



RESEARCH LETTER

10.1029/2021GL094977

Special Section:

The Arctic: An AGU Joint
Special CollectionArctic Amplification of Precipitation Changes—The
Energy HypothesisFelix Pithan¹ and Thomas Jung¹ ¹Helmholtz Centre for Polar and Marine Sciences, Alfred-Wegener-Institute, Bremerhaven, Germany

Key Points:

- Precipitation change is greater in the Arctic than anywhere else outside the deep Tropics in boreal winter
- Larger Arctic hydrological sensitivity is energetically driven and independent of sea-ice changes
- Arctic increases in atmospheric radiative cooling closely match increases in latent heat release from precipitation

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Pithan, F., & Jung, T. (2021). Arctic amplification of precipitation changes—The energy hypothesis. *Geophysical Research Letters*, 48, e2021GL094977. <https://doi.org/10.1029/2021GL094977>

Received 28 JUN 2021

Accepted 23 OCT 2021

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Abstract Temperature and precipitation change more strongly in the Arctic than at lower latitudes, with central Arctic boreal winter precipitation projected to double in the 21st century in a high-emission scenario. This enhanced hydrological sensitivity has been explained in terms of the Arctic moisture budget and attributed to either moisture advection or surface evaporation. Here, we show that boreal winter moisture availability is less sensitive to surface temperature change in the Arctic than at lower latitudes, questioning a central role of the moisture budget. Hydrological sensitivity, that is, precipitation change per unit temperature change, is similar in models with or without sea-ice changes, suggesting a secondary role of surface flux changes. Instead, we propose that the Arctic's larger hydrological sensitivity is energetically driven. Increases in latent heat release from precipitation locally balance increased atmospheric radiative cooling in Arctic winter, consistent with process-level understanding of radiatively driven cloud and precipitation formation.

Plain Language Summary As Earth's climate warms, globally averaged precipitation increases. Both warming and precipitation increase are larger in the Arctic than at lower latitudes. In the atmospheric energy budget, changes in precipitation correspond to changes in latent heat release and must be balanced by advection, surface fluxes, or radiation. This article shows that stronger Arctic than lower-latitude precipitation increases are mostly driven by stronger radiative loss of energy to space. Previous research had suggested that increased evaporation following the retreat of sea ice was a key driver of Arctic precipitation increases. Understanding the causes of amplified Arctic precipitation change is important to build confidence in model projections and to focus on the most important processes in further research and model development. The link between hydrological and radiative changes also allows to reconcile these two perspectives on Arctic amplification that have so far often been discussed as opposing views.

1. Introduction

Arctic precipitation increases can freshen the Arctic Ocean surface and reduce sea ice loss, and affect the mass balance of high-latitude glaciers and ice sheets (Bintanja et al., 2018; Bintanja & Selten, 2014; Min et al., 2008). Understanding what drives increased precipitation sensitivity to climate change in the Arctic is fundamental to build confidence in future projections of Arctic precipitation change and narrow their spread.

Arctic amplification of both temperature and humidity changes is strongest during the cold season, when incoming solar radiation is low or zero and the Arctic energy budget is dominated by advection of heat from lower latitudes, heat release from the ocean surface and radiative cooling to space (Collins et al., 2013; Serreze & Barry, 2011; Serreze et al., 2007). Enhanced Arctic warming compared to lower latitudes has been attributed to local radiative feedbacks (Stuecker et al., 2018) and increased advection of moist air masses from lower latitudes (Woods & Caballero, 2016). The increased absorption of solar radiation by darker surfaces caused by snow and ice melt (surface albedo feedback) and the weak Arctic infrared cooling to space caused by thermal stratification (lapse-rate feedback) are the most important local feedback mechanisms contributing to Arctic amplification (Hahn et al., 2021; Pithan & Mauritsen, 2014).

Prior research on Arctic amplification of precipitation changes has often been based on what we call the moisture hypothesis, arguing that additional moisture supply causes increased precipitation. This hypothesis assumes that Arctic precipitation and its increase under global warming are limited by moisture

availability, and that Arctic moisture availability increases by an exceptionally large amount, requiring a mechanistic explanation. Under the moisture hypothesis, the increase in moisture availability and precipitation has been attributed to stronger moisture advection from lower latitudes (Bengtsson et al., 2011), but also to increased local evaporation mostly caused by sea-ice retreat (Bintanja & Selten, 2014; Kopec et al., 2016). If the moisture hypothesis was true, we would expect moisture availability to increase more strongly in the Arctic than at lower latitudes. If sea-ice changes were a dominant driver of amplified Arctic precipitation changes, we would expect suppressed hydrological sensitivity in climate change experiments with fixed sea ice.

A fundamental objection to the moisture hypothesis is that moisture availability is a necessary, but not sufficient condition for generating precipitation. This is illustrated by the fact that globally averaged precipitation increases only by about 1%–2% per K warming, while atmospheric humidity increases by about 7%/K following the Clausius-Clapeyron relation. The increase in global precipitation is constrained by the tropospheric energy budget, that is, precipitation and thus latent heating of the atmosphere can only increase as much as the atmospheric radiative cooling (Allen & Ingram, 2002; Pendergrass & Hartmann, 2014).

In this manuscript, we present the energy hypothesis as an alternative explanation for amplified Arctic precipitation change. The energy hypothesis assumes that the tropospheric energy budget also constrains Arctic precipitation at the regional scale, and suggests that increases in atmospheric radiative cooling drive amplified Arctic precipitation changes.

Neglecting atmospheric heat capacity, atmospheric radiative cooling (R) over the polar cap has to balance the sum of latent heat release by condensation Lp and horizontal (DSE_{adv}) and vertical (SH , the surface sensible heat flux) transport of dry static energy, irrespective of whether the precipitated water vapor comes from advection or local evaporation (Allen & Ingram, 2002; Anderson et al., 2018; Muller & O’Gorman, 2011):

$$R = Lp + DSE_{adv} + SH. \quad (1)$$

If the energy hypothesis was true, we would expect increases in atmospheric radiative cooling to be larger in the Arctic than at lower latitudes, and to match the increased latent heat release from precipitation.

In this article, we test the moisture and energy hypothesis by analyzing changes in zonal mean precipitable water, precipitation and tropospheric energy budget between model simulations of the present-day, 21st century and Last Glacial Maximum climates. Our analysis includes model setups with fixed and changing sea-ice cover.

2. Methods

2.1. Data

We use model experiments from the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016). Models used for the different experiments and diagnostics are listed in Table S1 in Supporting Information S1. For the coupled runs, differences for the future projections are taken between years 2070 and 2099 of the ssp585 scenario runs (O’Neill et al., 2016) and years 1985–2014 of the historical runs. Historical experiments are forced with observed greenhouse gas and aerosol evolutions and natural forcings such as volcanoes and insolation changes. The scenario run ssp585 is based on a fossil-fuel driven development throughout the 21st century leading to a radiative forcing of 8.5 Wm^{-2} in 2100. We choose a strong forcing scenario to obtain a large signal-to-noise ratio. For the Last Glacial Maximum (LGM), differences between years 1985 and 2014 of the historical runs and the last 30 years of the Paeleomodel Intercomparison Project PMIP4 LGM simulations are used (Kageyama et al., 2017). Atmosphere-only experiments are differences between AMIPfuture4K and AMIP experiments. AMIP experiments are run with prescribed observed sea-surface temperatures and sea ice extent. In AMIPfuture4K experiments, sea-surface temperature anomaly patterns corresponding to a global mean warming of 4K from CMIP5 coupled models are added to the observed sea-surface temperatures, but sea-ice extent remains at the control climate extent and is the same as in AMIP experiments. This leads to nonconservation of energy within the climate system

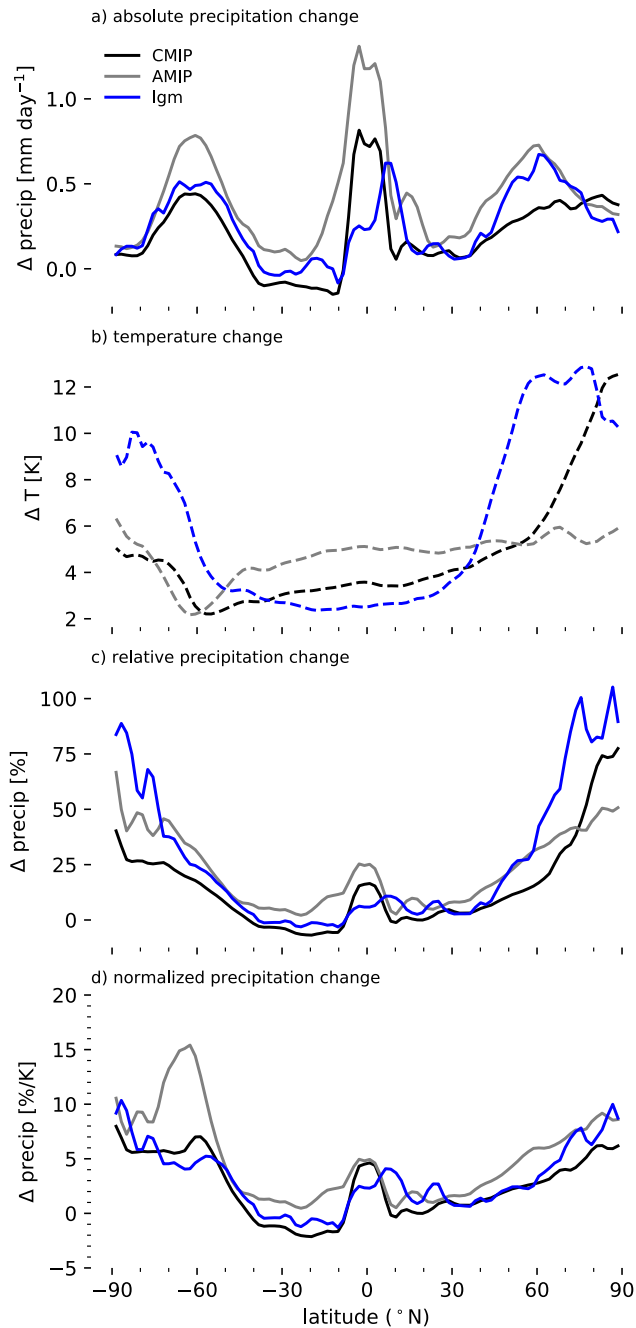


Figure 1. Temperature and precipitation changes in future projections of CMIP6 coupled models with interactive sea ice (CMIP), atmosphere-only models with constant sea ice across experiments (AMIP) and for the difference between present-day conditions and the Last Glacial Maximum (LGM) in coupled models.

3. Results

At the end of the 21st century, annual and zonal mean precipitation in the Arctic is projected to increase by almost half a millimeter per day (Figure 1a) under a scenario of strong greenhouse gas emissions. This is as much as in the Southern Hemisphere stormtracks and second only to the inner Tropics, where moisture convergence into the intertropical convergence zone (ITCZ) increases in a warmer climate, a phenomenon often referred to as “the rich get richer” (Chou & Neelin, 2004). Air parcels that are lifted from the tropical

(atmosphere, sea ice, and oceans) as fixed surface temperatures act as infinite heat sources or sinks. Within the atmosphere, energy and moisture are conserved in these simulations.

For each model, data are interpolated onto a common grid and averaged across ensemble members (realizations) before averaging across models to give equal weight to each model in creating the inter-model mean.

The histogram in Figure 3 uses 3-hourly November to April data north of 60°N from the historical run of the AWICM climate model (Semmler et al., 2020).

2.2. Budget Computations

We compute radiative cooling of the atmospheric column as the sum of top-of-atmosphere (TOA) and surface (sfc) radiative fluxes:

$$R = -SW\downarrow_{TOA} + SW\uparrow_{TOA} + LW\uparrow_{TOA} + SW\downarrow_{sfc} - SW\uparrow_{sfc} + LW\downarrow_{sfc} - LW\uparrow_{sfc}, \quad (2)$$

where SW and LW are shortwave and longwave radiative fluxes, the arrows indicate upward and downward directed fluxes and the subscripts the respective level.

Dry static energy convergence by advection is computed using the tropospheric energy budget (Equation 1) and assuming zero heat capacity:

$$DSE_{adv} = R - Lp - SH. \quad (3)$$

For the tropospheric energy budget, we define the total convergence of dry energy into the atmospheric column as the sum of convergence by advection (Equation 3) and the surface sensible heat flux.

Latent heat release due to precipitation includes the latent heat of freezing in the case of solid precipitation. Neglecting the latent heat of freezing, as is often done for the atmospheric energy budget on a global scale, does not noticeably change the results (not shown).

$$Lp = L_{condensation} * p_{total} + L_{freezing} * p_{snow}, \quad (4)$$

where $L_{condensation}$ and $L_{freezing}$ are the latent heat of vapourization and fusion for water, and p_{total} and p_{snow} the total and solid precipitation amounts.

While we do not explicitly compute the moisture budget, changes in moisture convergence can be inferred as the difference between changes in precipitation and evaporation (latent heat fluxes) from Figure S1 in Supporting Information S1. Note that changes in moisture convergence into the Arctic are not equivalent to changes in moisture advection from lower latitudes, as moisture export from the Arctic also increases in a warmer climate (Audette et al., 2021).

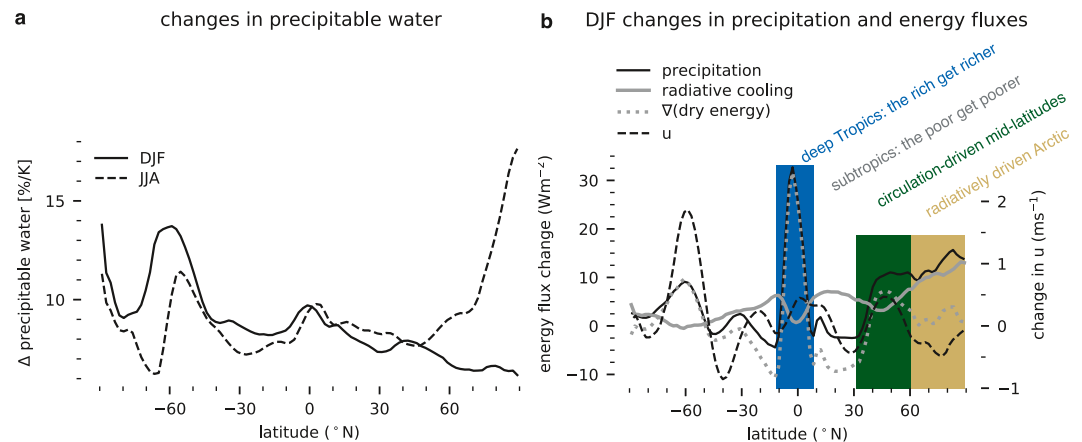


Figure 2. (a) Temperature sensitivity of zonal mean precipitable water in boreal winter (solid) and summer (dashed line) and (b) Boreal winter changes in atmospheric radiative cooling, latent heat release due to precipitation, divergence (∇) of dry energy and zonal wind u at 850 hPa in CMIP6 coupled models over the 21st century. Latent heat flux changes and results for other seasons are shown in Figure S1 in Supporting Information S1. Note that ∇ (dry energy) includes the surface sensible heat flux.

surface to the tropopause lose most of their initial moisture, and given a constant circulation, one would expect a precipitation scaling near 7%/K in areas dominated by deep convection (Held & Soden, 2006). The largest relative precipitation increase occurs at high latitudes (Figure 1c), where a substantial absolute increase in precipitation coincides with small precipitation rates in the present-day climate. Temperature change is also amplified at high latitudes (Figure 1b), but even when the relative zonal mean precipitation change is normalized by the zonal mean temperature change (Figure 1d), the polar regions stand out as having much stronger hydrological sensitivity rates than any other latitude outside the deep Tropics.

Between the Last Glacial Maximum and present-day conditions, Arctic amplification of climate change has occurred at substantially lower latitudes than projected for the 21st century (Figure 1b) due to the disappearance of large continental ice sheets and the associated changes in elevation and surface albedo (Miller et al., 2010). Once this is accounted for, the high-latitude increase in hydrological sensitivity is remarkably similar between the Last Glacial Maximum and present-day conditions and projections of 21st century climate change (Figure 1d).

The Arctic's hydrological sensitivity is in the range of 7%/K (Figure 1d), perfectly compatible with a moisture availability following Clausius-Clapeyron scaling and not requiring any particular mechanistic explanation of changes in the moisture budget. In stark contrast to expectations based the moisture hypothesis, changes in precipitable water per unit temperature change are smaller in the Arctic than elsewhere in boreal winter (Figure 2a), when Arctic amplification of precipitation change is most pronounced (see Figure S1 in Supporting Information S1; Bintanja & Selten, 2014). A below-average increase in moisture availability can hardly explain the above-average increase in precipitation in Arctic winter.

If sea-ice retreat causing increased latent heat release over the newly ice-free ocean was the main physical driver of this enhanced hydrological sensitivity (Bintanja & Selten, 2014), the enhanced sensitivity should disappear in model experiments in which sea-ice conditions remain fixed despite global warming. Such experiments are available from CMIP6, and once the effect of reduced Arctic amplification caused by the fixed sea-ice conditions is accounted for (gray line in Figure 1d), they show a very similar enhancement of the hydrological sensitivity at high latitudes. While the increase of latent heat release in areas of reduced sea-ice extent in winter (Bintanja & Selten, 2014; Kopec et al., 2016) is undisputed, it does not seem to be the key driver of enhanced Arctic hydrological sensitivity.

We thus investigate the energy hypothesis, in particular the idea that atmospheric radiative cooling can explain the Arctic's enhanced hydrological sensitivity. The strongest increase in atmospheric radiative cooling in boreal winter occurs in the Arctic (Figure 2b), where it exceeds 10 Wm^{-2} , twice as much as the increase at

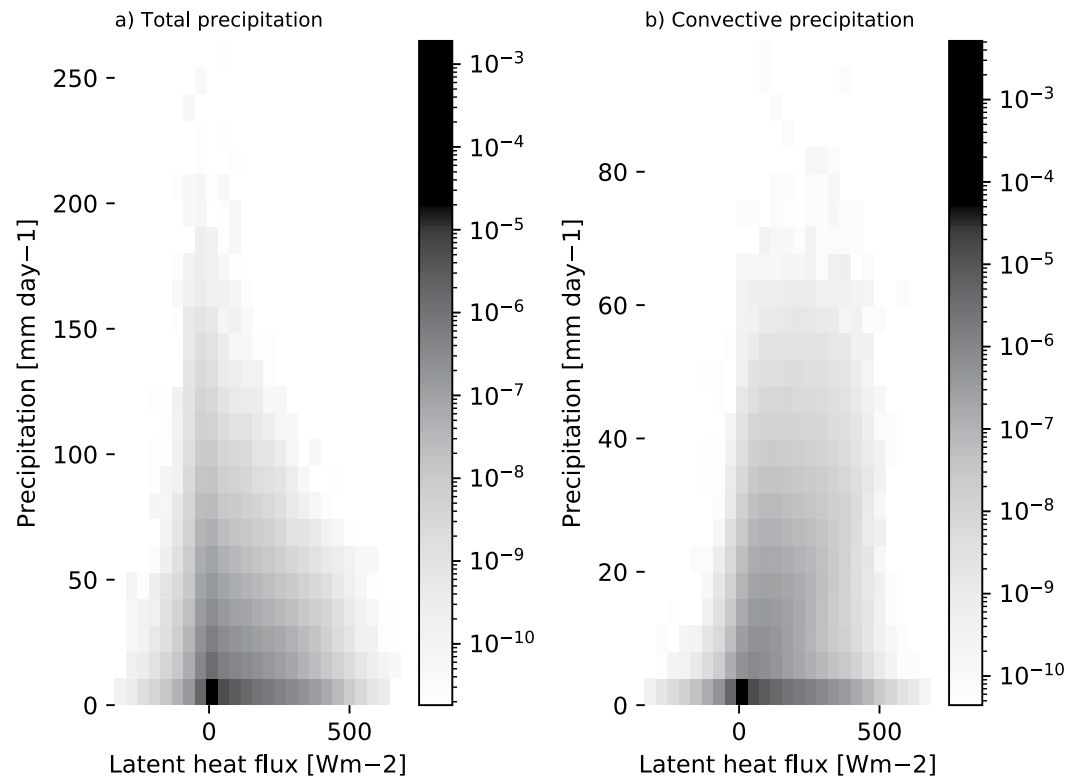


Figure 3. Occurrence of precipitation depending on surface latent heat fluxes in the Arctic (north of 60 °N) cold season (November to April) in present-day climate based on 3-hr model data. Note the logarithmic color scale, slightly darker tones correspond to much more frequently occupied bins.

lower latitudes. Consistent with the energy hypothesis, the increase in radiative cooling closely matches the increased latent heat release by precipitation in the Arctic. Both are much larger than the combined change in vertical and horizontal dry static energy convergence.

While there are substantial and compensating changes in the surface sensible heat flux and horizontal dry static energy divergence (see Figure S2 in Supporting Information S1), they cannot cause the amplified precipitation change in the energy budget framework. The surface sensible heat flux change is of the wrong sign, and it is physically implausible that dry static energy would spontaneously diverge or cease to converge, thereby cooling the atmospheric column and forcing precipitation. Note that air masses imported into the Arctic will be warmer in a warmer world, that is, contain more dry static energy. A reduction in net dry static convergence must thus be driven by larger warming of the exported than imported air masses. The most likely explanation for the compensating changes in dry energy fluxes is therefore that reduced and thinning sea-ice cover leads to enhanced sensible heat fluxes preferably into air masses leaving the Arctic (Audette et al., 2021) without interfering with the warm, moist air masses being advected into and precipitating in the Arctic (Figure 4). This is also consistent with both changes in horizontal divergence of dry static energy and surface sensible heat fluxes peaking near the ice edge, while changes in radiative cooling continue to increase to the pole.

In stark contrast to the Arctic, zonal mean changes in precipitation and atmospheric radiative cooling are anticorrelated at low latitudes. The increased latent heat release in the inner Tropics is almost exactly balanced by divergence of dry static energy to the subtropics, where dry energy converges, precipitation is reduced and atmospheric radiative cooling increases much more than in the inner Tropics. This zonal mean picture is often referred to as “rich get richer, poor get poorer” mechanism, as precipitation increases substantially in the moist Equatorial regions, but decreases even further over the subtropical dry zones (Trenberth, 2011).

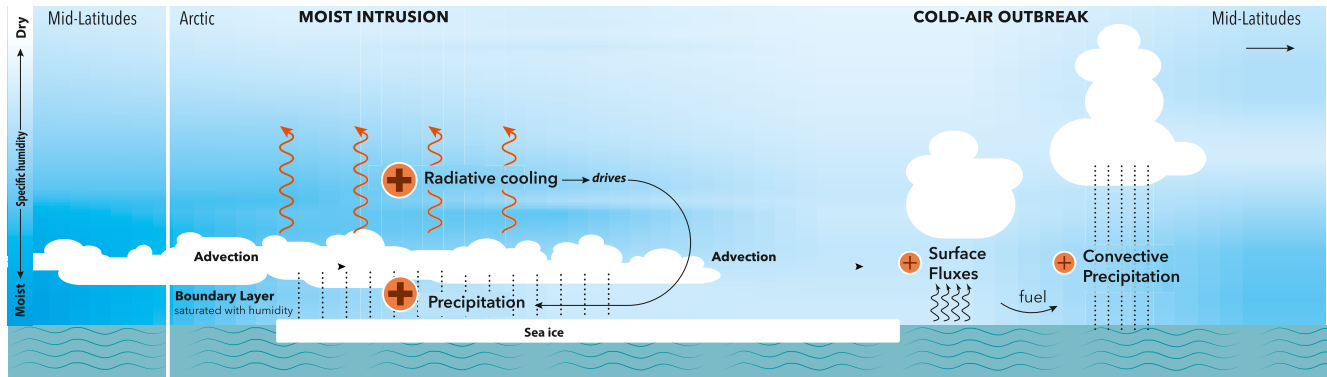


Figure 4. Sketch of the relationship between radiative cooling, surface fluxes and precipitation in the radiatively driven (moist intrusions) and surface-driven (cold-air outbreaks) precipitation regimes in Arctic winter.

In the mid-latitudes, the increase in zonal mean precipitation closely follows that in zonal-mean zonal wind, consistent with the idea that changes in mid-latitude precipitation are largely driven by changes in extratropical cyclones (Bengtsson et al., 2009; Zappa et al., 2013). We here use changes in the eddy-driven jet (zonal mean zonal winds at 850 hPa) as a proxy for the shift of mid-latitude storm-track activity (Novak et al., 2015). From the tropospheric energy-budget perspective, the increased latent heat release from precipitation is balanced by divergence of dry static energy but has no discernible relationship to changes in atmospheric radiative cooling.

The small intermediate peak in DJF precipitation increases between the circulation-driven and radiatively driven regimes around 60° N corresponds to a strong precipitation increase at the Alaskan cordillera (not shown). This is consistent with moister air masses being lifted over the mountains and losing much of their initial moisture content, a situation in which precipitation change can scale with the Clausius-Clapeyron rate of 7%/K (Trenberth, 1999).

Over Antarctica, the relative change of precipitation per unit temperature change is as high as or even higher than in the Arctic (Figure 1d), but the absolute increase is relatively small over the Antarctic plateau (Figure 1a), where high elevation and corresponding low temperatures prevent the advection of larger amounts of moisture from lower latitudes. Only a fraction of the increased radiative cooling over Antarctica is thus compensated for by latent heat release in austral winter (Figure S1c in Supporting Information S1). A larger role of dry static energy advection is consistent with the much lower rate of polar amplification (Figure 1b) and the different circulation structure with strong subsidence over the Antarctic plateau (Salzmann, 2017).

As noted above, sensible and latent heat fluxes into cold, dry air masses leaving the Arctic are projected to increase in the 21st century. This mostly affects cold-air outbreaks, in which cold, dry air masses originating over Arctic sea ice or land are transported over open ocean, where they pick up heat and moisture, which partly precipitates again within hours (Pithan et al., 2018; Papritz & Sodemann, 2018). Precipitation changes in this regime are mostly controlled by local boundary-layer dynamics rather than the large-scale energy or moisture budgets. However, they make a minor contribution to overall Arctic precipitation and precipitation changes: Most precipitation in Arctic winter occurs at zero or weak latent heat fluxes (Figure 3a). Only convective precipitation typically coincides with substantial latent heat fluxes and stronger convective precipitation rates are associated with stronger latent heat fluxes (Figure 3b). If the increase in Arctic cold-season precipitation was dominated by convective precipitation in coupled model experiments, this would suggest that surface-flux driven boundary-layer dynamics are the key driver of precipitation increases. However, convective precipitation only accounts for 24% of the additional 21st century precipitation in DJF over the central Arctic ocean, that is, north of 70° N, and its share is even lower in spring (14% in MAM) and fall (19% in SON).

Increases in latent heat flux and increases in precipitation directly associated with this surface forcing peak near the retreating sea-ice margin at about 80° N (see Figure S1a in Supporting Information S1). At the surrounding latitudes, the increase in latent heat release by precipitation somewhat exceeds the radiative

forcing, and the excess energy is balanced through corresponding changes in the dry fluxes, consistent with a minor contribution of surface-driven convective precipitation to Arctic precipitation increase and hydrological sensitivity. A similar, but substantially weaker effect can be seen near 70 °N in the LGM runs (Figure S4b in Supporting Information S1).

At the same time, additional evaporation over newly ice-free ocean areas does not necessarily correspond to additional precipitation and latent heat release in the atmosphere over the polar cap. The strongest evaporation occurs into dry, cold air masses leaving the ice-covered Arctic Ocean or polar land masses, for example during cold-air outbreaks (Nygård et al., 2019). This moisture may later precipitate within the polar cap, but may as well be exported to lower latitudes. An analysis of model experiments prescribing temperature changes only at lower or higher latitudes suggests that sea-ice retreat mostly leads to warming and moistening of air masses being exported from the Arctic (Audette et al., 2021).

4. Summary and Discussion

We have contrasted two hypotheses on Arctic amplification of precipitation change, the moisture hypothesis suggesting that enhanced Arctic hydrological sensitivity is caused by additional moisture convergence from advection or surface evaporation, and the energy hypothesis suggesting that the Arctic's larger increase in precipitation is mostly driven by increased radiative cooling of the atmosphere.

While the increases in moisture advection and surface evaporation reported in earlier studies (Bengtsson et al., 2011; Bintanja & Selten, 2014) are undisputed, we find that moisture availability (precipitable water) is less sensitive to warming in Arctic winter than at lower latitudes (Figure 2a). The change in moisture availability is thus unlikely to be the key factor in explaining a larger hydrological sensitivity in Arctic winter compared to lower latitudes.

Our regional analysis of the tropospheric energy budget suggests that that Arctic precipitation changes are energetically driven. Increases in atmospheric radiative cooling are almost exactly balanced by increased latent heat release from precipitation in 21st century projections for boreal winter. In contrast, zonal mean precipitation changes at lower latitudes are driven by the large-scale atmospheric circulation and its changes, and energetically balanced by divergence of dry static energy (Figure 2b).

In atmosphere-only experiments with fixed sea ice and model setups representing conditions of the Last Glacial Maximum, advection of dry static energy plays a larger role for the energy budget, such that changes in latent heat release and radiative cooling do not cancel at all Arctic latitudes. Nevertheless, these experiments confirm that Arctic hydrological sensitivity is amplified to a similar degree with or without changes in sea-ice extent. In boreal summer, that is, during polar day, the Arctic energy budget is very different from the cold season, and neither changes in precipitation nor in atmospheric radiative cooling strongly exceed those of lower latitudes (see Figure S1 in Supporting Information S1).

The energy hypothesis suggests that Arctic cold-season precipitation and its increase in a warming climate are primarily controlled by radiative cooling rather than surface fluxes. While our analysis relies on a correct representation of fundamental relationships between the Arctic energy and water cycle in climate models, the results are consistent with the established process-level understanding of radiation-driven and surface-driven precipitation regimes in the Arctic (see Figure 4). Precipitation out of moist air masses being advected into the Arctic is driven by cloud-top radiative cooling (Ali & Pithan, 2020; Pithan et al., 2018). As these air masses of oceanic origin are in equilibrium with the sea surface, their boundary layer is largely saturated with humidity (Ali & Pithan, 2020). A retreat of the sea ice edge delays the onset of the cooling process, but hardly leads to additional latent heat fluxes into or precipitation out of these air masses.

In contrast, precipitation in cold-air outbreaks (Papritz & Sodemann, 2018; Pithan et al., 2018) is fueled by surface fluxes and often falls in the form of convective precipitation. When wintertime sea-ice cover is reduced in a given region, latent heat fluxes and precipitation from cold-air outbreaks increase locally. We argue that changes in radiatively driven precipitation play a dominant role in the Arctic's amplified hydrological sensitivity, whereas changes in surface fluxes and resulting (mainly convective) precipitation may be locally important near the ice edge, but make a smaller contribution to average precipitation change over the Arctic Ocean.

So far, radiative changes in the Arctic atmosphere and increased moisture advection from lower latitudes have mostly been discussed as alternative explanations for the Arctic amplification of temperature change. Our finding that increases in atmospheric radiative cooling drive increased latent heat release inside the Arctic opens a pathway to reconciling those approaches and acknowledging the interconnection of the Arctic atmospheric energy and moisture cycles and the amplification of temperature and precipitation changes (Anderson et al., 2018). Our results underscore the importance of evaluating and improving how the processes causing cooling and precipitation out of moist air masses advected into the Arctic (Pithan et al., 2018) are represented in models and call for observational strategies that can capture this model-derived relationship.

Data Availability Statement

The data used for this study are freely available from the Earth System Grid Federation (ESGF) (<https://esgf-data.dkrz.de/search/cmip6-dkrz/>). Models used and their respective dois are listed in Table S1 in Supporting Information S1.

Acknowledgments

The authors acknowledge the climate modeling groups for producing and making available CMIP6 model output, and the World Climate Research Programme's Working Group on Coupled Modelling for organizing the CMIP6 project. The authors would like to thank L. Gartemann for assistance in preparing the data used in this study and K. Werner for helping prepare Figure 2. Figure 4 was designed by M. Kuensting. Comments by two anonymous reviewers have allowed us to substantially improve the manuscript. FP acknowledges funding from the Helmholtz Association (PD-300). Open access funding enabled and organized by Projekt DEAL.

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