Chapter 8
Comparative Analyses of Local Historical and Future Climate Conditions Important for Reindeer Herding in Finnmark, Norway and the Yamal Nenets Autonomous Okrug, Russia

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Abstract In Finnmark, average winter (Dec-Jan-Feb) temperatures in the period 1961–1990 were about −5 °C at the coast, slightly lower in the fjords, and typically 10 °C lower inland. In the Yamal Nenets Autonomous Okrug (YNAO) average winter temperatures were even lower, ranging from −20 to −25 °C. Temperatures are presently increasing in the area, and towards the end of this century, winter temperatures in the YNAO may, under a medium high emission scenario, resemble the previous conditions in the interior of Finnmark, while inland Finnmark may experience conditions that were earlier found along the fjords. The snow season in 1961–1990 typically lasted from 6 to 8 months in Finnmark. Higher temperatures lead to a reduced snow season and model calculations indicate a 3-month reduction along the coast, where it is shortest today, while the inland snow season may be one month shorter towards the end of the century. Along the coast, a 60% reduction in the winter maximum snow amount is projected towards the end of the century. In the interior of Finnmark, considerably smaller changes are projected in maximum snow amounts, as average precipitation is projected to increase, implicating increased snowfall during winter. Maximum snow amounts may even increase slightly at some inland sites. Higher winter temperatures will lead to changes in the snow

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structure. Compared to herders' reports, the SNOWPACK model successfully reproduced high-density snow layers during the past decades. To describe future snow structures of relevance for reindeer grazing conditions in Finnmark and YNAO, more detailed climate projections are needed.

Keywords Climate change · Snow conditions · Reindeer pastures

8.1   Introduction

Weather affects reindeer and reindeer husbandry in a number of ways, both directly and indirectly (e.g., Mysterud et al., 2001; Tyler et al., 2008, 2021; Uboni et al., 2016; Eira et al., 2018; see also Chaps. 3 and 4). Global warming implies changes in weather conditions, and according to IPCC (2021) the areas of maximum warming are those at high northern latitudes, including northern Eurasia. Knowledge of present and future climate in this area is thus important for assessing possible impact of climate change on reindeer ecology and husbandry.

Previous climate analyses from northern Eurasia (Fig. 8.1) show that from Finnmark in the west to Chukotka in the east, these areas are mostly characterized by permafrost, cold and reasonably dry winters, a long snow season, but rather small amounts of snow (Vikhamar-Schuler et al., 2010a; AMAP, 2017a, b). From Finnmark to the Republic of Sakha Yakutia (hereafter referred to as Sakha) the winters (Dec-Jan-Feb) become gradually colder and dryer towards the east

Fig. 8.1 Stations used in the climate analyses of northern Eurasia. The named stations are also used in the Finnmark – Yamal Nenets Autonomous Okrug (YNAO) comparison

(AMAP, 2017a). In Sakha the average winter temperature is usually between −35 to −45 °C. Further east, in Chukotka, the winters are milder, but still colder than in the west. In summer (Jun-Jul-Aug) the temperature differences between east and west are smaller, but in general coastal stations tend to be cooler than inland stations, because of the cooling effect by the cold ocean. The study areas in general experience a large year-to-year variability in temperature, which in the western parts is correlated to the North Atlantic Oscillation (NAO). Positive NAO phase is usually associated with advection of mild air masses from the west into these areas, while negative NAO is associated with blocking of the mild air masses. Further east, in Sakha, the NAO correlation is more variable and in Chukotka it tends to be negative (Vikhamar-Schuler, Førland, et al., 2010a). The temperature along the coast is largely affected by the year-to-year variability in sea ice concentrations in the area (AMAP, 2017b), especially in winter.

This chapter provides a more detailed description of air temperature, precipitation and snow conditions in Finnmark in Norway and Yamal Nenets Autonomous Okrug (hereafter YNAO) in Russia. The data and methods applied are described in Sect. 8.2. Climate descriptions are given for the past, present and – where local projections were available – also for the future. The climate descriptions are given at two levels of detail. For both Finnmark and the YNAO, basic climatology (1961–1990) is described and temperature projections for the end of the twenty-first century are given (Sect. 8.3). For Finnmark, it has also been possible to give more spatially detailed climate information concerning climatology, as well as past and future temperature, precipitation and snow conditions (Sect. 8.4).

Snow conditions, including snow structure, are crucial for the existence and livelihoods of reindeer herding communities; being critical for maintaining food supply, for tracking and for travel (Eira et al., 2018, Eira, 2022). Snow structure is not observed regularly but for one site in Finnmark, it has been possible to model snow layer structure based upon historical regular climate observations (Sect. 8.5). The snow model has not yet been run for projections but gives promising prospects for establishing scenarios for future snow structure.

8.2   Data, Methods, and Models

The historical analyses in this chapter are based on temperature, precipitation and snow data made available by the Norwegian Meteorological Institute (MET Norway) and the Arctic and Antarctic Research Institute (AARI). Data from the climate stations named in Fig. 8.1 were applied in Sects. 8.3.1, 8.3.2, 8.3.3, and 8.3.4, while also daily gridded datasets based on all high-quality Norwegian stations were used in the more detailed analyses for Finnmark in Sect. 8.4.

Several analyses are performed on a seasonal basis. Unless other definitions are given, winter is defined as Dec-Jan-Feb, spring Mar-Apr-May, summer Jun-Jul-Aug and autumn Sep-Oct-Nov.

The projections for changes in local temperatures under continued global warming in Sect. 8.3.5 are based upon output from coupled global climate models (IPCC, 2000, 2013). The results from these models are fairly realistic on a large scale, but downscaling is necessary to establish good local projections. Benestad et al. (2008) developed empirical statistical downscaling (ESD) techniques for downscaling temperature projections at stations with good quality observational series. By interpolating station values in a geographical information system, Benestad (2011) developed temperature projections valid for the period 2017–2100 for an area including Finnmark and the YNAO.

For Finnmark, also fine-scale temperature and precipitation projections from Hanssen-Bauer et al. (2015, 2017) are presented in Sect. 8.4. These were based upon regional climate model output, re-gridded and bias adjusted. These, as well as the observationally based gridded temperature and precipitation fields were applied as input in a hydrological model (HBV; Beldring et al., 2003) to produce maps showing historical snow conditions as well as projected changes.

For modeling snow properties (Sect. 8.5), the SNOWPACK model (Bartelt & Lehning, 2002; Lehning et al., 2002a, b) was applied. This model was developed in Switzerland for snow avalanche warning purposes but has later been validated for boreal conditions in Finland (Rasmus et al., 2007). It simulates snowpack development during winter based on meteorological input data. The resulting outputs are layer stratigraphy of, e.g., snow temperature, grain type, grain size, liquid water content and snow density. In the present study, 6-hourly meteorological observations from the Kautokeino weather station over the period 1956–2010 were applied. In addition to routinely observed weather data, the SNOWPACK model needs data for shortwave and longwave radiation as well as snow surface and ground temperatures. Incoming long-wave radiation was estimated using observed cloudiness from the weather station, while the potential incoming short-wave radiation was estimated by a method described in Hock (1999). Ground surface temperature was derived from available observations of air temperature and snow depth applying a ground surface temperature model (Vikhamar-Schuler et al., 2013). Validation of the modeling results was carried out in Kautokeino for the winter season 2009/2010. Snow profiles were measured twice a month and snow temperature was recorded every hour by sensors located at 0, 10 and 35 cm snow heights. Comparison of measured and modelled snow temperatures showed high correlation (R2 = 0.9). Some systematic errors were noticeable with small deviations at high temperatures (0 to −5 °C), and increasing deviations at lower temperatures (below −5 °C). As snow metamorphose is most efficient around 0 to −1 °C this is regarded to have minor influence on the results.

The figures in this chapter are, if no reference is given in the figure caption, produced by the authors especially for this book.

Table 8.1 Information on the stations used in the comparative analyses: Altitude is given in meters above sea level. Average annual temperature (°C) and average annual precipitation sum (mm) are given for the period 1961–1990

Station name/Nation	National number	Altitude	T (°C) 1961–1990	Precip. (mm) 1961–1990
Nordreisa/Norway	91750	1	1.4	661
Suolovuopmi/ Norway	93300	377	−2.4	456
Karasjok/Norway	97250	155	−2.2	365
Vardø/Norway	98550	10	1.3	583
Ust'-tsilma/Russia	23405	68	−1.8	567
Tarko-sale/Russia	23552	27	−6.4	480
Salekhard/Russia	23330	35	−6.6	451
Mare-sale/Russia	23032	24	−8.5	298

8.3   Comparative Analyses for Finnmark and the Yamal Nenets AO

The climate stations used in these analyses are those named in Fig. 8.1. Some basic information is given in Table 8.1. Nordreisa is representative of fjord areas in Finnmark. Vardø represents outer coastal areas. Suolovuopmi and Karasjok are inland stations representing different altitudes. In the YNAO, Mare Sale represents the coast, while the other stations represent an inland profile from west to east. Ust'Tsilma is situated in a neighboring region west of the Ural mountains, and represents the climate west of the YNAO. 'Present climate' is defined by the WMO standard climatological normal period 1961–1990, as the 1991–2020 climatology is not available for all stations. Though there has been a temperature increase during the later decades (see information for Finnmark in Sect. 8.4), the geographical temperature patterns are largely the same as reported by AMAP (2017a). However, changes in these patterns are expected when the winter sea ice concentration along the coast of YNAO is seriously reduced (AMAP, 2017b).

8.3.1   Temperature Climate in the Twentieth Century

Both Finnmark and the YNAO include coastal and inland areas. The western coastal stations in the region are strongly influenced by the temperate ocean currents in the Norwegian Sea. In Finnmark, this is reflected in the typical difference between the mild winter (about −5 °C) and the cool summer (less than 10 °C) climate at the coastal station in Vardø, and the colder winter/warmer summer climate in Karasjok (Fig. 8.2). In mid-winter, Karasjok is on average more than 10 °C colder than Vardø and in mid-summer about 5 °C warmer. Nordreisa, situated in a fjord area, has temperatures that lie between the values of the inland and the coastal stations in winter,
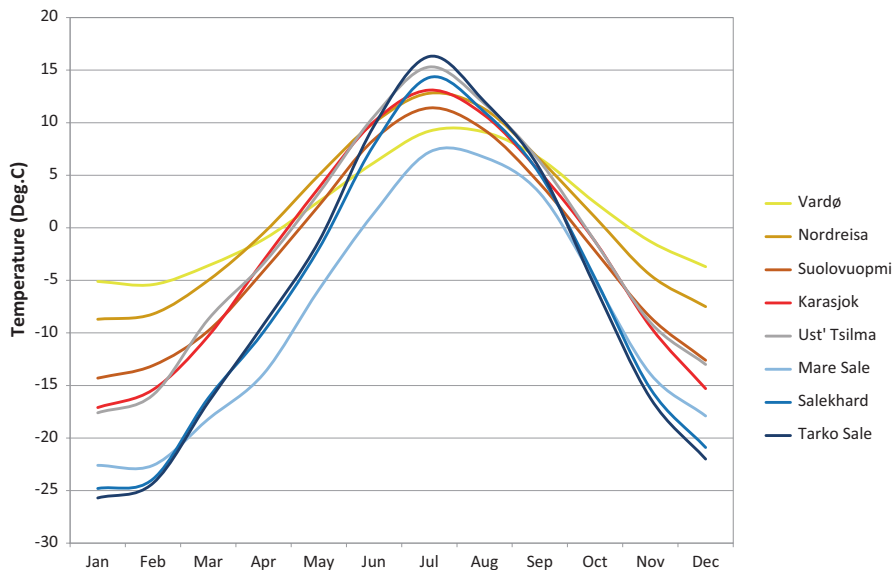
Fig. 8.2 Average monthly temperature (°C) for the period 1961–1990 at selected stations in Finnmark and the YNAO

while the summer temperatures are closer to the inland stations. Suolovuopmi, situated at a higher altitude than Karasjok, is on average slightly milder in winter when temperature inversions dominate this area, but cooler than Karasjok in summer, when temperatures normally decrease with altitude.

While Ust'Tsilma experiences winter temperatures close to those of Karasjok, the inland stations of the YNAO are significantly colder, with average January temperatures around −25 °C. The temperatures at the more coastal station Mare-Sale are almost as low as the inland stations. This "continental signature" of the Mare-Sale winter climate is caused by the sea ice which usually covers the Kara Sea in winter, and effectively shuts off heat transfer from the ocean. This is also reflected in the average number of "cold days" (Fig. 8.3). Both Salekhard and Mare-Sale have, on average, more than 20 days per year with mean temperature below −30 °C. The inland stations further west have fewer days with average temperature below −30 °C, while coastal areas in Finnmark normally have no such days. In Vardø, there are also few days with a mean temperature below −15 °C, while Salekhard and Mare-Sale on average have about 110 such days per year, and Karasjok and Ust'Tsilma about 60.

While the difference in winter temperatures between coast and the interior are smaller in the YNAO than in Finnmark, it is the other way around when it comes to summer temperatures (Fig. 8.2). The cold ocean limits the temperatures in Mare-Sale in summer, resulting in the lowest average summer temperature of all the stations, while the inland stations in the YNAO have higher July temperatures than any of the Finnmark stations. There are also systematic differences concerning annual mean temperatures, as the coast usually is warmer than interior Finnmark (Vardø:
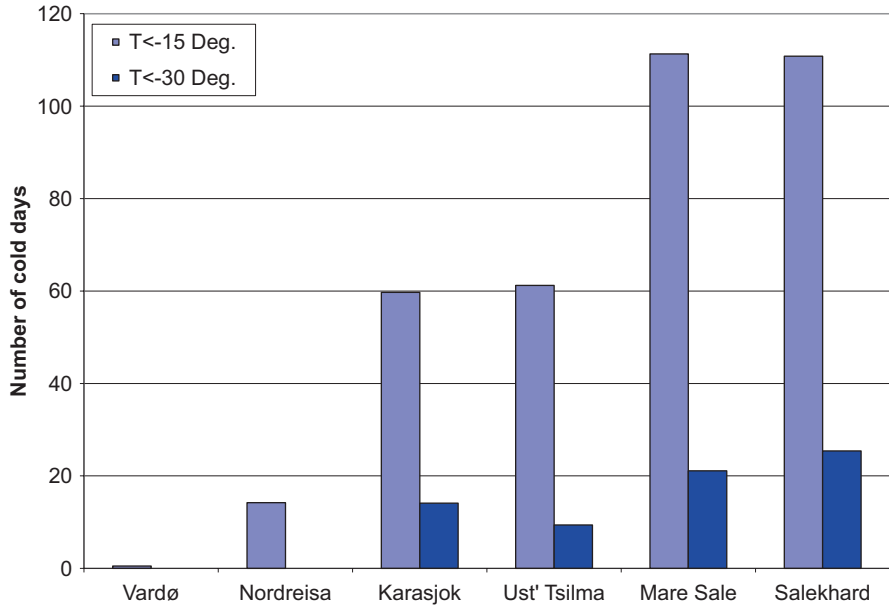
Fig. 8.3 Average annual number of days with mean temperature below −15 °C and −30 °C in the period 1961–1990 at selected stations in Finnmark and the YNAO

+1.3 °C, Karasjok: −2.3 °C), while the coast is colder in the YNAO (Mare-Sale: −8.5 °C, Salekhard: −6.6 °C).

Analyses of annual temperature series from Finnmark and the YNAO through the twentieth century show large inter-annual and inter-decadal variability (Vikhamar-Schuler et al., 2010a). In both areas, the decades around 1900 and around 1970 were cold. The 1930s were warm in Finnmark (cf. Fig 8.3), while the 1940s were warm in the YNAO, and from the 1990s it has been warm in both areas. The difference between warm and cold decades was up to 2 °C, while the mean annual temperatures increased typically by +0.5 to +0.7 °C during the century. Spring temperatures typically increased by 1.5 °C, and spring was the only season for which the long-term temperature trends were statistically significant during the twentieth century. Since 2000, the long-term temperature increase has continued and the annual trends are now statistically significant, at least in Finnmark, where updated series have been analyzed (Hanssen-Bauer et al., 2015, 2017).

8.3.2   Growing Season

The growing season is here defined as the period of the year when the average daily temperature is above 5 °C (Førland et al., 2004). The station Nordreisa, which represents fjord areas in Finnmark, has the longest growing season (almost 140 days;
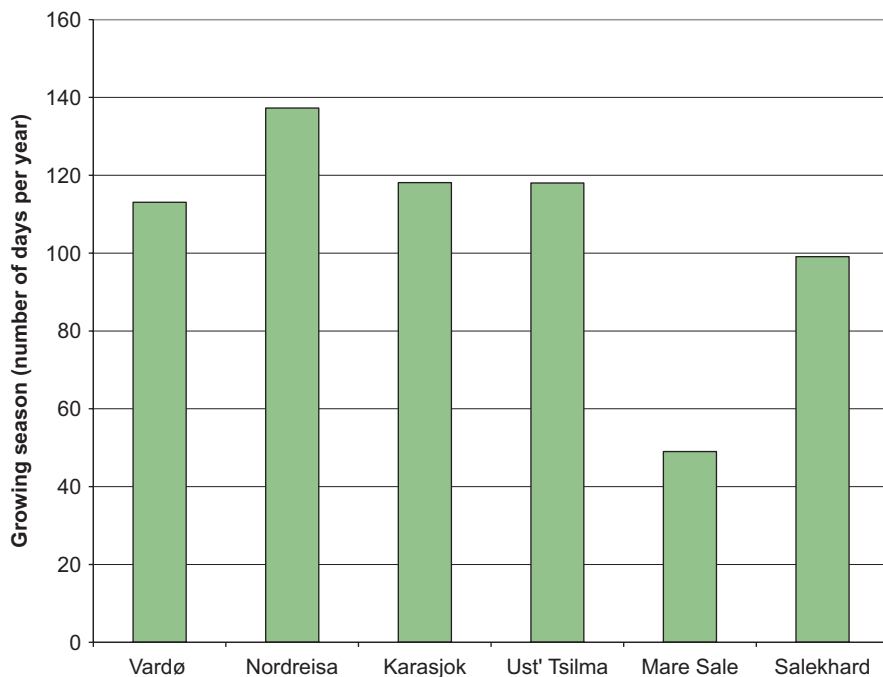
Fig. 8.4 Length of growing season: Average annual number of days with mean temperature above 5 °C in the period 1961–1990 at selected stations in Finnmark and the YNAO

Fig. 8.4). Even though the summer is warmer in most of the inland stations, the spring and autumn temperatures are higher in Nordreisa (Fig. 8.2), and the growing season usually starts before mid-May and lasts until the end of September. Both at the coast of Finnmark (Vardø) and in the inland areas (Karasjok), the growing season on average lasts between 110 and 120 days, and similar values are found in Ust'Tsilma. Even though the growing season is of similar length at these stations, the higher summer temperatures in the interior lead to higher heat sums (growing degree days, not shown) in Karasjok and Ust'Tsilma than in Vardø. In Salekhard, which represents the inland of the YNAO, the growing season on average lasts about 100 days, while Mare Sale has a growing season of less than 60 days.

Time series of the length of the growing season during the twentieth century show large variability from year to year, but there has been a trend toward a longer growing season since the 1960s (Vikhamar-Schuler et al., 2010a).

8.3.3 Precipitation in the Twentieth Century

In Finnmark, the annual precipitation is typically greater in coastal areas than inland. While Nordreisa and Vardø on average receive 550–600 mm precipitation per year, Suolovuopmi receives about 100 mm less, and Karasjok 200 mm less.
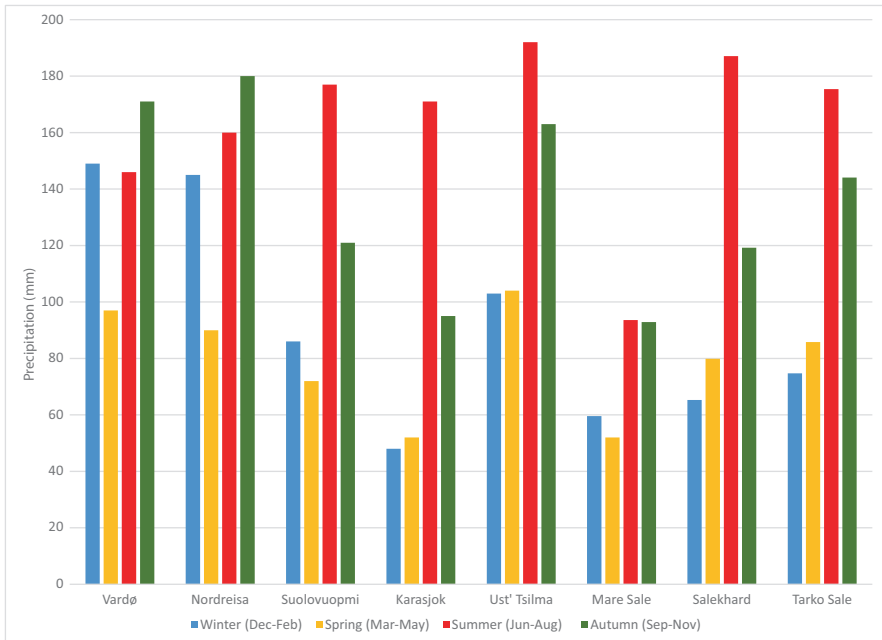
Fig. 8.5 Average seasonal precipitation (mm) during 1961–1990 at the selected stations in Finnmark and YNAO

Another difference is that the coastal stations get most of their precipitation in autumn and the least in spring, while the inland stations get most precipitation during the summer and have low values in winter and spring (Fig. 8.5).

The reason for these differences is that autumn and winter precipitation is often associated with weather systems to which the coastal stations are more exposed. The low inland winter temperatures also limit the air's capacity of carrying precipitable water. In summer, on the other hand, showers are dominating as the warmer inland stations have a larger potential for developing weather conditions favorable for convective precipitation.

The average annual precipitation sums at the inland stations in the YNAO are similar to the values from Suolovuopmi and – as with the inland Finnmark stations – these stations normally receive most of their precipitation during summer and the least in winter and spring. In spite of its coastal position, the winter sea-ice along the coast of Mare Sale leads to a "continental signature" and thus little precipitation during winter. In Mare Sale, the summer precipitation is also low, as low summer temperatures limit convective activity. Mare Sale is therefore the driest of all stations with an average annual precipitation of about 300 mm.

Time series during the twentieth century show that although the inter-annual and inter-decadal variation is considerable, there has been a statistically significant increase in annual precipitation in the area (Vikhamar-Schuler et al. 2010a, b). All stations with complete data series show an increase of more than 20%. The increase is in most cases more substantial in winter and spring.

8.3.4   Snow Climate of the Twentieth Century

The average number of days per year when the ground is covered by snow is slightly below 250 in the YNAO, both at the coastal station in Mare Sale and in Salekhard further inland (Fig. 8.6). In Finnmark, the average snow season is almost as long at the high-altitude inland station Suolovuopmi, but about 50 days shorter in Karasjok and Nordreisa.

Due to the limited number of daily snow data, the snow depth on the 31st of March is used as an indicator of snow accumulated on the ground during the snow season. This amount is usually larger at Suolovuopmi than at Karasjok and Nordreisa (Fig. 8.7). The reason for lower snow amounts in Karasjok compared to Suolovuopmi is that Karasjok generally gets less precipitation in autumn, winter and spring.

Nordreisa, on the other hand, has higher temperatures, so even if it gets more precipitation than Suolovuopmi, the snow accumulation starts later in the autumn and the total amount of snow is smaller. Data on snow depth are sparse at Mare-Sale, but the generally low precipitation level indicates that the average snow depth is rather low, even though the snow season is long. In the inland area, the conditions seem to be variable. Tarko Sale has on average a larger snow depth than all the Finnmark stations. The combination of relatively low temperatures and much precipitation during autumn at Tarko Sale may explain this. The average snow depth at the end of March in Ust'Tsilma is comparable to Karasjok. This is difficult to explain, as it receives considerably more precipitation, and the temperature conditions are similar. However, different conditions concerning drifting snow might explain this.
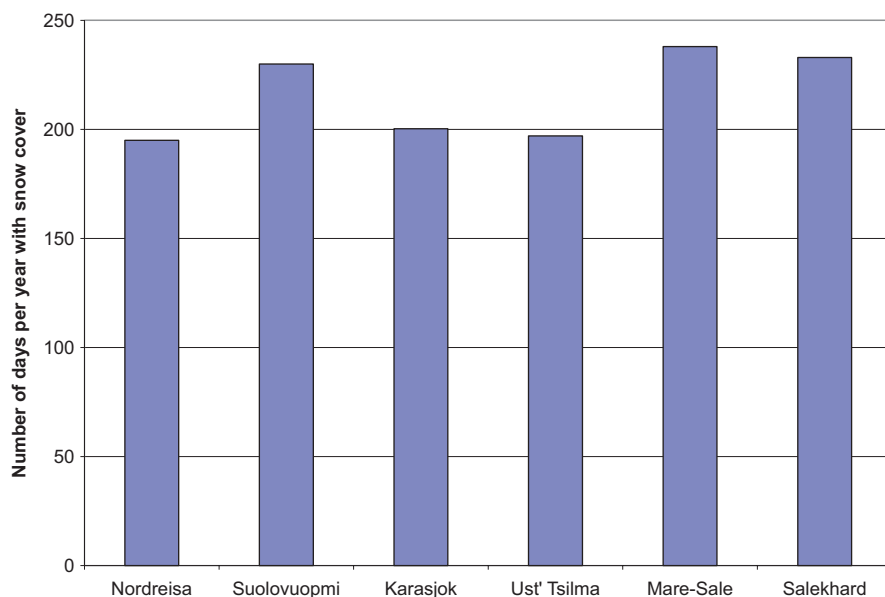

Fig. 8.6 Average annual number of days with 50% or more of the ground covered with snow in the period 1961–1990 at selected stations in Finnmark and the YNAO
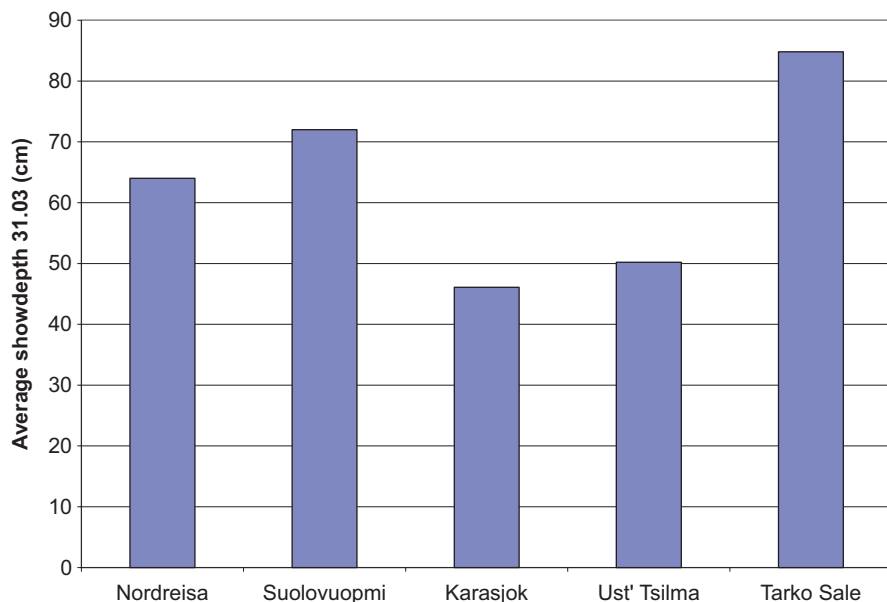
Fig. 8.7 Average snow depth (cm) on March 31st in the period 1961–1990 at selected stations in Finnmark and the YNAO

In Finnmark, the length of the snow season has decreased from the 1960s to 2018, while there has been a small increase in the average March snow depth. AMAP (2017b) indicates that also YNAO has seen a decreased length of the snow season during the later decades, while the signals concerning the winter maximum snow depth are more variable.

8.3.5   Temperature Projections for the End of the Twenty-First Century

As climate modeling is uncertain, projections should always be based upon results from several models. Figure 8.8 thus shows statistically downscaled winter temperature projections based upon 50 global models, run with a medium high emission scenario (A1B; IPCC, 2000). This work was updated by Benestad et al. (2016) for the Barents region, using the more recent scenario RCP4.5 (IPCC, 2013). The main features of the warming patterns remain the same as shown in Fig. 8.8, though the absolute value of the warming is somewhat lower under the more moderate RCP4.5 emission scenario. A comparison of the two emission scenarios is given by Hanssen-Bauer et al. (2015). In winter, there are regions in both the YNAO and in Finnmark where the projected warming is more than 7 °C towards the end of the century, assuming the A1B emission scenario (Fig. 8.8). Both Karasjok and
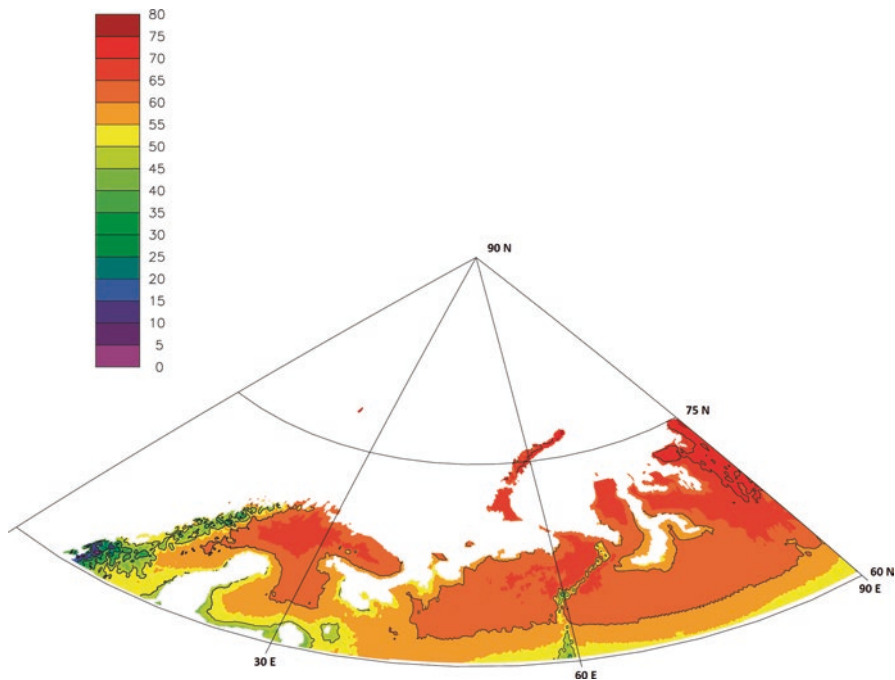
Fig. 8.8 Estimated winter temperature increase (°C) from 1975 to 2085. The estimates are averages based upon 50 downscaled climate models run with emission scenario A1B. The color scales are given in steps of 0.5 °C

Salekhard are situated in such regions. This implies that while the projected winter temperature in Salekhard is comparable to the present winter temperature in Karasjok, the future winter temperatures in Karasjok may be similar to present conditions in Nordreisa (Fig. 8.9). The geographical pattern of the projected winter temperature shows, for the most part, less increase further south on the continent, and also in mountainous areas and along the coast. An exception is coastal areas (e.g., Mare Sale) where ice-covered sea so far has been dominating in winter, but where projections indicate reduced ice cover (AMAP, 2017b). In such areas the temperature increase in winter may be larger than anywhere else. In summer (not shown), the projected warming is smaller, and more geographically homogeneous than in winter. For the YNAO and Finnmark, the average projected summer warming is around 3 °C under the A1B scenario.

8.4   Detailed Analyses for Finnmark

For Finnmark, more detailed analyses of both the present climate and possible future climate trends have been performed. A denser network of climate stations with available data (Fig. 8.10), as well as available projections not only for
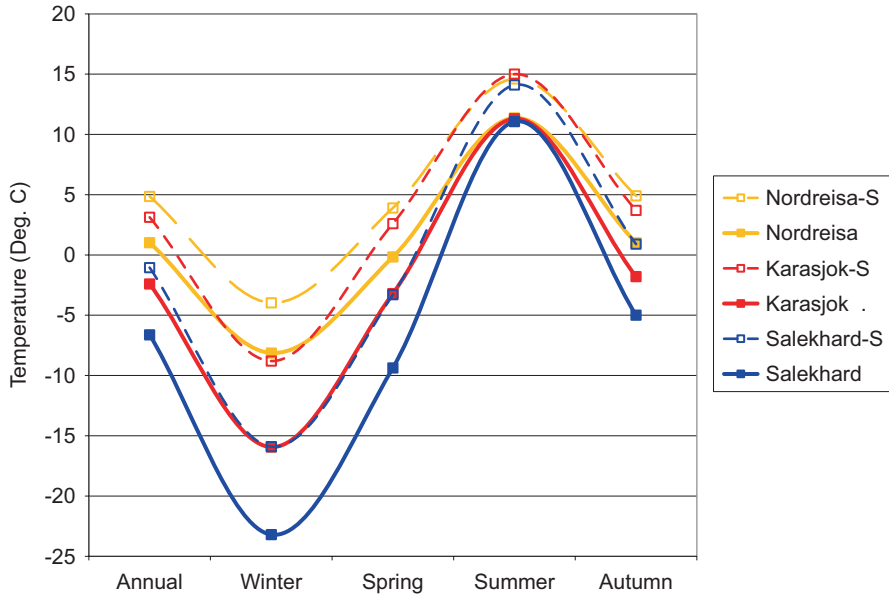
Fig. 8.9 Annual and seasonal temperature averages (°C) for 1961–1990 measured at Nordreisa, Karasjok, and Salekhard (solid lines) and the similar projections for the year 2085 calculated from 50 downscaled climate models (dotted lines)

temperature, but also for precipitation, snow season and snow water equivalent (SWE; the amount of water the snow contains) have made this possible.

8.4.1   Temperature in Finnmark

The average winter and summer temperatures in Finnmark shown in Figs. 8.11a and 8.11b confirm the impression from Sect. 8.3.1. Winter temperatures in the interior are about 10 °C lower than along the coast, while the fjord areas in general have winter temperatures between these extremes. In summer, the differences are smaller and the highest temperatures are found at low altitudes in the interior areas. The 1991–2020 climatology for Finnmark shows annual temperatures about 0.8 °C higher than the 1961–1990 values along the coast, and up to 1.2 °C higher inland (Tveito, 2021), but the main spatial features are still the same.

Winter temperature contrasts between coast and inland are especially strong for minimum temperatures. For example, while the average monthly minimum at the inland station Karasjok in January is −40 °C, it is −23 °C at the fjord station Nordreisa, and only −15 °C at the coastal station Vardø (Figs. 8.12a, 8.12b, and 8.12c). On the other hand, the average monthly maximum temperature for January is similar in Karasjok and Vardø (+2 to 3 °C) and just a few degrees more in Nordreisa. Note that the average monthly maximum temperature is above zero for all the winter months at all stations. Thus, melting events may occur in mid-winter,

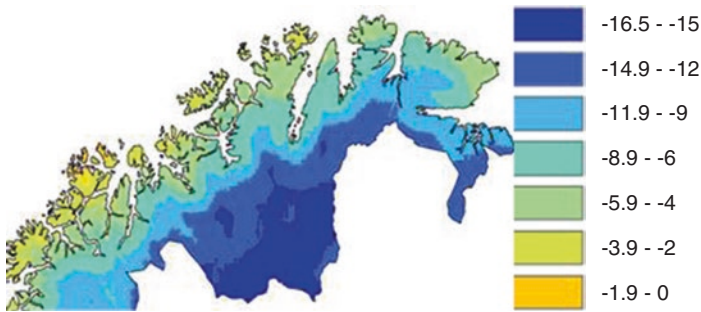**Fig. 8.10** Stations used in the detailed Finnmark climate analyses

Fig. 8.11a Average winter (upper panel) temperature (°C) in Finnmark for the period 1961–1990. (Source: Norwegian Meteorological Institute)

even in the interior. In summer, the maximum temperatures are – as the average temperature – in general higher in Karasjok than in Nordreisa and lowest in Vardø (Figs. 8.12a, 8.12b, and 8.12c).

The average daily minimum temperatures are similar at all stations, while the extreme minimum temperature is lowest in Karasjok, which is the only one of the three stations where below zero temperatures have been observed in July during the

■	-16.5 - -15
■	-14.9 - -12
■	-11.9 - -9
■	-8.9 - -6
■	-5.9 - -4
■	-3.9 - -2
■	-1.9 - 0
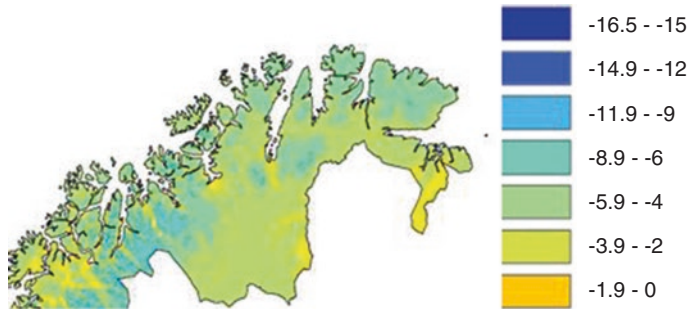
Fig. 8.11b Average summer (lower panel) temperature (°C) in Finnmark for the period 1961–1990. (Source: Norwegian Meteorological Institute)
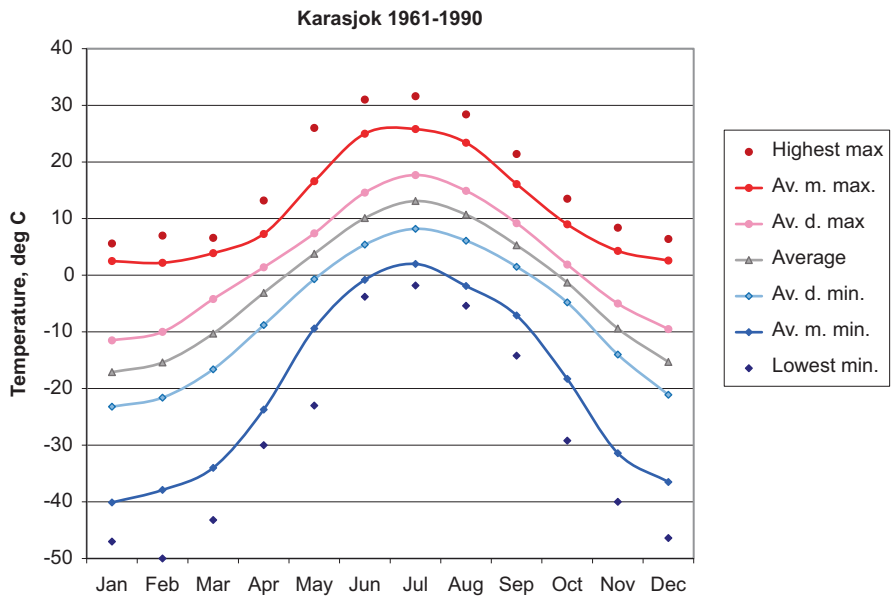

Fig. 8.12a Monthly average and extreme temperatures in Karasjok over the period 1961–1990. For each calendar month, "Highest max"/"Lowest min" are the highest maximum/lowest minimum temperatures observed at the stations, "Av. m. max"/"Av. m. min" are the averages of the highest monthly maxima/lowest monthly minima from each year (averages of 30 values), and "Av. d. max"/"Av. d. min" are the averages of all the daily maxima/minim from that specific month each year (averages of about 900 values)

period 1961–1990. The temperature variability is thus larger than at the other stations both in summer and winter. Karasjok and Kautokeino are the stations in Norway with the largest difference between the highest measured maximum and the lowest measured minimum temperature (>80 °C).

Historical series of annual mean temperatures from 1900 to 2019 show that the inter-annual temperature variation during the last 120 years is larger inland,
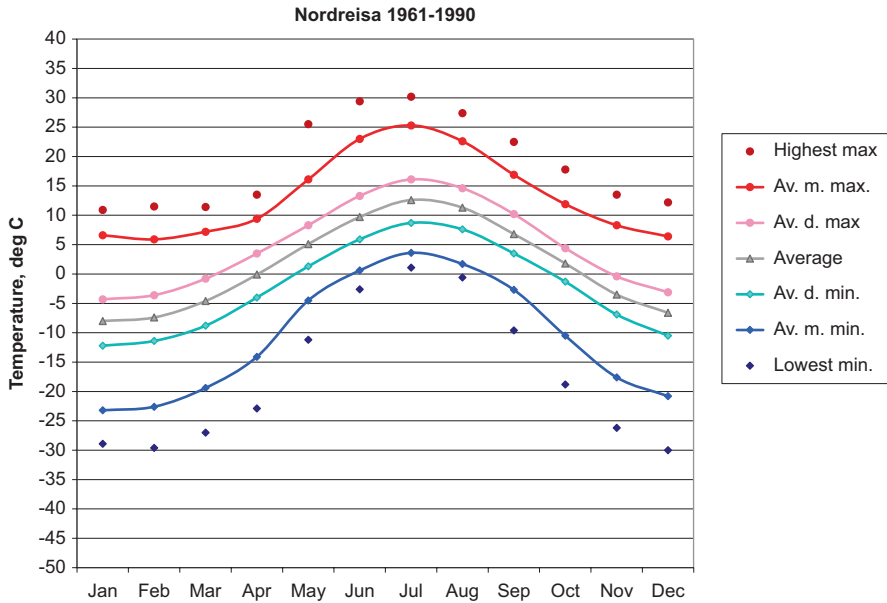
Nordreisa 1961-1990

Fig. 8.12b Monthly average and extreme temperatures in Nordreisa over the period 1961–1990. For each calendar month, "Highest max"/"Lowest min" are the highest maximum/lowest minimum temperatures observed at the stations, "Av. m. max"/"Av. m. min" are the averages of the highest monthly maxima/lowest monthly minima from each year (averages of 30 values), and "Av. d. max"/"Av. d. min" are the averages of all the daily maxima/minim from that specific month each year (averages of about 900 values)

represented by Karasjok, than at the coast, represented by Vardø (Figs. 8.13a, 8.13b, 8.14a, and 8.14b). Further, clusters with several cold or warm years lead to variability on a decadal and even on 30-year timescale which also is more pronounced in the interior areas. On the 30-year timescale, both series show positive trends before the 1930s, followed by negative trends toward 1970, and positive trends from 1970 to 2019. Winter and autumn temperatures show similar patterns, while spring temperatures show small trends before 1970, and thereafter an increase.

In Figs. 8.13a, 8.13b, 8.14a, and 8.14b, the historical time series are plotted together with the projected future temperature trends under a medium scenario for future climate gas emissions (RCP4.5; IPCC, 2013), downscaled by regional climate models. "M" shows the median in an ensemble of ten projections under this scenario, while "H" and "L" show the spread of the trend projections in the ensemble (Hanssen-Bauer et al., 2015, 2017). Note that the grey lines only show the projected trend, and that there will always be interannual variation around the long-term trend, similar to what is seen in the historical series. The observed temperature trend during the later decades fits well with the ensemble of projected trends. The average ESD projection from Benestad (2011), presented in Sect. 8.3.5, is also included in Figs. 8.13a, 8.13b, 8.14a, and 8.14b. The emission scenario used by Benestad is higher than RCP4.5, and thus on average expected to give somewhat higher
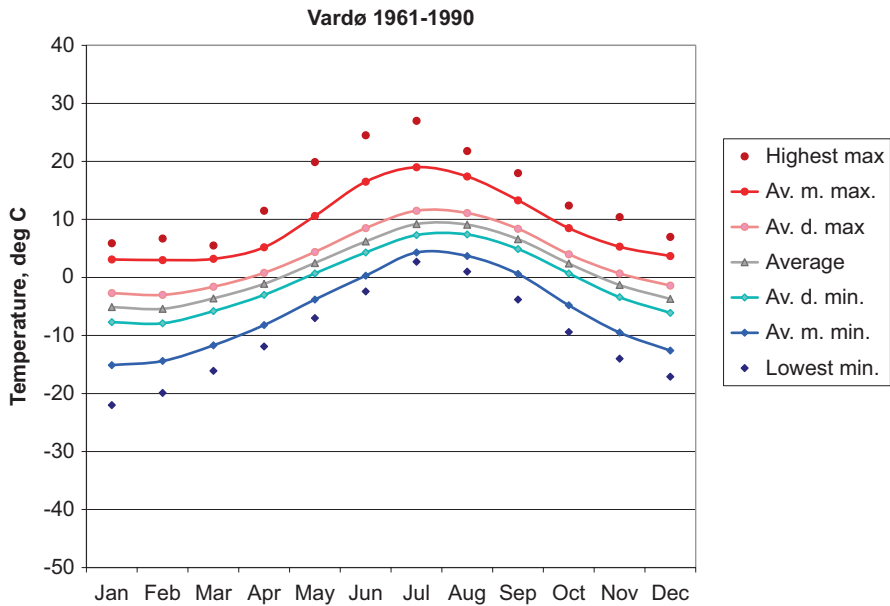
Fig. 8.12c Monthly average and extreme temperatures in Vardø over the period 1961–1990. For each calendar month, "Highest max"/"Lowest min" are the highest maximum/lowest minimum temperatures observed at the stations, "Av. m. max."/"Av. m. min" are the averages of the highest monthly maxima/lowest monthly minima from each year (averages of 30 values), and "Av. d. max"/"Av. d. min" are the averages of all the daily maxima/minim from that specific month each year (averages of about 900 values)
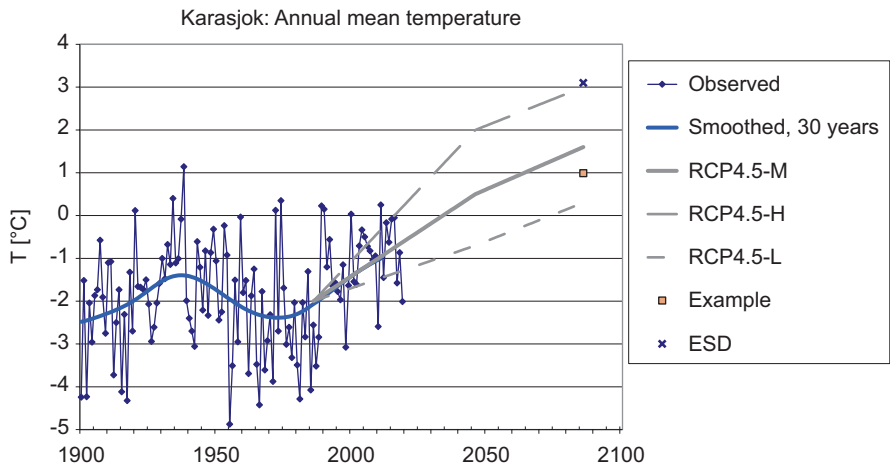
Fig. 8.13a Annual temperature series (°C) from 1900 to 2019, and temperature projections for 2031–2060 and to 2071–2100 in Karasjok. The historical series are given as curves smoothed at a 30-year time scale. For annual mean temperature, single values are also given. Grey lines show future projections for long-term trends based on a medium greenhouse gas emissions scenario (RCP4.5). "M", "H" and "L" show median, 90-, and 10-percentile from an ensemble of ten downscaled models. The cross shows the ESD projection from Sect. 8.3.5 (see Fig. 8.8). The yellow square represents the projection used in Sect. 8.4.3 to estimate future snow conditions
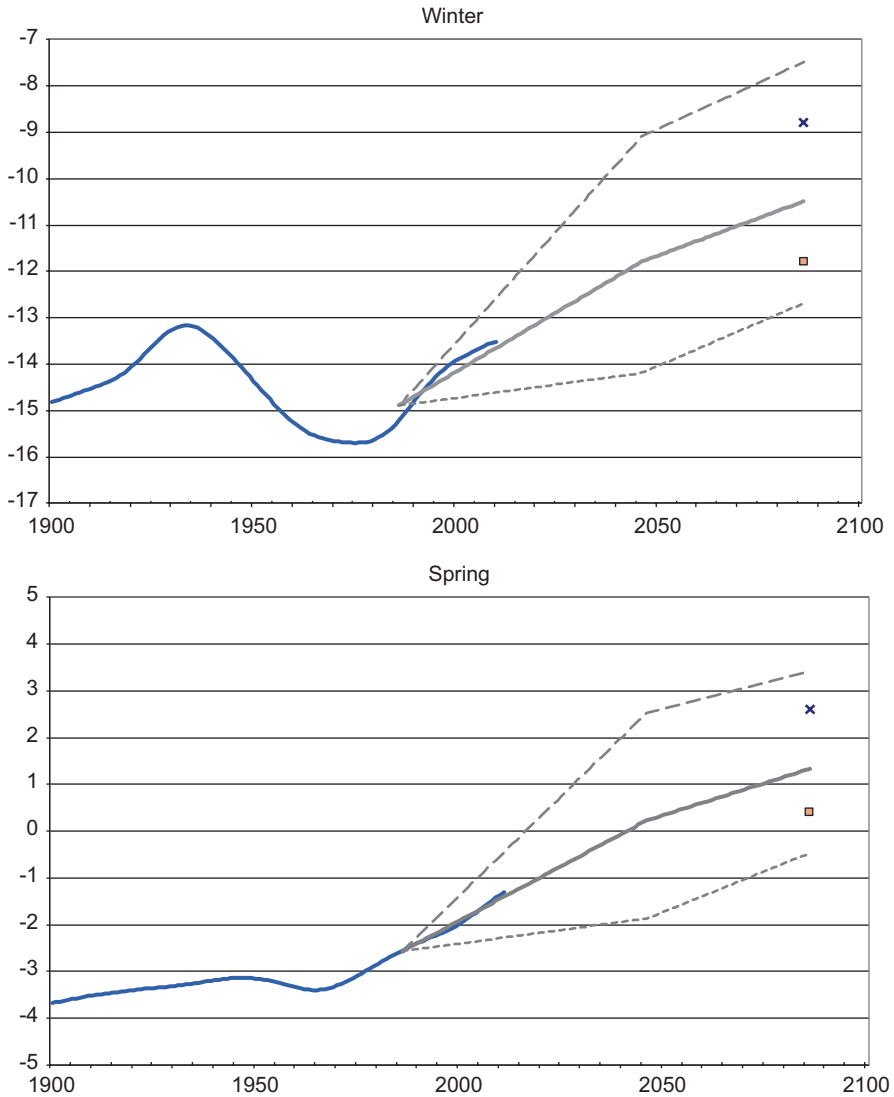
Winter

Spring

Fig. 8.13b Seasonal temperature series (°C) from 1900 to 2019, and temperature projections for 2031–2060 and to 2071–2100 in Karasjok. The historical series are given as curves smoothed at a 30-year time scale. For annual mean temperature, single values are also given. Grey lines show future projections for long-term trends based on a medium greenhouse gas emissions scenario (RCP4.5). "M", "H" and "L" show median, 90-, and 10-percentile from an ensemble of ten downscaled models. The cross shows the ESD projection from Sect. 8.3.5 (see Fig. 8.8). The yellow square represents the projection used in Sect. 8.4.3 to estimate future snow conditions
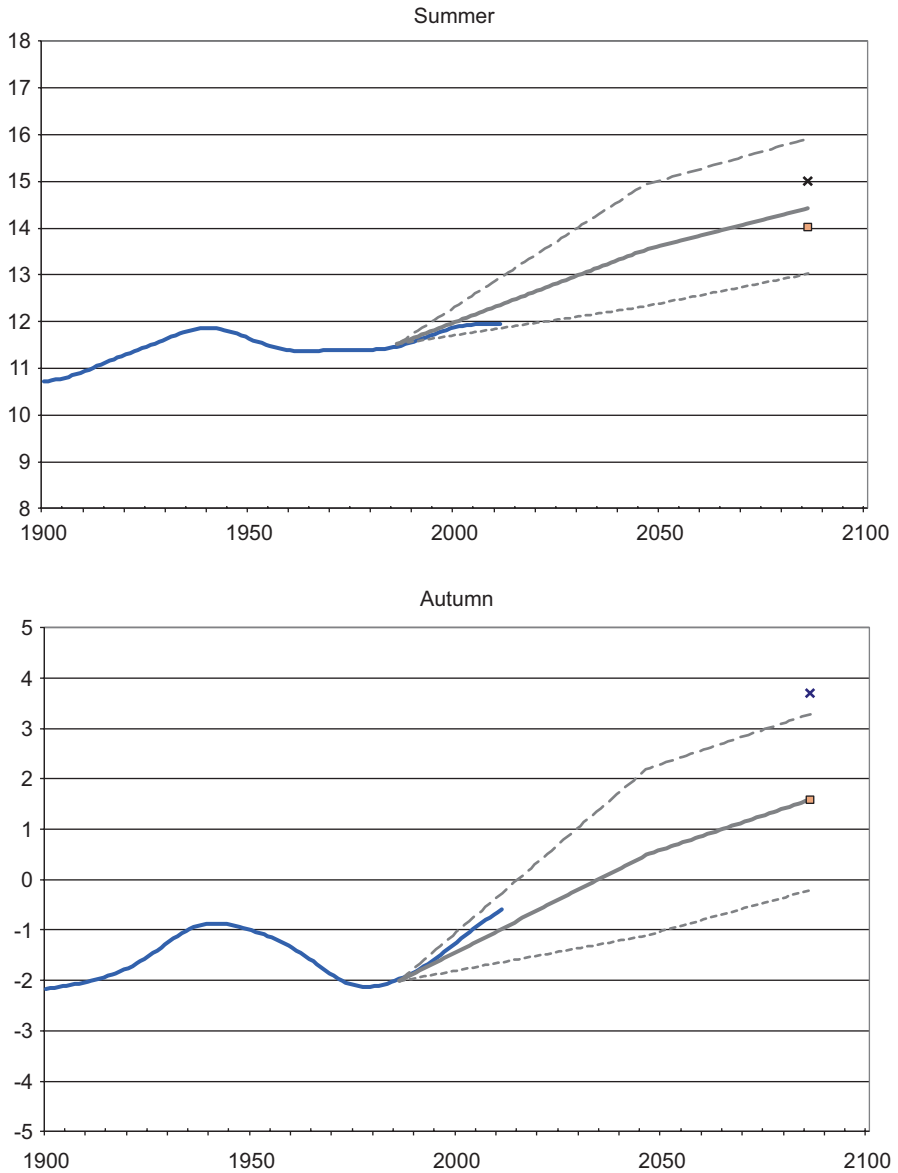
Fig. 8.13b (continued)

temperature projections. This is the case in Karasjok, where it is matching the high RCP4.5 projection. In Vardø, it is close to the medium projection. A reason for this may be that the ESD-technique better reflects the differences between coast and interior and thus indicates higher temperature increases in Karasjok than in Vardø.

Nilsen et al. (2020) studied past and projected future changes in the number of days when the temperature crosses 0 °C in different parts of Norway. For the future,
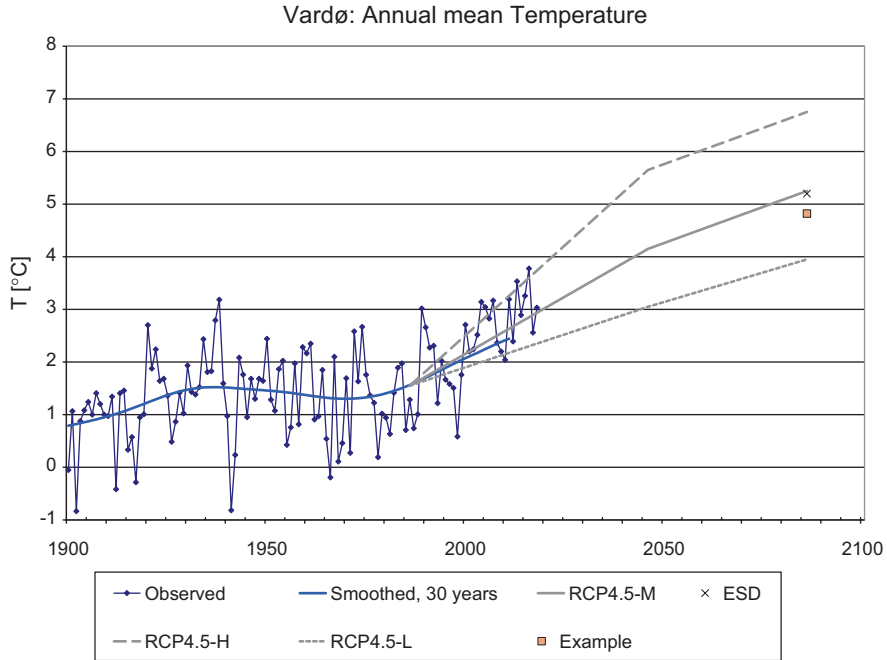
Fig. 8.14a Annual temperature series (°C) from 1900 to 2019, and temperature projections for 2031–2060 and to 2071–2100 in Vardø. The historical series are given as curves smoothed at a 30-year time scale. For annual mean temperature, single values are also given. Grey lines show future projections for long-term trends based on a medium greenhouse gas emissions scenario (RCP4.5). "M", "H" and "L" show median, 90-, and 10-percentile from an ensemble of ten down-scaled models. The cross shows the ESD projection from Sect. 8.3.5 (see Fig. 8.8). The yellow squares represent the projection used in Sect. 8.4.3 to estimate future snow conditions

they applied the climate projections shown in Figs. 8.13a, 8.13b, 8.14a, and 8.14b. They concluded that the number of such days in Finnmark during the later decades has increased significantly in spring, and that it will continue to increase throughout this century, both in winter and spring.

8.4.2   *Precipitation*

Some inland areas in Finnmark measure less than 400 mm precipitation in an average year and are among the areas in Norway with least precipitation. Figure 8.15 shows that annual precipitation usually increases toward the coast, and that coastal areas in western Finnmark on average receive more than 1000 mm a year. Fjord areas and eastern coastal areas receive less precipitation than the west coast, but more than the interior. As indicated in Sect. 8.3.3, the contrasts between coast and the interior are at a maximum in winter, when the inland precipitation is very low,
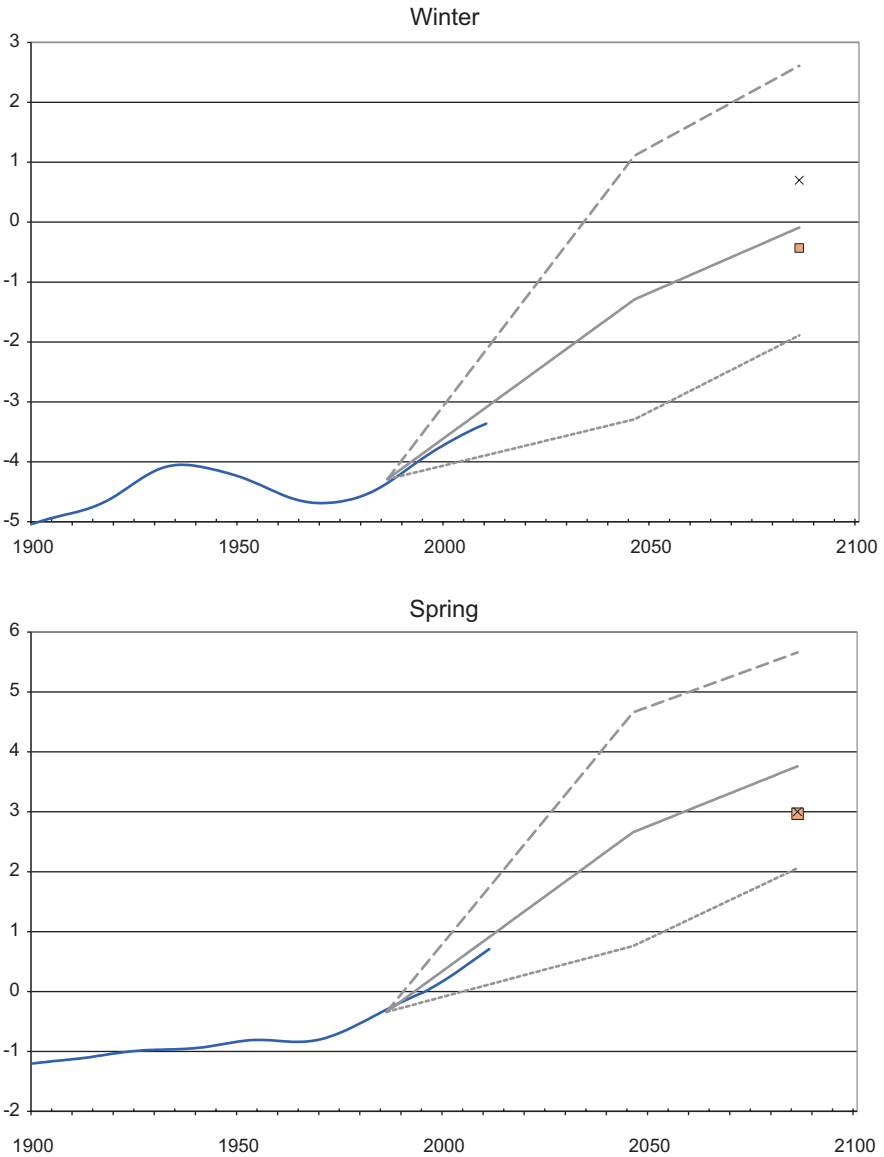
Fig. 8.14b Seasonal temperature series (°C) from 1900 to 2019, and temperature projections for 2031–2060 and to 2071–2100 in Vardø. The historical series are given as curves smoothed at a 30-year time scale. For annual mean temperature, single values are also given. Grey lines show future projections for long-term trends based on a medium greenhouse gas emissions scenario (RCP4.5). "M", "H" and "L" show median, 90-, and 10-percentile from an ensemble of ten down-scaled models. The cross shows the ESD projection from Sect. 8.3.5 (see Fig. 8.8). The yellow squares represent the projection used in Sect. 8.4.3 to estimate future snow conditions
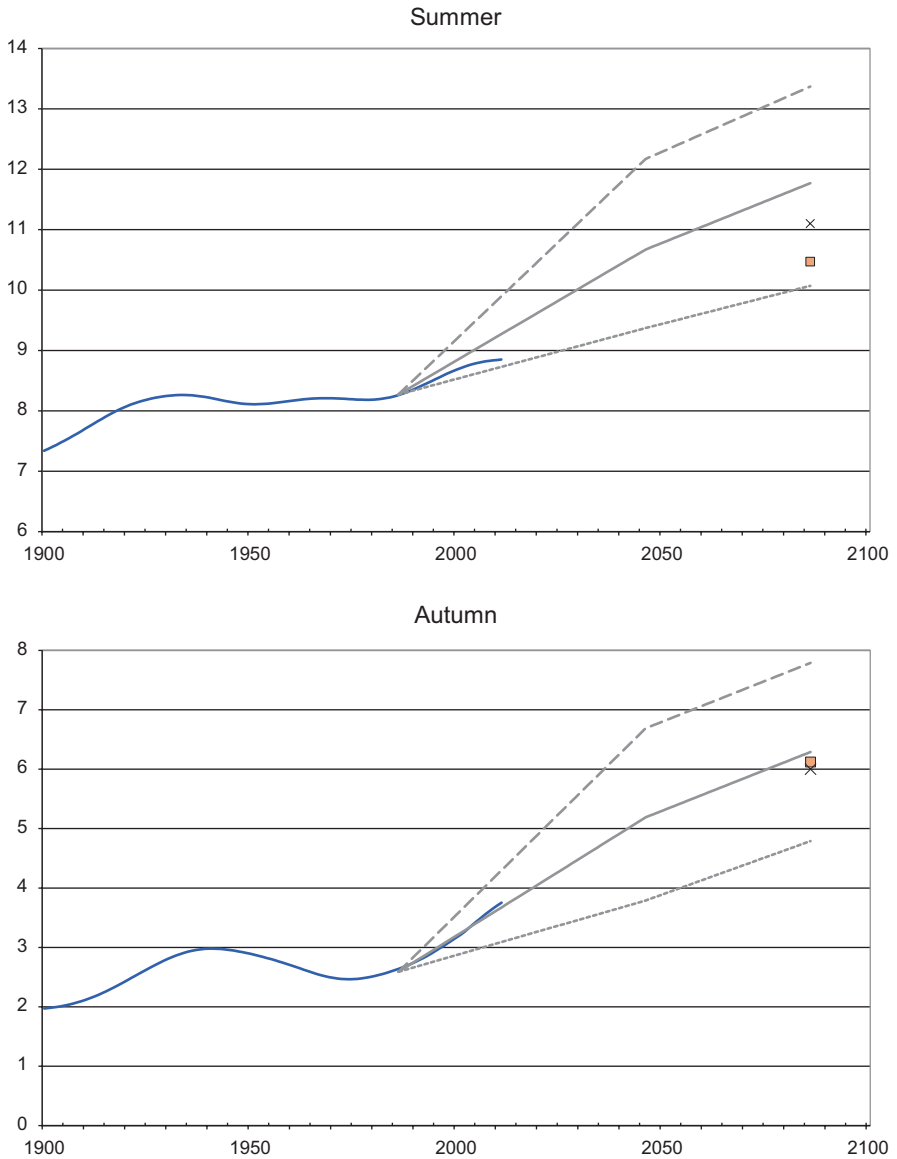
Summary

Summer

Autumn

Fig. 8.14b (continued)

and in autumn, which is the wettest season at the coast. Spring is a dry season in all regions, while summer is rather wet, especially inland. The 1991–2020 climatology for Finnmark shows an increase in annual precipitation of about 12% relative to 1961–1990, mainly caused by increased winter- and spring precipitation (Tveito, 2021).

Fig. 8.15 Average annual precipitation (mm) in Finnmark for the period 1961–1990. (Source: Norwegian Meteorological Institute)
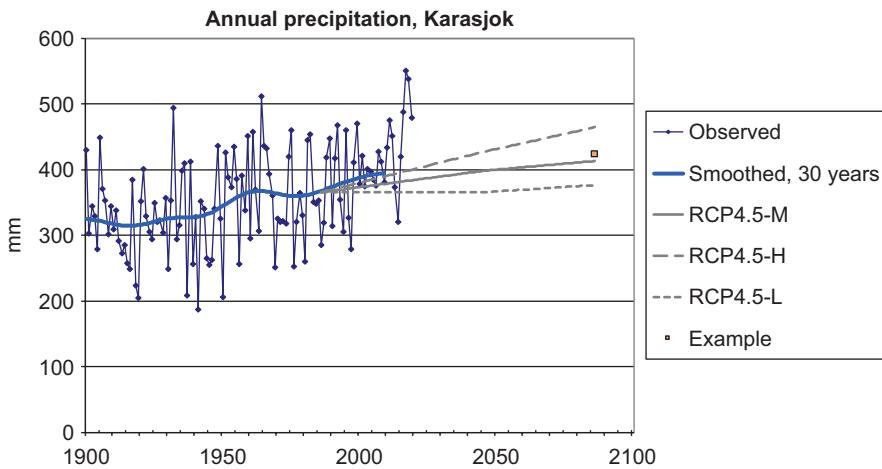

Fig. 8.16a Historical series of annual precipitation (mm) with curves smoothed at a 30-year time scale, and "high", "medium" and "low" precipitation trend projections from 1971–2000 to 2031–2060 and 2071–2100 for Karasjok. The yellow squares represent the projection used in Sect. 8.4.3 to estimate future snow conditions

Historical series of annual precipitation show that precipitation increased by almost 20% from 1900 to 2014 both in western and interior Finnmark, while there was no trend in the north-east (Hanssen-Bauer et al., 2015). In Figs. 8.16a, 8.16b, and 8.16c, these three regions are represented by Nordreisa, Karasjok and Vardø, respectively. The figure shows that the future precipitation projections under the medium emission scenario RCP4.5 indicate a continued increase of at average 10–15% during the twenty-first century, while the "low" projection indicates only minor change and "high" indicates up to a 30% increase (Hanssen-Bauer et al., 2015). As for temperature, interannual variability is projected to continue around the trend lines. The fit between observed trends during the later decades and
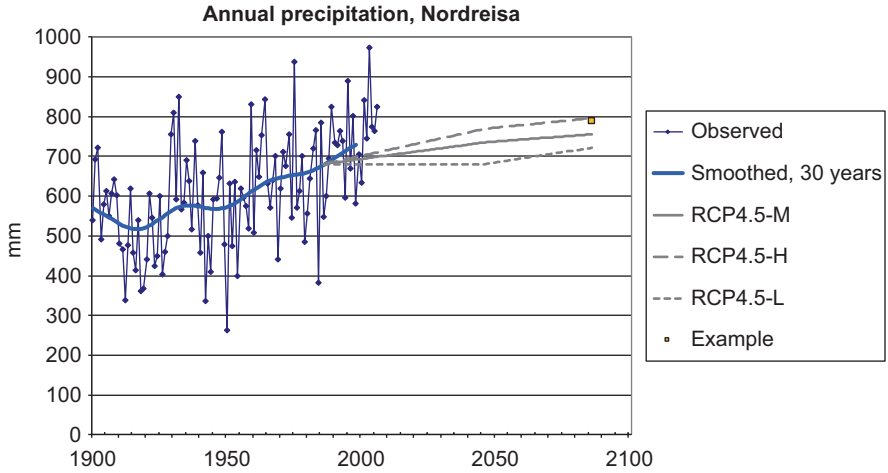
Fig. 8.16b Historical series of annual precipitation (mm) with curves smoothed at a 30-year time scale, and "high", "medium" and "low" precipitation trend projections from 1971–2000 to 2031–2060 and 2071–2100 for Nordreisa. The yellow squares represent the projection used in Sect. 8.4.3 to estimate future snow conditions

Fig 8.16c Historical series of annual precipitation (mm) with curves smoothed at a 30-year time scale, and "high", "medium" and "low" precipitation trend projections from 1971–2000 to 2031–2060 and 2071–2100 for Vardø. The yellow squares represent the projection used in Sect. 8.4.3 to estimate future snow conditions
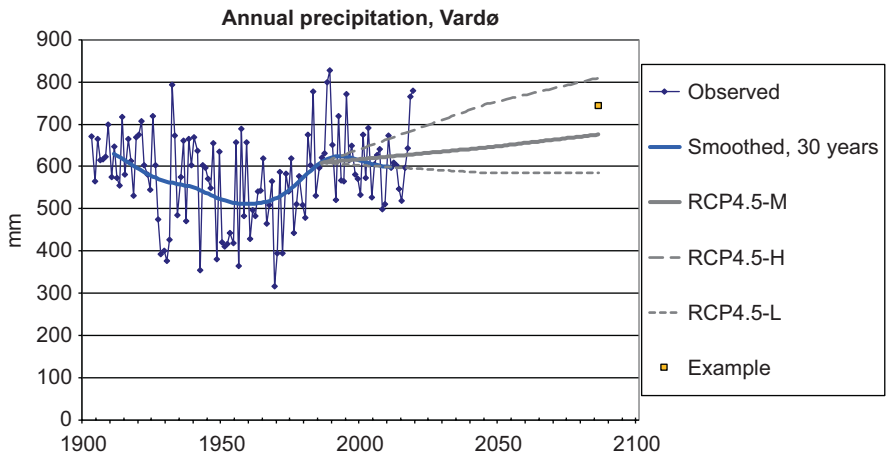
projected trends is not as good as for temperature. While the observations are close to the L trend in Vardø, it is comparable to the H trend in Karasjok, and in Nordreisa, it is even above the H trend. This illustrates that the model skills are poorer for precipitation than for temperature, partly because of the larger spatial variation in precipitation. Thus, a larger model ensemble is probably needed to map the real uncertainty of the projections.

8.4.3   Snow

There are few stations with high quality long-term snow measurements, and results from a hydrological model are used as a supplement to measurements in order to describe the snow conditions (Vikhamar-Schuler et al., 2006). Measurements indicate an average snow season of about 200 days in Karasjok, 230 in Suolovuopmi and 195 in Nordreisa for 1961–1990 (Fig. 8.19). Figure 8.17 shows that the results from the hydrological model are reasonably consistent with this, giving snow season durations between 176 and 225 days in coastal and fjord areas and in low altitude inland areas, but above 225 days in most of the interior.

The reason for the shorter snow season along the coast is that the temperatures are higher in spring and autumn, consequently the snow season starts later in autumn and the melting starts earlier in spring (Vikhamar-Schuler et al., 2010b). The reason for the shorter snow season in low altitude inland sites like Karasjok is little precipitation in winter, and thus small amounts of snow, as seen in Figs. 8.17 and 8.18. Figure 8.18 shows the average winter maximum snow equivalent (the water value of the snow) for the period 1961–1990 from the hydrological model. Though the values are not directly proportional to maximum snow depth, as the snow density varies, the map clearly indicates small amounts of snow inland, especially at low altitudes, and larger amounts closer to the coast, and especially at high altitudes.
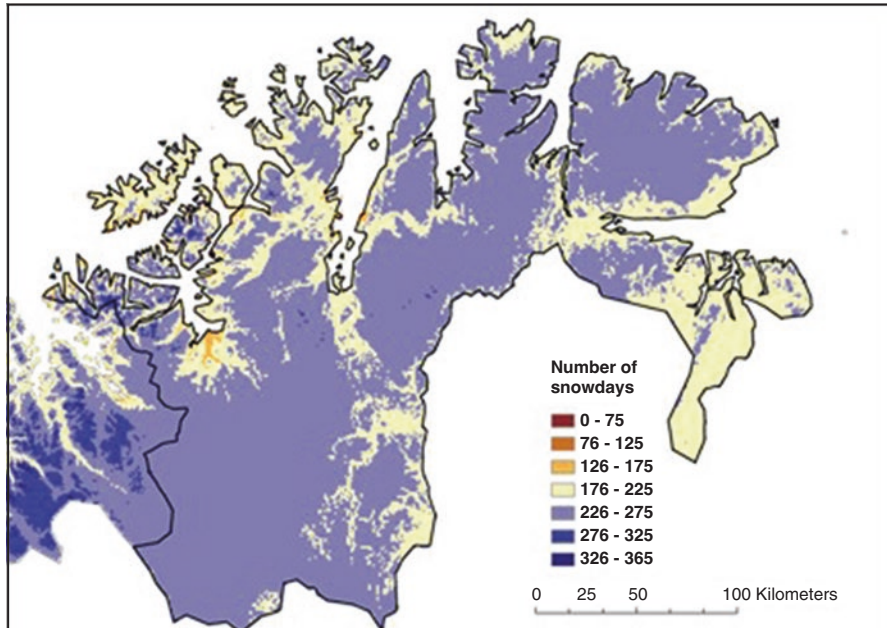

Fig. 8.17 Average number of days with snow cover in Finnmark for the period 1961–1990 calculated by a hydrological model. (From Vikhamar-Schuler et al., 2006)
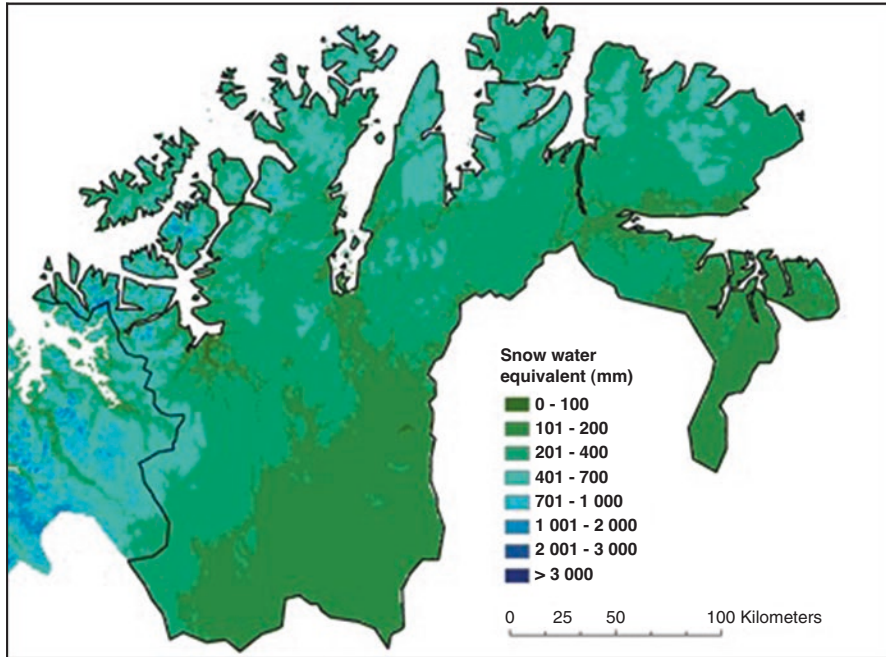
Fig. 8.18 Average maximum snow water equivalent (unit: mm) in Finnmark for the period 1961–1990 calculated by a hydrological model. (From Vikhamar-Schuler et al., 2006)

Trend analysis of historical time series from the twentieth century indicate that the snow season typically decreased by around 3 weeks from 1900 to 2019 at the stations with sufficiently long observational series, but that there is large inter-annual variation (Fig. 8.19). Vikhamar-Schuler et al. (2010b) showed that, especially in Karasjok, the main change is that the snow melts earlier in the spring now than it did around 1900. In Nordreisa, there is also a clear trend toward delayed start of the snow season.

Drifting snow may cause large local variations in snow depth. Trend studies of maximum snow depth are thus vulnerable to small relocations of the site of measurements, and also in its environments. The series from Karasjok and Nordreisa are believed to be reasonably homogeneous, while Suolovuopmi is not. Nordreisa shows no trend during the twentieth century, while the measurements indicate a trend toward higher maximum snow depth in Karasjok (Vikhamar-Schuler et al., 2010b).

The hydrological model which was used to produce the maps for snow cover and maximum snow water equivalent for 1961–1990 was also used to calculate a snow projection for 2071–2100, based upon the temperature and precipitation "example projections" which are plotted in Figs. 8.13a, 8.13b, 8.14a, 8.14b, 8.16a, 8.16b, and 8.16c. The results indicate a reduction in the average snow season everywhere towards the end of the twenty-first century (Fig. 8.20). The least reduction is
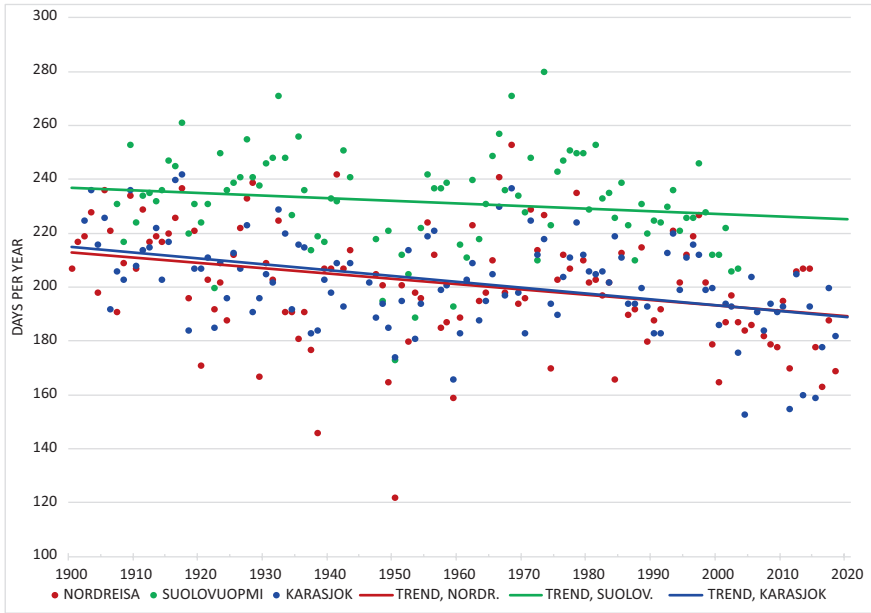
Fig. 8.19 Number of days per year with 50% or more snow cover in Karasjok, Suolovuopmi, and Nordreisa
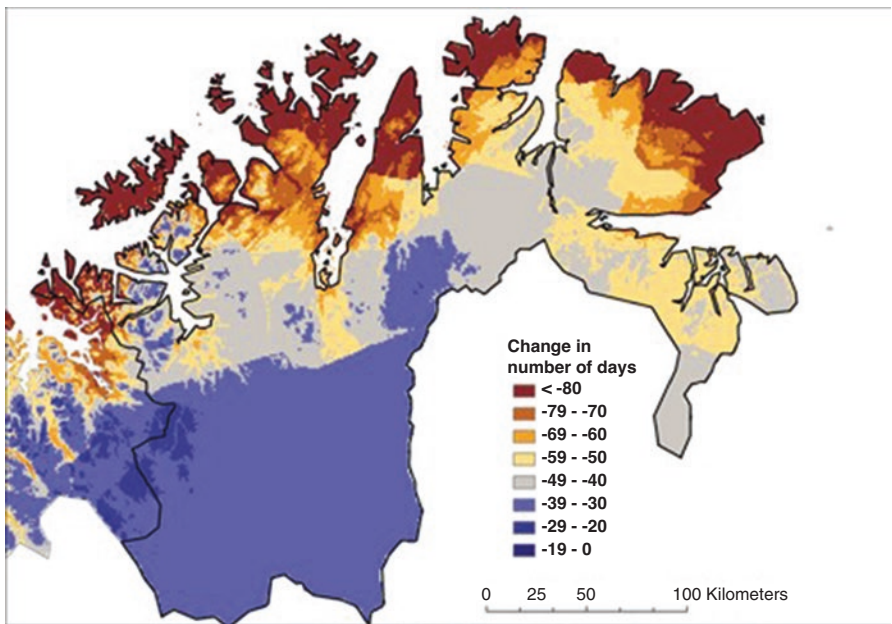

Fig. 8.20 Projected change in average number of days with snow cover in Finnmark towards 2100 according to the example projection. (From: Vikhamar-Schuler et al., 2006)

projected inland, where a reduction of 4–5 weeks is indicated over large areas. In the inner fjord areas, a reduction of 6–8 weeks is typically projected, while fjord mouths and coastal areas according to the projection may have a reduction of almost 12 weeks.

The projected changes in the average maximum snow water equivalent are also larger along the coast, where reductions of more than 60% are indicated in some areas. In the inner fjords, a 20–40% reduction is more typical. In inland areas, the projected reduction is smaller, and for a few sites, the average maximum snow water equivalent is even projected to increase slightly (Fig. 8.21). The reason for this is that the projected increase in precipitation can lead to larger snow accumulation even though the snow season is reduced. This may be the case for larger inland areas in the short run, and is consistent with the fact that there has been a trend towards higher maximum snow amounts in Karasjok so far.

When studying single years in the projection period, Vikhamar-Schuler et al. (2006) found that also in some inland areas where the average maximum snow water equivalent is projected to decrease, the maximum values for some individual years in the projection period are larger than they are in the reference period 1961–1990. This implies a possibility for increased variability in maximum snow amounts from one winter to the next in the future when compared to present conditions.
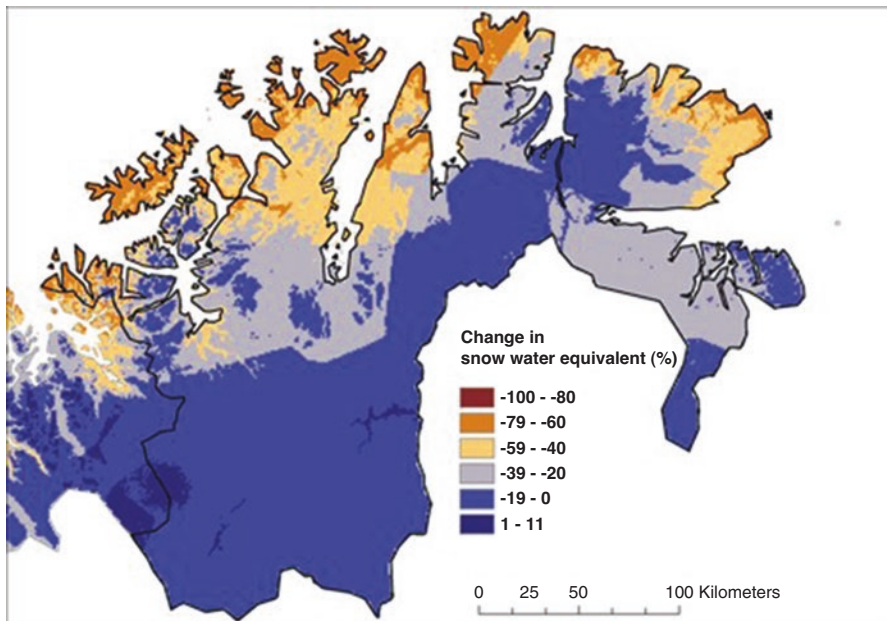

Fig. 8.21 Projected relative change in average maximum snow water equivalent (unit: % of the 1961–1990 values) in Finnmark towards 2100 according to the example projection. (From: Vikhamar-Schuler et al., 2006)

8.5   Modeling Snow Properties in Kautokeino, Finnmark

The ability of reindeer to access pasture through the snow has its own term (*guohtun*) in the Sámi language. Difficult grazing conditions are usually snow structures rather than snow amounts, e.g., ice-layers in the snowpack or at the snow-ground interface. On the other hand, loose snow structures (depth hoar) increase the accessibility of food below the snowpack. A review by Tyler (2010) questions snow conditions and the causes of the decline of circumpolar reindeer and caribou populations.

Structures in the snow layer are not observed regularly at climate stations. However, applying the SNOWPACK model (see Sect. 8.2) the EALÁT project was probably the first to set up such a model in order to describe *guohtun* (Eira, 2012). The goal was to simulate the evolution of the snow cover stratigraphy under past and present climate conditions. A summary of the study is given below. More details can be found in Vikhamar-Schuler et al. (2013).

8.5.1   Modeling the Snowpack over the Last 50 Winters in Kautokeino

In order to validate the SNOWPACK model, information from reindeer herders on the winter grazing conditions is crucial. Difficult winter conditions include ice layers in the snow, too deep snow or long snow season, while good conditions imply deep hoar layers, loose snow structures or shallow snow cover. From the limited information from reindeer herders that can be found in the scientific literature, it is clear that these conditions have varied greatly from year to year (Tyler et al., 2007; Lie et al., 2008; Päiviö, 2006). The information indicates difficult winter grazing conditions over the entire or parts of the Finnmark plateau during the winters 1917/18, 1957/58, 1961/62, 1966/67, 1967/68, 1989/1990, 1996/97, 2000/2001 as well as during the 1990s in general (Tyler et al., 2007; Lie et al., 2008). Good winter grazing conditions have been reported during the 1980s in general. The unfavorable grazing conditions during the winters 1957/58, 1961/62, 1967/68 were caused by ice layers in the snowpack (Lie et al., 2008). These ice layers were formed after mild weather events followed by extreme cold. For northern Sweden, Päiviö (2006) describes historical winter grazing conditions in the Jokkmokk region. He describes 1967/68 as a catastrophic year for reindeer herding, in addition to 1935/36 and 1955/56. Furthermore, he describes the second part of the 1970s and the entire 1980s as years with favorable winter grazing conditions, while the 1990s had unfavorable conditions. The present study is restricted to analyzing the weather situations that lead to the formation of high-density snow layers (ice layers) and to compare the modelled years with the documented years of favorable or unfavorable grazing conditions.

Model results for the catastrophic year 1967/68 are shown as an example. Observations from the Kautokeino weather station from autumn 1967 show rain-on-snow events occurring in the beginning of November (Fig. 8.22), followed by periods of cold weather. This created a very hard snow layer. Modelled snow density for the winter season 1967/68 (Fig. 8.23) shows that a high-density snow layer was formed at the ground and persisted throughout the winter.

Snow profiles as the one shown in Fig. 8.23 were computed for Kautokeino for every winter over the period 1956–2010. To compare all the winters, the depth of the high-density layers (density > 235 kg/m^3) in the snowpack were summarized for every timestep (Fig. 8.24). Overall, modeling indicates that both the winters of 1966/67 and 1967/68 had a significant element of high-density layers in the snow-pack, as compared to all the other years. Furthermore, the modeling results show few high-density layers during the 1970s and the 1980s, but more unstable situations during the 1990s and 2000s. This is consistent with the observed increasing number of days when the temperature crosses 0 °C (Sect. 8.4.1). These modeling results also correspond well with reindeer herders' reports of grazing conditions. Particularly, the winters 1991/92 and 2000/01 are modelled with some high-density layers in the snowpack (Figs. 8.25a and 8.25b).
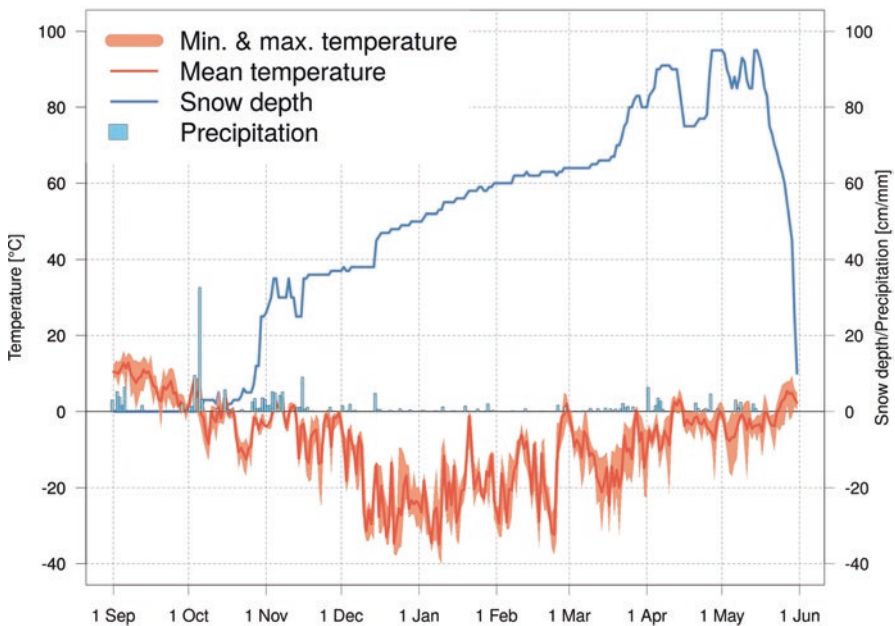

Fig. 8.22 Weather causing ice-layer formation during the autumn and winter 1967/68 in Kautokeino. (Data from the Norwegian Meteorological Institute)
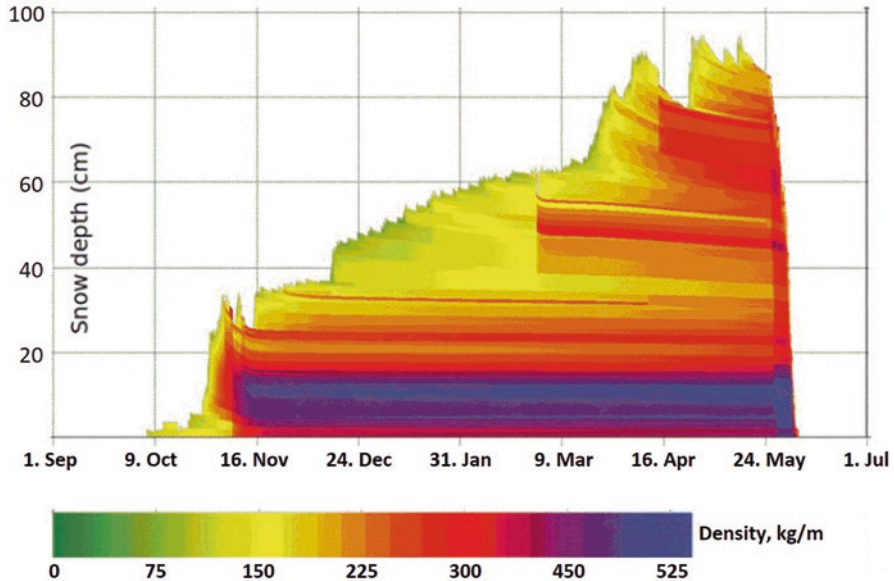
Fig. 8.23 High-density layers formed during autumn 1967 (modeling results). A mild weather event followed by extreme cold in mid-November created a high-density snow layer at the ground surface which persisted throughout the winter and spring. (From: Vikhamar-Schuler et al., 2013)

8.5.2 Further Perspectives for Modeling Snowpack Structure

The snow modeling results successfully:

- Reproduced periods with ground-ice conditions causing difficult grazing conditions: The years 1966/67, 1967–1968 and 2000/01, where 1966/67 is known to be a difficult year for the reindeer herding on the Finnmark plateau.
- Reproduced the period between the 1970s and the 1980s with favorable winter grazing conditions and there were no particular high-density layers in the snowpack.

The correspondence between herders' reports and the model results are promising, concerning the model's ability to describe some structures of relevance for reindeer grazing conditions. It should thus be possible to apply the model to produce projections for future *guohtun*.

A study by Rasmus et al. (2016), using the SNOWPACK model with input from four regional climate projections (based on two global models run under two scenarios), indicates on average a shorter snow season and less snow, but more frequent ice layers in northern Finland towards the mid-century. According to Turunen et al. (2016) the shorter snow season might be positive for reindeer herding, while an increased frequency of ice layers definitely will have a negative impact. These results cover a limited area, and the models applied also have a limited spatial resolution (about 50 km). The spatial variability of snow conditions is considerable,
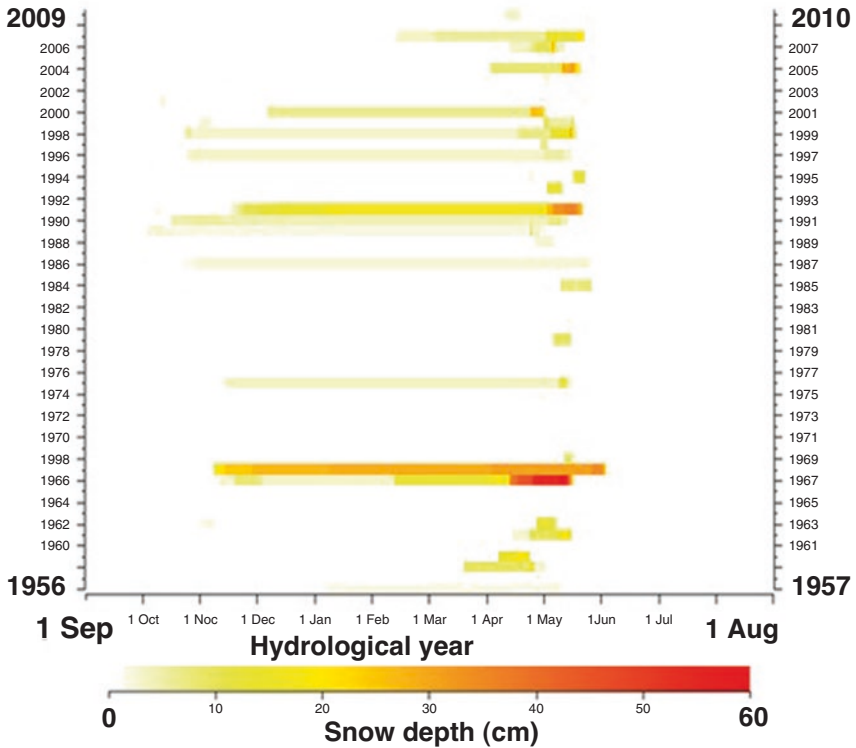
Fig. 8.24 High-density snow layers (density > 235 kg/m³) at the Kautokeino weather station, modelled with the SNOWPACK model. The white color represents periods without high-density layers present in the snowpack. Orange and red represent increasing thickness of high-density layers. (From: Vikhamar-Schuler et al., 2013)

Fig. 8.25a Spring migration of the Nenets reindeer herders crossing the Ob Bay, Russia on their way to summer pastures in the Yamal Peninsula, Russia (2007). (Photo: E.I. Turi)

Fig. 8.25b Spring migration of the Nenets reindeer herders crossing the Ob Bay, Russia on their way to summer pastures in the Yamal Peninsula, Russia (2007). (Photo: E.I. Turi)

because of small-scale variability of precipitation, as well as temperature variation caused by topography, and redistribution of snow by wind. It would thus be interesting to produce more detailed projections, and to cover a larger area. Forbes et al. (2016) reported a connection between an observed increasing frequency of rain-on-snow events on the Yamal peninsula and the shrinking winter sea-ice cover in the area. Modeling future winter conditions in coastal areas in YNAO may thus be of special interest.

8.6   Conclusions

Climatological data from selected sites in Finnmark, Norway, and the YNAO, Russia, show that the average summer temperatures lie typically between +10 and +15 °C in the inland area, and between +5 and +10 °C along the coast. Typical average winter temperatures range from −20 to −25 °C in the YNAO, while interior Finnmark has winter temperatures of around −15 °C with coastal Finnmark up to −5 °C. Local projections for climate change under a medium high global warming projection show that the average summer temperatures may increase by about 3 °C in 100 years both in Finnmark and the YNAO, while winter temperatures are projected to rise by more than 7 °C in some inland areas, and somewhat less in most coastal areas. This implies that the projected winter temperatures in the inland of the YNAO will be comparable to the present conditions in the interior of Finnmark, while the future winter temperatures in interior Finnmark may be similar to the present conditions in the fjord districts of Finnmark. The risk for warm events with above 0 °C temperatures as well as rain-on-snow events in winter will thus increase in both areas, compared to the present situation. Presently, the average annual precipitation in coastal Finnmark is about 600 mm, with a maximum in autumn and a minimum in spring. In the interior regions of Finnmark as well as the YNAO, precipitation is lower annually (350–500 mm), and also in autumn and especially

winter. Summer precipitation, on the other hand, is slightly higher in the interior regions. The coastal zone of the YNAO is presently the driest part of the area, as precipitation is sparse in all seasons. Global climate projections in general project increased precipitation at high latitudes. Local precipitation projections developed for Finnmark under a medium emission scenario indicate an increase of about 10–15% in 100 years, but are regarded as more uncertain than temperature scenarios.

The ground is presently covered by snow from about 6 to 8 months a year in Finnmark and the YNAO. The snow season tends to be longest in the coastal areas of the YNAO, while it is shortest in coastal Finnmark. Typically, the snow depth in early spring is between 0.4 and 0.9 m. A local snow projection for Finnmark indicates a considerable reduction in the snow season (3 months) and maximum snow depth (−60%) along the coast. In the interior, the projected snow season reduction is smaller (about 1 month), and the projected change in maximum snow depth is minor, as increased winter precipitation compensates for the shorter snow season.

Information from reindeer herders indicates that the grazing conditions in winter depend more on the structure of the snowpack than on the amounts of snow. Snow structure is not observed regularly, but a model which calculates snow structure from standard weather observations was tested for interior Finnmark. The model successfully identified winters with serious problems connected to ice layers in the snow in the near past. A study from Finland indicates that the model may also be used for projecting "difficult winters" in the future. More detailed climate projections than those available for the present study will be needed for making similar projections for Finnmark and YNAO.

The projected warming and precipitation changes in Finnmark and the YNAO will probably not by themselves challenge reindeer husbandry, however, the warming and increased precipitation will lead to changes in the hydrological cycle, including snow conditions, which may be important. Further, the warming leads to an increased growing season, which may affect the vegetation and thus pastures.

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