Responses to Reviewer Comments

Please see below responses to the comments of the reviewers for our paper egusphere-2025-3482 "Seasonal Characteristics and Trends in Precipitation Partitioning in the Arctic" submitted to "The Cryosphere". We thank the reviewers for their time and effort. As noted in an email exchange, when going over the figures we did find a coding bug, which influenced the scaling on some of the figures. Corrections to figures have not changed any of our interpretations.

Anonymous Reviewer #1

Summary:

This study explores patterns in precipitation partitioning (rainfall vs. snowfall) in the Arctic using ERA5 for 1979-2023. The authors provide a detailed breakdown of seasonal rainfall/snowfall occurrence, illustrating the more pronounced shift between winter snowfall and summer rainfall over land and the relatively high occurrence of snowfall over the central Arctic year-round. Temporal changes over the period are also explored, highlighting the shift towards higher liquid precipitation occurrence as temperatures have risen in recent decades.

The manuscript is very well written and provides a novel Arctic-wide analysis of precipitation and its partitioning between rain and snow, exploring both spatial and temporal patterns. The figures and discussion throughout are largely clear and fit well within the scope of the journal. I have several comments below that are primarily for clarification and increased discussion on a few points, particularly in the comparison of ERA5 to the other datasets included in the analysis.

We appreciate the reviewer's positive view of this manuscript and the very valuable comments and suggestions. We understand that reviews take much time and effort.

General comments:

For the ASOS data, where any missing data allowance thresholds applied? Figure 2 shows years of complete data – does this mean 100% coverage for the year, or is a threshold used to allow for years to be included if a small amount of data is missing?

We have modified the figure captions for Figures 1 and 2, as well as the text, to better explain what these two figures are showing. Figure 1 shows the number of years with complete data coverage with respect to precipitation type. We define a year with "complete data coverage" as one in which all twelve months

have at least one hour with precipitation type codes of any phase reported. Figure 2 shows the number of hours in each month with liquid precipitation reported for stations in the database.

In Section 2.1, “liquid precipitation” and “rainfall” are discussed as separate variables – if I understand correctly, the rainfall is directly from ERA5 and liquid precipitation is calculated separately (as total precipitation minus snowfall), but this isn’t very clear in the text. Additionally, in the analysis they seem to be used interchangeably. For example, Figure 3 shows “Average rainfall/total precipitation ratio” in the bottom right panel, but the caption says “liquid/total precipitation ratio” and then Figure 6 uses the terminology “rainfall-to-total precipitation ratio”. The language should be made more precise so that it is clear when only rainfall is being analysed versus rainfall+mixed phase, or the definitions need to be made clearer if I have misunderstood the “liquid precipitation” defined in Section 2.1.

This should have been made clearer that the analysis for liquid precipitation is just total precipitation - snowfall, and not a separate rainfall analysis. This has been clarified in the text.

Sections 3.3 and 3.4 are titled "Comparisons with ICOADS Records" and "Comparisons with ASOS Records", respectively, but there is little comparison of these datasets to the ERA5 results presented earlier. I think these sections would benefit from more direct comparisons to the ERA5 data (e.g., do the spatial patterns align? Do some variables (total precipitation, rainfall fraction, etc) see better/worse agreement than others?) to better illustrate agreement and disagreement between the different sources. In the conclusions, it is stated that ERA5 agrees well with these two independent datasets, but direct comparisons (e.g., a figure overlaying the observations over ERA5) or specific discussion of these comparisons are needed to support this statement.

What we can say with confidence is that there is general agreement between the ERA5 and the AROSS and ASOS records. But detailed qualitative comparisons are challenged by the different time periods covered by the data sets, that we (unfortunately) do not have the digital records from the ICOADS study and that the AROSS records provide no coverage over the Arctic Ocean (and only a few over Russia). One could do a new analysis of the ICOADS data using up-to-date records, but this is beyond the scope of the present study. Reviewer #2 also made us aware of a recent study that addresses precipitation phase from CloudSat data, but that study was only for four years and coverage does not extend poleward of about 80^{o}N. We now discuss these limitations in the Synthesis and Conclusions section. We have also added some text to further discuss the comparisons between data sets. Note that since we have ICOADS

maps for each month (not just January and July), we were able to better place the ICOADS results in context with ERA5.

Please add a Data Availability Statement.

This has been added.

Specific comments:
Line 23: Suggest either removing “which has numerous causes” or listing some examples of causes – this statement lacks specificity but also isn’t completely necessary in the sentence.

It has been removed.

Line 45: suggest saying “rainfall versus snowfall” or “liquid versus solid” instead of “liquid versus snowfall”
for consistency.

Done

Line 59: Please clarify which variables are directly from ERA5 and what is calculated separately (see General Comment 2)

This has been clarified.

Line 64: “ERA-5” should be “ERA5” for consistency

Corrected

Lines 79-81: What is the relevance of stating that most precipitation over the central Arctic Ocean comes at precipitation rates of < 1 mm/day? Suggest adding a statement of why this matters (e.g., difficulty observing or spurious drizzle in the reanalyses), or this sentence can be removed

The sentence has been amended: All reanalyses are prone to a problem of spurious drizzle over the Arctic Ocean, with daily amounts less than 1 mm/day.

Figure 2: I assume that the colourbar indicates the fraction of observations per month, but it is labelled "observations per month", please clarify

The colourbar label has been altered to "Fraction of observations per month"

Lines 124-125: Suggest including a reference for the statement about extratropical cyclones, since that isn't analyzed/shown in this study

This topic has a long history, so we think it appropriate to cite a fairly early reference: Serreze, M.C., Box, J.E., Barry, R.G. and Walsh, J.E. 1993. Characteristics of Arctic synoptic activity, 1952-1989. *Meteorology and Atmospheric Physics*, 1, 147-164.

Lines 142-144: References should be included for the discussion of the 2012 and 2019 warm air intrusions/Greenland melt events. Here are some potential references to consider:
Hermann, M., Papritz, L., & Wernli, H. (2020). A Lagrangian analysis of the dynamical and thermodynamic drivers of large-scale Greenland melt events during 1979–2017. Weather and Climate Dynamics, 1(2), 497–518. https://doi.org/10.5194/wcd-1-497-2020
Tedesco, M., & Fettweis, X. (2020). Unprecedented atmospheric conditions (1948–2019) drive the 2019 exceptional melting season over the Greenland ice sheet. The Cryosphere, 14(4), 1209–1223. https://doi.org/10.5194/tc-14-1209-2020

Thank you for these references, they are now cited and added to the references section.

Figure 3: what do the contours on the figures represent? Please clarify what the contours show on this figure and all following figures as I could not find definitions for the contours throughout.

The black contours are every 200 mm and are showing the same data at the colored shading. These were added for ease of viewing. This has been added to the figure captions.

Line 158: "Wm-2" the exponent should be superscript

Done

Figure 4: the labels on each panel should specify the season instead of just “January” and “July”, unless this is actually only the individual months being shown.

These figures were indeed just the months. This has been clarified in the caption as well as verbiage added to the text explaining this choice.

Lines 179-180: Please provide a little more insight into why the summer latent heat flux is at the maximum values in Figure 5 across all land areas other than Greenland? It is stated that this helps support the higher summer precipitation amounts over land, but no explanation is explored.

Our writing was confusing. We amended the section as follows: “Summer precipitation is at its seasonal maximum over most land areas, reflecting the seasonal maximum atmospheric moisture due to higher temperatures, surface heating fostering strong latent heat fluxes and in some areas convective activity, along with increased cyclone activity. The summer precipitation peak over the central Arctic Ocean…..”

Line 200: Suggest including “of Norway” after “west coast” for clarity. Also, are the observations referred to here the ones being analyzed in this study? Otherwise, suggest including a reference.

The sentence has been amended. As to the question, the answer is yes.

Line 209: missing a period at the end of this sentence (after “ERA5”).

Fixed.

Line 210-214: What is meant by “early autumn” here? More discussion/clarification is needed for this paragraph as I do not understand what is meant by “precipitation phase shifts over the central Arctic Ocean are more prominent” as much larger changes are seen in other regions over the course of the year (e.g., Baffin Bay). Please clarify.

Early autumn is September. This has been added to the text. We also altered the text as follows: “By contrast, the seasonal shift from rainfall to snowfall is prominent over the ice-covered central Arctic Ocean where autumn temperatures sharply drop.”

Line 218: Is this referring to January and July (as in only those months) or winter/summer (as in Figure 4)?

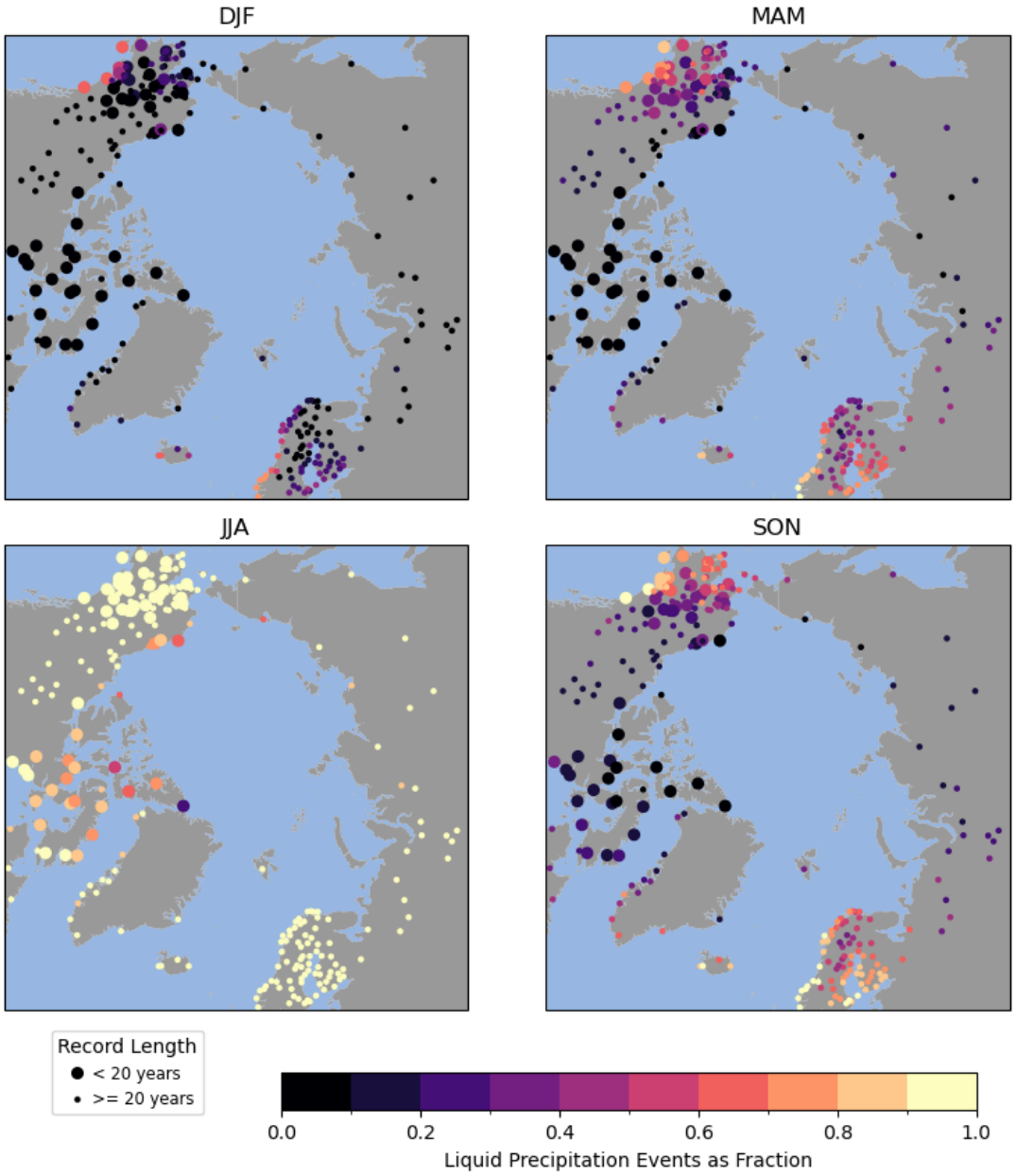
This is referring to the seasons, which has been clarified in the text.

Figure 7/8 captions: “based on COADS data” – should this be ICOADS?

Corrected

Figure 9: I think having the varied sizes indicating station length is helpful to highlight stations with longer records! Would it be possible to make the circle sizes proportional to record length/years of data (instead of just 2 sizes), or would that make the plot difficult to interpret?

We decided to go with a version with fixed circles, as it looks cleaner. See below.



Lines 260-265: This is interesting discussion of the rain-on-snow events – can the correspondence between rain events and occurrence of snow on the ground be included as a supplementary figure? I think it would be valuable to readers looking to connect this work more directly to rain-on-snow, but isn't necessarily required in the paper

Rain on snow is certainly a key topic, and we are looking at it in a focused paper now in the works using the ASOS database. We would rather go this route rather than dilute the present effort which is focused on precipitation partitioning.

Lines 305-307: Figure 11 is very interesting and is an effective way to illustrate the changes in liquid precipitation that may not be captured in a linear trend! I suggest adding a bit more discussion in this paragraph discussing Figure 11, perhaps highlighting the differences shown here that aren't captured in the linear trend and why they differ.

We added the following: "While the spatial pattern of trends in liquid precipitation (Figure 10) is similar to the pattern of decadal differences shown in Figure 11, the latter suggests more recent increases in liquid precipitation and decadal variability over land areas not captured in linear trends."

Anonymous Reviewer #2

This article presents an analysis of the climatology and trends of Arctic precipitation partitioning from the ERA5 reanalysis product, with comparisons to a database of station-based terrestrial observations and historical interpolated observations over the Arctic Ocean. Regional climatological characteristics of precipitation are identified, with increased precipitation in the Atlantic sector consistent with the north Atlantic storm track. Precipitation is increasing overall, with increased summer liquid precipitation in all regions, and increased liquid precipitation in all regions in the Atlantic sector.
This article is well-written, and the scientific reasoning is generally sound, with just a few points requiring some clarification as per my comments below. The findings are well-motivated, with well-reasoned connections to physical and climatological explanations. The results are, to my knowledge, scientifically original, and fit well within the scope of the journal. The figures are generally clear and illustrative. I just have a few points where I think the article could benefit from some clarification and/or expansion, which I will describe in my comments below.

We appreciate this positive review of our paper, and the time and effort of the reviewer.

General comments:
This may be a matter of phrasing, but some of the points mentioned in the conclusion do not, in my view, follow from the analysis. ERA5 is stated as capturing trends in precipitation phase consistently with observations (cf lines 330-331), but in this work, I only see a comparison to climatological averages for both the AROSS data and the COADS data, with no observational comparison of trends or decadal differences. As such, I think that either the conclusion needs some rephasing for clarity, or some additional analysis needs to be conducted where observational trends or decadal differences are compared

to the reanalysis data. (E.g. since some of the AROSS time series span both the 1979-1989 and 2013-2023 decades, a decadal comparison could potentially be carried out and compared with Fig 11.) Furthermore, I would urge caution on reporting consistency with observations over the Arctic Ocean given the inconsistency in time periods examined (1950-1995 for COADS vs 1979-2023 for ERA5). I am very sympathetic to the challenges involved in validating reanalysis precipitation products over polar ocean regions where there is a general absence of station or observational campaign data, and I agree that reanalysis products are a good tool for assessing variability. However, I think care is necessary to not overstate the representativeness of reanalysis products in regions where there is little contemporary validation data. One option the authors may potentially consider is to add some brief discussion of how the results compare with results from contemporary examinations of precipitation phase, e.g. from remote sensing observations (such as Edel et al., 2020), similarly how results are discussed in comparison with QuikSCAT at line 260. Although these observational data products likewise have caveats, they can provide at least some additional contemporary observational basis for comparison; the results from Edel et al. (2020) also do appear generally consistent with the authors' results in this manuscript.

The above points are well taken, and we have expanded the Synthesis and Discussion section to address them. See our response to the last comment of the reviewer.

The article is missing a data availability statement, and some figures are directly reproduced from other publications without clear attribution of the direct source (I expand on this in my line-by-line comments).

This has been added.

Some of the figure captions could benefit from more description; in general, I would appreciate if the authors would check that they specified which dataset is plotted in each figure (e.g. Figures 5 and 6 do not mention that the data shown is from ERA5). Additional description of how some datasets were averaged for plotting would also be helpful for reproducibility.

We were indeed lazy with our figure captions, and have added more information as appropriate.

Finally, I think some discussion in the article could be expanded particularly with regards to caveats of some of the data products. For example, ERA5 has been found to have a warm bias over Arctic sea ice (Tian et al., 2024; Graham et al., 2019) and I am curious as to how this could introduce biases to the results. I would appreciate if the authors could comment on this in the text.

We now note the warm bias in discussion of ERA5 and return to the issue in the expanded Synthesis and Discussion section. See our response to the reviewers' final comment.

Line by line comments:
12: "extreme south": how is this defined (e.g. south of which latitude)? This phrasing is vague to me.

Changed to "southern limits"

34: The year should be 1996 for the Clark et al. reference, I assume

Correct. 1996.

52: I think it would be worth mentioning here (or later in the article when results are being discussed) that precipitation is generally not assimilated into ERA5 (except over the continental United States region over a limited time period, if my recollection of the documentation is correct).

Done.

61: Please also mention that latent heat fluxes are taken from ERA5 (the ones in Figure 5)

Done. Good catch.

64: Unnecessary hyphen in ERA5

Corrected.

Paragraph at line 71: here or later in the text, it may be worth mentioning the ERA5 warm bias over Arctic sea ice (as discussed in e.g. Tian et al., 2024, or Graham et al. 2019) which may impact the results of this study

We were not aware of this. We now cite the Tian et al. (2024) study. From reading that paper, the bias seems to be over sea ice.

79-81: Re: this drizzle effect, some studies apply a threshold to exclude these precipitation values, arguing that they are physically unlikely. Is there a reason why you opted not to apply this threshold?

No, there is no reason. We used the precipitation data as is, but note the drizzle issue with reference to the study of Barrett et al. (2020), who show (from comparisons with data from the North Pole drifting stations) that a 1mm cutoff used in many past studies misses a significant amount of precipitation.

94: Why is the data resampled to hourly frequency rather than 6-hourly frequency (for consistency with the reanalysis frequency)? Alternatively, why was hourly reanalysis data not used?

Figure 9 showed analysis that had been previously done before the analysis for the current manuscript. While the temporal resolution differs, the intention is to show that the general patterns of the seasonal distribution of liquid precipitation compares well between the observations and ERA5.

Figure 2: This figure is illustrative, but somewhat illegible due to size; consider scaling up the figure size so it spans the full page width. Please also specify in the caption that each horizontal band corresponds to a different station. Also, how are the bands in the plot organized within each country? (E.g. are the lower bands within Canada more northern regions?)

Figure 2 has been scaled-up to span a full page width.

114: How coarse is the grid onto which data were interpolated? Please specify if possible

This does not appear to be clearly specified in the NSIDC special report where the original figures appear. Apologies.

117: Perhaps consider mentioning that this old dataset is being used due to a general lack of long-term widespread in-situ measurements of precipitation type in the region

Good idea; We now start this section as: “Direct measurements of precipitation are particularly sparse over the Arctic Ocean. However, Serreze and Barry (2014) provide two figures of precipitation phase and intensity over the Arctic Ocean (January and July) based on present weather codes included within the Integrated Comprehensive Ocean-Atmosphere Data Set (ICOADS)”.

122: What is meant by “annual means (totals)”? I assume this refers to annual cumulative precipitation, rather than annual averages of daily-mean precipitation or similar, but please clarify.

They are “mean annual totals.” The text has been amended.

144: Could you clarify what you mean by temperatures not being high enough for rainfall to occur? Was it a case of surface temperatures being warm enough for melt but precipitation falling as frozen snow, or a lack of coincident timing of precipitation during periods of warm intrusion (given that this is a low-precipitation region in general).

The text has been amended: ..”temperatures over its northern portion are still generally cold enough in the lower troposphere (according to ERA5) for most precipitation to fall as snow.”

158: Superscript needed for Wm-2

Done.

Figure 5: Please specify how these fluxes were averaged (is this a monthly average of daily averages or something else?) Also please specify that these are from ERA5.

The caption has been updated to state the data source. The fluxes are monthly averages of the hourly data.

199-200: The point is well-made here, but please cite a reference for the statement connecting this infrequent snowfall to the North Atlantic Drift Current.

We now state: “This is consistent with observations that even Bergen, Norway, lying at about 60°N along the west coast of Norway, seldom sees snowfall in winter, due to the North Atlantic Drift Current, which results in high air temperature relative to latitude.”

Fig 7 and 8: I was confused because these figures were cited as being reproduced from Clark et al. 1996, but I did not find them in that publication, although they do use data from that publication. Please additionally clarify the specific source from where the figures were reproduced. I’ve identified that these specific versions of the figures themselves are reproduced from “The Arctic Climate System” by Serrze &

Barry (https://doi.org/10.1017/CBO9781139583817), having been reproduced there from an NSIDC special report (https://nsidc.org/sites/default/files/nsidc_special_report_4.pdf, pg. 93 & 99) which therein cites Clark et al. 1996. I am aware that one of the coauthors of this preprint is a coauthor of these publications, so I assume permissions are not an issue, but in the interest of data availability, I think more specific citations would be beneficial.

Great catch. The second author of the present paper, who is responsible for this error, is humbled. Yes, the Clark et al. paper uses the data set, but the figures themselves, which are in "The Arctic Climate System", were taken from the NSIDC special report. This is now clarified in the text, and we cite the special report as the original source.

221-222: How is moderate-to-heavy precipitation defined (in terms of precipitation amount) for this dataset? Given how a large fraction of reanalysis precipitation is light precipitation (as mentioned above), this comparison may warrant some justification.

Our understanding is that it is not specified. It's up to the manual observer as to what qualifies as moderate or heavy precipitation, hence it is somewhat subjective. We presume that guidelines are available somewhere in a WMO report, but we have been unable to locate this. This is of course a drawback of the present weather code data. We now mention this in the text: "Precipitation frequency is the percent of all reports for which any precipitation was observed. Frequency is also given for reports of "medium" and "heavy" precipitation, the designation being up to the observer and hence somewhat subjective."

288: Missing word, did you mean "that increased Arctic precipitation" or similar?

Corrected.

294: "is in part convective precipitation": this is somewhat vague, please be more specific. Is the increase in convective precipitation apparent when examining the ERA5 convective and large-scale precipitation products? I agree with the statement about convective precipitation moving into higher latitudes, but I would like to see this substantiated more. Perhaps consider including a supplementary figure with the convective precipitation, since this is mentioned a few times in the text.

As part of the precipitation analyses performed by co-author Serreze for the 2025 NOAA Arctic Report Card, an analysis was performed of linear trends of the ratio of convective to total precipitation by season, using the full-length ERA record (1950-2024). While it was recommended to not include the figure given the concern over the highly parameterized nature of convective precipitation, the finding is nevertheless worth mentioning here, but we do not see the need for a new figure:
"Digging into this further, the increase in winter precipitation as depicted by ERA5 in the Barents and Kara Seas appears to be in part convective precipitation. Analysis of the full-length ERA5 record indicates, based on linear trends, statistically significant 4-5% increases since 1950 in the ratio between convective and total precipitation in this area (not shown), with smaller increases in autumn and spring".

299: Local increases poleward of Svalbard: are these likely also associated with the convective precipitation moving to higher latitudes? If so perhaps mention that.

It is. The text has been amended.

Figure 11: I found this figure quite illustrative, could you include alongside this some analogous plots for the snowfall and total precipitation, following the format of Figure 10? (Since, as mentioned in the text, linear trends can be misleading.)

Great suggestion. The new Figure 11 now shows the decadal differences in total precipitation, snowfall and liquid precipitation. Text has been added to highlight the results - positive differences in total precipitation are largest in the Atlantic sector, attended by the largest negative differences in snowfall and the largest positive differences in liquid precipitation.

Figure 12: The grey over the continents makes it appear as if the entire ocean still has a weak trend; please either make grey the no-trend value for land and ocean, or make the no-trend continent values white as well.

These have been recreated to take out the grey.

330-331: I would suggest some caution in the phrasing of this statement. I agree that ERA5 is broadly consistent with observations where observations exist, and that this study has demonstrated consistency of ERA5 with independent datasets in the climatological sense. That said, the comparison is less robust over ocean/sea-ice regions since the observation-derived data cover a different time period than the reanalysis

data. As such, I think caution needs to be taken with stating that ERA5 is representative in that region, particularly since this work did not validate with time-coincident observations in the region. Furthermore, although this study did examine decadal differences and trends in ERA5, I did not see an examination of decadal differences or trends in this article for the AROSS database or for the other observational data to provide an observational comparison, so I do not think the claim can be made here that ERA5 captures precipitation trends consistently with observations, without additional analysis in which the trends (or at least decadal differences) in observed precipitation phase are compared to ERA5. Please rephrase these lines to clarify, or provide some additional analysis to support this statement.

Excellent points. We expanded the Synthesis and conclusions section to include the following:
"To address this question, it was first necessary to ask: Is ERA5 up to the task of providing sufficiently reliable estimates of precipitation and its phase? Prior validation studies, as well as the work presented here based on the ASOS and ICOADS climatologies, argue that the answer is a qualified yes. While uncertainty remains, ERA5 has demonstrated consistency with the ICOADS records and the ASOS records (the AROSS database) in capturing precipitation phase. The study by Edel et al. (2020), based on CloudSat data, provides further supporting evidence, at least in a qualitative sense, showing that on an annual basis, the frequency of solid precipitation is greater than 70% over the Arctic Ocean, 95% over Greenland, with mixed precipitation (50% solid) over the North Atlantic. However, this study was limited to a four year period (January 2007 to December 2010) and CloudSat provides no coverage poleward of about 80^{o}N.

This general agreement between data sources is important given that the Arctic's surface station network is sparse and insufficient for capturing spatial precipitation patterns (Thoman et al., 2023). Therefore, reanalysis data remain the best tool for evaluating large-scale precipitation patterns (including phase) and trends across the region. However, this must be viewed with the caveats that the available observations for validation either cover a different time period than the reanalyses or do not provide full spatial coverage. Time coincident data is wanted. While further analysis of the AROSS database is warranted, this data set unfortunately provides no coverage over the Arctic Ocean for which to assess either seasonal patterns or trends in precipitation partitioning. Similarly, while for the Arctic as a whole, both the gauge network and ERA5 show that precipitation in the Arctic is increasing, the gauge network is insufficient to make meaningful comparisons with the spatial patterns of ERA5 trends. Yet another issue to be aware of is the known warm bias in surface air temperatures over the sea ice cover in ERA5 (Tian et al., 2024), which, especially if affecting a deeper part of the atmosphere, could influence precipitation phase".

References:

Edel, L., Claud, C., Genthon, C., Palerme, C., Wood, N., L'Ecuyer, T., & Bromwich, D. (2020). Arctic Snowfall from CloudSat Observations and Reanalyses. Journal of Climate, 33(6), 2093–2109. https://doi.org/10.1175/jcli-d-19-0105.1

Graham, R. M., Cohen, L., Ritzhaupt, N., Segger, B., Graversen, R. G., Rinke, A., Walden, V. P., Granskog, M. A., & Hudson, S. R. (2019). Evaluation of Six Atmospheric Reanalyses over Arctic Sea Ice from Winter to Early Summer. Journal of Climate, 32(14), 4121–4143. https://doi.org/10.1175/jcli-d-18-0643.1

Serreze, M. C., & Barry, R. G. (2014). The Arctic Climate System. Cambridge University Press. https://doi.org/10.1017/cbo9781139583817

Tian, T., Yang, S., Høyer, J. L., Nielsen-Englyst, P., & Singha, S. (2024). Cooler Arctic surface temperatures simulated by climate models are closer to satellite-based data than the ERA5 reanalysis. Communications Earth & Environment, 5(1). https://doi.org/10.1038/s43247-024-01276-z

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