The role of atmospheric and oceanic heat transport in polar* amplification: *themes, thoughts, and opinions*

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US CLIVAR Polar Amplification of Climate Change Across Hemispheres and Seasons workshop
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* Mostly Arctic

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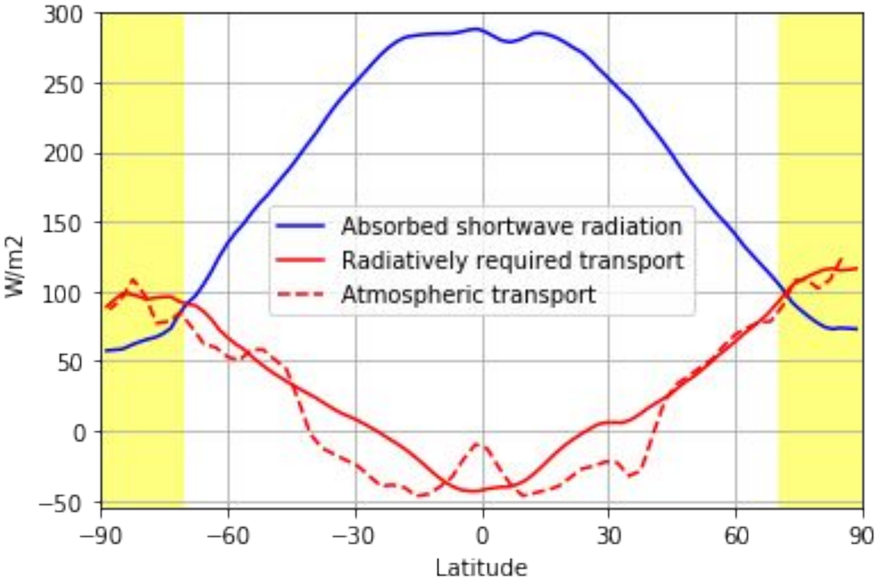
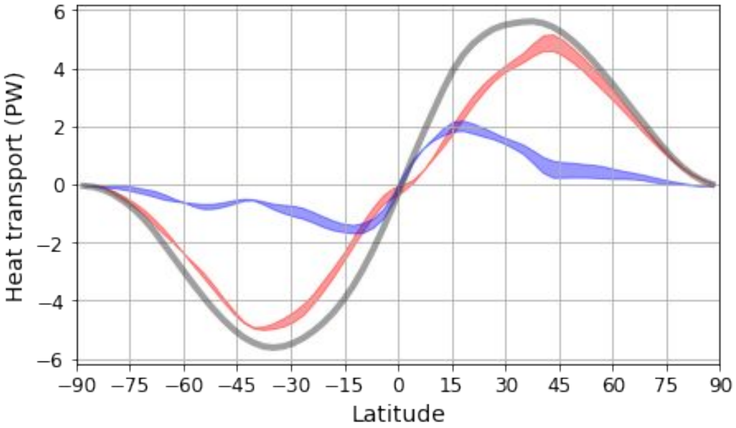
State University of New York

The poles are special: *radiative-advective equilibrium*

The polar caps are the only regions receiving more energy through atmospheric transport than from solar heating





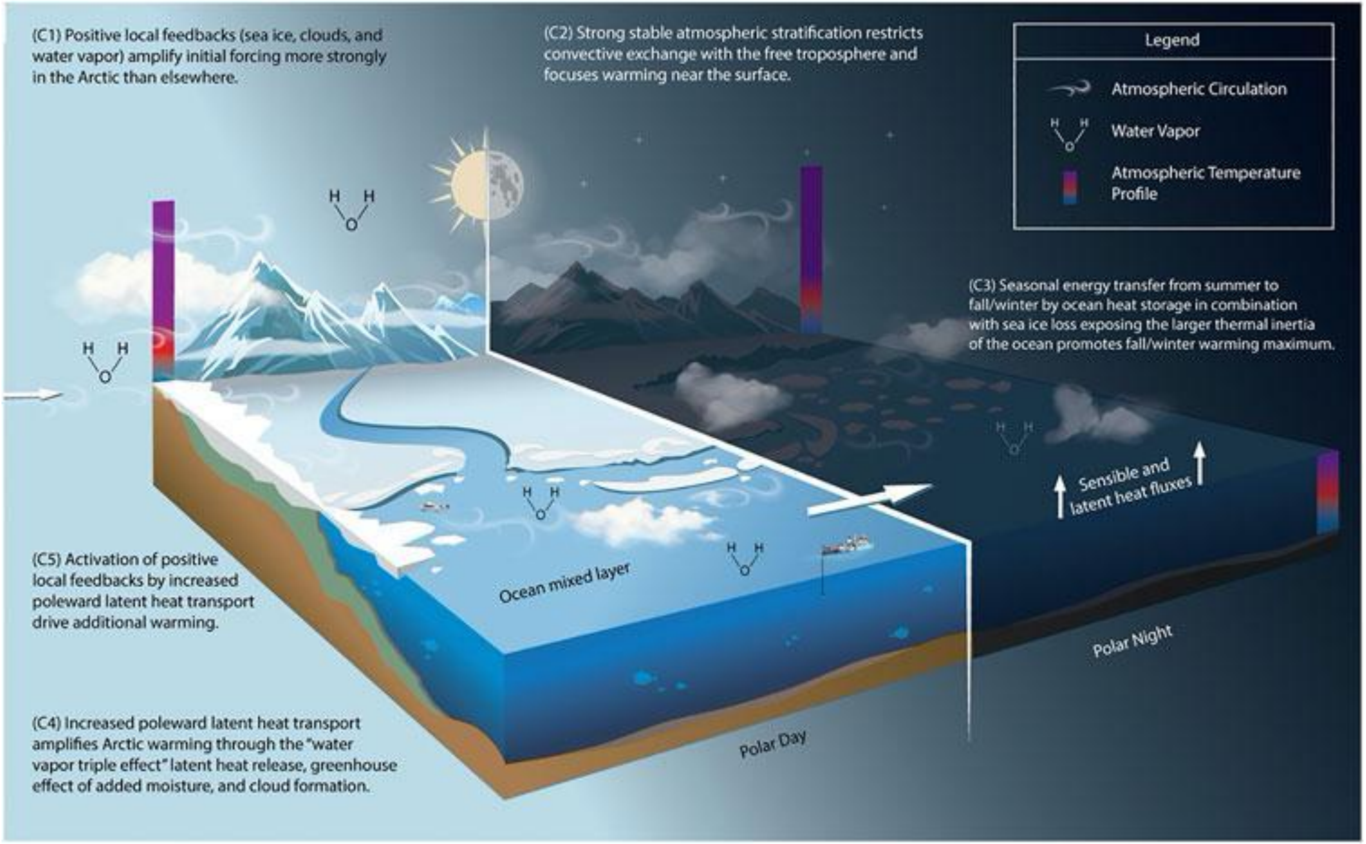
Based on data from NCEP Reanalysis and Trenberth and Caron (2001)

Stands to reason that changes in energy transport might play an important role in polar climate change!

Things we think we know about Arctic Amplification

- Arctic Amplification (AA) is a highly seasonal phenomenon
- Sea ice loss and seasonal heat storage is a key reason
- Increased poleward moisture transport is a robust feature of global warming
- Local positive radiative feedbacks in Arctic (including but not limited to surface albedo feedback) contribute to AA
- Lapse rate feedback in the Arctic is positive but this is not a mechanism – it's a consequence of other mechanisms
- Feedbacks are not independent of each other and are coupled to changes in circulation / heat transport
- Nature seems to be on the high end of our model-based AA distribution

Things we think we know about Arctic Amplification (Taylor's Version)



(C1) Positive local feedbacks (sea ice, clouds, and water vapor) amplify initial forcing more strongly in the Arctic than elsewhere.

(C2) Strong stable atmospheric stratification restricts convective exchange with the free troposphere and focuses warming near the surface.

(C3) Seasonal energy transfer from summer to fall/winter by ocean heat storage in combination with sea ice loss exposing the larger thermal inertia of the ocean promotes fall/winter warming maximum.

(C5) Activation of positive local feedbacks by increased poleward latent heat transport drive additional warming.

(C4) Increased poleward latent heat transport amplifies Arctic warming through the "water vapor triple effect" latent heat release, greenhouse effect of added moisture, and cloud formation.

Taylor et al. (2021) Front. Earth Sci. https://doi.org/10.3389/feart.2021.758361

Polar amplification in response to CO_2- even the most primitive GCMs agree

Fig. 1. Diagram illustrating the distribution of continent and "ocean." Cyclic continuity is assumed at the eastern and western ends of the domain.

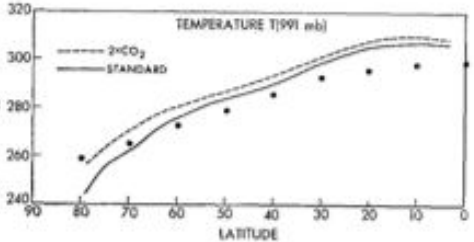


Fig. 5. Zonal mean temperature at the lowest prognostic level (i.e., ~991 mb). Dots indicate the observed distribution of zonal mean surface air temperature (Oort and Rasmusson, 1971).

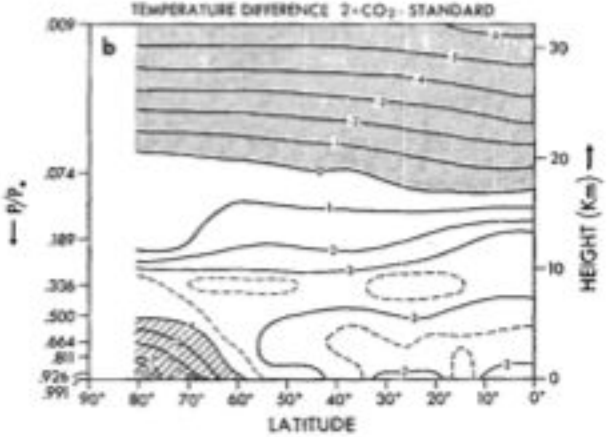


Fig. 4. Latitude-height distribution of the zonal mean temperature (K) for the standard case (a) and of the increase in zonal mean temperature (K) resulting from the doubling of CO_2 concentration (b). Stippling indicates a decrease in temperature.

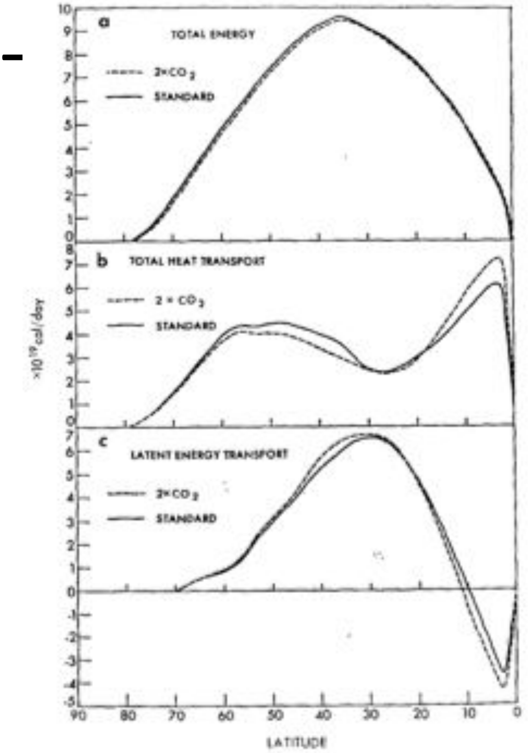
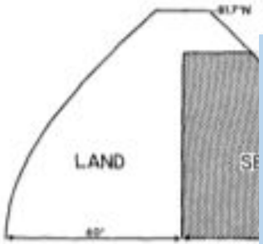


Fig. 12. Poleward transport of total energy ($C_pT+\phi+K+Lr$), a., poleward transport of heat energy ($C_pT+\phi+K$), b., and poleward transport of latent energy (Lr), c.

Manabe and Wetherald (1975) JAS https://doi.org/10.1175/1520-0469(1975)032<0003:TEODTC>2.0.CO;2

Polar amplification in response to CO2- even the most primitive GCMs agree

"... the tropospheric warming is most pronounced in the lower troposphere in high latitudes. This large warming is associated with the decrease in the area of snow (or ice) cover, which has a much larger albedo than the soil surface... the warming in high latitudes is confined within a relatively shallow layer next to the earth's surface because the vertical mixing by turbulence is suppressed in the stable layer of the troposphere in polar regions... In short, the effects of suppression of vertical mixing together those of snowmelt are responsible for the large warming in the polar region."



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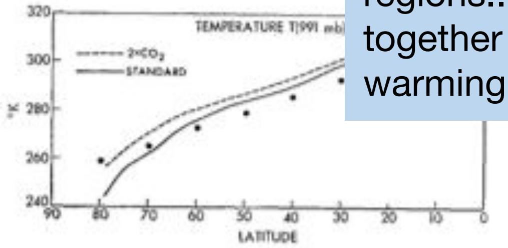

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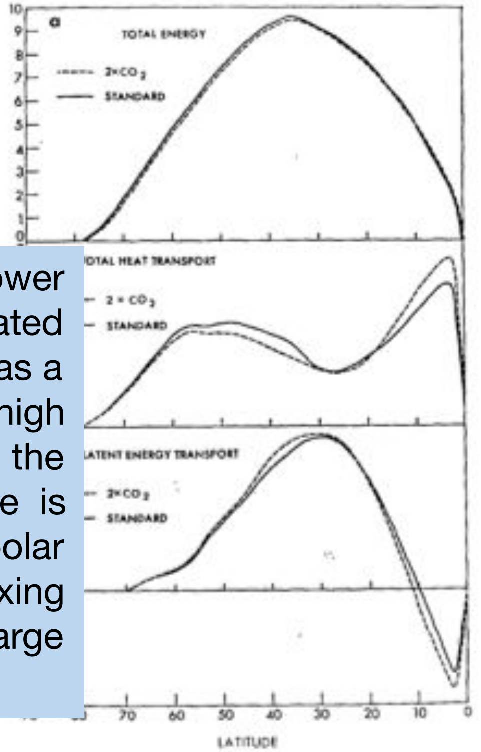

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Seasonal structure of Arctic Amplification dominated by sea ice loss and seasonal heat storage

*Global model with **seasonal cycle** and realistic geography. Mixed layer ocean with no OHT, prognostic sea ice model*

Seasonality of sea ice thickness in 1x and $4xCO_2$

Seasonal temperature anomaly from 4xCO2

Manabe and Stouffer (1980) JGR https://doi.org/10.1029/JC085iC10p05529

Seasonal structure of Arctic Amplification dominated by sea ice loss and seasonal heat storage

Global model with ***se*** *el*

> "The warming owing to the quadrupling of CO2 concentration... in high latitudes... is generally larger and varies markedly with season, particularly in the northern hemisphere. **The warming is at a maximum in early winter and is small in summer.**"
>
> "Although the poleward retreat of highly reflective snow cover and sea ice is mainly responsible for the large annual mean warming in high latitudes, the change of the thermal insulation effect of sea ice strongly influences the seasonal variation of the warming over the polar regions..."
>
> "The large increase of the absorbed solar energy in late spring or early summer results in the ... fall maximum in the warming of the mixed layer ocean which, in turn, is followed by the maximum warming of the surface atmospheric layer in early winter (i.e. November at the North Pole and January at 70°N)... The CO2-induced delay in the growth of sea ice accounts for this large winter warming of the atmosphere."

Seasonal tempera
from 4xCO2

Manabe and Stouffer (1980) JGR https://doi.org/10.1029/JC085iC10p05529

Things that are less well known / agreed-upon

- Physical mechanisms and causality in links between AHT and Arctic radiative feedbacks
- Role of synoptic-scale variability in AHT changes and their effects on AA
- Almost everything related to ocean heat transport and ocean–sea ice interaction

Ocean heat transport and Arctic Amplification

Coupled models tend to predict increased OHT associated with ice loss and Arctic Amplification

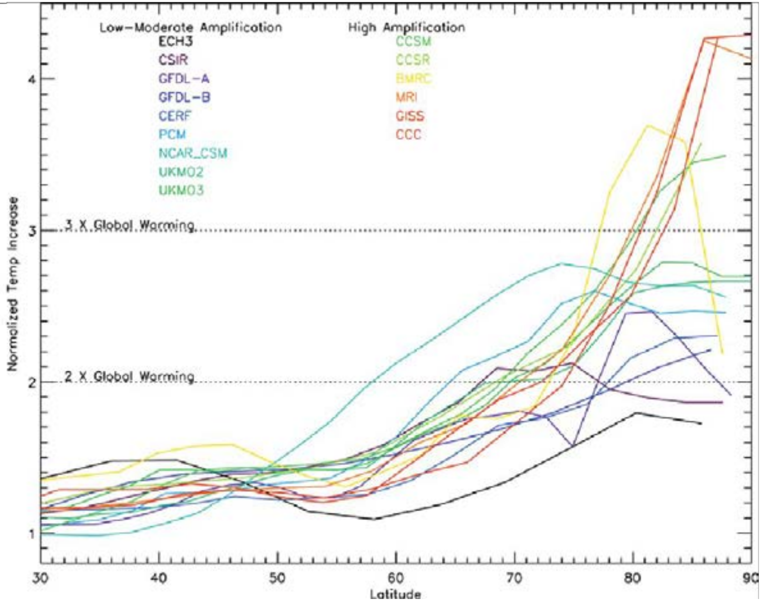
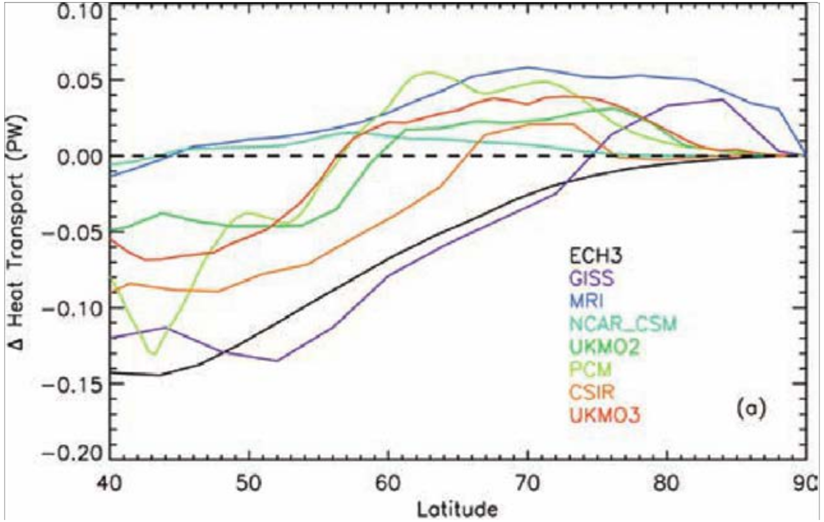
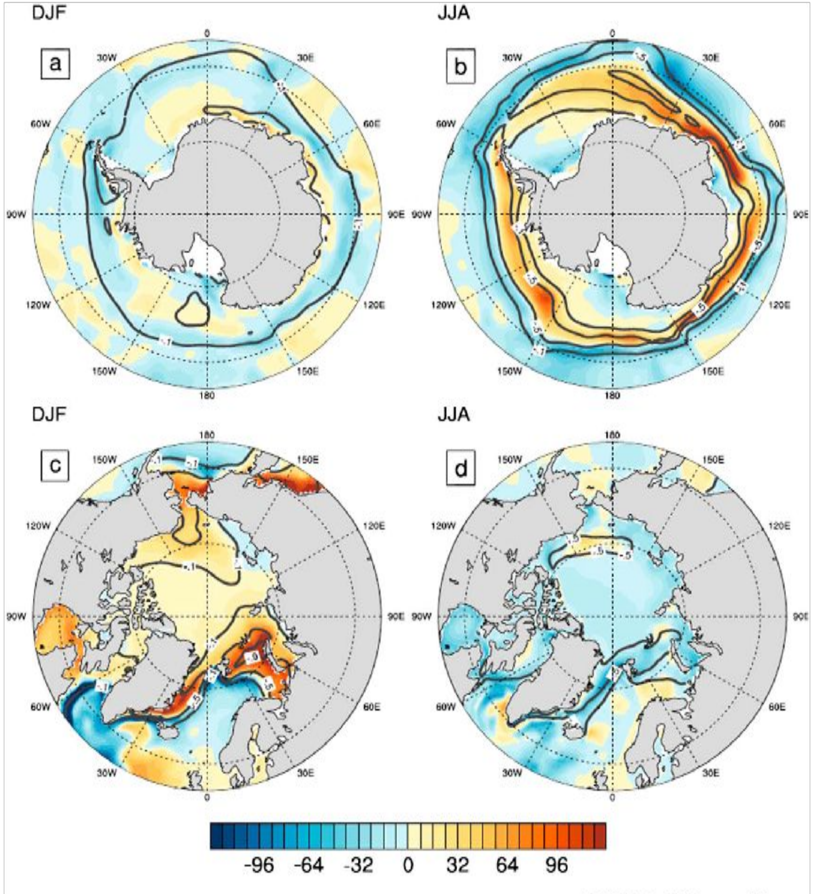


Fig. 1 The increase in zonally averaged 2 m air temperature for 2×CO_2 conditions as a function of latitude normalized by the globally averaged air temperature increase



Holland and Bitz (2003) Clim. Dyn., https://doi.org/10.1007/s00382-003-0332-6

Close connection between OHT changes and winter ice loss (more modern example)



2xCO2 in a fully coupled model

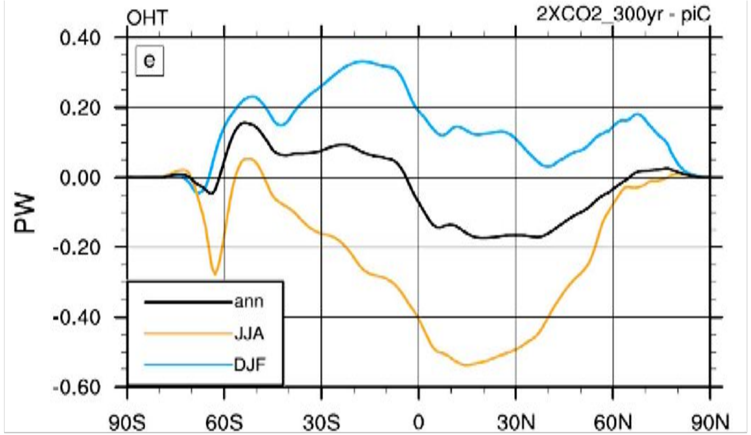


Figure 1. (a–d) Change in ocean heat flux convergence (OHFC) into the mixed layer (colors; in W m^{-2}) and change in sea ice concentration (contours at −0.1, −0.5, −0.9) between the preindustrial control (piC) simulation and the CO_2 doubling (2XCO2_300yr) simulation, for the Antarctic in (a) December, January, March (DJF) and (b) June, July, August (JJA) and Arctic in (c) DJF and (d) JJA. (e) Change in ocean heat transport in the mixed layer (2XCO2_300yr – piC, in PW) in DJF (yellow), JJA (blue), and the annual mean (black).

Singh, Rasch, and Rose (2017) GRL, https://doi.org/10.1002/2017GL074561

But the causality is hard to disentangle

Comparing 2xCO2 to artificial sea ice darkening

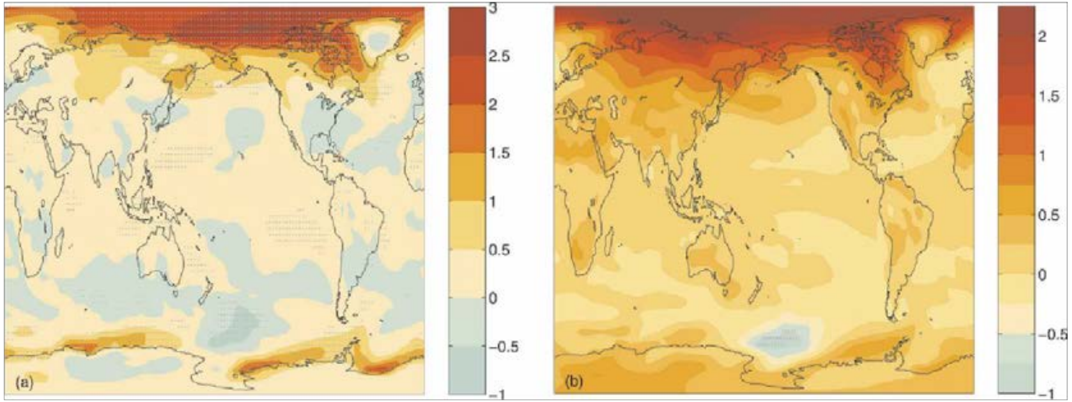


FIG. 1. Change in 2-m surface air temperature in °C resulting from (a) lowering sea ice albedo and (b) doubling CO_2, compared to the control. In (a), the gray dots mark grid cells with statistically significant warming or cooling ($p = 0.95$). In (b), gray Xs mark grid cells with significant cooling. Nearly all other grid cells in (b) have significant warming.

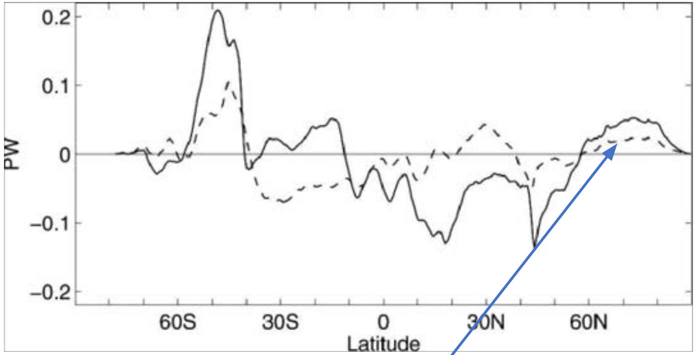


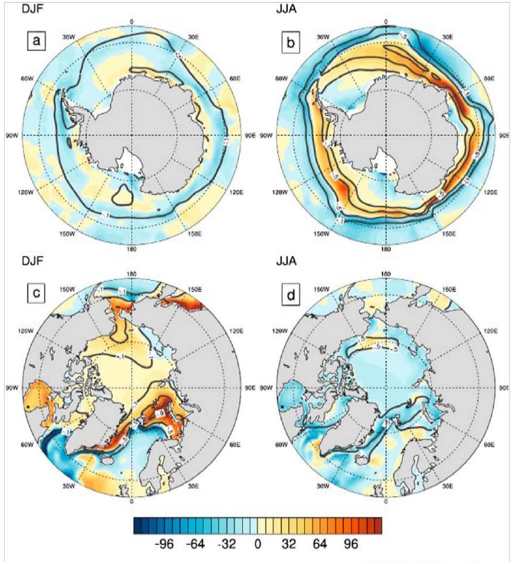
FIG. 4. The change in zonal mean northward heat transport into the global oceans resulting from doubling CO_2 (solid) and lowering sea ice albedo (dashed).

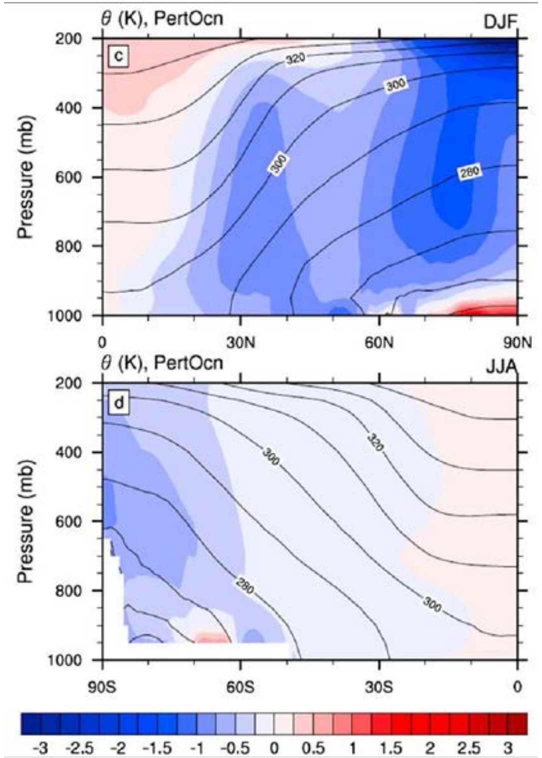
OHT into Arctic increases with imposed ice loss!

Bitz et al. (2006) JClim, https://doi.org/10.1175/JCLI3756.1

OHT also influences AA indirectly by modifying other feedbacks

Diagnose OHT changes from fully coupled model, impose them in a slab ocean model





Arctic surface warming and mid-tropospheric cooling – a positive lapse rate feedback!

Singh, Rasch, and Rose (2017) GRL, https://doi.org/10.1002/2017GL074561

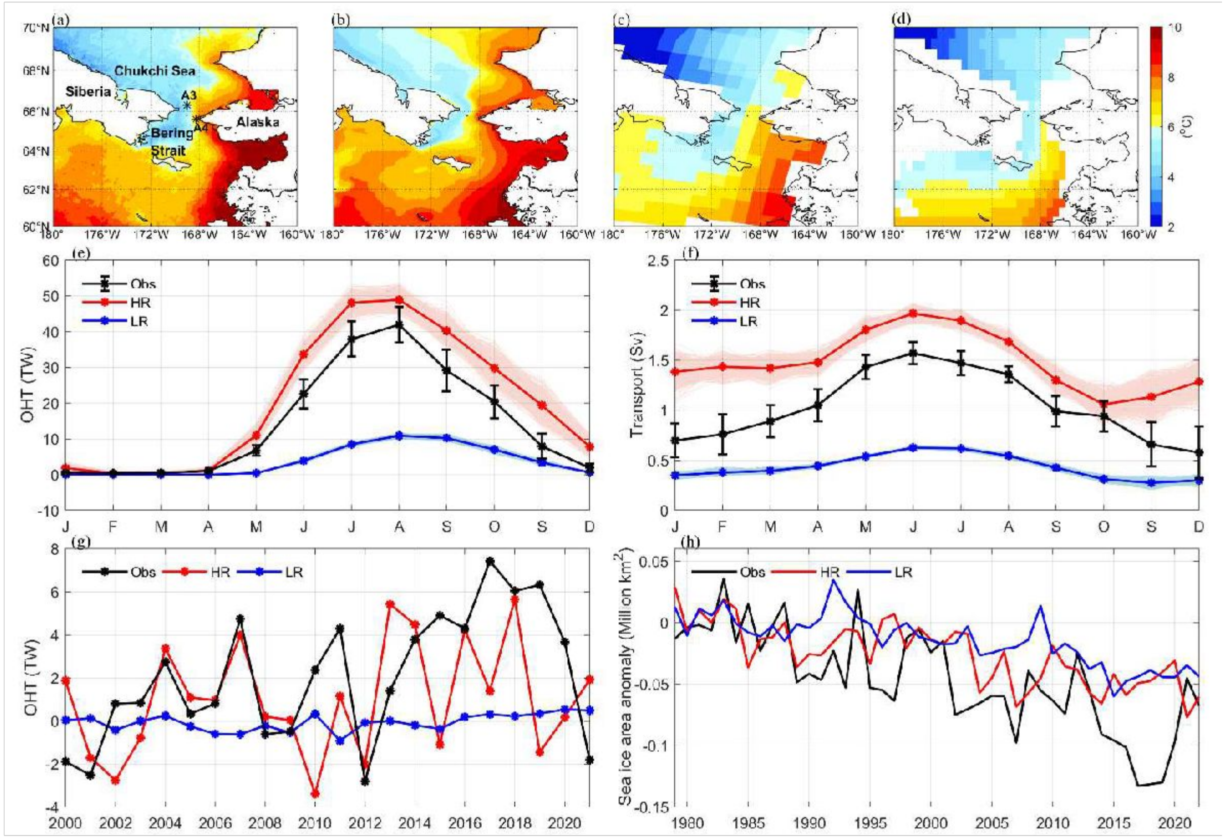
- Orders of magnitude fewer observations of the ocean's interior
- Order of magnitude smaller spatial scales required to resolve the basic geostrophic turbulent flow
- Likely to be more surprises emerging from high resolution eddy-permitting models

Effects of ocean model resolution:

More realistic heat transport through Bering Strait leads to stronger AA

HR: 0.1º ocean, 0.25º atm
LR: 1º ocean, 1º atm

SST: obs HR LR CMIP



Ping Chang et al. preprint (2023), https://doi.org/10.21203/rs.3.rs-3425469/v1

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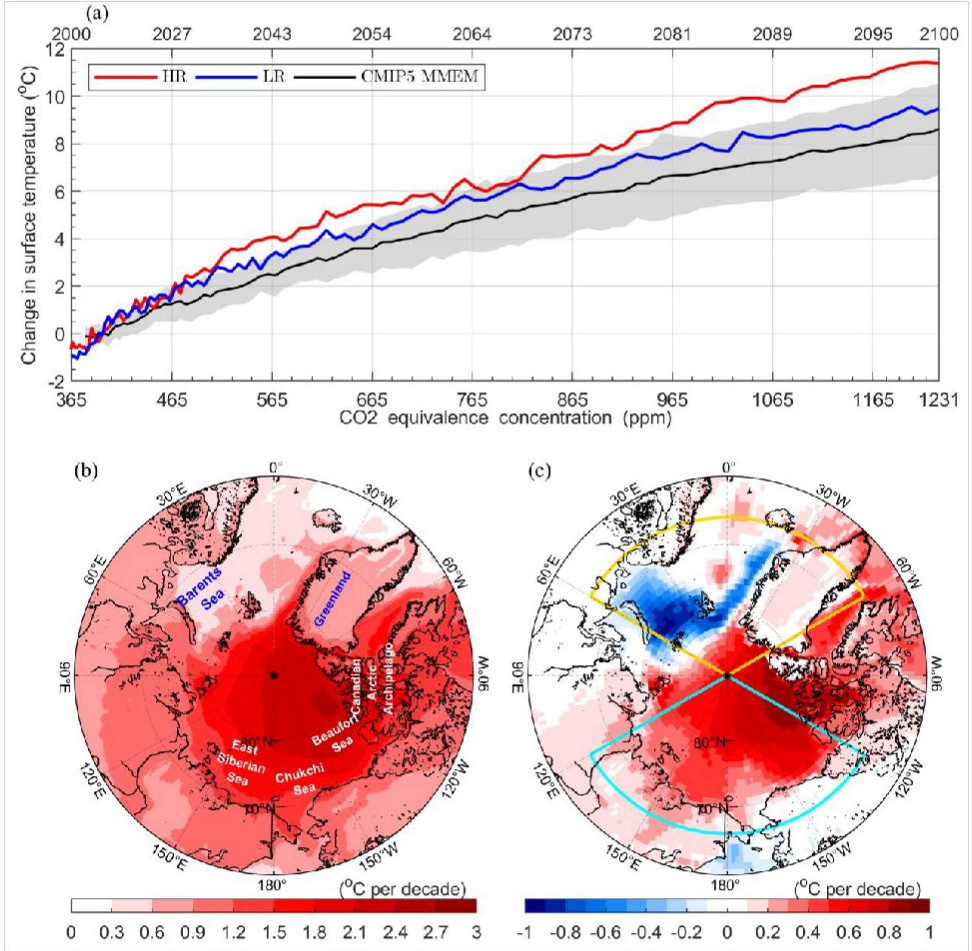


Annual-mean Arctic surface warming in RCP8.5 scenario

Warming rate in HR (left) and HR – LR anomaly

Ping Chang et al. preprint (2023), https://doi.org/10.21203/rs.3.rs-3425469/v1

Atmospheric heat transport and Arctic amplification

Models disagree about changes in total AHT – but agree that moisture transport goes up

Moisture transport is a driver of polar amplification…

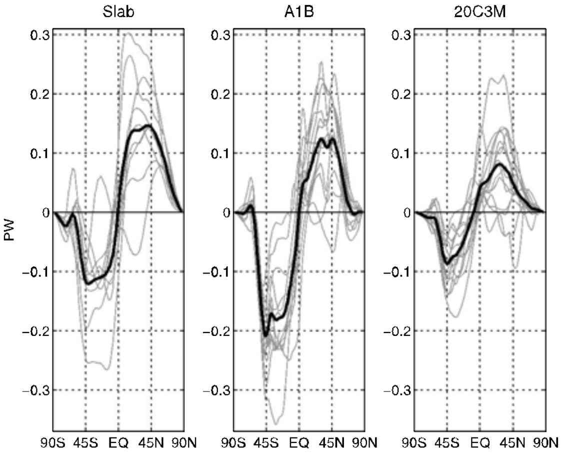


Figure 1. Zonal average changes in northward MSE flux (PW) in (left) slab ocean models, (middle) the SRES A1B scenario, and (right) the 20C3M scenario. Multi-model means are in bold.

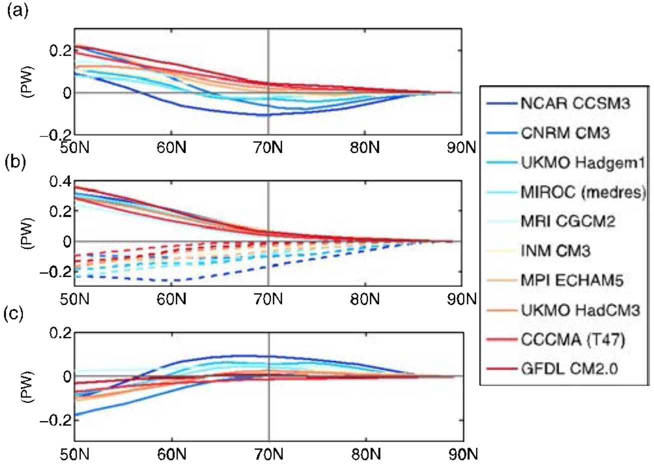


Figure 1. Changes in northward energy transports in PW from 2001~2020 to 2081 ~2100 in the A2 Scenario: (a) atmospheric energy transport, (b) moisture (solid) and DSE (dashed) transport, and (c) oceanic energy transport.

Effect is well described by a moist diffusive Energy Balance Model

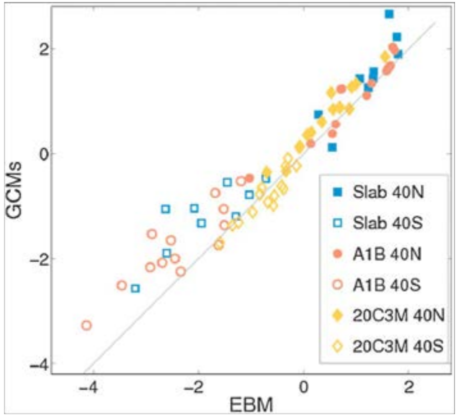


Figure 2. EBM predicted changes in MSE fluxes at 40N/S versus the actual changes in GCMs (in PW).

Hwang and Frierson (2010), https://doi.org/10.1029/2010GL045440

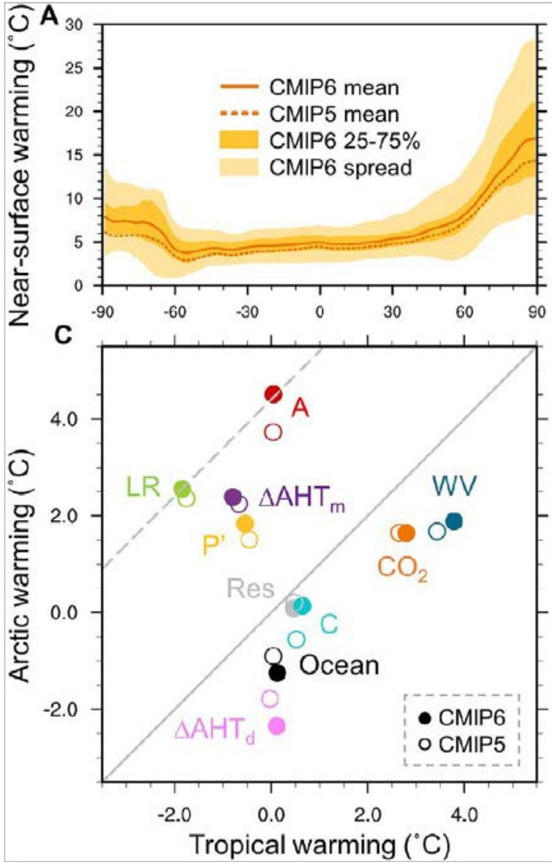
Correction https://doi.org/10.1029/2011GL047604

Hwang, Frierson, and Kay (2011), https://doi.org/10.1029/2011GL048546

Energy budget attribution studies support the idea that moisture transport contributes to AA

$$\Delta T = -\frac{ERF}{\overline{\lambda_p}} - \frac{\lambda_p'\Delta T}{\overline{\lambda_p}} - \frac{\sum_i \lambda_i \Delta T}{\overline{\lambda_p}} - \frac{\Delta AHT}{\overline{\lambda_p}} - \frac{\Delta O}{\overline{\lambda_p}} - \frac{\Delta R_{res}}{\overline{\lambda_p}}$$

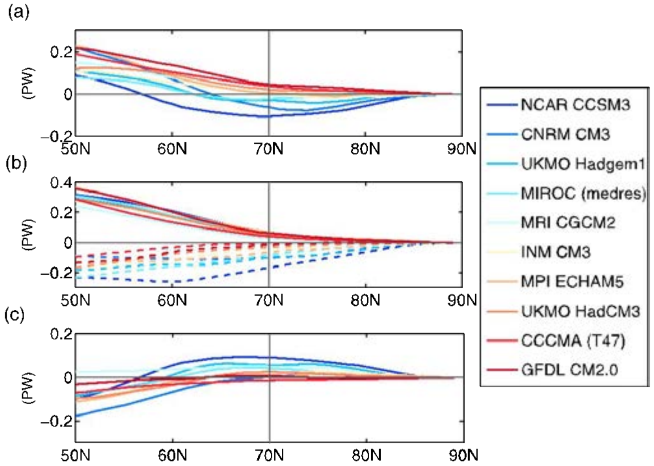
The linear partial warming framework based on a local energy budget



Hahn et al. (2021) https://doi.org/10.3389/feart.2021.710036

AHT changes are anti-correlated with AA across models

AHT is a response to polar amplification…



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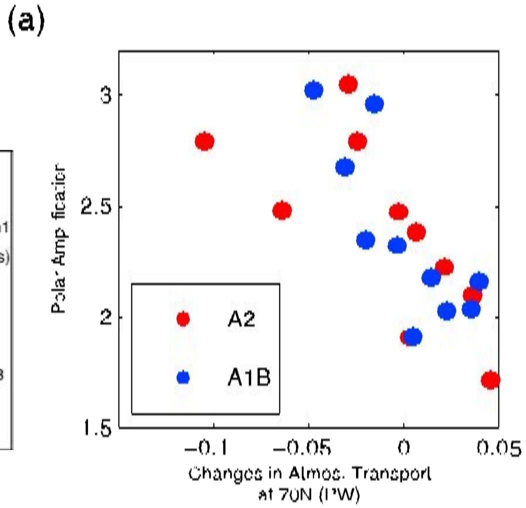


Figure 2. (a) Polar amplification versus changes in atmospheric energy transport at 70N. (b) Polar amplification versus changes in oceanic transport at 70N. (c) EBM predicted changes in atmospheric energy transport versus actual changes in atmospheric energy transport in the GCMs at 70N. Blue dots are from the A1B scenario, and red dots are from the A2 scenario.

"Model spread in atmospheric energy transport cannot explain model spread in polar amplification; models with greater polar amplification must instead have stronger local feed- backs. Because local feedbacks affect temperature gradients, **coupling between energy transports and Arctic feedbacks cannot be neglected when studying Arctic amplification**."

Hwang, Frierson, and Kay (2011), https://doi.org/10.1029/2011GL048546

Disentangling causality in polar amplification requires thinking about **spatial** and **temporal** structures of energy transports

Changes in climatological energy budgets don’t give us enough information

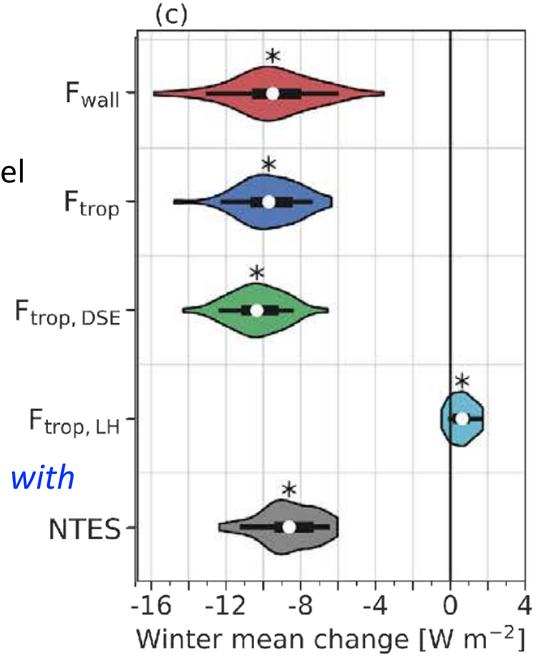
Poleward heat transport: friend or foe of polar amplification?

CESM-LE predicts a ***decrease*** *in heat transport across 70ºN with warming*

Roughly 10 W/m2 decrease in winter-season polar-cap convergence, consistent with the relatively strong Arctic amplification in this model

So atmospheric dynamics are acting to mitigate Arctic amplification, right?

Do the climatic impacts of heat transport actually scale with the total integral heating of the atmosphere?



Punchline:
NO

Not all heating events are created equal

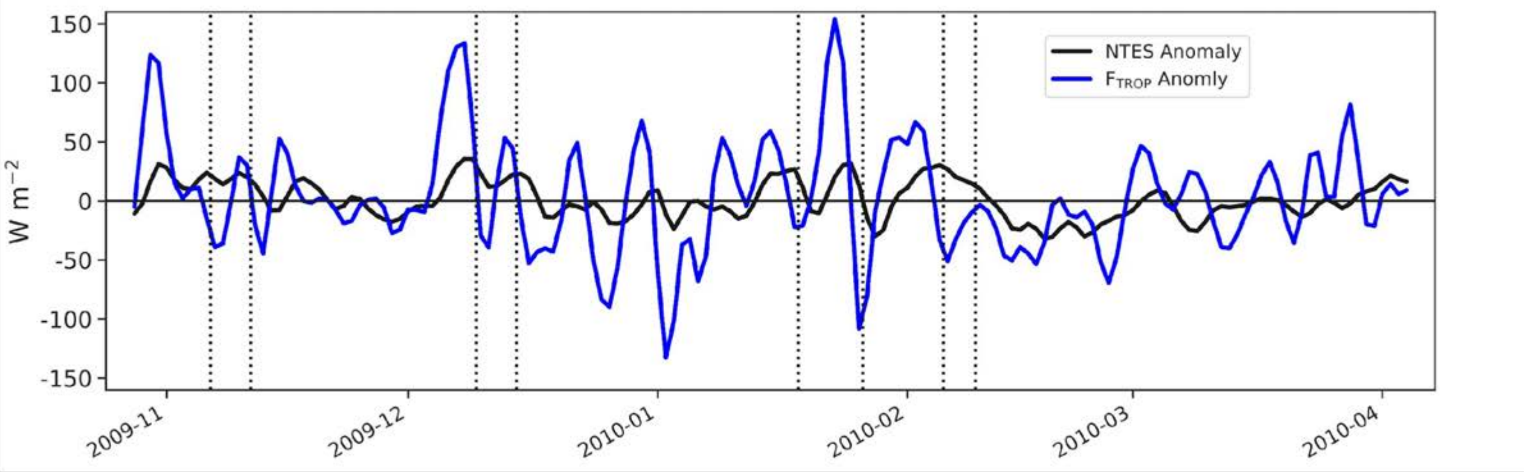
And the impactful ones increase more with warming

Cardinale and Rose (2023) GRL, https://doi.org/10.1029/2022GL100834

Efficiency of tropospheric energy flux events

The basic idea

1. *There's a surge of excess moist static energy into the Arctic polar cap*
2. *The air column becomes warmer and moister*



*Timeseries of total tropospheric energy flux convergence, illustrating occasional surges of heating (**single winter**, from MERRA-2 data)*

Cardinale and Rose (2022) J. Climate, https://doi.org/10.1175/JCLI-D-21-0852.1

Efficiency of tropospheric energy flux events

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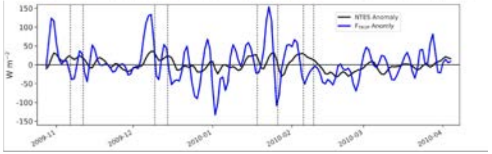
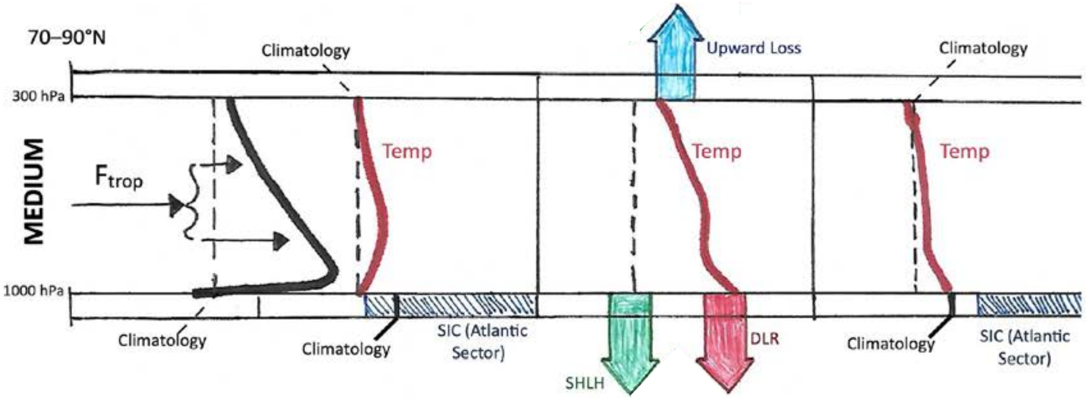


Then what? … the excess must be disposed either up or down!



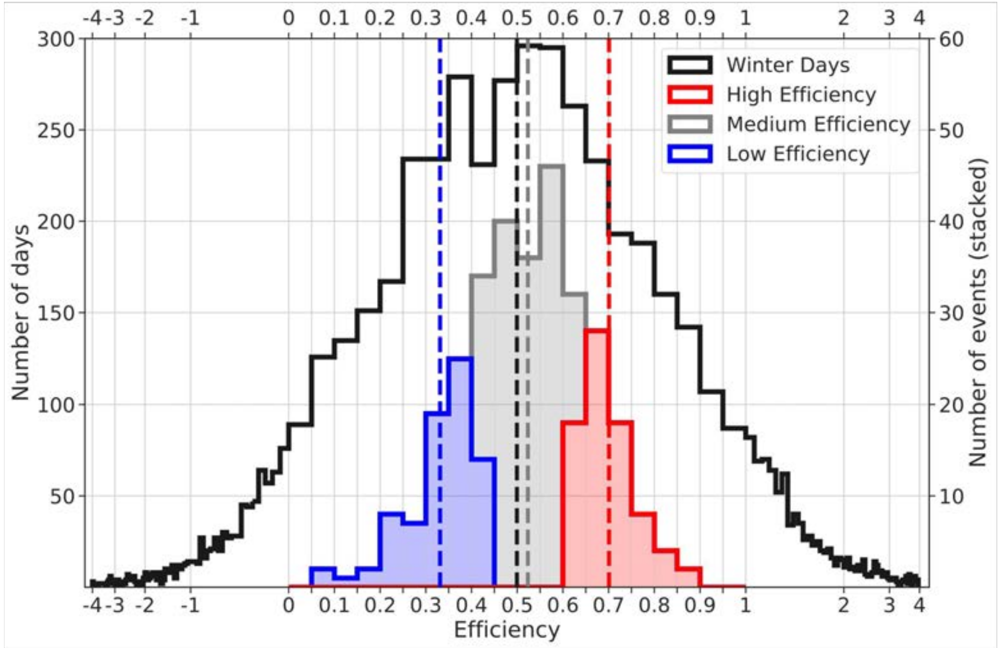
***Efficiency** is the fraction of the excess energy that goes down!*

i.e., the ratio of anomalous net surface heat flux to anomalous energy source

Cardinale and Rose (2022) J. Climate, [*https://doi.org/10.1175/JCLI-D-21-0852.1*](https://doi.org/10.1175/JCLI-D-21-0852.1)

Climatological efficiency

- e is the ratio of anomalous surface energy flux to anomalous atmospheric heating – how much of the heating event is “captured” by the surface
- Compute e for individual synoptic heating events from high-frequency reanalysis or model data

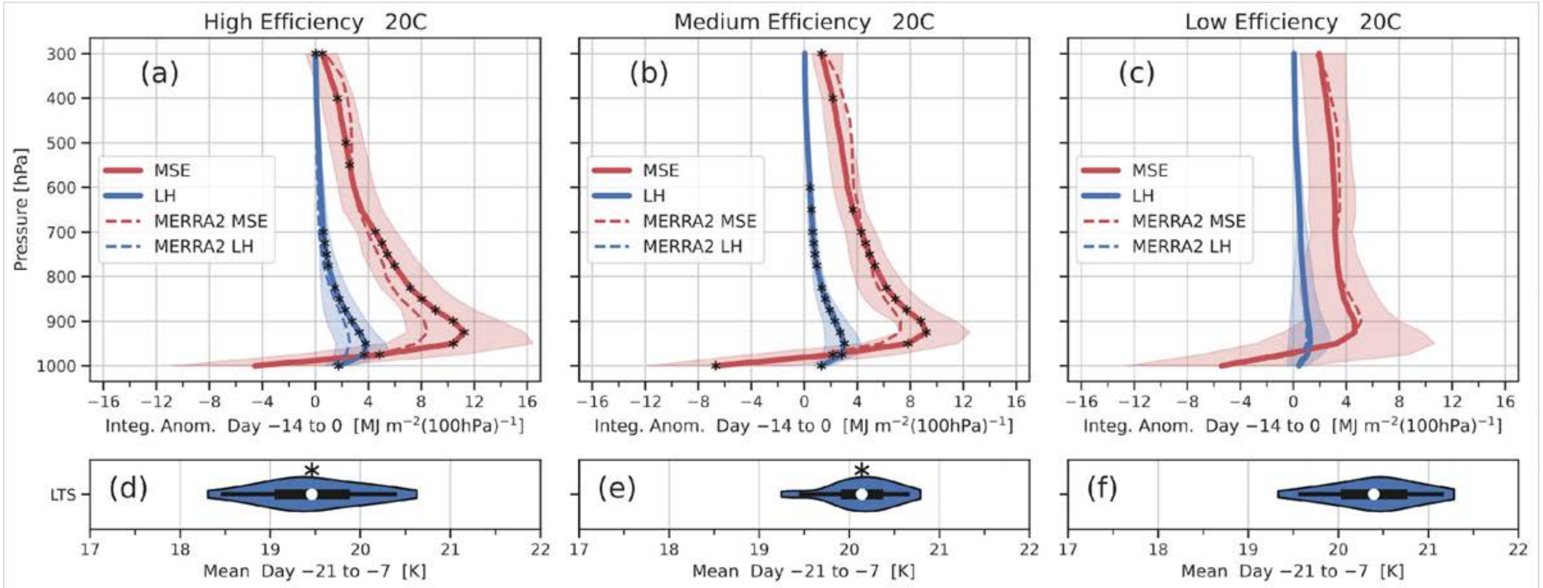


*We separate **events** into **three bins** based on efficiency: **low**, **medium**, and **high***

*And then look at **composites** of events for all three bins*

Cardinale and Rose (2022) J. Climate, *https://doi.org/10.1175/JCLI-D-21-0852.1*

Factors influencing efficiency from event composites



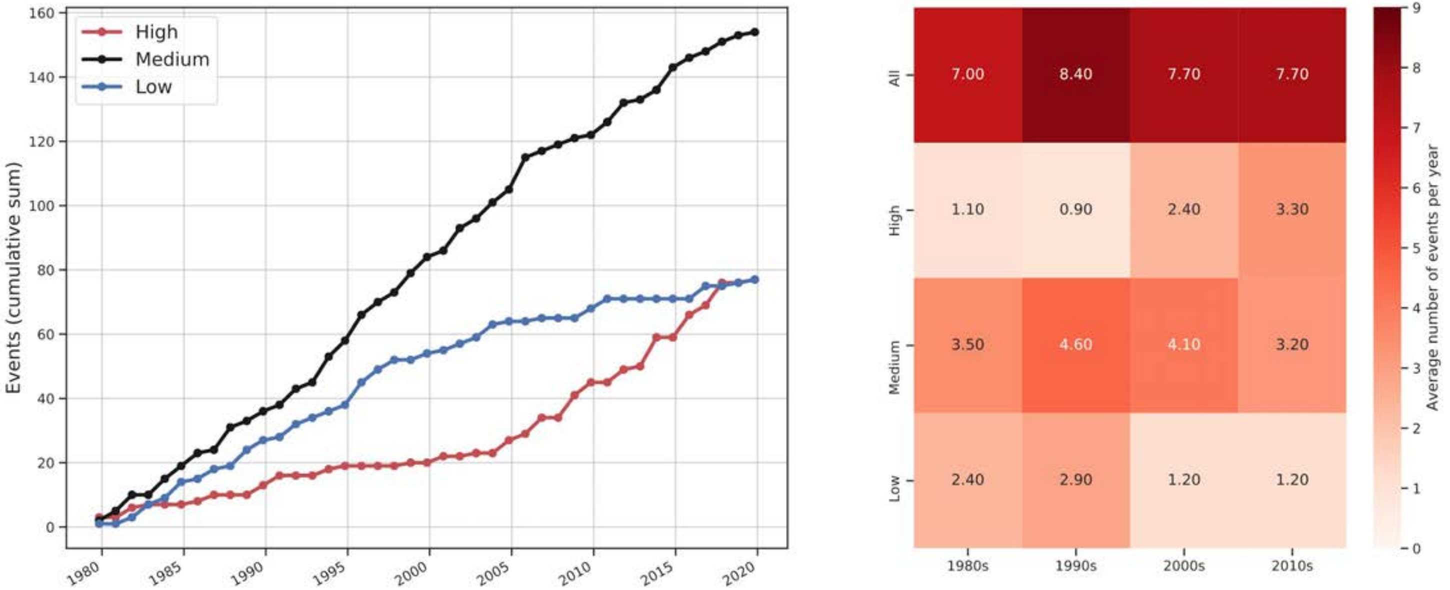
High efficiency *associated with "bottom heavy" heat transport profiles and antecedent weak stratification / low sea ice anomalies*

Low efficiency *associated with more vertically uniform heat transport profiles and antecedent high stratification / high sea ice anomalies*

Cardinale and Rose (2023) GRL, *https://doi.org/10.1029/2022GL100834*

Is efficiency changing?

*YES, according to the MERRA-2 reanalysis**



	1980s	1990s	2000s	2010s
All	7.00	8.40	7.70	7.70
High	1.10	0.90	2.40	3.30
Medium	3.50	4.60	4.10	3.20
Low	2.40	2.90	1.20	1.20

***High-efficiency** event frequency is **increasing** at the expense of low-efficiency events*

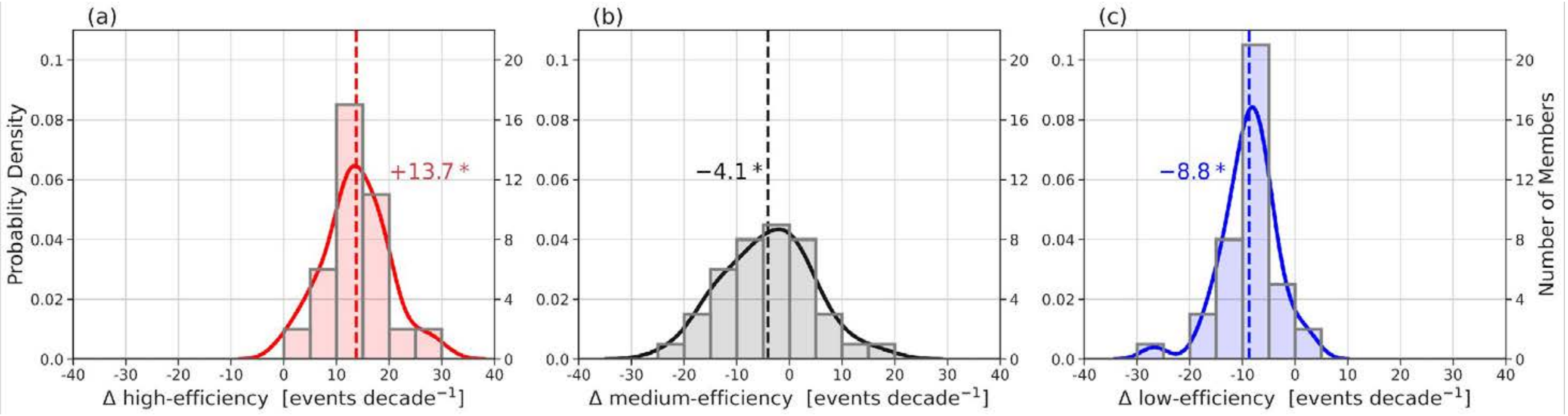
* raw MERRA-2 data were de-trended prior to computing trends in event counts

Cardinale and Rose (2022) J. Climate, https://doi.org/10.1175/JCLI-D-21-0852.1

What about the future?

Computing efficiency in climate model projections

We use high-frequency output from the **CESM Large Ensemble**
to compare the recent historical period to a next-century scenario



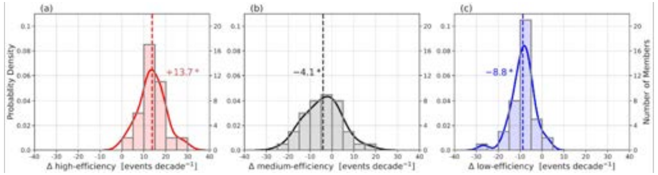
We find a robust **increase in efficiency** of events in these warmer futures

Cardinale and Rose (2023) GRL, https://doi.org/10.1029/2022GL100834

Poleward heat transport: friend or foe of polar amplification?

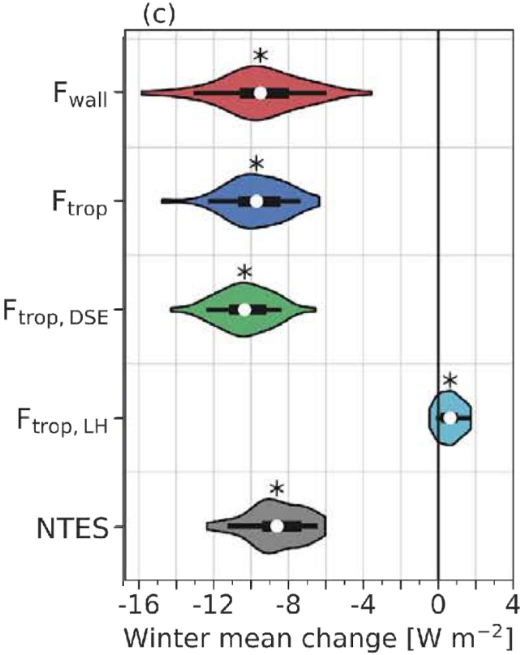
*CESM-LE predicts a **decrease** in heat transport across 70ºN with warming*

We lose 10 W/m2 of heat transport



But the surface receives a larger fraction of the energy per event

How does this play out?



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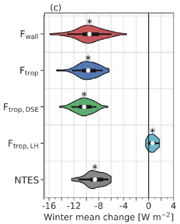
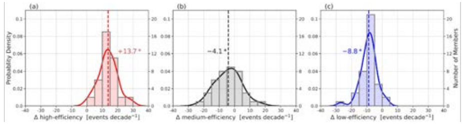
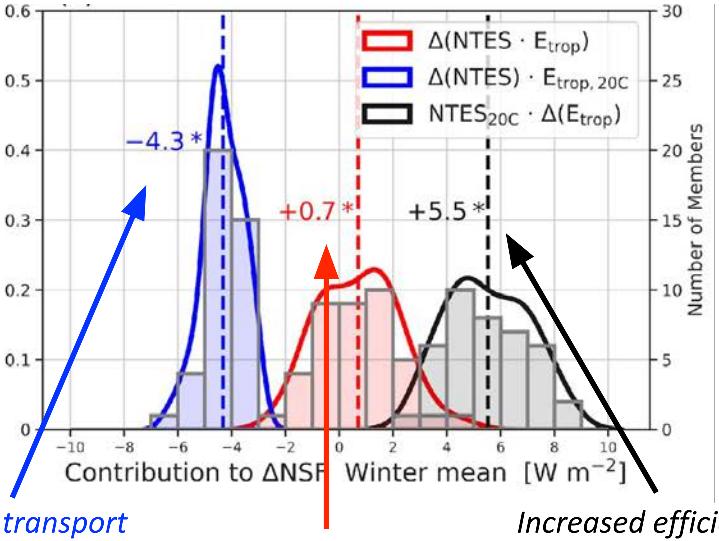
Poleward heat transport: friend or foe of polar amplification?





Impact on surface energy budget of…



Reduced transport

Net combined

Increased efficiency

The increase in per-event efficiency more than compensates for the decreased atmospheric heat transport

Cardinale and Rose (2023) GRL, https://doi.org/10.1029/2022GL100834

Arctic heat transport efficiency: summary

- The **surface heating impact** of synoptic events can be quantified through an **efficiency** metric
- **High-efficiency** events become **more frequent** with warming, both in reanalysis (MERRA-2) and a model (CESM-LE)
    - The primary mechanism seems to be **reduced stratification**, stronger turbulent coupling of troposphere to surface
- Increased efficiency **more than compensates** reduced total poleward energy transport in CESM-LE
- Total poleward energy transport is the **wrong diagnostic** for understanding drivers of Arctic Amplification
- We need to look at **synoptic** timescales to understand the impact of **atmospheric circulation** on Arctic energetics.
- Caveat / future work: we looked at **winter only**. Informed by Lily Hahn's work on impacts of seasonal heating, it would be very interesting to look more closely at summer heat transport

Cardinale, Rose, Lang, and Donohoe (2021) J. Climate doi:10.1175/JCLI-D-20-0722.1
Cardinale and Rose (2022) J. Climate, https://doi.org/10.1175/JCLI-D-21-0852.1

Cardinale and Rose, GRL, https://doi.org/10.1029/2022GL100834

Heat transport and amplification: some paths forward

- Maybe there’s not much left to learn from looking at changes in climatological energy budgets with warming
- A priority needs to be better understanding the **causality** between heat transport, local feedbacks, and amplification
  - Let’s do more coordinated, thoughtfully constructed mechanism denial experiments.
  - In the atmosphere, let’s think about synoptic timescales and the impact of individual weather events.
    - *(Unfortunately) this means prioritizing making high-frequency diagnostics available!*
  - In the ocean, let’s continue to work on process understanding of ice-ocean interactions with an eye toward the limitations of our coarse resolution models.