Responses to Reviewer #1

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 use sea-surface temperature (SST) warming patch experiments to quantify how the Arctic energy budget is impacted by remote warming. They find a central role for changes in atmospheric heat transport, primarily due to stationary eddies, for connecting tropical SST changes to changes in Arctic surface and top-of-atmosphere radiation. They also highlight the opposite response of Arctic radiation to warming in the Indian Ocean versus Western Pacific, as a result of differences in the stationary eddy response.

The premise of this paper is novel and interesting: while past studies have explored the remote impacts of SST-patch changes on atmospheric circulation and global warming, the polar warming response has been less explored, and there are many open questions about the role of atmospheric heat transport for polar warming. This paper will be of interest to research communities studying polar climate change, the pattern effect and climate sensitivity, and the teleconnections between tropical SSTs and atmospheric circulation. However, I recommend some changes to the analysis to more clearly and mechanistically interpret the results and situate them within the context of previous literature.

Response:

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

Major Comments:

Rossby wave response to tropical SST forcing

1. There are some previous relevant papers that would be helpful to add when discussing the opposite response to Indian Ocean versus tropical Pacific warming. Annamalai et al (2007; https://doi.org/10.1175/JCLI4156.1) have a review of some of these in their introduction paragraph 4, with a focus on how SST anomalies from different ocean basins affect the Pacific-North American (PNA) pattern. Barsugli and Sardeshmukh (2002) use SST patch experiments to show that warm SST anomalies in the tropical Pacific produce positive PNA index values, while warm SST anomalies in the Indian Ocean produce negative PNA index values, both by triggering a Rossby wave response. Others like Ding et al. (2014; https://doi.org/10.1038/nature13260) have connected this atmospheric circulation response to changes in Arctic warming. It seems like your experiments are consistent with these results: the Indian Ocean and tropical Pacific generate opposite temperature responses in the Arctic by producing different Rossby wave responses and changes in stationary eddy heat transport.

Response:

Thanks for the suggestions. We added these references when we discuss the opposite response to Indian Ocean versus tropical Pacific warming (L278-282):

"*Figure 8 presents the responses of surface temperature (ΔT_s), 200hPa geopotential height (ΔZ_{200}), and 500hPa geopotential height (ΔZ_{500}) to warmings in these patches, providing background information to later AHT studies. Consistent with previous studies (Annamalai et al., 2007; Barsugli & Sardeshmukh, 2002; Ding et al., 2014), our experiments reveal that SST anomalies in different ocean basins induce contrasting atmospheric circulation patterns, primarily through Rossby wave responses affecting the Pacific-North American (PNA) pattern.*"

2. As in the references above, to investigate this Rossby wave response, can the authors plot the 200-hPa geopotential height response to these two SST experiments? It would be helpful to more clearly illustrate this mechanism linking tropical SST perturbations to changes in Arctic temperature and radiation.

Response:

We plotted 200-hpa and 500-hpa geopotential height (Fig. 8) response to investigate the Rossby wave response. Below are the specific changes made to the manuscript (L278-290):

"*Figure 8 presents the responses of surface temperature (ΔT_s), 200hPa geopotential height (ΔZ_{200}), and 500hPa geopotential height (ΔZ_{500}) to warmings in these patches, providing background information to later AHT studies. Consistent with previous studies (Annamalai et al., 2007; Barsugli & Sardeshmukh, 2002; Ding et al., 2014), our experiments reveal that SST anomalies in different ocean basins induce contrasting atmospheric circulation patterns, primarily through Rossby wave responses affecting the Pacific-North American (PNA) pattern.*

Specifically, warming in the TPO region leads to ΔT_s increase over the Tibetan Plateau, Eastern Europe, tropical Africa, northeastern North America, and most of Antarctica. Concurrently, ΔZ_{200} exhibits a local increase over the TPO region, a decrease over the North Pacific, and increases over north-eastern North America and Antarctica. The ΔZ_{500} response mirrors the ΔZ_{200} pattern but with reduced intensity. In contrast, warming in the TIO region induces ΔT_s increases over Antarctica and significant warming over the Indian subcontinent, while the Tibetan Plateau experiences cooling. Notably, the northwest of North America shows marked cooling under TIO warming. The ΔZ_{200} response to TIO warming displays a dipole pattern, characterized by increases in the tropical warming regions and decreases toward the poles, followed by subsequent increases. The ΔZ_{500} response follows a similar trend to ΔZ_{200} with weaker intensity."

*3. I think Equation (7) is wrong: In Kaspi and Schneider (2013) Equation (3), the stationary eddy response is defined as Vbar*Sbar – Vbar,bracket*Sbar,bracket, but the authors here have written (V*S)bar – Vbar,bracket*Sbar,bracket, which is actually equal to the stationary plus transient eddy response. This will impact the results shown in Figure 8. Also, Figure 8 has 16 panels—consider whether all are necessary.*

Response:

Thanks for pointing out the issue. We deleted the equation, and now we are directly calculating $\overline{V^*S^*}$ from our model data,

$$V^* = V - [V]$$

$$S^* = S - [S]$$

and updated Figure 8 (now Figure10) accordingly (L329-331):

"*To better understand the opposite response of SE heat flux to warmings in TPO and TIO, we analyzed the spatial distribution of SE heat fluxes. The vertically integrated SE heat flux (ϕ) can be computed through the following integral:*

$$\phi = \int_0^{P_s} V^* S^* \frac{dp}{g} , \qquad (11)”$$

Figure 10 explains how the change of V, S_{Ta}, S_Q and S_Z contribute to ϕ (ϕ_{Ta}, ϕ_Q, ϕ_Z), so there are 8 panels for each case, and as a result there are 16 panels.

4. Figure 6 and L199-212: I didn't find this figure helpful, other than illustrating that the Pacific patch warms the Arctic while the Indian Ocean patch cools the Arctic (although I would suggest a smaller scale for the color bar in 6a,e to be able to see the Arctic response). How do zonal-mean V and Q changes in Figure 6c and 6d help us understand this response (given that the authors later show stationary eddies are key, the covariance of V and MSE anomalies from the zonal mean would be more relevant)—please add mechanistic interpretation or remove this.

Response:

Thank you for your valuable feedback. We have revised the content of Figure 6 (now Figure 8). It now presents "The spatial distribution of ΔT_s (a), ΔZ_{200} (b), and ΔZ_{500} (c) in response to an increase in SST over the TPO, and the spatial distribution of T_s (d), ΔZ_{200} (e), and ΔZ_{500} (f) following an increase in SST over the TIO." Additionally, we have conducted an analysis as detailed in Response for major comments 1&2.

Mechanisms of Arctic warming response

1. Introduction: Where is this statement that 50-85% of Arctic warming is induced by non-local drivers coming from (L48)? Some of the papers cited here (e.g. Stuecker et al., 2018) actually show the opposite—that very little polar amplification results from non-polar forcing. Papers like Dai et al. (2019) also show that local feedbacks due to sea-ice loss are needed to produce strong polar amplification. Pithan and Mauritsen (2014), Goosse et al. (2018), and Hahn et al. (2021) show that the local lapse-rate and albedo feedbacks contribute most to Arctic warming, followed by changes in poleward moisture transport. A more nuanced summary is needed: past studies have suggested a dominant role for local processes in driving polar amplification, but have also suggested that poleward moisture transport is another important contributor, and would support Arctic amplification even in the absence of local sea-ice feedbacks (e.g. Alexeev 2005). Moreover, local and remote processes interact, so remote heat transport may further contribute by amplifying local feedbacks.

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 (L27-57):

"*The polar energy budget is highly sensitive to various local feedback mechanisms. One important mechanism is the ice-albedo feedback. Global warming reduces snow cover and sea ice cover in the polar regions, leading to more solar radiation being absorbed, which in turn accelerates climate warming and further decreases albedo (Dickinson et al., 1987; Hall, 2004; Boeke and Taylor, 2018; Duan et al., 2019; Dai et al., 2019). Additionally, temperature feedback is another significant contributor to AA (Pithan and Mauritsen, 2014; Laîné et al., 2016; Sejas and Cai, 2016). It involves the processes of radiative cooling and is characterized by the Planck and lapse-rate feedbacks. 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). Simultaneously, the decrease in lower tropospheric stability increases Arctic cloud cover and optical thickness (Barton* *et al., 2012; Solomon et al., 2014; Taylor et al., 2015; Yu et al., 2019), contributing to Arctic autumn and winter warming (Boeke and Taylor, 2018). These local feedbacks are considered primary contributors to Arctic amplification (Pithan and Mauritsen, 2014; Goosse et al., 2018; Hahn et al., 2021; Dai et al., 2019).*

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. To understand the polar feedback and atmospheric heat transport response, I would recommend dividing the TOA radiation response (and heat transport convergence) (in W/m2) by the Arctic near-surface temperature response (in K), as in Kay et al. (2012; https://doi.org/10.1175/JCLI-D-11-00622.1). This would better show how remote warming impacts Arctic feedbacks and heat transport convergence.

Response:

We understand the reviewer's suggestion to quantify the feedback strength by dividing the ΔR_{TOA} and ΔR_{AHT} by the Arctic ΔT_s, and below is an illustrative figure. However, the main purpose of this paper is to analyze how SST anomalies in the mid/low latitudes affect the energy budget in the polar regions, while the effects of polar sea ice change (which are important in determining polar feedback parameter) are not analyzed in this paper, so the polar feedback parameter is not analyzed in this paper. To maintain the consistency and simplicity of the figures and to ensure a clear presentation of the results, we are not presenting these results in this paper.

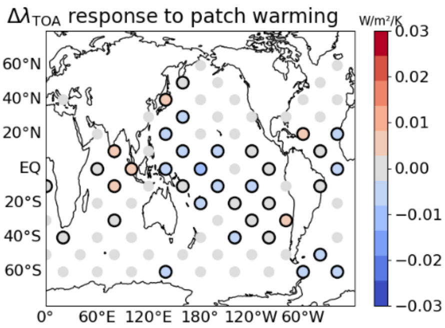

Figure R2. Response of annual mean Arctic ΔR_{TOA} normalized by annual mean Arctic temperature response, $\lambda_{TOA} = \Delta R_{TOA}/\Delta T_s$.

I would also consider expanding the current feedback decomposition to include the water vapor feedback and to split the temperature feedback into a Planck and lapse-rate response, consistent with previous studies. Similarly to Figure 9, can the authors also show the sensitivity of the Arctic-averaged near-surface temperature to the local SST changes? I also find Figure 9 with the Green's function approach to be more informative than figures with the individual patch responses like Figure 1, so would suggest combining the patch experiments to create maps like Figure 9 for the feedback analysis, too.

Response:

We have expanded the current feedback decomposition to split the temperature feedback (fixed-RH) into Planck and lapse-rate responses. We are still using the fixed-RH decomposition framework because the RH value does not change significantly.

Following the reviewer's suggestion, we are now using sensitivity maps to perform the feedback analysis.(Figs. 6-7). Given the negligible sensitivity of $\partial R_{RH}/\partial SST_i$, we have decided not to include its discussion in the paper（Figure R3）.

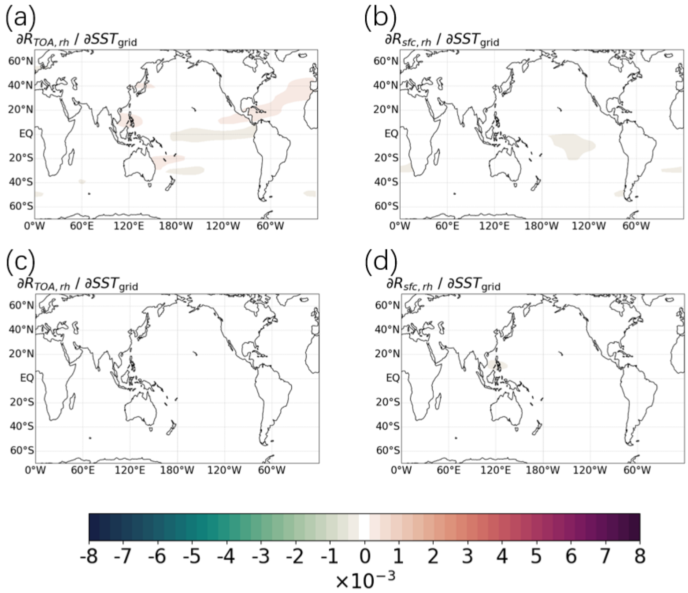

Figure R3 Difference of annual mean $\partial R_{TOA,RH}/\partial SST_i$**(a),** $\partial R_{sfc,RH}/\partial SST_i$**(b) for Arctic and annual mean** $\partial R_{TOA,RH}/\partial SST_i$ **(c),** $\partial R_{sfc,RH}/\partial SST_i$ **(d) for Antarctica between conjugate warming and cooling patch experiments.**

Minor Comments

L18: Suggest adding a sentence to the abstract to indicate why the reader should care about these results—what's the key takeaway, and what are the implications.

Response:

We have added the following sentence to the abstract (L19-20):

"*These results help explain how the polar climate is affected by the magnitude and spatial pattern of remote SST change.*"

L23: "its lower albedo"—I don't think this is true, and would delete. Also would add a reference for Southern Ocean heat uptake in L24 (like Armour et al. 2016) alongside the elevation/feedback references that are here already (Salzmann and Hahn).

Response: Yes, it should be "weaker albedo reduction" instead of "lower albedo". We changed the statement, and added a reference to Armour et al. (2016) to support the discussion on the Southern Ocean's heat uptake alongside the existing references (L24-26):

"*However, the mechanisms in Antarctica differ from the Arctic 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).*"

L27: after "snow cover" add something like "and melts sea ice" (a huge contributor to the albedo feedback)

Response: We have revised the sentence to include the melting of sea ice as a significant contributor to the albedo feedback (L28):

"*Global warming reduces snow cover and sea ice cover in the polar regions*".

L30-33: Suggest editing this incomplete description of the temperature feedback's contribution to AA. The main mechanism in the cited Pithan and Mauritsen reference is the lapse-rate feedback—in which surface warming is trapped by surface temperature inversions and contributes little to warming at higher altitudes (unlike in the tropics), which leads to less efficient radiative cooling in the Arctic than in the tropics. The Planck feedback also contributes to AA—in part because surface warming starting from colder temperatures in the Arctic produces less outgoing longwave radiation than when starting from warmer temperatures in the tropics, following the Stefan-Boltzmann equation.

Response:

We have revised this section, and a detailed response is provided in the reply to the major comment under 'Mechanisms of Arctic warming response'.

L41: The phrasing of "efficiency" is vague—I would reword this. Also, the main point of the cited Stuecker et al. (2018) paper is the opposite of the point of this paragraph—they find that polar amplification is dominated by local, not remote forcing.

Response:

We have revised this section, and a detailed response is provided in the reply to the major comment under 'Mechanisms of Arctic warming response'.

We reworded "efficiency" as "more effective"(L48):

"*Under global warming, the AHT from low latitudes is more effective …*"

L52: Consider just writing out "polar energy budget"—I don't think PEB is very common as an acronym, and it would be easier to read without the acronym.

Response:

We have revised the manuscript by replacing all instances of "PEB" with "polar energy budget" to enhance readability.

L59: Suggest rewording this sentence, as the literature supports a large role of synoptic-scale waves for poleward heat transport—synoptic-scale transient eddies contribute significantly to both mean-state poleward heat transport and its changes under increased CO2 (e.g., Donohoe et al., 2020: https://doi.org/10.1175/JCLI-D-19-0797.1). I think the authors are saying that planetary waves are more important for the response to tropical warming, but should make this clearer.

Response:

We revised this sentence following the comment (L61-67):

"*For instance, intensified convective activity within the Pacific Warm Pool not only strengthens the propagation of Rossby waves toward the poles but also increases the frequency of these fluctuations. This enhancement in Rossby wave activity boosts the transport of water vapor to the Arctic, augmenting the downward longwave radiation in the Arctic regions (Rodgers et al., 2003; Lee et al., 2011; Lee, 2012; Lee, 2014). While synoptic-scale transient eddies contribute significantly to mean-state poleward heat transport and its changes under increased CO2 (Donohoe et al., 2020), their overall impact is relatively minor compared to that of amplified planetary waves in responses* *to tropical warming (Baggett and Lee et al., 2017).*"

L90: What magnitude of SST anomaly, A, is imposed?

Response: We added information on it (L95-96):

"*… which is set to be +4 K and -4 K in this study*".

L111: Should say "western and central tropical Pacific," not eastern?

Response:

We have corrected the text in L144 from "eastern tropical Pacific" to "western and central tropical Pacific".

L110-120: This comes across as a descriptive list rather than telling a cohesive and interesting story. The authors might instead consider first discussing the advective, TOA, and surface responses to the tropical Pacific warming, and then the advective, TOA, and surface responses to the Indian Ocean warming. It would be helpful to add some mechanistic interpretation here, too, like these results suggest that in response to tropical Pacific warming, there is increased poleward atmospheric heat transport, which warms the Arctic atmosphere and therefore increases TOA radiative cooling and surface radiative heating. Also considering the rest of the paper, it would be generally helpful to include more mechanistic interpretation.

Response: We have revised the paper accordingly, optimizing the logical order of the content to ensure a clearer structure and a more coherent narrative (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: Should be Kaspi and Schneider (2013). Many of the other citations in the text are also missing "et al."—suggest checking the citation formatting throughout the paper.

Response：

We have deleted the citation "Kaspi and Schneider (2013)." Additionally, we have reviewed all citations throughout the manuscript and have updated them to ensure proper formatting, including the use of "et al."