Sea Ice Loss, Water Vapor Increases, and Their Interactions with Atmospheric Energy Transport in Driving Seasonal Polar Amplification

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• The polar amplification (PA) is a robust feature of global warming.
• PA reaches its maximum during winter and minimum during summer.

Near-surface Arctic warming of 4xCO2 in CMIP6 (K)

(Hahn et al. 2021)
Popular diagnostic frameworks attribute polar amplification to ice albedo feedback and positive lapse rate feedback. 

(Pithan and Mauritsen 2014; Goosse et al., 2018; Hahn et al. 2021)

Contributions of each feedback to warming

- Despite the water vapor feedback contributing to tropical warming, it plays a role in PA by amplifying other positive feedbacks in the polar region. (Beer and Eisenman 2022)
- Positive polar feedbacks decrease poleward dry energy transport. (Feldl et al. 2017; Henry et al. 2021)
- However, it is unclear how these feedbacks and transports manifest and interact seasonally.

(Hahn et al. 2021)
We apply a radiative transfer hierarchy to an idealized GCM (Isca, Vallis et al. 2018) coupled to thermodynamic sea ice model (Semtner 1976; Zhang et al. 2021) to investigate the role of sea ice and water vapor and their interaction with atmospheric energy transport across the seasonal cycle in polar amplification.

Sea ice model includes energy fluxes at base, top, and through the sea ice.

- Slab ocean aquaplanet
- Seasonal insolation
- Mixed layer depth=60 m
- No clouds, Q-flux
- T42 resolution * 30 levels

(Zhang et al. 2022)
1. Total response \((\text{CO2+WV+sea ice loss})\)
2. Response to CO2
3. Response to water vapor radiative effect
4. Response to sea ice loss \((\text{sea ice retreat}+\text{sea ice thinning})\)
5. Response to sea ice retreat
6. Response to sea ice thinning
Zonal and annual mean temperature response (K)
Results

- Tropical warming in the upper troposphere □ Response to WV radiative effect
- Polar amplification □ Response to sea ice retreat
Results

Zonal mean surface temperature response (K)

• Response to CO2 and WV: weak seasonality

Contour: sea ice edge (fraction=1%) in CTL and PTB
Results

Zonal mean surface temperature response (K)

- Response to CO2 and WV: weak seasonality
- Response to sea ice retreat: strong winter warming
- Response to sea ice thinning: summer cooling and winter warming
- The latent heat of melting ice suppresses summer warming; the increasing conductive heat flux due to thinning ice cause the winter warming. (Feldl and Merlis 2021; Hahn et al. 2022)

Contour: sea ice edge (fraction=1%) in CTL and PTB
Results

Warming Contribution method

\[ F + (\lambda_p + \sum_i \lambda_i) \delta T_s + \delta AHT_d + \delta AHT_q + \delta SEB + \delta R_{res} = 0 \]

Surface temperature anomaly

\[ \delta T_s = - \frac{F}{\lambda_p} - \frac{\lambda'_p \delta T_s}{\lambda_p} - \frac{\Sigma_i \lambda_i \delta T_s}{\lambda_p} - \frac{\delta AHT_d}{\lambda_p} - \frac{\delta AHT_q}{\lambda_p} - \frac{\delta SEB}{\lambda_p} - \frac{\delta R_{res}}{\lambda_p} \]

Forcing
Climate Feedback
(PLK, LR, ALB, WV)
Dry and Moist
Atmosphere Heat Transport
Surface Energy Budget
(Ocean term)

\[ \lambda'_p = \lambda_p - \bar{\lambda}_p \]

(Feldl and Roe 2013; Pithan and Mauistsen 2014; Goosse et al. 2018; Stuecker et al. 2018; Hahn et al. 2021)
Results

Annual Mean Warming Contribution

a. Total Response
b. Response to CO2
c. Response to WV Radiative Effect
d. Response to Sea Ice Loss
e. Response to Sea Ice Retreat
f. Response to Sea Ice Thinning
• Alb dominates PA
• AHTq plays a moderate role
• WV, AHTd contributes to tropical amplification

Surface Temp. Forcing
- Alb: Albedo
- PLK: Planck
- LR: Lapse Rate
- WV: Water Vapor
- Dry AHT
- Moist AHT
- SEB: Surface Energy Budget
- Residual
Results

- The primary physical process to PA
- Strong Alb and decreased AHTd
Annual Mean Warming Contribution

- **Ts** Surface Temp.
- **F** Forcing
- **alb** Albedo
- **PLK** Planck
- **LR** Lapse Rate
- **WV** Water Vapor
- **AHTd** Dry AHT
- **AHTq** Moist AHT
- **SEB** Surface Energy Budget
- **Re** Residual

- **WV** contributes to tropical amplification
- **AHTq** contributes to PA
- Uniform surface warming by the two
Seasonal Polar Warming Contribution

- Alb, SEB, AHTd are the primary terms
- Alb contributes to summer warming
- But it is balanced by ocean heat uptake
- Ocean release energy back to atm in winter, causing PA
- PA induce the decrease in AHTd
SEB leads to winter warming & summer cooling

Summer cooling slightly increases the AHTd

- **SEB** leads to winter warming & summer cooling

- Summer cooling slightly increases the AHTd

**Surface Temp.**
- Ts

**Forcing**
- F
- alb

**Albedo**
- PLK
- LR

**Planck**
- WV

**Lapse Rate**
- AHT
- AHTq

**Water Vapor**
- AHTd
- Re

**Dry AHT**
- SEB

**Moist AHT**
- Residual

**Surface Energy Budget**
- Residual

**Residual**
The decomposition of seasonal surface energy budget

• When sea ice retreats, the ocean absorbs surface SW during summer and release heat during winter
• The winter warming trigger the upward turbulent flux (latent + sensible heat flux)

See also Shaw and Smith (2022). Jenkins and Dai (2021)
Results

Seasonal Polar Warming Contribution

- WV contributes to summer warming
- AHTq contributes to winter warming
- Uniform surface warming by the two

Forcing
- Ts
- F
- alb
- PLK
- LR
- LW
- WV
- AHTd
- AHTq
- SEB
- Re

Surface Temp.
- Albedo
- Planck
- Lapse Rate
- Water Vapor
- Dry AHT
- Moist AHT

Surface Energy Budget
- Residual

*The axes in b and c are different
Seasonal Polar Warming Contribution

- WV contributes to summer warming
- AHTq contributes to winter warming
- Uniform surface warming by the two

*The axes in b and c are different*
Results

Seasonal Northward Dry Transport Anomaly (PW)

a. Total Response
b. Response to CO2
c. Response to WV Radiative Effect

d. Response to Sea Ice Loss
e. Response to Sea Ice Retreat
f. Response to Sea Ice Thinning
Results

Seasonal Northward Latent Transport Anomaly (PW)

a. Total Response

b. Response to CO2

c. Response to WV Radiative Effect

d. Response to Sea Ice

Seasonal q anomaly, Response to WV Radiative Effect

Response to Sea Ice Thinning
We separate the effect of CO$_2$, WV, sea ice retreat and sea ice thinning to PA by the hierarchy of the idealized models (Isca coupled with sea ice thermodynamic).

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- The latent heat of melting ice suppresses summer warming while winter sea ice thinning causes the warming through increasing conductive heat flux.
- Summer polar warming contributed by WV feedback is compensated by its induced winter increase in poleward moist transport.
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- The summer ice-albedo feedback contributes to winter PA through ocean heat uptake/release
- The latent heat of melting ice suppresses summer warming while winter sea ice thinning causes the warming through increasing conductive heat flux
- Summer polar warming contributed by WV feedback is compensated by its induced winter increase in poleward moist transport
- The change in seasonal dry energy transport is a passive response to seasonal warming pattern

Our results highlight the importance of the interaction between feedbacks and atmospheric energy transports on the seasonality polar amplification, and thus improve understanding of its mechanisms


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Models

Isca: a framework for the idealized modelling of the global circulation of planetary atmospheres at varying levels of complexity. ([https://execlim.github.io/IscaWebsite/](https://execlim.github.io/IscaWebsite/))

- Default Isca: prescribe surface albedo. No active sea ice.
- Thermodynamic sea ice model: Thermo-fluxes are read to simulate sea ice activity

\[
\begin{align*}
L_i \frac{dh_i}{dt} &= F_{\text{atm}} - F_{\text{base}} \\
F_{\text{base}} &= F_0(T_{ml} - T_{\text{base}}) \\
F_i &= k_i \frac{T_{\text{base}} - T_s}{h_i} \\
F_{\text{rad}} + F_{\text{SH}} + F_{\text{LH}} &= k_i \frac{T_{\text{base}} - T_s}{h_i}
\end{align*}
\]

\[(Zhang \text{ et al. 2022})\]
Fig. S1. Differences in (a) zonal mean feedbacks and (b) warming contributions between the Gray_{ice-lock} and RRTM_{ice-lock} simulations. Planck (PLK), lapse rate (LR), and temperature (PLK+LR).
Fig. S2. Vertical temperature profiles of RRTM ice CTL, PTB and anomaly in polar region (60°N to 90°N).
Fig. S3. Seasonal northward atmospheric energy transport at 60°N (PW) response to (a) all drivers, (b) CO2, (c) water vapor radiative effect, (d) sea ice loss, (e) sea ice retreat, and (f) sea ice thinning.
Lapse rate feedback

• Though the warming profile is bottom-heavy in DJF (expected to promote a positive LR feedback), the DJF RRTM radiative kernel is weak and hence lower tropospheric warming has little impact of the TOA radiative flux. The weak kernel is likely related to the lack of clouds of our models.

• A more realistic lapse rate feedback may support a stronger polar amplification via the response to sea ice retreat, especially in winter, offset to some extent by a correspondingly larger decrease in dry energy transport.

Fig. DJF temperature kernel in (left) RRTM, (middle) CESM1 CAM5 all-sky, and (right) CESM1 CAM5 clear-sky.
Cloud feedback

• Only about half of the literature supports that cloud feedback contributes to polar amplification, while the other half supports that it contributes to tropical amplification or is unsure (Previdi et al. 2021).

• Low cloud formation by increasing turbulent heat fluxes over the newly exposed ocean enhances the downward LW (Kay and Gettelman 2009), which may lead to stronger PA in fall and winter.

• The condensational heating of clouds by increasing turbulent heat fluxes during winter also mediates the impact of sea ice loss on the vertical structure of Arctic warming (Kaufman and Feldl 2022).

• Cloud enhance the impact of latent energy transport increases through their LW effect, contributing to winter PA (Taylor et al. 2022; Dimitrelos et al. 2023).
Even though moist transport is not as strong as the ice-albedo feedback or lapse rate feedback, its interaction with other processes is nonnegligible.

The scientific questions are:

- We identify “the moisture change can explain the sign of moist transport change”. We plan to quantify the magnitude of the change in AHTq induced by warming pattern.
Future work

- Even though moist transport is not as strong as the ice-albedo feedback or lapse rate feedback, its interaction with other processes is nonnegligible.

The scientific questions are:

- We identify “the moisture change can explain the sign of moist transport change”. We plan to quantify the magnitude of the change in AHTq induced by warming pattern.

- How does the magnitude of PA respond to moist transport change? How does the efficacy of thermodynamic and dynamic component of AHTq compare?

- Previous work suggest that PA \(\rightarrow\) AHTd. Additionally, AHTq is a contributor to PA. We hypothesize that AHTq \(\rightarrow\) PA \(\rightarrow\) AHTd. We will evaluate the hypothesis in a transient analysis.
\[ \tau_0 = \tau_e + (\tau_p - \tau_e) \sin^2 \varphi \quad \tau = \tau_0 f_1 \left( \frac{p}{p_s} \right) + (1 - f_1) \left( \frac{p}{p_s} \right)^4 \]

\((\tau_p, \tau_e) = (2.5, 5.8)\) and \(f_1 = 0.2\)