

“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 Wenwen 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, 5-7, and Figure 8 (for M23 AR index) 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. Additionally, we updated Table 1 and Tables S1-S3 to include regional averages of the total contribution to the respective climatology (new panel (c)).

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, $(F_{AR} - F_{All}) * t_{AR}$, 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, 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) 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:

$$\text{net SEB} = \text{LWN} + \text{SWN} + \text{SH} + \text{LH} \quad (1)$$

Where LWN, SWN, SH and LH denote the net longwave radiation, net shortwave radiation, sensible heat flux, and latent heat flux, respectively. LWN represents the difference between surface downward longwave radiation (LWD) and surface upward longwave radiation (LWU), while SWN is the difference between surface downward shortwave radiation and surface upward shortwave radiation.

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)
 - o 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
 - o Section 4.2: Surface turbulent heat fluxes (original Section 3.2.2)
 - o Section 4.3: Net Surface energy budget (original Section 3.2.3)
- Section 5: AR's surface impacts
 - o Section 5.1: AR-induced surface and air temperature response (original Section 4.1)
 - o Section 5.2: AR's crucial role in triggering Greenland Ice Sheet melt (original Section 4.2)
- Section 6: Uncertainties and limitations
 - o Section 6.1: Influence of AR detection methods on results (original Section 4.3)
 - o Section 6.2: Arctic AR and cyclone interactions in surface energy budgets (new added section)
 - o Section 6.3: 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 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 net 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) in the revised manuscript. 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.

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

Mathematically, 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: $|\text{net SEB}_{All}| * t_{All}$, where $|\text{net SEB}_{All}|$ 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).

$$\frac{(F_{AR}-F_{All}) * t_{AR}}{|\text{net SEB}_{All}| * t_{All}} = \frac{\text{panel (b)} * \text{Fig.1}}{|\text{Fig.7(a)}|} \quad (3)''$$

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 Figs. 1-8 into Table 1 and Table S1-S3 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 calculate area-averaged means by summing the area weighted (by cosine of their latitude) values from grid points within each region. 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 6.2 (Arctic AR and cyclone interactions in surface energy budgets) and cited accordingly, shown below:

“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 SEB 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, 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 6.2 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:

Bao, J. W., Michelson, S. A., Neiman, P. J., Ralph, F. M., and Wilczak, J. M.: Interpretation of enhanced integrated water vapor bands associated with extratropical cyclones: Their formation and connection to tropical moisture, *Mon Weather Rev*, 134, <https://doi.org/10.1175/MWR3123.1>, 2006.

Blanchard-Wrigglesworth, E., Webster, M., Boisvert, L., Parker, C., and Horvat, C.: Record Arctic Cyclone of January 2022: Characteristics, Impacts, and Predictability, *Journal of Geophysical Research: Atmospheres*, 127, <https://doi.org/10.1029/2022JD037161>, 2022.

Dacre, H. F., Clark, P. A., Martinez-Alvarado, O., Stringer, M. A., and Lavers, D. A.: How do atmospheric rivers form?, *Bull Am Meteorol Soc*, 96, <https://doi.org/10.1175/BAMS-D-14-00031.1>, 2015.

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 System Dynamics*, 9, <https://doi.org/10.5194/esd-9-91-2018>, 2018.

Fearon, M. G., Doyle, J. D., Ryglicki, D. R., Finocchio, P. M., and Sprenger, M.: The Role of Cyclones in Moisture Transport into the Arctic, <https://doi.org/10.1029/2020GL090353>, 2021.

Guo, Y., Shinoda, T., Guan, B., Waliser, D. E., and Chang, E. K. M.: Statistical relationship between atmospheric rivers and extratropical cyclones and anticyclones, *J Clim*, 33, <https://doi.org/10.1175/JCLI-D-19-0126.1>, 2020.

Hegyi, B. M. and Taylor, P. C.: The unprecedented 2016–2017 Arctic sea ice growth season: the crucial role of atmospheric rivers and longwave fluxes, *Geophys Res Lett*, 45, 5204–5212, 2018.

Mattingly, K. S., Mote, T. L., and Fettweis, X.: Atmospheric River Impacts on Greenland Ice Sheet Surface Mass Balance, *Journal of Geophysical Research: Atmospheres*, 123, <https://doi.org/10.1029/2018JD028714>, 2018.

Mattingly, K. S., Mote, T. L., Fettweis, X., As, D. V. A. N., Tricht, K. V. A. N., Lhermitte, S., Pettersen, C., and Fausto, R. S.: Strong summer atmospheric rivers trigger Greenland ice sheet melt through spatially varying surface energy balance and cloud regimes, *J Clim*, 33, <https://doi.org/10.1175/JCLI-D-19-0835.1>, 2020.

Mattingly, K. S., Turton, J. V., Wille, J. D., Noël, B., Fettweis, X., Rennermalm, Å. K., and Mote, T. L.: Increasing extreme melt in northeast Greenland linked to foehn winds and atmospheric rivers, *Nat Commun*, 14, <https://doi.org/10.1038/s41467-023-37434-8>, 2023.

Murto, S., Papritz, L., Messori, G., Caballero, R., Svensson, G., and Wernli, H.: Extreme Surface Energy Budget Anomalies in the High Arctic in Winter, *J Clim*, 36, <https://doi.org/10.1175/JCLI-D-22-0209.1>, 2023.

Neiman, P. J., Ralph, F. M., Wick, G. A., Lundquist, J. D., and Dettinger, M. D.: Meteorological characteristics and overland precipitation impacts of atmospheric rivers affecting the West coast of North America based on eight years of SSM/I satellite observations, *J Hydrometeorol*, 9, <https://doi.org/10.1175/2007JHM855.1>, 2008.

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

Ralph, F. M., Neiman, P. J., and Wick, G. A.: Satellite and CALJET aircraft observations of atmospheric rivers over the Eastern North Pacific Ocean during the winter of 1997/98, *Mon*

Weather Rev, 132, [https://doi.org/10.1175/1520-0493\(2004\)132<1721:SACAOO>2.0.CO;2](https://doi.org/10.1175/1520-0493(2004)132<1721:SACAOO>2.0.CO;2), 2004.

Ralph, F. M., Neiman, P. J., Wick, G. A., Gutman, S. I., Dettinger, M. D., Cayan, D. R., and White, A. B.: Flooding on California's Russian River: Role of atmospheric rivers, *Geophys Res Lett*, 33, <https://doi.org/10.1029/2006GL026689>, 2006.

Ralph, F. M., Dettinger, M. C. L. D., Cairns, M. M., Galarneau, T. J., and Eylander, J.: Defining "Atmospheric river" : How the glossary of meteorology helped resolve a debate, *Bull Am Meteorol Soc*, 99, <https://doi.org/10.1175/BAMS-D-17-0157.1>, 2018.

Villamil-Otero, G. A., Zhang, J., He, J., and Zhang, X.: Role of extratropical cyclones in the recently observed increase in poleward moisture transport into the Arctic Ocean, *Adv Atmos Sci*, 35, <https://doi.org/10.1007/s00376-017-7116-0>, 2018.

Webster, M. A., Parker, C., Boisvert, L., and Kwok, R.: The role of cyclone activity in snow accumulation on Arctic sea ice, *Nat Commun*, 10, <https://doi.org/10.1038/s41467-019-13299-8>, 2019.

Zhang, P., Chen, G., Ting, M., Ruby Leung, L., Guan, B., and Li, L.: More frequent atmospheric rivers slow the seasonal recovery of Arctic sea ice, *Nat Clim Chang*, 13, 266–273, 2023.

Zhang, Z., Ralph, F. M., and Zheng, M.: The Relationship Between Extratropical Cyclone Strength and Atmospheric River Intensity and Position, *Geophys Res Lett*, 46, <https://doi.org/10.1029/2018GL079071>, 2019.

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,

$$\text{net SEB} = \text{LWN} + \text{SWN} + \text{SH} + \text{LH} \quad (1)$$

Where LWN represents the difference between LWD and surface upward longwave radiation (LWU), while SWN is the difference between surface downward shortwave radiation and upward shortwave radiation.”

- 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 $150 \text{ kg m}^{-1} \text{ s}^{-1}$ 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 discrepancy with Mattingly et al., (2020) possibly results from the utilization of different AR detection algorithms. Their detection method imposes a strict minimum threshold of $150 \text{ kg m}^{-1} \text{ s}^{-1}$ 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 6.2 (new added section) of our manuscript as follows:

“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 AR database was sourced from 3-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 appreciate the Reviewer’s insight regarding the role of ARs on LWD. However, we are cautious about drawing this conclusion that ARs are the nearly exclusive cause of LWD over Arctic land areas during winter solely based on the results presented in the manuscript. Even in the new Fig. 2 (c) in the revised manuscript, which shows the relative contribution of AR-related LWD anomalies normalized by the mean of LWD climatology, we find that AR-induced total large positive LWD anomalies are 2-5% of their climatology over the Arctic land areas during winter. This result reflects the fact that even though the AR LWD anomalies are large (Fig. 2b) because ARs occur for a small percent of the time and even when an AR is not present there is still positive LWD means that when compared to the total seasonal accumulated LWD ARs still make a relatively small contribution. This is in contrast to the results for LWD contribution relative to the total SEB (Fig. 2d) since in this case the SEB has a small seasonal total due to

both positive and negative contributions from various fluxes unlike LWD which is always positive regardless of whether an AR is present.

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 appreciate the Reviewer's observation regarding the negative contribution over central Siberia. We are also surprised by the negative results in this area in Figure 3. While we currently do not have any thoughts as to why this occurs, we have conducted additional statistical test to assess its significance.

As per RC3's suggestion, in the revised manuscript, we evaluate the anomalies in panel (b) at the 95% confidence level using a two-tailed t-test. To account for temporal autocorrelation, we adjust the effective sample size by dividing the total number of AR time steps at each grid point by the average number of time steps during individual AR events, allowing the sample size to reflect distinct AR events at each grid point. The results, now included in Figure S6, indicate that these negative anomalies over central Siberia are not statistically significant at 95% confidence level. Additionally, we notice that these negative values in this region are quite small, ranging from -0 to -4.5 W m⁻². These findings suggest that the observed negative contribution in this area is likely not a robust signal and is statistically insignificant.

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 m² to -0. As per RC3’s suggestion, we assessed the statistical significance of AR-induced TH anomalies at the 95% confidence level using a two-tailed t-test. To account for temporal autocorrelation, we adjusted the effective sample size by reducing the AR time steps to distinct AR events at each grid point. For clarity and to avoid overwhelming detail, these results are presented in Fig. S8, which shows that the weak negative AR-induced anomalies along the Greenland coastlines are not statistically significant at the 95% level. 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. Although these weak coastal anomalies are not statistically significant (Fig. S8), 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, results of AR-related SEB impacts strongly depend on detection methods, as restrictive AR detection algorithms that emphasize extreme AR events, with large AR-related anomalies, do not necessarily indicate a large overall contribution to the SEB climatology due to the low occurrence frequency of these events.”

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 changed to “especially during non-summer seasons, particularly winter”.

References:

Mattingly, K. S., Turton, J. V., Wille, J. D., Noël, B., Fettweis, X., Rennermalm, Å. K., and Mote, T. L.: Increasing extreme melt in northeast Greenland linked to foehn winds and atmospheric rivers, *Nature Communications*, 14, 1743, <https://doi.org/10.1038/s41467-023-37434-8>, 2023.

Zhang, C., Tung, W., and Cleveland, W. S.: *Climatology and decadal changes of Arctic atmospheric rivers based on ERA5 and MERRA-2*, *Environ. Res.: Climate*, 2, 035005, <https://doi.org/10.1088/2752-5295/acdf0f>, 2023a.

Zhang, P., Chen, G., Ting, M., Ruby Leung, L., Guan, B., and Li, L.: *More frequent atmospheric rivers slow the seasonal recovery of Arctic sea ice*, *Nature Climate Change*, 13, 266–273, <https://doi.org/10.1038/s41558-023-01599-3>, 2023b.

References

Baggett, C., Lee, S., and Feldstein, S.: *An investigation of the presence of atmospheric rivers over the North Pacific during planetary-scale wave life cycles and their role in Arctic warming*, *J Atmos Sci*, 73, <https://doi.org/10.1175/JAS-D-16-0033.1>, 2016.

Blanchard-Wrigglesworth, E., Webster, M., Boisvert, L., Parker, C., and Horvat, C.: *Record Arctic Cyclone of January 2022: Characteristics, Impacts, and Predictability*, *Journal of Geophysical Research: Atmospheres*, 127, <https://doi.org/10.1029/2022JD037161>, 2022.

Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., Randles, C. A., Darmenov, A., Bosilovich, M. G., Reichle, R., Wargan, K., Coy, L., Cullather, R., Draper, C., Akella, S., Buchard, V., Conaty, A., da Silva, A. M., Gu, W., Kim, G. K., Koster, R., Lucchesi, R., Merkova, D., Nielsen, J. E., Partyka, G., Pawson, S., Putman, W., Rienecker, M., Schubert, S. D., Sienkiewicz, M., and Zhao, B.: *The modern-era retrospective analysis for research and applications, version 2 (MERRA-2)*, *J Clim*, 30, <https://doi.org/10.1175/JCLI-D-16-0758.1>, 2017.

Goldenson, N., Leung, L. R., Bitz, C. M., and Blanchard-Wrigglesworth, E.: *Influence of atmospheric rivers on mountain snowpack in the western United States*, *J Clim*, 31, <https://doi.org/10.1175/JCLI-D-18-0268.1>, 2018.

Gorodetskaya, I. V., Tsukernik, M., Claes, K., Ralph, M. F., Neff, W. D., and Van Lipzig, N. P. M.: *The role of atmospheric rivers in anomalous snow accumulation in East Antarctica*, *Geophys Res Lett*, 41, <https://doi.org/10.1002/2014GL060881>, 2014.

Guan, B., Waliser, D. E., Ralph, F. M., Fetzer, E. J., and Neiman, P. J.: *Hydrometeorological characteristics of rain-on-snow events associated with atmospheric rivers*, *Geophys Res Lett*, 43, <https://doi.org/10.1002/2016GL067978>, 2016.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., and Thépaut, J. N.: *The ERA5 global reanalysis*, *Quarterly Journal of the Royal Meteorological Society*, 146, <https://doi.org/10.1002/qj.3803>, 2020.

Ma, W., Chen, G., and Guan, B.: Poleward Shift of Atmospheric Rivers in the Southern Hemisphere in Recent Decades, *Geophys Res Lett*, 47, <https://doi.org/10.1029/2020GL089934>, 2020.

Ma, W., Chen, G., Peings, Y., and Alviz, N.: Atmospheric River Response to Arctic Sea Ice Loss in the Polar Amplification Model Intercomparison Project, *Geophys Res Lett*, 48, <https://doi.org/10.1029/2021GL094883>, 2021.

Mattingly, K. S., Mote, T. L., Fettweis, X., As, D. V. A. N., Tricht, K. V. A. N., Lhermitte, S., Pettersen, C., and Fausto, R. S.: Strong summer atmospheric rivers trigger Greenland ice sheet melt through spatially varying surface energy balance and cloud regimes, *J Clim*, 33, <https://doi.org/10.1175/JCLI-D-19-0835.1>, 2020.

Mattingly, K. S., Turton, J. V., Wille, J. D., Noël, B., Fettweis, X., Rennermalm, Å. K., and Mote, T. L.: Increasing extreme melt in northeast Greenland linked to foehn winds and atmospheric rivers, *Nat Commun*, 14, <https://doi.org/10.1038/s41467-023-37434-8>, 2023.

Murto, S., Papritz, L., Messori, G., Caballero, R., Svensson, G., and Wernli, H.: Extreme Surface Energy Budget Anomalies in the High Arctic in Winter, *J Clim*, 36, <https://doi.org/10.1175/JCLI-D-22-0209.1>, 2023.

Serreze, M. C., Barrett, A. P., Slater, A. G., Steele, M., Zhang, J., and Trenberth, K. E.: The large-scale energy budget of the Arctic, *Journal of Geophysical Research: Atmospheres*, 112, 2007.

Shields, C. A., Rutz, J. J., Leung, L. Y., Martin Ralph, F., Wehner, M., Kawzenuk, B., Lora, J. M., McClenny, E., Osborne, T., Payne, A. E., Ullrich, P., Gershunov, A., Goldenson, N., Guan, B., Qian, Y., Ramos, A. M., Sarangi, C., Sellars, S., Gorodetskaya, I., Kashinath, K., Kurlin, V., Mahoney, K., Muszynski, G., Pierce, R., Subramanian, A. C., Tome, R., Waliser, D., Walton, D., Wick, G., Wilson, A., Lavers, D., Prabhat, Collow, A., Krishnan, H., Magnusdottir, G., and Nguyen, P.: Atmospheric River Tracking Method Intercomparison Project (ARTMIP): Project goals and experimental design, *Geosci Model Dev*, 11, <https://doi.org/10.5194/gmd-11-2455-2018>, 2018.

Shields, C. A., Wille, J. D., Marquardt Collow, A. B., MacLennan, M., and Gorodetskaya, I. V.: Evaluating Uncertainty and Modes of Variability for Antarctic Atmospheric Rivers, *Geophys Res Lett*, 49, <https://doi.org/10.1029/2022GL099577>, 2022.

Tung, W., Zhang, C., and Cleveland, W. S.: Arctic Atmospheric River Labels and Climatology Based on 3-hourly ERA5 and MERRA-2 From 1980 to 2019. , Purdue University Research Repository. , 2023.

Webster, M. A., Parker, C., Boisvert, L., and Kwok, R.: The role of cyclone activity in snow accumulation on Arctic sea ice, *Nat Commun*, 10, <https://doi.org/10.1038/s41467-019-13299-8>, 2019.

Wille, J. D., Favier, V., Dufour, A., Gorodetskaya, I. V., Turner, J., Agosta, C., and Codron, F.: West Antarctic surface melt triggered by atmospheric rivers, *Nat Geosci*, 12, <https://doi.org/10.1038/s41561-019-0460-1>, 2019.

Wille, J. D., Favier, V., Gorodetskaya, I. V., Agosta, C., Kittel, C., Beeman, J. C., Jourdain, N. C., Lenaerts, J. T. M., and Codron, F.: Antarctic Atmospheric River Climatology and Precipitation Impacts, *Journal of Geophysical Research: Atmospheres*, 126, <https://doi.org/10.1029/2020JD033788>, 2021.

Wille, J. D., Alexander, S. P., Amory, C., Baiman, R., Barthélemy, L., Bergstrom, D. M., Berne, A., Binder, H., Blanchet, J., Bozkurt, D., Bracegirdle, T. J., Casado, M., Choi, T., Clem, K. R., Codron, F., Datta, R., Di Battista, S., Favier, V., Francis, D., Fraser, A. D., Fourré, E., Garreaud, R. D., Genthon, C., Gorodetskaya, I. V., González-Herrero, S., Heinrich, V. J., Hubert, G., Joos, H., Kim, S. J., King, J. C., Kittel, C., Landais, A., Lazzara, M., Leonard, G. H., Lieser, J. L., MacLennan, M., Mikolajczyk, D., Neff, P., Ollivier, I., Picard, G., Pohl, B., Ralph, F. M., Rowe, P., Schlosser, E., Shields, C. A., Smith, I. J., Sprenger, M., Trusel, L., Udy, D., Vance, T., Vignon, É., Walker, C., Wever, N., and Zou, X.: The Extraordinary March 2022 East Antarctica “Heat” Wave. Part I: Observations and Meteorological Drivers, *J Clim*, 37, <https://doi.org/10.1175/JCLI-D-23-0175.1>, 2024a.

Wille, J. D., Alexander, S. P., Amory, C., Baiman, R., Barthélemy, L., Bergstrom, D. M., Berne, A., Binder, H., Blanchet, J., Bozkurt, D., Bracegirdle, T. J., Casado, M., Choi, T., Clem, K. R., Codron, F., Datta, R., Di Battista, S., Favier, V., Francis, D., Fraser, A. D., Fourré, E., Garreaud, R. D., Genthon, C., Gorodetskaya, I. V., González-Herrero, S., Heinrich, V. J., Hubert, G., Joos, H., Kim, S. J., King, J. C., Kittel, C., Landais, A., Lazzara, M., Leonard, G. H., Lieser, J. L., MacLennan, M., Mikolajczyk, D., Neff, P., Ollivier, I., Picard, G., Pohl, B., Ralph, F. M., Rowe, P., Schlosser, E., Shields, C. A., Smith, I. J., Sprenger, M., Trusel, L., Udy, D., Vance, T., Vignon, É., Walker, C., Wever, N., and Zou, X.: The Extraordinary March 2022 East Antarctica “Heat” Wave. Part II: Impacts on the Antarctic Ice Sheet, *J Clim*, 37, <https://doi.org/10.1175/JCLI-D-23-0176.1>, 2024b.

Zhang, C., Tung, W., and Cleveland, W. S.: Climatology and decadal changes of Arctic atmospheric rivers based on ERA5 and MERRA-2, *Environmental Research: Climate*, <https://doi.org/10.1088/2752-5295/acdf0f>, 2023a.

Zhang, P., Chen, G., Ting, M., Ruby Leung, L., Guan, B., and Li, L.: More frequent atmospheric rivers slow the seasonal recovery of Arctic sea ice, *Nat Clim Chang*, 13, 266–273, 2023b.

Reply to RC3:

We appreciate the Reviewer for insightful and detailed reviews. We have made changes to the manuscripts, accordingly, as replied below.

RC3:

In this paper, authors aim to analyze the contribution of atmospheric rivers (ARs) to the seasonal surface energy budget (SEB) in the Arctic using ERA5 reanalysis data for 1980-2019. ARs are detected using the 85th percentile of IVT and components of the seasonal SEB are anomalies are assessed for times when ARs are detected. The aim of improving understanding the importance of ARs in net SEB in the Arctic is important and interesting, and the authors provide a very detailed analysis with discussion of implications and connections to previous work. Analysis regarding absolute anomalies is thorough, but I am unsure of the appropriateness of the metric used to quantify the contributions of ARs to seasonal SEB (detailed in Major Comment 1).

Reply: We appreciate the Reviewer's dedication to scrutinizing our metric and proposing new approaches to evaluate the contributions of ARs to net SEB.

Major Comments:

1. The metric used for evaluating the contribution of ARs to net SEB may not be appropriate for the conclusions drawn. It is difficult to interpret the physical meaning of the contributions when the seasonal net SEB is very small. Please see the attached file for a description of a potential solution and further reasoning. Regardless of how the authors proceed, the equation used to calculate this metric should be included, rather than only described in words to make sure it is very clear what is being shown.

Reply: We appreciate Reviewer's diligent examination of our original metric, proposing and detailed description of two new metrics we could use to evaluate the contribution of ARs to net SEB. As the Reviewer rightly pointed out, the main goal of this work is to estimate the relative contribution of different SEB components to the net SEB. To achieve this, we utilize original panel (c) in the Figures 2-3, 5-7 of the manuscript 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.

A relative 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. Very large relative contributions indicate that the climatological SEB results from a small difference in large, oppositely signed terms in the SEB and that one of those large terms has a large AR signal. We believe that this is useful information to show since this normalization facilitates consistent comparison across different SEB components, allowing readers to discern

relative contributions effectively. The inclusion of panel (b), depicting composite absolute AR-related SEB term anomalies adjacent to original panel (c), serves to remind readers to consider absolute anomaly values alongside relative contributions. Presenting both the anomaly (panel (b)) and relative contribution (original panel (c)) aims 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 are small in absolute anomalies but substantial relative to the overall surface energy budget (e.g., SEB terms over continents).

We appreciate the Reviewer's suggestion to show each AR SEB term normalized by just the mean of that term and think that this is a very useful suggestion. As such we have included this with a slight modification as an additional panel (now panel (c)) in Figures 2, 3 and 5-7 and moved the AR SEB contribution normalized by the total SEB (original panel (c)) to panel (d). We have included the equations used to calculate these results of new 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.

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

Mathematically, 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).

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

The alternative solution presented in Equation 6 would yield results equivalent to

$\frac{(LWD_{noAR} - LWD_{AR}) * t_{AR}}{SEB_{All} * t_{All}} = \frac{(LWD_{noAR} - LWD_{AR}) * t_{AR}}{SEB_{All}}$. This alternative approach also involves the net SEB as the denominator in the calculation, resulting in results greater 100% or less than -100%. After careful consideration, we decide to add the metric of each anomalous AR SEB term normalized by just the mean of that term (new panel (c)) and maintain our original metric of AR SEB contribution normalized by the total SEB (now panel (d)). The corresponding specific equations are provided in the manuscript, as stated above. Accordingly, we added the corresponding statements and discussions on the new panel (c) of Figs. 2-3, and 5-8.

2. I am unable to reproduce the “contribution to SEB” values shown in Table 1 using the description of how it was calculated in Section 2.3. Since the AR frequencies, anomalies and net SEB values are provided for each region, the contribution should be able to be calculated without any further information (based on Section 2.3). Please see the attached document for an example of this calculation not resulting in the same value seen in Table 1.

Reply: We apologize for any lack of clarity in our methodology section. For each SEB term, we summarize key metrics in Table 1 and Table S1, such as AR occurrence frequency (Fig.1), climatology (panel a), composite anomalies (panel b), AR contribution to individual SEB component (panel c), and total AR contribution to absolute net SEB (now panel d). These results listed in the tables are derived from area-averaged calculations, which involves summing the results of grid points falling within each region and weighing them using the cosine values of their corresponding latitudes. Mathematically, the weighted average of a metric f over a grid with latitude θ can be represented as:

$$\langle f \rangle = \frac{\sum_{i=1}^n w_i f_i}{\sum_{i=1}^n w_i}$$

where $\langle f \rangle$ represents the weighted average of the metric f , f_i is the value of f at grid point i , w_i is the weight associated with the grid point i , which is the cosine of the latitude at that point, ($w_i = \cos(\theta_i)$), and n is the total number of grid points within each region.

The results of the relative contribution of AR LWD to absolute net SEB listed in Table 1 are calculated as below.

1. For each grid point i within a specific region during each season, we calculate the metric of f_i using Eq. (2):

$$f_i = \frac{(F_{AR,i} - F_{All,i}) * \frac{t_{AR,i}}{t_{All,i}}}{|net SEB_{All,i}|} = \frac{panel(b)_i * Fig.1_i}{|Fig.7(a)|_i}$$

2. We then multiply the value of f_i by the weight w_i ($w_i = \cos(\theta_i)$), resulting in $f_i * \cos(\theta_i)$

3. We sum up these products of $f_i * \cos(\theta_i)$ for all the grid points (n) within each region as $\sum_{i=1}^n f_i * \cos(\theta_i)$

4. This sum is divided by the total sum of weights: $\langle f \rangle = \frac{\sum_{i=1}^n f_i * \cos(\theta_i)}{\sum_{i=1}^n \cos(\theta_i)}$

However, it is important to note that the weighted area-averaged result of the relative contribution to net SEB using all the grid points within each season is not equivalent to the result calculated directly using the weighted average results of composite anomalies ($\langle Fig. 2b \rangle$), AR frequency ($\langle Fig. 1 \rangle$) and net SEB ($\langle Fig. 7a \rangle$) listed in the table.

For example, the weighted average of composite LWD anomalies (Fig.2b) can be written as:

$$\langle Fig. 2b \rangle = \frac{\sum_{i=1}^n Fig. 2b_i * \cos(\theta_i)}{\sum_{i=1}^n \cos(\theta_i)}$$

Similarly, the weighted average of AR occurrence frequency (Fig. 1) and net SEB (Fig. 7a) are calculated as:

$$\langle Fig. 1 \rangle = \frac{\sum_{i=1}^n Fig. 1_i * \cos(\theta_i)}{\sum_{i=1}^n \cos(\theta_i)}$$

$$\langle Fig. 7a \rangle = \frac{\sum_{i=1}^n Fig. 7a_i * \cos(\theta_i)}{\sum_{i=1}^n \cos(\theta_i)}$$

The weighted average of AR LWD contribution to absolute of net SEB can be written as:

$$\langle Fig. 2d \rangle = \frac{\sum_{i=1}^n \frac{Fig. 2b_i * Fig. 1_i}{|Fig. 7a_i|} * \cos(\theta_i)}{\sum_{i=1}^n \cos(\theta_i)}$$

However, it is important to highlight that $\sum_{i=1}^n \frac{Fig. 2b_i * Fig. 1_i}{|Fig. 7a_i|} * \cos\theta_i$ is not simply equivalent to

$$\frac{(\sum_{i=1}^n Fig. 2b_i * \cos\theta_i) * (\sum_{i=1}^n Fig. 1_i * \cos\theta_i)}{\sum_{i=1}^n |Fig. 7a_i| * \cos\theta_i}$$

$$\text{Thus, } \langle Fig. 2d \rangle \neq \frac{\langle Fig. 2b \rangle * \langle Fig. 1 \rangle}{\langle Fig. 7a \rangle}$$

To illustrate, I provide a specific example of a few values to calculate the AR-related LWD contribution to the total net SEB, as mentioned by the Reviewer:

longitude (170 °E)	point i=1	point i=2	point i=3	point i=4	point i=5	point i=6	point i=7	point i=8	weighted results
Latitude (°N)	70	75	78	74	76	80	82	86	
LWD_{AR} – LWD_{All} ($W m^{-2}$)	29.8	30.1	32.3	28.7	31.7	31.5	31.7	32.4	30.7
$\frac{t_{AR}}{t_{All}}$ (%)	12.0	11.4	10.7	11.8	11.2	10.5	9.7	8.4	11.1

net SEB ($W m^{-2}$)	-8.3	-14.8	-15.8	-14.4	-15.4	-16.7	-17.8	-19.1	-14.3
$\frac{(F_{AR}-F_{All}) * \frac{t_{AR}}{t_{All}}}{ net SEB_{All} }$ (%)	43.1	23.2	21.9	23.5	23.1	19.8	17.3	14.2	25.9

Based on this example with just 8 grid points, the area-averaged result of the relative AR contribution to the net SEB is 25.9%; while directly using the weighted results will lead to the relative contribution of $30.7 * 11.1 / 14.3 = 23.8\%$. In fact, the total number of grid points for the four sub-regions range from 51844 to 85175, leading to much greater differences in the results using the two approaches mentioned before. The calculation of area-averaged results weighted by the cosine of latitudes accounts for the convergence of meridians towards the poles, ensuring a more accurate representation of the area-averaged results. Additionally, we have included the methods to calculate the results listed in the table in Section 2.3 for clarity, as follows:

“We summarize key features from Figs. 1-8 into Table 1 and Table S1-S3 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 calculate area-averaged means by summing the area weighted (by cosine of their latitude) values from grid points within each region. 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.”

3. Consider performing statistical testing to determine if the absolute anomalies during ARs are statistically different from the mean conditions (which could be shown in the b rows of Figures 2-7). Since ARs exist in a location likely for more than one timestep, there is some temporal autocorrelation which may be accounted for by randomly selecting a smaller sample of AR timesteps to compare to a randomly selected sample of non-AR timesteps. Determining the statistical significance of these anomalies may help to identify SEB components that are more important with more confidence.

Reply: Thank you for the valuable suggestion. We agree that evaluating the statistical significance of these anomalies is indeed valuable for identifying important AR-related SEB components with greater confidence. To address this, we assessed the significance of these anomalies (panel (b)) at the 95% confidence level using a two-tailed t-test. To account for temporal autocorrelation, we adjust the effective sample size by dividing the total number of AR time steps at each grid point by the average number of time steps during individual AR events, allowing the sample size to reflect distinct AR events at each grid point. However, we have concerns that labeling all the grid points that are statistically significant may potentially

overwhelm readers and make it hard to interpret the figure. To ensure clarity, we have presented these statistical significance results in Supplementary Figures S5–S14. Additionally, we used symbols in Table 1 and Table S1-S3 to indicate the proportion of significant anomalies within each region: one asterisk (*), two asterisks (**), and bolded values with two asterisks (X**) denote >50%, >90%, and >95% of grid points meeting the 95% confidence level, respectively, based on these supplementary figures. This approach aims to maintain clarity while still conveying the statistical confidence of our findings effectively. We have also included the details of the statistical test in Section 2.3 of the manuscript as outlined below, and made corresponding edits to the main text.

“To assess statistical significance, anomalies are evaluated at the 95% confidence level using a two-tailed t-test. To account for temporal autocorrelation, we adjust the effective sample size by dividing the total number of AR time steps at a grid point by the average number of time steps during individual AR events, allowing the sample size to reflect distinct AR events at each grid point. To avoid overwhelming the main figures, these significance results are displayed in Supplementary Figures. S5-S13.”

Minor Comments:

45-46: ARs typically being associated with extratropical cyclones is mentioned here, but isn't discuss it again. I think more discussion regarding the linkage between cyclones and ARs would be valuable here for context of when/how ARs occur in the Arctic.

Reply: We have addressed your comments by expanding the discussion on the relationship between ARs and cyclones, particularly focusing on their association in the Arctic region, as follows:

“Atmospheric rivers (ARs) are long and narrow filaments of enhanced moisture transport typically associated with a low-level jet and extratropical cyclone (Ralph et al., 2018). 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).”

100: *It is mentioned that times are only used during neutral or weak El Niño-Southern Oscillation. I assume it's because of IVT anomalies associated with strong ENSO events, but it is worth briefly stating in the text for clarity.*

Reply: We only preserved the dates during neutral or weak ENSO events to establish a standard climate threshold for testing ARs. For instance, in the event of updating 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.”

123-125: *Is it necessary to give multiple names for these first 3 ERA5 variables?*

Reply: The term “surface thermal radiation downward”, “surface net thermal radiation”, and “surface net solar radiation” are the names provided in the original ERA5 source data. However, in the literature, the commonly used terms are “surface downward longwave radiation”, “surface net longwave radiation”, and “surface net shortwave radiation”. We choose to use these commonly used names while also mentioning their origins in ERA5 for the benefit of readers who wish to replicate the results.

147-149: *This sentence uses both “three-hourly” and “3-hourly” referring to the data – I suggest picking one to remain consistent.*

Reply: We have selected “3-hourly” and replaced all instances of “three-hourly” to “3-hourly” throughout the manuscript.

287-289: *What is meant by “ARs make their most significant relative contribution to the average net SEB in spring, accounting for at least 45% of the net SEB, surpassing the corresponding AR frequency by more than 34%”? I don't think subtracting the frequency from the contribution has a physical meaning since they are percentages of different things.*

Reply: The difference between the area-averaged AR contribution to the net SEB and the area-averaged AR frequency, indicates additional AR contribution. The difference signifies the extent to which ARs contribute to the net SEB beyond their occurrence frequency.

358: *I suggest starting a new paragraph at “The results over the central Arctic” as this is a long paragraph, and a new topic is being introduced here.*

Reply: We have started a new paragraph for this topic.

Section 3 is titled “Analysis and Results” and Section 4 “Discussion”, but Section 3 includes a lot of discussion (i.e., discussing potential impacts of the anomalies, comparing to previous work) and Section 4 still discusses some results (particularly temperature). A potential solution for this would be to rename Section 3 to focus on SEB and Section 4 to focus on impacts, and perhaps create another section for limitations/uncertainties (for 4.3 and 4.4)

Reply: We have taken this suggestion into account and restructured the manuscript, accordingly, as stated at the beginning. Therefore, the sections have been retitled as per the suggestion.

References

- Bao, J. W., Michelson, S. A., Neiman, P. J., Ralph, F. M., and Wilczak, J. M.: Interpretation of enhanced integrated water vapor bands associated with extratropical cyclones: Their formation and connection to tropical moisture, *Mon Weather Rev*, 134, <https://doi.org/10.1175/MWR3123.1>, 2006.
- Dacre, H. F., Clark, P. A., Martinez-Alvarado, O., Stringer, M. A., and Lavers, D. A.: How do atmospheric rivers form?, *Bull Am Meteorol Soc*, 96, <https://doi.org/10.1175/BAMS-D-14-00031.1>, 2015.
- 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 System Dynamics*, 9, <https://doi.org/10.5194/esd-9-91-2018>, 2018.
- Fearon, M. G., Doyle, J. D., Ryglicki, D. R., Finocchio, P. M., and Sprenger, M.: The Role of Cyclones in Moisture Transport into the Arctic, <https://doi.org/10.1029/2020GL090353>, 2021.
- Guo, Y., Shinoda, T., Guan, B., Waliser, D. E., and Chang, E. K. M.: Statistical relationship between atmospheric rivers and extratropical cyclones and anticyclones, *J Clim*, 33, <https://doi.org/10.1175/JCLI-D-19-0126.1>, 2020.
- Neiman, P. J., Ralph, F. M., Wick, G. A., Lundquist, J. D., and Dettinger, M. D.: Meteorological characteristics and overland precipitation impacts of atmospheric rivers affecting the West coast of North America based on eight years of SSM/I satellite observations, *J Hydrometeorol*, 9, <https://doi.org/10.1175/2007JHM855.1>, 2008.
- Ralph, F. M., Neiman, P. J., and Wick, G. A.: Satellite and CALJET aircraft observations of atmospheric rivers over the Eastern North Pacific Ocean during the winter of 1997/98, *Mon Weather Rev*, 132, [https://doi.org/10.1175/1520-0493\(2004\)132<1721:SACAOO>2.0.CO;2](https://doi.org/10.1175/1520-0493(2004)132<1721:SACAOO>2.0.CO;2), 2004.
- Ralph, F. M., Neiman, P. J., Wick, G. A., Gutman, S. I., Dettinger, M. D., Cayan, D. R., and White, A. B.: Flooding on California’s Russian River: Role of atmospheric rivers, *Geophys Res Lett*, 33, <https://doi.org/10.1029/2006GL026689>, 2006.

Ralph, F. M., Dettinger, M. C. L. D., Cairns, M. M., Galarneau, T. J., and Eylander, J.: Defining “Atmospheric river” : How the glossary of meteorology helped resolve a debate, *Bull Am Meteorol Soc*, 99, <https://doi.org/10.1175/BAMS-D-17-0157.1>, 2018.

Villamil-Otero, G. A., Zhang, J., He, J., and Zhang, X.: Role of extratropical cyclones in the recently observed increase in poleward moisture transport into the Arctic Ocean, *Adv Atmos Sci*, 35, <https://doi.org/10.1007/s00376-017-7116-0>, 2018.

Zhang, Z., Ralph, F. M., and Zheng, M.: The Relationship Between Extratropical Cyclone Strength and Atmospheric River Intensity and Position, *Geophys Res Lett*, 46, <https://doi.org/10.1029/2018GL079071>, 2019.