Final Author’s response by Lilian Schuster et al.

In the following, you can find the final response to Reviewer #1 (Sect. 1), the final response to Reviewer #2 (Sect. 2) and the changes in the revised manuscript (Sect. 3).

In the responses to the reviewers, we present a detailed point by point response (the reviewer’s comments are given in italics, our answer in normal font). When appropriate, we indicate the text that has been added to the revised manuscript as a separate paragraph in quotation marks and the page and line numbering corresponds to the revised manuscript.

1 Final response to Reviewer #1

We would like to thank the anonymous referee for taking the time to read our manuscript and provide constructive comments which helped us to improve our manuscript. We hope that our response is clarifying and we remain available for further questions.

General comments:

RC (summary): This manuscript uses the ERA-interim reanalysis in combination with a Lagrangian diagnostic to investigate precipitation and moisture sources for a small arid region in northeast Greenland during the years 1979 to 2017. The results show a strong seasonal cycle in moisture sources, with dominant contributions from the North Atlantic and Arctic Ocean in winter, and from local sources and Eurasia in summer. In contrast to the temperature and sea ice trends, the authors found no significant temporal trends in precipitation or moisture sources, apart from a slight positive trend for precipitation in autumn. They showed that the North Atlantic Oscillation (NAO) can explain some of the variability: NAO+ leads to more and more variable precipitation in the study region and more moisture transport from the Norwegian Sea than NAO-. The manuscript helps to place paleoclimate records from northeast Greenland into the context of present-day climate (change). It is well written and has a clear structure, and the figures are very nice and easy to understand. I only have two general comments(see below), and recommend that the paper be published after minor revisions.

AR: Thank you for the positive assessment of our study.

RC: I assume that the diagnosed moisture sources would look different if different thresholds and/or time steps were chosen. For example, a shorter time step would probably lead to more local moisture sources, because more moisture losses would discount earlier moisture uptakes. The minimum moisture increase that counts as a moisture uptake (what is it?) might be important as well. It would be good to include some sensitivity tests (e.g. in the supplement) that quantify this, and how it affects the conclusions of the manuscript.

AR: We agree that both the input data we are using (ERA-Interim) as well as the methodology (adapted from Sodemann et al., 2008a) are subject to uncertainties. ERA-Interim
data is available at $\Delta t=6h$ in the analysis fields and at the different model levels (shorter time steps of $\Delta t=3h$ are only used for forecast surface parameters such as precipitation). Shortening the timestep with ERA-Interim would therefore imply interpolating between the 6H timesteps, which would introduce other uncertainties and with unclear added value. Similar studies (e.g., Langhamer et al., 2018; Fremme and Sodemann, 2019) also used at 6H timestep, and the method of Sodemann et al. (2008a) was developed and tested on a 6H step.

However, we fully agree that a smaller time step and grid resolution could give a finer picture of moisture uptake, because the applied moisture source diagnostic needs the assumption of either evaporation or precipitation dominating in one time step. It should now be possible to realise such sensitivity studies using the newer ERA5 dataset (not yet available when we started our study) albeit with considerably increased data management and computational requirements. Such analyses would be very demanding at this stage, and we argue that this should be left for follow-up studies.

To emphasize the uncertainties mentioned by the reviewer, we added the following sentence into the "Limitations" section of the revised manuscript (p. 21, l. 392–394):

"In the moisture source diagnostic, either evaporation or precipitation can occur in each time step of 6 h. Therefore, using shorter time steps and a finer grid resolution (e.g. using the ERA5 reanalysis dataset instead of ERA-Interim) could influence the diagnostic."

In our study we did not use any threshold for the minimum moisture increase, hence we set the threshold $\Delta q^0_c$ that was used in Sodemann et al. (2008a) ($0.2 \text{ g kg}^{-1}$ with ERA-40 for Greenland winter moisture sources) to zero. According to Sodemann et al. (2008a), this threshold was necessary in their study to suppress spurious uptakes from numerical noise and reduced the computational cost. However, as we used ERA-Interim and had enough computational power, we decided to not use any threshold at all. We clarified this by adding the following into Sect. 2.2 (p. 5, l. 110–111):

"...and we also did not use any minimum moisture uptake threshold in contrast to Sodemann et al. (2008a)."

**RC:** The low percentage of accounted precipitation (less than 50%) makes all the conclusions regarding moisture sources relatively weak. If possible, it would be good to increase this percentage somehow. If a large part of the moisture uptakes are unidentifiable because they occurred before the start of the trajectories, this could easily be achieved by running longer backward trajectories. Another idea (in line with the first general comment above) is to use shorter time steps by including the forecast data of ERA-interim, or by using the hourly ERA5 output instead of ERA-interim. This would likely shift the moisture sources closer to the study site and increase the percentage.

**AR:** Yes, you are totally right that accounting for less than 50% of precipitation is not the detection efficiency that we would have hoped for. The suggested extension of the backward trajectories has only a minor effect on the detection efficiency, e.g. in the case of Dec 1999 65% of moisture sources could be detected (below scaled PBL), 35%
were above the PBL and only 5% is the preexisting moisture at the end of the backward trajectory. In addition, the trajectory density after 15 days backward is very low and spread out over a large surface. In the case of the South Patagonian Icefield, extending the trajectories backward to 20 days only diminished the preexisting moisture to 3%. The main reason for the weak detection efficiency is that we distinguish between moisture uptake below and above the scaled PBL height. Above the PBL one can not assume anymore that the air is well-mixed, so the moisture uptake there can not be directly assumed to be a result of evaporation occurring at the surface. There are studies, which apply the same methodology and consider moisture uptake in the free atmosphere as well (e.g., Baker et al., 2015; Fremme and Sodemann, 2019; Hu et al., 2020), however it is unclear how they justify this approach. Another study uses the same approach but does not mention the detection efficiency (Bohlinger et al., 2017).

As discussed above, shorter time steps could also improve the percentage, however, this would need to be analysed in a further study. A much better detection efficiency below the scaled PBL height was found when using lagrangian moisture source diagnostic of (Sodemann et al., 2008a) that we used but with dynamically downscaled ERA-20C reanalysis data (coupled COSMO-CLM+NEMO, personal communication with Amelie Krug, https://doi.org/10.5194/egusphere-egu2020-2315)

We argue however that we discussed this uncertainty at length in the manuscript (by describing it, discussing probable causes, and by comparing our values with previous studies). Furthermore, the fact that we observe a high correlation between precipitation amounts and accounted precipitation is an indicator that our variability analyses are robust.

Specific comments:

RC: L21 Add references for this first sentence?
AR: Thanks. We added "(Screen and Simmonds, 2010; Bintanja and Van der Linden, 2013; Bintanja and Selten, 2014; Bintanja and Andry, 2017)" into that sentence (see p. 2, l. 22–23).

RC: L92 Why three different time periods? This is a bit confusing (but a detail).
AR: Yes, this is a bit confusing. However, we wanted to use the most out of each dataset we had. Moisture sources could not be computed for the full month of January 1979 because of the computation of the backward trajectories that would have needed data from December 1978. Therefore, we only computed moisture sources from February 1979 onwards. For moisture source trends we had to use only full years and therefore we had to shorten the time period.

RC: L155 fewer → less
AR: Thanks, we changed this as suggested.

RC: L157 less → few
AR: Thanks, we changed this as suggested.

RC: L167 Maybe write explicitly that this is not shown.

AR: Thanks for pointing that out. Because of specific comments of reviewer 2, we deleted this part of the paragraph.

RC: Figure 5 It looks like the geopotential height lines stop at 5700 (?)

AR: For July or August there was actually also a 5800 geopotential height line. As suggested by reviewer 2, we increased the amount of contour lines (every 50 m, but labelling only every 100 m). We hope that this makes it easier to distinguish the differences from month to month.

RC: Figure 6: Is the different map projection here on purpose?

AR: Thanks. As reviewer 2 correctly noted the large white spaces by the orthographic projection, we switched to the North polar stereographic projection (on Fig. 5 and Fig. 11). For the legends of Fig. 7 and Fig. 8, we preferred the orthographic projections to show the full extent of the clusters.

RC: L200 Are clusters calculated based on the absolute or relative moisture source contribution?

AR: The K-means clustering is based on the relative moisture source contribution. Maybe this was not clear enough, therefore we added the word relative into the description (p. 8, l. 181):

..., here based on the annual cycle of "relative" moisture source contributions to precipitation ...

RC: L210/211 Add Fig 7d in brackets.

AR: Thanks, we changed it as suggested.

RC: L217 I wonder what the k-means algorithm would do for 11 clusters. Would they look similar to the manual clusters?

AR: What we aimed to do with the K-Means clustering is to find clusters/regions that have a similar behaviour over the annual cycle (e.g. all gridpoints of the brown region have a maximum in September and minimum in June). We also tried higher number of clusters, however in this case the differences between the seasonal cycles were not large enough and they did not give us further information (only very similar new clusters). The manual separation into land/ocean was necessary to better interpret the results. Another more complex approach could have been to first separate land and ocean, and then do some kind of K-means clustering where annual, NAO and sea ice variability are included.

RC: L222 There are no land regions for the former blue cluster → mention land regions later
AR: Thanks for the suggestion. We have restructured the paragraph and mention the distinction between land and ocean areas first (p. 11, l. 201). In addition, we clarified that the former blue cluster is an ocean region (p. 11, l. 204).

RC: L233 Maybe mention also 6O and 7O

AR: Thanks. We added the following into Sect. 3.2.1 (p. 13, l. 215–216):

"The ocean clusters 10, 70 peak in June and the 60 cluster peaks in October possibly as a consequence of more sea ice free areas in October."

RC: Figure 8, caption: (e, g) → (e, f)

AR: Thanks, this was a typo. We changed it as you suggested.

RC: L247 northeastward-oriented → southwesterly

AR: Thanks. We changed it as suggested (p. 13, l. 230).

RC: L252 What is meant by NAO is at its weakest? NAO-, or neutral?

AR: We meant with that NAO− and clarified this by writing instead (p.13, l. 235):

"(when NAO is weakest, hence most negative)"

RC: Figure 10 Switch 3O and 2O?

AR: Thanks, we switched the order of 30 and 20 as you suggested.

RC: Figure 11 Is the sum of all values zero (it does not look like)? If not, I am not sure how they were normalised.

AR: To analyse the moisture source deviations between NAO+ and NAO− months, we subtracted for each gridpoint the moisture sources of the months with NAO− from NAO+. In order to better compare this between the months we divided each grid point by the maximum difference between the months with NAO+ and the months with NAO−. This means the gridpoint where there is the largest positive difference has a normalised deviation of 1. So, summing up all gridpoints times multiplying them with the maximum moisture source difference between NAO+ and NAO− gives the number that is written below the month as absolute mean total deviation of contributing moisture sources. We added this information in a shortened version to the legend and caption of Fig. 11.

RC: Section 4.2 Suggestion: What I would find useful here is a figure showing the correlations on a map instead of in a table for the clusters.

AR: We have considered to present the results on a geographical map comparable to Fig.8 with the respective correlation coefficients. However, this would result in 13*2 subplots which would not improve the layout and readability of the results. Therefore, we decided to leave the table.
**RC: L282+ What about evaporation alone? Did it increase with decreasing sea ice?**

**AR:** We expect that evaporation alone increases with decreasing sea ice indeed (e.g. described in Bintanja and Selten, 2014).

**RC: Figure 13 Is the p-value for the linear regression or Mann-Kendall test? Please clarify.**

**AR:** Thanks for pointing this out. The p-values that are written in Fig. 13 are from the linear regression. We added the following into the caption of Fig. 13 to clarify this:

"with estimates of a possible linear trend and its corresponding p-values".

**RC: L347 This is a bit confusing, before only October was mentioned, but it was a different unit.**

**AR:** In this paragraph, we describe the months with a slight significant correlation of increasing precipitation for higher surface temperature. It is true that October is the only month where we could see a temporal trend (see p. 18, l. 306–308), but when looking at the relation between precipitation and surface temperature there are other months with a significant correlation (see p. 19, l. 340–341). We added into the subsection name (Sect. 5.2, p. 19, l. 335) where this paragraph is located ...Relation to "temperature" and sea ice... which might clarify that the first of the two paragraphs is about temperature.

## 2 Final response to Reviewer #2

We would like to thank the anonymous referee for taking the time to read our manuscript and provide constructive comments which helped us to improve our manuscript. We hope that our response is clarifying and we remain available for further questions.

**General comments:**

**RC (summary):** The author presents moisture source analysis with a focus on a specific site in Greenland. Using moisture source diagnostics and cluster analysis the sources are explored. The relationship to NAO and sea ice changes are explored. Temporal evolution is also addressed. The analysis of NAO and cluster analysis as well as the arguments for the validity of the PBL assumptions can be strengthened (see below). The paper is a good paper, well written, clear to understand and with sufficient references. There is some work to be done in terms of framing the introduction as a classical science paper but based on the quality of the rest of the paper, this should be no problem to change. I therefore suggest publication with major revision.

**AR:** Thank you for your positive evaluation of our manuscript. We hope that our revisions to the manuscript have addressed your comments.

**RC: NAO/cluster analysis It is a nice idea to use cluster analysis for moisture sources. It is
unclear whether it is reasonable to assume constant clusters throughout all seasons. It is ok to continue with clusters based on all months, but please document using relevant numbers, that the assumption holds. Since sea ice trends are also explored later, is it reasonable to assume that the clusters are constant in time? Please document why. Can you also add information regarding variability on the relevant timescales?

AR: Thanks for this comment, which we believe also points out some weaknesses in the first manuscript version, mostly in the explanations of the clustering algorithm.

To find gridpoints that behave similarly, we used the K-means clustering algorithm. We estimated similarities between the gridpoints over the mean annual cycle of relative moisture source contributions, meaning that gridpoints of one cluster have a similar mean annual cycle of relative moisture source contributions. This rules out the possibility to build seasonal clusters (at least with this method), because the clusters are based on seasonality.

We did however try to find other ways to cluster the data. In Fig. 1, we did the K-means clustering by using the features of relative NAO−, NAO neutral and NAO+. However, the regional clusters that arise are qualitatively harder to identify and interpret, so we preferred to stick to the current method.

![Figure 1: K-means clustering of gridpoints into five clusters grouped after similarities in NAO−, NAO neutral and NAO+](image_url)
In order to use a clustering algorithm we needed to assume constant clusters as we used the mean relative annual cycle as features. To analyse how the clusters change with time, we did a simple sensitivity check by repeating the clustering over the annual cycle of the relative moisture sources for the first half of the time series and for the second half of the time series. We found that the clustering is nearly identical for the two time series, as only a few of the gridpoints change their cluster between the 1st and 2nd half of the time series (Fig. 2). The K-means clustering should not be over-

Figure 2: The red gridpoints are clustered in a different cluster when comparing the clustering using the mean relative annual moisture source cycle of the first half of the time series against the second half of the time series (for each 230 months)

interpreted, as it was used as a help to construct different regions and to quantitatively describe the features we observed. To clarify the limitations of this clustering approach we added the following into Sect. 5.4 (p. 21, l. 382–386):

"The K-means clustering algorithm was used as a simple tool to construct different regions in which each gridpoint shares a common feature, i.e. the mean annual cycle of relative moisture source contributions. By dividing the time series in half and repeating the K-means clustering approach for these two time series separately, we found almost no differences in the classification of the clusters (not shown) which gives a hint that the clusters are stable over time. Incorporating a more complex clustering approach that takes the annual cycle, NAO and sea ice into account could, however, give interesting new insights."

RC: Analysis of NAO variations are also done in this manuscript. It has been documented that NAO is important for southern/central Greenland (Vinther 2010, Sodemann 2008). But is NAO really the dominant driver for this given location? Fig 9b is not strongly convincing regarding this. There are a few ways to approach this. Either explore other weather patterns (ScB, EAtl, NAO+/-) (see e.g. Ortega et al 2014) and GBI for summer (Hanna et al. 2015) or use the already analyzed clusters and connecting circulations to document variability. Or come up with a third alternative. No matter what, it is important to argue that the chosen index (e.g. NAO) is indeed a driving circulation pattern for the location.

AR: Thanks for pointing this out.
The Greenland Blocking Index (GBI) is freely available and allowed us to repeat the NAO analysis with the GBI, see Fig. 3 and Fig. 4.

Figure 3: Same as Fig. 9 from the manuscript but with GBI instead of NAO-index: (a) Scatterplot of precipitation in study region against the GBI for in total 460 months (February 1979–May 2017). Months were separated into months with GBI below or equal to the 25% percentile (GBI−), above or equal to the 75% percentile (GBI+), or in between the 25% and 75% percentile (GBI neutral). (b) Mean annual cycle of precipitation in study region for months with GBI being below or equal to the 25% percentile (GBI−) and above or equal to the 75% percentile (GBI+). For each month of the year, month-specific 25% and 75% percentile thresholds were computed. The shaded areas represent the 95% confidence interval of the mean.

Figure 4: Same as Fig. 11 from the manuscript but with GBI instead of NAO-index: Normalised moisture source deviation between months with GBI being above or equal the 75% percentile (GBI+) and months being below or equal the 75% percentile (GBI−). The same thresholds as in Fig. 3b were chosen. To better compare the moisture source deviations they were normalised by dividing each grid point by the maximum difference between the months with GBI+ and the months with GBI−, which gives e.g. the gridpoint with the largest positive difference a normalised deviation of 1.

We added the insights about the GBI into Sect. 5.1 (p. 19, l. 328–334):
"We repeated the analysis of the NAO-index for the Greenland Blocking Index (GBI, dataset from NOAA, 2020 based on Hanna et al. (2016)) that is defined by the mean 500 hPa geopotential height for the 60°N–80°N, 20°W–80°W region (e.g., Hanna et al., 2016). The higher the GBI, the weaker and less variable is the precipitation, specifically in January and April (not shown). Due to the strong negative correlations between the NAO-index and the GBI with Pearson correlation coefficients of minimum -0.96 in June and maximum -0.74 in December, we get relations between GBI and precipitation or moisture sources that are very similar but reversed to those from the NAO-index, which is in line with Hanna et al. (2016) and Nusbaumer et al. (2019)."

To our knowledge, there exists no freely available time series dataset of e.g. Scandinavian Blocking/Atlantic Ridge/NAO-/NAO+. Therefore, we would need to classify the weather patterns ourselves, and use daily instead of monthly aggregated data. This would substantially increase the length and complexity of an already long manuscript, and we prefer to argue for a subsequent study (ideally with ERA5 data as pointed out by Reviewer #1). We added the following into Sect. 5.4 (p. 20, l. 378–381) to add this limitation of our study and open the way for further research:

"Instead of using only the NAO-index or GBI, a more sophisticated classification into 4–7 weather patterns (e.g., Ortega et al., 2014; Grams et al., 2017; Falkena et al., 2020) together with a case study analysis of the pathway of moisture source transport for each weather pattern could be done in a subsequent study to better understand the dominant drivers and sources of precipitation in our study region."

**RC: Introduction:** The introduction is interesting reading, yet not optimal in terms of structure and content for a journal paper introduction. The manuscript is about moisture sources for Greenland, with a specific focus on a single location. Please spend less text on Arctic amplification and instead use the introduction to introduce relevant literature related to this topic. Especially highlight the current knowledge gap and motivate for why your analysis is relevant and explain the regional focus of Greenland. And address why this region of interest for our science community.

**AR:** Thanks for this suggestions. We tried to restructure the introduction as suggested. We also removed some parts of the Arctic amplification and we reformulated other parts to explain better the knowledge gap and to justify further why we chose the specific study region in northeast Greenland (e.g. p. 3, l. 50ff). The full track of changes in the introduction can be found in Sect. 3.

**RC: Uniqueness of the location -state differences and highlight benefits.** The study focuses on a rather specific site on the north eastern margins of the Greenland ice Sheet. The authors refer sufficient to other studies that have explored Greenland moisture sources, but these studies have also addressed that moisture sources are not uniform over Greenland. How this location differs from other findings due to location is under explored in this study. It is encouraged that the authors throughout the text further motivate that their site is beneficial for Greenland studies since it is has a unique location in close proximity to areas of recent strong sea ice decline (as shown in fig 11)
AR: Thanks for pointing this out. We emphasised the high sensitivity of northeast Greenland more in the introduction (e.g. p. 2, l. 27–42; p. 3, l. 55ff) and we added some text into the discussion part (p. 19, l. 343–346):

"The study region in northeast Greenland is in close proximity of the Greenland Sea that has lost sea ice rapidly in the last decades, specifically in winter (Onarheim et al., 2018; Bliss et al., 2019). While the Greenland Sea has lost around a third of its initial winter sea ice extent, the Barents Sea has even lost half of their winter sea ice extent (compared to ice conditions of 1979–1989, Stroeve and Notz, 2018)."

It must also be mentioned that the presence of the caves (and their potential paleoclimate archive) still is a strong driver for our study (as emphasised now in p. 3, l. 58).

Specific comments:

RC: L85 "...a model without spatial or temporal gaps..."-unclear. Just delete this sentence.
AR: Agreed. We removed the entire sentence.

RC: L88 It is ok to use ERA-Interim but try to address this point and potential implications briefly in the discussion rather than here.
AR: Yes, we added the following into the limitation section (p. 21, l. 392–394):

"In the moisture source diagnostic either evaporation or precipitation can occur in each time step of 6 h. Therefore, using shorter time steps and a finer grid resolution (e.g. using the ERA5 reanalysis dataset instead of ERA-Interim) could influence the diagnostic."

RC: Sec 2. The methods described are partly unclear. As a reader without prior knowledge of back trajectories, the description of how ERA-Interim and moisture source diagnostics works together is unclear. Please clearly state this and maybe consider reorganization of this section.
AR: Thanks for pointing this out. The 15 days backward trajectory calculations are based on the 3D windfield of ERA-Interim. Additionally, fields such as the specific humidity, 2m-Temp and the PBL height are needed from ERA-Interim as well to apply the moisture source detection method. In our revised manuscript we mention this at p. 4, l. 79–81. We have also added the following to the revised manuscript to clarify the link between ERA-Interim and the moisture source diagnostic (p. 5, l. 93):

... the trajectory calculations are ... "based on the ERA-Interim dataset".

RC: L110 "In the next step..."The next step of what? Are you here referring to the moisture source diagnostics?
AR: Yes, this was a bit confusing. We meant with "in the next step" just the working step that is done afterwards and did not mean the 'time step' from the sentence beforehand. We replaced it by "Afterwards," (p. 5, l. 95) to clarify that.

RC: L115 – Moisture uptakes above PBL. Be clear about why this is neglected--does Sodemann2008 argue for this?

AR: Yes, Sodemann et al. (2008a) argue for using only the below PBL height moisture uptake as evaporation source. We have clarified more in the text that we follow the Sodemann et al. (2008a) approach (p. 5, l. 100):

"According to Sodemann et al. (2008a), ...."

Above the PBL one can not assume anymore that the air is well-mixed, so the moisture uptake there can not be directly assumed to be a result of evaporation occurring at the surface (p. 5, l. 98ff). There are studies which apply the same methodology and consider moisture uptake in the free atmosphere as well (e.g., Baker et al., 2015; Fremme and Sodemann, 2019; Hu et al., 2020), however it is unclear how they justify this approach (see p. 21, l. 395–396). Another study uses the same approach but does not mention the detection efficiency (Bohlinger et al., 2017).

RC: L121-122 The wording of why to choose Lagrangian rather than Eulerian methods is not optimal hereafter you have already described that you use Lagrangian methods. Please rewrite or replace.

AR: Thanks. We removed this sentence from the methods into the limitation part (p. 21, l. 396–400):

"For this climatological study, we had do use a lagrangian approach instead of a more comprehensive Eulerian tagging approach to keep the computational costs low. Although the case study of Winschall et al. (2014) found similar moisture source regions for both approaches," a direct comparison to other models would be necessary ...

RC: L123 -126 Please clearly describe, wherein your methods do you lift the PBL height by 1.5? Is this done on ERA-interim data or in the moisture diagnostic? To the best of my knowledge this is have not been done for the North Atlantic before. Is the PBL height also underestimated in this region, please argue with references and please argue with numbers, what difference this have for the amount of moisture uptake in this study? As a reader I would like to be convinced that this approach is better than the existing ones, and also clearly know what differences this makes compared earlier studies such as Sodemann 2008. Please clearly state this.

AR: The PBL scaling approach is suggested by Sodemann et al. (2008a), maybe the text was not clear on this point. They also lifted the PBL by 1.5 to account for the underestimation of the marine PBL height and its small-scale variability. So, instead of using the PBL as it comes out of ERA-Interim, we use instead 1.5xPBL as threshold for moisture uptake.
uptake. The exact same PBL scaling procedure has also been done e.g. in Sodemann and Zubler (2010); Winschall et al. (2014); Langhamer et al. (2018). We added some explanations of Sodemann et al. (2008a) into the revised manuscript at Sect. 2.2:

"marine PBL height can vary on small scales" (p. 5, l. 106)

and clarified that the scaling was done

"same as in Sodemann et al. (2008a)" (p. 5, l. 107).

RC: L127 – “A measure for performance of the method” Is fig 3 a measure for performance? Do we trust that moisture sources and their variability are adequate after?

AR: Yes, it is true that Fig. 3 is no real measure for performance (there is no way to truly verify the methodology) and we removed this sentence (see p. 5, l. 112ff). Fig. 3 rather describes the detection efficiency variability. There is no dependence of this efficiency with the amount of monthly mean precipitation visible. We added the following into Sect. 2.2 (p. 5, l. 114) to clarify this:

... "with the detection efficiency being roughly independent of the monthly precipitation" ...

The performance analysis of the lagrangian moisture source diagnostic in general is given by Winschall et al. (2014) (p. 21, l. 398–400).

RC: L129 52% is moisture uptake that is not accounted for? This seems like a lot. Great that this is also treated later. But what effects have 1.5 PBL on this fraction? What is the argument for only including moisture uptake below PBL rather than all moisture uptake? Please demonstrate with relevant numbers that this assumption does not strongly influence the results.

AR: Yes, only accounting for 48% of moisture uptake is weak but, as discussed in the paper, Sodemann and Zubler (2010) had similar numbers (50%). We still believe that using the moisture uptake above the scaled PBL of a grid point would lead to “better results for the wrong reasons”, and does not represent well the underlying evaporation at the surface as the atmosphere can not be assumed to be mixed above the PBL (p. 5, l. 98ff and p. 21, l. 394ff). In the case of the southern Patagonian ice field, 15% of moisture sources are between 1xPBL and 1.5xPBL (personal communication with Lukas Langhamer). A comparison study that analyses the pros and cons of this threshold and the relevance of scaling the PBL height would be necessary but we argue that this should to be done in a subsequent study (described in Sect. 5.4, p. 21, l. 398–400). Furthermore, the fact that we observe a high correlation between precipitation amounts and accounted precipitation is an indicator that our variability analyses are robust (see Fig. 3).

RC: L144 Generally, there is an issue here that (at least the DJF) NAO index values for the ERA-interim are not evenly distributed. This is just nature, but please add numbers to describe the ranges for NAO+, NAO-and NAO neutral.
AR: The way we defined the monthly thresholds to distinguish between NAO+/- was such that for each month of the year, we have the same amount of entries for NAO+ as for NAO- (see Sect. 2.3, p. 6, l. 129ff). Therefore, we used a classification that differs between years below the NAO 25% percentile and above the 75% percentile. So, the NAO-index threshold is different for each month. While the NAO 25%/75% threshold is [-0.67, 0.77] for all months together, it is e.g. for August [-1.17,0.67], for December [-0.46, 0.84], for April [-0.63, 1.01] and for May [-0.92, 0.57]. We included these numbers into the text at p. 6, l. 132–134 to clarify that.

RC: L163-168 If you mention this –please relate to your findings and the site of this study. The site is so north that it is only partly close to the North Atlantic storm track. But what does fig 4 show?

AR: It is correct that our study region is not so affected by the cyclone track, also reflected by the annual cycle of precipitation in ERA-Interim. Therefore, we deleted these two sentences.

RC: L167-168 Is this expected to be the case for your site? What role does increased moisture content in the air due to warmer temperatures play relative to this?

AR: Yes, it is true that in our study region the contrast between snow-free land and snow areas might not be the reason for more precipitation occurring in summer, so we removed this sentence.

RC: L170 Is precipitation really constant during the year? The accounted precipitation is, but not the ERA-interim precipitation. Spring/summer is clearly lower than the rest of the year. E.g. July median is roughly 3 times lower than September

AR: Yes, you are right. We removed the first part of the sentence (...While precipitation amounts are relatively constant during the year...) that was in Sect. 3.2 (p. 7, l. 151) to clarify that.

RC: L173. How do you define “local sources” -please describe?

AR: We meant with local sources the moisture source from the study region or its direct surrounding and added that into the text at p. 7, l. 154:

... local moisture sources "(from the study region or its direct surrounding)"

RC: L170-179 Avoid the use of the word “seem”. Either the sources are there or they are not.

AR: Thanks, we changed this as suggested.

RC: Fig 5 There is too large of a region on the globe which is white. This makes it more
difficult to look at the plot. Consider a different projection (e.g. polar stereographic) where North Atlantic/Arctic is emphasized (and apply to other relevant plots such as fig. 6). Also, fig 5 contours of z500 could be closer so it is easy to distinguish differences from month to month.

**AR:** Thanks for pointing this out. We switched to the North polar stereographic projection (on Fig. 5 and Fig. 11). We chose a minimum latitude threshold of 35° N as there are less than 3% of the moisture sources further southward. For the legends of Fig. 7 and Fig. 8, we preferred the orthographic projections to show the full extent of the clusters. As suggested, we increased the amount of contour lines (every 50 m, but labelling only every 100 m). We hope that this makes it easier to distinguish the differences in the geopotential height from month to month.

**RC:** Fig. 6 - The colors on this plot looks very similar blue-toned with little contrast on my (and maybe others) printer. Please change to a color scale with stronger contrasts. The signs and meaning on the legend for 15 and 30 IVT are unclear in figure and caption, please improve this. Please add a comment on an uneven color scale on this.

**AR:** Thanks for recognizing that. We increased the contrast by using a colormap that also changes colors (‘viridis’- colormap of matplotlib). In addition, we improved the color scale, noted the uneven color scale in the caption and increased a bit the arrow length and width.

**RC:** Fig 6 Is figure of anomalies a better way to display this?

**AR:** We have thought about this as well. However, in this case, the reader has to be familiar with the mean IVT to understand their anomalies. Therefore we thought it would be misleading the readers’ interpretation and decided to not plot the anomalies.

**RC:** L211-217 This section here is unclear. Please reformulate. Are sea ice areas defined as constants throughout the year or are they changing months by months?

**AR:** Thanks for pointing this out. We used the sea ice concentration time series of each gridpoint from February 1979 – May 2017. We clarified this by adding the following sentence into the caption of Fig. 7d:

"The values for the sea ice concentration and hence the sea ice areas change throughout the months and years."

We also added a sentence into the text at p. 11, l. 198–199:

Note that, sea ice areas as defined in Fig. 7d (gridpoints with sea ice concentration ≥ 0.5) change from month to month.

**RC:** L278ff This analysis is interesting and relevant, but the method and text are a bit unclear. Please reformulate to enhance clarity and clearly state relevant findings.
AR: Thanks for pointing this out. We hope that Sect. 4.2 got clearer by reshaping the text, adding the R$^2$-values of the found correlations (p. 15, l. 264–265)

"increasing precipitation in autumn and winter for decreasing maximum sea ice (R$^2$-values of 0.14 and 0.13)"

and adding the following at p. 15, l. 265–267 to the revised manuscript:

"The moisture uptake region 3O (mainly Norwegian Sea) is one of the major moisture source contributors, however it is also mostly sea ice-free which might explain why we could not find strong relations between precipitation in the study region and Arctic sea ice area."

RC: Sec 6 (Conclusion) The content of the conclusion is unclear and unprecise and does currently not let the key methods and findings of the manuscript stand out. This will improve the many "skim-readers"understanding of the paper strongly. Please improve and address all key components of the manuscript

AR: We added some additional information about the used methods (lagrangian moisture source diagnostic and K-means clustering approach) into the conclusions (p. 21, l. 403–405):

" We used the lagrangian moisture source diagnostic of Sodemann et al. (2008a) to estimate the origin of water vapour for precipitation over the study region. We applied a classification algorithm (K-means clustering) to group gridpoints into clusters after their similarities based on the annual cycle of relative moisture source contributions."

We also reference to the corresponding figures and added some additional quantities:

maximum over the Norwegian Sea "(30 % in the mean in January ..." (p. 21, l. 408)

... "with the exception of autumn where precipitation increases by 8.2 [0.8, 15.5] mm dec$^{-1}$ over the period" ... (p. 22, l. 419)

References


Bintanja, R. and Selten, F.: Future increases in Arctic precipitation linked to local evap-


3 Author’s changes in revised manuscript (using latexdiff)

Besides the changes that are visible in the latexdiff file which is attached below, we also changed Fig. 5, Fig. 6, Fig. 10 and Fig. 11 due to comments from the two reviewers.
Lagrangian detection of precipitation moisture sources for an arid region in northeast Greenland: relations to the North Atlantic Oscillation, sea ice cover and temporal trends from 1979 to 2017

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Abstract. Temperature in northeast Greenland is expected to rise at a faster rate than the global average as consequence of anthropogenic climate change. Associated with this temperature rise, precipitation is also expected to increase as a result of increased evaporation from a warmer and ice-free Arctic Ocean. In recent years, numerous palaeoclimate projects have begun working in the region with the aim of improving our understanding of how this highly-sensitive region responds to a warmer world. However, a lack of meteorological stations within the area makes it difficult to place the palaeoclimate records in the context of present-day climate. This study aims to improve our understanding of precipitation and moisture source dynamics over a small arid region located at 80° N in northeast Greenland. The origin of water vapour for precipitation over the study region is detected by a Lagrangian moisture source diagnostic, which is applied to reanalysis data from the European Centre for Medium-Range Weather Forecasts (ERA-Interim) from 1979 to 2017. While precipitation amounts are relatively constant during the year, the regional moisture sources display a strong seasonality. The most dominant winter moisture sources are the North Atlantic above 45° N and the ice-free Atlantic sector of the Arctic Ocean, while in summer the patterns shift towards local and north Eurasian continental sources. During the positive phases of the North Atlantic Oscillation (NAO), evaporation and moisture transport from the Norwegian Sea is stronger, resulting in larger and more variable precipitation amounts. Testing the hypothesis that retreating sea ice will lead to increase in moisture supply remains challenging based on our data. However, we found that moisture sources are increasing in case of retreating sea ice for some regions, in particular in October to December. Although the annual mean surface temperature in the study region has increased by 0.7 °C dec⁻¹ (95% confidence interval [0.4, 1.0] °C dec⁻¹) according to ERA-Interim data, we do not detect any change in the amount of precipitation with the exception of autumn where precipitation increases by 8.2 [0.8, 15.5] mm dec⁻¹ over the period. This increase is consistent with future predicted Arctic precipitation change. Moisture source trends for other months and regions were non-existent or small.
1 Introduction

The Arctic region is known from both observational and modelling studies to be highly-sensitive to changes in climate. This high sensitivity is the result of Arctic amplification, a process in which positive feedbacks act to amplify changes as compared to the rest of the Northern Hemisphere. Observational studies have shown the effect of Arctic amplification during both former warm climates such as Quaternary interglacials, as well as cold climates such as Quaternary glacials (e.g., Dahl-Jensen et al., 1998; Miller et al., 2010). In the future, under a regime of increasing atmospheric greenhouse gas concentrations, surface air temperature rise in the Arctic is also expected to be amplified (e.g., Serreze and Barry, 2011) predominantly as a result of surface albedo changes (e.g., Serreze et al., 2009), oceanic heat loss (e.g., Screen and Simmonds, 2010) and infrared radiation feedbacks (e.g., Bintanja and van der Linden, 2013). Many lines of evidence already suggest that Arctic amplification is a feature of Earth’s changing climate (e.g., Serreze et al., 2009) (e.g., Dahl-Jensen et al., 1998; Miller et al., 2010).

Between 1875 to 2008, surface air temperature north of 60°N increased at twice the pace of the Northern Hemisphere average (e.g., Bekryaev et al., 2010), with the winter season being the most affected because of the delayed onset of sea ice resulting in a loss of heat from the open ocean to the atmosphere (e.g., Screen and Simmonds, 2010; Bintanja and van der Linden, 2013). Recent warming within the Arctic has not, however, been homogeneous, and in some parts average winter surface temperatures have risen by as much as 4 °C to 5 °C over the last 50 years (GISTEMP Team, 2016; Shepherd, 2016). The areas that were most affected included northwest North America and northeast Greenland.

Amplified precipitation: These temperature changes are expected to accompany amplified temperature changes (e.g., Collins et al., 2013) and indeed evidence already exists to suggest an increase in Arctic precipitation during the last century (e.g., Kattsov and Walsh, 2000). Unfortunately, a lack of stations north of 70°N does; however, limit our understanding of the evolving hydrological regime (e.g., Kattsov and Walsh, 2000; Kurita, 2011; Bintanja and Selten, 2014). The majority of models agree that in the future, mean annual precipitation will increase in the mid-latitudes and polar regions, driven largely by the increase in surface temperature (e.g., Collins et al., 2013). Rain is predicted to become the dominant form of precipitation in the Arctic in all areas apart from the interior of the Greenland Ice Sheet (e.g., Bintanja and Andry, 2017), and be accompanied by precipitation changes (e.g., Collins et al., 2013; Bintanja and Andry, 2017). Within the Arctic, the greatest increases in precipitation are simulated over the Arctic Ocean and northeast Greenland by the end of this century, the greatest changes in Arctic precipitation, which could be as much as 50% with up to 50% increase in an RCP 8.5 scenario, are found over the Arctic Ocean and northeast Greenland (Bintanja and Selten, 2014), with the majority of change occurring in the late-summer–winter months. Models predict that (Bintanja and Selten, 2014). Generally, enhanced precipitation predictions in the Arctic may be explained by the increase in surface temperature (Collins et al., 2013), that is accompanied by a predicted increase of moisture transport towards the Arctic will increase in the future reaching a maximum during summer months, when meridional temperature and moisture gradients are at their maximum (e.g., Bintanja and Selten, 2014). However, whilst the absolute values of moisture transported to the Arctic are expected to increase, the relative contribution of this source remote sources will diminish in comparison to locally sourced moisture, which will be enhanced due to increased surface evaporation from open ice-free Arctic waters in late autumn–winter (e.g., Bintanja and Selten, 2014).
Models for the coming decades indicate that within the Arctic, northeast Greenland is **Strong sea ice loss in the Greenland Sea** (Onarheim et al., 2018; Bliss et al., 2019) and the expected changes in local evaporation and temperature are likely to impact the climate of Northeast Greenland. Average winter surface temperatures there have risen by as much as 4°C to 5°C over the last 50 years (GISTEMP Team, 2016; Shepherd, 2016), and model projections indicate that northeast Greenland will be one of the most sensitive terrestrial areas to changing temperatures and precipitation (Koenigk et al., 2013; Bintanja and Selten, 2014; GISTEMP Team, 2016). Furthermore, terrestrial areas with the highest temperature changes (Koenigk et al., 2013; GISTEMP Team, 2016; Shepherd, 2016)

Simulations of the Greenland Ice Sheet during the last interglacial suggest that the northeast sector is most vulnerable to increases in temperature because of a strong ice-elevation feedback that is further hampered by low accumulation rates (Born and Nisancioglu, 2012).

Therefore, climate and palaeoclimate research activities in northeast Greenland have increased in recent years in response to various needs to improve fundamental understanding of the climate and environment of this highly sensitive region. For example, several projects (e.g., NEGIS project, 2020; EastGRIP, 2018) are researching the dynamics of the Northeast Greenland Ice Stream (NEGIS), which is an important component of the Greenland Ice Sheet that delivers ice into a part of the Atlantic Ocean that is sensitive to freshwater forcing (NEGIS project, 2020). Of these projects, EastGRIP and its interaction with the Atlantic Ocean via freshwater forcing are investigated with the NEGIS Project (NEGIS project, 2020). “EastGRIP” (EastGRIP, 2018) has been drilling and analysing an ice core in order to improve understanding of ice stream dynamics and their role in future sea-level change (EastGRIP, 2018), whilst the “NEGIS Project” has been researching ocean sediment cores in order to better understand the response of the NEGIS to increased temperatures. Elsewhere in northeast Greenland, modelling research has shown that the region is expected to undergo the greatest expansion of supraglacial lakes during the 21st century as compared to the rest of the ice sheet (Ignéczi et al., 2016), whilst the role that surface meltwater plays in recharging submarine lakes in northeast Greenland has also been shown to be important (Willis et al., 2015). Simulations of the Greenland Ice Sheet during the last interglacial suggest that the northeast sector is most vulnerable to increases in temperature because many years of accumulation are lost creating a strong ice-elevation feedback that is further hampered by low accumulation rates (Born and Nisancioglu, 2012).

Finally, new research into speleothems in northeast Greenland by the Greenland Caves Project (2015) is aiming to improve knowledge of past climates and environments in this region in a warmer world (Moseley, 2016).

In summary, northeast Greenland is known to be highly sensitive to global climate changes, which has resulted in an increase in fundamental research in recent years. Despite this, a distinct knowledge gap exists with regards to the present day climatology of northeast Greenland. Unfortunately, a lack of stations north of 70°N does, however, limit our understanding of the evolving hydrological regime (e.g., Kattsov and Walsh, 2000; Kurita, 2011; Bintanja and Selten, 2014). Climatological moisture source studies have thus far tended to concentrate on the Greenland Ice Sheet (30 selected winter months, Sodemann et al., 2008a, b) using the ERA-40 dataset, whereas Nusbaumer et al. (2019) separated Greenland moisture sources into four sectors but focused mainly on northwest Greenland. Here we aim to address this knowledge gap through investigation of the climatology of precipitation and its using water tracers from the Goddard Institute for Space Studies climate model and MERRA2 horizontal winds (mean of 1980–2015). Therefore, the purpose of this study is to specifically analyse precipitation and moisture sources over a 39-year period (1979 to 2017) in the presently arid region located at the study one of the most
Figure 1. Average of yearly ERA-Interim precipitation (1979–2018). The study region is depicted with the nine gridpoints located between 22.5° W and 21° W and between 79.5° N and 81° N. The exact location of the studied caves is (21.7419° W, 80.3745° N). Average precipitation in the study region is 207 mm year⁻¹ (95 % confidence interval of [192, 224] mm year⁻¹).

Sensitive areas of the Arctic, northeast Greenland. Although this study focuses on an arid study region around the field site of the Greenland Caves Project (80° N, 22° W, 740 m a.s.l) in northeast Greenland (Fig. 1–2). The results will, however, have wider implications for other studies working in the area. Moisture and hence gives a direct background for interpreting paleoclimate data from these caves, its results will also address a fundamental knowledge gap for many other research activities in the region.

Methodologically, moisture sources are diagnosed from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis dataset applying the Lagrangian moisture source diagnostic by Sodemann et al. (2008a) with the adjustment of the planetary boundary layer (PBL) height according to Langhamer et al. (2018). In particular, we aim to investigate: (1) in addition, we analyse the annual cycle of precipitation in the region and its moisture sources; (2) the inter-annual variability of moisture sources and their relation with amount and moisture source and investigate whether or not distinctive changes can be detected in relation to the North Atlantic Oscillation (NAO) and, in the changing sea ice cover variability, and (3) whether the precipitation characteristics and moisture sources have shown any significant changes in recent decades and temperature over the 39-year period, 1979–2017. Given the predicted increase in precipitation, the increase in temperature and the reduction in sea ice that has already taken place within the Arctic, we attempt to establish whether noticeable changes in precipitation amount and moisture source can already be detected as well.
2 Data and Methods

2.1 Reanalysis data

In this study, reanalysis data from the European Centre for Medium-Range Weather Forecasts (ERA-Interim) was used (Berrisford et al., 2011; Dee et al., 2011; Owens and Hewson, 2018) for both precipitation and moisture source estimates. This product was chosen because a consistent model without spatial or temporal gaps was needed to apply the moisture source diagnostic (see Sect. 2.2). ERA-Interim has a fully revised humidity scheme and higher spatial resolution (~79 km) than ERA-40, that was used by Sodemann et al. (2008a) to compute Greenland winter precipitation sources. The even newer ERA5 reanalysis data was not yet available at the time we conducted these analyses. The study region (21° W–22.5° W, 79.5° N–81° N, Fig. 1) consists of nine gridpoints with a horizontal resolution of 0.75°, which are located around the caves in northeast Greenland. Several gridpoints were chosen to smooth out local inhomogeneities. The ERA-Interim dataset is used in the time span of February 1979–May 2017 for which we computed the Lagrangian diagnostics. For the temporal precipitation trends and for the total average precipitation the time period was extended to January 1979–December 2018. For the estimates of moisture source trends, the period was shortened to January 1980–December 2016 in order to cover full years only. To estimate the moisture sources of the study region by the Lagrangian moisture source diagnostic (Sect. 2.2), 6-hourly specific humidity, 3D-wind field, surface pressure, PBL height and two metre temperature were used. Moisture sources over land and ocean are distinguished by using the land/sea mask of ERA-Interim on the same 0.75° grid. For each gridpoint, the monthly sea ice area was computed by multiplying the ERA-Interim sea ice fraction (0–1) by the latitudinally-weighted gridpoint area. To classify gridpoints into land, ocean and sea ice, a threshold of 0.5 was set for the fractional land/sea mask and sea ice fraction.

In addition, relations between precipitation and its moisture sources to other ERA-Interim parameters were examined. These are the sea ice area, the mean 500 hPa geopotential height, and the vertically integrated water vapour transport (sum of the integrated northward and eastward cloud liquid, cloud frozen, and water vapour transport). To relate precipitation and moisture
source variability to large-scale teleconnection patterns, we computed correlations to the monthly NAO index data from the National Oceanic and Atmospheric Administration climate prediction centre (NOAA, 2020, a).

### 2.2 Trajectory calculation and Lagrangian moisture source diagnostic

To compute the motion of air parcels, 15-day backward trajectory calculations by the Lagrangian Analysis tool LAGRANTO version 2.0 (Sprenger and Wernli, 2015), first version by Wernli and Davies (1997), were realised for every six hours from February 1979 to May 2017 based on the ERA-Interim dataset. Trajectories start at the node of the 0.75° regular grid of the study region (9 gridpoints, Fig. 1) on 11 vertical levels from the surface to a height of 500 hPa ($\Delta p = 49.9$ hPa). This corresponds to 99 trajectories per time step. Afterwards, the trajectories that aren’t leading to precipitation in the study region were filtered out. The requirements for the selected trajectories were that relative humidity exceeded 80% and specific humidity ($q$) decreased in the last time step (Sodemann et al., 2008a).

Evaporation and precipitation of precipitation-trajectories are identified by temporal changes in specific humidity ($\Delta q$). Using the assumption of a well-mixed PBL, the moisture content of air parcels increases within the PBL in case of a positive $\Delta q$. Moisture According to Sodemann et al. (2008a), moisture uptakes that occur above the PBL, however, are detached from the surface and are assumed to be explained by physical or numerical processes, e.g., convection, evaporation of precipitating hydro-meteors, change of liquid water content, or ice water content, subgrid-scale turbulent fluxes, numerical diffusion, and errors, or physical inconsistencies (Sodemann et al., 2008a). Along each trajectory, moisture uptake locations inside the PBL are weighted by their contribution to the total precipitation in the study region by taking en route precipitation into account. Each moisture uptake is interpolated on a 1° grid and we calculate the monthly means on this basis.

This Lagrangian approach of Sodemann et al. (2008a) is suitable for our study as it gives similar moisture source regions and needs lower computation cost than a more complex Eulerian approach (Wunschall et al., 2014, for a case study in Europe). The marine PBL height can vary on small scales and is often underestimated in numerical weather prediction models (Zeng et al., 2004). Therefore, same as in Sodemann et al. (2008a), the threshold for a moisture source location inside the PBL height is lifted by a factor of 1.5. Similar to Langhammer et al. (2018), the height of the PBL was converted in our study into pressure coordinates by applying the barometric formula with surface pressure and temperature as free variables (and a constant temperature lapse rate of 0.0065 K m$^{-1}$) and we also did not use any minimum moisture uptake threshold in contrast to Sodemann et al. (2008a).

A measure for the performance of the method is shown in Fig. 3. The Lagrangian evaporation sum that contributed to precipitation in the study region correlates very well with the total precipitation over the study region from ERA-Interim, indicating that the method is able to reproduce the variability of precipitation with the detection efficiency being roughly independent of the monthly precipitation (Fig. 3). 48% of the total moisture sources could be assigned to specific evaporation locations with the applied Lagrangian moisture source diagnostic. For comparison, similar studies by Sodemann and Zuber (2010) in the European Alps and Langhammer et al. (2018) in Patagonia reached 50% and 71% attribution, respectively. The remaining moisture sources could not be identified to evaporation at the surface (moisture uptake above PBL) or were unidentifiable. There is no clear annual cycle visible in the attribution: the fraction ranges from a minimum of 41% in August to a maximum of 57%
in June (Fig. 4). Specifically in summer, precipitation in the study region varies more than its attributed moisture sources. We discuss the possible implications of these uncertainties in Sect. 5.4.

2.3 Statistical methods

To compute confidence intervals of our trends and averages, we estimate the 95% confidence intervals of the mean or median (significance level of 0.05) without assuming a parametric distribution by using the bootstrapping method (Wilks, 2011). This is done because some subsets of daily precipitation averaged over a month as well as other related parameters reject the null hypothesis that their distributions are drawn from a normal distribution using a Shapiro-Wilk normality test (Wilks, 2011). To describe the uncertainties, these 95% confidence intervals of the values are indicated in brackets [ , ] behind the actual value. Therefore, significant differences in e.g., the mean of two values occur at the 5% significance level if the 95% confidence intervals do not overlap.

For the climate indices, months with exceptionally low NAO values (below the 25% percentile) are herein referred to as NAO−. Months with exceptionally high NAO values (above the 75% percentile) are herein referred to as NAO+. NAO values that fall between the lower and upper quartile are referred as NAO neutral. This classification is either done for all months together \((\text{NAO } 25\%/75\% \text{ threshold: } [-0.67, 0.77])\), or in the case of the annual cycle separate thresholds for each month of the year were computed \((\text{e.g., for August } [-1.17, 0.67], \text{ for December } [-0.46, 0.84], \text{ for April } [-0.63, 1.01] \text{ and for May } [-0.92,} \ldots)}
0.57). To measure the association between two variables, we mostly use the Spearman’s rank correlation coefficient instead of the Pearson correlation coefficient, as it reflects the strength of a monotonic relationship instead of a linear relationship, and is therefore more robust to outliers (Wilks, 2011).

3 Precipitation and moisture source characteristics

3.1 Mean and Annual cycle of precipitation

According to ERA-Interim, for the period February 1979–May 2017, the mean precipitation is $207 \pm [192, 224]$ mm year$^{-1}$ averaged over the study region. At the nearest gridpoint to the caves, it is slightly drier with $171 \pm [158, 185]$ mm year$^{-1}$. The North Atlantic cyclone track decays northward (Serreze and Barry, 2014), and up to ten times less precipitation occurs in northeast Greenland than on the southeast coast (Fig. 1). As is typical for regions with little precipitation (e.g., Pendergrass and Knutti, 2018), fewer events bring most of the total precipitation. On average, the five wettest days in a year produce 24% and around 16 days produce 50% of the total annual precipitation in the study region. Precipitation can happen throughout the year, but May and June are slightly drier on average whereas September is wettest (Fig. 4). September is the wettest month for 9 of 40 years, June is the driest month for 6 of 40 years, and April is the driest month for 8 of 40 years. September (as the wettest month) has the greatest variability (interquartile range of $0.30–1.24$ mm day$^{-1}$), whereas June (as the driest month) displays the least variability (interquartile range of $0.14–0.30$ mm day$^{-1}$). April also shows a large variability (interquartile range of $0.10–
0.80 mm day$^{-1}$) and is the month with the most positively skewed monthly precipitation distribution. Generally, precipitation over the Atlantic Arctic sector is stronger in winter months due to the enhanced North Atlantic cyclone track over the relatively warm open water and the moisture flux convergence specifically near to the Icelandic Low. For continental areas above 60° N, however, most precipitation occurs in July, August and September (ERA-Interim and ASRv1, Bromwich et al., 2016). This can be explained by higher cyclone and frontal activity in summer because of heating contrasts between snow-free land and snow areas (Serreze and Barry, 2014).

3.2 Mean and Annual cycle of moisture sources

While precipitation amounts are relatively constant during the year, the corresponding contributing moisture sources display a strong seasonality in magnitude and location (Fig. 5). In winter, most moisture sources are located over the North Atlantic above 45° N and the ice-free Atlantic sector of the Arctic Ocean with a maximum between Scandinavia and Svalbard. This maximum is most pronounced in January and then gradually diminishes until May. Starting with May, local moisture sources (from the study region or its direct surrounding) begin to contribute to precipitation and peak in June. In July, moisture sources seem to come mostly from land areas over the north Eurasian continent. September has the minimum amount of sea and land ice and represents a transitional phase, where there seems to be both land sources over Scandinavia and the majority of ocean sources over the North Atlantic. This could be a possible indicator why precipitation is strongest in September (Fig. 4). From October, the pronounced maximum over the Norwegian Sea appears again with minimal contributions from land.

The gradual transition from more North Atlantic, North Sea, Norwegian Sea and Barents Sea contributing moisture sources in winter to more local and continental Scandinavian and Eurasian contributions in summer can be partially explained by changes in the geopotential height of the 500 hPa surface (Fig. 5). The zonal geostrophic flow south of Greenland is stronger in winter than in summer, as shown by the stronger gradient of the geopotential height. The westerly zonal flow weakens in summer, specifically in June, which could explain why June has the smallest and least variable precipitation.

Another way to describe moisture transport is to look at the integrated water vapour transport (IVT, mean annual cycle in Fig. 6). Moist air masses from the North Atlantic are transported northeastward to the Scandinavian coast. By the influence of polar easterlies, moist air masses over the Norwegian Sea seem to be transported in the direction of northeast Greenland. This emphasises why the maximum of moisture source contribution is diagnosed over the Norwegian Sea for most months.

Evaporation over the Arctic Ocean seems to be prevented by sea ice and in summer, a gradual transition occurs towards more IVT in the Arctic. In June, IVT is larger near to the study region, which is an indicator for the more local moisture sources found by the Lagrangian moisture source diagnostic (Fig. 5). Furthermore, from July till September there is generally larger IVT over the Eurasian continent. This coincides with the large fraction of contributing moisture sources over the north Eurasian continent found by the Lagrangian diagnostic in these months.
To analyse regional contributions of moisture sources, different moisture source regions were defined by applying a classification algorithm (K-means clustering, e.g., Wilks, 2011). K-means clustering separates data in samples grouped after their similarities. In our case, we estimated similarity by first selecting the gridpoints that have contributed moisture sources over the study period and then computing the percentage of each gridpoint’s moisture source contribution to the total mean precipitation for each month of the year. Therefore, a table of 24051 gridpoints x 12 months (where \( \sum \text{gridpoints}=100\% \)) was fed to the algorithm (here: `sklearn`, Pedregosa et al., 2011). The algorithm then separates the gridpoints in a user-chosen number of clusters, here based on the annual cycle of relative moisture source contribution to precipitation in the study region.

The raw output of the K-means clustering is plotted in Fig. 7a. Although the gridpoints’ locations were not included in the algorithm, the clusters mostly cover homogeneous areas, which means that gridpoints that are near to one another display a similar behaviour in the relative moisture source contribution throughout the year. The algorithm recognises the features of cluster formations from Fig. 5: the green coloured cluster corresponds to the area of a pronounced maximum in moisture sources for most months, and the cyan coloured cluster corresponds to the local sources in summer directly above the study region. The K-means clustering algorithm separated the gridpoints into clusters displaying significantly different behaviour with respect to the 95\% confidence interval (Fig. 7b, c). The number of five distinct clusters shown here was chosen because it produced the best compromise between differentiating behaviour patterns and still having significantly different clusters. Another algorithm, spectral clustering (also available in `sklearn`, Pedregosa et al., 2011), produced similar results.

In winter, moisture sources over land contribute minimally (in January \( \sim 6\% \)), however, in summer, the majority of moisture sources come from land regions (in July \( \sim 62\% \), Fig. 7d). The moisture source contribution of sea ice areas is relatively low, but highest in June (23\%, Fig. 7d). As June is the driest month with the highest contribution of local moisture sources (Fig. 7), there is an indication that evaporation over sea ice near to the study region is contributing to precipitation in the study region. However, if those gridpoints are chosen that are defined with a sea ice concentration equal or above 0.9 (instead of 0.5, see Sect. 2.1), the contributions in all months decrease to a maximum of 15\% in June and is in most other months around 3\% (not plotted). Hence, large parts of contributing evaporation over a defined sea ice area occur over those gridpoints where the total area of the gridpoint is partially sea ice covered. Note that, sea ice areas as defined in Fig. 7d (gridpoints with sea ice concentration \( \geq 0.5 \)) change from month to month.

For more detailed analyses (and because the clustering algorithm cannot separate ocean from land sources), we now further refine the automated clusters with manual intervention. We distinguished between ocean (with sea ice) and land regions (compare Fig. 7a and Fig. 8a). The blue coloured ocean cluster in Fig. 7a does not differ between the Norwegian/Greenland and the Barents Sea moisture sources. To interpret the results in the context of NAO, we split the former blue coloured region into two ocean regions (2O and 4O), and distinguished between ocean (with sea ice) and land regions (compare Fig. 7a and Fig. 8a). Moreover, we divided the large former violet coloured cluster of Fig. 7a into two new groups: the 7O/7L cluster that contributed least (in total only 10\% of the former violet coloured cluster area) and into the 6O/6L cluster that contributed most (in total 90\% of the former violet coloured cluster area). This gives a better impression of areas contributing that are far away...
from the study region. Hence, the new separation results in seven ocean and four land clusters (Fig. 8a, the small 4L cluster area is not a significant contributor and therefore neglected).

For the ocean clusters 2O, 3O, 4O & 5O, the relative maximum is in winter while the minimum is in summer (Fig. 8e). The Norwegian Sea (3O, Fig. 8) is one of the main moisture sources, specifically during winter. The Norwegian Sea is located below the North Atlantic storm track and is a main region for convective warming (Tsukernik et al., 2004) because of the relatively warm ice-free ocean and the relatively dry and cold air above resulting in the highest total column vapour (precipitable water) in the Arctic. In addition, in the colder seasons, more evaporation in 2O, 3O, 4O & 5O occurs because of larger vertical humidity gradients and stronger moisture transport due to higher temperature gradients between the subtropics and the Arctic (Serreze and Barry, 2014). The ocean clusters 1O, 7O peak in June and the 6O cluster peaks in October possibly as a consequence of more sea ice free areas in October.

All land clusters have their maximum contribution in July except for the local 1L cluster where the maximum occurs in June (Fig. 8d, g). A large part of summer Arctic precipitation comes from evapotranspiration over nearby land regions by regional recycling of water vapour that peaks in summer due to enhanced convection from stronger solar insolation (Serreze and Barry, 2014). The moist continental air masses from non-local regions over the north Eurasian continent are transported in summer towards northeast Greenland by a cyclone with a trough axis between Iceland and Svalbard (see 500 hPa geopotential height in Fig. 5 and IVT of Fig. 6). Large parts of these land clusters (1L, 5L, 6L, Fig. 8a) and the study region itself are located in the continuous permafrost zone (Brown et al., 1998). Thus, enhanced evapotranspiration in summer could also be explained by thawing of the uppermost permafrost layers (Biskaborn et al., 2019).

4 Changes to precipitation characteristics and moisture sources

4.1 Interannual variability from the North Atlantic Oscillation (NAO)

The NAO is one of the most important patterns of atmospheric circulation variability over the middle and high latitudes, specifically in the cold season (November–April; Hurrell et al., 2003). In its negative phase (NAO−), there is a weaker subpolar low over Iceland and a less pronounced subtropical high over the Azores, while in its positive phase (NAO+), a larger pressure gradient leads to stronger northeastward-oriented southwesterly surface winds over the North Atlantic. In the following, we assess whether variability in the NAO affects the inter-annual variability of precipitation and moisture sources of the study region.

4.1.1 Relationship between NAO and precipitation

Generally, precipitation in the study region increases with increasing NAO index and is more variable (Fig. 9a). Mean precipitation with NAO+ is larger than with NAO− (Fig. 9a), specifically for January and April (Fig. 9b). As expected, variability in summer precipitation is not driven by NAO variability (when NAO is at its weakest, hence most negative). The
month with the largest variability, September (Fig. 4), shows a non-significant increase in precipitation for months with NAO+ compared to those with NAO− (Fig. 9b).

4.1.2 Relationship between NAO and moisture sources

We start by analysing whether there are differences in the contributing moisture sources of the study region for NAO+ versus NAO− months for each individual cluster region separately over the annual cycle (Fig. 10). Significant differences between the NAO phases could only be found for some regions in January, April and September (Fig. 10), thus, these months were investigated in more detail (Fig. 11). For January NAO+ months, evaporation and moisture transport to the study region was stronger from the eastern Norwegian Sea and Barents Sea (Fig. 11a), which corresponds mainly to the 3O and 4O cluster (Fig. 8a). In those clusters, significant differences between NAO− and NAO+ were found only for January (Fig. 10). For April and September NAO+ months, evaporation and moisture transport to the study region was enhanced from large parts of the North Atlantic above 45° N and of the ice-free Atlantic sector of the Arctic Ocean (Fig. 11b, c). Moisture source dependence on NAO in April was largest in the 2O, 3O, 4O, and 5O ocean clusters as well as the 5L land cluster (Fig. 10). In September, the 2O ocean as well as the 5L and 6L land moisture source clusters contributed significantly more for NAO+ than for NAO− months (Fig. 10). The larger NAO dependency of the 4O cluster, part of Barents Sea, compared to the 2O cluster, part of northeast Atlantic and western Norwegian Sea (Fig. 10), is another justification for the manual splitting of these areas that were clustered as one region by the K-means clustering (compare Fig. 7a and Fig. 8a). To conclude, there was an increased moisture uptake and transport to the study region for NAO+ months in January, April and September from the North Atlantic above 45° N and the ice-free Atlantic sector of the Arctic Ocean, specifically from the Norwegian Sea, which resulted in more precipitation over the study region for these months in the NAO+ phase.

4.2 Relationship to sea ice

A clear decreasing sea ice trend north of 30° N has been observed for the last 40 years. From ERA-Interim data, we compute 0.35 [0.26, 0.43] million km² decade⁻¹ yearly minimum sea ice area decrease (mostly September) and 0.67 [0.54, 0.80] million km² decade⁻¹ yearly maximum sea ice area decrease (mostly March). Bintanja and Selten (2014) showed that decreasing sea ice will enhance future evaporation in the Arctic, as open water at freezing point will replace ice at temperatures far below zero. We now test the working hypothesis that reduced sea ice results in larger contributing moisture sources for our study region.

For total precipitation in the study region, Generally, there is no significant correlation between precipitation in the study region and Arctic sea ice area was found when looking at each month of the year separately. Adding a time lag between sea ice and resulting precipitation of plus one or two months also resulted in no significant correlation. When comparing the seasonal mean precipitation against the maximum sea ice area of that year, we found some significant but small relations of increasing precipitation in autumn and winter and NAO− for decreasing maximum sea ice (R²-values of 0.14 and 0.13). The moisture uptake region 3O (mainly Norwegian Sea) is one of the major moisture source contributors, however it is also mostly sea ice-free which might explain why we could not find strong relations between precipitation in the study region and Arctic sea ice area.
A clearer insight might emerge when looking at the relation of each ocean cluster’s attributed moisture sources against the respective relative sea ice area. When considering the total attributed moisture sources for each ocean cluster across the whole year, no significant correlations (Spearman’s rank correlation with p-value<0.05) between moisture sources and relative sea ice area are found (Fig. 12a). If individual months are considered for each ocean region, then few significant correlations are observed. The main exception is for December, where the majority of regions display a significant correlation with relative sea ice area (Fig. 12a). Changes in the sea ice area can only poorly describe the variance in the moisture sources of entire ocean cluster areas (Fig. 12a) because large parts of them never had sea ice from 1980 till 2016 (for that month of the year or even not at all). Thus, the effect of sea ice in a given area on the attributed moisture source was further investigated by considering sub-regions of clusters with only those gridpoints that had once over the study period a sea ice concentration of above 0.5 (Fig. 12b). As this is different for each month of the year, for each month a different fraction of the ocean cluster was analysed. Compared to Fig. 12a, Fig. 12b shows that the annual contribution from sea ice related fractions of the 4O, 5O and 6O clusters is significantly correlated to decreasing sea ice. In addition, some more correlations for individual months were found over those specific fractions of the clusters (strongest in autumn-winter months, Fig. 12b). However, moisture sources over the sea ice related sub-regions as defined in Fig. 12b contribute on average only 16% to the entire diagnosed moisture sources. Hence, the correlations of moisture sources against sea ice (Fig. 12b) describe only a very small fraction of the entire moisture sources for the study region, which also explains why we did not find correlations between Arctic sea ice area and precipitation in the study region.

When specifically considering moisture source regions, the 1O ocean cluster (closest to the study region) displays significant correlations for seven months (September till April) with increasing attributed moisture sources over 1O for decreasing relative sea ice area (Fig. 12a, b). Changes in the sea ice amount in 1O change the general evaporation over the area, possibly directly influencing precipitation in the study region. For clusters located further away, changing sea ice might also directly effect the evaporation over that area. However, contributing moisture sources depend also on the moisture transport to the study region, which changes with decreasing sea ice as well. This might be one reason for the weak relations that we found. Looking at all ocean clusters together, we only found a correlation for June, which was positive: this is not expected and is likely a statistical coincidence.

### 4.3 Temporal evolution

According to ERA-Interim, the study region has warmed by 2.8 [1.6, 4.0] °C (two metre temperature) in the 40-year period 1979–2018. We now test whether such a trend is also detectable for precipitation (or regional moisture sources) by looking at its temporal evolution (Fig. 13a). A possible trend was tested by computing the Pearson correlation coefficient through a linear fit between time and precipitation or moisture sources. Linear regression analysis requires that residuals from the fitted regression line are normally distributed, which is not always the case for monthly data. Therefore, the more robust non-parametric Mann-Kendall trend test was also applied to detect whether a monotonic upward (downward) trend had occurred, which does not necessarily need to be linear (Wilks, 2011). The yearly, winter, spring and summer precipitation from 1979
to 2018 at the study region do not show a significant trend. There is a small increasing trend in autumn precipitation of 0.09 [0.01, 0.17] mm day$^{-1}$ decade$^{-1}$ (significant at the 5 % level for both the linear regression and Mann-Kendall trend tests).

Of specific interest is the changing contribution of different moisture source regions to the precipitation of the study region over time (1980–2016). Over the annual mean, no temporal trends were identified from any of the land or ocean clusters and also not from the relative land-ocean moisture source contribution. When looking at the monthly time series, some sporadic slight trends are visible, however, they are too small in absolute numbers to be further considered. For example, in October, the only month with a small overall detectable increasing precipitation trend, very small significant trends of increasing contributing moisture sources with time were detected for the 7O cluster and for the overall land contributions. This is also in-line with the increasing attributed moisture sources that were found for decreasing sea ice over the 7O cluster in October (Fig. 12a, b).

The possible reasons for the absence of precipitation trends, despite the observed increase in temperature and loss of Arctic sea ice during recent decades (Comiso and Hall, 2014) are discussed in Sect. 5.3.

5 Discussion

5.1 Moisture source regions and relation to the NAO and GBI

In Sodemann et al. (2008a), the majority of moisture sources (>85%) of the northern and east-central Greenland Ice Sheet are over the North Atlantic and Nordic Seas above 35° N, similar to our findings. In Nusbaumer et al. (2019), Greenland moisture sources were estimated by water tracers using the Goddard Institute for Space Studies climate model and MERRA2 horizontal winds (mean of 1980–2015). They also found similar results: the dominant moisture source in northeast Greenland is the North Atlantic and the ice-free Atlantic sector of the Arctic Ocean except for summer (JJA) where continental sources are substantial.

For NAO+ winter months, Sodemann et al. (2008a) found that moisture sources for the northern and east-central Greenland Ice Sheet are larger over the Norwegian Sea, which is qualitatively similar to our findings. In case of NAO− winter months, moisture sources were found to be further southward (maximum over 40° N–60° N), which does not agree with our study, possibly because of the different regions considered. The same general relationship of increasing precipitation for higher NAO indices was found over the ice sheet by Sodemann et al. (2008a) and Koyama and Stroeve (2019). With a high NAO index, the pressure gradient between the subpolar low and subtropical high is larger, specifically in winter months, which results in stronger westerlies and increased intensity and number of storms in Iceland and the Norwegian Sea (Hurrell et al., 2003). This shift in the North Atlantic storm activity explains the larger moisture sources over the Norwegian Sea for NAO+ and the positive correlation between NAO index and precipitation amount.

We repeated the analysis of the NAO-index for the Greenland Blocking Index (GBI, dataset from NOAA, 2020 (b) based on Hanna et al. (2016)) that is defined by the mean 500hPa geopotential height for the 60° N–80° N, 20° W–80° W region (e.g., Hanna et al., 2016). The higher the GBI, the weaker and less variable is the precipitation, specifically in January and April (not shown). Due to the strong negative correlations between the NAO-index and the GBI with Pearson correlation coefficients of minimum -0.96 in June and maximum -0.74 in December, we get relations between GBI and precipitation or
moisture sources that are very similar but reversed to those from the NAO-index, which is in line with Hanna et al. (2016) and Nusbaumer et al. (2019).

5.2 Relation to temperature and sea ice

Bintanja and Selten (2014) predicted a relative change of Arctic precipitation per degree surface temperature warming of 4.5 % K$^{-1}$ in the 21st century, which is larger than the global rate (1.6–1.9 % K$^{-1}$), due to feedback mechanisms associated with retreating winter sea ice. For our study region, we did not yet observe significant amplified precipitation sensitivity for the recent decades, but our estimates of 3.8 [-1.6, 9.3] % K$^{-1}$ over the annual mean do not contradict Bintanja and Selten (2014). We also found slight significant correlations of increasing precipitation for higher surface temperatures for January, February, March, September and November. A more in-depth analysis could look at temperature changes from the top of the inversion height or from the actual moisture source location.

The study region in northeast Greenland is in close proximity of the Greenland Sea that has lost sea ice rapidly in the last decades, specifically in winter (Onarheim et al., 2018; Bliss et al., 2019). While the Greenland Sea has lost around a third of its initial winter sea ice extent, the Barents Sea has even lost half of their winter sea ice extent (compared to ice conditions of 1979–1989, Stroeve et al., 2016). According to our analyses, only 16 % of the diagnosed moisture sources come from the sea ice relevant sub-regions, which might explain why we found only weak correlations between precipitation and sea ice extent. In Svalbard, for example, more moisture comes from regions where sea ice loss over the last decades was largest, e.g., Barents/Kara Sea (Faber et al., 2017), and the influence of changing sea ice might be stronger there.

5.3 Temporal trend of precipitation and moisture sources

According to Bintanja and Selten (2014), precipitation will increase around 50 % (RCP 8.5 scenario, 25 % for RCP 4.5) in northeast Greenland based on the differences between the means 2006–2015 and 2091–2100. The reasons are a strong increase in local surface evaporation through Arctic warming and retreating sea ice and to a lesser degree enhanced moisture inflow from lower latitudes. We did not find a temporal trend in annual precipitation for the 40-year period 1979–2018. At Danmarkshavn (Fig. 1), no precipitation trend was found for the period 1981–2012 either but a significant trend (p-value<0.05) was found for 1971–2000 with 36 mm year$^{-1}$ decade$^{-1}$ and for 1961–1990 with 48 mm year$^{-1}$ decade$^{-1}$ (Mernild et al., 2015). From the reanalysis products ASRv1 and ASRv2 for 2000–2012, no precipitation trend was visible for northeast Greenland and also not from observations for Danmarkshavn or Station Nord for 2000–2007 (Bromwich et al., 2016; Koyama and Stroeve, 2019).

Some of the inter-annual variability of precipitation occurs because of variability in the NAO. NAO has decreased in summer since the 1990s and winter NAO variability has increased (Hanna et al., 2015). This might be a reason why a significant annual temporal trend in the precipitation of the study region is not yet visible (Fig. 13a). According to Hurrell and Deser (2010), since 2001, there have been more winter days with strong anticyclonic ridges over Scandinavia (“Blocking”) and over western Europe (“Atlantic Ridge” regime) compared to NAO+ or NAO−, hence, differentiating between four regimes could improve the analysis.
We found a small trend of increasing precipitation over the 40-year period 1979–2018 for autumn (Fig. 13e). October is among the months where relations were observed between increasing moisture source contributions and decreasing sea ice in some of the ocean clusters (Fig. 12b). It is also the month with the largest temperature increase of \(1.5 \pm 0.9, 2.1\) °C decade\(^{-1}\) compared to \(0.7 \pm 0.4, 1.0\) °C decade\(^{-1}\) in the annual mean for 1979–2018. This is consistent with future predictions of Bintanja and Selten (2014) where autumn is the most sensitive season with the largest predicted precipitation increase.

5.4 Limitations

Precipitation is difficult to quantify, specifically at higher latitudes and in remote areas (Serreze and Barry, 2014). No direct precipitation measurements exist that could have been compared to the reanalysis data. The nearest observational stations are exposed to a more maritime climate (Station Nord & Danmarkshavn, Fig. 1), but the study region is inland over heterogeneous terrain at around 740 m a.s.l., where orographic uplift of moist air masses might alter local precipitation (Serreze and Barry, 2014). Precipitation measurements (corrected for undercatch) of Station Nord and Danmarkshavn show a good agreement with the Arctic System Reanalysis (ASRv1, Koyama and Stroeve, 2019). ASRv1 and ERA-Interim have similar precipitation estimates in the study region (December 2006–November 2007, Bromwich et al., 2016), providing some confidence in the ERA-Interim estimates. Instead of using only the NAO-index or GBI, a more sophisticated classification into 4–7 weather patterns (e.g., Ortega et al., 2014; Grams et al., 2017; Falkena et al., 2020) together with a case study analysis of the pathway of moisture source transport for each weather pattern could be done in a subsequent study to better understand the dominant drivers and sources of precipitation in our study region.

The K-means clustering algorithm was used as a simple tool to construct different regions in which each gridpoint shares a common feature, i.e., the mean annual cycle of relative moisture source contributions. By dividing the time series in half and repeating the K-means clustering approach for these two time series separately, we found almost no differences in the classification of the clusters (not shown) which gives a hint that the clusters are stable over time. Incorporating a more complex clustering approach that takes the annual cycle, NAO and sea ice into account could, however, give interesting new insights.

Besides the uncertainties from precipitation estimates, there are also limitations from the Lagrangian moisture source diagnostic. We showed in Sect. 2.2 that only 48.3% of precipitation could be attributed to moisture sources. The remaining sources were detached from the surface (moisture uptake above the PBL) or were unidentifiable. This number is lower than in comparable studies, and could be explained by the dry conditions in the region. Parametrised convection could also be responsible for a significant amount of vertical moisture transport and increases the non-accounted moisture uptake during summer (Sodemann and Zuber, 2010). In the moisture source diagnostic, either evaporation or precipitation can occur in each time step of 6 h. Therefore, using shorter time steps and a finer grid resolution (e.g., using the ERA5 reanalysis dataset instead of ERA-Interim) could influence the diagnostic. Not distinguishing between below and above PBL height moisture uptake could be a way to increase the attribution (Fremme and Sodemann, 2019) (e.g., Baker et al., 2015; Fremme and Sodemann, 2019; Hu et al., 2020). We found similar moisture source regions for both
approaches, a direct comparison to other models would be necessary to estimate uncertainties resulting from the choice of the Lagrangian model itself (Van Der Ent and Tuinenburg, 2017; Winschall et al., 2014).

6 Conclusions

We analysed the present-day moisture sources for a region in northeast Greenland at 80° N, a polar desert with a mean annual precipitation of 207 [192, 224] mm year\(^{-1}\) (1979–2018, ERA-Interim). We used the Lagrangian moisture source diagnostic of Sodemann et al. (2008a) to estimate the origin of water vapour for precipitation over the study region between February 1979 and May 2017. We applied a classification algorithm (K-means clustering) to group gridpoints into clusters after their similarities based on the annual cycle of relative moisture source contributions.

The main moisture source region is the North Atlantic above 45° N and the ice-free Atlantic sector of the Arctic Ocean with a maximum over the Norwegian Sea (30% in the mean in January, Fig. 8e), which is largest for months in the NAO+ phase, specifically in January and April (Fig. 10, 11). This leads to stronger and more variable precipitation in the study region for these months (Fig. 9). While the main moisture sources are over the ocean in winter months, in summer the contributions from land regions (locally or north Eurasian continent) are largest (60% in July, Fig. 7d). The month with the highest precipitation is September (contributions from both land and ocean moisture sources), whereas the month with the least precipitation is June (mostly land sources, Fig. 4, 5).

The study region has warmed by 2.8 [1.6, 4.0] °C and surrounding Arctic sea ice has retreated for the 40-year period considered. The amount of moisture uptake (and transport) from sea ice related regions increased with decreasing sea ice for the study region, specifically in October and December (Fig. 12). Thus, one might expect to see already an increasing trend in precipitation in the study period. However, as most moisture source contributions come from permanently ice-free ocean regions and because of the large inter-annual variability from the NAO, we could not detect considerable trends in precipitation in the study region with the exception of autumn where precipitation increases by 8.2 [0.8, 15.5] mm dec\(^{-1}\) over the period. To better understand the underlying mechanisms, future studies could focus on the pathway of moisture source transport during extreme precipitation events, which account for a large part of total precipitation.

Longer time periods need to be considered for more robust results. The acquisition and analysis of palaeoclimate proxies might yield further insights into the long-term climate dynamics of the region, thus further providing a baseline and enabling improved predictions in this highly sensitive region in the future.

Data availability. The ERA-Interim reanalysis data used in this study can be accessed from the European Center for Medium-Range Weather Forecasts (ECMWF; https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim Dee et al., 2011). The monthly moisture source estimates from the Lagrangian diagnostic (February 1979 – May 2017) are made publicly available via Zenodo: https://doi.org/10.5281/zenodo.3972882.
Author contributions. LS undertook the majority of the analyses, interpreted the data, and wrote the majority of the manuscript. LL undertook the computation of the Lagrangian moisture source diagnostic. GM and FM conceived the project and wrote parts of the manuscript. All authors directly contributed to the manuscript through discussion or writing.

Competing interests. The authors declare that they have no competing interests.

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Figure 5. Annual cycle of mean monthly attributed moisture sources contributing to precipitation in study region over the period February 1979–May 2017 (gridpoints coloured after their contribution between $35^\circ\text{N}$–$90^\circ\text{N}$, contributions $<3\%$ further southward). The mean sum of moisture sources over all gridpoints (i.e. accounted precipitation) is given for each month with its 95\% confidence interval and is only a part of the total precipitation (Fig. 4). The averaged mean 500 hPa geopotential height (grey lines) and the mean ice area cover (grey shaded area) are depicted as well.
Figure 6. Annual cycle of integrated water vapour transport (ERA-Interim monthly mean of February 1979–May 2017) [40°–35° N–90° N]. The magnitude of IVT is depicted by the colours (note the uneven color scale) and the arrows indicate the IVT direction. The same scale is applied for each month. For gridpoints with IVT < 30 kg m⁻¹ s⁻¹ only, the arrow length depicts also the IVT magnitude.
Figure 7. (a) K-means clustering of gridpoints into five clusters. The annual cycle of mean contributing moisture sources to the precipitation in the study region is plotted for each cluster in (b) absolute and (c) relative number. Shaded areas represent the 95% confidence interval of the mean. In (d), relative moisture source contributions from the ice-free ocean (sea ice concentration <0.5), the sea ice (sea ice concentration \(\geq 0.5\)) and the land areas (same thresholds for land/sea mask) are depicted. The values for the sea ice concentration and hence the sea ice areas change throughout the months and years.
Figure 8. (a) K-means clustering with additional manual separation. The annual cycle of moisture sources contributing to precipitation in the study region is plotted for each cluster in (b, c, d) as absolute number and in (e, f, g) as relative number in % of the total diagnosed moisture source amount. The ocean (with sea ice) regions in (b, c, e, f) are separated from the land regions in (d, g), and land regions have in (a) more transparent colours. We use two graphs for the ocean regions for readability; grey lines in (b, c, e, f) correspond to the missing ocean regions for comparison. Shaded areas represent the 95% confidence interval of the mean. Summing up the different regions of relative contribution for ocean (e, f) and for land (g) would give the total land or ocean (with & without sea ice) contribution shown in Fig. 7d. In (h), the used cluster abbreviations and descriptions of approximate geographical regions of the K-means clusters of (a) are listed.
Figure 9. (a) Scatterplot of precipitation in study region against the NAO index for in total 460 months (February 1979–May 2017). Months were separated into months with NAO indices below or equal to the 25% percentile (NAO−), above or equal to the 75% percentile (NAO+), or in between the 25% and 75% percentile (NAO neutral). (b) Mean annual cycle of precipitation in study region for months with NAO being below or equal to the 25% percentile (NAO−) and above or equal to the 75% percentile (NAO+). For each month of the year, month-specific 25% and 75% percentile thresholds were computed. The shaded areas represent the 95% confidence interval of the mean.
Figure 10. Mean annual cycle of contributing moisture sources distinguishing between months with NAO indices above or equal the 75% percentile (NAO+), below or equal the 25% percentile (NAO−) and those in between (NAO neutral) for the different clusters. The same thresholds as in Fig. 9b were chosen. Shaded areas represent the 95% confidence interval of the mean of months for the highest and lowest NAO index quartile (February 1979–May 2017). The legend for the used cluster abbreviations is in Fig. 8a, h.
Figure 11. Normalised moisture source deviation between months with NAO indices being above or equal the 75% percentile (NAO+) and months being below or equal the 25% percentile (NAO−). The same thresholds as in Fig. 9b were chosen. To better compare the moisture source deviations they were normalised by dividing each grid point by the maximum difference between the months with NAO+ and the months with NAO−, which gives e.g. the gridpoint with the largest positive difference a normalised deviation of 1.

Figure 12. (a): Spearman’s rank correlation coefficients between moisture sources from each ocean cluster against relative ice area for each month and year. If there is no significant correlation (p-value ≥ 0.05), the corresponding box is shaded in grey. (b): same as in (a) but looking only at the area of those ocean gridpoints that had once a sea ice concentration of above 0.5 during the study period (effectively reducing each cluster’s area to the sea ice relevant areas). The legend for the used cluster abbreviations is in Fig. 8a, h.
Figure 13. (a) Annual and (b-e) seasonal temporal evolution of precipitation amount in the study region from ERA-Interim with estimates of a possible linear trend and its corresponding p-values. In autumn (SON), the existence of a positive upward linear trend can not be rejected under the 6% level.