**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) in the manuscript, noting the ratio of $t_{AR}$ to $t_{All}$ is simply the AR frequency shown in Fig. 1

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

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

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

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.

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Reply to RC1, Jeff Ridley:
We appreciate the Reviewer for the valuable criticisms and constructive comments. We are particularly grateful to the Reviewer for suggesting interesting avenues for future research. Regrettably, due to the journal length limitation, we cannot incorporate every suggestion. However, we assure the Reviewer that we have carefully considered each recommendation and integrated those feasible within the scope of our paper. Regarding the concern about the methodology of our analysis, we have provided a detailed explanation below.

***RC1, Jeff Ridley:***
*The methodology of this paper is flawed. Not only are the atmospheric rivers (AR) included in the climatologies used, and thus cannot exceed 100% of the budgets, but the local fluxes within the bounds of the AR are calculated as an anomaly without consideration of the budget for region as a whole i.e. reflecting the fractional area of the AR to the area of the region as a whole (e.g. Greenland, marginal seas etc.*
Reply: We appreciate the Reviewer's insightful comments and apologize for any lack of clarity in our methodology section. Below, we describe in detail our methodology to attempt to alleviate any confusion, although we are unsure of what the Reviewer is suggesting with the comment "*without consideration of the budget for region as a whole*". We will be happy to address further comments in a subsequent review if our explanation below is not sufficient.

The primary objective of our work is to assess the relative impacts of AR on various surface energy budget (SEB) components as shown in Figures 2, 3 and 5-7. To achieve this we calculate, on a grid point basis, the average SEB terms when ARs are present and compare this to the grid point mean for each term (panel a). The AR anomaly is the difference between the AR mean SEB term and the overall mean of that term (panel b). To quantify the contribution of the AR SEB to the overall SEB we compare the seasonal total of each SEB term during AR events to the total SEB (original panel c). Thus, original panel c illustrates the relative AR contribution to SEB components, normalized by the absolute 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.

A relative AR SEB contribution exceeding 100% indicates that the considered term has a greater AR contribution than the total SEB, implying that other SEB terms counteract to yield a small net SEB. We do not agree with the Reviewer that values greater than 100% are not possible or lack meaning. If we consider just the mean SEB the contribution of downward longwave radiation in winter will exceed the overall mean SEB because other terms in the SEB oppose the energy gain from downwelling longwave radiation, namely outgoing longwave radiation. Similarly for our AR results, values greater than 100% simply indicate that that term is contributing more energy than the total SEB and thus other terms in the SEB must oppose it. Further, very large, normalized values indicate that the overall SEB is the result of large, oppositely signed terms and that the AR term being considered is one of those large terms. This normalization facilitates consistent comparison across different SEB components, allowing readers to discern relative contributions effectively.

Additionally, following another Reviewer's suggestion, we chose to calculate the relative contribution of AR-related SEB component normalized by the mean of each respective component, shown in the Equation (2). This approach aims to estimate the accumulated AR contribution of each SEB component relative to their total values. We chose to present the results as an additional panel, now panel (c), in Figures 2-3, and 5-7. Consequently, we have reassigned the original panel (c), the AR SEB contribution normalized by the total SEB, to panel (d) to accommodate these results.

To summarize the revisions made in the manuscript, panel (a) presents the climatology of SEB component. The inclusion of panel (b), depicting composite absolute AR-related SEB term anomalies adjacent to panel (c) and panel (d), which now respectively display the relative AR contribution to the average value for each component and total net SEB. By presenting both the anomaly (panel (b)) and relative contribution (panel (c) and panel (d)), we aim to provide readers a comprehensive perspective, highlighting terms that are large in both absolute and relative senses (e.g., downward longwave radiation over sea ice-covered central Arctic Ocean), as well as those that, despite small absolute anomalies, are substantial relative to the overall surface energy budget (e.g., SEB terms over continents).

Furthermore, we have included the equations used to calculate these results of panel (c) and (d) in Section 2 (Data and Methods) for transparency and clarity in the manuscript, as follows:

*"Mathematically, the results shown in 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,* $(F_{AR} - F_{All}) * t_{AR}$*, where* $F_{AR}$ *represents the mean of any term in the SEB equation when an AR is present,* $F_{All}$ *denotes the seasonal mean of any term in the SEB equation (panel (a)), and* $t_{AR}$ *indicates the total number of 3-hourly time steps during which ARs are present.*
2. *Calculate the total energy for each component as,* $F_{All} * t_{All}$*, where* $t_{All}$ *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.*

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

*Furthermore, the results depicted in panel (d) stem from the following calculation conducted at each individual grid point within the study domain for each season.:*

1. *Calculate the total extra energy contributed by each term in the SEB equation when ARs are present as:* $(F_{AR} - F_{All}) * t_{AR}$
2. *Compute the absolute value of total SEB energy as:* $|netSEB_{All}| * t_{All}$, *where* $|netSEB_{All}|$ *represents the absolute value of seasonal mean net SEB at a given grid point.*
3. *The ratio of these two terms indicates the relative contribution of the AR anomaly for each SEB term to the total seasonal SEB, as shown in Eq (3).*

$$\frac{(F_{AR} - F_{All}) * t_{AR}}{|net\ SEB_{All}| * t_{All}} = \frac{panel\ (b) * Fig.1}{|Fig.7(a)|} \qquad (3)$$ *"*

As the reviewer comment suggests there is also a value in considering the AR impacts on a regional basis, and this is done for each SEB term in Table 1 and Table S1. These tables summarize AR occurrence frequency, climatological mean of each SEB term, composite AR anomalies for each SEB term, total AR contribution to individual SEB component, total AR contribution to absolute net SEB (AR anomaly times the time when ARs are present), and relative AR contribution to net SEB compared to the AR frequency across four regions. These results are derived from area-averaged calculations. Which involves summing the results of grid points falling within each region and weighting them using the cosine values of their corresponding latitudes. This approach ensures a representative assessment of AR impact across different regions. We have included the methods to calculate the results in Section 2.3 for clarity, as follows:

*"We summarize key features from Figures 2-3,5-7 into Table 1 and Table S1 to analyze each SEB component and the net SEB across four sub-regions: the central Arctic (including the Barents and Kara Seas), sub-polar oceans, continents, and Greenland (Fig. S1), for every season. These tables present regional averages for several metrics, including climatology (panels a), composite anomalies (panels b), AR contribution to individual SEB component (panels c), AR contribution to absolute net SEB (panels d), along with AR frequency (as shown in Fig.1). To derive these results, we perform area-averaged calculations by summing the values from grid points within each region and weighting them based on the cosine values of their corresponding latitudes. Additionally, we calculate the difference between the area-averaged AR contribution to the net SEB and the area-averaged AR frequency, representing additional AR contribution, which is presented in the last row of the tables."*

*Additionally, the authors to not make the case for AR vs extratropical cyclones. AR are not a standalone feature and thus the tropical cyclone itself is the story not the AR.*

Reply: Indeed, ARs are not a standalone feature and are always associated with a low-level jet and extratropical cyclone (according to Ralph et al., 2018: Defining "Atmospheric River": how the glossary of meteorology helped resolve a debate). We also agree with the reviewer that performing an analysis similar to what we present in this manuscript for extratropical cyclones would be a worthy future research direction. However, the research community does consider assessing the contribution of solely ARs to be a relevant research topic as indicated by the numerous references cited in the manuscript.

Previous studies have predominantly focused on the individual impacts of ARs, emphasizing their roles in enhancing moisture, downward infrared radiation, and the consequent surface energy budgets (SEB) in specific contexts, such as case studies or limited geographic and seasonal domains (e.g., Hegyi and Taylor, 2018; Mattingly et al., 2018, 2023, 2020; Zhang et al., 2023). These existing literatures have motivated us to build upon their findings and undertake a comprehensive assessment of AR impacts on the SEB. Thus, we believe that following previously published AR studies, there is an interest within the research community to simply assess the role of ARs separate of any other associated features such as extratropical cyclones.

*Some other line by line points*
*Line 46. The argument here is that atmospheric rivers are a distinct feature when they are simply associated with extra-tropical cyclones. It is the cloud associated with the cyclone warm front that is leads to the excessive LW-down. The detrainment of water vapor from the cyclone could be adding to LW-down, but the authors are not distinguishing the two characteristics here. Include further references to add to Ralph et al., 2018 to show that there is considerable mechanistic literature on the cause of 'atmospheric rivers'.*

*Eiras-Barca, J., Ramos, A. M., Pinto, J. G., Trigo, R. M., Liberato, M. L. R., and Miguez-Macho, G.: The concurrence of atmospheric rivers and explosive cyclogenesis in the North Atlantic and North Pacific basins, Earth Syst. Dynam., 9, 91–102, https://doi.org/10.5194/esd-9-91-2018, 2018.*

*Zhang, Z., Ralph, F. M., & Zheng, M. (2019). The relationship between extratropical cyclone strength and atmospheric river intensity and position. Geophysical Research Letters, 46, 1814–1823. https://doi.org/10.1029/2018GL079071*

*Dacre, H. F., P. A. Clark, O. Martinez-Alvarado, M. A. Stringer, and D. A. Lavers, 2015: How Do Atmospheric Rivers Form?. Bull. Amer. Meteor. Soc., 96, 1243–1255, https://doi.org/10.1175/BAMS-D-14-00031.1.*
Reply: We have incorporated discussions on the linkage between cyclones and ARs into the manuscript, along with citations to the recommended literature, as follows:

*"In mid-latitudes, ARs are commonly identified in the warm conveyor belts of synoptic-scale cyclones, particularly low-level jets (Ralph et al., 2004, 2006). Some literature even considers*

*ARs as part of cyclones (Bao et al., 2006; Neiman et al., 2008; Dacre et al., 2015). ARs and cyclones exhibit strong statistical and dynamic relationships (Zhang et al., 2019; Guo et al., 2020; Eiras-Barca et al., 2018). In the Arctic, poleward moisture transport is also closely linked to cyclone activity, including intensity, frequency, and duration (Villamil-Otero et al., 2018). Arctic cyclones account for over 70% of the average annual moisture transport, with their track orientation and upper-level steering flow significantly influencing poleward moisture flux (Fearon et al., 2021).”*

*If you accept that ‘atmospheric rivers’ are manifestations of subtropical cyclones, as the above papers suggest, then reference to previous Arctic budget analysis is required.*

*Villamil-Otero, G.A., Zhang, J., He, J. et al. Role of extratropical cyclones in the recently observed increase in poleward moisture transport into the Arctic Ocean. Adv. Atmos. Sci. 35, 85–94 (2018). https://doi.org/10.1007/s00376-017-7116-0*
Reply: We have incorporated this literature you provided into the manuscript (as demonstrated in the above passage).

*Line 68. In any estimation of energy budget on needs to calculate the impact of snowfall associated with the cyclones on sea ice and land energy budgets, because of the high albedo of snow in spring.*
*Webster, M.A., Parker, C., Boisvert, L. et al. The role of cyclone activity in snow accumulation on Arctic sea ice. Nat Commun 10, 5285 (2019). https://doi.org/10.1038/s41467-019-13299-8*
Reply: Indeed, our findings did uncover distinct responses to AR SEB impacts across surfaces with varying albedos, as discussed in the manuscript’s section on surface shortwave radiation associated with ARs. Specifically, we observed larger AR-related net surface shortwave radiation anomalies in lower albedo subpolar regions, contrasting with lower anomalies in the high albedo central Arctic Ocean and Greenland. However, as stated earlier, the primary objective of this study is to conduct a comprehensive examination of the impact of ARs on SEB impacts. While we acknowledge the insightful findings regarding cyclone activity and snow accumulation on Arctic sea ice from the study by Webster et al., 2019, it lies beyond the scope of our current focus. We have incorporated this discussion in the Section 6.1(original Section 4.3) and cited accordingly, shown below:

*“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."*

*Line 79. There are other mechanisms for extremes (which have a disproportionate impact) of the energy budget eg.*

*Papritz, L., S. Murto, M. Röthlisberger, R. Caballero, G. Messori, G. Svensson, and H. Wernli, 2023: The Role of Local and Remote Processes for Wintertime Surface Energy Budget Extremes over Arctic Sea Ice. J. Climate, 36, 7657–7674, https://doi.org/10.1175/JCLI-D-22-0883.1.*

*But it may be sensible not to extend the length of the submission by avoiding discussion of extremes as this is whole topic in itself.*
Reply: We have incorporated a brief discussion of the mechanisms underlying the SEB events and cited the recommended paper in the manuscript. This addition is as follows:

*"ARs are not solely responsible for the occurrence of extremely large SEB anomalies events, which also involve Arctic air mass and their local transformation (Murto et al., 2023; Papritz et al., 2023). However, gaining a comprehensive understanding of the intricate relationship between ARs and the surface energy budgets provides valuable insights into the remote mechanisms driving Arctic warming, sea ice melt, and changes in the regional climate."*

*Line 95. You should note here that ECMWF does not directly assimilate tropospheric water vapour over land or sea ice, except for radio occultation which does not have the capability to detect AR, and so there is no actual measurements*
Reply: We have included this note in the new Section 6.2-Limitations of the reanalysis data (original Section 4.4), as follows:

*"Notably, ECMWF does not directly assimilate tropospheric water vapor over land or over sea, except for radio occultation, resulting in a lack of actual measurements for detecting ARs."*

*Line 96. If you just did explosive cyclone tracking, would you get the same answer? After all, it is the clouds that matter for LW-down rather than the water vapour itself.*
Reply: We have incorporated this point into the Section 6.1 (original Section 4.3) of our manuscript. But, as we noted above, the research community does consider assessing the impact of ARs as stand-alone features to be an appropriate topic and thus we retain this focus in our manuscript.

*Line 175. Rewrite such that Figure 1 is not the subject of the sentence but supports the statements e.g. 'The seasonal frequency of AR occurrence (Fig 1) shows…*

Reply: We rewrote this sentence as "The spatial distributions of 40-year average AR occurrence frequency (Fig. 1) exhibits prominent seasonality and regional characteristics."

*Line 176. Avoid putting detail in the text which should be in the figure caption (eg. The index used and the limitation of the period 1980-2019. Otherwise, you are repeating what should have been in the methods section. Have a new sentence to introduce the topic of Table 1*

Reply: We have deleted the statement of "1980-2019" and the AR index, and the new sentence was stated above. Because the methods to calculate the Table 1 is detailed in Section 2.3, we only briefly introduce the topic of Table 1 here, as follows:

*"Table 1 summarizes the area averaged AR occurrence frequency for four sub-regions during each season".*

*Table 1. I do not understand this table. The AR are already included in the seasonal climatology so how can they contribute more than 100% of the LWD or surface energy budget? E.g. Greenland. The only way to do this properly is to total the number of J/m2/s for the time without AR and then sum over the time with AR.*

Reply: We have now included the equations used to calculate the metrics evaluating AR's contribution to the net SEB, along with a detailed description of the calculation process for the results presented in Table 1, in Section 2.3. We hope this addition will provide the Reviewer and others reading our manuscript with a clearer understanding of the methodology used for this metric.

References:

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