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CLIMATOLOGY

Strong future increases in Arctic precipitation variability linked to poleward moisture transport

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The Arctic region is projected to experience amplified warming as well as strongly increasing precipitation rates. Equally important to trends in the mean climate are changes in interannual variability, but changes in precipitation fluctuations are highly uncertain and the associated processes are unknown. Here, we use various state-of-the-art global climate model simulations to show that interannual variability of Arctic precipitation will likely increase markedly (up to 40% over the 21st century), especially in summer. This can be attributed to increased poleward atmospheric moisture transport variability associated with enhanced moisture content, possibly modulated by atmospheric dynamics. Because both the means and variability of Arctic precipitation will increase, years/seasons with excessive precipitation will occur more often, as will the associated impacts.

INTRODUCTION

In general, climate warming will invoke changes in the global hydrological cycle (*1*, *2*). Climate model results consistently show that global mean precipitation will increase at a rate of only ~2% per degree global mean temperature change (*3*) (although atmospheric moisture content varies by ~7%/K). In the Arctic, projected long-term trends in precipitation are much larger (~4.5% per degree Arctic mean temperature change) than the global mean (*2*, *4*), owing mainly to massive sea ice retreat–induced increases in surface evaporation (Fig. 1A). This implies that changes in Arctic mean precipitation are much more pronounced than would be expected on the basis of Arctic warming alone, with concurrent increases in rainfall (*5*).

Changes in the mean climate are important, but only tell part of the story, however, because superimposed on long-term trends are naturally occurring interannual and decadal variations with certain amplitudes, phasings, and time scales (*6*, *7*). Moreover, the nature of such climate variations will change when the mean climate evolves (*8*). This hinders the attribution of climate trends to specific forcings, especially in regions where climate variability is high, such as in the Arctic region (*9*). Climate extremes are a by-product of climate variability (*8*), which, if its magnitude increases, might amplify trend-induced changes in the amplitude of extremes and subsequent impacts. It is therefore vital to quantify (changes in) climate variability and elucidate the associated climate mechanisms.

Climate model results have shown that interannual temperature variability in the Arctic will probably diminish as climate warming proceeds (*4*), which has been linked to the long-term retreat in sea ice and the associated expansion of permanent open water in the Arctic Ocean. In contrast, recent studies have shown that, globally, interannual precipitation variability over continental areas will generally increase (*8*), owing mainly to the rise in atmospheric moisture content. With (relative) precipitation trends strongly increasing toward the Arctic (*2*), one would intuitively expect a poleward amplification in interannual precipitation variability and a strong link with surface evaporation and sea ice retreat.

RESULTS

Here, we use state-of-the-art global climate model simulations (*1*) for the period 1870–2100 to show that Arctic interannual precipitation variability will indeed increase in the (near) future but that this increase is linked to changes in poleward atmospheric moisture transport variability (Fig. 1B). Similar to the mean moisture budget components, model mean interannual variability has remained fairly constant over most of the 20th century. Around the start of the current century, however, both mean precipitation and its interannual variability appear to increase suddenly. While the intensification in Arctic mean precipitation is dominated by surface evaporation (Fig. 1A) (*2*), model results suggest that enhanced interannual precipitation variability closely follows poleward moisture transport variability. Although reanalysis data and/or observations do not yet exhibit notable changes in Arctic interannual precipitation variability, climate models seem to indicate that the rise in Arctic interannual precipitation variability should become significant and observable fairly soon (i.e., the coming decades). However, spatial and intermodel variations are considerable (Figs. 1B and 2A): The average relative change in Arctic interannual precipitation variability is about 25% but exhibits a wide range (−50% to +150%). Hence, projected future trends in Arctic interannual precipitation variability are not only comparatively large but also quite uncertain (*8*) owing to (i) intermodel differences and (ii) decadal (or longer) natural variability (i.e., intramodel uncertainty, within one model) as inferred by evaluating large ensembles (see the Supplementary Materials).

Unexpectedly, simulated future increases in Arctic interannual precipitation variability are not directly related to Arctic warming, as there is no intermodel (and temporal) correlation between these two variables. Instead, there is a statistically significant intermodel relation between the changes in interannual precipitation variability and poleward moisture transport variability (Fig. 2B). In other words, climate models that exhibit an increase in poleward moisture transport variability project largely enhanced interannual precipitation

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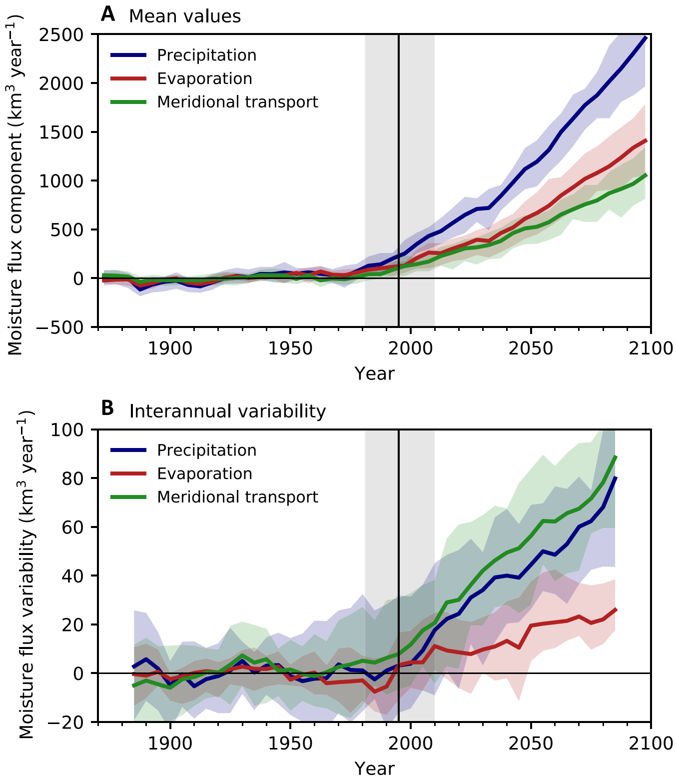


Fig. 1. Long-term changes in Arctic moisture budget components (precipitation, surface evaporation, and moisture transport across 70°N). (**A**) Mean values and (**B**) interannual variability, defined as the SD of consecutive detrended 30-year segments. All values represent the multimodel mean [35 Coupled Model Intercomparison Project, Phase 5 (CMIP5) models] subtracted from the average over the period 1870–1980. Uncertainty envelopes express the interquartile ranges of intermodel differences, evaluated after subtracting the respective 1870–1980 means. The gray bar denotes the "current" period 1981–2010, represented by the values at 1995 (black line).

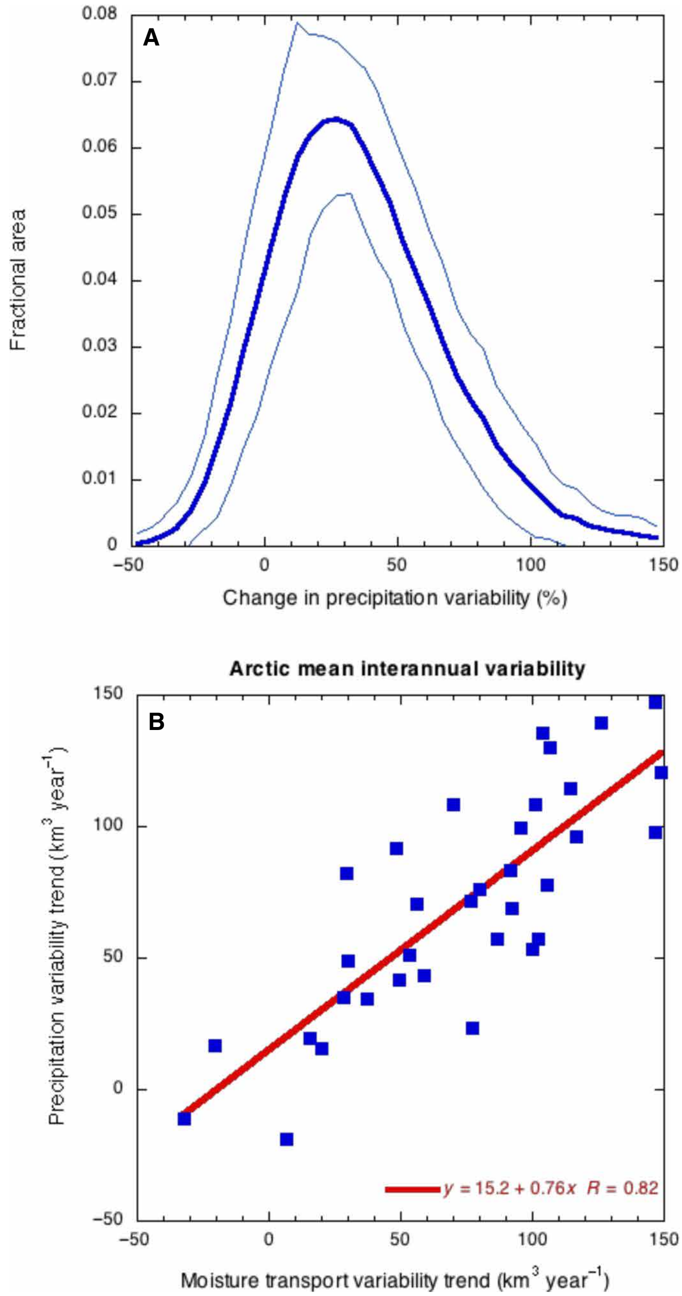
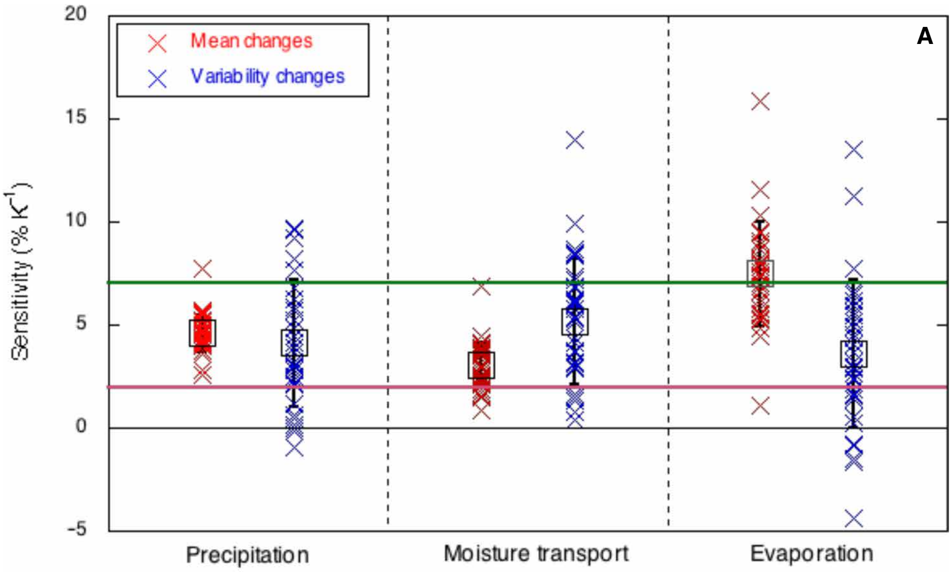


Fig. 2. Changes in Arctic preciptation variability. (**A**) Multimodel-mean relative changes in Arctic precipitation variability in terms of fractional area exhibiting a certain change (thick line, multimodel-mean values; thin lines, intermodel uncertainty expressed as the 1 − σ SD from the mean). (**B**) Intermodel dependence of trends in Arctic precipitation variability and poleward moisture transport variability. Each square represents one CMIP5 climate model (the first member; see Materials and Methods), and the red line is the best linear fit (coefficients in the lower-right corner).

variability values, and vice versa. Years with anomalously high (low) poleward moisture transport will cause higher (lower) than average Arctic precipitation. Note that interannual variations in poleward moisture transport must quickly be converted into precipitation fluctuations because the moisture holding capacity of the frigid Arctic atmosphere is quite small (*2*).

The sensitivity (expressed as percentage changes per degree Arctic warming) in Arctic mean moisture budget terms and their variability reveals a notable difference between the mechanisms governing Arctic precipitation trends versus interannual variability (Fig. 3). The moisture influx from extrapolar regions dominates changes in Arctic interannual precipitation variability, whereas interannual variations in Arctic surface evaporation exhibit a comparatively small sensitivity (compared to changes in its mean value). While models mostly agree on the sign of the changes in sensitivity of interannual precipitation variability, intermodel and intramodel uncertainties are substantial and reflect both the impact of differences between models (physics/parametrizations) and decadal or longer variability (see the Supplementary Materials).

The changing variability in moisture influx from extrapolar regions governs Arctic interannual precipitation variability through atmospheric processes. Changes in poleward moisture transport are governed by (i) the meridional moisture gradient (thermodynamical component) and (ii) atmospheric dynamics (dynamical component) (*10*). Model mean sensitivities in the moisture gradient at 70°N and its variability amount to 3.1 ± 1.1 and 5.2 ± 3.0%/K, respectively, similar to those in moisture transport (Fig. 3), suggesting that the reinforced moisture transport variability (compared to its mean value) can largely be attributed to changes in the mean north-south moisture gradient. The thermodynamic component of the moisture



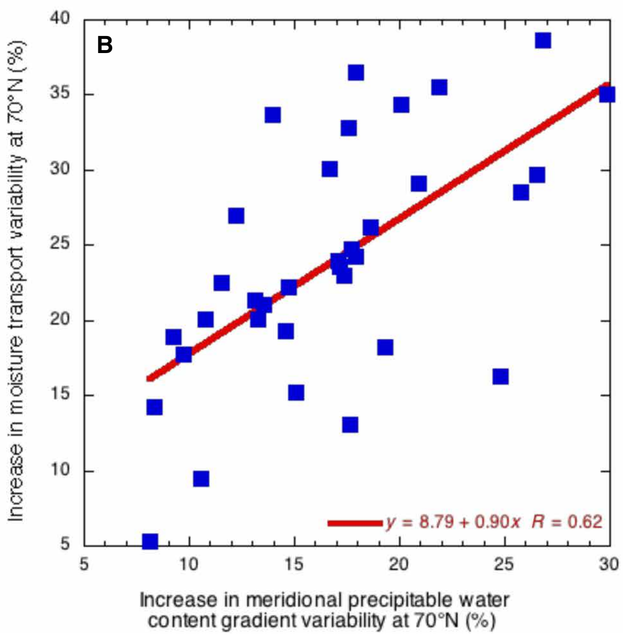


Fig. 3. Changes in the variability of Arctic hydrological cycle components. (**A**) Sensitivity in Arctic moisture budget components with respect to mean changes and changes in the interannual variability [defined as percentage change per degree warming (*2*): $\Delta X/(X\Delta T)$, where T is the Arctic mean surface air temperature, and X is the precipitation, surface evaporation, or atmospheric moisture transport through 70°N]. Crosses represent individual climate models. Black open squares are the multimodel means with the black error bars being the intermodel SDs. The horizontal green and pink lines represent the Clausius-Clapeyron relation for atmospheric water vapor changes (~7%/K) and the global mean precipitation sensitivity (~2%/K), respectively. (**B**) Intermodel dependence of trends in Arctic precipitation variability and poleward moisture transport variability. Every square represents one CMIP5 climate model, and the red line is the best linear fit (coefficients in the lower-right corner).

gradient variability increase is thus equal to 3.1%/K (all else being equal, increases in the mean will cause a similar increase in its variability). This would suggest that the additional increase in moisture gradient variability of 2.1%/K can be attributed to altered atmospheric dynamics. Atmospheric variability through changes in dynamics such as a northward shift in the position of the jet stream and associated storm tracks (*11*), more intense cyclones entering the Arctic (*12*), enhanced frequency/intensity of poleward atmospheric moisture rivers (*13*), and altered circulation patterns (*14*) can all modulate the thermodynamic increase in poleward moisture transport variability. However, intermodel differences as well as intramodel uncertainties in the changing atmospheric dynamics and the processes related to poleward moisture transports are considerable. The origin of atmospheric moisture being transported toward the Arctic also likely varies among models. Surface evaporation from the midlatitude boreal continents constitutes the main source of atmospheric moisture being transported into the Arctic, especially during summer (*15*), but there is no intermodel correlation between changes in moisture gradient variability and those in surface evaporation. Moreover, conditions in the Arctic (e.g., excessive surface evaporation during anomalously low sea ice years) may affect the meridional moisture gradient. However, links between (changes in) surface evaporation variability and moisture transport variability remain as of yet unclear.

Changes in atmospheric dynamics associated with dominant patterns in variability such as the Arctic Oscillation (AO) and the North Atlantic Oscillation may affect poleward moisture transport. Some models show that the AO index might increase in a warming climate (*16*), but other studies exhibit a decrease (*17*); likewise, there is strong intramodel (i.e., within one model) uncertainty in future AO trends. Changes in Arctic interannual precipitation variability attain maximum values in summer, closely following those in poleward moisture transport variability (Fig. 4A). The latter might be due to an increase in the number and intensity of cyclones, mainly in summer (*11*, *18*, *19*), which would suggest a poleward shift in the storm tracks and a deeper penetration of cyclones into the Arctic (but other studies report an equatorward shift of the jet stream). Extreme precipitation events in the Arctic exhibit an increase that has been linked to reinforced transient eddies protruding farther into the Arctic (*20*). Moreover, reinforced summer moisture convergence in the Arctic can spur the development and intensification of local/mesoscale systems that produce convective precipitation (see the Supplementary Materials) and thereby augment summertime interannual precipitation variability. While changes in atmospheric dynamics associated with poleward moisture transport variability are subject to considerable (intermodel and intramodel) uncertainty, the geographical distribution of model mean relative changes in interannual precipitation variability exhibits a robust poleward amplification (Fig. 4B).

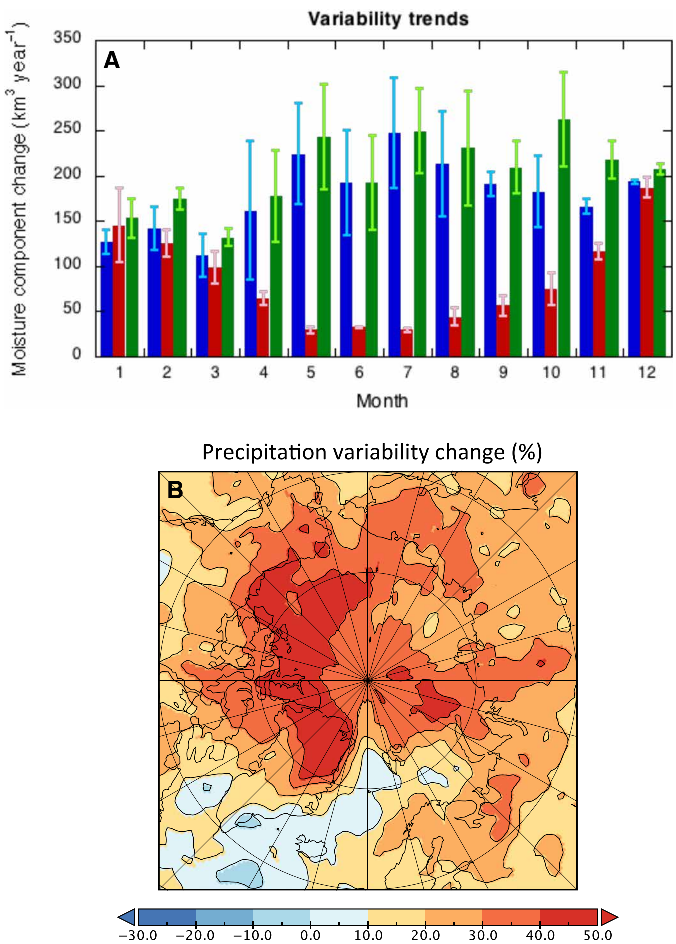


Fig. 4. Seasonal and geographical patterns of multimodel-mean 21st-century changes in Arctic moisture budget variability. (**A**) Seasonal changes for precipitation (blue), poleward moisture transport through 70°N (green), and surface evaporation (red). Error bars indicate intermodel uncertainty defined as the 1 − σ SD from the mean. (**B**) Geographical distribution of relative changes in interannual precipitation variability.

DISCUSSION

Arctic mean precipitation and its interannual variability exhibit increases in multimodel-based projections of 21st-century climate change (notwithstanding considerable uncertainties related to intermodel differences and intramodel uncertainties linked to decadal and longer-scale climate fluctuations) but for different reasons. The simulated future increase in interannual precipitation variability is linked to changing fluctuations in poleward atmospheric moisture transport through atmospheric moisture content, possibly modulated by altered atmospheric dynamics. These findings are corroborated by dedicated climate model simulations, which demonstrate that fast atmospheric processes govern (changes in) interannual Arctic precipitation variability, whereas comparatively slow oceanic mechanisms (through surface evaporation) dominate changes/variations on longer (decadal, longer-term trends) time scales (see the Supplementary Materials).

Increased precipitation variability on top of rising mean precipitation rates can potentially exert severe consequences (*10*), since both increase the likelihood of wet extremes (*21*) with large and possibly irreversible hydrological/ecological (e.g., water availability, marine productivity, and permafrost thaw), societal (e.g., local communities), and economic (e.g., infrastructural damage) impacts (*10*, *22*–*26*). Extremely wet episodes are thus likely to become far more common in the Arctic's (near) future; the unusually wet autumn/winter of 2015/2016 and 2016/2017 in Svalbard (causing a number of climate refugees to abandon their homes) may already have signaled the emergence of extreme Arctic precipitation events along with their long-lasting impacts.

MATERIALS AND METHODS

In all analyses, we applied the collection of Coupled Model Intercomparison Project, Phase 5 (CMIP5) state-of-the-art global climate models, which were used in a series of standardized forcing scenarios for the period 1870–2100. We applied the strong (Representative Concentration Pathway RCP8.5) forcing scenario for the period 2006–2100, for which the combined greenhouse, aerosol, and other radiative forcings in the year 2100 total 8.5 W m^{-2} (*1*). We used all models (35) for which monthly mean output coverage of precipitation (P), surface evaporation (E), and surface air temperature was complete and without obvious errors (other than that, no selection of models was made); one ensemble member per model (the first) was used.

The Arctic (70° to 90°N) atmospheric moisture reservoir is very small; the mean residence time of atmospheric moisture (Q) is less than 1 week, meaning that $\partial Q/\partial t \ll P$ or E (*2*). We therefore evaluated the total poleward moisture transport through 70°N (F) using $F = P - E$ with sufficient accuracy (*27*), although the contribution of E (F) to P will be slightly overestimated (underestimated). Interannual variability is defined as the SD over consecutive detrended 30-year periods. Twenty-first-century trends in Arctic moisture budget means and variability were evaluated using linear regressions (of both mean and variability values) over the period 1981–2100. The atmospheric moisture gradient at 70°N is defined as the difference in vertically integrated atmospheric specific humidity between the regions 50° to 70°N and 70° to 90°N.

Uncertainties in (trends in) interannual precipitation variability are due primarily to intermodel differences (i.e., model physics and details) and intramodel uncertainties (owing to decadal and longer fluctuations). Since we used only one ensemble member per model, the intramodel uncertainty contribution cannot be properly quantified. Both components of the total uncertainty in Arctic climate variability trends are more closely investigated and quantified in the Supplementary Materials using various types of large ensembles for a subsection of the CMIP5 model collection.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/6/7/eaax6869/DC1

Climate model validation of Arctic precipitation (mean and variability)

Model-based interannual versus decadal variability

Separating interannual and decadal variability

Changes in convective (small-scale) precipitation in the Arctic

Intermodel differences and decadal variations in interannual precipitation variability uncertainty

Intermodel versus intramodel uncertainties in interannual precipitation variability trends

Fig. S1. Arctic (70° to 90°N) mean and annual mean precipitation (average and interannual variability) as simulated by 35 CMIP5 global climate models compared with six observation-driven reanalysis datasets for the period 1981–2010.

Fig. S2. Arctic (70° to 90°N) mean and annual mean precipitation, surface evaporation, and poleward moisture transport across 70°N for each of the 16 randomly chosen initial conditions in the 2000-year EC-Earth climate model ensemble of the present-day climate.

Fig. S3. Relations between mean and variability of Arctic moisture budget components.

Fig. S4. Arctic (70° to 90°N) and annual mean precipitation anomaly (i.e., mean value subtracted) for a 400-year simulation of the current climate using the global climate model EC-Earth.

Fig. S5. Arctic moisture budget component variability estimates of the current climate and the $2xCO_2$ climate (both 400-year quasi-equilibrium climates simulated by EC-Earth) for the complete time series (ALL), only decadal variations (DEC), and only interannual variations (INT).

Fig. S6. Time scale–dependent correlations between time series of annual mean Arctic precipitation and moisture transport at 70°N (blue lines) and precipitation and surface evaporation (red lines) for the current climate (full lines) and the $2xCO_2$ climate (dashed lines).

Fig. S7. Model-simulated (EC-Earth) change in convective precipitation in the Arctic between a $2xCO_2$ and a $1xCO_2$ simulation expressed as the difference in the ratio (in percentage) of convective to total precipitation occurrence, evaluated using annual means.

Fig. S8. Arctic precipitation variability and its uncertainty in CMIP5 preindustrial simulations, determined by taking the SD over subsequent 30-year detrended periods (annual means), per model.

Fig. S9. Arctic interannual precipitation variability trends (1980–2100) and their intermodel (between models) and intramodel (within one model) uncertainties for six state-of-the-art global climate models, determined by taking the SD over subsequent 30-year detrended periods (annual means) and then taking a linear regression of the resulting time series in variability.

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