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

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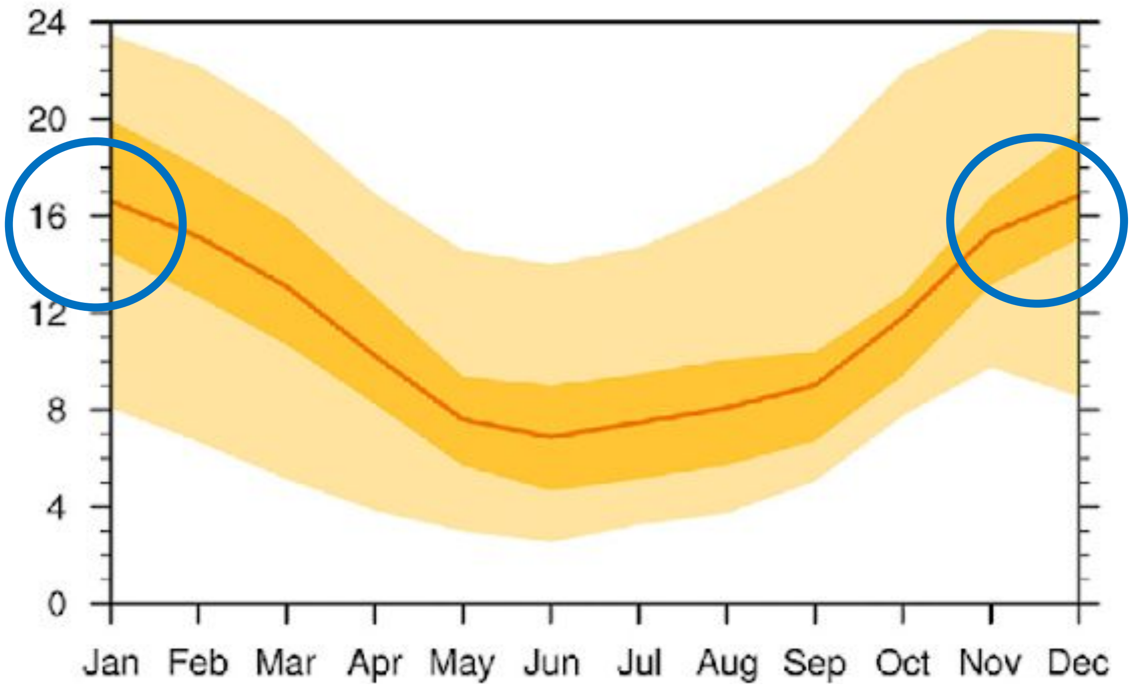
Introduction

- 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)

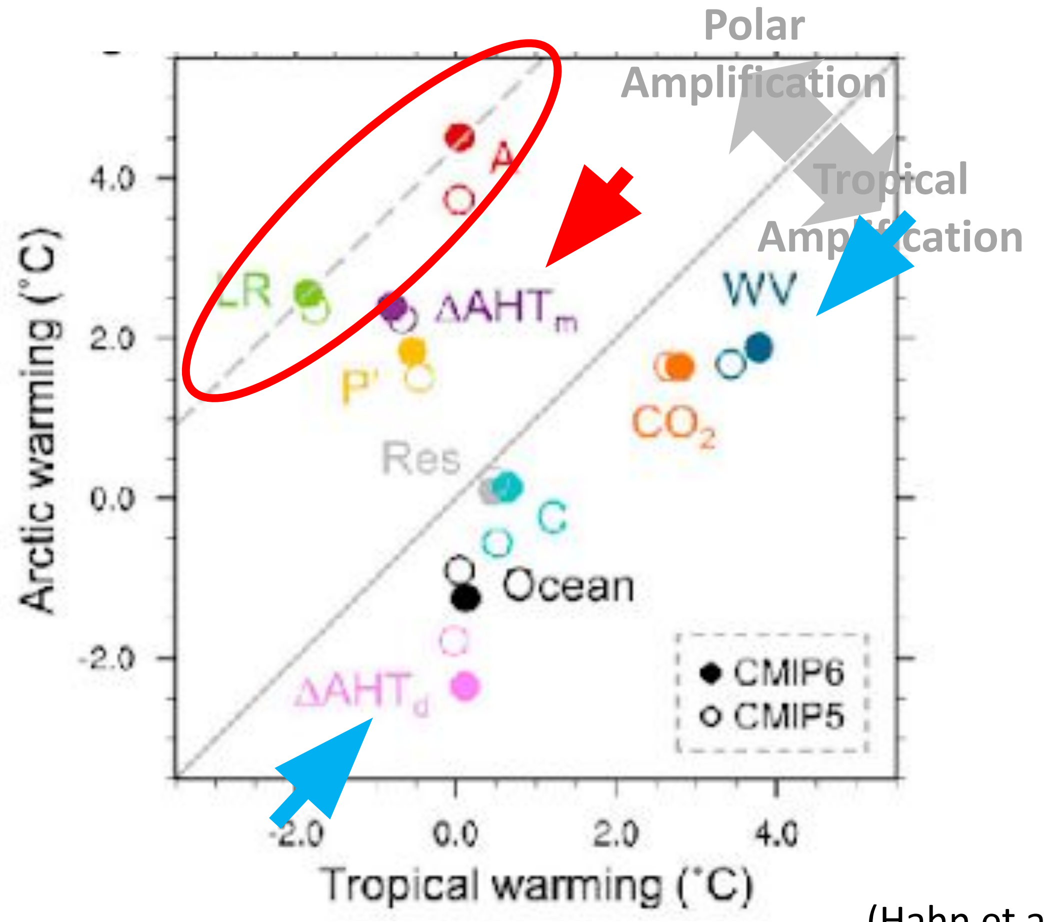


(Hahn et al. 2021)

Introduction

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



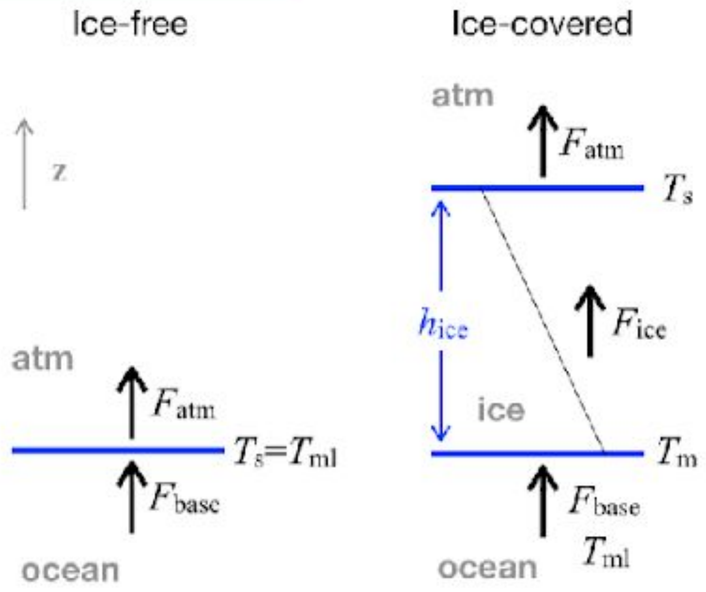
(Hahn et al. 2021)

- 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.

Models

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**.

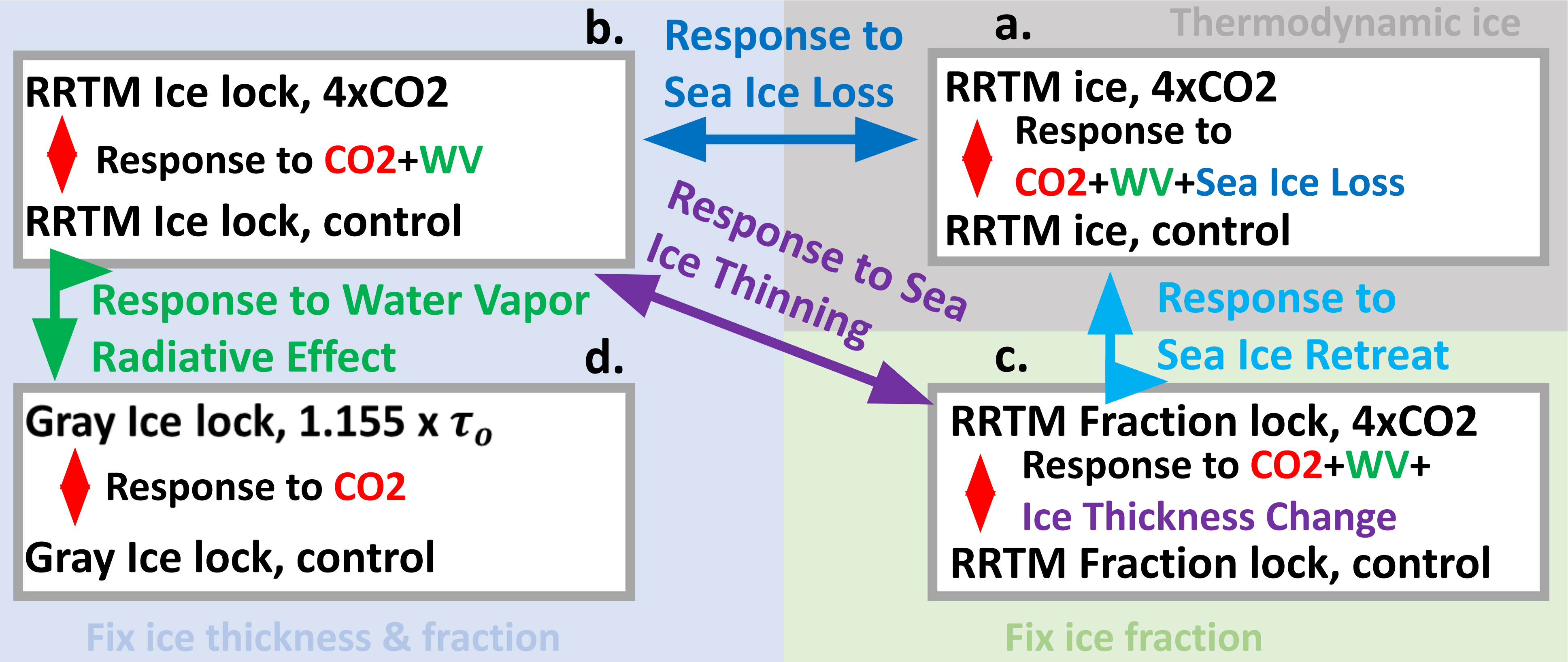
Sea ice model includes energy fluxes at base, top, and through the sea ice.



(Zhang et al. 2022)

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

Models



b.

RRTM Ice lock, 4xCO2

♦ Response to CO2+WV

RRTM Ice lock, control

Response to Sea Ice Loss

a.

Thermodynamic ice

RRTM ice, 4xCO2

♦ Response to CO2+WV+Sea Ice Loss

RRTM ice, control

Response to Sea Ice Thinning

Response to Water Vapor Radiative Effect

Response to Sea Ice Retreat

d.

Gray Ice lock, 1.155 x τ_o

♦ Response to CO2

Gray Ice lock, control

c.

RRTM Fraction lock, 4xCO2

♦ Response to CO2+WV+ Ice Thickness Change

RRTM Fraction lock, control

Fix ice thickness & fraction

Fix ice fraction

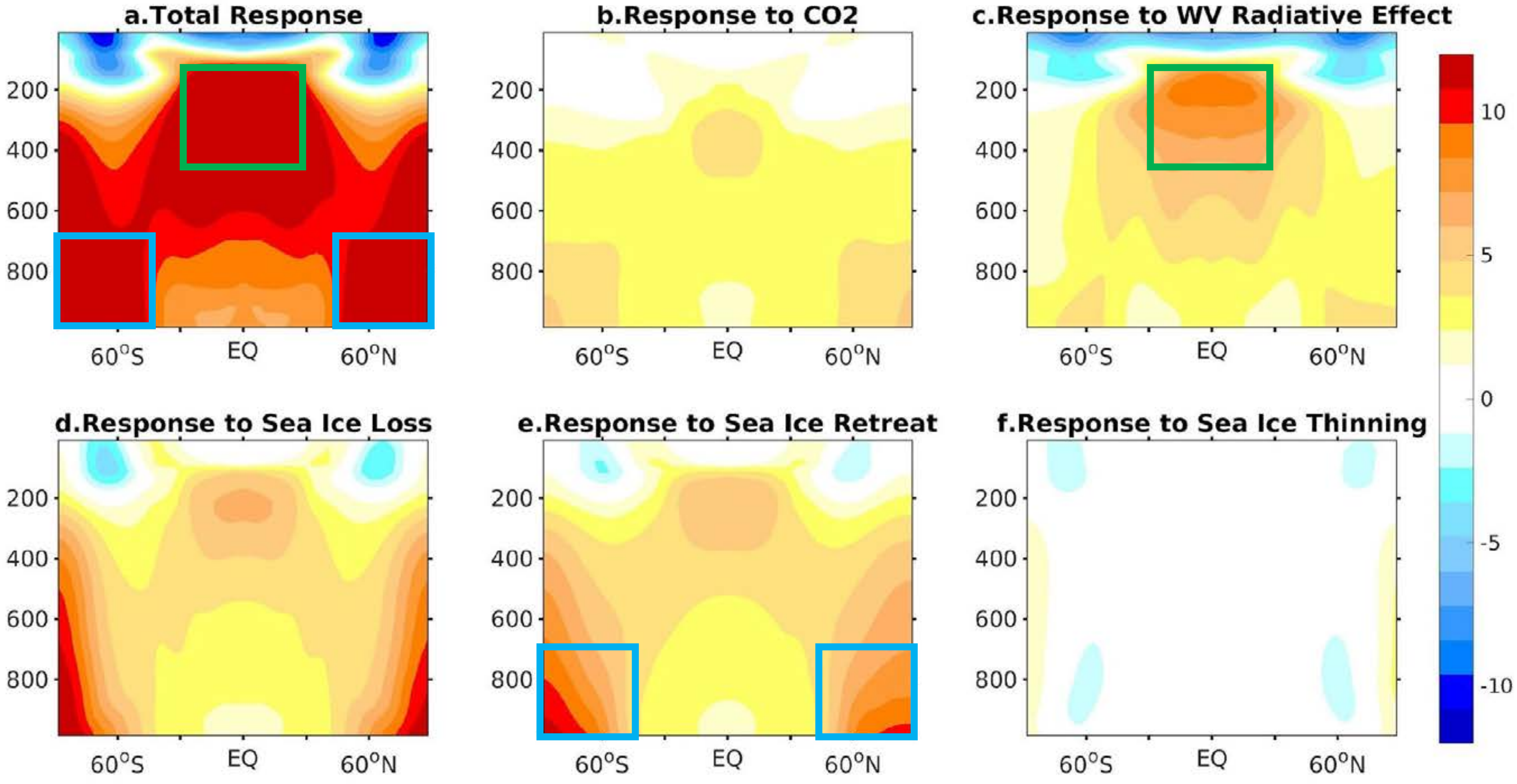
(a) 1. Total response (CO2+WV+sea ice loss)
(d) 2. Response to CO2
(b-d) 3. Response to water vapor radiative effect
(a-b) 4. Response to sea ice loss (sea ice retreat+ sea ice thinning)
(a-c) 5. Response to sea ice retreat
(c-b) 6. Response to sea ice thinning

Results

Zonal and annual mean temperature response (K)

Results

Zonal and annual mean temperature response (K)


a.Total Response

b.Response to CO2

c.Response to WV Radiative Effect

d.Response to Sea Ice Loss

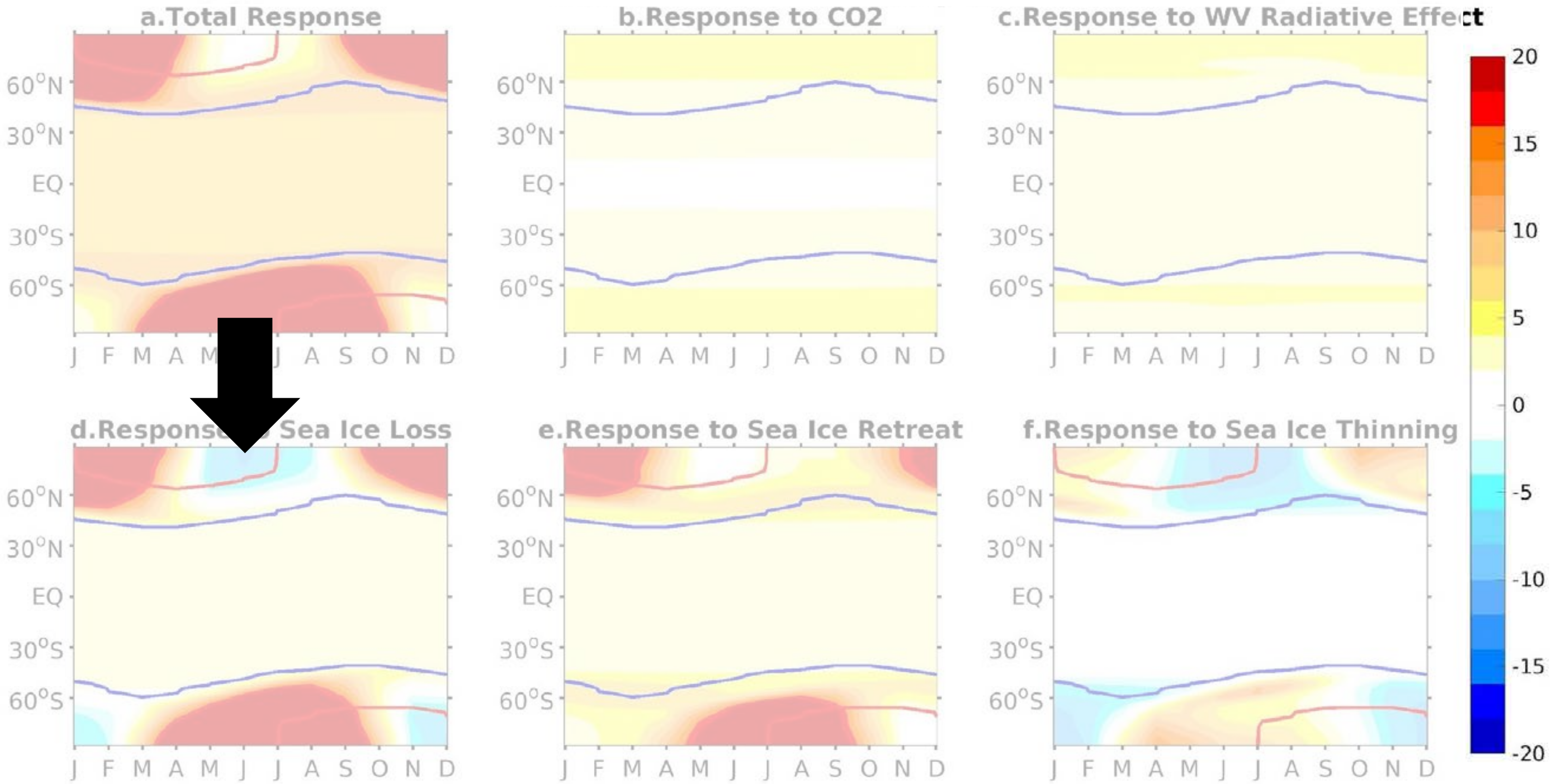
e.Response to Sea Ice Retreat

f.Response to Sea Ice Thinning

- 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)

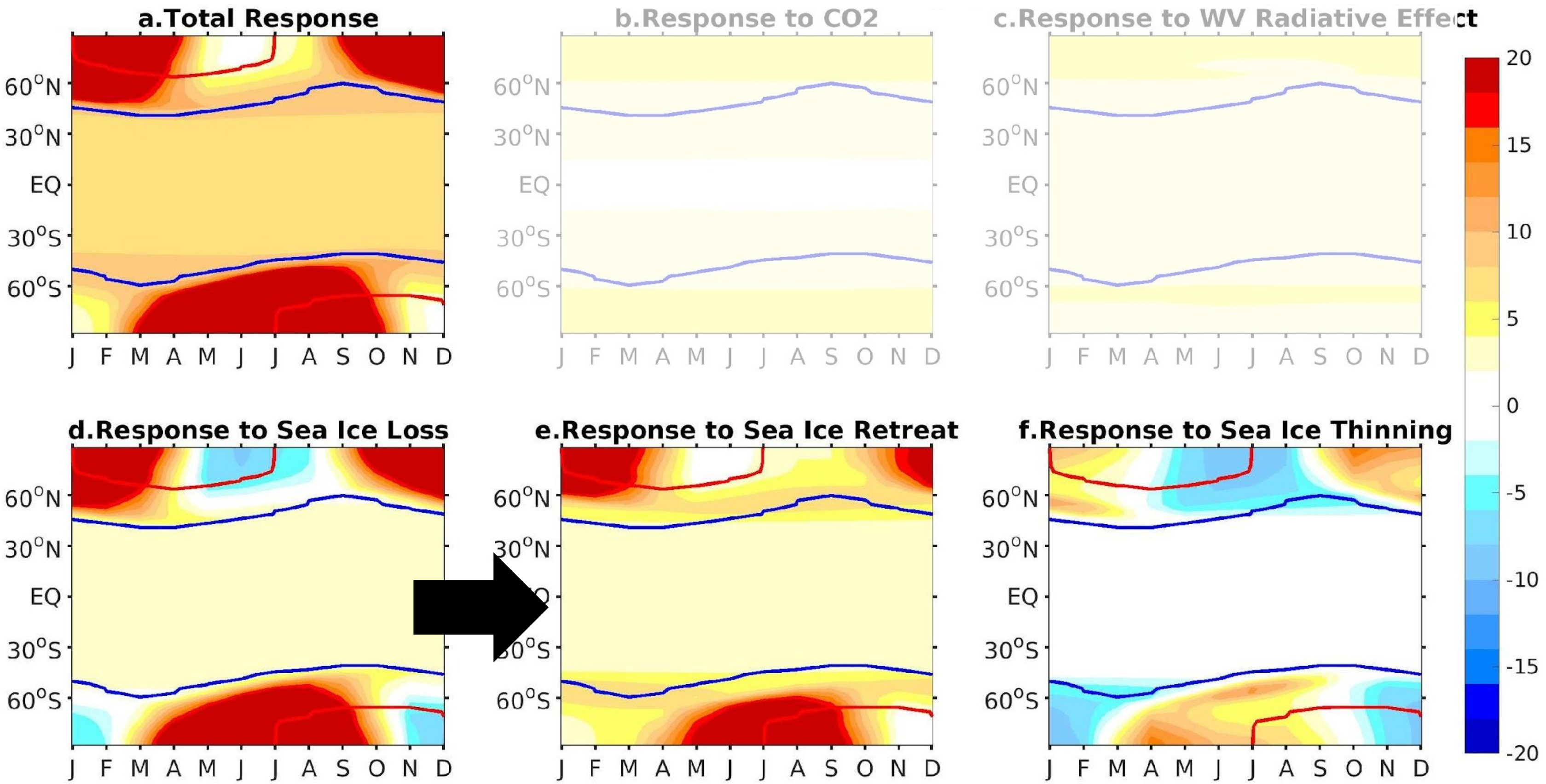


Contour:
sea ice edge
(fraction=1%) in CTL and
PTB

- Response to CO2 and WV: weak seasonality

Results

Zonal mean surface temperature response (K)



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

- 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)

Warming Contribution method

$$F + (\lambda_p + \Sigma_i \lambda_i)\delta T_s + \delta \mathrm{AHT_d} + \delta \mathrm{AHT_q} + \delta \mathrm{SEB} + \delta R_{\mathrm{res}} = 0$$

Surface temperature anomaly

$$\delta T_s = -\frac{F}{\overline{\lambda_p}} - \frac{\lambda_p' \delta T_s}{\overline{\lambda_p}} - \frac{\Sigma_i \lambda_i \delta T_s}{\overline{\lambda_p}} - \frac{\delta \mathrm{AHT_d}}{\overline{\lambda_p}} - \frac{\delta \mathrm{AHT_q}}{\overline{\lambda_p}} - \frac{\delta \mathrm{SEB}}{\overline{\lambda_p}} - \frac{\delta R_{\mathrm{res}}}{\overline{\lambda_p}}$$

Forcing

Climate Feedback (PLK, LR, ALB, WV)

Dry and Moist Atmosphere Heat Transport

Surface Energy Budget (Ocean term)

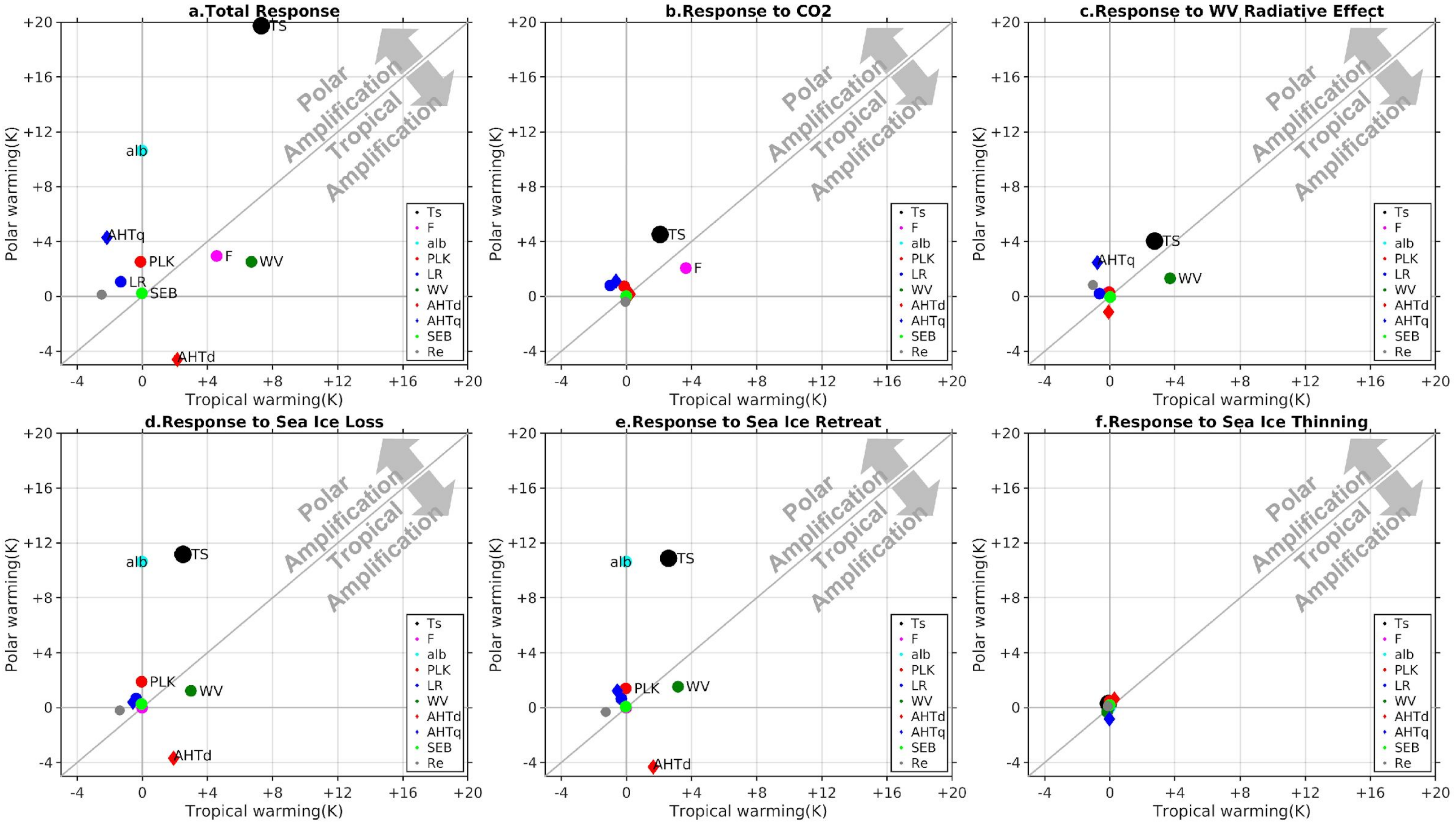
$$\lambda_p' = \lambda_p - \overline{\lambda_p}$$

Annual- and global-mean value

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

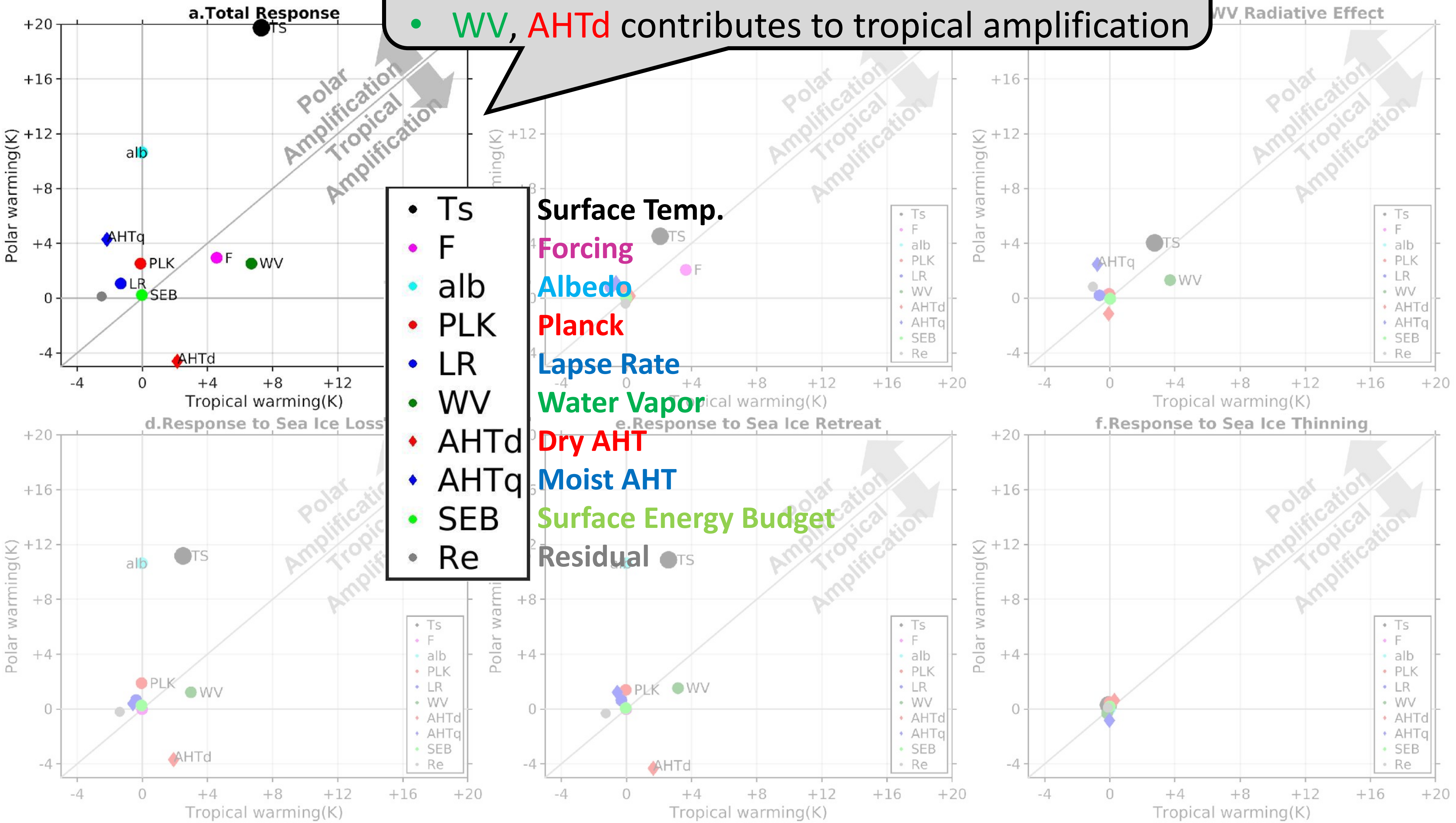
Results

Annual Mean Warming Contribution



Results

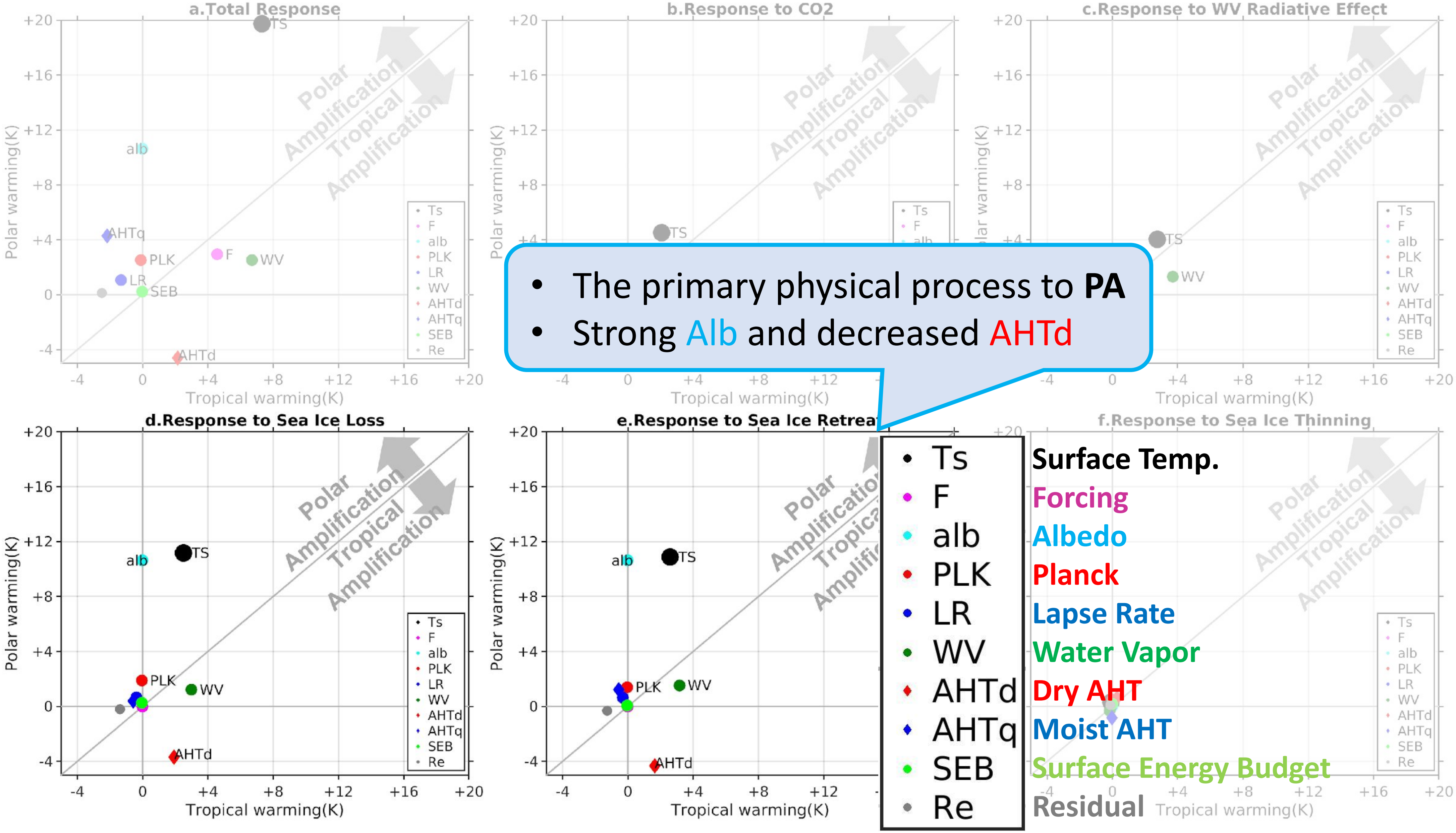
- Alb dominates **PA**
- AHTq plays a moderate role
- WV, AHTd contributes to tropical amplification



●	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**

Results

Annual Mean Warming Contribution



- The primary physical process to **PA**
- Strong Alb and decreased AHTd

●	Ts	**Surface Temp.**
●	F	**Forcing**
●	alb	**Albedo**
●	PLK	**Planck**
●	LR	**Lapse Rate**
●	WV	**Water Vapor**
♦	AHTd	**Dry AHT**
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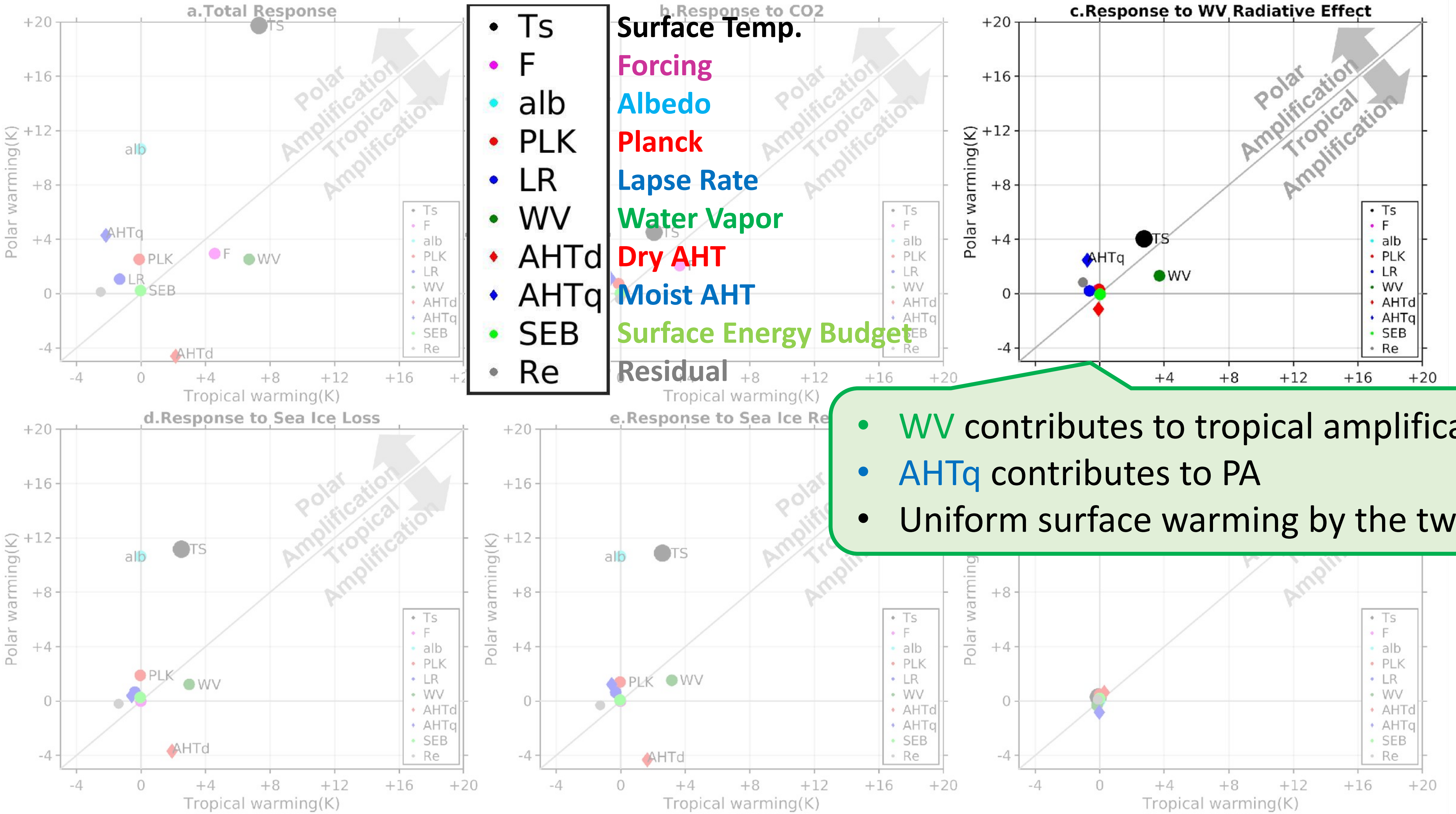
●	Re	**Residual**

Results

Annual Mean Warming Contribution



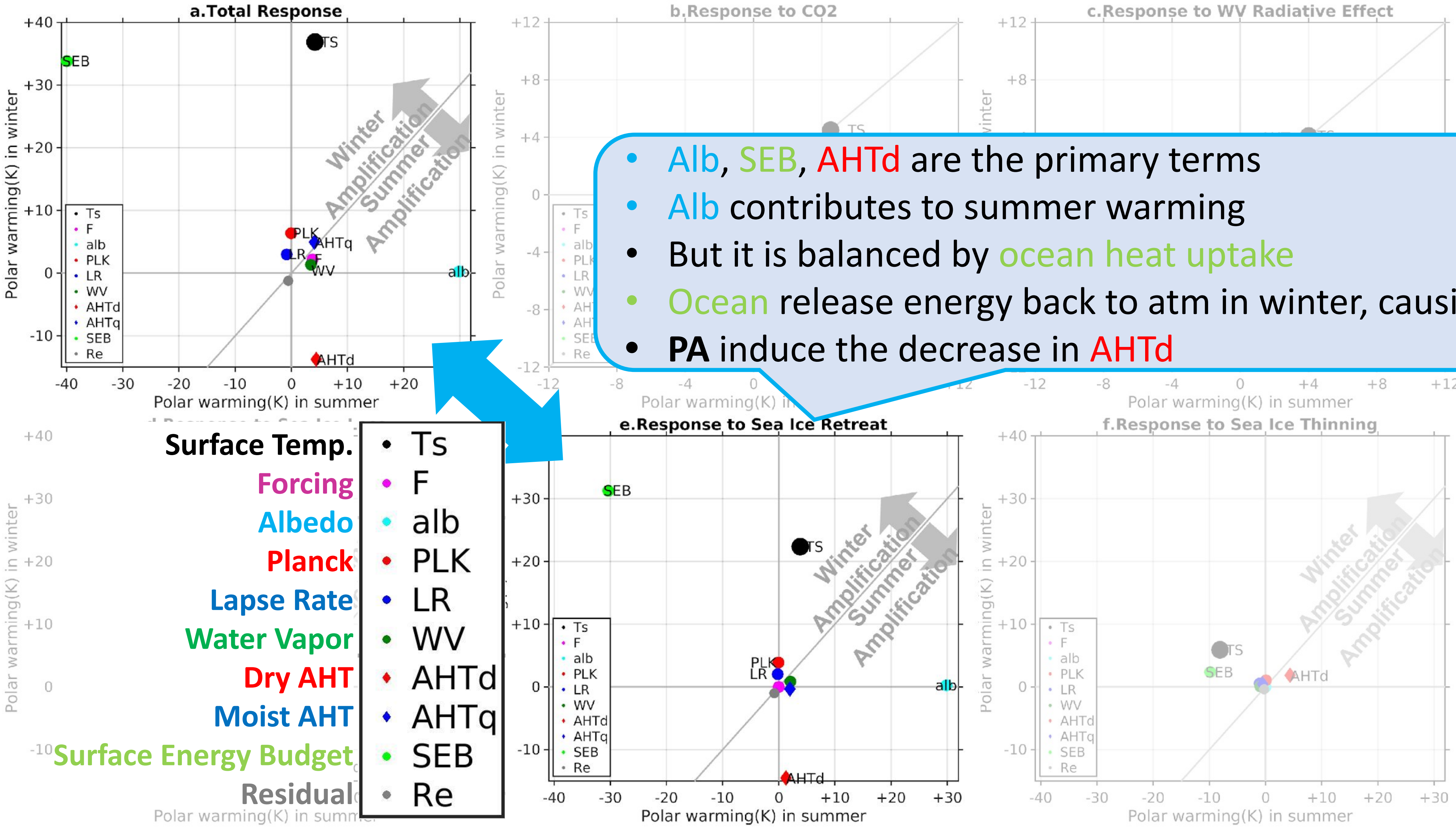
● Ts	**Surface Temp.**
● F	**Forcing**
● alb	**Albedo**
● PLK	**Planck**
● LR	**Lapse Rate**
● WV	**Water Vapor**
◆ AHTd	**Dry AHT**
◆ AHTq	**Moist AHT**
● SEB	**Surface Energy Budget**
● Re	**Residual**

- WV contributes to tropical amplification
- AHTq contributes to PA
- Uniform surface warming by the two

Results

Seasonal Polar Warming Contribution

*The axes in b and c are different



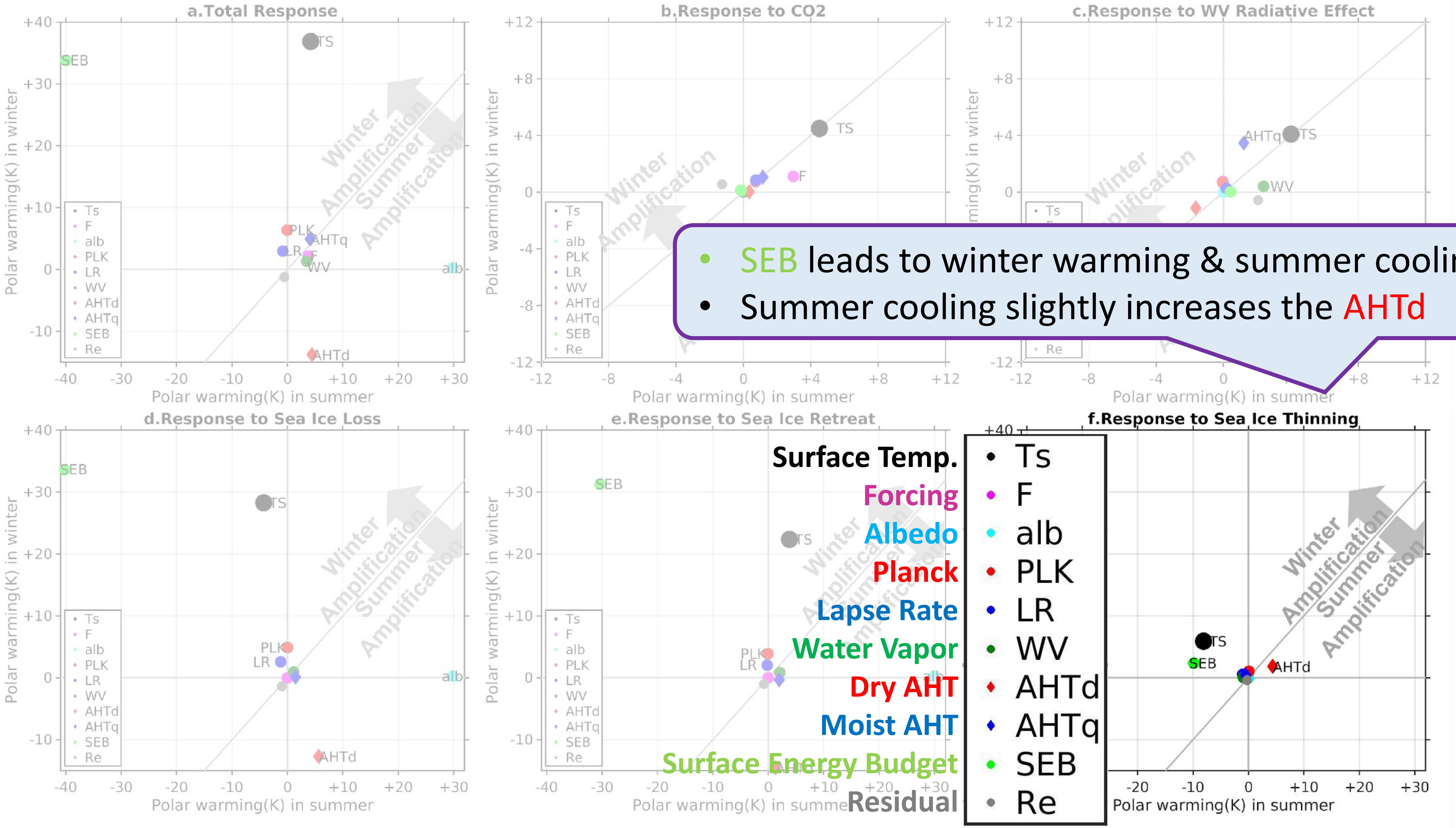
- Alb, SEB, AHTd are the primary terms
- Alb contributes to summer warming
- But it is balanced by ocean heat uptake
- Ocean release energy back to atm in winter, causing **PA**
- **PA** induce the decrease in AHTd

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

Results

Seasonal Polar Warming Contribution

*The axes in b and c are different



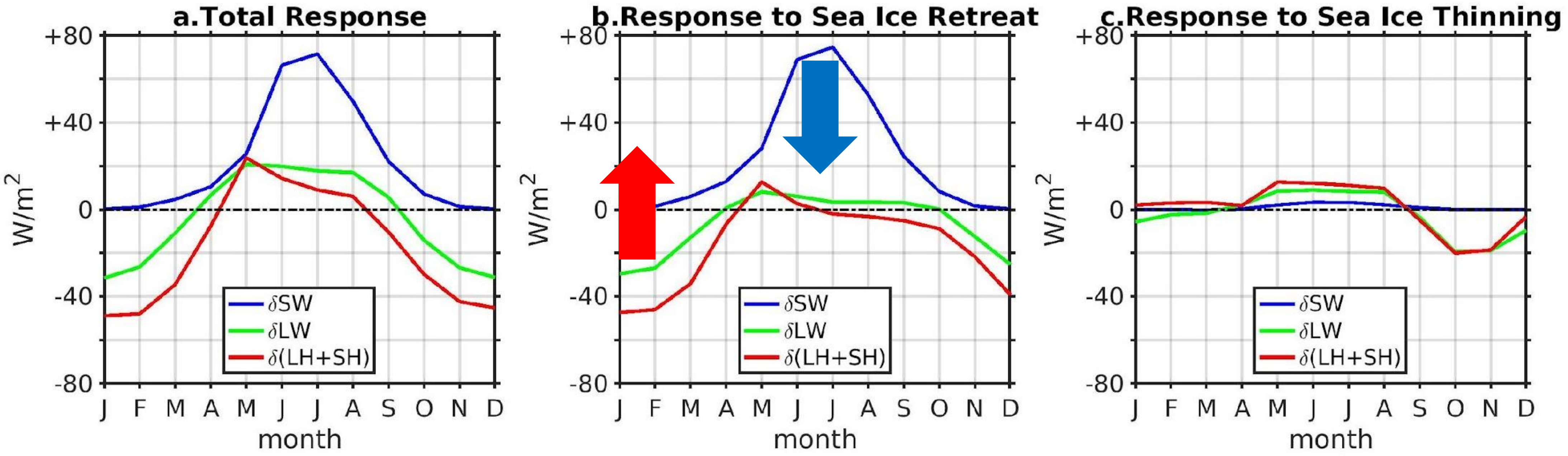
- SEB leads to winter warming & summer cooling
- Summer cooling slightly increases the AHTd

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

Results

*downward positive

The decomposition of seasonal surface energy budget



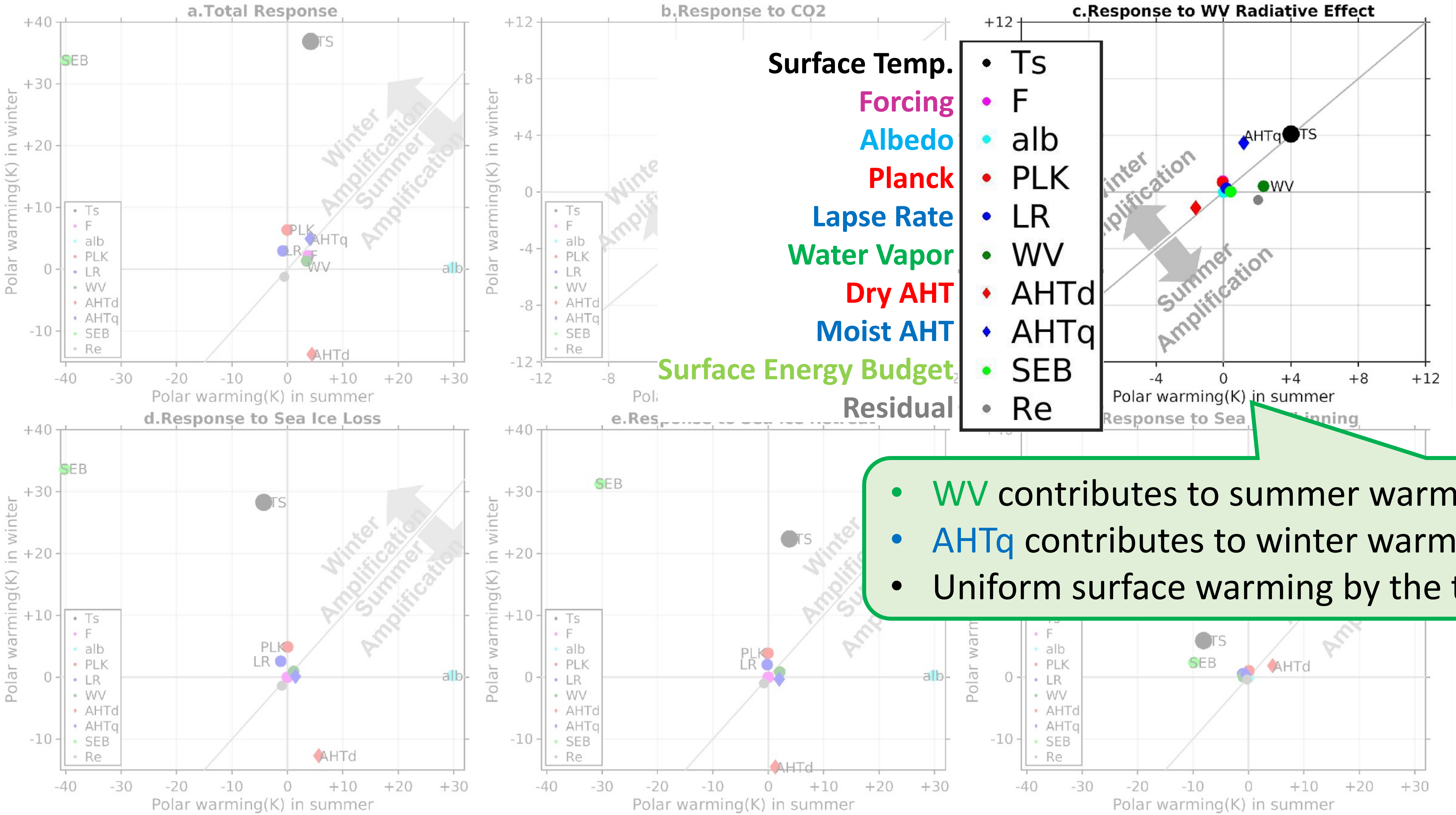
- When sea ice retreats, the ocean absorbs surface SW during summer and release heat during winter
- The winter warming trigger the upward turbulent flux (latent + sensible heat flux)

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

Results

Seasonal Polar Warming Contribution

*The axes in b and c are different



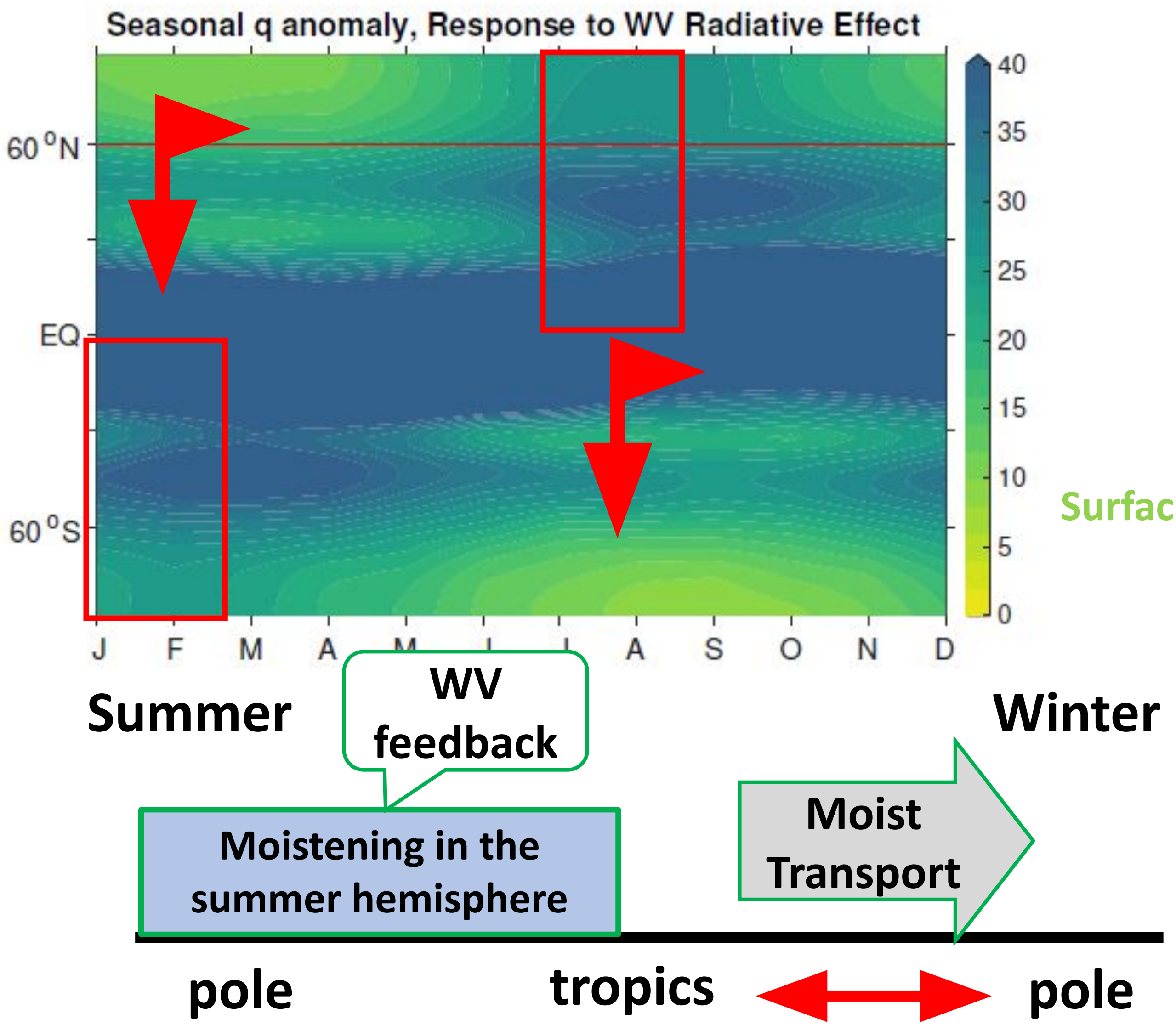
Surface Temp.	• Ts
Forcing	• F
Albedo	• alb
Planck	• PLK
Lapse Rate	• LR
Water Vapor	• WV
Dry AHT	♦ AHTd
Moist AHT	♦ AHTq
Surface Energy Budget	• SEB
Residual	• Re

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

Results

Seasonal Polar Warming Contribution

*The axes in b and c are different



Summer

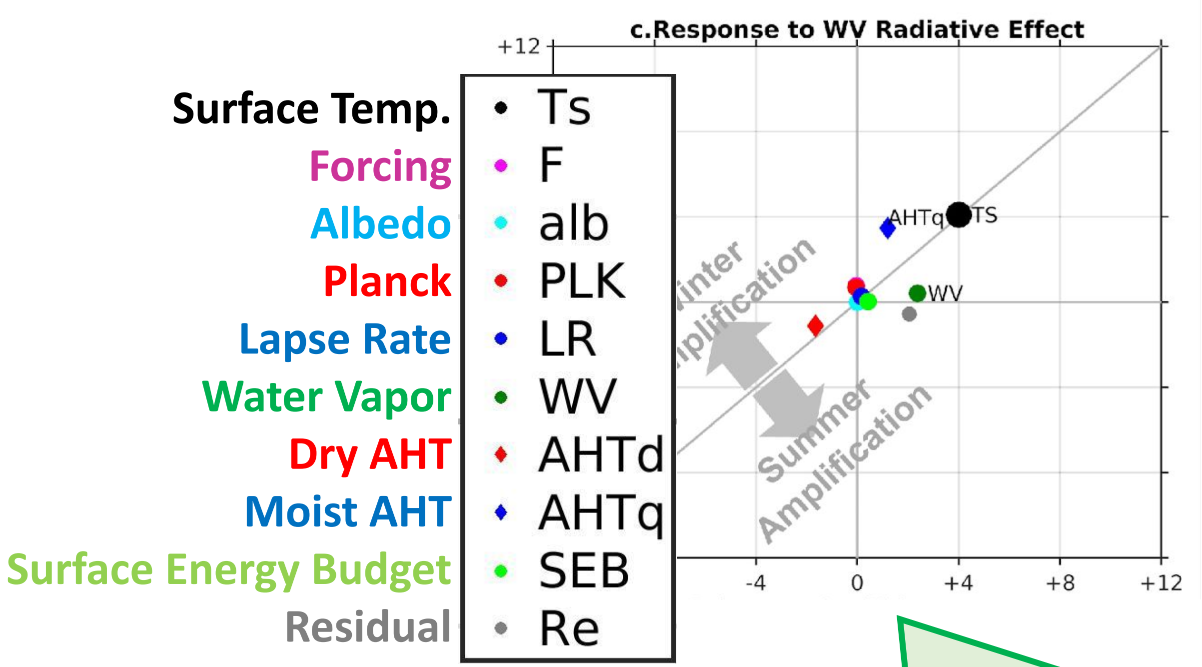
WV feedback

Moistening in the summer hemisphere

Moist Transport

Winter

pole **tropics** **pole**

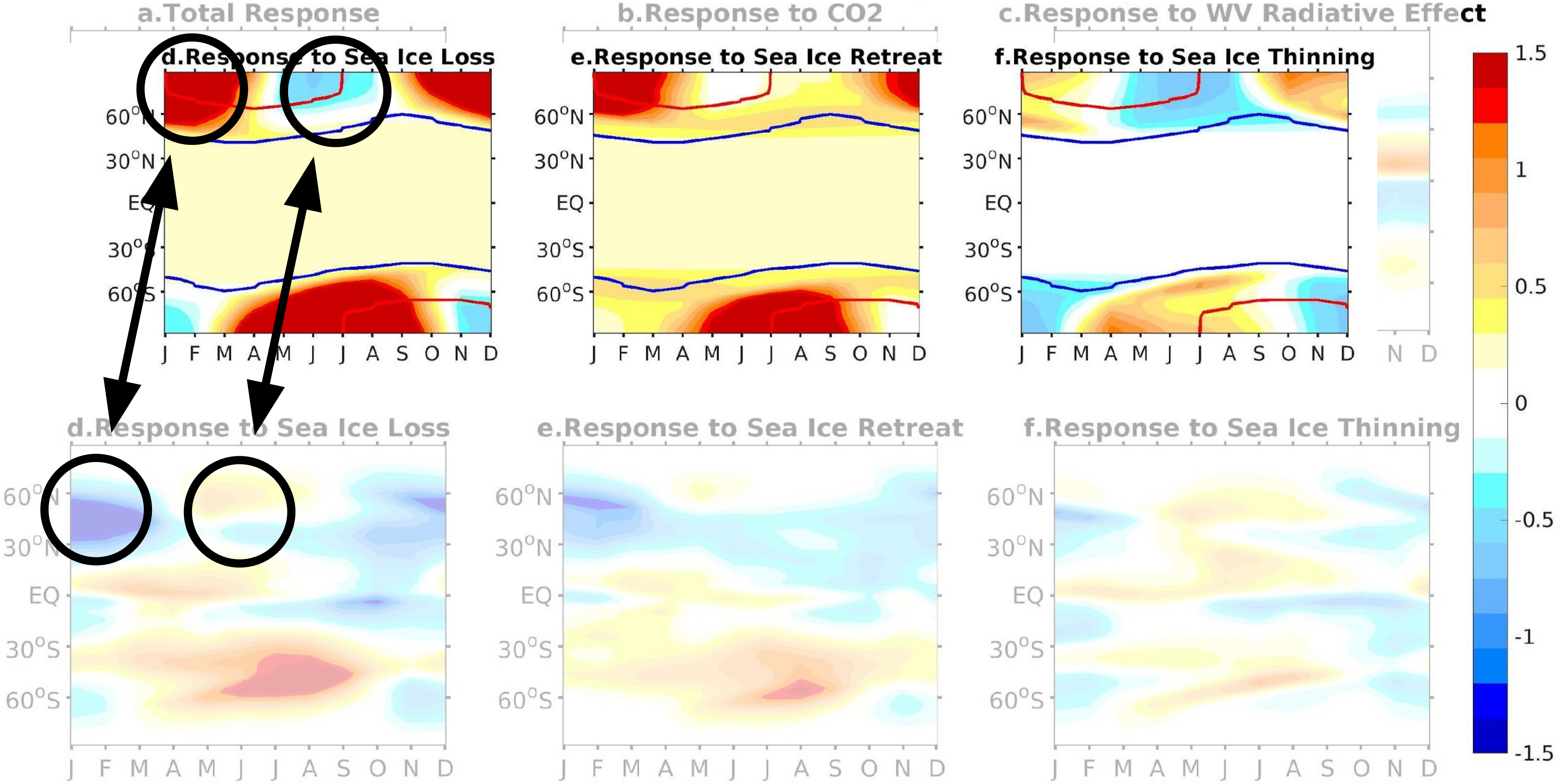


- WV contributes to summer warming
- AHTq contributes to winter warming
- Uniform surface warming by the two

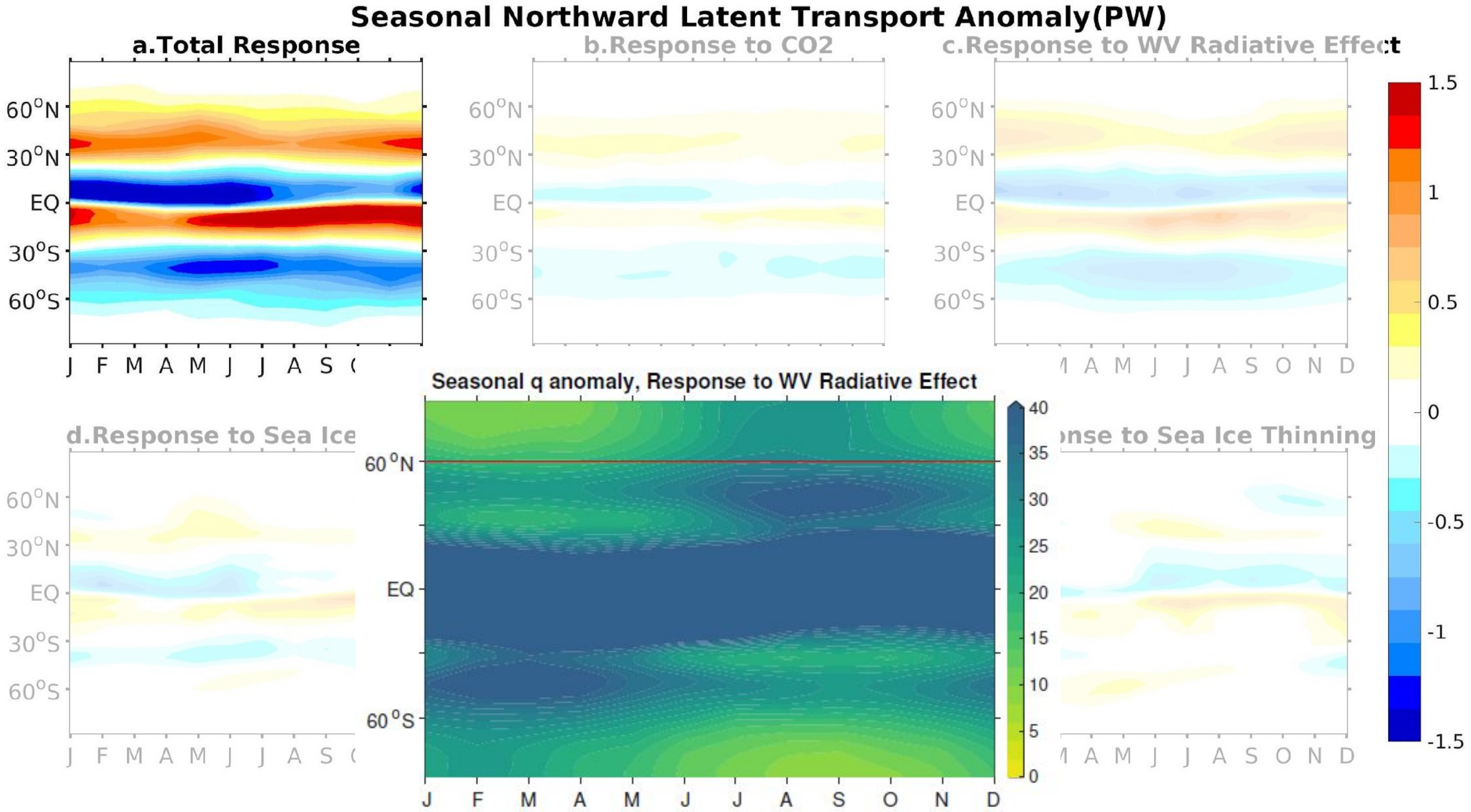
Increases meridional moisture gradient

Results

Seasonal Northward Dry Transport Anomaly(PW)



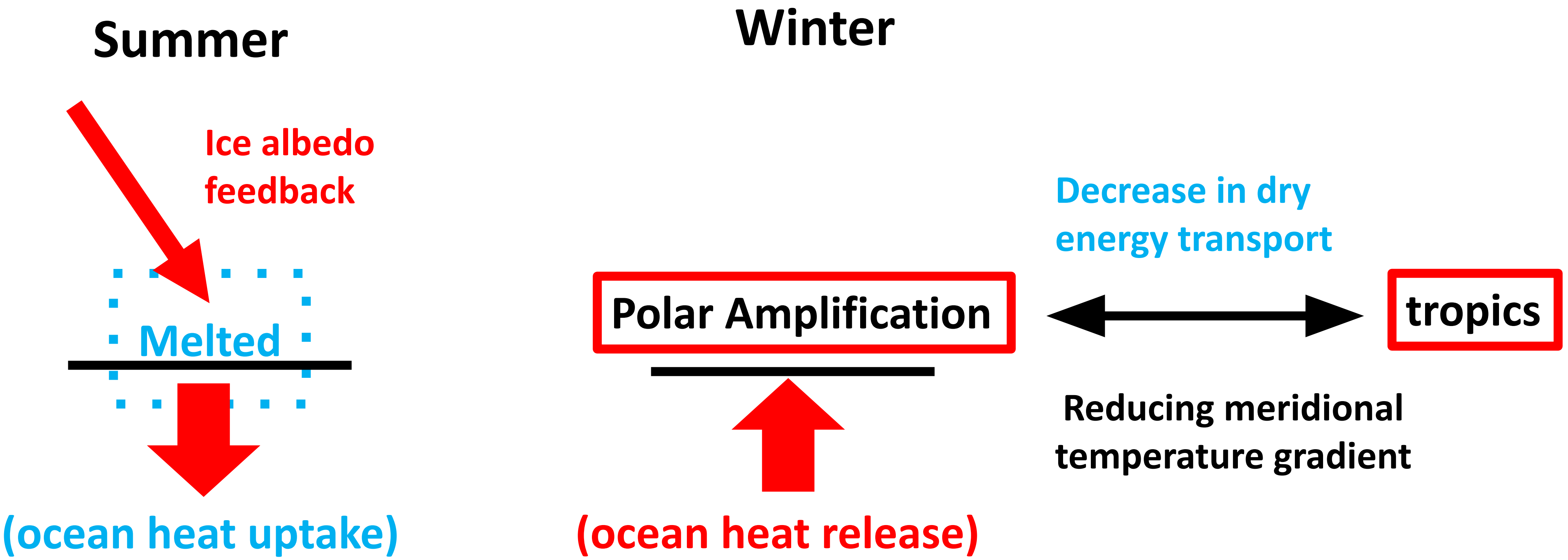
Results


Seasonal Northward Latent Transport Anomaly(PW)
a.Total Response
b.Response to CO2
c.Response to WV Radiative Effect
d.Response to Sea Ice
nse to Sea Ice Thinning
60°N
30°N
EQ
30°S
60°S
J F M A M J J A S (
/I A M J J A S O N D
1.5
1
0.5
0
-0.5
-1
-1.5
Seasonal q anomaly, Response to WV Radiative Effect
60°N
EQ
60°S
J F M A M J J A S O N D
40
35
30
25
20
15
10
5
0

Summary

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).

- The summer ice-albedo feedback contributes to winter PA through ocean heat uptake/release



Summer

Winter

Ice albedo feedback

Melted

(ocean heat uptake)

Decrease in dry energy transport

Polar Amplification

tropics

Reducing meridional temperature gradient

(ocean heat release)

Summary

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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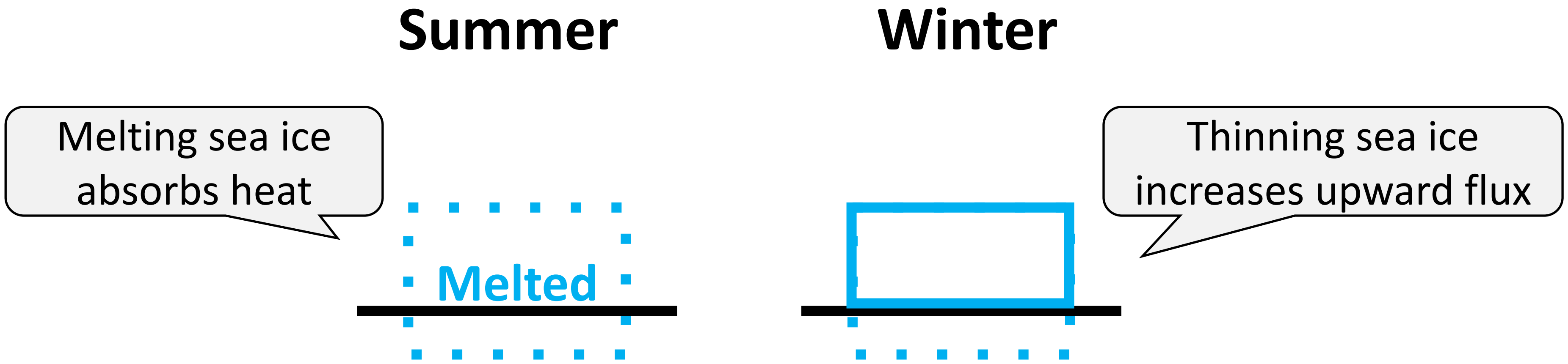
- The latent heat of melting ice suppresses summer warming while winter sea ice thinning causes the warming through increasing conductive heat flux



Summer

Winter

Melting sea ice absorbs heat

Melted

Thinning sea ice increases upward flux

Summary

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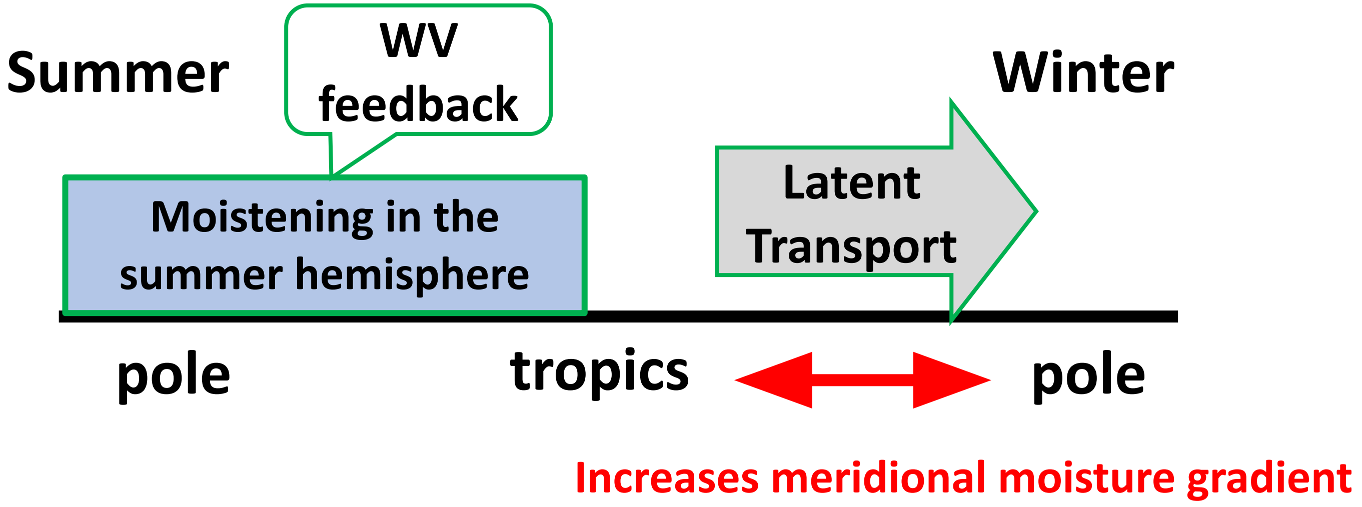
- Summer polar warming contributed by WV feedback is compensated by its induced winter increase in poleward moist transport



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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
- The change in seasonal dry energy transport is a passive response to seasonal warming pattern

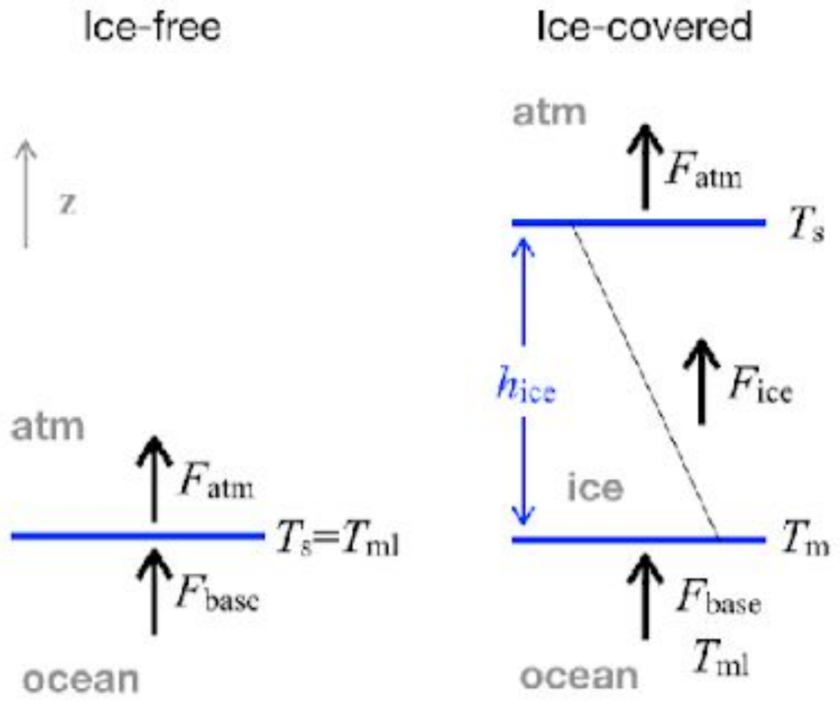
Our results highlight the importance of the interaction between feedbacks and atmospheric energy transports on the seasonality polar amplification, and thus improve understanding of its mechanisms

Chung, P. C., & Feldl, N. (2023). Sea Ice Loss, Water Vapor Increases, and Their Interactions with Atmospheric Energy Transport in Driving Seasonal Polar Amplification. *Journal of Climate*, 1-28.
Email: pochung@ucsc.edu / Github: https://github.com/pochunchung

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/)

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



(Zhang et al. 2022)

$$L_i \frac{dh_i}{dt} = F_{\mathrm{atm}} - F_{\mathrm{base}}$$

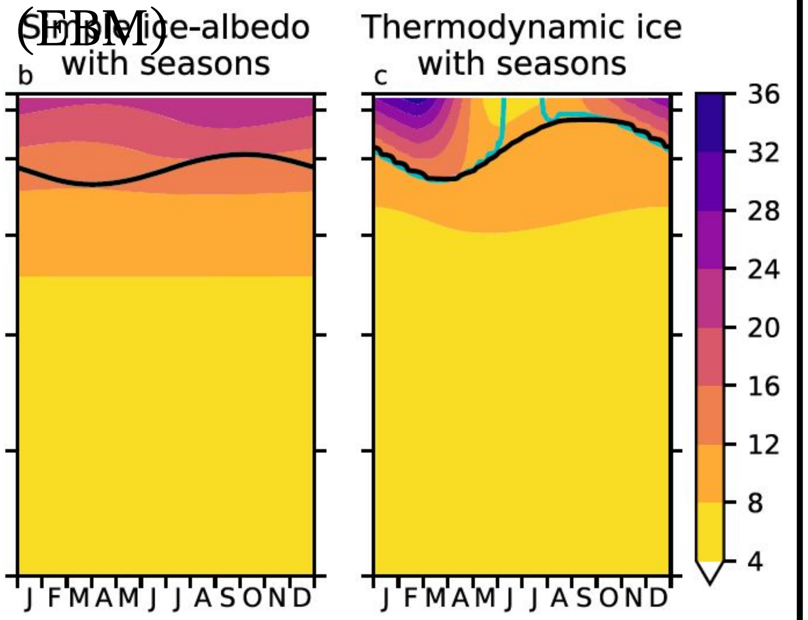
$$F_{\mathrm{base}} = F_0(T_{ml} - T_{\mathrm{base}})$$

$$F_i = k_i \frac{T_{\mathrm{base}} - T_s}{h_i}$$

$$F_{\mathrm{rad}} + F_{\mathrm{SH}} + F_{\mathrm{LH}} = k_i \frac{T_{\mathrm{base}} - T_s}{h_i}$$

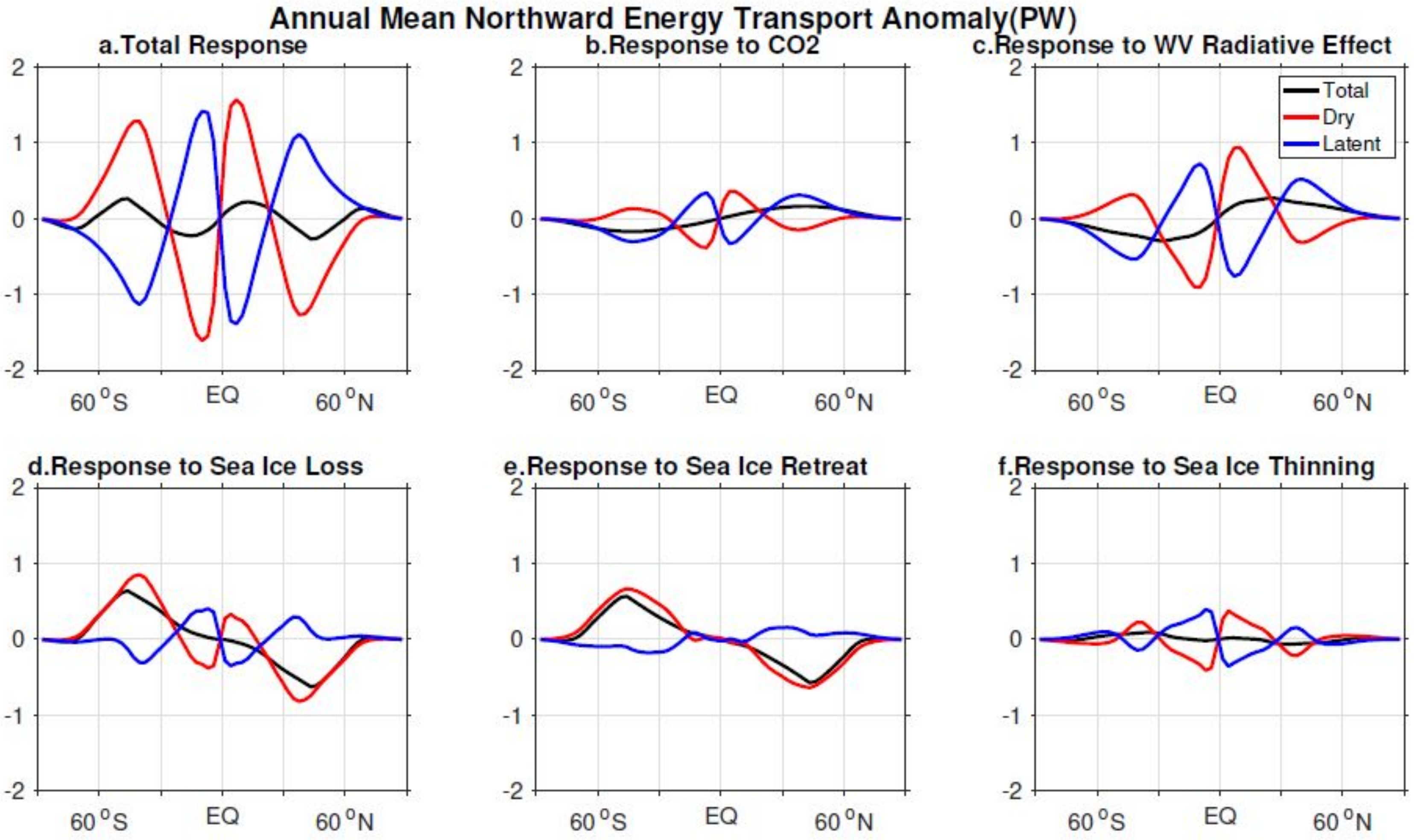
$$\rho_w c_w h_{ml} \frac{dT_{ml}}{dt} = \begin{cases} -F_{\mathrm{base}} & \text{where ice is present} \\ -F_{\mathrm{atm}} & \text{under ice-free condition} \end{cases}$$

Temp. change in the moist energy balance model (EBM)



(Feldl and Merlis 2021)

Results


Annual Mean Northward Energy 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
Total
Dry
Latent
2
1
0
-1
-2
60°S
EQ
60°N

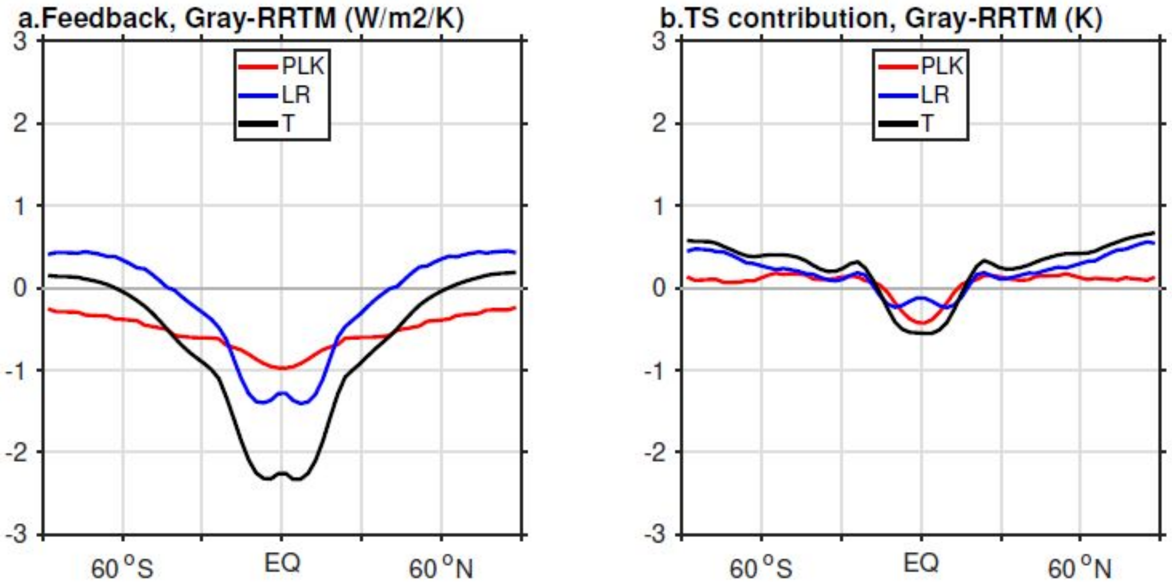


FIG. S1. Differences in (a) zonal mean feedbacks and (b) warming contributions between the $Gray_{\text{ice-lock}}$ and $RRTM_{\text{ice-lock}}$ simulations. Planck (PLK), lapse rate (LR), and temperature (PLK+LR).

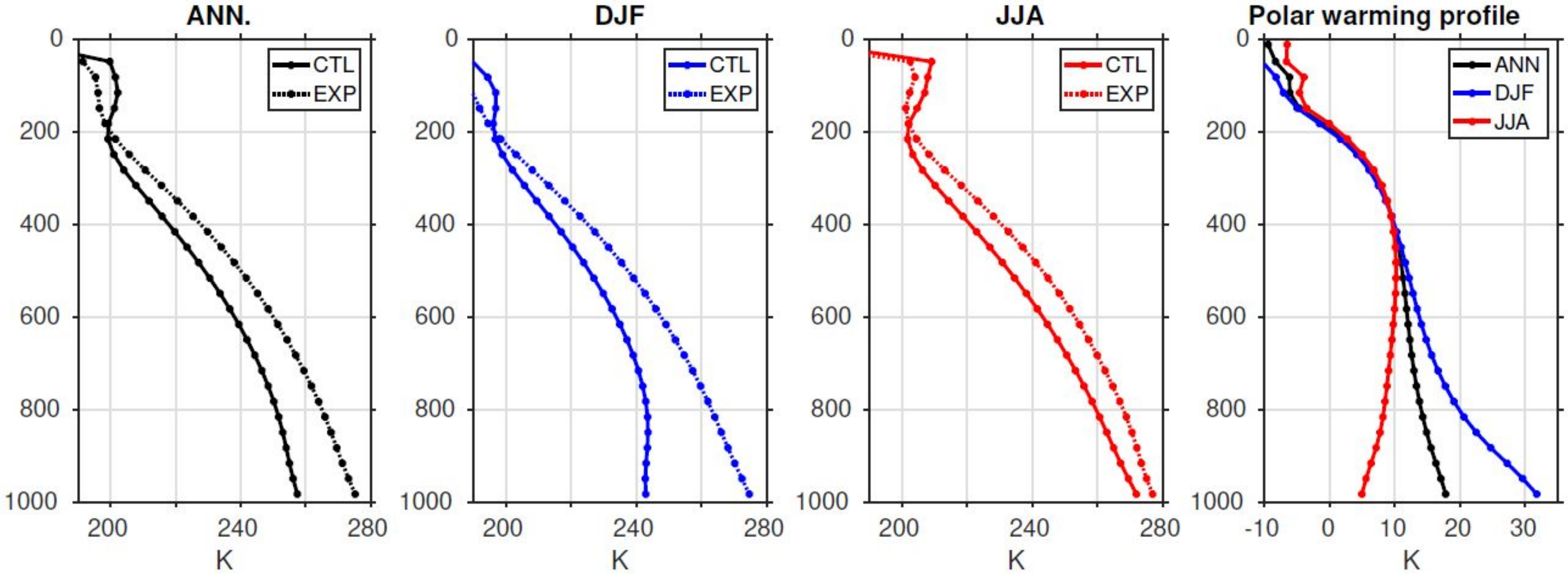


FIG. S2. Vertical temperature profiles of RRTM ice CTL, PTB and anomaly in polar region (60°N to 90°N).

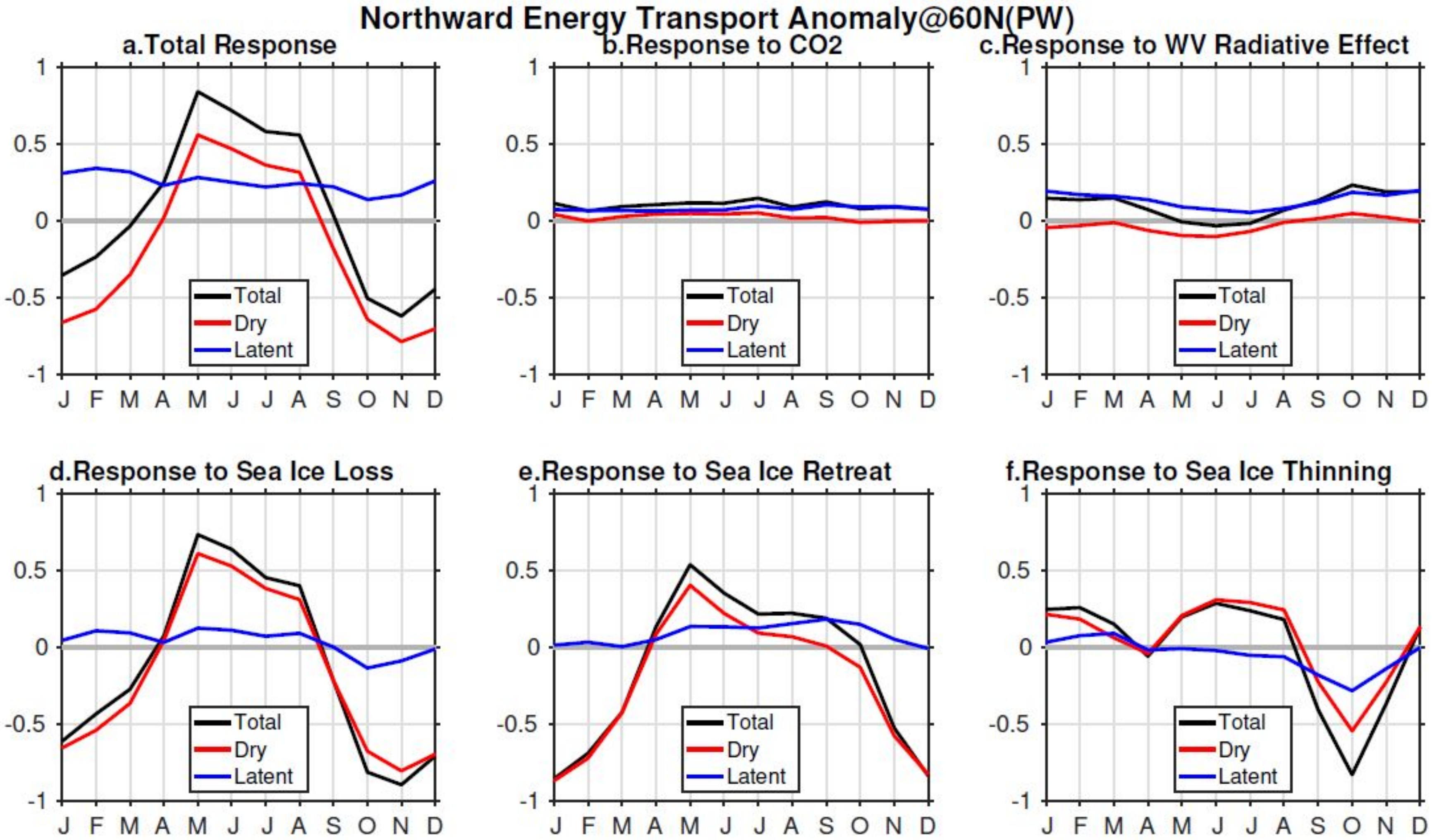
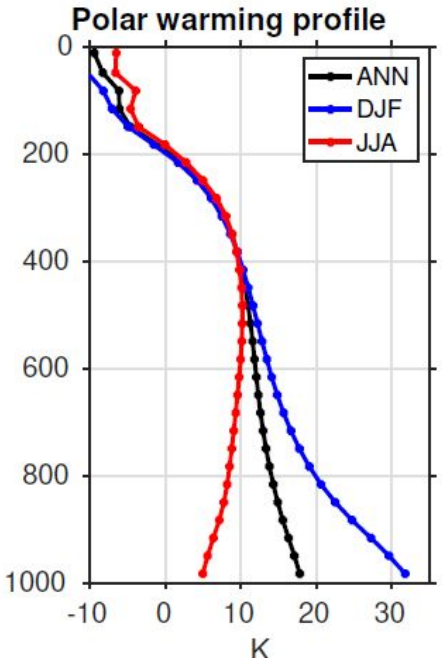


FIG. S3. Seasonal northward atmospheric energy transport at 60°N (PW) response to (a) all drivers, (b) CO_2, (c) water vapor radiative effect, (d) sea ice loss, (e) sea ice retreat, and (f) sea ice thinning.

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.



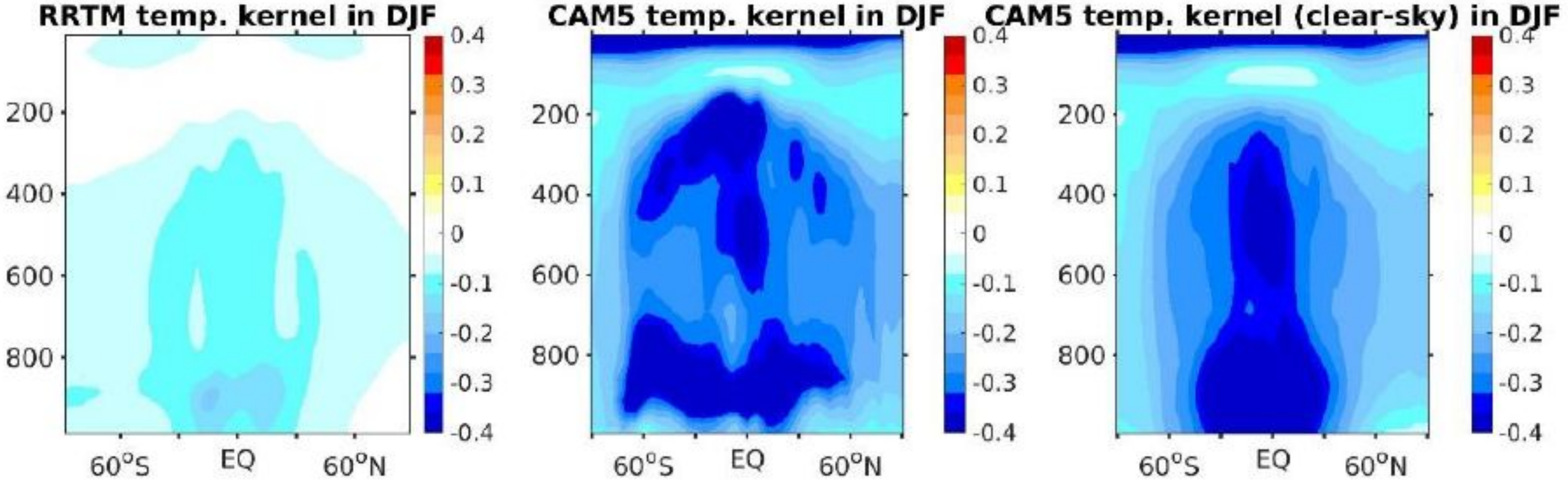


Fig. DJF temperature kernel in (left) RRTM, (middle) CESM1 CAM5 all-sky, and (right) CESM1 CAM5 clear-sky.

- 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.

Cloud feedback

- Only about half of the literature supports that cloud feedback contributes to polar amplification, while the other half supports that is 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).

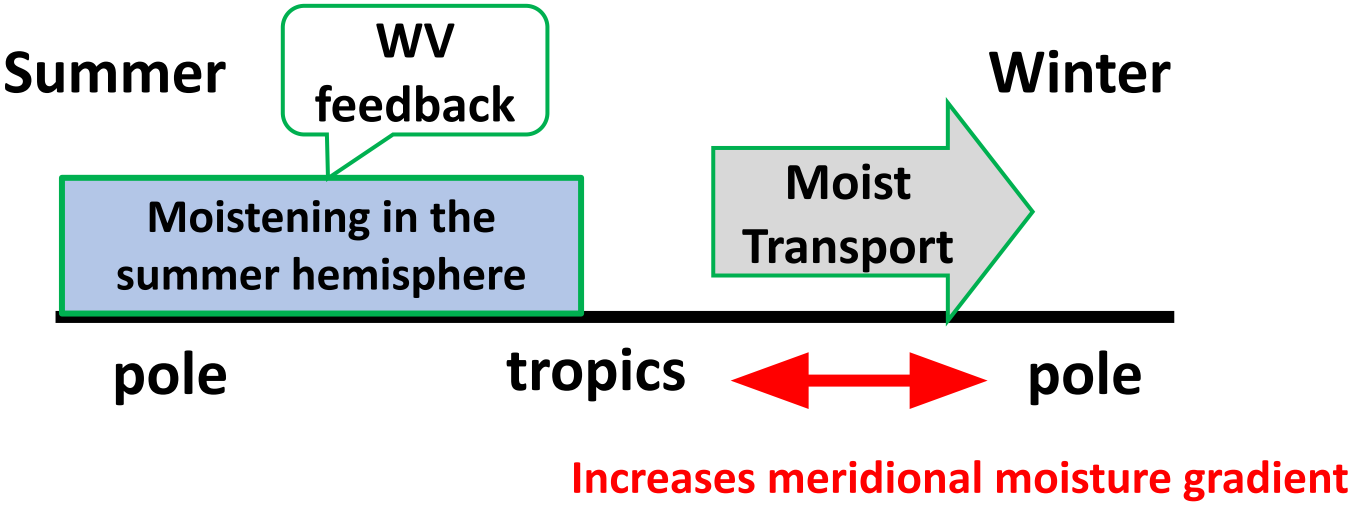
- Cloud enhance the impact of latent energy transport increases through their LW effect, contributing to winter PA (Taylor et al. 2022; Dimitrelos et al. 2023).

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.



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 □ AHTd. Additionally, AHTq is a contributor to PA. We hypothesize that AHTq □ PA □ AHTd. We will evaluate the hypothesis in a transient analysis.

Models

$$\tau_0 = \tau_e + \left(\tau_p - \tau_e\right) \sin^2 \varphi \ ; \ \tau = \tau_0 [f_1 \left(\frac{p}{p_s}\right) + (1 - f_1) \left(\frac{p}{p_s}\right)^4]$$

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

(Taylor et al. 2021)