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Invited Review

Nordic boreo-arctic lands under rapid climatic change: A review of recent and future trends and extreme events

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ABSTRACT

The Arctic amplification affects the geology, cryosphere, and the total environment of high-latitude maritime-influenced lands. This study synthesizes information on recent and future climatic changes within the Nordic boreo-arctic region. The study area includes Greenland, Iceland, and the central and northern parts of Finland, Norway (incl. Svalbard), and Sweden. The climate scenarios used are derived from the CMIP6 ECEarth3 Earth System Model (ESM) data for the period 2015–2100 under the SSP2–4.5 scenario. The synthesis builds upon a comprehensive range of sources, addressing both gradual climatic changes and the frequency of extreme weather events across all seasons. Ongoing and projected changes to the cryosphere, soil, freshwater systems, wind, precipitation, and frequency of hazardous events are comprehensively reviewed and discussed.

1. Introduction

Global climate is under rapid change; the last 9 years (2015–23) were the nine warmest years on record (Dunn et al., 2023). Annual mean surface air temperature anomaly for recent years for terrestrial areas poleward of 60° N is ca. 2.1 °C above the 1981–2010 average (AMAP, 2021; Box et al., 2022; Ballinger et al., 2023), i.e., a nearly four times faster warming than the global average (Rantanen et al., 2022). The northern warming amplification has also led to a significant downward trend in Arctic sea-ice extent of −2.6 % decade^{-1} over the 1979–2022 record (Meier et al., 2023). Declining sea ice results in higher-than-average warming trends of nearby land areas due to positive feedback loops, with numerous impacts on terrestrial ecosystems and species.

The climate of the boreo-arctic areas of the Nordic region is buffered by its proximity to open sea, i.e., the climate is under moderate to high maritime influence, which leads to lower temperature difference between the coolest and warmest months as compared to more continental regions (Tuhkanen, 1984). Numerous research show that the combination of a strong warming trend and a maritime climate is affecting maritime-buffered boreo-arctic lands in multiple ways which differ from continental regions (e.g., Crawford, 2000; Bokhorst et al., 2016; Vikhamar-Schuler et al., 2016; Walsh et al., 2020), with potentially severe impacts on northern livelihoods. For example, indigenous reindeer herding in Finland, Norway, and Sweden, and indigenous traditional winter hunting of musk oxen and caribou in Greenland, are under enhanced pressure from year-round warming-induced stress to the

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animals (Andersen, 2022; Cuyler et al., 2020; Jørgensen, 2019; Rasmus et al., 2020; Skarin et al., 2021).

To the best of our knowledge, there is currently no comprehensive recent summary of on-going climate change and its effects on land areas in the boreo-arctic Nordic region, as well as the anticipated feedback resulting from projected changes (Michel et al., 2022).

To address these issues, an extensive literature survey combined with state-of-the-art climate projections used in the IPCC AR6 report (Allan et al., 2023) was undertaken by a multi-national, interdisciplinary research team concentrating on the boreo-arctic land areas of the Nordic countries, focussing on essential climate variables. Both recent and future elements of climate change are treated.

We provide downscaled climate scenarios relying on the IPCC Shared Socio-economic Pathways (SSPs). The SSPs are based on five narratives: a world of sustainability-focused growth and equality (SSP1); a 'middle of the road' world where trends broadly follow their historical patterns (SSP2); a fragmented world of 'resurgent nationalism' (SSP3); a world of ever-increasing inequality (SSP4); and a world of rapid and unconstrained growth in economic output and energy use (SSP5) (Rekker et al., 2023). SSP5 is considered as the most aggressive scenario. Projections presented graphically in this review rely on the "middle of the road" scenario, also known as SSP2–4.5, which currently appears as a realistic scenario (Dellink et al., 2017; Kotz et al., 2024). That said, other narratives either have lower (SSP1) or higher (SSPs 3–5) slope trends (Rekker et al., 2023; Kotz et al., 2024). This review will aid in the understanding of the major ongoing and future climate changes within the study area, and their impacts.

2. Study area

This study concentrates on the terrestrial boreo-arctic areas within the Nordic region on both sides of the Atlantic Ocean (Fig. 1). This region is already experiencing exceptionally rapid climate change and anticipates further intensification across the 21st century (e.g. AMAP, 2017, 2021; Allan et al., 2023; López-Blanco et al., 2024). The study area, excluding Greenland, is also the most densely populated region at these high northern latitudes. Hence, climatic change has major impacts not only on the lithosphere and the biosphere, but also on the anthroposphere. The area is characterized by long summer days and cold-tolerant ecosystems, corresponding largely to the northern boreal, alpine and arctic vegetation zones as defined by Tuhkanen (1984) and Bakkestuen et al. (2008), but also including middle boreal vegetation where it is present at high latitudes. The southern limit of the study area follows the southern range of the middle boreal zone (Fig. 1). This line is not drawn across the Atlantic Ocean. Both Greenland and Iceland are north of the southern limit of the middle boreal zone. The Faroe Islands are south of this limit, and hence not included in our study area. A few literature examples of climatic events are provided from areas immediately south of this southern limit but represent events that also are typical for the study area. Studies from North American and Russian boreo-arctic regions are in a few cases cited where they have relevance for the study area.

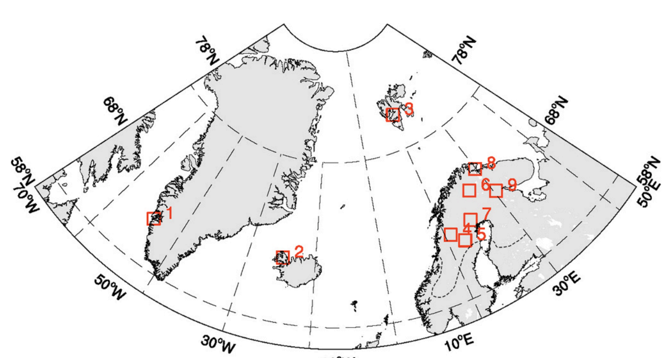

Fig. 1. The Nordic boreo-arctic study area, covering the land areas of Greenland, Iceland, Svalbard, and central and northern parts of Norway, Sweden, and Finland. The southern limit of the middle boreal climatic-phytogeographical zone, as defined by Tuhkanen (1984), is applied as the southern limit of the study area, and is shown as a stippled line across Norway, Sweden, and Finland. The eastern limit of the study area follows the country borders of Norway and Finland towards Russia.

3. Recent climatic trends

3.1. Air temperature

Globally, each of the last four decades has been successively warmer than any preceding decade since 1850 (IPCC AR6; see Allan et al., 2023). Warming has been most pronounced poleward of 60° N, particularly over Arctic seas and associated islands and archipelagos (e.g., Svalbard, Novaya Zemlya, Banks Island, and the north-eastern part of Greenland), but also over the northern stretches of the North American and Siberian continental landmasses (GISTEMP Team, 2024).

For the most recent 5-year period (2019–2023), the annual temperature of Finland, Sweden, and Norway incl. Svalbard was 1–4 °C warmer than the period 1951–1970 (GISTEMP Team, 2024). Most of Greenland was 0.5–2.0 °C warmer than 1951–1970, while trends for Iceland vary much over short distances; from −0.2 °C to 2.0 °C. Anomalies vary much between seasons and regions (Fig. 2). Svalbard and adjacent seas have strong anomalies in all seasons, and especially so in winter (Fig. 2a). Most land areas within the boreo-arctic region are becoming warmer in winter. Spring anomalies are strongest in western

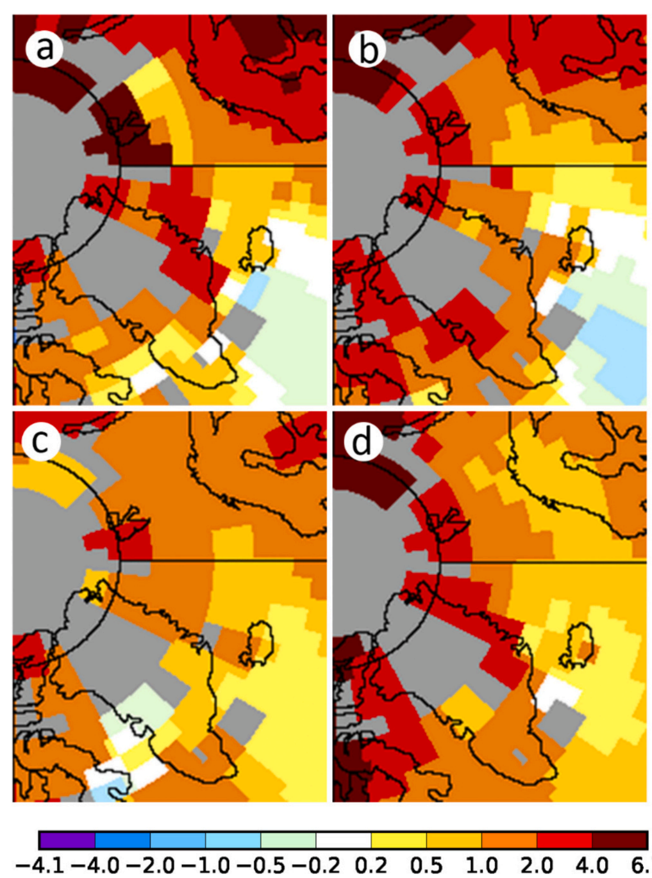

Fig. 2. Temperature anomalies (°C) for the Nordic boreo-arctic region and adjacent areas (2019–2023 vs 1951–1970), based on GISTEMP v4 data (Lenssen et al., 2019) and retrieved from NASA GISTEMP (GISTEMP Team, 2024). (a) winter (December–February), (b) spring (March–May), (c) summer (June–August), (d) autumn (September–November). Grey: no data.

Greenland, north-eastern Greenland, Svalbard, and the north-eastern parts of Finland, Norway, and Sweden (Fig. 2b). The strongest anomaly in summer is in Svalbard (2–4 °C warming), while the boreo-arctic parts Finland, Norway, and Sweden, and most parts of Greenland are also becoming warmer compared to the 1951–1970 period. An exception is western central Greenland, which shows a slight cooling trend (Fig. 2c). The High Arctic parts of the study area (Svalbard, north-western and north-eastern Greenland) show the strongest warming anomaly in autumn (Fig. 2d). The strong warming in autumn is largely a result of sea-ice loss (Ballinger et al., 2022, 2023).

The high-latitude warming has led to longer thermal growing seasons; a trend analysis covering the period from 1950 to 2019 shows a lengthening of the thermal growing season of northern parts of Finland, Norway and Sweden with up to 3.5 days per decade, but that there is large heterogeneity over short distances (Aalto et al., 2022). This study shows that the strongest growing season increase of ca. 5 days per decade has taken place in coastal parts of northern Norway. The more continental upland parts of the study area have had an increase of 3–4 days per decade, while the Swedish and Finnish lowlands have had an increase of 2–3 days per decade.

These trends in growing season length are strongly correlated to changes in growing season degree days sum, which for Norway, Finland and Sweden vary between 0 and 40 degree-days per decade. The thermal growing season is defined as the period of suitable conditions for plant growth, and is, hence, not equivalent to the biological growing season, which is the actual period of plant growth. An important factor for discrepancies between the thermal and the biological growing season is the plants' hibernating state, which is not switched off easily by warmer temperatures. The earlier in the year with temperature conditions suitable for growth, the deeper is the hibernation (frost hardening) and hence, the more unlikely it is that plants will initiate physiological activity.

3.2. Precipitation

A warmer atmosphere can hold more water vapour (Piao et al., 2020). Thus, the recent warming has been associated with increasing precipitation rates at northern high latitudes. Specific humidity and precipitation have increased in these regions (Prowse et al., 2017). This is also evident from long-term precipitation records from the study area. For example, Finnmark in northernmost mainland Norway have had a significant annual precipitation increase of 1.6 % per decade (data period 1900–2014) (Hanssen-Bauer et al., 2017). The same trend is evident within the Swedish part of the study area; the yearly normal for precipitation increased by 12 % (± 4.9 % SD) from the 1961–1990 normal to the 1991–2020 normal for weather stations north or 64° N (Fig. 3a). Analyses of a much longer time series, from 1902 to 2018, also show that northern Sweden has become significantly wetter in all seasons (Chen et al., 2020), while homogeneity-tested stations distributed throughout Norway reveal a 19 % increase in precipitation from 1900 to 2019, during which the steepest increase took place between 1995 and 2015 (Konstali and Sorteberg, 2022). Available meteorological data from Nuuk in Greenland, covering the period from 1958 to 2020 (Cappelen, 2020, 2021), show that annual precipitation rates did not change during this period (linear $r^2 = 0.02$, Fig. 3b), while variability increased significantly (Fig. 3c), caused by large year-to-year variation in precipitation which started around the turn of the millennium. Yet, caution should be taken when interpreting time series from rain gauges. Wind and turbulence may in some cases lead to a severe underestimation of actual precipitation of up to 60 %, according to a study of time series from West Greenland (Mernild et al., 2015).

Annual precipitation at the northernmost parts of the Svalbard hub has increased substantially; there is large variation over short distances, thus the increase spans between 40 and 100 mm, and the majority of this is due to increasing snowfall rates (Box et al., 2022). Overall, within our study area, there is considerable variation in trends in total annual precipitation.

Seasonal trends in precipitation largely follow the annual trends, meaning that all seasons have become wetter in recent decades, albeit with some discrepancies from this general trend, as treated here. Circumpolar high-latitude (poleward of 60°N) total annual precipitation, i.e., both rainfall and snow, increased by 9 % from 1971 to 2019, driven by a 25 % increase in rainfall, with no overall snowfall trend (Box et al., 2022). They concluded that the largest precipitation increases north of 65°N have taken place during the freeze-up season from October through May – when temperature increases are the greatest – especially along the south-eastern coasts of Greenland and Iceland, across the northern North Atlantic and the Barents Sea and in the vicinity of Svalbard.

Iceland has had a minor total increase in precipitation, but with strong local gradients. For example, in Vestfirðir (The Westfjords) in the north-western part of Iceland, annual rainfall at the north-western side has increased by 60–80 mm, while rainfall on the south-eastern side has barely increased (0–20 mm) (Box et al., 2022).

Most of the study area within Finland, Norway and Sweden has become wetter from 1971 to 2019, with increases between 0 and 60 mm during this period (Box et al., 2022). The interior Swedish-Finnish border area has the strongest trend, while coastal sections of Finnmark, have, according to ERA5, no net change or may have become slightly drier. However, when it comes to rainfall only, Finland, Norway and Sweden have received more, while snowfall shows opposite trends to rainfall. The exception is the above-mentioned Finnish-Swedish border area which has a weakly increasing snowfall trend (0–20 mm). Western Greenland shows negligible annual trends, but substantially increasing rainfall and decreasing snowfall trends, according to this ERA5 dataset.

Local weather data largely confirm these ERA5 trends. For northern Norway, there is a steep increasing trend in annual precipitation (Meteorological Institute of Norway, 2022). In a 122-year dataset, the frequency of wet years (i.e., years with more precipitation than the 1991–2020 normal) was 59 % for the period after the turn of the millennium. For 1961–1990, the frequency was 27 %, for 1931–1960 it was 10 %, while for 1901–1930, it was 5 %. All seasons except autumn contribute to this increasing trend. Autumn precipitation is in a declining trend after a peak period in the 1980s and is currently (2014–2022) 8 % lower compared to the 1991–2020 normal.

Autumn is also the season in northern Sweden that differs slightly in trend from the other seasons. While the other three seasons have become significantly wetter, autumn shows a much weaker, only near-significant trend, i.e., the significance level P is between 0.05 and 0.10 (Chen et al., 2020).

3.3. Snow cover

The steadily increasing winter warming has had strong impacts on the snow season in the study area, affecting both the duration of the snow season and the properties of the snow cover, i.e., thickness, hardness, wetness, etc. (Bokhorst et al., 2016; Vikhamar-Schuler et al., 2016; Brown et al., 2017; Rixen et al., 2022). As with rain (see Section 3.2), in situ measurements of snowfall are often problematic due to severe gauge undercatch combined with a sparse and unevenly distributed network of monitoring sites (Behrangi et al., 2019; Colli et al., 2020). Hence, remote sensing has become a vital tool for large-scale analysis of snow cover trends. A satellite-based analysis of land areas north of 60°N, excluding Greenland, covering the period 1972–2014, showed a reduction in snow cover duration corresponding to 3.8 days per decade (Estilow et al., 2015). A 57-year record of snow cover extent (SCE) from the Eurasian Arctic show declining trends for the months May and June (Mudryk et al., 2023). Snow mass across the Arctic tends to peak annually during April, when snowfall has accumulated since the preceding autumn but before increasing temperatures during May and June lead to snow melt (Mudryk et al., 2023). Snow mass in the Eurasian

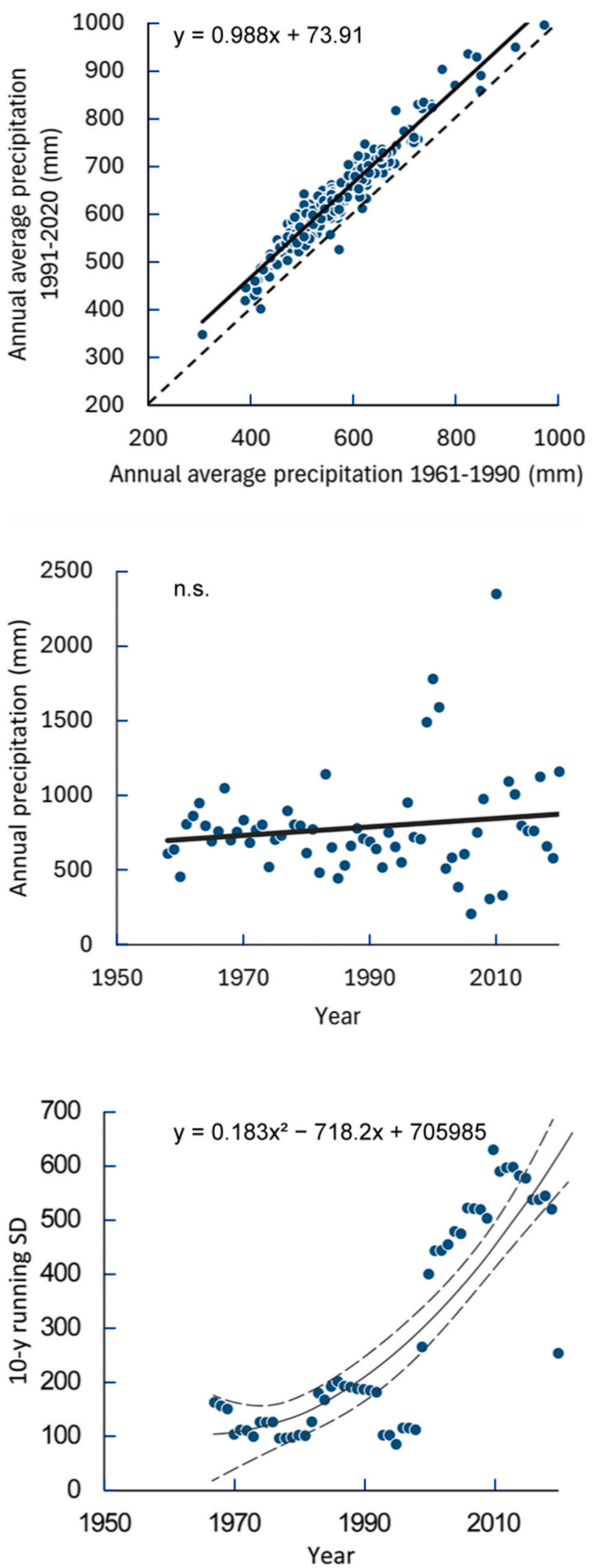

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Fig. 3. Precipitation trends from two contrasting regions of the study area. (a) 30-year average annual precipitation rates from Swedish meteorological stations north of 64° N. Each data point represents a meteorological station (n = 287). Two 30-year normal periods are compared: 1961–1990 (horizontal axis) and 1991–2020 (vertical axis). Some stations lack data from the start and/or the end of this 60-y period. Only stations with more than 10 years of data from both periods are included. Data retrieved from the Swedish Meteorological and Hydrological Institute (2023). (b-c) Precipitation data from Nuuk, Greenland; (b) annual precipitation rates from 1958 to 2020; linear model, r^2 = 0.023, n.s., eq. not shown. (c) 10-year running standard deviation (SD) of annual precipitation. Each point represents the plotted year + the previous 9 years; curvilinear model, r^2 = 0.742, p = 0.005, trend shown as a solid line and 95 % confidence intervals as stippled lines.

Arctic in fact shows an increasing trend since 2011, with the last April on record (2023) having the fifth highest snow accumulation in the 57-year long dataset. This increasing trend is largely due to more snowfall in a milder, but still freezing Siberia, while the North Atlantic region (Finland, Iceland, Norway, Sweden) show declining trends from March to June, whereas Greenland is not represented consistently among the data products and is therefore excluded from the trend analyses (Mudryk et al., 2023).

Snow seasons in the northern parts of the Nordic Region show high interannual variability, partly caused by variation in cyclone activity, which affect predominating patterns of wind, weather, and energy balance, including albedo (Vikhamar-Schuler et al., 2016; Brown et al., 2017). Moreover, even if the study area within Finland, Norway, and Sweden is becoming warmer also in winter, mean temperature in winter is still well below freezing. This, combined with a generally wetter atmosphere (Marshall et al., 2020), can result in major snowfalls events. As an example, the meteorological station in Kautokeino, Finnmark, northern Norway, had a snow depth of 64 cm on 5 January 2022. In a 68-y long snow observation dataset, this day of year had never previously had such deep snowpack (Meteorological Institute of Norway, 2023). An increasing trend in maximum snow depth was also confirmed by gridded observation-based data modelling covering the years from 1958 to 2017 for the Troms region in northern Norway; the interior parts of Troms, including areas close to Kautokeino, show increasing trends of up to 60 % in *winter maximum snow water equivalent* (Dyrrdal et al., 2020). A study from Finnish Lapland covering winters until 2014, also documents increasing snow depths (Luomaranta et al., 2019), and the same trend is observed at Abisko in the Swedish mountain region where snow depth measurements have been undertaken since 1913. Maximum snow depth was considerably thicker in the period 1956–2004 than in the period 1913–1955 (Kohler et al., 2006). Average maximum snow depth for the 1913–2004 dataset was 51.5 cm. This increasing trend has continued after the period covered in Kohler et al. (2006); the average maximum snow depth since the winter season 2003/04 is 79.0 cm (n = 20; data retrieved from the Swedish Meteorological and Hydrological Institute, 2023), i.e., a 48.4 % increase compared to the 1913–2004 average.

A general pattern for Finland, Norway and Sweden is that snow seasons are highly variable. For example, this was shown in a 25-year dataset (1990–2014) from a coastal site in northern Norway, reporting a 9-fold year-on-year variation in cumulative snow depth with a similarly extreme variation in cumulative soil frost (Bjerke et al., 2015). Moreover, long-term snow depth measurements from the northernmost part of Sweden (Norra Norrland, i.e., Lapland, Norrbotten and Västerbotten) show large interannual variation in number of days with snow cover and no significant temporal trends (Swedish Meteorological and Hydrological Institute (2023), dataset covering the winters from 1949/50 to 2022/23). While the period 1949/50 to 1966/67 mostly had winters with lower-than-average snow cover duration, the period from 1967/68 to 1998/99 had longer-than-average snow cover duration (reference period 1961–1990). Except for two winters, all winters from 1999/2000 to 2020/21 had lower-than-average snow cover duration.

This latter period, however, did not differ from the first period (1949/50–1966/67) of this time series.

The uplands in the Finnish-Norwegian-Swedish border region treated above are within a small area of Scandinavia that has experienced increasing snow cover fractions (SCF) after the turn of the millennium (2001–2016), according to a pan-arctic study relying on MODIS satellite imagery data (Eythorsson et al., 2019). This study thus largely shows the same trends as those reported by Box et al. (2022) treated above. However, while Box et al. (2022) included the years until 2019, and in such context provide more updated information, the study by Eythorsson et al. (2019) applied significance analyses to evaluate whether any trends are significant or not. Eythorsson et al. (2019) further concluded that SCF trends in most of the Finnish, Norwegian and Swedish study area was stable between 2001 and 2016. They further documented significant declining SCF trends in ice-free areas of southern Greenland.

For Iceland, Eythorsson et al. (2019) reported increasing SCF trends, but only for the eastern part. A study specifically focussing on Iceland confirms increasing snow trends for all months except October and November (Gunnarsson et al., 2019). The increasing snow cover trends in Iceland are mostly restricted to upland areas and are associated with significant positive post-millennial trends of winter mass balance of Icelandic glaciers. In contrast, the longer trend from 1951 to 2019 suggest declining snowfall trends for Iceland (Box et al., 2022).

In Svalbard, the snow season in spring is becoming shorter with ca. 2.8 days per decade, according to a time study of satellite imagery from 1982 to 2015 from Nordenskiöld Land, i.e., the area surrounding Longyearbyen (Vickers et al., 2021). Due to much wind-driven snow, the scarce network of snow depth monitoring sites in Svalbard are generally not reliable for trend analyses (see, e.g., Bjerke et al., 2017).

The steadily milder atmosphere during winter increases the frequency of rain falling on snow, which results in hard, icy layers on top of, and within, the snowpack during freeze-thaw cycles (Bjerke et al., 2014, 2015, 2017; Hansen et al., 2014; Turunen et al., 2016; Vikhamar-Schuler et al., 2016; Serreze et al., 2021; Rasmus et al., 2021).

3.4. Soil and permafrost

Climate change in soil largely follow the aboveground trends described above, meaning that soil temperature increases when air temperature increases. There is large spatiotemporal heterogeneity in the global offset between soil and air temperature, often in the order of several degrees annually and up to more than 20 °C during winter months at high latitudes (Lembrechts et al., 2019, 2022). Such large offset is found in the most continental areas at high northern latitudes where an insulating snowpack causes the large difference between ambient and soil thermal conditions. While temperature differences between soil and air of our study area are generally much lower, snowpack indeed has a strong insulating impact also here.

Long time series on soil temperature are less frequent than standard air temperature time series. Thus, there are comparatively few reports on soil temperature trends, especially from our study area. Petersen (2021) summarized recent studies globally, and most studies show a warming trend. Petersen's soil dataset from Hveravellir, a weather station in the Icelandic highlands, covering the years from 1977 to 2019, revealed that soil warming was significant in all months except May and June, i.e., the snowmelt period, which varies much in duration between years. The warming trends at this site were largest in autumn and winter, showing a delay of 2–3 weeks in autumn cooling. The annual trend at 50 cm depth was 0.22 °C per decade. An extensive Russian soil temperature dataset includes locations in the Kola Peninsula adjacent to Finland and Norway (Chen et al., 2021). The time series for these Kola sites, covering the period from 1975 to 2016, show a warming trend of 0.1 to 0.5 °C per decade in annual mean temperature at 80 and 160 cm depth.

A 25-year long time series of freezing soil measured by frost tubes (hence not monitoring exact temperature – only whether soil at depths down to 2 m is frozen or not) from a subarctic coastal grassland in northern Norway showed large interannual variation and no significant temporal trends (Bjerke et al., 2015). The multi-model analysis of this time series showed that number of snow-free days with freezing temperatures was the primary regulator of duration and depth of freezing.

Permafrost temperatures in the upper 30 m of land surface is increasing both in Eurasia and North America (Streletskiy et al., 2015; Wang et al., 2022; Wolken et al., 2021; Box et al., 2022). The Finnish, Norwegian, Swedish, and Greenlandic monitoring sites follow this pan-Arctic trend of increasing permafrost temperature (Biskaborn et al., 2019; Karjalainen et al., 2019; Isaksen et al., 2022).

3.5. Sea level rise

Primarily because of melting glaciers, sea level is rising (The IMBIE Team, 2020). Another factor causing sea level rise is the expansion of seawater as it warms. Since 1900, global sea level has risen with ca. 205 mm, half of which has taken place since 1993 (Shaftel, 2022). The most recent update shows that the increase since 1993 is 101.2 mm, viz. an average annual increase of ca. 3.5 mm.

Sea level rise is affecting coastal parts of our study area, but impacts will be more severe during the next decades. Finnmark is among the areas of Norway that will be experiencing the most rapid sea level rise at national level (Simpson et al., 2015). The recent sea level rise in Norway has, however, been much lower than the global average, partly due to land uplift, but sea level varies much between the various parts of the country. Stations in Finnmark have had an increase of ca. 3.6 mm per year, and annual rates are accelerating (Breili, 2022). Recent sea level change in Iceland is estimated to be 0.9–1.6 mm per year (Jóhannsdóttir, 2020).

Sea level rise is a concern in coastal areas. The combination of storm surge and sea level rise is already causing severe damage to coastal infrastructure and ecosystems in our study area and elsewhere (Brisson et al., 2014; Aarrestad et al., 2015; Simpson et al., 2015; Jóhannsdóttir, 2020; Zinke, 2021).

4. Current state in frequency and adversity of extreme weather

Large, short-term deviations from seasonal normals are termed “pulse weather”. The most deviating types of pulse weather are considered as being “extreme”. The Intergovernmental Panel on Climate Change (IPCC), the European Environment Agency (EEA) and other organizations early distinguished between the impacts of gradual change in essential climate variables and the impacts of changes in the magnitude or frequency of extreme weather (IPCC, 2001; European Environment Agency, 2004; Jentsch et al., 2007).

Extreme weather and its equivalent term “extreme climate event” refer to a weather or climate event that is rare at a particular place (and, sometimes, time of year) including, for example, heat waves, cold waves, heavy rains, periods of drought and flooding, and severe storms (National Academies of Sciences, Engineering, and Medicine, 2016). Definitions of *rare* vary, but an extreme weather event would normally be as rare as or rarer than a particular percentile (e.g., 1st, 5th, 10th, 90th, 95th, 99th) of a probability density function estimated from observations expressed as departures from daily or monthly means.

Extreme climate events have substantial negative impacts on human societies and natural ecosystems. In this section, we summarize the current state-of-the-art for extreme weather that recently have occurred in our study area and discuss these weather types in a climate change context.

4.1. Storminess, extreme precipitation, and inland floods

Precipitation and wind in the North Atlantic region crucially depend on horizontal advection of moisture from remote regions (Trenberth, 1999, 2011; Hov et al., 2013). Atlantic windstorms are intense and related to traveling cyclones associated with larger areas of low atmospheric pressure, and they occur most frequently during winter, although there are certain occurrences in all seasons (European Academies Science Advisory Council (EASAC), 2013; Walsh et al., 2020). Activity of synoptic cyclones (> 1000 km in horizontal length) in the North Atlantic has increased at a rate of six events per decade (Rinke et al., 2017; Walsh et al., 2022), and this trend is largely due to an increase in November and December, consistent with a diminished sea-ice cover (Moore, 2016; Walsh et al., 2020, 2022).

Polar lows are low-pressure systems on mesoscale, i.e. horizontal length is lower than 1000 km. Polar lows are some of the most intense Arctic cyclones. Historically, such cyclones have led to loss of numerous boats and lives at open sea and along the coasts of the North Atlantic (Syse, 1979; Amdahl, 2022). Polar lows develop rapidly when cold air flows over open water and are most common at the high latitudes of the North Atlantic, but there are no indications of any trends, partly because of little available information on historical frequencies of such mesoscale cyclones (Walsh et al., 2020, 2022).

Polar lows that hit land are associated with heavy snowfall, avalanche risk, and dangerous driving conditions (Moreno-Ibáñez et al., 2021). The lack of evidence of recent trends in cyclone activity results in limited knowledge on trends in high-wind events at northern high latitudes (Walsh et al., 2020). However, increasing trends in maximum snow depth in upland areas of our study area (see treatment above) may be associated with a recent increase in impacts from polar lows.

In the Atlantic High Arctic, Svalbard has been warming rapidly, and especially so in winter. Winter weather on Svalbard is characterized by cold, stable high pressure interrupted by warmer, wetter low-pressure systems traveling northwards along the North Atlantic storm track (Hanssen-Bauer et al., 1990; Rogers et al., 2005; Hancock et al., 2021). Atmospheric circulation conducive to elevated precipitation, wind speeds, and air temperatures near Svalbard are associated with increased avalanche activity in Nordenskiöld Land, i.e., the areas surrounding Longyearbyen, which has led to a recent increase in avalanche-induced loss of human lives (Hovelsrud et al., 2020; Hancock et al., 2021).

Walsh et al. (2020, 2022) discussed the challenges of assessing historical trends in extremes of precipitation in the Arctic. A sparse network of gauges and a severe gauge undercatch in windy places are some of the reasons why such assessments are challenging. Still, valuable trend data exist; northern Europe is one of the few regions globally where there is high confidence that human influence has contributed to increasing frequency of extreme precipitation (Seneviratne et al., 2021). A large database of daily rainfall events from 281 sparsely distributed weather stations in Finland provide further support to the northern European trend. Using data from 1961 to 2016, this Finnish dataset identified statistically significant increases in extreme precipitation in some parts of the country including Lapland in northern Finland, and particularly during summer and autumn seasons (Pedretti and Irannezhad, 2019).

The case of flooding events at northern high latitudes was recently treated extensively by Walsh et al. (2020, 2022). River floods on inland plains are generally more persistent than river floods in steep valley terrains, but shorter-lasting floods in steep valleys can also have large impacts on floodplain ecosystems and human infrastructure. Hydropower dams have been constructed on several of the large rivers in the Nordic region. While such dams have major environmental impacts above and below the area of construction, the dams help in alleviating flooding impacts by reducing water height during flood situations (Räsänen et al., 2020; Goytia, 2021). For example, in the northern Finnish Kemijoki river, which is the second largest river basin in Finland, the most severe floods took place more than 100 years ago. The floods had drastic impacts on the entire city of Rovaniemi, which is surrounded by river channels. During the two recent major spring flooding events, in 1993 and 2020, i.e., occurring after completion of several dam projects and local flood prevention infrastructure development, only a few buildings and roads suffered from damage (Räsänen, 2021).

A time study of Norwegian catchments, covering the years from 1962 to 2012, identified decreasing flood frequencies in northern Norway because of decreasing trends in the frequency of snowmelt-dominated floods (Vormoor et al., 2016). The study also shows that the timing of snowmelt-dominated floods has shifted and is occurring earlier. A 40-year long time series from a Svalbard glacial catchment revealed a 2-week earlier onset of snowmelt-driven floods, large increases in autumn flows, prolongation of the hydrologically active season (starting earlier and lasting longer), and a decrease in flows in the latter half of June and the early part of August (Osuch et al., 2022). This resulted in a change from snowmelt-dominated to a bimodal flooding regime with peaks in both summer and autumn.

Two other types of floods have been occurring in Iceland, namely glacier outburst floods and volcanically triggered floods (Björnsson, 2010; Carrivick and Tweed, 2019). Warming-induced glacier outburst floods also occur on Greenland and Svalbard, and to a lesser extent from glaciers in Sweden and Norway (Rachlewicz, 2009; Carrivick and Tweed, 2019). In Greenland, ice-dam failure has frequently led to flooding. With the proximity of the Greenland glacier lakes to the coast this means that most proglacial channels in Greenland are flood-hardened and most landscape impact is offshore in estuaries and fjords. Smaller ice-dam events that drain only a small fraction of the lake volume, have been more frequent than large events, and have had much lower environmental impact (Carrivick and Tweed, 2019).

Flash floods caused by extreme rainfall events have occurred frequently in the warm season. Such floods have caused great geomorphological changes and fatal consequences for ecosystems, humans, livestock, and infrastructure (Bjerke et al., 2014; Blöschl et al., 2020; Kahle et al., 2022; Lawrence, 2016; Moraru et al., 2021).

4.2. Winter warming events

The temperature threshold at 0 °C for when water will be in liquid or solid state is a strong regulator of all life at northern high latitudes. Thus, temperature trends affecting the predominance of freezing vs. thaw weather have major implications for human life, ecosystems, and nature-based industries (Bokhorst et al., 2016). In northern coastal regions where open sea water modulates temperature, mean winter temperature is rather close to the freezing temperature threshold (Skagseth et al., 2008; Førland et al., 2009). However, this changes over short distances inland. Continental sections traditionally have a much drier and colder winter climate than nearby coastal sections, which means average winter temperature well below freezing (Vikhamar-Schuler et al., 2016). During recent decades, winter warming events have increased in frequency and duration at northern high latitudes (Graham et al., 2017; Zhang et al., 2022).

For the study area, the crossing of the 0 °C temperature threshold is an important aspect when evaluating whether a warming event is extreme or not (Phoenix and Bjerke, 2016). In coastal regions, where thaw periods and rainfall events occur nearly every year in the middle of winter, such events may not be considered extreme from a meteorological viewpoint. For the Nordic region, such yearly events are traditionally restricted to the most oceanic regions along the North-Norwegian coast (Moen, 1999; Bakkestuen et al., 2008). Similar rainfall-dominated winter climate is prevalent in the lowlands of Iceland. Terrestrial ecosystems in these oceanic landscapes are much more tolerant to temperature fluctuations around the freezing point than more continental ecosystems (Crawford, 2000).

Warm events during winter are associated with cyclone activity i.e., westerlies bringing in warm and humid air from the sea (Hanssen-Bauer et al., 2003; Akperov et al., 2018). Thus, warm events are associated with high precipitation rates, which for most of a cyclone's life falls as rain – at least along the coast and in the lowlands. Rainfall across coastal and lowland regions of the study area has led to complete snow thaw, destroying the subnivean environment that under normal winter conditions protects short vegetation and animals (e.g., rodents and invertebrates), against the harsh ambient winter environment (Bjerke et al., 2014; Williams et al., 2015).

Normally, after a winter warming event, temperature returns to below freezing point. Meltwater and remaining snow refreeze, and vegetation surfaces that experienced full snowmelt during the warming event are exposed to more severe freezing than experienced in the subnivean environment to which they are adapted (Bokhorst et al., 2015, 2016). Remaining snow is turned into a hard crust, which does not insulate as well as an airy snowpack unaffected by thaw weather. Under such conditions, soil freezes deeper than normal and may result in delayed soil thaw. Deep soil frost can be persistent and have large negative consequences on infrastructure, agriculture, and ecosystems far into the growing season (Kullman, 1989; DeGaetano et al., 2001; Brown and DeGaetano, 2011; Bjerke et al., 2015).

After winter warming events, aboveground shoots of evergreen plants are free of snow and are reactivated by the first warm weather in spring. However, since their roots are in frozen soil, water is not transported to the reactivated leaves, quickly leading to leaf wilting, a phenomenon known as “spring drought” (Kalberer et al., 2006; Bjerke et al., 2014; Hammond et al., 2019; Treharne et al., 2020; Song et al., 2021). Despite this negative impact on evergreens, modelling shows that 55 % of northern non-barren land is estimated to increase gross primary productivity with spring meteorological drought, which likely is related to the positive effects on deciduous vegetation types that are more resilient to the damaging effects of springs droughts (Miller et al., 2023). There is high uncertainty regarding future trends for this type of drought events for the study area.

4.3. *Summer drought*

A study covering mid to high latitudes found a sixfold increase in historical northern hemisphere concurrent large heatwaves during the snow-free season from May to September (Rogers et al., 2022). Our study area (Fig. 1) includes a summer climate gradient from very wet to relatively dry areas, i.e., from highly oceanic climates (Iceland, Lofoten Archipelago in Norway) to continental climates (north-eastern Finland, Svalbard, parts of Greenland) (Tuhkanen, 1984). Summer drought is a rare event in the more oceanic-influenced parts of the study area, but even there, drought occasionally occurs. For example, an atmospheric dipole blocking in July 2009 led to the driest month in Iceland in a 19-year study period, from 2001 to 2019 (Olafsson and Rousta, 2021). The drought of summer 2009 led to much lower-than-average vegetation greenness (NDVI), as measured by satellites, indicating drought-induced reduction in plant vitality.

Such blocks can remain in place for several days or even weeks and are the driver of several extreme climatic events, since affected areas have the same kind of weather for prolonged periods (Woollings et al., 2018; Lupo, 2020; Kautz et al., 2022). There is a clear increasing trend of northern hemisphere blocking occurrences since 1965 (Lupo, 2020). Europe is identified as a dominant region of blocking in most indices, due to the configuration of a strong, meridionally tilted storm track upstream of a large landmass, and blocking also occurs frequently over Greenland with strong downstream impacts on Europe associated with the negative phase of the North Atlantic Oscillation (NAO) (Davini et al., 2021; Kautz et al., 2022). Recent extreme droughts over eastern Europe (including parts of our study area) and western Russia are driven by the occurrence of prolonged blocking episodes, as well as surface processes, and have become more common during the 21st century. Even to this day, weather and climate models tend to underestimate the duration and intensity of blocking (Woollings et al., 2018; Lupo, 2020; Lupo et al., 2021), especially over Europe (Davini et al., 2021).

The summers of 2018 and 2019 were very dry in different parts of the study area, providing excellent examples on how extreme summer drought affects hydrology. July 2018 was record-warm in large parts of Finland, Norway, and Sweden, resulting in extremely low streamflow and groundwater level (Bakke et al., 2020). The 2018 drought was caused by persistent blocking high-pressure systems over Scandinavia in May as well as large parts of July and early August (Wilcke et al., 2020).

In 2019, a very dry period in June led to drought in Iceland causing river depletion with negative impacts on the salmon fishing season as the fish was unable to swim upstream to complete their breeding cycle (Anonymous, 2019). The entire year of 2019 was in fact very dry in Iceland; the western parts of the island received less than 60 % of normal precipitation, with a small area receiving less than 40 % (Bissolli et al., 2020). In particular, the period from March to June was very dry. June 2019, and the entire summer, was also very warm and dry in other parts of Europe, in June with a centre in northern Poland and Germany, and with warmer-than-average temperatures northwards to northern Sweden (Bissolli et al., 2020; Sulikowska and Wypych, 2020). These heatwaves over Europe in summer 2019 contributed to the advection of anomalously warm air over Iceland and Greenland, which led to several temperature records and extreme glacier melt events (Hanna et al., 2021; Walsh et al., 2022).

5. Climate projections until 2100

Projections are unanimous: the world, including all its regions, will become warmer (Allan et al., 2023). Global surface air temperature will continue to increase until at least mid-century under all emissions scenarios considered, and global warming of 1.5 °C and 2 °C will be exceeded during the 21st century unless deep reductions in carbon dioxide (CO_2) and other greenhouse gas emissions occur in the coming decades (Allan et al., 2023). Northern high latitudes will be warming faster than the global average due to the ‘Arctic amplification’ phenomenon; the amplitude of Arctic mean warming will remain stable at roughly twice the global mean warming (Wang et al., 2022).

Waterbodies (oceans, lakes, rivers, glaciers, sea ice, permafrost) are also becoming warmer. Glaciers and sea ice are melting at an unprecedented rate. Arctic amplification is also taking place in oceans. By 2081–2100, the upper 700 m of near-coastal North-Atlantic oceans will be 2.5 to 5.0 °C warmer than the 1981–2000 average (Shu et al., 2022). Marine waters adjacent to Svalbard, Finnmark in northernmost Norway, and in the Bothnia Bay will experience the highest ocean warming, while the waters south of Iceland will warm at a slower rate, being ca. 2.5 to 3.5 °C warmer in 2081–2100. The study by Shu et al. (2022) thus shows that the Arctic Ocean warming will occur at an increasing rate, which can be attributed to the fact that the enhancement of ocean heat convergence into the Arctic Ocean will be greater than the increase of Arctic Ocean surface heat loss. Even the deep sea (below 900 m) will warm.

In the remaining part of this section, we analyse more closely the climate projections for temperature, precipitation, and snow cover within our study area. We extracted the projections from Earth System Models (ESMs). ESMs include dynamically self-consistent climate estimations that are reconciled with atmospheric properties and physics; thus their variability is, as is generally the case for a freely running GCM, uncorrelated with the actual climate evolution as only the radiative forcing from greenhouse gases and other anthropogenic drivers are specified as boundary conditions (López-Blanco et al., 2022). CMIP6 ECEarth3 products for the period 2015–2100 under the SSP2 4.5 scenario (Lavoie et al., 2013, 2019;, Coppola et al., 2021) were extracted. All projections come with a degree of uncertainty. Generally, uncertainty increases with time range, meaning that there is larger uncertainty for 2081–2100 than for 2031–2050 (Collins et al., 2013). In projections, uncertainty is often manifested as minor ups and downs over a longer time scale. Thus, the longer time scales (for example from 2020 to 2100) can have a clear increasing or decreasing pattern, but at shorter time scales (for example 2030 to 2050), the same pattern may not be visible. Pixel resolution of the CMIP6 dataset is nearly 70 km. Point-based datasets, (e.g. from meteorological stations within the respective CMIP6 pixel, are generally not directly comparable with CMIP6 data both due to pixel size and the fact that GCMs are out-of-phase with real observations.

The downscaled CMIP6 projections from the selected study sites confirm the general warming trends for the boreo-arctic regions in focus in this review (Fig. 4). The arctic amplification effect results in more intense warming at the northernmost site, Svalbard. In recent decades, the archipelago has warmed at a rate of 0.7–0.9 °C per decade (Wang et al., 2022). According to the SSP2 projection, Svalbard will be ca. 8 °C warmer than the 2015–2020 period (Figs. 4a,b, 5a).

By the end of the century (2085–2100) all other study sites will be between 3.0 and 4.0 °C warmer than during the 2015–2020 period (Fig. 5a). The Greenland site Nuup Kangerlua is at the lower range. Despite having an arctic climate, it is situated ca. 14 latitudinal degrees south of the High Arctic site Svalbard. The amplification at higher latitudes explains why Svalbard is projected to warm much faster than Nuup Kangerlua. Nevertheless, the air temperature of a marine stretch in the Labrador Sea-Davis Strait area – just west of Nuup Kangerlua – is one of the areas that warmed quickest during the 1975–2014 period with a trend of 0.7–0.9 °C per decade (Wang et al., 2022). This is largely related to rapid sea ice decline which shows that warming rates can be very “High Arctic-like” also at latitudes well south of the Arctic Circle.

Increasing precipitation is projected for most areas poleward of 60° N (Wang et al., 2022). There will also be a significant change in the partitioning of snow and rain, i.e., a transition from snow to rain with major implications for winter snowpack (Vikhamar-Schuler et al., 2016; Landrum and Holland, 2020; Ye et al., 2021; Ford and Frauenfeld, 2022; Bonsoms et al., 2024). The precipitation projections based on the SSP2 pathway for the period 2015–2100 confirm these previously reported projections (Fig. 5b). The selected study sites will receive ca. 100 to 200 mm more annual precipitation in 2085–2100 than during 2015–2020 period. A generic feature of most CMIP6 models is a relatively modest increase in precipitation until ca. 2050 followed by accelerated increases until 2100, which is also evident in Fig. 5b. An exception is Vestfirðir in

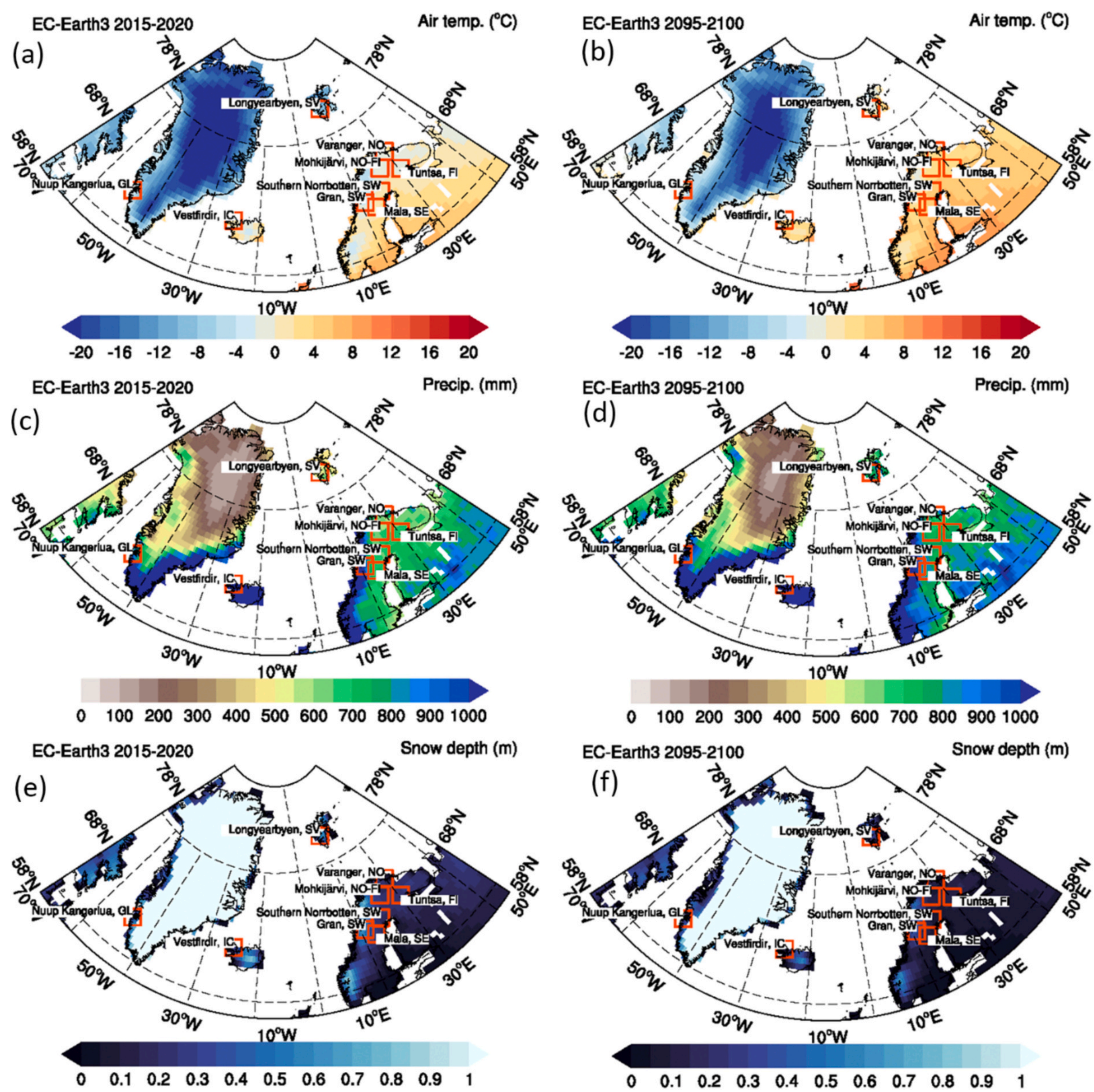

Fig. 4. 21st century climate projections according to the SSP2–4.5 emission scenario. Red squares show locations from where projections are presented (see Figs. 4–5 for location-specific projections). Left column (a, c, e): situation in 2015–2020; right column (b, d, f): projections for 2095–2100. (a-b) Mean annual temperature (°C). (c-d) Mean annual precipitation (mm). (e-f) Maximum snow depth (m). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

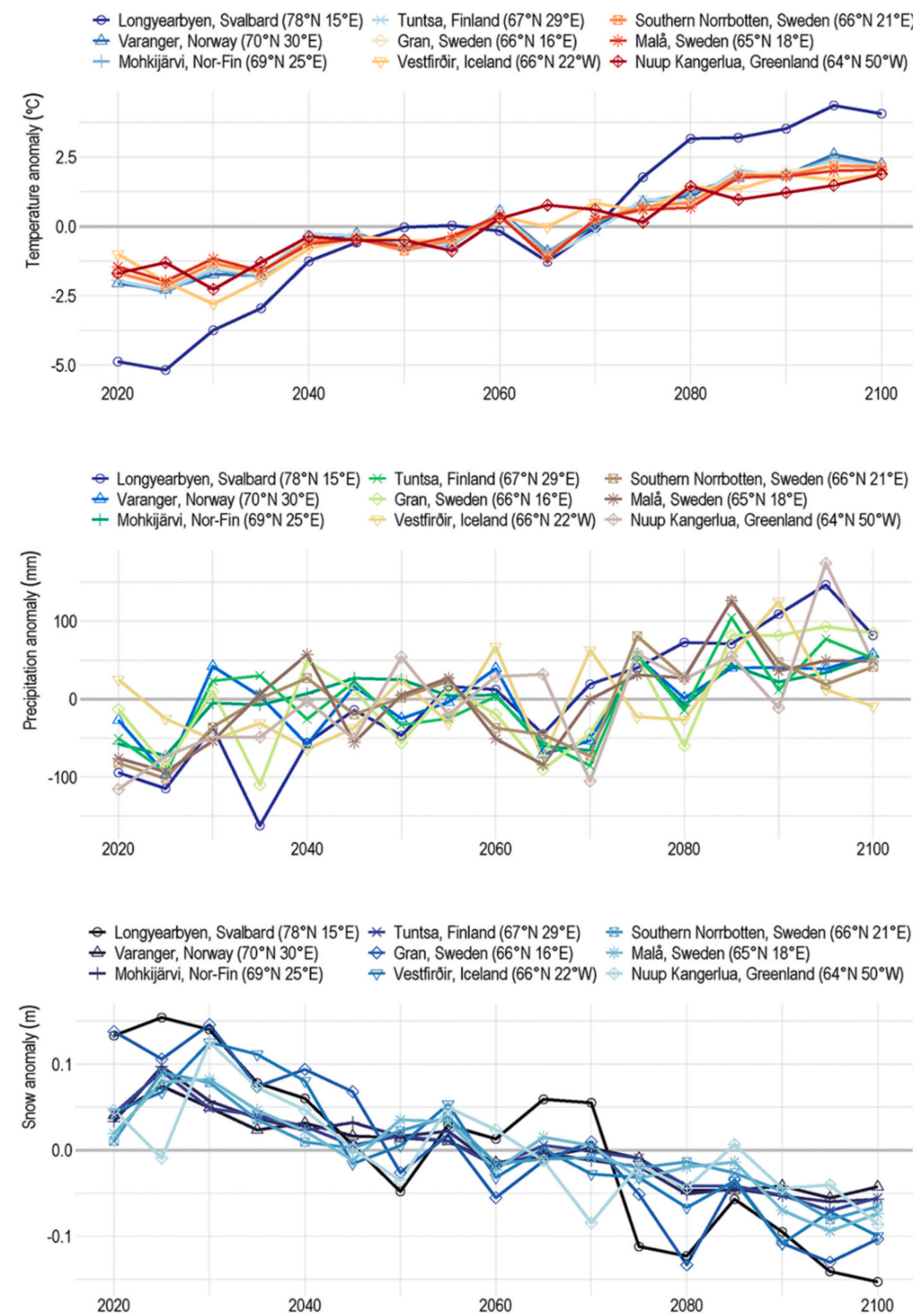

Fig. 5. Downscaled 21st century SSP2–4.5 climate projections until year 2100 for nine selected study sites (see map in Fig. 1). (a) Mean annual temperature anomalies (°C). (b) Mean annual precipitation anomalies (mm). (c) Maximum snow depth anomalies (m).

northwestern Iceland, whose projection shows large temporal variability, and with the 2095–2100 projection being slightly lower than the 2015–2020 data.

All sites will experience strong declines in maximum snow depth by 2100 under the SSP2 pathway (Fig. 5c). The largest declines will take place at the northernmost (Longyearbyen) and the southernmost (Gran) sites (Fig. 5c). Some sites show slightly increasing trends until 2035. This includes the sites Southern Norrbotten in northern Sweden, Varanger in north-eastern Norway, and the Icelandic site Vestfirðir. From ca. 2050, snow accumulation will decline at all sites.

Finally, in Fig. 6, seasonal plots of temperature, rainfall, and snow depths are shown for each site for the periods 2015–2020 and 2095–2100. The temperature projections (Fig. 6a) show that, under the SSP2–4.5 pathway, monthly temperature of all sites will increase substantially from 2015 to 2020 to 2095–2100. The largest change will take place at the northernmost site, Longyearbyen at Svalbard, where July temperature is projected to increase by ca. 7 °C and January temperature by ca. 12 °C. Most other sites will experience warming in the range of 2–4 °C both in the coolest and warmest months from 2015 to 2020 to 2085–2100. Mean temperature during the coldest months (December–January) will for all these stations be 2–10 degrees below the freezing point.

Rainfall trends are more variable and with higher uncertainties than trends in temperature (Fig. 6b). Monthly snow depths and snow season duration (Fig. 6c) are projected to decline at all sites. Also for snow, the most dramatic changes are projected to take place on the northernmost site, Longyearbyen, where the snow-free season will increase from 1 to 4 months.

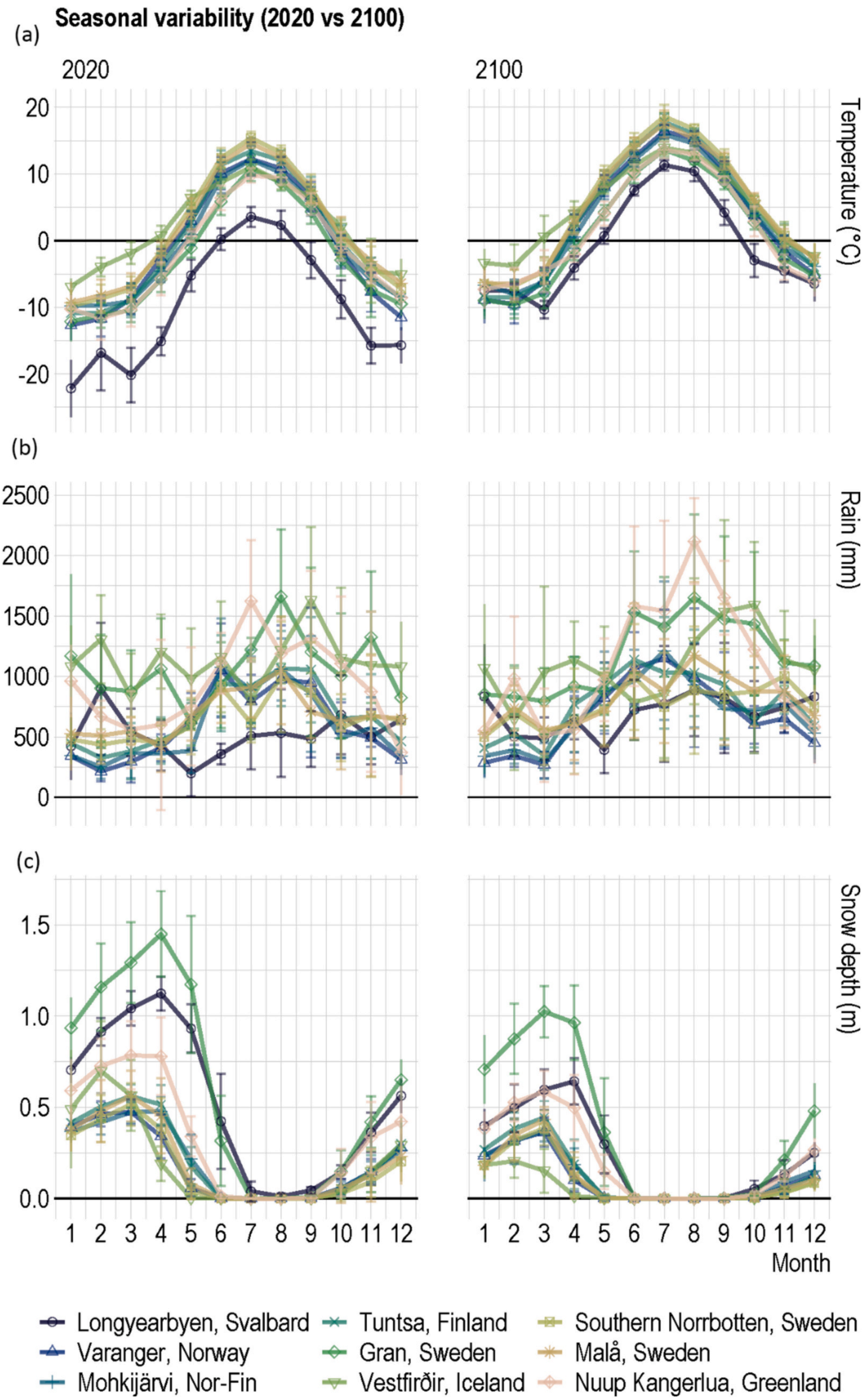

Fig. 6. Monthly trends for the nine selected study sites in three key weather parameters. (a) Air temperature (°C), (b) rainfall (mm), and (c), snow depth (m). Left: 2015–2020 period ("2020" in figure); right: 2095–2100 period ("2100" in figure), according to the SSP2–4.5 pathway, analyzed with the CMIP6 EC-Earth3 model. Legends for vertical axes are on the right-hand side. Months are numbered from 1 (January) to 12 (December). Error bars represent the standard deviation from the monthly average within each time interval (left: 2015–2020, right: 2095–2100).

6. Changing frequency of extreme weather events by 2100

In this section, we summarize the current understanding of projected frequency and nature of extreme weather events, which partly rely on the sources cited in section 4, but extensively supplemented with results from primary research articles.

6.1. Cold seasons

The Arctic-CORDEX regional climate models project an increase of cyclone frequency in winter (DJF) and a decrease in summer (JJA) to the end of the 21st century (Akperov et al., 2019). Within the study region, winter increases are projected to occur in the Barents Sea and north of Greenland, while decreases are projected in the Nordic seas, which is largely equivalent to the Greenland Sea, the Norwegian Sea, and the Iceland Sea. Reduced sea ice will enhance intensification of winter storms over the Arctic Ocean, by enhancing the surface turbulent heat fluxes and lessening static stability while also strengthening vertical shear of horizontal wind (Crawford et al., 2022). This means that future sea ice reductions (e.g., related to delayed autumn freeze-up) will likely enhance Arctic cyclone intensification in winter and spring and increase cyclone-associated precipitation.

The projected increase in annual mean precipitation at northern high latitudes will also result in increased frequency of extreme precipitation events, where frequency of extremes will increase faster than the mean (Sillmann et al., 2013; Myhre et al., 2019; Walsh, 2021). As more of the precipitation in winter will fall as rain, it is likely that there will be fewer snowstorms towards the end of the century in the entire study region, even at the northernmost site Svalbard. Increased frequency of extreme rainstorms in winter implies an increasing number of flash floods, more soil erosion, and abrupt permafrost thaw. Snowstorm frequency will be declining, but will still occur, albeit at a lower frequency, and be restricted to the northernmost regions, especially towards the end of the 21st century.

Rain-on-snow (ROS) events adversely affect humans, vegetation, hydrology, and wildlife, and further affect the local climate by altering snowmelt, runoff, and soil temperatures. ROS events are projected to increase in frequency at continental northern high latitudes, such as the interior parts of Alaska, but will most likely decrease in more maritime-influenced areas (Bintanja and Andry, 2017; Bieniek et al., 2018). Thus, winter rain will at a higher frequency fall on bare ground, and not on snow. Northern terrestrial ecosystems are adapted to the hibernating state provided by a permanent snow cover and frozen soils. Winter rain will thus affect ecosystems negatively in at least two ways: it will remove any remaining protective snow layer, and it will cause increased soil erosion, which also will negatively affect infrastructure and livelihoods.

Ecosystem-damaging winter warming events, which have increased in frequency over the past 50 years, are associated with fluctuations in temperature around 0 °C. While freezing conditions currently are still prevalent at northern high latitudes, long and frequent periods of thaw weather with limited snow accumulation will become the norm for most northern regions during the 21st century. Thus, ecosystems adapted to a long, stable period of frost during winter will severely suffer from near-constant mild weather with sporadic freezing events (Crawford, 2000; Bokhorst et al., 2016). Even the most High Arctic site, Svalbard, will by 2071–2100 have an average midwinter (DJF) temperature close to 0 °C; recent (1971–2000) midwinter temperature on Svalbard Airport Longyearbyen is −13.9 °C, while median projected increase in midwinter temperature under the extreme SSP5 scenario is 15.1 °C (Hanssen-Bauer et al., 2019).

Sporadic episodes of atmospheric blocking may drive future winter climate change in opposite directions than the overall trends. An example of such blocking occurred during the winter of 2012/13 resulting in an unusually long period of easterlies and dry, cold weather in parts of Finland, Sweden, and Norway (Iden et al., 2012; Kristiansen et al., 2013; Bjerke et al., 2017; Treharne et al., 2019).

6.2. Growing season

For the growing season, the climate models simulate an increase of cyclone frequency over the Central Arctic and Greenland Sea and a decrease over the Norwegian and Kara Seas by the end of the 21st century (Akperov et al., 2019). It implies that Iceland will be more affected by heavy winds and rainstorms in summer seasons during the 21st century, while the study areas in Finland, Norway, Sweden, and western Greenland will be less affected. Jet streams are bands of strong high atmospheric winds that blow from west to east. Such winds influence the weather conditions in the north by dictating where events such as heat waves and storms would strike. During the last decades, there has been a trend of jet streams shifting northwards during mid-winter (Keel et al., 2024). A jet stream positioned further north will increase the possibility for increasing frequency of warm and dry summer conditions over most of Europe. (Xu et al., 2024).

The projected increase in episodes of heavy rain due to a moister and warmer atmosphere will result in an increasing frequency of flash floods, surface water, rock avalanches, landslides, permafrost thaw, and soil erosion (European Academies Science Advisory Council (EASAC), 2013; Hanssen-Bauer et al., 2017; O'Gorman, 2015; Kharin et al., 2018; Dyrrdal and Førland, 2019; Sorteberg et al., 2018). It is also expected that glacier outburst floods will increase in frequency due to more extreme rainfall events and increasing velocity on ice melt (How et al., 2021; Carrivick et al., 2023). Increasing frequency of such events is already ongoing in parts of the study area, especially within the High Arctic regions, i.e., Greenland and Svalbard (Christensen et al., 2021; Ding et al., 2021; Nicu et al., 2023).

The combination of increasing frequency of extreme rainfalls and increasing number of river channelization structures will likely lead to increasing number of flash flood events with severe socio-economic costs (Lawrence, 2016; Räsänen, 2021). Walsh et al. (2020, 2022) showed for the pan-Arctic region that while temperature and sea ice rank at the high end of the spectra of evidence for future change, flooding ranks at the lower end of the spectra. On the other hand, for Svalbard, Hanssen-Bauer et al. (2019) project increasing frequency of floods and flood-related damage caused by climate change.

While summer climate will become wetter, warming will induce increased evaporation. In addition, earlier snowmelt will result in lower water volumes in rivers during summer months. Overall, for the Finnish, Norwegian and Swedish study area, this will increase the risk for summer drought and forest fire during the 21st century (Hanssen-Bauer et al., 2017; Stensen et al., 2019; Chen et al., 2020; Eckdahl et al., 2022).

An uncertainty for future climate, and hence for distribution of precipitation, is the future frequency of atmospheric blocking events; see treatment of some blocking phenomena in Section 4.3. In their review of atmospheric blocking and weather extremes over the Euro-Atlantic sector, Kautz et al. (2022) conclude that there is much uncertainty regarding the frequency and intensity of future blocking events, but that the size of blocking systems is projected to increase with climate change. For the Nordic study area, Kautz et al. (2022) projects more blocking during summer due to a poleward shift of blocking activity during this season. Thus, summer drought events and extreme rainfall may increase more than modelled by large-scale climate projections that do not include blocking in their models. For the study region, it is thus not possible with the current knowledge to state with certainty which regions will be affected the most by increasing atmospheric blocking events.

7. Conclusions

In this review, we have explored the full range of climate change and its impacts on large land areas on both sides of the North Atlantic Ocean. Assemblies of meteorological, climatological, biological, and community data were also analyzed. By combining these various information sources, we were able to provide detailed assessments on the impacts of climate change on the cryosphere, the hydrological cycle, soil, also briefly covering the biosphere and human dimensions.

It is clear that climate change has already impacted this large boreo-arctic region in multiple ways, including reductions of the cryosphere, an increasing frequency of extreme weather events, and a heightened risk of flooding, avalanches, landslides, and other geohazards. It is also evident that these changes will continue and most likely intensify in our nearest future. These rapidly and ongoing changes not only threaten local ecosystems and landscapes but also pose significant challenges to human livelihoods in this part of the world. Hence, as these climate-driven risks escalate, they will increasingly affect infrastructure, economic stability, and safety of communities, complicating efforts to maintain sustainable living conditions. Adapting to these shifts will require proactive measures to support resilient communities and safeguard both natural and human systems.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The CMIP6-EC-Earth3 modelling datasets used in this study have been used previously by López-Blanco et al. (2024) and can also be accessed and downloaded freely from ESGF repositories (e.g. https://esgf-data.dkrz.de/search/cmip6-dkrz/). All other data used were also retrieved from open sources, and sources for these data are cited in the main text.

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