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What Are the Most Important Contributors to Arctic Precipitation—When, Where, and How?

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ABSTRACT

The Arctic climate system is experiencing large changes associated with global warming. Precipitation is a crucial factor linking the atmosphere with other climate compartments, for example, ocean and cryosphere. Using atmospheric reanalysis (ERA5) we assess the role of atmospheric weather systems, that is, atmospheric rivers, cyclones, and fronts. When: Averaged over the whole Arctic (> 70° N), a strong seasonal cycle exists with twice as much precipitation in summer than in winter when frozen precipitation is mainly brought by cyclones. In summer, the highest total precipitation amounts are rather equally contributed by all weather systems. Where: In winter, the Arctic North Atlantic region experiences by far the highest precipitation amounts, whereas in summer precipitation is more evenly distributed over the whole Arctic. How: Overall, cyclones are the most important contributor to precipitation. The highest precipitation intensity occurs when atmospheric rivers, cyclones, and fronts coincide, whereas the lowest precipitation rates occur when precipitation cannot be attributed to any of these weather systems. This residual makes up almost half of the annual snowfall, most of it in the central Arctic, and 25% of rainfall. Marine Cold Air Outbreaks can explain part of the residual. The amount and drivers for light "trace" precipitation requires further investigation.

1 | Introduction

The Arctic cryosphere is an integral part of the Earth's climate system, which has experienced significant changes due to climate change (Wendisch et al. 2023). In general, the Arctic warming amplifies the hydrological cycle and, therefore, the precipitation in the Arctic (Box et al. 2018; Bintanja et al. 2020). Previous studies (Gimeno-Sotelo et al. 2018; Vihma et al. 2016) have shown that the different effects of precipitation in the Arctic climate system depend strongly on the type of precipitation and the season. However, due to the high uncertainty of precipitation observations in polar regions (Levizzani et al. 2011; McCrystall et al. 2021), large uncertainties in the spatio-temporal distribution and phase composition of precipitation exist. Given the observational limitations, most studies of Arctic precipitation rely on reanalysis data. Thereby, the European Reanalysis ERA5 has been recommended by Barrett et al. (2020) for precipitation analysis.

Generally, two major moisture sources contribute to the precipitation in the Arctic. These are the locally enhanced evaporation due to the missing insulation effect of sea ice (Bintanja and Selten 2014) and the poleward moisture transport from lower latitudes (Zhang et al. 2013). Bintanja et al. (2020) suggest that the increase in precipitation is mainly related to an increase in poleward moisture transport. Generally, poleward moisture transport is mainly associated with extratropical cyclones (CYCs) and atmospheric rivers (ARs) (Sorteberg and Walsh 2008; Woods and Caballero 2016). ARs are defined as long-narrow bands that transport a huge amount of heat and moisture from the lower latitudes toward higher latitudes. Generally, they are responsible for the majority of the poleward moisture transport in and across mid-latitudes, although they only cover 10% of the Earth's circumference (Nash et al. 2018). Although the relevance of extratropical CYCs and ARs for poleward moisture transport into the Arctic is generally acknowledged, there is still a lack of knowledge regarding to what extent they contribute to precipitation in the Arctic. Therefore, the overarching goal of this study is to gain a better understanding of the extent to which different weather systems contribute to precipitation in the Arctic. Herein, an important aspect relates to the phase of precipitation that has strong implications for the surface characteristics of the Arctic climate system (Vihma et al. 2016).

Within a recent study (Lauer, Rinke, et al. 2023), we established a new methodology to analyze the influences of weather systems, that is, ARs, CYCs, and also atmospheric fronts (FRONTS), on Arctic precipitation and applied it to two field campaigns in the Arctic North Atlantic sector. The analysis of two periods covered about a month each in early spring and early summer, respectively, and led us to hypothesize that during early spring, precipitation is mainly associated with CYCs, whereas during early summer, ARs and FRONTS are more effective. About one-third of the precipitation was classified as residual, that is, not related to any weather system. The residual was reduced significantly when a precipitation threshold (to exclude light precipitation) was applied, which is often used to eliminate immeasurable precipitation. The neglect of precipitation with rates less than $0.1\,\mathrm{mm\,h^{-1}}$ would increase the contribution of ARs, CYCs, and FRONTS to the total precipitation by a factor of two. To investigate whether these results can be generalized, we now apply the methodology of Lauer, Rinke, et al. (2023) to the long-term (1979–2022) ERA5 reanalysis record over the full Arctic and address the following questions:

Q1: Is there a seasonal dependence in the relation of precipitation to different weather systems?

Q2: How is the precipitation phase associated with different weather systems?

Q3: What is the main contributor to residual precipitation, that is, precipitation not associated with weather systems on the synoptical scale?

2 | Methods and Material

The results in this study rely on the fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF) global climate and weather reanalysis ERA5 (Hersbach et al. 2020). In this study, data from 1979 to 2021 is used as satellite measurements have been available since then, which are essential for the Arctic due to the sparse ground-based observations. ERA5 provides different forms (convective, large-scale) and types (snow, rain) of precipitation with one hourly temporal resolution and 0.25°×0.25° (about 31 km) horizontal resolution. As in the latitude–longitude system, the area of the ERA5 grid cells decreases toward higher latitudes, we compute area-weighted averages when calculating region-wide precipitation averages. For convenience, we convert the original output, that is, precipitation accumulated over the last hour, into mm per day.

To analyze the contributions of the different weather systems to precipitation in the Arctic, we distinguish between AR-, CYC-, and front-related precipitation for each grid cell following Lauer, Rinke, et al. (2023). Herein, the ARs are detected with the second version of the detection algorithm by Guan and Waliser (2015) (Guan et al. 2018; Lauer, Mech, and Guan 2023) based on an integrated water vapor transport threshold and geometry criteria. For CYC detection, the sea level pressure-based algorithm of Wernli and Schwierz (2006), refined by Sprenger et al. (2017) was used. FRONTS are diagnosed from the horizontal gradient of the equivalent potential temperature at 700 hPa (Jenkner et al. 2010; Schemm et al. 2015). As these weather systems can be simultaneously diagnosed at one grid point, we define seven different components: only ARs (O-AR), only cyclones (O-CYC), only fronts (O-FRONTS), ARs co-located with cyclones (AR-CYC), ARs co-located with fronts (AR-FRONTS), AR co-located with cyclones and fronts (AR-CYC-FRONTS), and cyclones co-located with fronts (CYC-FRONTS). Further, we define grid cells in which the precipitation cannot be assigned to any of these features as *residual*. We aggregate data to monthly means and divide the Arctic (northerly than 70° N) into eight equally sized subregions (Table 1): Arctic Ocean Pacific, Arctic Ocean Atlantic, Arctic North Atlantic, Kara and Barents Seas, Laptev Sea, Chukchi and Beaufort Seas, Canadian Archipelago, and Greenland.

3 | Results

3.1 | Spatiotemporal Variation in Total Precipitation

The cold conditions of the Arctic, here defined as north of 70° N, lead to snow being the dominant type of precipitation across the Arctic. Based on ERA5 reanalysis data, 70% of the Arctic annual

TABLE 1 | Definition of eight subregions based on their coordinates.

Region	Latitude	Longitude
Arctic Ocean Pacific	80°–90° N	90° E–90° W
Arctic Ocean Atlantic	80°–90° N	90° W–90° E
Arctic North Atlantic	70°–80° N	20° W–40° E
Kara and Barents Seas	70°–80° N	40° E–100° E
Laptev Sea	70°–80° N	100° E–160° E
Chukchi and Beaufort Seas	70°–80° N	160° E–140° W
Canadian Archipelago	70°–80° N	80° W–140° W
Greenland	70°–80° N	20° W–80° W

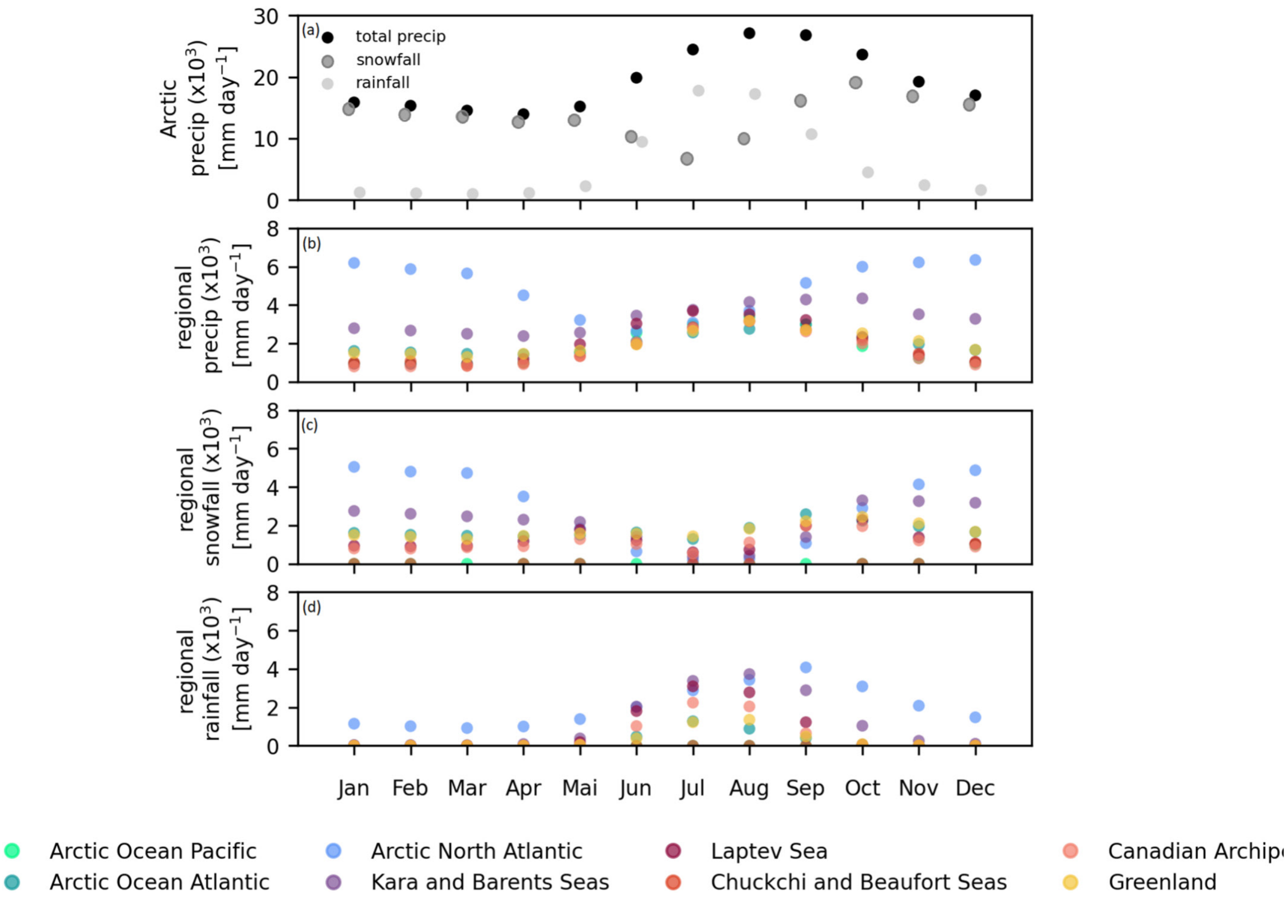

FIGURE 1 | Annual cycle of (a) total precipitation (black dots), snowfall (dark grey dots), and rainfall (light grey dots) for the entire Arctic (north of 70° N), (b) regional total, (c) snowfall, and (d) rainfall for each subregion (indicated by colors). All based on ERA5 (1979–2021).

precipitation falls as snow, while the other 30% is in the form of rain (Figure 1a). Overall, convective precipitation plays a minor role, with only 7% on average, already hinting at the importance of synoptic systems. However, there are distinct seasonal and regional differences in the distribution of rain and snow (Figure 1). Most precipitation falls in late summer and early autumn (July–October) as a consequence of rain peaking in July–August and the rising amount of snowfall in September at the time of the sea ice minimum, and thus highest evaporation from the ocean. In contrast, the lowest precipitation amounts occur during the extended winter (December–April), being roughly a factor of two lower than the maximum in August.

Liquid precipitation (rain) only shows notable amounts from June to October and has the highest values in the Arctic North Atlantic and Kara and Barents Seas (Figure 1). In spring, autumn, and winter, snow is the dominant type of precipitation and is mainly concentrated over the Arctic North Atlantic (~30%) and, to a lesser extent, over the Kara and Barents Seas (~15%). The other 55% is rather evenly distributed over the other regions. In summary, the Arctic North Atlantic region, featuring the largest fraction of open ocean, dominates Arctic precipitation most of the year, though during a short summer period (June to September), all regions contribute rather equally to Arctic precipitation. The special role of the Arctic North Atlantic region can also be seen when looking at convective precipitation that only has a significant contribution from early autumn to early spring (October–April) in this region (not shown).

3.2 | Precipitation Related to ARs, CYCs, and FRONTS

We now investigate the contribution of the weather systems, that is, ARs, CYCs, and FRONTS, to the total precipitation. In total, 56% of the total annual precipitation is associated with at least one of these systems, while 44% of the precipitation is classified as residual (Figure 2a). Nearly 70% of the weather system-related precipitation is associated with CYCs, whereby more than half of the CYC-related precipitation (58%) is concentrated in O-CYC events when CYCs are not co-located with ARs and FRONTS. This is even the case on the regional level, with O-CYC being the dominating weather system related to precipitation in each region (Figure 2a,b). In contrast to CYCs, ARs (33%), and FRONTS (43%) contribute more to precipitation if they are co-located with at least one of the other weather systems. Although AR-related precipitation rates are lower compared to CYCs and FRONTS, they are more intense as they only cover small areas (Figure 2c,d). The higher precipitation fractions associated with CYCs and FRONTS are due to the fact that they occur more frequently and cover a larger area compared to ARs. In general, CYCs and FRONTS are 2–4 and 2–3 times larger in area than ARs, respectively (Figure 2c). Further, they occur 2–3 times more often than ARs (not shown).

The highest precipitation rates associated with ARs, CYCs, and FRONTS are concentrated over the Arctic North Atlantic and the Kara and Barents Seas. In total, 70% of the weather

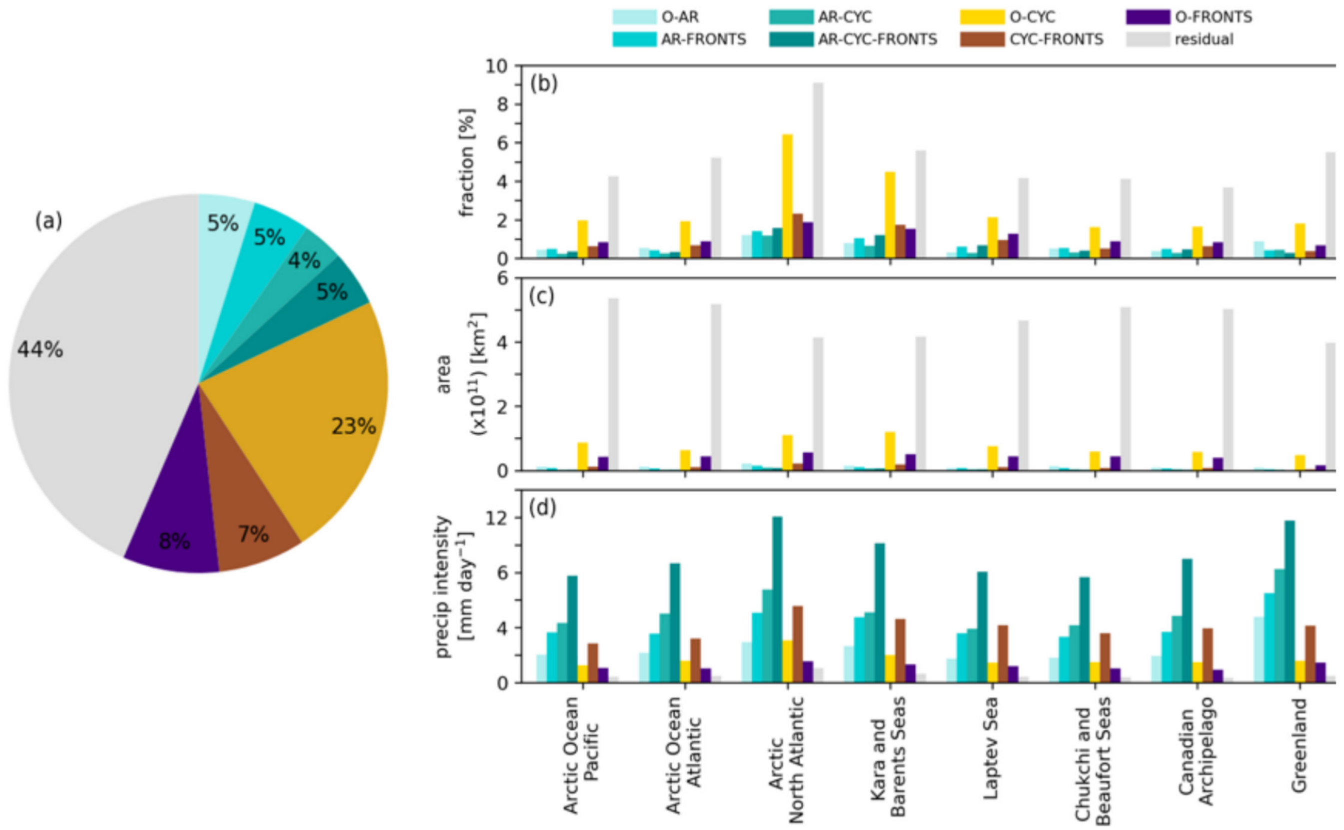

FIGURE 2 | (a) Fraction [%] of annual precipitation attributed to the different weather systems over the full Arctic; (b) same as (a) but split into the different subregions of Table 1; (c) same as (b) for the precipitation area covered by the different weather systems; (d) same as (b) for precipitation intensity. All based on ERA5 (1979–2021).

system-related precipitation is confined to these two regions, while the other 30% is evenly distributed over the other subregions, similar to total precipitation. Not surprisingly, the highest intensities in all regions occur when all three features occur in conjunction. The highest O-AR intensity occurs in Greenland, likely triggered by the interaction with orography. In all regions, precipitation diagnosed as residual occupies the largest area. This might be related to too strict detection criteria for the boundaries of the synoptic systems or other precipitation production mechanisms, which will further be investigated in Section 3.3.

Considering the seasonal cycle (question Q1), we can confirm the hypothesis from Lauer, Rinke, et al. (2023) that CYCs are most dominant in winter to spring, and ARs and FRONTS play a stronger role in summer (Figure 3). However, there are rather strong regional variations: In the Arctic Ocean Pacific, Laptev Sea, and the Canadian Archipelago, the AR-related precipitation is to a large degree confined to the summer months, whereas the wintertime precipitation is nearly exclusively due to CYCs or attributed to the residual. On the contrary, in the other regions, ARs are important over the full year.

With respect to the precipitation phase (question Q2), summer rainfall is mainly related to ARs (Figure 3), which typically transport warm and moist air into the Arctic. ARs can therefore cause liquid precipitation even in the winter months, especially in the Arctic Ocean—Atlantic and Greenland. We would also like to highlight the AR-related rainfall in autumn present in several regions, which, together with AR-related energy fluxes, could contribute to a later sea ice freeze-up during this time of the year (Francis et al. 2020; Stroeve et al. 2014) and thus to reduced sea ice extent in September. Although it is striking that the residual precipitation has a rather high fraction, especially for liquid precipitation in the first winter months of certain regions, one has to keep in mind the overall rather low rainfall amount here (Figure 1). This becomes obvious when looking at central Greenland, where sub-zero temperatures dominate over the full year, which shows a 100% residual for rainfall (Figure 4).

3.3 | Residual Precipitation

Almost half of the annual snowfall in the Arctic and 25% of rainfall cannot be attributed to any of the weather systems (ARs, CYCs, FRONTS) and are classified as residual. In particular, in the Central Arctic and central Greenland, the residual makes up more than 50% of the precipitation (Figure 4). Lauer, Rinke, et al. (2023) highlighted the importance of light precipitation ($< 0.1\,\mathrm{mm\,h^{-1}}$) related to the residual. Therefore, we first analyze the effect of light precipitation and afterwards try to identify another weather system contributing to the residual.

Eliminating light precipitation by applying a threshold of $0.1\,\mathrm{mm\,h^{-1}}$ to the long-term ERA5 data set, the residual decreases by 40% (from 44% to 26%), and the contribution of ARs,

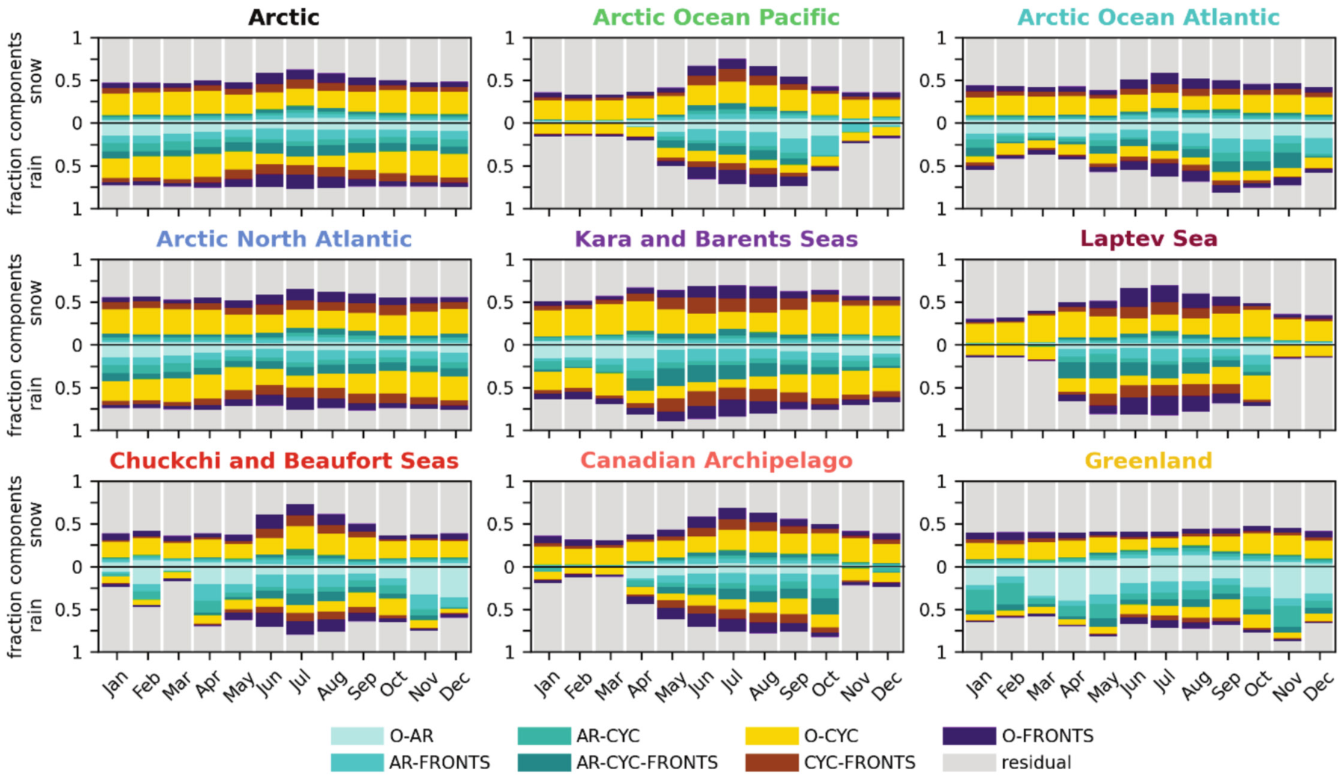

FIGURE 3 | Contribution of individual weather systems to the total monthly snow and rainfall for the entire Arctic as well as the individual sub-regions. All based on ERA5 (1979–2021).

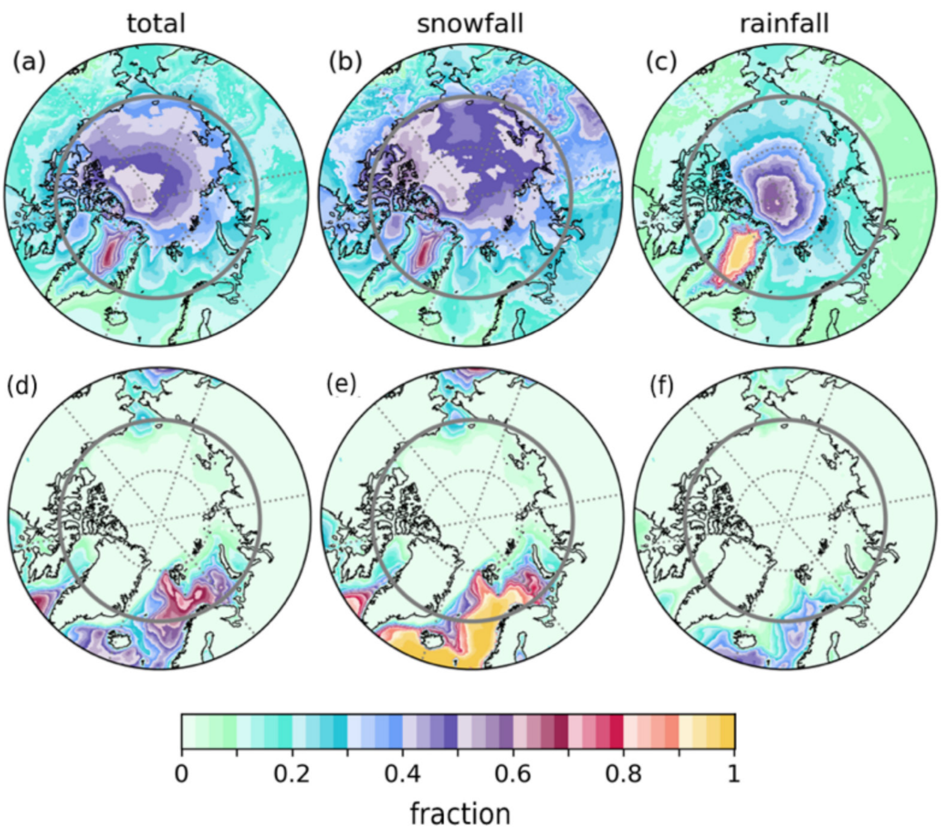

FIGURE 4 | Top row: fraction of light precipitation ($< 0.1\,\mathrm{mm\,h^{-1}}$) for (a) total precipitation, (b) snowfall, and (c) rainfall, relative to their respective totals. A value of "0" indicates that all precipitation rates exceed $0.1\,\mathrm{mm\,h^{-1}}$, whereas "1" indicates that all rates are below this threshold. Bottom row: fraction of MCAO-related precipitation (excluding events co-located with ARs, cyclones, and fronts) contributing to the residual of (d) total precipitation, (e) snowfall, and (f) rainfall. In this case, a value of "0" indicates no MCAO contribution to the residual; "1" indicates MCAOs account for the entire residual. All based on ERA5 data (1979–2021).

CYCs, and FRONTS increases subsequently. One explanation might be related to the detection algorithms. If an algorithm does not detect the full area of precipitation associated with a weather system but only a core part, some associated precipitation is falsely attributed to the residual. Because lighter precipitation is preferably found at the edges of weather systems, thresholding can eliminate the problem of the false residual. Note that most detection algorithms are not developed for the special conditions of the Arctic, and Lauer, Rinke, et al. (2023) showed that different AR detection algorithms have significant differences in the detected AR area. The increase in precipitation after thresholding is more pronounced for ARs and FRONTS, whereas the lower increase for CYCs hints at a higher robustness for their associated detection algorithms as it does not depend on moisture content. However, as Boisvert et al. (2018) state "... the presence or absence of small but immeasurable daily precipitation events, or trace precipitation, is largely unknown." Thus, it is also no surprise that different reanalyses show their largest differences in the occurrence of rather low precipitation rates as shown by Barrett et al. (2020, their fig. 7) for the Arctic Ocean.

The Arctic Ocean, the Chukchi, and Beaufort Seas are the regions where thresholding of low precipitation rates has the strongest effect (Figure 4a–c). These regions receive the lowest total precipitation amount (Figure 1), and their high share of light precipitation leads to high sensitivity with respect to thresholding. In contrast, the Arctic North Atlantic and Kara and Barents Seas—regions with higher precipitation rates (Figure 1) – are less affected by thresholding (Figure 4).

Next, we searched for another weather system possibly contributing to the residual. The fact that the residual is high during snowfall (Figure 3) and also for convective situations (not shown) led us to hypothesize that Marine Cold Air Outbreaks (MCAO) might play a key role. MCAOs are a frequent phenomenon in the Arctic, especially during winter when cold airmasses formed over sea ice flow southward over the relatively warm ocean. Strong air–sea heat fluxes and boundary layer processes lead to the formation of clouds and precipitation downstream. Even in the initial phase, close to the sea ice, light snowfall has been observed during such events (Schirmacher et al. 2024).

Following Dahlke et al. (2022), we compute the MCAO index (M) as the difference between the potential skin temperature and the potential temperature at 850 hPa for all grid cells over the open ocean. Grid cells with $M > 0$ are classified as MCAOs. To calculate the contribution of MCAOs to the residual, we only consider MCAOs that are not co-located with ARs, CYCs, and FRONTS. Strikingly, MCAOs account for up to 90% of the total precipitation residual over the Arctic North Atlantic (Figure 4d–f), a known hot spot for MCAOs. Generally, MCAOs contribute to the precipitation in regions with open water, for example, Kara and Barents Seas, Baffin Bay, and northern Bering Strait (Figure 4). They contribute predominantly to snowfall rather than to rainfall (Figure 4). In fact, over the Arctic North Atlantic and the Kara and Barents Seas, 60%–100% of the snowfall residual can be attributed to MCAOs. Although for rainfall, MCAOs become more influential further south (up to 70%), close to Scandinavia, where higher temperatures prevail. However, their overall impact on the total precipitation residual north of 70° N is modest, reducing it only from 44% to 40%.

In summary, MCAOs, together with the other synoptic features, can explain nearly all precipitation in the Arctic North Atlantic region, which makes the strongest contribution to precipitation in the Arctic. Nevertheless, especially in the central Arctic, very light precipitation seems to play a major role. However, here the derivation of snowfall is especially challenging, as has been shown for case studies during the MOSAiC expedition (Kirbus et al. 2023).

4 | Summary and Discussion

We related the Arctic precipitation to the occurrence of weather systems by attributing it to contributions by ARs, CYCs, and FRONTS, following the methodology developed by Lauer, Rinke, et al. (2023). The long-term ERA5 record (1979–2021) is considered to allow for a robust seasonal and regional perspective needed to answer the following questions:

Q1: Is there a seasonal dependence in the relation of precipitation to different weather systems? Clearly, CYCs dominate winter precipitation while AR- and front-associated precipitation dominate in summer. This confirms the hypothesis of Lauer, Rinke, et al. (2023) that only addressed 2-month periods in early spring and early summer. However, there are strong regional differences. For the Arctic Ocean Pacific, Canadian Archipelago, and the Laptev Sea, there is nearly no precipitation related to ARs and FRONTS, while in other regions such as Greenland, the Arctic Ocean Atlantic, and the Arctic North Atlantic, ARs can bring precipitation. This highlights the importance of the North Atlantic pathway of ARs, which also exhibits the highest precipitation amounts across the Arctic. Concerning precipitation intensity, the strongest events occur when all weather systems AR–CYC–FRONTS occur together.

Q2: How is the precipitation phase associated with different weather systems? Weather systems can explain 76% of the rain and only 50% of snowfall. The difference mainly arises from a stronger occurrence of AR- and front-related precipitation for rain. Cyclone-associated precipitation is more important for snowfall, as CYCs contribute most to wintertime precipitation.

Q3: What is the main contributor to residual precipitation, that is, precipitation not associated with weather systems on the synoptical scale? We find that Arctic-wide, 44% of the precipitation cannot be attributed to at least one of the weather systems. This residual is about twice as frequent for snow than for rain, and its share strongly reduces if a threshold to eliminate very light precipitation is applied. In fact, there is high uncertainty about the occurrence of this very light precipitation (also called trace precipitation or drizzle) as it challenges both observations and microphysical modeling (Boisvert et al. 2018). It is especially frequent in regions with low precipitation amounts, such as the central Arctic where large differences between reanalyses have been found (Barrett et al. 2020), likely resulting from differences in cloud microphysics of the underlying model. When we introduce a threshold of 0.1 mm h^{-1}, the total precipitation in the Arctic reduces by 23%, highlighting the need to get better observations to constrain the Arctic water budget. The thresholding leads to a strong reduction of the residual from 44% to 26%, such that subsequently the weather systems explain 74% of the Arctic precipitation. However, it is also important to check the sensitivity of the weather system detection as most algorithms are not made for the special conditions of the Arctic. Because we also found a rather frequent occurrence of the residual over the Arctic North Atlantic, we speculated that MCAOs contribute to the residual precipitation. Our analysis confirms that indeed they can explain up to 75% of the residual over oceans, especially over the Arctic North Atlantic. However, MCAOs are a small-scale phenomenon that shows significant variability on the kilometer scale and involves complex mixed-phase microphysics (Schirmacher et al. 2024). Therefore, MCAO-associated precipitation might be difficult to capture in reanalysis, and investigations on the quality of the reanalysis precipitation are especially important for this precipitation contribution.

Having shown the importance of weather system-associated precipitation for the Arctic, it would now also be interesting to investigate past and future precipitation changes by looking at how the location, strength, and frequency of occurrence of these systems change.

Author Contributions

Melanie Lauer: conceptualization, methodology, software, data curation, writing – original draft, visualization. **Annette Rinke:** conceptualization, writing – review and editing, supervision. **Susanne Crewell:** conceptualization, writing – review and editing, funding acquisition, supervision, writing – original draft.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The ERA5 data for this study are retrieved from the German Climate Computing Center in Hamburg, Germany.

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