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LETTERS

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Towards a rain-dominated Arctic

R. Bintanja[1,2]* and O. Andry[1]

Climate models project a strong increase in Arctic precipitation over the coming century[1], which has been attributed primarily to enhanced surface evaporation associated with sea-ice retreat[2]. Since the Arctic is still quite cold, especially in winter, it is often (implicitly) assumed that the additional precipitation will fall mostly as snow[3]. However, little is known about future changes in the distributions of rainfall and snowfall in the Arctic. Here we use 37 state-of-the-art climate models in standardized twenty-first-century (2006–2100) simulations[4] to show a decrease in average annual Arctic snowfall (70°–90° N), despite the strong precipitation increase. Rain is projected to become the dominant form of precipitation in the Arctic region (2091–2100), as atmospheric warming causes a greater fraction of snowfall to melt before it reaches the surface, in particular over the North Atlantic and the Barents Sea. The reduction in Arctic snowfall is most pronounced during summer and autumn when temperatures are close to the melting point, but also winter rainfall is found to intensify considerably. Projected (seasonal) trends in rainfall and snowfall will heavily impact Arctic hydrology (for example, river discharge, permafrost melt)[5–7], climatology (for example, snow, sea-ice albedo and melt)[8,9] and ecology (for example, water and food availability)[5,10].

Changes in surface evaporation, atmospheric water vapour content and moisture transports modulate precipitation rates. Globally, precipitation is projected to increase at only about 2% per degree warming owing mainly to infrared radiation constraints[11]. Regional precipitation changes, however, can diverge considerably from this global value. In the Arctic, for instance, precipitation rates have been shown to increase much faster than the global rate (4.5% per degree)[2]. This has been attributed primarily to sea-ice retreat, with open water allowing more evaporation, cloud formation and precipitation. Increased moisture transport from southerly latitudes was found to be of secondary importance, but both contributions (local and remote) exhibit considerable seasonal variations[2,12]. In any case, projected increases in Arctic precipitation of over 50% (model-mean value) during the coming century (see Supplementary Information) are conclusively linked to amplified Arctic warming[2]. All current climate models depict an increase in Arctic precipitation (albeit at different magnitude), which can thus be regarded as a robust feature of projected climate change. Therefore, potentially broad and long-lasting impacts of increased Arctic precipitation on hydrology[13], climate feedbacks[9], ice-sheet mass balance and flow speed[14], sea ice, ocean circulation[2] and biology/ecosystems[5] should be taken into consideration.

The issue of increased Arctic precipitation and its possible consequences is complicated, however, by the fact that in cold regions such as the Arctic, precipitation can fall as either rain or snow, depending primarily on the ambient atmospheric temperature[6,9]. With projected Arctic warming varying considerably with season (strong in winter, moderate in summer)[15], the seasonally varying fraction of rain/snow will inevitably change as well. Whereas increased precipitation leads to more snowfall, higher atmospheric temperatures tend to reduce snowfall[16]. Because of these opposing mechanisms, whose magnitude varies with location and season, it is a priori unclear whether Arctic warming will reduce or enhance total Arctic snowfall. In any case, a changing ratio of liquid to solid Arctic precipitation may have broad and wide-ranging consequences for: hydrology, as it governs the seasonality of snow cover[17] as well as snow melt and runoff[6] (thereby modulating Arctic Ocean salinity[2,18]); climatology, for instance because it affects the surface reflectivity of snow-covered regions and of sea ice (snowfall increases the snow albedo, whereas rain will reduce the albedo by increasing the snow grain size[19], and reinforce snowmelt), and because it reinforces ice-sheet melt rates and flow speeds[14]; biology/ecosystems, since for instance winter rainfall and icing have been shown to inhibit reindeer food availability[10], causing a dramatic population decline and associated strong fluctuations in the fragile Arctic ecosystem; economy, with more frequent icing conditions causing infrastructural and related problems[20]. For these and other reasons, it is of vital importance to quantify future changes in Arctic precipitation in terms of the rain/snow fraction.

Here we use output from 37 state-of-the-art global climate models within the framework of CMIP5 (Coupled Model Intercomparison Project, phase 5)[4] to analyse projected seasonally varying trends in Arctic (70°–90° N) precipitation, including the subdivision between rainfall and snowfall. For this purpose we use standardized simulations for the period 2006–2100 based on intermediate and strong forcing scenarios[4] (see Methods). In the current climate (2006–2015), snowfall governs precipitation in the frigid central Arctic and in the high-elevation expanses of Greenland with 70 to 100% of the annual precipitation falling as snow (Fig. 1a). The annual snowfall fraction, defined as the ratio of snowfall and total precipitation, drops to 40% in the milder peripheral regions of the Arctic. Nevertheless, the majority of annual and total Arctic precipitation currently falls as snow[21]. Towards the end of the twenty-first century (2091–2100), however, with Arctic precipitation rates increasing by 50 to 60% (Supplementary Information), the simulated snowfall fraction reduces dramatically with only Greenland continuing to experience snowfall fractions over 80% (Fig. 1b). In the central Arctic, the snowfall fraction barely remains larger than 50%, and precipitation will be dominated by rainfall in much of the Arctic. The most dramatic reductions in snowfall fraction will occur over the North Atlantic and especially the Barents Sea (Fig. 1c)[22], where most climate models project strong twenty-first-century surface warming (Supplementary Information). With Arctic warming causing a ubiquitous increase in precipitation as well as an overall decrease in snowfall fraction, the question is how, according to the climate models, these opposing effects translate into twenty-first-century trends in Arctic rainfall and snowfall.

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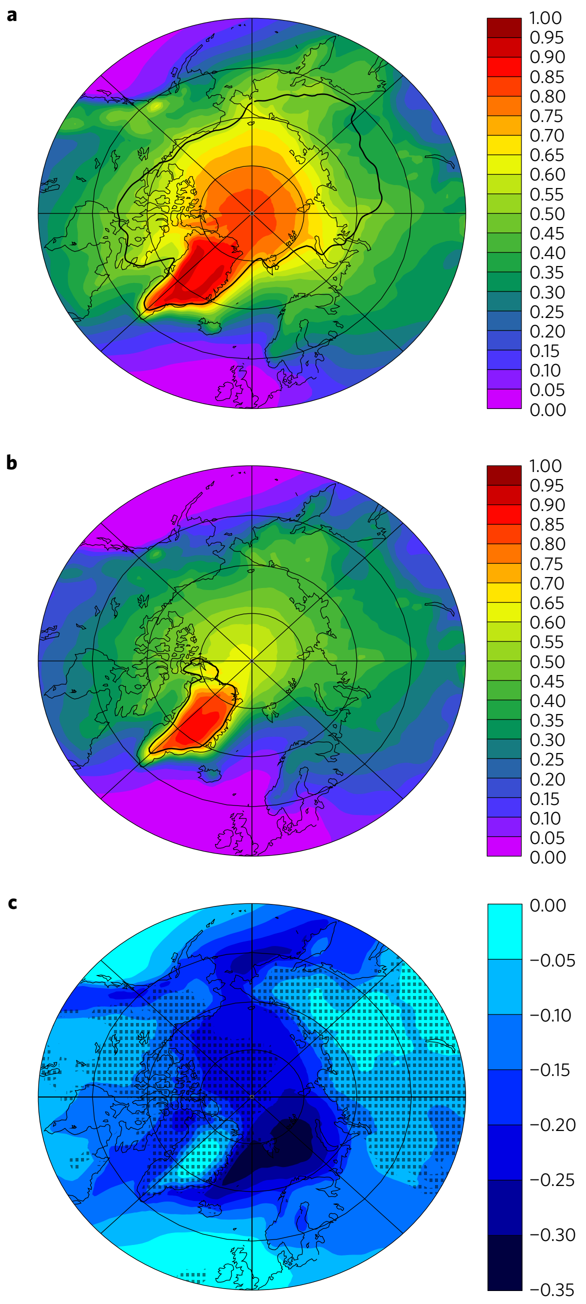

Figure 1 | Geographical distribution of simulated (model-mean) snowfall fraction (ratio of snowfall and total precipitation) in the Arctic region for RCP8.5 forcing. a, Present-day (2006–2015). **b**, Future (2091–2100). **c**, Twentieth-century trend, defined as the absolute difference between future and present-day snowfall fractions. Stippling denotes regions where the difference is not statistically significant (see Methods). In **a**,**b**, the black solid line represents the model-mean −10 °C isotherm.

Under the strong forcing scenario, annual mean surface air temperatures in the Arctic (70°–90° N) increase by 8.5 ± 2.1 °C (model-mean value and intermodel standard deviation) over the course of the twenty-first century. This vigorous warming, which peaks in winter[15,23], clearly dominates changes in rain/snow fraction since all models agree that most of the additional precipitation will fall as rain (Fig. 2a). Changes in total Arctic snowfall are generally small. This can be attributed to a strong north–south gradient in the snowfall trend (which changes sign roughly at the −10 °C isotherm)[24]. Models simulating comparatively strong warming even project a decrease in snowfall (despite the substantial increase in precipitation) owing to the considerable reduction in snowfall fraction in these relatively 'warm' models (Fig. 2b). In fact, twenty-first-century changes in annual snowfall are projected to be much smaller than those in rainfall throughout the entire Arctic except central Greenland. A reduction in snowfall fraction of only 0.17 leads to the total precipitation change being entirely due to rainfall changes (Fig. 2c), which occurs at a warming of about 7 °C. Since most models exhibit an annual Arctic warming of more than 7 °C, all but a few models project Arctic snowfall to decrease. For the simulated changes in annual snowfall and rainfall to be equal, hypothetically, the snowfall ratio should decrease by a mere 0.05, which would occur at a warming of only 2 °C. All models project an annual mean Arctic warming far greater than 2 °C (Fig. 2a), reinforcing the likelihood that increases in rainfall will dominate twenty-first-century Arctic precipitation trends. This suggests that in more moderate warming scenarios than the one considered here most of the additional Arctic precipitation would still consist of rainfall, which can thus be considered a robust feature of Arctic climate change.

Simulated Arctic warming exhibits a huge seasonal cycle, with the warming peaking in late autumn and winter[15,23]. Since trends in Arctic precipitation are dictated by climate warming[2], the precipitation increase also peaks in late autumn and winter. Mild, near-freezing temperatures cause the snowfall fraction to severely diminish in summer and autumn. Enhanced rainfall rates (Fig. 3a) will considerably lower the surface albedo of snow and sea ice when insolation is relatively high, thereby reinforcing surface warming and snow/ice retreat[19]. The decrease in snowfall fraction indeed peaks in early autumn (Fig. 3a), when moderately strong warming (Fig. 3b) regularly leads to above-zero Arctic temperatures; winter warming, albeit more vigorous (Fig. 3b), results in the end of the twenty-first-century Arctic winters still being cold enough to enhance snowfall[24]. However, winter rain also becomes more abundant, with its projected increase even matching that in solid precipitation (Fig. 3a). This may have drastic consequences. As an example, observations suggest that Arctic winter rainfall is already currently increasing, with refreezing and icing posing considerable problems for foraging reindeer, leading to starvation and major population declines[10]. These result in considerable fluctuations, and possibly even (irreversible) trends, in the vulnerable Arctic ecosystem[5].

In the present-day climate, the mean annual precipitation in the Arctic (70°–90° N) is dominated by snowfall, with 65 ± 5% of precipitation currently falling in solid form (Fig. 4a) (this model-mean value compares favourably to the 68 ± 2% as evaluated from the observationally driven JRA-55 reanalysis data set[25], see Supplementary Information). According to the climate models, however, the rain/snow subdivision will change drastically over the course of the twenty-first century. While total Arctic precipitation will increase by about 40%, snowfall will actually diminish. Climate models project that, at the end of the twenty-first century under strong forcing (RCP8.5), about 60% of Arctic precipitation will consist of rain; hence, rainfall will become the dominant form of Arctic precipitation. If the snowfall fraction (which depends chiefly on surface air temperature as per Fig. 2b) were artificially held constant, the future Arctic would still be dominated by snowfall (Fig. 4a, middle column). The 'regime' shift towards a rainy Arctic is due primarily to Arctic warming and the associated strong reduction in snowfall fraction, and, more specifically, to the warming of the near-surface boundary layer (where Arctic warming is maximum[22]) so that snowfall melts into rain before it reaches the surface. The average of the 'best' five climate models (see Supplementary Information) also projects a future with strongly reduced Arctic snowfall and rain dominating future Arctic precipitation (Fig. 4b). Even under a more moderate climate forcing (RCP4.5, Fig. 4c), Arctic rainfall will dominate precipitation changes, as could already be deduced from Fig. 2. Interestingly, snowfall actually increases

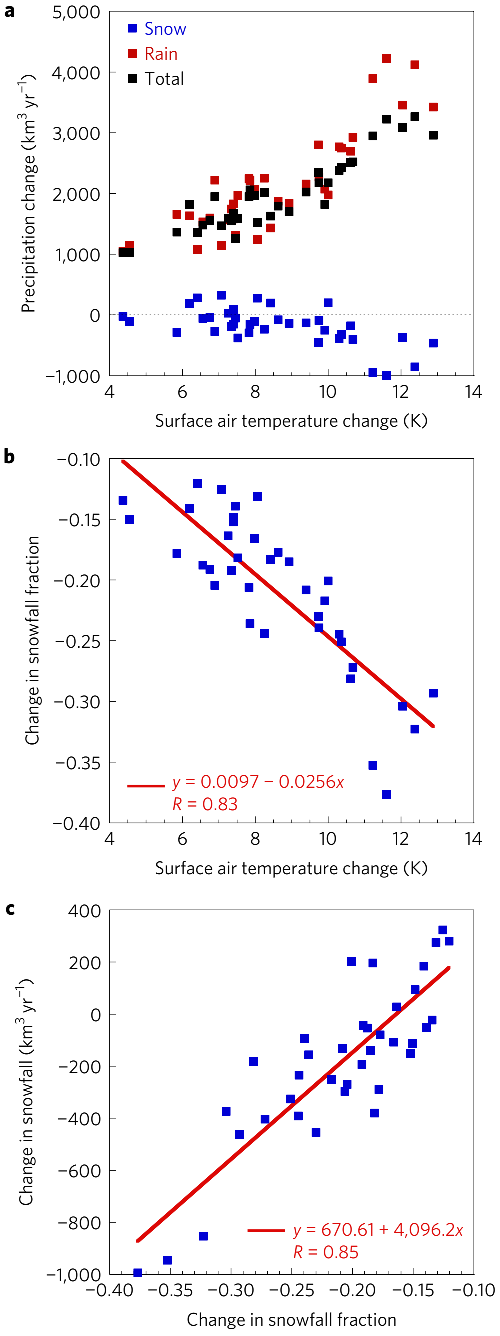

Figure 2 | Model-dependent Arctic-mean (70°–90° N) twenty-first-century changes in surface air temperature, precipitation components and snowfall fraction for RCP8.5 forcing. a, Intermodel dependence of absolute changes in total precipitation, snowfall and rainfall on changes in surface air temperature. **b**, Intermodel dependence of changes in snowfall fraction on changes in surface air temperature. **c**, Intermodel dependence of changes in snowfall on changes in snowfall fraction. Red lines depict the best linear fits to the data (in **b**,**c**), with the coefficients of the fits shown in red.

over continental regions in the Arctic (Fig. 4d), in contrast with the Arctic average, but consistent with the relatively minor decrease in snowfall fraction over land (Fig. 1c). Separating latitude regions to assess the importance of the initial climate on trends (Fig. 4e) reveals that even over the centre of the Arctic Ocean (80°–90°) rainfall will increase considerably (compared with changes in snowfall). Hence, warming-induced Arctic rainfall changes will occur throughout the entire Arctic region.

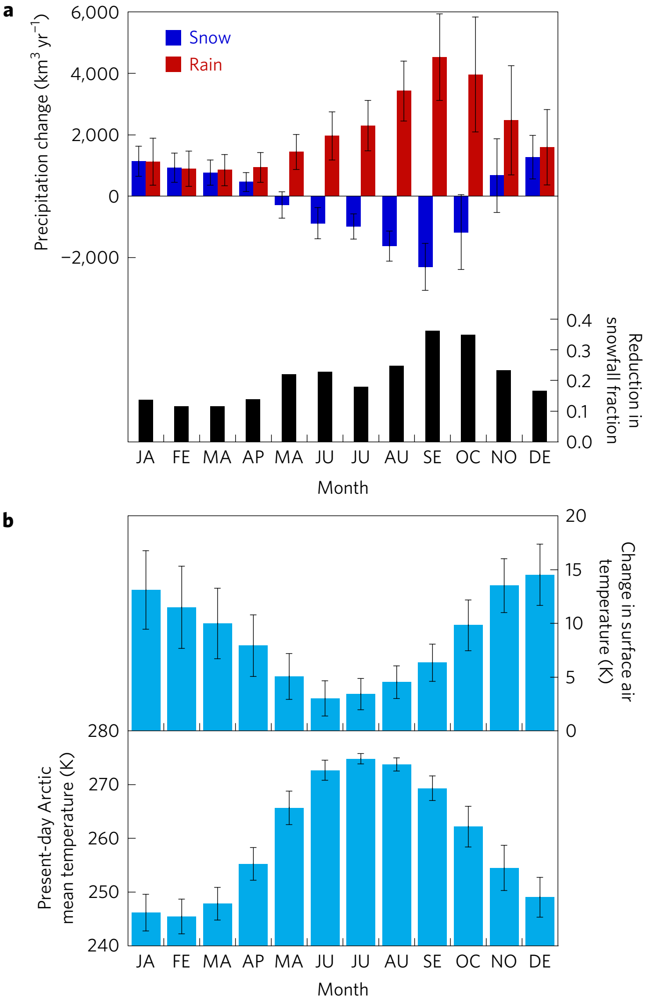

Figure 3 | Simulated model-mean monthly twenty-first-century changes in Arctic-mean (70°–90° N) precipitation variables and surface air temperature for RCP8.5 forcing. a, Absolute changes in total snowfall and rainfall (top), and reduction in snowfall fraction (bottom). **b**, Present-day surface air temperature (bottom) and changes in surface air temperature (top). Error bars represent the multi-model standard deviations and indicate model uncertainty.

Climate models are extremely consistent in simulating a twenty-first-century increase in Arctic precipitation as a by-product of amplified Arctic warming[2]. Intuitively, most of this extra precipitation might be expected to fall as snow because the Arctic climate still is quite cold, especially in winter[3]. However, it is found that models are equally consistent in projecting strong increases in rainfall throughout the entire Arctic. Climate models also simulate a moderate decrease in snowfall, especially models that exhibit relatively strong Arctic warming. This is because near-surface atmospheric warming considerably diminishes the snowfall fraction[16,24]. Hence, the Arctic is projected to become rain-dominated, a robust yet unexpected feature of future climate change that will impact the Arctic region in many ways. First, the hydrology of the Arctic and subarctic continental regions and of the Arctic Ocean depends strongly on whether precipitation falls in solid or liquid form. Rain causes more (extensive) permafrost melt[7,26], which most likely leads to enhanced emissions of terrestrial methane[27] (a powerful greenhouse gas), more direct runoff (a smaller seasonal delay) and concurrent freshening of the Arctic Ocean[18]. Rainfall also diminishes snow cover extent and considerably lowers the surface albedo of seasonal snow, ice sheets and sea ice[9], reinforcing surface warming and amplifying the retreat of ice and snow; in fact, enhanced rainfall will

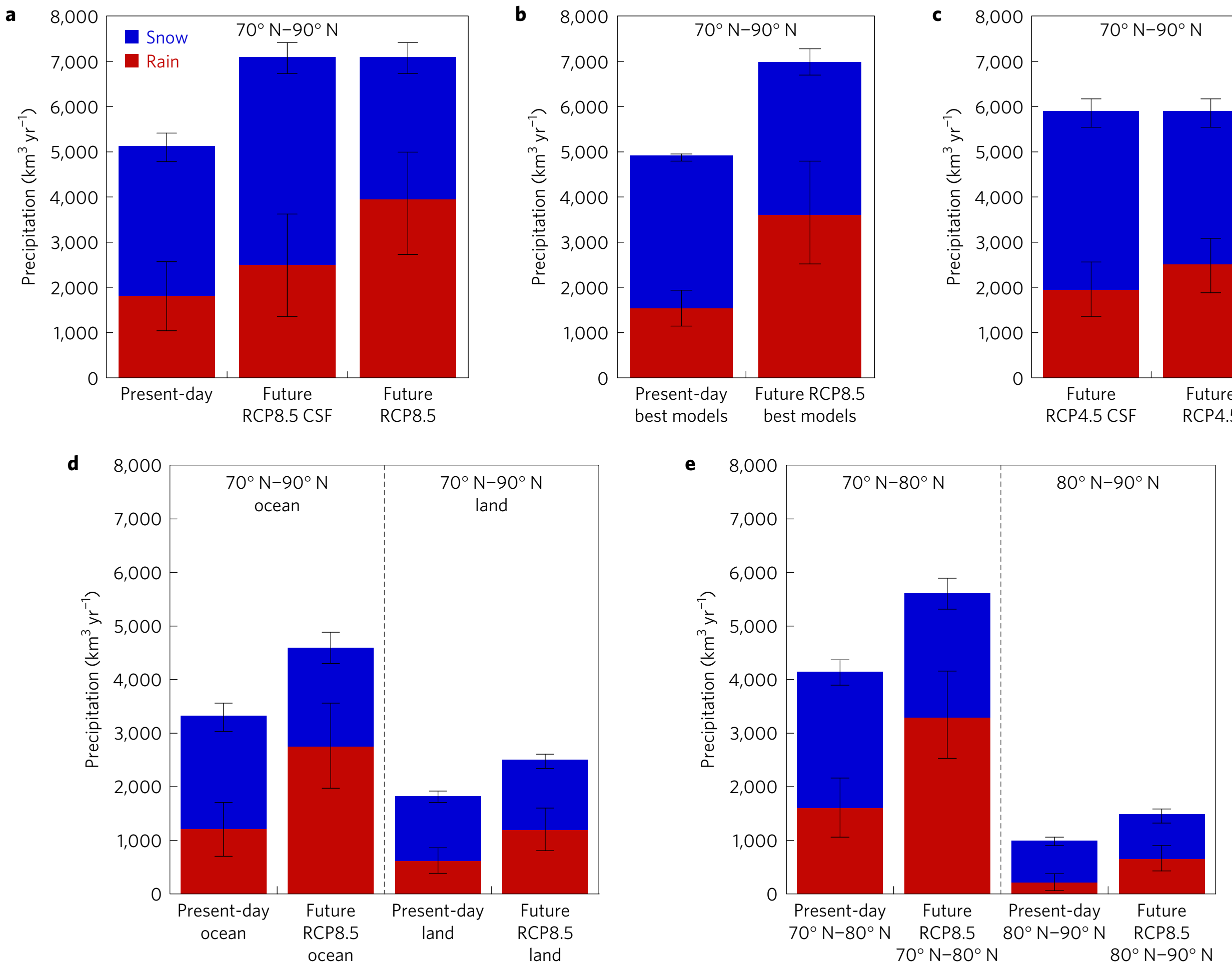

Figure 4 | Simulated model-mean Arctic total snowfall and rainfall. a, Present-day and future (left and right bars, respectively) total (70°–90° N) snowfall and rainfall for the strong forcing scenario (RCP8.5), as well as the future situation in which it is hypothetically assumed that the current snowfall fraction remains constant (constant snowfall fraction, CSF). **b**, Present-day and future snowfall and rainfall (RCP8.5) for the 'best' five models (see Supplementary Information). **c**, Future snowfall and rainfall for the intermediate forcing scenario RCP4.5 (actual and assuming CSF). **d**, Present-day and future snowfall and rainfall (RCP8.5) averaged over ocean (left) and land (right) regions within the Arctic (70°–90° N). **e**, Present-day and future snowfall and rainfall (RCP8.5) over the regions 70°–80° N (left) and 80°–90° N (right). Error bars represent the multi-model standard deviation and indicate model uncertainty.

most likely accelerate sea-ice retreat by lowering its albedo (compared with that of fresh snowfall). Furthermore, rain enhances the chance of icing conditions, with potential infrastructural and economic impacts[20]. Finally, precipitation falling as rain instead of snow strongly impacts Arctic ecosystems, with more frequent episodes of relatively mild weather, rainfall and icing (especially in winter) affecting faunal food availability[10,28], vegetation changes[29,30] and biodiversity. All taken together, the projected twenty-first-century transition towards a rain-dominated Arctic will have widespread, long-lasting and possibly even irreversible consequences.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

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Author contributions

R.B. developed the ideas that led to this paper. R.B. analysed the climate model simulations, while O.A. analysed the reanalyses data. R.B. wrote the main paper, with input from O.A. All authors discussed the results and implications and commented on the manuscript at all stages.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to R.B.

Competing financial interests

The authors declare no competing financial interests.

Methods

General. In all analyses we used the Coupled Model Intercomparison Project, phase 5 (CMIP5) state-of-the-art global climate models (see Supplementary Information), which were applied in a series of standardized forcing scenarios for the period 2006–2100 (ref. 4). We focus on the strong (RCP8.5) forcing scenario, for which the combined greenhouse, aerosol and other radiative forcings in the year 2100 total 8.5 W m^{-2} (ref. 4), but also show results for the more moderate RCP4.5 scenario (4.5 W m^{-2} forcing) to illustrate scenario dependence. Observed current Arctic sea-ice decline (and most likely also related Arctic climate changes) seem to be best represented by a strong forcing scenario, although even RCP8.5-driven models underestimate current changes[1]. We use monthly mean output from all available models (37) for which data coverage was complete and without obvious errors (other than that no selection of models was made); one ensemble member per model (the first) was used. Twenty-first-century trends in Arctic precipitation (including the model-generated subdivision between rainfall and snowfall) are defined as the difference between the means over the periods 2091–2100 and 2006–2015. We use these periods for consistency with earlier results[2]; moreover, twenty-first-century RCP8.5-forced trends in Arctic precipitation components are much larger than the associated decadal variability in these variables, meaning that using 10-year means samples the twenty-first-century trends with sufficient accuracy (compared to for instance using 30-year means). The differences in Fig. 1c and Supplementary Figs 4 and 5 are considered significant if the present-day and future multi-model means plus/minus one standard deviation do not overlap.

Data availability. All climate model output data used in this study are an integral part of the Coupled Model Intercomparison Project, phase 5 (CMIP5) initiative. As such, all data are publicly available at http://cmip-pcmdi.llnl.gov/cmip5 and at designated data centres, and are available from the corresponding author on reasonable request. All reanalyses data used in this study (ERA-Interin, NCEP/NCAR, JRA-55) are publicly available through the respective web portals, and are available from the corresponding author on reasonable request.