Responses to Editor #1

We thank the editor for handling our submission and the reviewer for the valuable comments. The manuscript has been modified according to the suggestions. Below are our specific responses to the reviewer's comments.

This study, through extensive simulation experiments and complex diagnostic analyses, explores the response of polar energy budget to sea surface temperature anomalies. The conclusion of this paper is clear. However, this paper still requires revision and further clarification.

Response:

We thank the reviewer for the valuable comments.

Major comments:

1. *The model description is unclear. I suppose the model used in this paper is CAM (only uncoupled atmosphere component), not CESM (coupled). The patch experiments are also incomplete. Does each warm or cold patch experiment consist of 80 sub-experiments, and every sub-experiments utilize different SST anomalies? What is the integration time of the sub-experiment?*

Response:

We thank the reviewer for their valuable feedback. Now we use "CESM1.2.1-CAM5.3" to describe the model. While CAM is the atmospheric module of CESM, other modules of CESM is also used when we perform the simulations. For example, CLM 4.0 (Community Land Model) and CICE (Community Ice Code) modules are active in our simulations.

2. *In the method section, authors should provide a detailed introduction to the radiative kernels technology.*

Response:

We have provided a more detailed description and illustration of radiative kernel decomposition methodology in section 2.3 (L112-135):

"***2.3 Radiative Kernel Decomposition Methodology***

This study employs the radiative kernel approach (Soden et al., 2008, Huang et al., 2017) to decompose both surface and TOA radiation into the radiative effects of various meteorological *variables, measured in watts per square meter (Wm^{-2}). The core calculation involves multiplying the radiative kernels with the monthly anomalies of the corresponding climate fields as follows::*

$$\Delta R_X = K_X \cdot \Delta X \qquad (5)$$

where X *denotes an arbitrary non-cloud climate variable,* ΔR_X *represents the radiative effect at the surface or TOA associated with that variable,* K_X *is the corresponding radiative kernel, and* ΔX *is the monthly anomaly of the climate variable, calculated as the deviation from the monthly climatological average. Positive values of* ΔR *indicate an increase in net incoming radiation, which corresponds to a warming effect on the Earth. The radiative kernels used in this analysis are derived from the ERA-Interim climatological fields and have been validated to perform well with climate model surface outputs (Huang et al., 2017; Liu et al., 2024).*

Cloud radiative effects are calculated following the methodology of Soden et al. (2008):

$$\Delta R_{cld} = \Delta CRF - \sum_X (K_X - K_X^0)\, \Delta X \qquad (6)$$

In this equation, ΔR_{cld} *denotes the cloud-induced radiative anomalies, and* CRF *(Cloud Radiative Forcing) is defined as the difference in surface net radiation fluxes between all-sky and clear-sky conditions. The superscript* ^{0} *means the clear-sky kernels..*

Building upon this framework, the study further decomposes the TOA and surface radiative anomalies into specific feedback components to achieve a more detailed analysis of the factors influencing the Earth's radiation balance. ΔR_{TOA} *is partitioned into cloud-induced radiative anomalies (*$\Delta R_{TOA,cld}$*), albedo-induced radiative anomalies (*$\Delta R_{TOA,alb}$*), Planck feedback-induced radiative anomalies (*$\Delta R_{TOA,plk}$*), and lapse-rate feedback-induced radiative anomalies (*$\Delta R_{TOA,LR}$*). Similarly,* ΔR_{sfc} *is broken down into cloud-induced surface radiative anomalies (*$\Delta R_{sfc,cld}$*), albedo-related surface radiative anomalies (*$\Delta R_{sfc,alb}$*), Planck feedback-induced surface radiative anomalies (*$\Delta R_{sfc,plk}$*), lapse-rate feedback-induced surface radiative anomalies (*$\Delta R_{sfc,LR}$*), LH anomalies (*ΔLH*) and SH anomalies (*ΔSH*).”*

3. *Lines 48-49, “50%-85% of Arctic warming is induced by non-local drivers”, this conclusion is a great shock and is certainly not a mainstream view. The references provided by the authors is also not compelling.*

Response:

Sorry for the inappropriate expression. To avoid misunderstanding, we deleted these numbers: “Therefore, remote processes play an important role in driving Arctic warming, and the remote forcings are further amplified by local feedback processes.”

In the previous draft, the 50-85% numbers denote the ratio of non-local forcings to total forcings (feedbacks are not regarded as forcings), which came from the following sentences:

In Chung and Räisänen (2011), they wrote: "the remotely-induced warming contributes more to the total annual-mean Arctic warming in ECHAM5 (≈85%) than in CAM3 (≈60%)."

In Taylor et al. (2022,), they wrote: “Chung and Räisänen (2011) attribute 60–85% of Arctic warming to non-local drivers, Yoshimori et al. (2017) find 60–70%, Park et al. (2018) ~50%, Shaw and Tan (2018) ~60%,…” Link to Taylor et al. (2022):

https://www.frontiersin.org/journals/earth-science/articles/10.3389/feart.2021.758361/full

We revised the introduction to provide a more nuanced summary of the roles of local and remote processes in Arctic amplification (L42-57):

“*Polar climate is also affected by remote influences, whose interaction drives Arctic warming (Li et al., 2021). While some studies suggest that remote forcing plays a relatively minor role in Arctic amplification (Stuecker et al., 2018), other research highlights the significant impact of poleward heat and moisture transport from lower latitudes in enhancing Arctic warming, and AA exists even in the absence of local sea-ice feedbacks (Alexeev et al., 2005; Graversen and Burtu, 2016). Specifically, poleward atmospheric heat transport (AHT) and moisture transport are critical components that contribute substantially to the observed warming in the Arctic.*

Under global warming, the AHT from low latitudes is more effective in reaching the polar regions compared to the equatorward transfer from high latitudes (Alexeev et al., 2005; Chung and Räisänen, 2011; Park et al., 2018; Shaw and Tan, 2018; Semmler et al., 2020), and multiple global climate model experiments have been conducted to measure the remote influence on Arctic warming (Alexeev et al., 2005; Chung and Räisänen, 2011; Yoshimori et al., 2017; Park et al., 2018; Shaw and Tan, 2018; Stuecker et al., 2018; Semmler et al., 2020). The transport of water vapor from mid-latitudes also plays an important role by enhancing the greenhouse effect prior to condensation and increasing cloudiness after condensation, which together warm the Arctic during winter (Graversen and Burtu, 2016). Graversen and Burtu (2016) showed that latent heat transport can lead to significantly more Arctic warming than dry static energy (DSE) transport, even when delivering an equivalent amount of energy. Therefore, remote processes play an important role in driving Arctic warming, and the remote forcings are further amplified by local feedback processes.”

4. *Lines 173-175, The responses of Arctic RLH and RSH are negative. This is very interesting, and I encourage the authors further discuss it in detail. I suppose that the warm Arctic caused by energy transport from low latitude suppresses the Arctic surface turbulent heat flux (increase the downward turbulent heat flux). Since the directions of LH and SH are positive upward (see minor comments #3), the responses of LH and SH are negative. It is worth noting that if the Arctic warming is driven by the local drivers, such sea ice reduction, it will lead to upward turbulent heat flux anomalies on the Arctic surface. The surface heat flux in the Arctic has shown an upward anomaly in recent years, and the warming of the Arctic should be dominated by local factors (see major comments #3).*

Response:

Thank you for your insightful comments and for highlighting the negative responses of Arctic latent heat flux and sensible heat flux in our study.

Yes, we agree that the negative responses indicate a suppression of upward turbulent heat fluxes at the Arctic surface. We interpret this suppression as primarily resulting from enhanced energy transport from lower latitudes into the Arctic region. Specifically, as warm air masses are advected poleward, the associated increase in downward longwave radiation warms the Arctic surface. This surface warming stabilizes the lower atmospheric boundary layer, thereby reducing the vertical turbulence necessary for effective heat exchange between the surface and the atmosphere. Consequently, both LH and SH, which represent the upward fluxes of latent and sensible heat respectively, decrease, leading to their negative anomalies.

Regarding local drivers like sea ice reduction leading to upward turbulent heat flux anomalies, we plan to analyze them with idealized sea ice experiments in the future. (It is likely that sea ice reduction leads to an increase of LH and SH, because the surface temperature increases in response to sea ice reduction)

We have discussed the negative response of LH and SH (L249-254):

"*The negative responses of Arctic ΔLH and ΔSH in response to warmings in the tropical western Pacific indicate a suppression of upward turbulent heat fluxes at the Arctic surface, primarily due to enhanced energy transport from lower latitudes into the Arctic region. As warm air masses are advected poleward, the associated increase in downward longwave radiation warms the Arctic* *surface. This warming stabilizes the lower atmospheric boundary layer, thereby reducing the vertical turbulence necessary for effective heat exchange between the surface and the atmosphere."*

5. Line 222, Should a barotropic mass-flux correction be applied before the computation of the energy transport? See the paper for more details.

Graversen RG. 2006. Do changes in midlatitude circulation have any impact on the Arctic surface air temperature trend?. J. Clim. 19: 5422–5438.

Response:

Thank you for your valuable comments.

In this study, model simulation data are used to analyze energy transport. The model simulation data inherently incorporate mass-flux processes through their internal parameterization schemes, ensuring the physical consistency of atmospheric dynamics. Therefore, an additional barotropic mass-flux correction is not necessary for this study.

Minor comments:

Lines 31-33, I cannot agree that the temperature feedback proposed by the authors creates a feedback loop.

Response:

We thank the reviewer for the valuable comments. We are now using "Planck feedback" and "lapse rate feedback" to describe the feedback processes. These two terms are commonly used in climate feedback studies (L32-L38):

"The Planck feedback, driven by the nonlinear relationship between blackbody radiation and temperature, provides negative feedback to TOA fluxes at all latitudes, especially in low latitudes (Pierrehumbert, 2010). The lapse-rate feedback is a significant driver of AA: in the Arctic regions, stable stratification and temperature inversions trap surface warming and reduce radiative cooling, thereby enhancing warming. In contrast, the tropics experience significant upper-atmosphere warming due to convection, which does not similarly trap heat (Pithan and Mauritsen, 2014). During climate warming, the transformation of ice clouds into water clouds increases cloud albedo, leading to negative feedback (Mitchell et al., 1989; Li and Le Treut, 1992)."

Line 80, remove the brackets.

Response:

We've corrected it.

Line 98. The directions of SH and LH are not defined, I assume they are positive upward.

Response:

Yes, in our manuscript, SH and LH are defined as positive in the upward direction. The relevant clarification has been added (L105-106):

"*Additionally, both SH and LH are defined as positive upward.*"

Line 111, western tropical Pacific?

Response:

Thank you for identifying the issue. We have revised the description of Figure 1 to reflect these changes appropriately (L143-145):

"*In response to western and central tropical Pacific SST warming, there is a significant increase in poleward energy transport towards the Arctic regions (Figure 1c),*"

Line 112, western tropical Pacific?

Response:

We have revised it.

Lines 115-117, the descriptions of the Rsfc responses are not consistent with Figure 1b.

Response:

We have completely revised our description of Figure 1.

Line 119-120, the descriptions of the Radv responses are not consistent with Figure 1c.

Response:

Thank you for your comments, as answered in the previous comment, we have completely revised our description of Figure 1.

Lines 128-129, I can't understand how the Radv calculated at 60° What is the physical meaning? I suppose this should be the mean Radv north of 60°N.

Response:

Yes, it is averaged from 60-90°N using Eq. (4), which reflects the heat transport acrossing 60°N. We changed the statement of R_{adv} (now R_{AHT}): "heat fluxes resulting from atmospheric heat transport to the polar regions", and it is averaged as the mean value north of 60°N.

Line 124, The negative response of Rsfc around 60°S may attributed to the Antarctic mean calculations of Rsfc (60°S-90°S). The imposed warm SST south of 60°S will increase the surface upward heat flux, thus the negative Rsfc.

Response:

Thanks to your comments, we have included this idea in our revision of Figure 1 (L158-160):

"*Both ΔR_{TOA} and ΔR_{sfc} decrease in response to warmings in patches centred at 60°S, because patches centred at 60°S cover part of the Antarctic region (60°S to 90°S in this study), and the surface emit more energy to space as the sea surface warms, leading to a cooling radiative effect.*"

Line 152, the tropical western Pacific.

Response:

We've revised it.

Lines 154-155, the contribution of cloud is important because it is statistically significant, despite the value is relatively small.

Response:

Thank you for your valuable feedback regarding the contribution of clouds. We have updated the manuscript (L223-224):

"*Figure 6a shows that the contribution of cloud changes is relatively small to the Arctic* ΔR_{TOA} *response. Pacific SST warming results in a negative Arctic* $\Delta R_{TOA,cld}$*, whereas Indian Ocean warming generates a positive Arctic* $\Delta R_{TOA,cld}$*.*"

Note that in response to another reviewer's suggestion, we re-plotted the cloud response, and the new figure does not include a statistical significance analysis.

Line 158, western tropical pacific

Response:

We've revised it.

Line 159, eastern tropical pacific.

Response:

We've revised it.

Lines 191-192, Do the authors consider Radv to partly represent AHT?

Response:

Thanks for the comment. We have replaced all instances of ΔR_{adv} with ΔR_{AHT}.

There is no significance test in Figure 6.

Response:

We tested Figure 6 (now Figure 8) for significance, L292.

Line 240, Figure 7a and Figure 7b.

Response:

We've corrected it.

Lines 276-277, I didn't noticed the poleward propagation of SE in the tropical warm pool.

Response:

It should be the poleward moist static energy transported by SE. We have removed this sentence.