egusphere-2024-320
“Quantifying the Impacts of Atmospheric Rivers on the Surface Energy Budget of the Arctic Based on Reanalysis”
Response to the Reviewers

By Chen Zhang, John J. Cassano, Mark Seefeldt, Hailong Wang, Weiming Ma, and Wen-wen Tung

We appreciate the valuable comments provided by the Reviewers. Before addressing each point individually, we would like to acknowledge the two common concerns raised by Reviewers.

Firstly, there were concerns regarding the methodology of our analysis. The primary objective of this work is to estimate the relative contribution of different surface energy budget (SEB) components to the net SEB. To achieve this, original panel (c) in the Figures 2-3, 5-7 of the manuscript aims to illustrate the relative AR contribution to SEB components, normalized by the net SEB. This normalization involves calculating the ratio of the accumulated AR SEB term, which accounts for both the magnitude of individual AR anomalies and their frequency of occurrence, to the accumulated seasonal net SEB. By adopting this normalization approach, we enable consistent comparisons across different SEB components, thereby allowing readers to discern relative contributions effectively.

Furthermore, following RC3’s suggestion with a slight modification, we chose to calculate the relative contribution of AR-related SEB component anomaly normalized by the mean of each respective component. This approach aims to estimate the accumulated AR contribution of SEB component relative to their total values. We chose to present the results as an additional panel, now labeled as new panel (c), in Figures 2-3, and 5-7 of the revised manuscript. Consequently, the original panel (c), depicting the AR SEB contribution normalized by the total SEB, has been reassigned to panel (d) to accommodate this adjustment.

Specifically, the results shown in new panel (c) result from the following calculation at each individual grid point within the study domain for each season:

1. Calculate the total extra energy contributed by each SEB component when ARs are present as, $(\mathrm{F_{AR}} - \mathrm{F_{All}}) * \mathrm{t_{AR}}$, where $\mathrm{F_{AR}}$ represents the mean of any term in the SEB equation when an AR is present, $\mathrm{F_{All}}$ denotes the seasonal mean of any term in the SEB equation, and $\mathrm{t_{AR}}$ indicates the total number of 3-hourly time steps during which ARs are present.
2. Calculate the total energy for each component as, $\mathrm{F_{All}} * \mathrm{t_{All}}$, where $\mathrm{t_{All}}$ signifies the total number of 3-hourly time steps within each season.
3. Determine the ratio of these two terms, which provides an estimate of the magnitude of AR anomaly for each SEB term relative to the average value for each component. This is

presented in Eq. (2), noting that the ratio of t_{AR} to t_{All} is simply the AR frequency shown in Fig. 1

$$\frac{(F_{AR}-F_{All})*t_{AR}}{F_{All}*t_{All}} = \frac{\text{panel (b)}*\text{Fig.1}}{\text{panel (a)}} \tag{2}$$

Additionally, we include the net SEB equation in the revised manuscript, labeled as Eq. (1), as follows:

$$\text{net SEB} = \text{LWN} + \text{SWN} + \text{TH} = \text{LWD} - \text{LWU} + \text{SWD} - \text{SWU} + \text{SH} + \text{LH} \tag{1}$$

Where LWN, SWN and TH denote the net longwave radiation, net shortwave radiation, and turbulent heat flux, respectively. LWD, LWU, SWD, SWU, SH, LH represent downward longwave, upward longwave, downward shortwave, upward shortwave, sensible and latent heat flux, respectively.

Secondly, two Reviewers expressed concerns about the organization of our sections, particularly noting overlapping discussions between Section 3 (Analysis and Results) and Section 4 (Discussion). To address this issue, we have restructured the sections as follows:

- Section 3: AR occurrence frequency (original Section 3.1)
- Section 4: AR's influence on the surface energy budget component of the Arctic (original Section 3.2)
  - Section 4.1: Surface radiative fluxes (original Section 3.2.1)
    - Section 4.1.1: Surface downward longwave radiation
    - Section 4.1.2: Net Surface longwave radiation
    - Section 4.1.3: Net Surface shortwave radiation
  - Section 4.2: Surface turbulent heat fluxes (original Section 3.2.2)
  - Section 4.3: Net Surface energy budget (original Section 3.2.3)
- Section 5: AR's surface impacts
  - Section 5.1: AR-induced surface and air temperature response (original Section 4.1)
  - Section 5.2: AR's crucial role in triggering Greenland Ice Sheet melt (original Section 4.2)
- Section 6: Uncertainties and limitations
  - Section 6.1: Influence of AR detection methods on results (original Section 4.3)
  - Section 6.2: Limitation of the reanalysis data (original Section 4.4)
- Section 7: Conclusions (original Section 5)

We believe these adjustments will enhance the clarity and coherence of our manuscript, addressing the concerns raised by the Reviewers effectively.

Below, we respond in blue text to the Reviewer's comments, using an italic font to indicate text that has been copied verbatim from the Reviewer's reports.

Reply to RC2, Jonathan Wille:
We appreciate the Reviewer for insightful and detailed reviews. We have made changes to the manuscript, accordingly, as replied below.

RC2, Jonathan Wille:
General comments
This study is a comprehensive examination of the atmospheric river (AR) influence of the surface energy budget (SEB) across the entire Arctic. Using an AR detection algorithm based on relative monthly integrated vapor transport (IVT), the authors identify the distinctions of AR SEB influence across land, open ocean, and sea ice regions. Their results help confirm and build upon previous understandings about AR impacts on Greenland surface melting and especially the hampering of winter sea-ice growth. Regarding this AR impact on winter sea-ice growth, the observation that this process is highly sensitive to the choice of AR detection algorithm is a great distinction between the impacts observed while using an AR detection algorithm designed to capture extreme events and an algorithm designed to capture more frequent events. There is a clear line of progression from the authors' previous first work on Arctic AR climatology to this study on Arctic AR SEB behavior. The methods are clear and well formulated, and the results are exhaustive and detailed. To my knowledge, previous studies have looked at localized Arctic SEB impacts from ARs, but this is the first study to make a comprehensive analysis on this topic across the entire Arctic. After some minor revisions, this manuscript will serve as an excellent reference for other researchers looking to understand the overall influence of ARs on the polar SEB. I would be happy to see this manuscript published after some global comments and a series of minor comments are addressed.
Reply: Thank you for the positive comments.

Specific comments

1. *Section 2.3: Please consider including the equation for the SEB so the reader can quickly understand the various SEB components presented in this manuscript.*

Reply: We have included the equation for the SEB in Section 2.2, as Eq. (1) in the manuscript:

"Moreover, we define total surface turbulent heat flux (TH) as the sum of SH and LH. The net SEB is expressed as the sum of the net radiation at the surface (i.e., sum of the LWN and SWN) and net total TH (i.e., sum of the SH and LH), that is,

$$net\ SEB = LWN + SWN + TH = LWD - LWU + SWD - SWU + SH + LH \qquad (1)$$

Where LWU and SWU represent upward longwave and shortwave radiation, respectively."

2. *Sec 3.1: Please discuss how the AR frequency results presented here compare to the analysis in Zhang et al., (2023). Assuming that this is a similar analysis as Zhang et al., (2023), it may be helpful to mention that you have repeated this AR frequency analysis to*

help contextualize your later SEB results. I do like that you made this a small section as to not detract from the SEB analysis.

Reply: It is acknowledged that Sec 3.1 presents a similar analysis compared to that conducted in Zhang et al., (2023). In response, we have included a clarifying statement in the manuscript, stating:

"It is noted that the AR occurrence frequency presented in Fig. 1 resembles the analysis in Zhang et al., (2023), with the distinction that we emphasize the seasonal frequency as a percentage of total time steps within each season instead of annual percentage."

3. *Figure order: Consider changing the order of the results so that the net SEB is presented first and followed by the components of the SEB. This could improve the readability since currently Figure 7 is referenced before Figures 3-6 when discussing the LWD results.*

Reply: We appreciate the Reviewer's suggestion, but we prefer to retain the order of figures and discussion as originally shown in our manuscript. Our rationale for this is that many previous Arctic AR studies highlight the large impact of ARs on longwave radiation and thus we chose to begin our discussion with this SEB term. We then feel that it makes sense to proceed through other individual terms in the SEB and ending with the net SEB, which sums the previously discussed results.

4. *Section 4.2: This is a good discussion comparing the melting implications of your study with previous works, but it could use some more elaboration and clarity. In the beginning, you mention is disparity between the results of Mattingly et al., 2020 which found ARs delivered large sensible heat fluxes while your study links ARs to smaller turbulent heat fluxes and more net longwave anomalies. You attribute these differences to the focus on stronger ARs in Mattingly et al., 2020, but could elaborate on why a focus on stronger ARs might cause these differences?*

Reply: The discrepancy from Mattingly et al., (2020) could be attributed to the use of distinct AR detection algorithms. Their approach applies a stringent minimum threshold of 150 kg m^{-1} s^{-1} for IVT and exclusively allows for northward moisture transport from the Arctic, potentially leading to highly intense northward AR transport and heightened sensible heat flux. We have elaborated on this discussion as follows:

"This deviation from Mattingly et al., (2020) may stem from the utilization of different AR detection algorithms. Their methodology imposes a strict minimum threshold of 150 kg m^{-1} s^{-1} for IVT, and exclusively considers northward moisture transport from the Arctic. Moreover, their focus is on the strongest AR days, where the maximum IVT exceeds the 90th percentile of all AR IVT at each basin and each season. These criteria are designed to capture extremely strongly northward AR transport events affecting Greenland, potentially resulting in heightened SH."

Then you discuss your findings in Northeast Greenland which point to a larger influence of turbulent heat fluxes which actually agrees a bit with Mattingly et al., 2020 and aligns closer to Mattingly et al., (2023) which discusses more the foehn effect from ARs. It would be good if you can mention this agreement with Mattingly et al., (2023) and how your sensible heat flux results might be picking up on the AR-related Foehn contribution in the region.

Reply: We have integrated this discussion into the manuscript as follows:

"These patterns align with findings from Mattingly et al., (2023, 2020), where they suggest that the foehn effect from ARs leads to increased SH."

5. *Section 4.3: Naturally, some readers will wonder if you would get similar results using a cyclone-detection algorithm to study SEB impacts. I'm not suggesting you make an additional analysis with a cyclone-detection algorithm, but perhaps it could be beneficial to add a few sentences to the end of this section relating your results with other studies that did track SEB-impacts from cyclones and then argue why it is more informative to use ARs instead of cyclones to quantify SEB-impacts.*

Reply: ARs are indeed strongly associated with cyclones. Exploring the role of Arctic cyclones in SEB impacts and comparing them with results of ARs in this study is a direction that requires further investigation. We have incorporated this point into the Section 6.1 (original Section 4.3) of our manuscript as follows:

"In addition, Arctic ARs are closely linked with Arctic cyclones, which strongly influence surface heat fluxes, particularly TH (Blanchard-Wrigglesworth et al., 2022), subsequently impacting the net SEB. Moreover, studies suggest that large SEB anomaly events in the Arctic are often associated with an increased frequency of cyclone occurrence (Murto et al., 2023). Additionally, cyclones affect snowfall accumulation on sea ice, thereby influencing SEB due to high albedo of snow (Webster et al., 2019). Our findings indicate that surfaces with varying albedos exhibit distinct responses to AR SEB impacts, particularly AR-related SWN impacts. Further research is warranted to comprehensively investigate the relationship between Arctic ARs and Arctic cyclones, and their synergistic role in surface SEB impacts, with a particularly focus of cyclone-induced snow on ice. Additionally, it is crucial to compare these findings with the results obtained from ARs in this study."

Minor comments

Line 29: First sentence is a run-on. Consider breaking it up.

Reply: We have broken the sentence into two sentences, as follows:

"The Arctic is a multifaceted environment, distinguished by close interactions among its atmosphere, ocean, sea ice and land components. It is influenced by various forcing from lower latitudes, operating across a wide range of time and space scales (Serreze et al., 2007)."

Line 41: "Remote perspective" is slightly vague. Maybe "remote forcing perspective"
Reply: We have changed to "remote forcing perspective". Thank you.

Line 47: Consider distinguishing the studies that focus on Antarctic ARs and Arctic ARs.
Reply: We have categorized the literature into Arctic and Antarctic ARs, and expanded our references on Antarctic ARs, as follows:

"This growing attention is evident in various Arctic studies (Baggett et al., 2016; Ma et al., 2021; Mattingly et al., 2023, 2020; Zhang et al., 2023a, b) and Antarctic studies (Gorodetskaya et al., 2014; Guan et al., 2016; Ma et al., 2020; Wille et al., 2021; Shields et al., 2022; Wille et al., 2019, 2024b, a)…"

Line 53: Add an oxford comma after "ocean"
Reply: Added.

Line 67-68: It's good you cited the importance of the AR impacts on the SEB in relation to sea ice. But since this paper also discusses the SEB over land, you should also state the importance of the AR SEB impacts over land ice.
Reply: We have incorporated the importance of AR SEB impacts over land ice, as follows:

"… Moreover, the impacts of AR on the SEB can extend beyond sea ice regions to encompass land ice dynamics. These impacts include various facets, including melting rates, warming of the snowpack, affecting snowmelt timing, alterations in ice mass balance, and overall surface energy exchange process (Goldenson et al., 2018; Guan et al., 2016)."

Line 68: "accelerate or decelerate ice growth" you should clarify that you refer to sea ice growth here.
Reply: We have changed to "sea ice growth".

Line 80: Correct "AR's impact" to "AR impacts on the Arctic surface energy budget". Surface energy budget should be singular unless you reference multiple locations in the sentence.
Reply: We have corrected "AR impacts", and we have also replaced "surface energy budget" with the abbreviation of "SEB" consistently throughout the text.

Line 86-91: This is a really long sentence. Consider breaking it up around when you describe MERRA-2 being the source data for ARTMIP.

Reply: We have rewritten this sentence, as follows:

"An ensemble Arctic AR index database (Tung et al., 2023) was developed by Zhang et al., (2023a), where a total of 12 AR indices were created based on combinatory conditions of either integrated water vapor transport (IVT) or integrated water vapor (IWV) applied with three levels of monthly climate thresholds (75th, 85th, and 95th percentiles). The data utilized for this development were sourced from3-hourly fifth generation of ECMWF atmospheric reanalysis (ERA5, Hersbach et al., 2020) and 3-hourly NASA Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2, Gelaro et al., 2017) from 1980 to 2019. The NASA MERRA-2 source data was obtained from the AR Tracking Method Intercomparison Project (Shields et al., 2018)."

Line 100: Can you briefly say why you only choose dates during neutral or weak ENSO events?
Reply: We only preserved the dates during neutral or weak ENSO events to have a standard climate threshold to test for ARs. For example, if we wanted to update the AR index to the MOSAiC year, we do not need to collect the data and recalculate the thresholds. To clarify this approach, we have included the following note in the manuscript:

"The selection of the neutral or weak ENSO events aim to establish a standard climate threshold for testing ARs."

Line 133: It seems odd that surface energy budget is first abbreviated here and not earlier in the introduction on its first use.
Reply: We have addressed the issue by removing the abbreviation in this instance and ensuring consistency in the use of "SEB" throughout the manuscript.

Line 159: Consider changing to "underscores the potential role of ARs driving net SEB fluctuations"
Reply: Changed it.

Line 164: Comma after "To do this"
Reply: Fixed.

Section 3.2: Just wanted to say that I appreciate you outlining the different figures and tables here before continuing to the sub-sections. This is very helpful for the reader to follow along.
Reply: Thank you for this comment.

Line 227-228: Nice result here. You could comment that ARs are nearly the exclusive cause of LWD over Arctic land areas during winter. This would make them the main cause for warming during the winter since winter warming is driven by LWD

Reply: We are cautious about drawing this conclusion solely based on the results presented in the manuscript. As stated at the beginning, we will calculate the relative contribution of AR-related SEB components normalized by the mean of each respective component. These findings will be presented in the new panel (c) in the revised manuscript, providing further insights to verify the suggested comment.

Figure 2c,3c,5c,6c,7c: On both ends of the color bar, there is a gray color to represent values exceeding -100 and 100%. In Figure 2c, the caption says these gray areas represent percentage results greater than 100%. However, in some other figures, the gray areas represent percentages less than 100%, but this isn't mentioned in their figure captions. Please clarify this either in the Figure 2 caption or the following figure captions.

Reply: We consistently use the gray color to represent the percentage results greater than 100% or less than -100% across Figs 2-3c,5-7c. We have adjusted the description to accurately reflect this:

"The percentage results greater than 100% or less than -100% are shaded in grey for clarity."

Line 257: Figure 7 is cited before Figures 3-6. While I appreciate that this is meant to enhance the discussion of the results in Figure 2, it is disorientating to the reader since they haven't had a chance to understand the meaning of Figure 7 and forces them to skip ahead in the manuscript. Please considering moving Figure 7 to Figure 3, moving this text to the discussion, or devise another solution to improve the order of results here.

Reply: Please see our response to your specific comment 3.

Line 274: You mean the AR-related LWD contribution here?

Reply: Yes, we have changed it to "AR-related LWD contribution".

Line 276-284: While I do like some reflection on the meaning of the results in the Results section, this paragraph feels more appropriate for the Discussion section. Especially since you are citing Figure 7 before Figures 3-6.

Reply: In addressing this concern, we have retitled this section to specifically focus on surface downward longwave radiation.

Line 294: This might be a question for the editor, but it would be helpful if there was some label or subsection break between the LWD and LWN results (and for the other SEB components). Even just "Net surface long radiation" written in bold would help the reader follow along.

Reply: We have reorganized the manuscript. This part has been rearranged as a new subsection, titled "Section 4.1.2 Net surface longwave radiation".

Line 328: You should cite Zhang et al., (2023b) here concerning the AR impacts on marginal sea ice zones
Reply: We have included this citation.

Figure 3: Is there a particular reason why it appears AR have a negative LWN contribution in this patch over central Siberia?
Reply: We are also surprised by the negative contribution of ARs over central Siberia in Figure 3, but we do not have any thoughts as to why this occurs. We do note that the negative anomaly values in this region are quite small, ranging from -0 to -4.5 W m^{-2}.

Line 360-361: Does this mean that AR-related warm air advection is more important than the AR-related SEB influence?
Reply: There's no necessity for this to imply that AR-related warm air advection is more important than the AR-related SEB influence. Our observation simply indicates that the AR-related surface temperature response is more closely associated with the AR-related LWD effects compared to AR-related SEB impacts.

Line 394: Add space in (Fig.5b).
Reply: Corrected.

Line 408-409: Here and other places you should clarify that this warming role is confined to the SEB and does not include warm air advection related to ARs.
Reply: We explicitly mentioned that "AR-related LWN and SWN anomalies differ by less than 1 W m^{-2}, indicating little overall radiative impact of ARs at this time of the year over ice-covered surfaces…". Therefore, the assertion regarding warming is specific to the radiative perspective associated with ARs, including the longwave and shortwave radiation that is being analyzed in the current section of the manuscript. It does not encompass the sensible heat flux associated with warm air advection related to ARs.

Line 414: Play not plays
Reply: Fixed.

Line 415: Add oxford comma.
Reply: Added.

Line 441: Comma after "Unlike other Arctic regions"
Reply: Added.

Line 456: Comma after "Arctic Ocean"
Reply: Done.

Line 474: Add "the" between "highlights AR's"
Reply: Added.

Line 474-483: I was wondering why the AR contribution to turbulent heat fluxes is negative around the coastline of Greenland, but positive over the Greenland interior. Perhaps you can comment on this in this last paragraph of the section.
Reply: The anomaly values (Fig. 6b) around the coastline of Greenland are indeed very small in terms of magnitude, ranging from -11 m^{-2} to -0. These values may be influenced by the complex geographic features present in high latitudes near the coastline. Additionally, we observe distinct differences in AR-related turbulent heat flux patterns between Greenland interior and the surrounding ocean areas. The coastlines of Greenland serve as a transition zone between the land and ocean, resulting in complicated TH features. However, the specific reasons for the negative anomalies observed around the coastlines require further investigation. We have included a comment at the end of this paragraph to acknowledge the need for additional research:

"Additionally, AR-related TH features over the coastlines are different from those observed over the Greenland interior, such as the presence of weak negative anomalies and corresponding negative AR contribution to the net SEB. Further exploration is necessary to understand the underlying factors contributing to these features."

Line 506: This delay in sea-ice refreezing is also a result from Zhang et al., (2023b) and should be mentioned here.
Reply: We have added this reference.

Line 529: Comma after "central Arctic"
Reply: Added.

Line 559-561: I'm very happy to see these AR temperature anomalies quantified so extensively for the Arctic region
Reply: Thank you for this comment.

Line 657-659: This remark about the sensitivity of the AR effect on the hampering of the winter sea-ice freeze to the choice in detection method is one of the more compelling implications from this study. You make a great point about the risks of only capturing extreme AR events for studying impacts. Although not necessary, this would be a good point to include in the abstract if you can replace another sentence as the abstract is already long.
Reply: We agree that this is one of the important results in this paper, which highlights that different AR detection methods may lead to different physical results. Therefore, we have included this point in the abstract, as follows:

"… Additionally, AR-related SEB impacts strongly rely on AR detection methods, as the use of restrictive AR detection algorithms tends to emphasize extreme AR events but may minimize their total contribution to the SEB climatology due to their low occurrence frequency. Overall, this study quantifies the role of ARs on surface energy budget, contribution to our understanding of the Arctic warming and sea ice decline in ongoing Arctic amplification."

Line 675: "rely" not "relies"
Reply: Fixed.

Line 693-695: Suggest rewording this sentence. "partially offsetting the large LWD anomalies, thus resulting in moderate impacts on the LWN anomalies"
Reply: We have adjusted this sentence accordingly. Thank you!

Line 727-728: "especially during cold seasons, particularly winter". Suggest rephrasing since most people would consider winter the cold season.
Reply: We have removed "especially".

References:

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