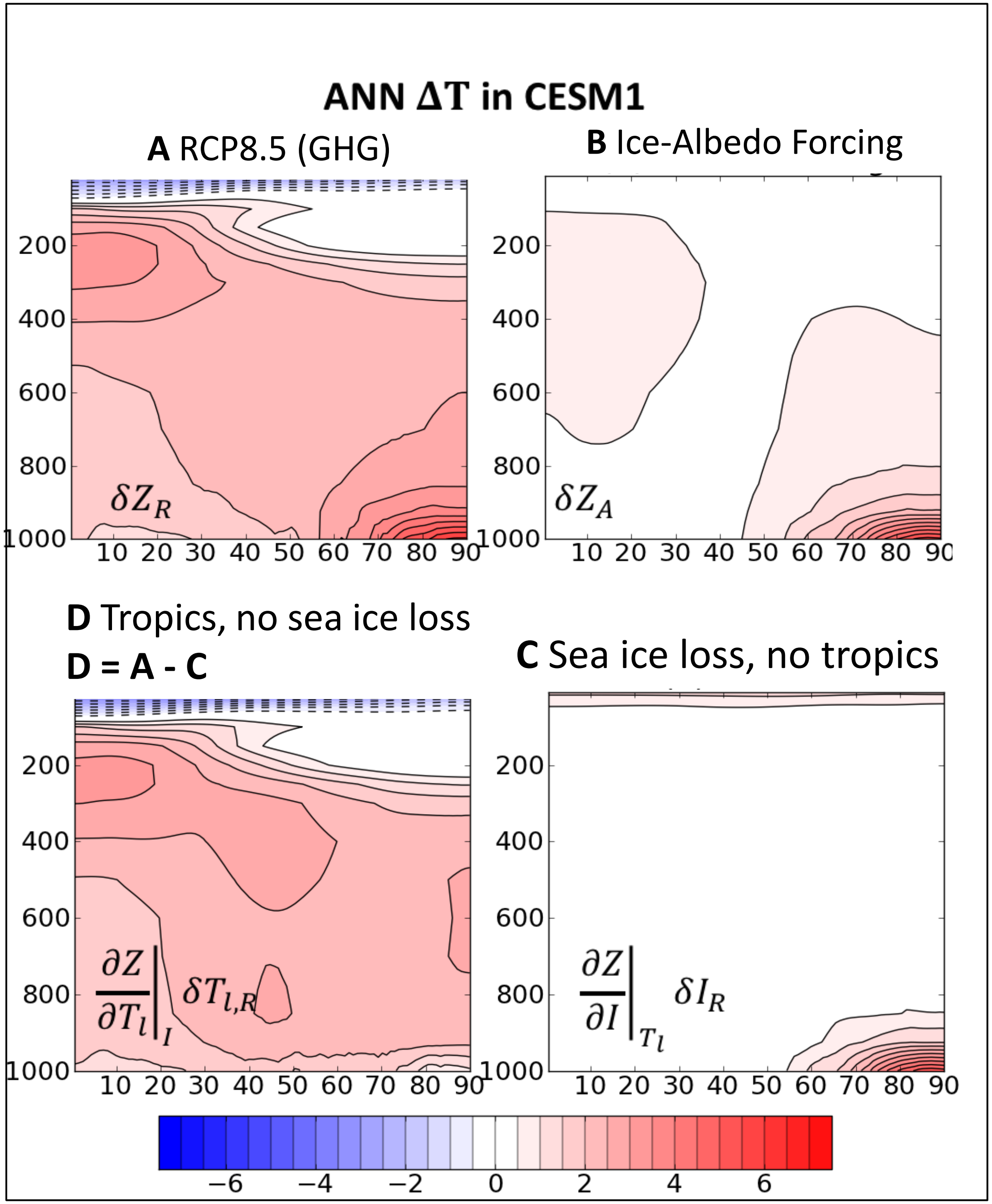
Pattern scaling to isolate tropics from high latitudes

RHS: from coupled model simulations.

$$\begin{pmatrix} \left.\frac{\partial Z}{\partial T_l}\right|_I \\ \left.\frac{\partial Z}{\partial I}\right|_{T_l} \end{pmatrix} = \begin{pmatrix} \delta T_{l,R} & \delta I_R \\ \delta T_{l.A} & \delta I_A \end{pmatrix}^{-1} \begin{pmatrix} \delta Z_R \\ \delta Z_A \end{pmatrix}$$

LHS: Diagnosed sensitivity to ice loss or low latitude warming in isolation.

Blackport, R., and P. J. Kushner, 2017: Isolating the Atmospheric Circulation Response to Arctic Sea Ice Loss in the Coupled Climate System. *J. Climate*, **30**, 2163–2185, doi:[10.1175/JCLI-D-16-0257.1](https://doi.org/10.1175/JCLI-D-16-0257.1).



ANN ΔT in CESM1

A RCP8.5 (GHG)

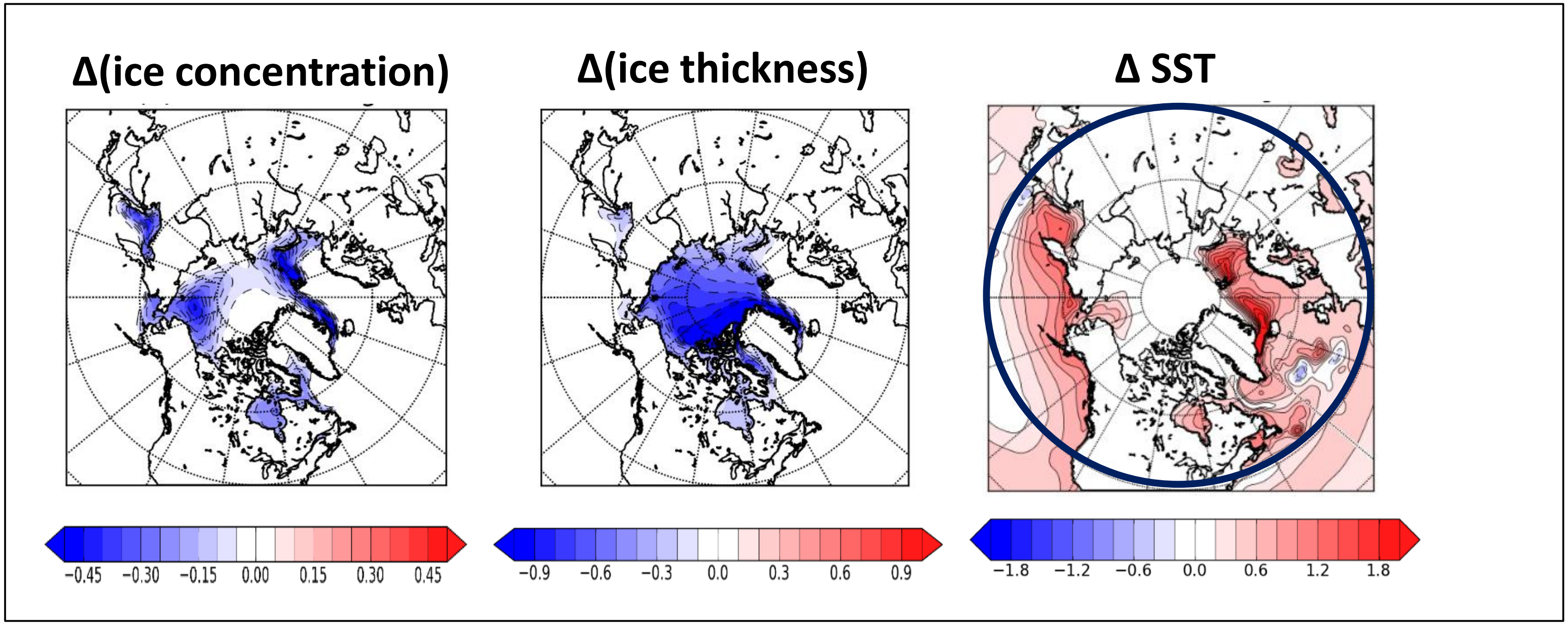
B Ice-Albedo Forcing

D Tropics, no sea ice loss

D = A - C

C Sea ice loss, no tropics

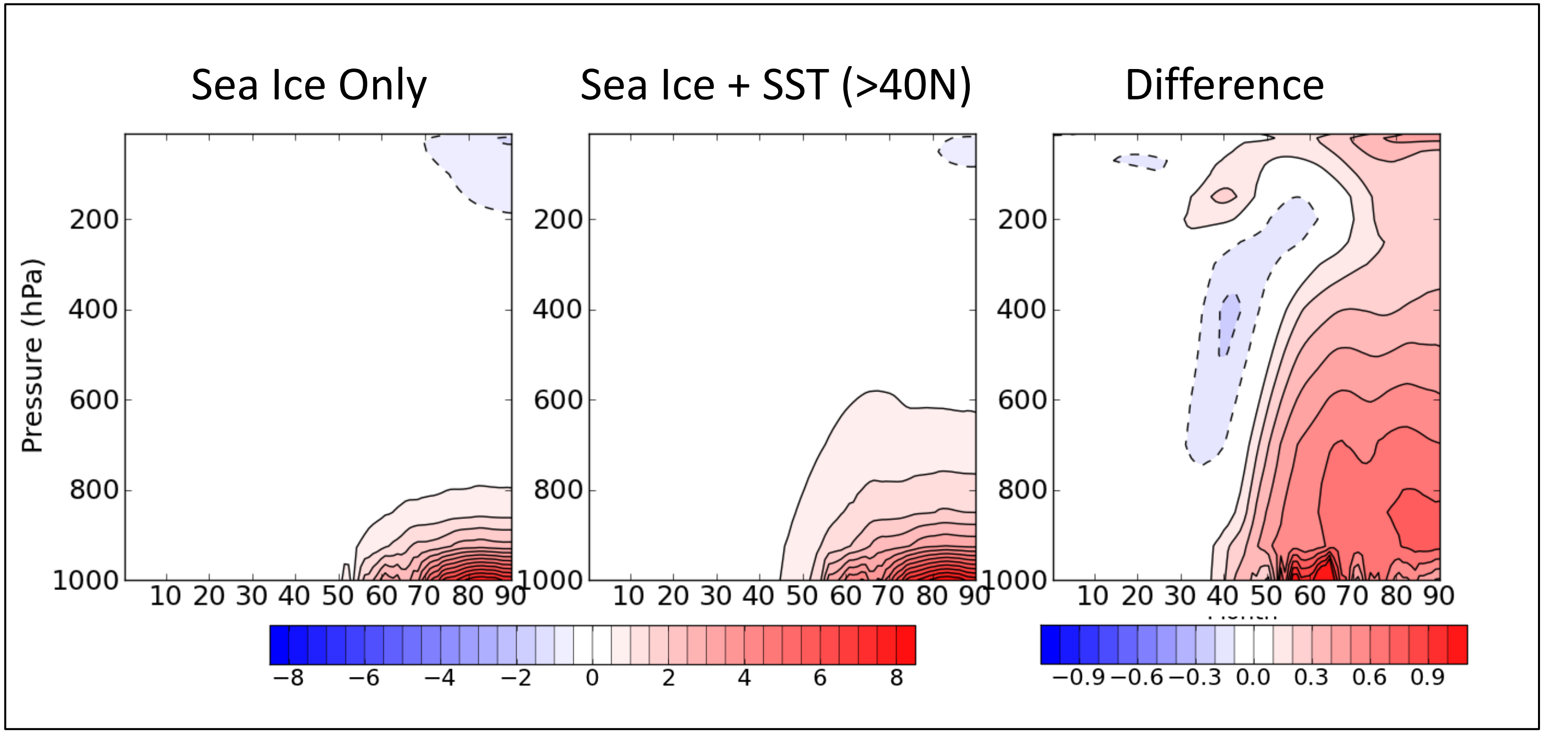
Examining the feedback effects of sea ice loss



- These are the DJF ice-loss and SST warming patterns from Blackport and Kushner 2017 sea ice loss simulations.
- Test the impact of midlatitude SST warming on the Arctic troposphere using AGCM CAM5.

Blackport and Kushner submitted

DJF T Response, CAM5



Sea Ice Only

Sea Ice + SST (>40N)

Difference

Blackport and Kushner submitted

Models: Recap

- Greenhouse warming drives sea ice loss.
- Sea ice loss, in turn, feeds back positively onto the warming response, and in particular warms the midlatitude ocean.
- This reinforces Arctic tropospheric warming, beyond the direct impact of sea ice alone.

Models: Recap

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- Sea ice loss, in turn, feeds back positively onto the warming response, and in particular warms the midlatitude ocean.
- This reinforces Arctic tropospheric warming, beyond the direct impact of sea ice alone.

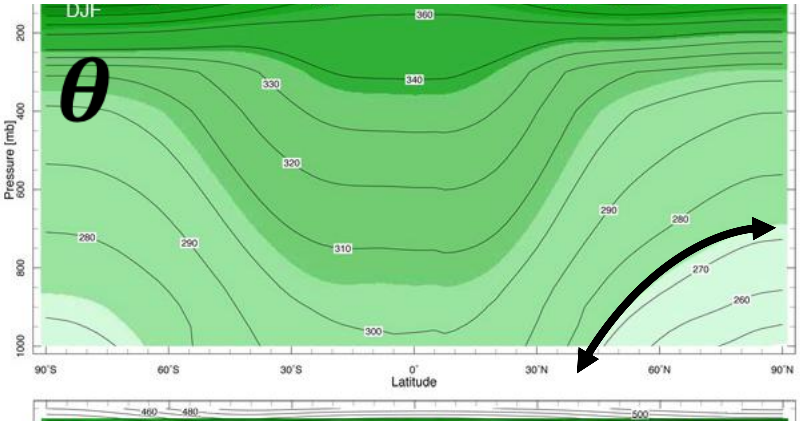
But you still haven't answered our question. *Why* does the Arctic troposphere warm?

Lots of Ideas about Burners that Heat the Arctic Atmosphere

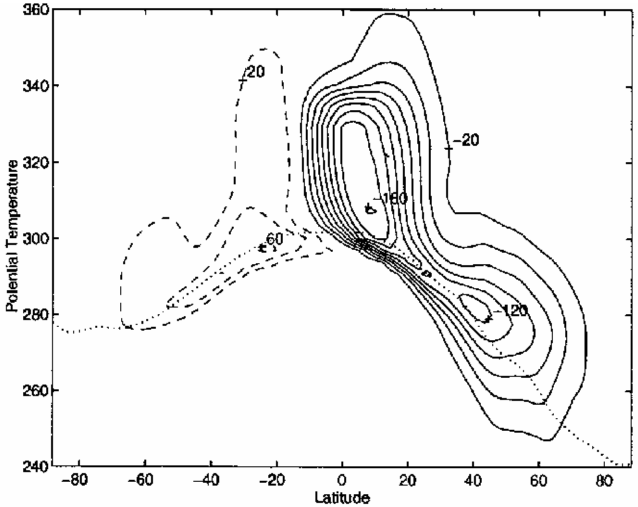
- Tropical:
  - Tropically forced atmospheric responses (e.g. Ding et al. 2014).
  - Tropically forced coupled ocean-atmosphere dynamics (e.g. Tomas et al. 2016).
- Midlatitude:
  - Radiative impacts of poleward advected moisture (e.g. Lee et al. 2017, Caballero et al. 2016).
  - Latent heat release through poleward (and upward) moisture transport (e.g. Skific et al. 2013, Laliberte and Kushner 2013, Caballero et al. 2016, Merlis and Henry in review, Armour et al. in review).
- We'll now focus on the latter mechanism.

Isentropic Circulation Perspective

Annual Mean Potential Temperature



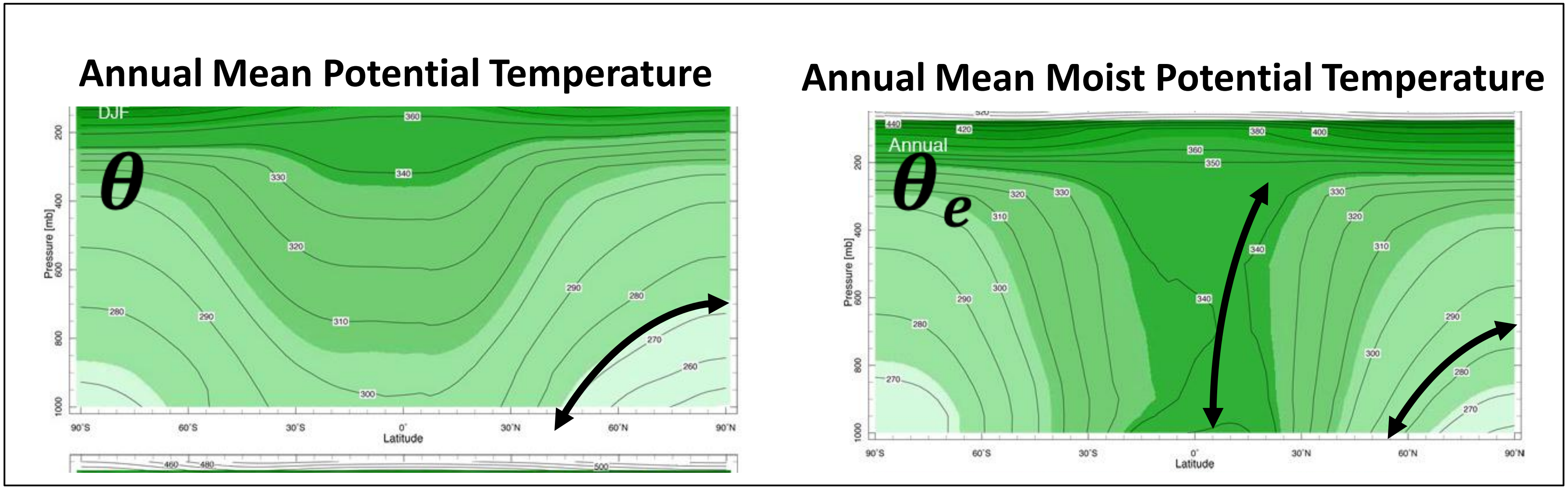
Isentropic Mass Transport Stream Function



Held, I. M., and T. Schneider, 1999: The Surface Branch of the Zonally Averaged Mass Transport Circulation in the Troposphere. *J. Atmos. Sci.*, **56**, 1688–1697, doi:10.1175/1520-0469(1999)056<1688:TSBOTZ>2.0.CO;2.

- In extratropics, wave-driven circulations flux mass along isentropic surfaces.
- Isentropes link the Arctic troposphere to the midlatitude surface.

Isentropic Circulation Perspective

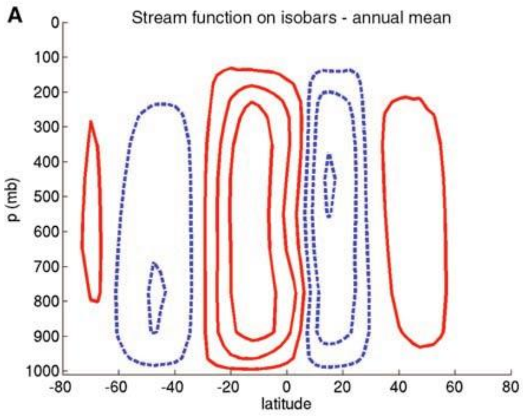

Annual Mean Potential Temperature

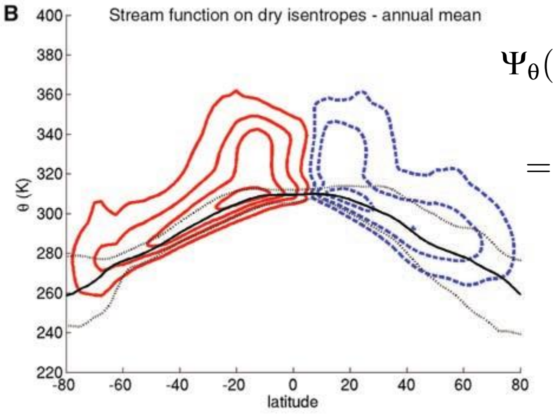
Annual Mean Moist Potential Temperature

http://paoc.mit.edu/labweb/notes/chap5.pdf

- Midlatitude surface moist isentropes are 10-15^0 latitude poleward of corresponding dry isentropes.
- Moistening and latent heat in warm cores of baroclinic cyclones lead to warmer drier air at high latitudes.

Isentropic Circulation Perspective



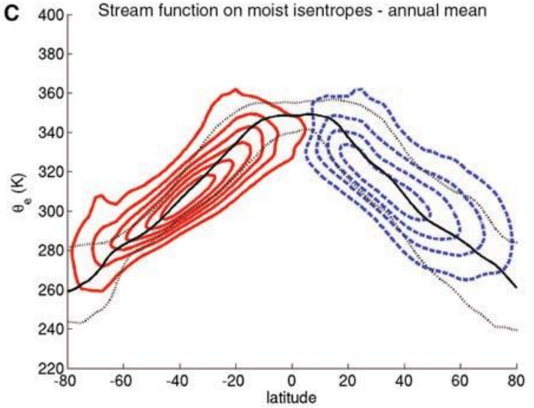


$$\Psi_\theta(\theta_0,\phi)$$

$$= \frac{1}{\tau}\int_0^\tau\int_0^{2\pi}\int_0^{p_{\mathrm{surf}}} H(\theta_0-\theta)\, va\cos\phi\,\frac{dp}{g}\,d\lambda\, dt$$

$$\Psi_p(p,\phi) = \frac{1}{\tau}\int_0^\tau\int_0^{2\pi}\int_p^{p_{\mathrm{surf}}} va\cos\phi\,\frac{dp}{g}\,d\lambda\, dt$$

Pauluis, O., A. Czaja, and R. Korty, 2008: The Global Atmospheric Circulation on Moist Isentropes. *Science*, **321**, 1075–1078, doi:10.1126/science.1159649.

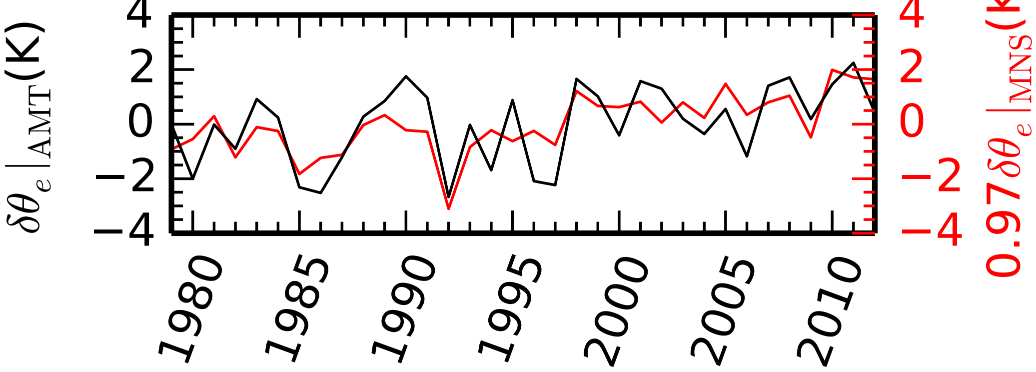


$$\Psi_{\theta_e}(\theta_{e0},\phi)$$

$$= \frac{1}{\tau}\int_0^\tau\int_0^{2\pi}\int_0^{p_{\mathrm{surf}}} H(\theta_{e0}-\theta_e)\, va\cos\phi\,\frac{dp}{g}\,d\lambda\, dt$$

- Moist Mass Circulation > Dry Mass Circulation
- Poleward branch reflects moist effect of eddies (e.g. Jukes 2000, Woods and Caballero 2016)

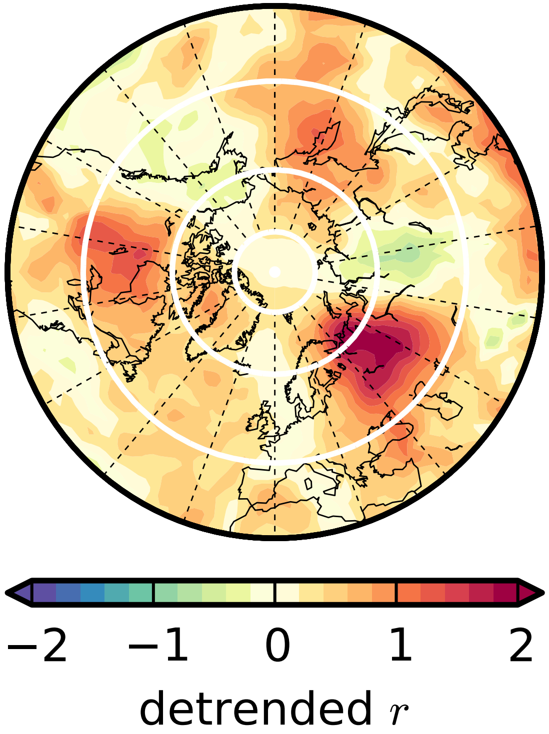
Moist Potential Temperature Propagation



8/15 time series
predictor -30 days lag

- Strong correlation and near unity regression between midlatitude near surface θ_e and Arctic mid troposphere θ_e but with a 30-day lag (July-August).
- A wave-3 surface temperature pattern in July precedes warm, moist Arctic in August.

Correlation of August Arctic Midtroposphere θ_e with July surface

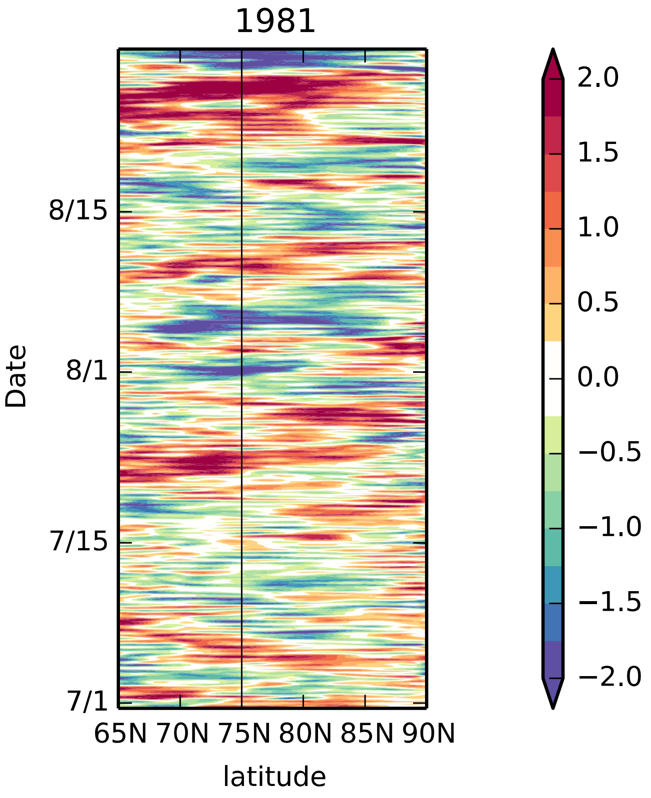


Laliberte, F., and P. J. Kushner, 2014: Midlatitude Moisture Contribution to Recent Arctic Tropospheric Summertime Variability. *J. Clim.*, **27**, 5693–5707, doi:10.1175/JCLI-D-13-00721.1.

The Intermittent Character of the Linkage

- The Arctic midtroposphere moist entropy budget in MERRA is dominated by moist entropy input.
- The input occurs in discrete pulses (Messori and Czaja 2013, 2016).
  - Five events typically account for about ¾ of the total entropy flux.

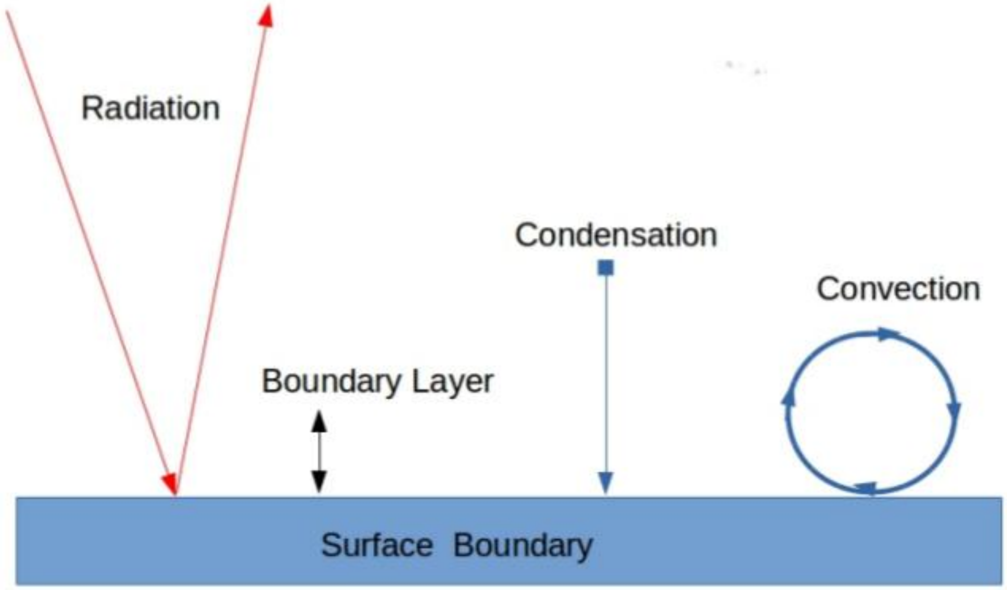
Poleward moist entropy flux through 75N in AMT



Laliberte, F., and P. J. Kushner, 2014: Midlatitude Moisture Contribution to Recent Arctic Tropospheric Summertime Variability. *J. Clim.*, **27**, 5693–5707, doi:10.1175/JCLI-D-13-00721.1.

Investigating tropospheric AA on short timescales in a simplified moist GCM

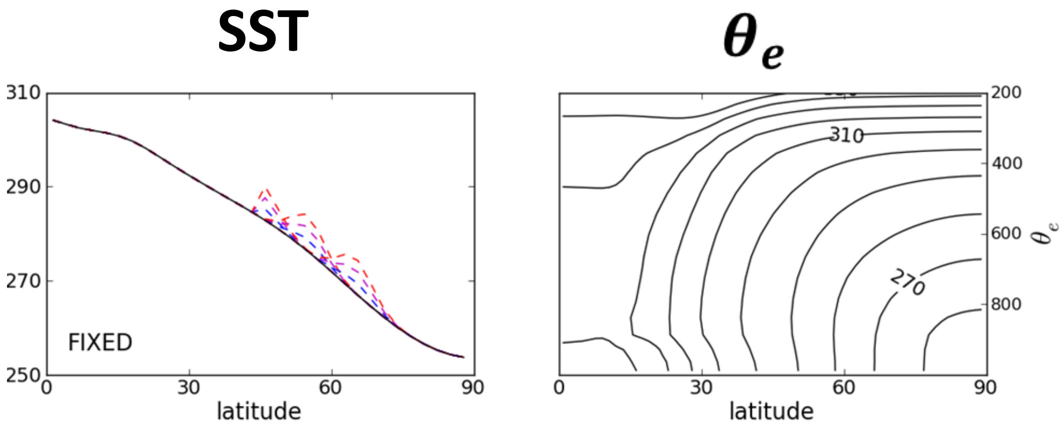
Robert Fajber



Frierson et al. 2006, 2007; O'Gorman and Schneider 2008

Model Set Up

Fixed SST Boundary Condition

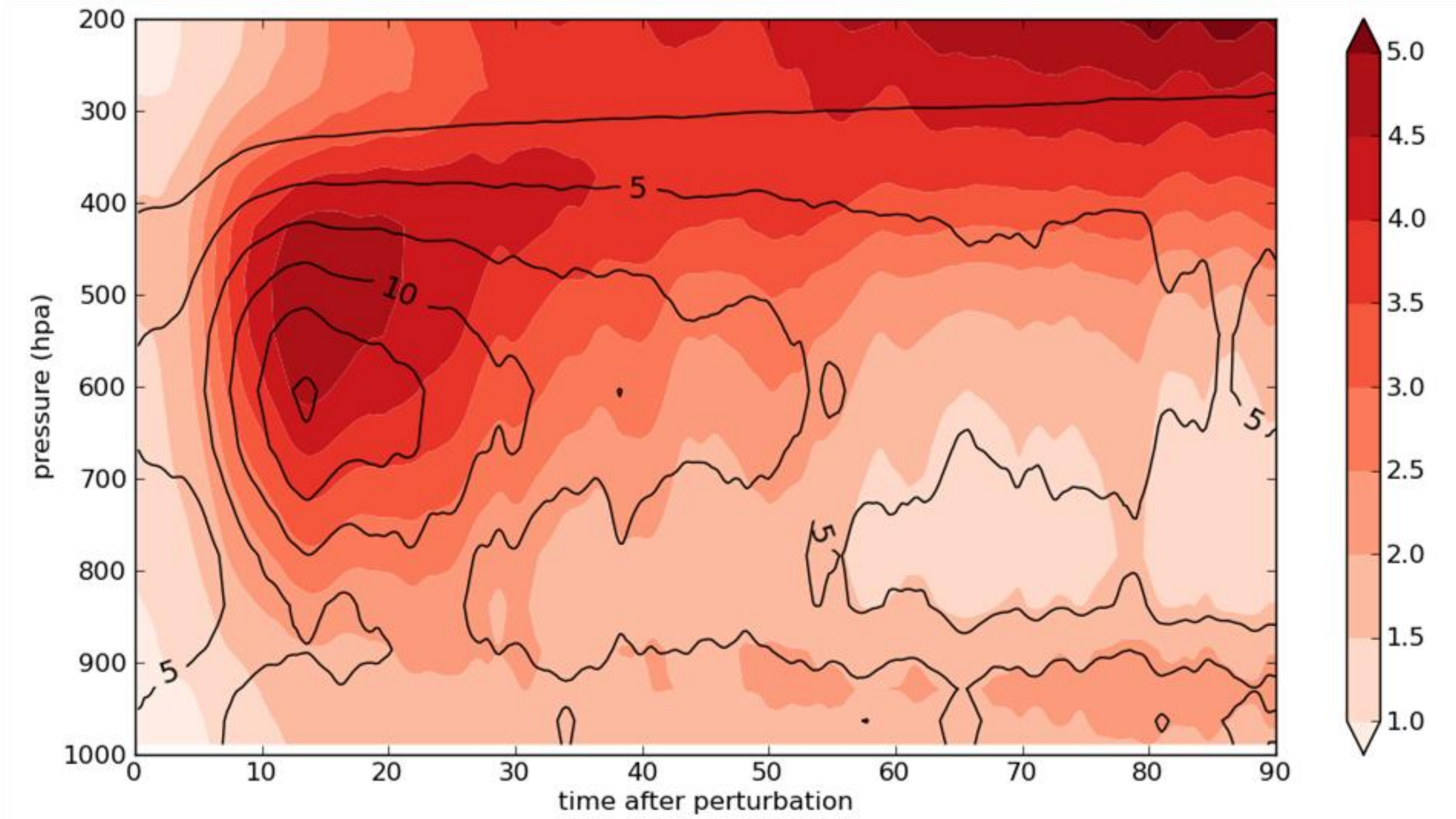


- Fixed SST mimics surface energy balance.
- Our experiments:
  - Long control run, zonally symmetric boundary condition.
  - Zonally symmetric SST perturbations, various latitude and strength.
  - Switch on 120 realizations branched from control run.

Fajber, R., P. J. Kushner, and F. Laliberté, 2018: Influence of Midlatitude Surface Thermal Anomalies on the Polar Midtroposphere in an Idealized Moist Model. *J. Atmos. Sci.*, **75**, 1089–1104, doi:10.1175/JAS-D-17-0283.1.

Ensemble Mean Polar-Cap Response

7.5K/45⁰ Response, $\Delta\theta_e$ (shading), $10^4\Delta q$ (contours),



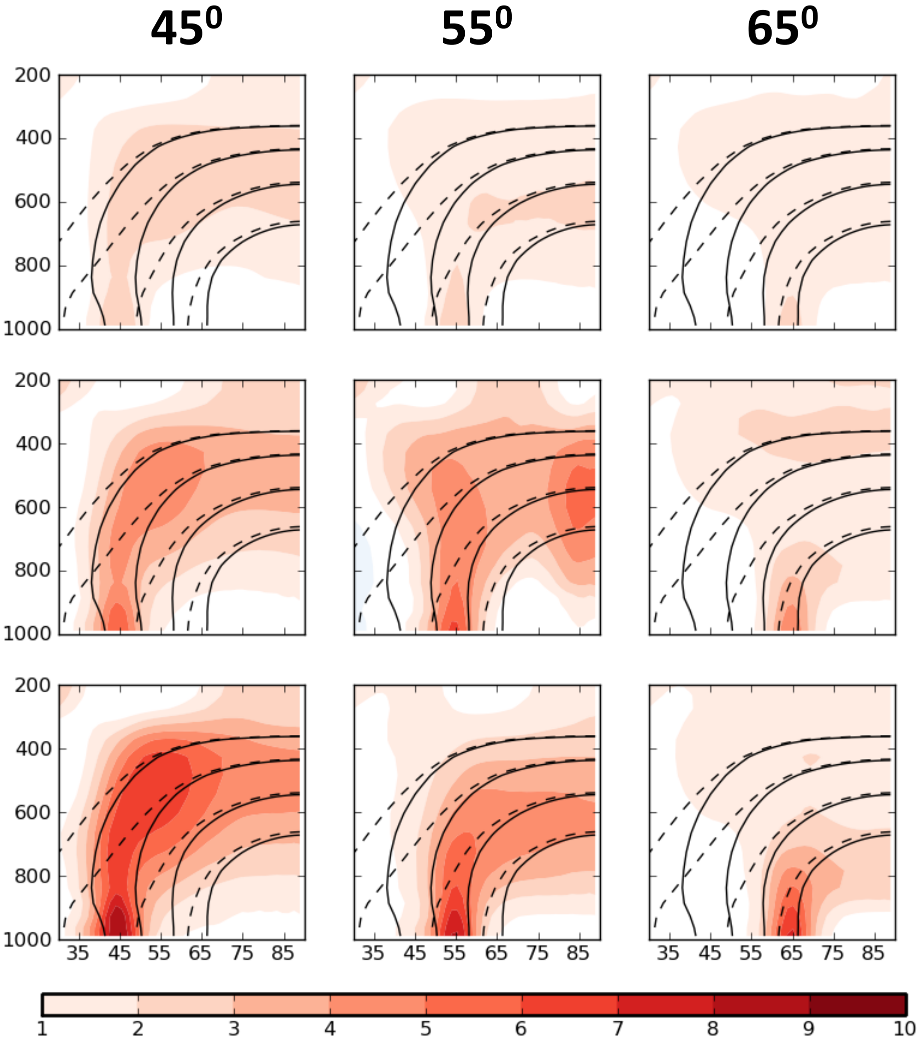
- Peak heating in polar midtroposphere, two weeks after perturbation.

Fajber, R., P. J. Kushner, and F. Laliberté, 2018: Influence of Midlatitude Surface Thermal Anomalies on the Polar Midtroposphere in an Idealized Moist Model. *J. Atmos. Sci.*, **75**, 1089–1104, doi:10.1175/JAS-D-17-0283.1.

Day 10-20 Ensemble Mean Response

- Response roughly organized by θ_e distribution.

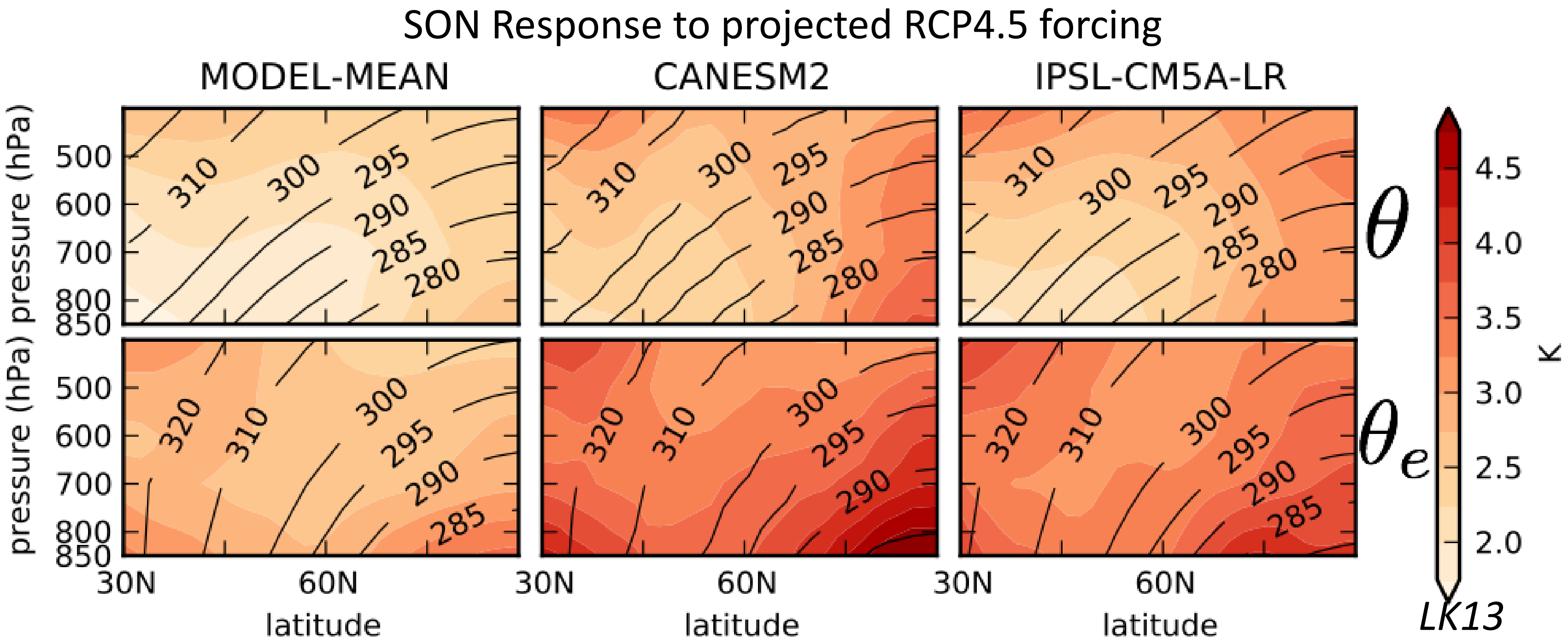
- Response stabilizes the polar troposphere.



Solid: Control θ
Dashed: Control θ_e

Fajber, R., P. J. Kushner, and F. Laliberté, 2018: Influence of Midlatitude Surface Thermal Anomalies on the Polar Midtroposphere in an Idealized Moist Model. *J. Atmos. Sci.*, **75**, 1089–1104, doi:10.1175/JAS-D-17-0283.1.

Projected Global Warming – Isentropic Perspective



- Contours: Control. Shading: Response
- Arctic response tends to align with control run’s moist isentropes.
- What happens if we adiabatically propagate surface temperature warming along adiabats from the control run (fixed RH)?

Midlatitude-Arctic Signal

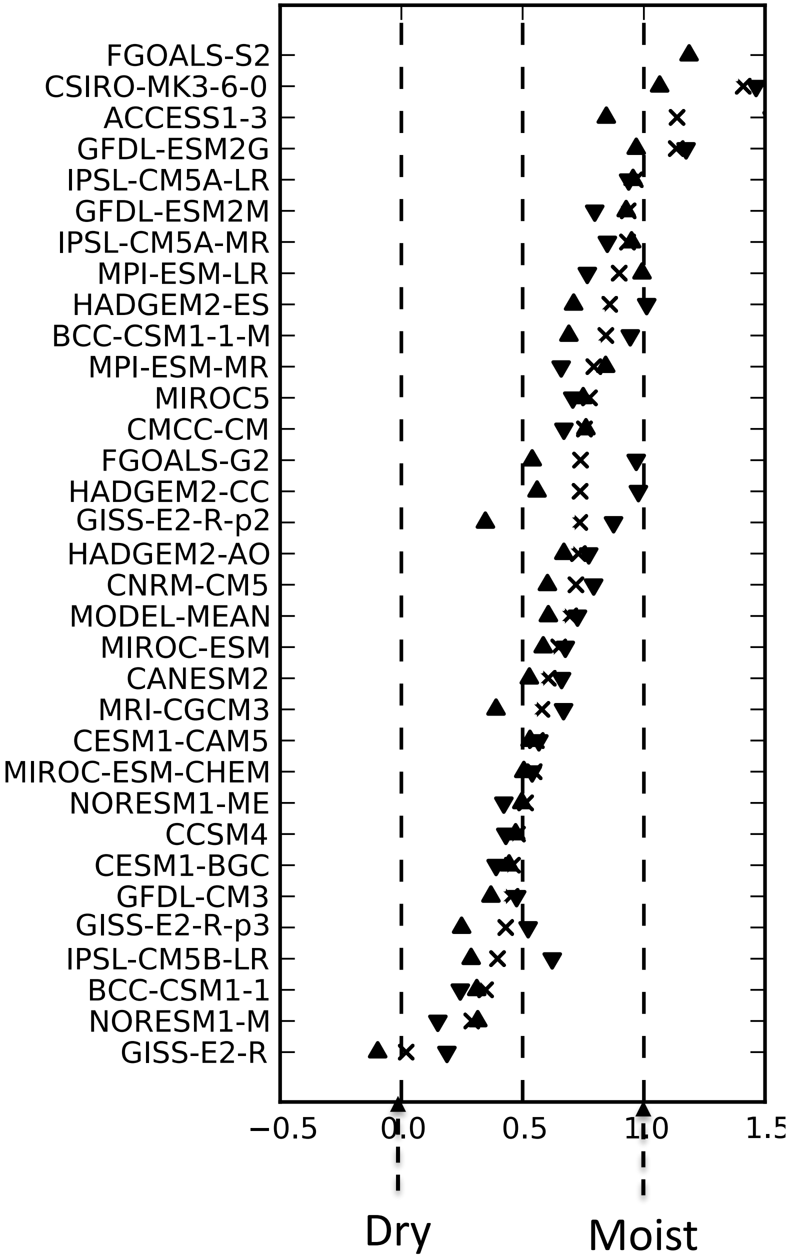
Arctic midtropospheric warming falls between dry and moist adiabatic propagation.

Some models are “moister” than others.

This scaling works particularly well in the boreal fall.

At right: measure of polar warming attributable to moist adiabatic versus dry adiabatic transport from midlatitudes.

Most CMIP5 models are closer to moist than to dry.



LK13

Conclusions

- We can capture Arctic amplification in the troposphere in current climate simulations.
- There are several candidate mechanisms - uncertain if we are capturing tropospheric AA warming for the right reasons.
- All pathways highlight the role of boundary layer coupling in driving large-scale dynamical changes.
- Our recent work has highlighted how sea ice loss might feed back onto the Arctic troposphere through midlatitude surface processes, and the role for moist isentropic transport.

Conclusions

Thanks for your attention!

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- There are several candidate mechanisms - uncertain if we are capturing tropospheric AA warming for the right reasons.
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