Responses to Reviewer #2

We thank 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.

The authors investigated the influence of the regional SST change on polar amplification through a set of idealized SST patch experiments. Their findings indicate that sea surface warming in most tropical regions enhances poleward energy transport, with the exception of the Indian Ocean, which is due to different responses of stationary waves. The innovative method employed is commendable, and the results are reasonable. I would recommend a minor revision for this paper.

Arctic is experiencing a faster warming rate than the global average during the recent decade, and the underlying reasons for this amplification remain somewhat unclear. Previous energy budget analyses, such as Pithan & Mauritsen (2014), showed the significance of local feedbacks. Stucker et al. (2018) demonstrated through model simulations that Arctic amplification is primarily driven by local forcing and feedbacks. However, Ding et al. (2017) highlighted the role of circulation in influencing September sea-ice extent. Some observations also indicate short-period warming events in the Arctic often follow a period of anomalous energy transport. This highlights the necessity for a deeper understanding of how changes in poleward energy transport interact with local feedbacks in the Arctic region. This paper makes a valuable contribution to addressing this important question.

Response:

Thanks for the valuable comments. We have revised the paper to address all the comments.

Major Comments:

1. The motivation of this paper could be further clarified in the Introduction section. The authors provide a substantial summary of the ongoing debate regarding the drivers of Arctic amplification (AA), specifically whether it is driven by local processes or remote factors. While it seems the authors will discuss the importance of atmospheric heat transport (AHT) later on, this point is not revisited in detail. The authors summarized that 50%-85% of Arctic warming is induced by non-local drivers in the Introduction, which also seems overstated. Given that this paper specifically focuses on how SST warming patterns influence the Arctic rather than quantifying the relative contributions from local and nonlocal drivers, I recommend that the authors either include a discussion or quantification of how their results support the importance of AHT in AA, or step back to enhance the literature review in the Introduction regarding the influence of SST warming patterns on AA. This would help readers understand what has been explored and what this paper aims to contribute.

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."

2. The slower warming rate of the Antarctic is another interesting question. Since the authors have quantified how SST patches influence the energy budget in both the Arctic and Antarctic, I wonder if it could be possible to further discuss how the SST warming patterns might influence the asymmetry of AHT in polar regions. This may provide additional insights into the contrasting warming rates observed in the two areas.

Response:

Yes, we agree with this point. We added a paragraph to discuss it (L161-163):

"*The response of Arctic* ΔR_{AHT} *to tropical warmings is generally greater than Antarctic* ΔR_{AHT}*, indicating that more heat is transported to the Arctic region than that to the Antarctic region when the tropics warms. This difference may partly contribute to the faster Arctic warming than Antarctic warming under global warming.*"

Minor Comments:

L8: "The results show…". This sentence is quite general; it would be beneficial to provide more specific details.

Response:

Thanks for your feedback. We added a sentence beginning with "specifically" to explain this sentence (L11-13):

"*Specifically, an increase of poleward atmospheric energy transport to polar regions results in an increase of surface and air temperature, and the corresponding Planck feedback leads to a radiative warming at surface and radiative cooling at TOA.*"

L23: "which is also applicable to the Antarctic". The mechanisms of Antarctic warming are different from the Arctic. The mechanism studies regarding the two regions are always separate.

Response:

We've revised it (L24-26):

"However, the mechanisms in the Antarctic region differ from the Arctic region due to factors like the high elevation of the Antarctic ice sheet, weaker albedo reduction and strong Southern Ocean heat uptake, which delay the response (Salzmann, 2017; Armour et al., 2016; Hahn et al., 2021; Smith et al., 2019)."

L48: "50%-85% of Arctic warming". This number is followed by several cited papers. This number is much higher than expected. I recommend the authors clarify the scenarios and methods used to obtain the number to avoid confusion.

Response:

We have revised this section, see the reply to the major comment.

L68: "(Lee, 2011; 2012; 1204". Typo, the closing parenthesis is missing.

Response:

We have corrected the missing closing parenthesis

L111: "The response of …". This is an important conclusion, but this sentence is difficult to understand. Suggest rephrasing.

Response:

Thank you for your suggestion. We have reorganized our description of Figure 1 to improve clarity and make the important conclusion easier to understand (L143-160):

"*Figures 1(a-c) show the responses of the Arctic energy budgets to SST warmings in global oceanic regions. 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), as indicated by the positive poleward heat transport to the Arctic region (positive ΔR_{AHT}). This enhanced energy transport warms the Arctic atmosphere, leading to an increase in surface radiation (positive ΔR_{sfc}, Figure 1b) due to higher surface and air temperatures. Simultaneously, the warmer atmosphere emits more longwave radiation to space, resulting in a decrease in TOA radiation (negative ΔR_{TOA}, Figure 1a). Conversely, warming in the tropical Indian Ocean reduces the poleward energy transport to the Arctic region (negative ΔR_{AHT}), leading to cooler Arctic atmospheric temperatures, and there is a decrease in surface radiation (negative ΔR_{sfc}, Figure 1b) and increase in TOA radiation (positive ΔR_{TOA}, Figure 1a). Sea surface warming in the midlatitudes of the northern hemisphere increases Arctic surface radiation, but has insignificant impact on TOA radiation.*

For the Antarctic energy budget, warming in the tropical Pacific and Indian Oceans generally leads to increased poleward energy transport (positive ΔR_{AHT}, Figure 1f), which warms the Antarctic atmosphere and results in increased Antarctic surface radiation (positive ΔR_{sfc}, Figure 1e) and decreased Antarctic TOA radiation (negative ΔR_{TOA}, Figure 1d). However, the response of ΔR_{TOA} to warmings in the tropical Atlantic is positive (Figure 1d). Warming in the Southern Ocean also leads to an increase of Antarctic surface radiation and decrease in Antarctic TOA radiation. Antarctic energy budget is generally not sensitive to warmings in subtropical regions. 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."

L252: "Yohai". Typo, there's an extra space.

Response:

We've removed this reference.

L357: "This knowledge…". This paper emphasizes the role of AHT, rather than the observed radiation in the Arctic.

Response:

We have deleted this sentence.

Figures 1-5: The colors are a bit faint, making it difficult to clearly distinguish the points.

Response:

We have modified the color bars of Figures 1–5 (now Figures 1, 2, 3, and 6, 7), using smaller intervals.

Figure 7: The black is not bolded, while the blue line is bolded.

Response:

The different line weights were intentionally designed to highlight the role of SE, represented by the blue line. By making the blue line bold, we aim to emphasize its significance in the analysis.