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Abstract

Observational series and downscaled scenarios of air temperature are used to describe long-term variations 1900–2050 in different climatic indices that are important for the living conditions in the Nordic Arctic (Northern Fennoscandia, Svalbard, Faeroe Islands, and the Greenland-Iceland-Norwegian Sea regions). In addition to air temperature; indices illustrating vegetation conditions (growing season), energy consumption (heating season), and frost conditions (freezing season) are studied. The analyses are based on smoothed daily temperature series deduced from monthly averages for 27 Nordic climate stations, and are focusing on conditions in the climatological 30-yr reference periods 1901–1930, 1931–1960, and 1961–1990, and the scenario period 2021–2050. Also values for two recent time periods (1976–2000 and 1990–2002) are included. The results show substantial variations in growing, heating and freezing indices in the Nordic Arctic during the 20th century. Compared to the period 1961–1990, the growing season has increased during the recent decades in large parts of the region. Projections up to 2050 indicate that the growing season may increase by 3 to 4 wk at most of the stations in the region. The heating season has been reduced during the latest decades, and the projections indicate a further reduction during the next 50 yr.

Introduction

Dealing with the harsh climate is of paramount importance for the living conditions in the Arctic. Important changes in the Arctic climate have occurred during the 20th century, including a marked increase in surface air temperature since 1970. Moritz et al. (2002) state that this warming was correlated with important changes in many other Arctic climate and environmental variables, such as precipitation, sea-ice extent, snow cover, permafrost temperature, and vegetation distribution. Serreze et al. (2000) documented increased plant growth in the Arctic, attended by greater shrub abundance and northward migration of the tree line. These changes imply considerable impacts on people and ecosystems in the Arctic and may also have global impacts through a variety of climate feedback mechanisms.

Reconstructions from proxy sources (Overpeck et al., 1997) imply that the Arctic air temperatures in the 20th century are the highest in the past 400 yr. Annual mean temperatures in the Arctic fell during the period 1940–1970. While recognizing sampling problems in the early part of the 20th century, it appears that the annual temperature rose even more markedly from 1920 to 1940 than during the post 1970s period (Serreze et al., 2000). The largest temperature increases in recent decades have occurred over Northern Hemisphere land areas from about 40–70°N. Air temperature increases over northwest North America and Eurasia have been greatest during winter and spring, but there has also been a warming over the Arctic Ocean in spring and summer (Serreze et al., 2000).

The current coupled atmosphere-ocean general circulation models (AOGCMs) predict a greater warming for the Arctic than for the rest of the globe (Cubasch et al., 2001). This enhanced warming in the Arctic is reflecting the amplification of the effects of anthropogenic greenhouse warming in the northern high latitudes, due to feedbacks in which variations in snow and sea ice extent, the stability of the lower troposphere, and thawing of permafrost play key roles (Serreze et al., 2000). The impacts of this warming, including the melting of sea ice and change to terrestrial systems, are likely to be significant (Källen et al., 2001).

An intercomparison of 19 global climate change simulations (Räisänen, 2002) reveals that though the models generally show a larger increase in annual mean temperatures over the Arctic than anywhere else in the world, the scatter amongst the individual models is substantial on a regional scale. The disagreement is partly connected to differences between the models concerning the description of sea-ice. As stated by Benestad et al. (2002b), the projections of future climate in the Svalbard region are extremely sensitive to sea-ice conditions in the northern North Atlantic and Barents Sea. The scenarios presented in this paper have thus to be considered as tentative.

A substantial increase in annual and seasonal temperatures is also projected for the Arctic part of Fennoscandia (Räisänen, 2001), indicating that the winter temperatures in northern parts of Fennoscandia might increase by 3 to 4°C during 2000–2050. More detailed local scenarios deduced for Svalbard Airport/Longyearbyen have indicated that the winter temperature might increase by ca. 6°C during the next 50 yr (Hanssen-Bauer, 2002).

In the present study, past and future temperature variations are applied to discuss variations in climatic indices of importance for the living conditions in the Arctic, i.e. indices illustrating variations in vegetation conditions (growing season), energy consumption (heating season) and frost conditions (freezing season). Based on observations during 1900–2002 and on empirically downscaled scenarios for 2021–2050, both length and degree-day sums for these indices are studied. The analyses do mostly involve stations in the Nordic High Arctic, but for comparison reasons climatic series from capitals in the Nordic countries are also included (Fig. 1).

Data and Methods

OBSERVATIONS

Climate analysis in the Arctic is seriously hampered by deficiencies in the data sets. The observational base is quite limited with few long-term stations and a paucity of observations in general.

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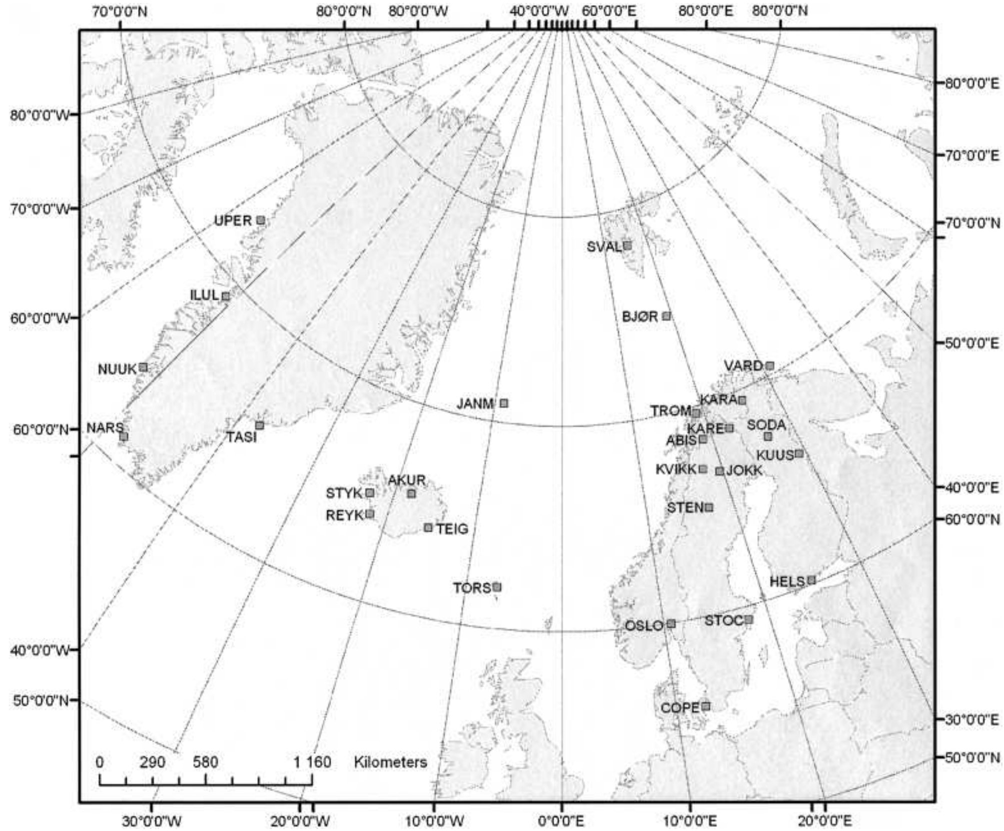

FIGURE 1. Map of stations. The stations are identified by the first four letters in the station names, see Table 1.

However, both in the northern part of Fennoscandia, in Greenland, Iceland and the Faeroe Islands systematic weather observation were initiated at a few sites before 1900. In the Svalbard region the first permanent weather observations started in 1911, and around 1920 weather stations were established at Bjørnøya and Jan Mayen. In a joint Nordic effort, a consistent high-quality monthly data set (the NARP-dataset) for a selection of stations in the Nordic Arctic was established (Førland et al., 2002) covering the period 1890–2002 (http://projects.met.no/~narp). The data series were quality-checked and homogenized as far as possible at the national meteorological institutes.

When the World Meteorological Organisation (WMO) in 1935 agreed to calculate reference values ("normals"), it was decided to operate with averaging periods of 30 yr. The climatological standard normals are thus defined as "averages of climatological data computed for consecutive periods of 30 yr as follows: 1901–1930, 1931–1960, 1961–1990, etc" (WMO, 1989). As these climate normal values often are used as references for global, regional and local climate conditions, the present analyses are mainly based on mean values for the specific 30-yr periods. To illustrate the current conditions, mean values for two recent time periods (1976–2000 and 1990–2002) are also included.

DOWNSCALED SCENARIOS

The temperature scenarios in this study are based on the ECHAM4/OPYC3 AOGCM with the transient GSDIO integration (Roeckner et al., 1999), which includes greenhouse gases, tropospheric ozone, and direct as well as indirect sulphur aerosol forcing. In this integration, the concentrations of greenhouse gases have been specified according to the IPCC IS92a scenario. Compared to IPCCs new set of emission scenarios (SRES) (IPCC, 2001: 532), the projected increase in the global mean temperature up to 2050 for the IS92a scenario is similar to SRES B1, and lower than for the other SRES scenarios.

The present study focuses on empirically downscaled monthly mean temperature. Empirical downscaling consists of revealing empirical links between large-scale patterns of climate elements (e.g., air pressure, sea surface temperature, etc.) and local climate elements (e.g., temperature, precipitation, etc.), and applying them on output from global or regional models (Benestad, 2001). Hanssen-Bauer et al. (2003) showed that empirical downscaling has the potential for describing spatial climate features that are not resolved by the currently available regional climate models.

The empirical downscaling was based on an approach utilising common EOFs as described in Benestad (2001, 2002), using multiple regression for calibrating the empirical models. The predictor consisted of gridded 2-m temperature fields from the NCEP reanalysis (Kalnay et al., 1996) and the ECHAM4/OPYC3 GSDIO results. In order to carry out the common EOF analysis, the AOGCM results were interpolated onto the same grid as the NCEP reanalysis. The predictors for deriving the local climatic series were taken from three domains (Fig. 2): Greenland: Domain I (90°W30°W–52°N80°N); Fennoscandia and Iceland: Domain II (40°W40°E–52°N80°N); Svalbard (Bjørnøya and Svalbard Airport): Domain III (35°W40°E–67°N85°N). The downscaled results for Svalbard were sensitive to the choice of predictor domain, and are therefore subject to high degree of uncertainty. Part of this uncertainty may be related to the sparse observational network in the Arctic, affecting the quality of the predictor fields in this region.

The downscaled results may be sensitive to the choice of domain (Benestad, 2002), and it is therefore important to find an appropriate region that yields realistic results and has a solid physical justification. High R^2 values from the multiple regressions are a minimum criterion for an appropriate predictor domain. The downscaling was applied to the 12 calendar months separately for each location.

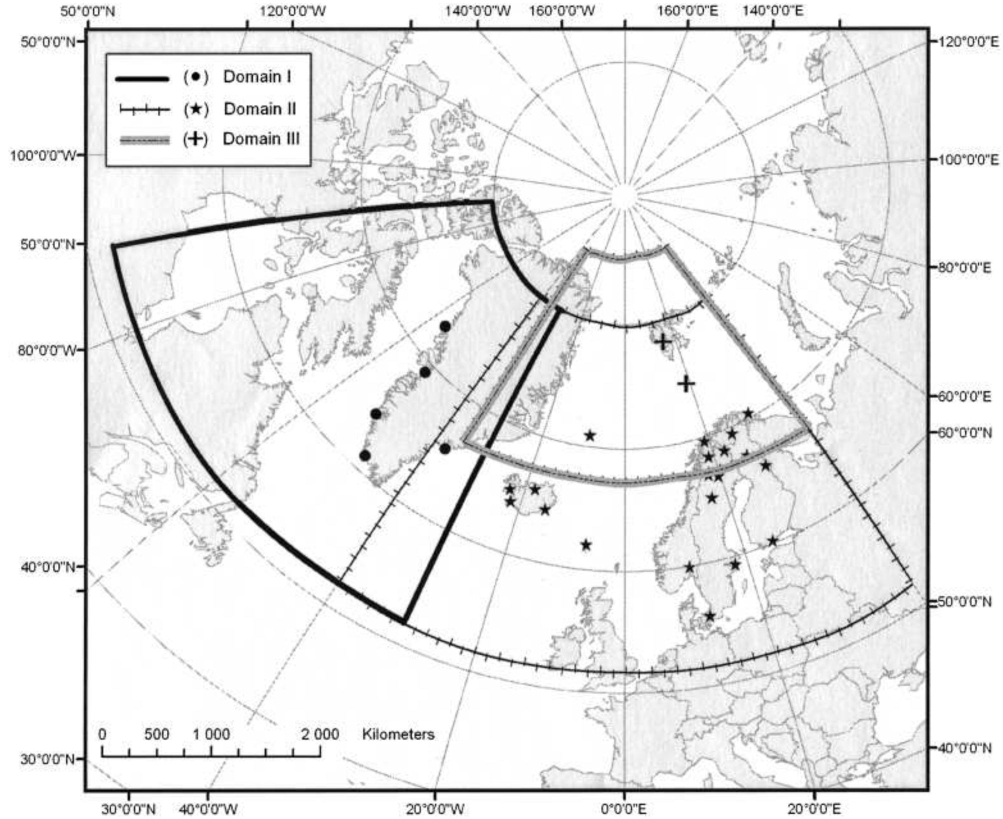

FIGURE 2. Domains used for empirical downscaling.

It is important to keep in mind the fact that one climate scenario represents one plausible description of a future climate, and should not be interpreted as a "forecast". Benestad (2003) analyzed climate model reproductions of past temperature trends for 1880–1999 and concluded that one single model cannot provide a reliable description of these trends due to the presence of strong chaotic variability. On the other hand, different AOGCMs give different accounts of internal variability, and multimodel ensembles are able to span the past historic evolution. Some members of multimodel ensembles may give a less realistic description of the local climatic conditions than others, such as the HadCM3 and the NCAR-CSM models producing too cold climates in the Barents Sea or around Iceland (Benestad et al., 2002a). Hence, the use of multimodel ensembles is not straight forward, since some climate models are less realistic than others (Giorgi and Mearns, 2002).

ESTIMATION OF DAILY TEMPERATURES

Estimates of the length and degree-day-sum of growing, heating and freezing seasons are usually based on daily mean temperatures. For the Nordic Arctic, very few digitized long-term series of daily temperatures are available. On the other hand, the NARP-dataset contains monthly records back to 1890. In the present study, daily mean temperatures were interpolated from the mean monthly temperatures by fitting a spline curve through the 12 monthly mean temperatures (Press et al., 1992). A constraint was added to the spline equation to ensure that the deviation between the original mean monthly temperature, and the mean monthly temperature based on the estimated daily values did not exceed a tolerance criterion of 0.001°C. The amplitude of the spline curve was adjusted by shifting the positions of the monthly mean (default in the middle of the month). This was done iteratively until the tolerance criterion was fulfilled. The technique provides a simple, fast and robust method that can be applied everywhere where only mean monthly temperatures are available. Figure 3 shows examples of smoothed and averaged daily temperatures for Karasjok and Bjørnøya for the period 1961–1990.

Past and Future Variations

AIR TEMPERATURE

The mean annual temperature in the Nordic Arctic has undergone large variations during the 20th century (Førland et al., 2002). Because of substantial differences in standard deviations, the variation in annual mean temperatures is more affected by the variation in winter temperatures than by summer temperatures. For most of the stations in the region there is a positive trend up to the late 1930s, a negative trend from the 1930s to the 1960s, and from the late 1960s the temperature has increased at all stations except for Nuuk. For all stations, the warmest two decades on annual basis were the 1930s and the 1950s. Despite the significant increase in global (Folland et al., 2001) and Fennoscandian (Tuomenvirta et al., 2000) temperatures during the 20th century, the trends in annual mean temperature in the Nordic Arctic are not statistically significant at any station (Førland et al., 2002). This is partly due to the large year-to-year variations, and the consequent low "signal-to-noise" ratio. Even though climate models indicate substantial greenhouse induced warming in the Arctic, the low "signal-to-noise" ratio implies that it is not evident that the first significant "greenhouse signal" will be found in this region.

Table 1 shows that the 1961–1990 normal annual temperature at the Nordic arctic stations varies between –7.3°C at Upernavik to +6.5°C at Torshavn. The temperature during the normal period 1901–1930 was lower than the present normals at all stations, except for Karasjok and Karesuando. For the western Greenland stations Upernavik and Illullisat the normal values were around 0.5°C lower than the present normals. The 1961–1990 normal period was colder than the 1931–1960 normal period at all arctic stations, with the largest

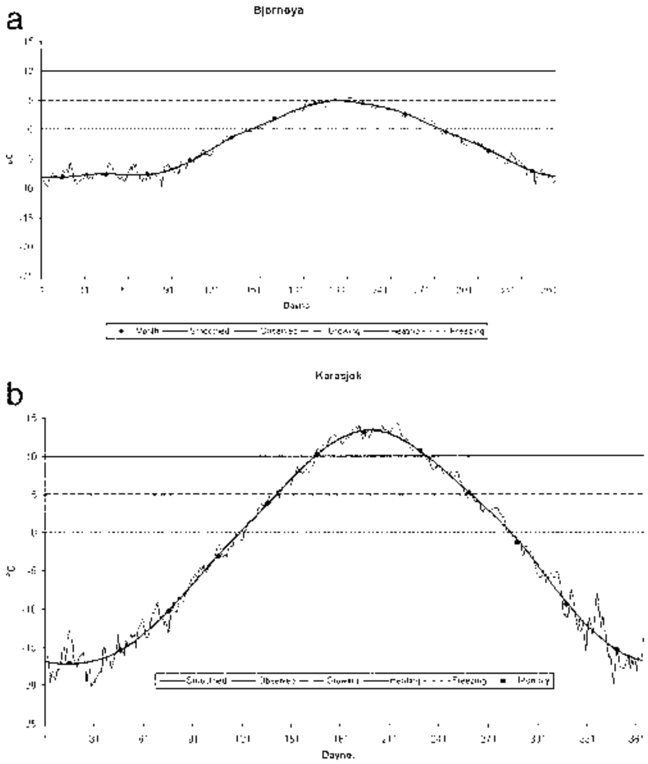

FIGURE 3. Daily mean temperatures (1961–1990) Karasjok and Bjørnøya estimated by fitting a spline curve through monthly mean temperatures ("smoothed") and by averaging daily temperatures ("observed"). Also shown are threshold values used for defining growing, heating, and freezing seasons.

deviation (>1°C) at Tasilaq, Svalbard Airport and Jan Mayen. The recent decades (1976–2000 and 1990–2002) have been warmer than the 1961–1990 normals at all stations, except for stations in western Greenland. At Svalbard Airport and Jan Mayen the mean annual temperature during 1990–2002 was 1.3 to 1.5°C higher than the 1961–1990 normals.

The downscaled scenarios for 2021–2050 suggest further warming over the entire region, with mean annual temperatures 3 to 5°C higher than the present normals in the Svalbard region and large parts of northern Fennoscandia. A more modest temperature increase (<2°C) is projected for the stations in Iceland, Greenland, and the Faeroes. The low temperature increase in this area, and particularly in southeastern Greenland, is consistent with the large-scale temperature pattern from several AOGCMs (e.g., ECHAM4, HadCM2, HadCM3 [Raïsänen, 2001]).

Smoothed daily temperatures for four locations are shown in Figure 4. For single months the downscaled scenarios may give unstable results, as, e.g., for Karasjok in December. For Karasjok the period 1961–1990 has lower winter temperatures than the other time-slices, while the scenario-period 2021–2050 has the highest values for most of the year. Also for Svalbard Airport the scenario indicates a warming during most of the year. For Torshavn a small warming is projected for parts of the year, while the projected temperatures for Tasilaq are similar to what has been experienced in the 20th century.

GROWING SEASON

Plant growth is in general influenced by air temperature, and is especially vulnerable during spring (Menzel, 2002). The air temperature is found to be a limiting factor for growth potential, thus the growing season is rather short at high latitudes. Different species

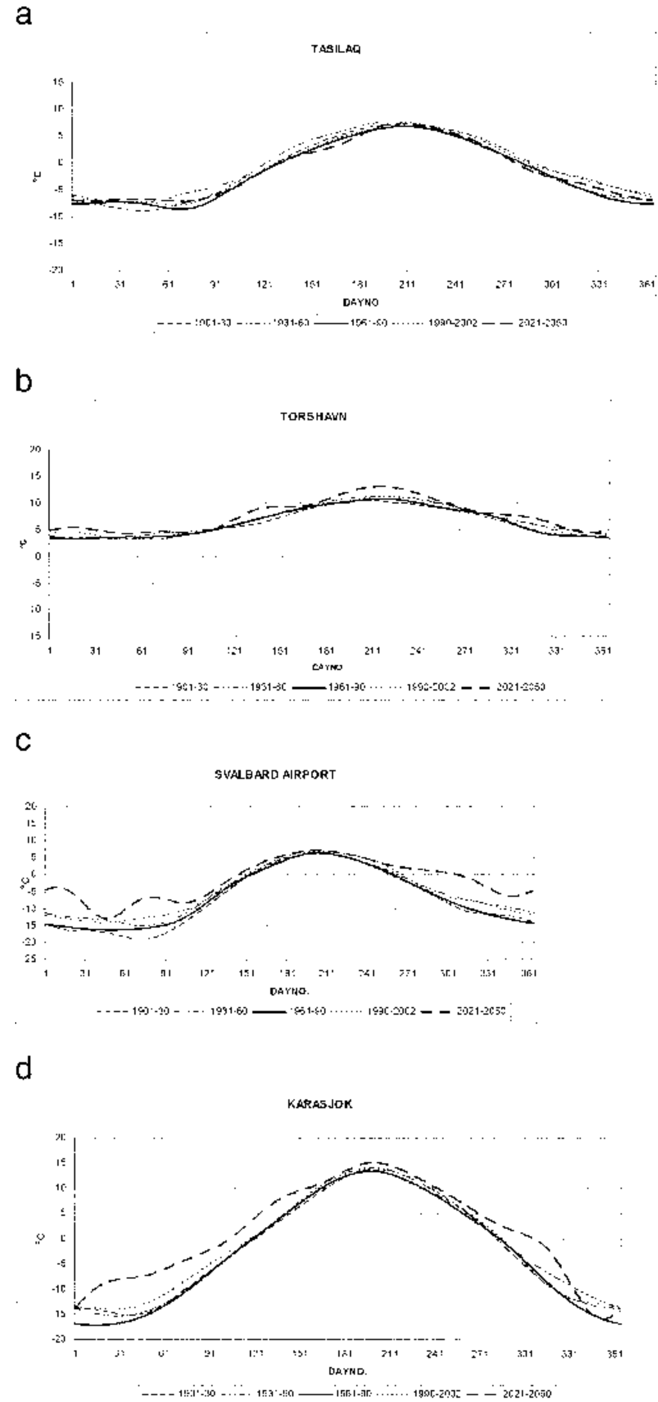

FIGURE 4. Smoothed daily temperatures (°C) for Tasilaq, Torshavn, Svalbard Airport, and Karasjok for the periods 1901–1930, 1931–1960, 1961–1990, 1990–2002, and 2021–2050.

respond differently to air temperature, some are sensitive to lower temperatures while others are more resistant to cold climate. It should however be emphasized that plant growth also depends on additional factors, both climatological (precipitation, snow cover, radiation) as well as soil, moisture, exposure, etc. Since the early 1960s, the length of the growing season has increased through advanced onset during spring in mid latitudes (Menzel and Fabian, 1999, Chmielewski and Rötzer, 2002). Groisman et al. (2003) found that during the past 50 yr the largest absolute and relative changes in duration of the growing season in the Arctic occurred over Alaska and western Canada (increase of 15 and 10 d, or 19 and 8% per 50 yr, respectively), but

TABLE 1.

Annual air temperature (°C) in the Nordic Arctic, 1901–2050. (ΔT is the difference between actual period and the standard normal period 1961–1990)

Station Name	Start	Average	ΔT				
		1961–1990	1901–1930	1931–1960	1976–2000	1991–2002	2021–2050
UPERnavik	1873	−7.32	−0.49	0.84	−0.29	−0.36	1.6
ILLUllissat Airport	1873	−4.43	−0.62	0.30	−0.26	−0.34	1.4
NUUK	1890	−1.41	−0.21	0.65	−0.35	−0.34	1.2
NARSarsuaq	1873	0.96	−0.41	0.49	−0.32	−0.28	1.3
TASIlaq	1895	−1.66	0.12	1.28	0.28	0.69	0.4
STYKkisholmur	1890	3.51	−0.21	0.67	0.11	0.43	1.6
AKUReyri	1882	3.31	−0.31	0.64	0.12	0.37	2.0
TEIGarhorn	1890	3.69	−0.18	0.61	0.19	0.51	1.3
TORShavn	1890	6.46	−0.27	0.34	0.04	0.26	1.3
KARAsjok	1890	−2.41	0.30	0.85	0.33	1.09	3.6
VARDø	1880	1.32	−0.24	0.28	0.19	0.58	2.5
TROMsø	1880	2.53	−0.28	0.36	0.14	0.43	2.3
BJØRnøya	1920	−2.35	—	0.89	0.52	1.09	4.4
SVALbard Airport	1912	−6.67	—	1.26	0.71	1.57	4.8
JAN Mayen	1921	−1.42	—	1.01	0.64	1.27	2.0
STENsele	1890	0.50	−0.29	0.38	0.24	0.93	3.3
KVIKKjokk	1890	−1.25	−0.16	0.40	0.24	0.92	3.4
JOKKmokk	1890	−0.88	−0.23	0.34	0.11	0.70	3.3
ABISko	1913	−0.83	—	0.38	0.31	0.93	2.9
KAREsuando	1890	−2.20	0.02	0.67	0.27	0.98	3.6
KUUSamo	1912	−0.56	—	0.48	0.14	0.62	3.3
SODAnkylä	1908	−1.04	—	0.66	0.16	0.74	3.6
REYKjavik	1871	4.31	−0.18	0.64	−0.04	0.32	1.7
COPEnhagen	1890	8.66	−0.76	−0.17	0.22	0.63	1.6
OSLO-Blindern	1890	5.69	−0.25	0.18	0.30	0.85	2.5
HELSinki	1890	5.24	−0.49	0.11	0.21	0.78	2.9
STOCkholm	1890	6.61	−0.22	0.17	0.27	0.97	2.2

a significant increase of the growing season duration was also found for Russia (from 7 in the east to 10 d in the west, or 8% per 50 yr). On average over the entire land area north of 50°N, an increase of 6% per 50 yr was found in the length of the growing season (Groisman et al., 2003).

Based on a normalized vegetation index derived from satellite images, Høgda et al. (2001) found that the growing season had increased in large parts of Fennoscandia between 1982 and 1998, particularly in Denmark, southern Sweden, and in southernmost parts of Norway. For northern continental parts of Fennoscandia the growing season had been stable, or slightly shortened.

Different definitions of the thermal growing season exist (Brinkmann, 1979; Carter, 1998). The number of days with daily mean air temperatures (2 m) above a given threshold temperature is often used. Carter (1998) argues that the season for active plant development and growth in the Nordic countries should be defined as the period during which the mean daily air temperatures remain above 5°C, and that this threshold should also be adopted as a base temperature for computing the growing degree-days sum (GDD). The GDD provides a measure of the intensity of the growing season.

The thermal growing season is in this study defined as the period of the year when the smoothed daily mean temperature (T_i) is above 5°C, while the growing-degree-days (GDD) are the accumulated degree sum above the threshold temperature $\hat{T} = 5°\mathrm{C}$:

$$GDD = \sum_{i=1}^{365} (T_i - \hat{T}), \quad T_i \geq \hat{T} \tag{1}$$

where T_i is the daily mean temperature for day number i.

By the above definitions, the thermal growing season in the Nordic arctic (Table 2) in the present normal period starts between 17 April at Torshavn and 2 August at Jan Mayen, and ends between 16 August (Upernavik and Svalbard Airport) and 9 November (Torshavn). The length of the growing season varies between zero days at Bjørnøya (cf. Fig. 3) to 207 d at Torshavn. In Copenhagen on the other hand, the thermal growing season for the normal period lasts for 322 d; from 4 April to 18 November.

During 1901–1930 the growing season was shorter than during 1961–1990 at most stations, while it during 1931–1960 was substantially longer at the Icelandic stations and at the Greenlandic stations Nuuk and Tasilaq. During the recent decades (1976–2000 and 1990–2002), the results indicate a substantial increase in the thermal growing season at Jan Mayen and Bjørnøya, but the low GDD-values imply that the thermal conditions for plant growth are still marginal.

The downscaled scenarios for 2021–2050 project a further increase in the length of the growing season at all stations, except for eastern Greenland (Tasilaq). For most of the locations in Table 2, the length of the growing season is projected to increase by more than 3 wk.

The degree-day-sum (GDD) during the growing season varied from zero at Bjørnøya, to nearly 800 at Jokkmokk. At most stations the GDD was lower during 1901–1930 and higher during 1931–1960 than for the present normal period. The GDD values for the latest decades are generally higher than for the normal period 1961–1990. However, at the Faeroes and some stations at Iceland and Greenland, the 1931–1960 values were higher than during the most recent decades. The projected values for 2021–2050 indicate a substantial increase in GDD-values at all stations, with the largest absolute increase at the Icelandic stations. Carter (1998) studied the projected change in growing season up to 2050 at nine locations in Fennoscandia, including Stykkisholmur, Helsinki, and Stockholm, and found estimates quite similar to the values in the present study.

TABLE 2.

Length of growing season and sum of growing degree-days (GDD) 1901–2050 (The Δ-values are differences between actual period and standard normal period 1961–1990)

	1961–1990				ΔLength					ΔGDD				
Station name	Start	End	Length (days)	GDD	1901–1930	1931–1960	1976–2000	1990–2002	2021–2050	1901–1930	1931–1960	1976–2000	1990–2002	2021–2050
Upernavik	12 Jul	16 Aug	36	12	−17	7	0	2	38	−11	14	5	4	167
Ilullissat Airport	19 Jun	31 Aug	74	127	−6	0	4	7	27	−13	0	19	29	214
Nuuk	26 Jun	01 Sep	68	83	4	21	−7	2	32	7	61	−26	−10	138
Narsarsuaq	14 May	19 Sep	129	445	−8	−1	0	6	19	−40	35	16	48	172
Tasilaq	24 Jun	29 Aug	67	76	9	27	0	10	−2	23	76	−2	15	23
Stykkisholmur	17 May	04 Oct	141	452	−3	13	1	10	19	4	102	24	78	229
Akureyri	12 May	28 Sep	140	522	−1	12	2	10	24	−8	82	34	87	348
Teigarhorn	22 May	12 Okt	144	361	−10	10	1	11	33	−34	81	35	88	185
Torshavn	17 Apr	09 Nov	207	729	0	34	6	14	25	−85	63	4	48	295
Karasjok	22 May	17 Sep	119	620	−1	1	2	3	28	−21	42	15	63	229
Vardø	05 Jun	28 Sep	116	344	−7	0	1	3	32	−32	15	0	46	221
Tromsø	18 May	28 Sep	134	577	−13	−1	0	−5	32	−84	0	10	−48	218
Bjørnøya	—	—	0	0	—	0	30	46	68	—	0	5	18	87
Svalbard Airport	05 Jul	16 Aug	43	34	—	0	4	13	23	—	1	15	30	53
Jan Mayen	02 Aug	20 Aug	19	3	—	29	18	35	27	—	17	10	33	22
Stensele	11 May	27 Sep	140	780	−7	0	1	2	19	−38	38	4	52	213
Kvikkjokk	18 May	16 Sep	122	621	−3	1	4	5	27	−42	40	16	79	189
Jokkmokk	14 May	23 Sep	133	798	−6	−2	1	−1	21	−45	22	−9	29	165
Abisko	26 May	17 Sep	115	457	—	−1	0	4	27	—	59	19	77	139
Karesuando	23 May	16 Sep	117	594	−5	−1	1	2	25	−15	49	5	67	148
Kuusamo	16 May	21 Sep	129	749	—	−1	0	−3	20	—	0	−15	15	191
Sodankylä	16 May	20 Sep	128	733	—	0	0	−3	18	—	46	−2	36	187
Reykjavik	04 May	11 Oct	161	570	−8	6	−5	2	17	−6	121	8	78	293
Copenhagen	04 Apr	18 Nov	229	1780	−16	0	2	6	14	−193	−33	32	95	354
Oslo-Blindern	19 Apr	23 Oct	188	1388	−5	1	1	4	29	−64	9	16	76	285
Helsinki	25 Apr	24 Oct	183	1380	−9	−3	1	2	22	−119	35	−6	43	310
Stockholm	19 Apr	31 Oct	196	1513	−6	0	3	8	29	−98	42	17	112	331

HEATING SEASON

The heating season is the period of the year when buildings need to be heated. The sums of heating degree-days closely correlate to energy consumption for heating, and have numerous other practical implications (Quayle and Diaz, 1980; Guttman and Lehman, 1992). The amount of energy for heating of buildings is also depending on other climatological factors (wind speed, radiation), as well as factors related to demographic changes, living standards, and building instructions (e.g., volume of heated buildings, preferred indoor temperatures, thermal insulation, etc.) (Venäläinen et al., 2004). The heating season is in the present study defined as the period of the year when the smoothed daily mean temperature is below a threshold $\hat{T}$, while heating degree-days (HDD) are the sum of the difference between a base temperature T_{base} and the daily mean temperature T_i (Taylor, 1981):

$$HDD = \sum_{i=1}^{365} (T_i - T_{base}), \quad T_i < \hat{T} \quad \text{HDD} = 0, \quad T_i \geq \hat{T} \qquad (2)$$

In the USA, the base temperature T_{base} is 65F (Groisman et al., 2003) while in Norway $T_{base} = 17°\text{C}$ and $\hat{T} = 10°\text{C}$ (Skaugen and Tveito, 2002). The latter values are used in the present analysis.

Groisman et al (2003) found a statistically significant decrease in annual heating degree-days during the past 50 yr of 6% over the entire Arctic, with a maximum absolute and relative reduction in heating degree-days over western Canada and Alaska (9 and 8% per 50 yr, respectively). For Eurasia, significant reductions were found for Russia (6–7% per 50 yr), indicating that there have been reduced heating costs in relative terms.

Table 3 indicates that the heating season lasts the whole year through at most of Greenland and in the Svalbard region (cf. Fig. 3). This is true for all normal periods, for the latest decades, and for most of the stations in this region it is also true for the scenario period 2021–2050. In Copenhagen on the other hand, the heating season in the present normal period lasts for 204 d, and is projected to decrease by 26 d up to 2021–2050.

Generally the length of the heating season and sum of heating-degree-days (HDD) were higher for 1901–30 and lower for 1931–60 than for the present normal period. During the recent decades the length and HDD–sum have been lower than for the normal period 1961–90. The highest HDD-sum (>8500 degrees) for the normal period 1961–90 are found for Upernavik and Svalbard Airport, while it in e.g. Oslo, Helsinki and Stockholm is ca. 3500–4000, and in Copenhagen ca 2700 degrees. The projected values for the scenario period 2021–2050 indicate a reduction of heating-degrees of 10 to 20% at most of the stations in Iceland and Fennoscandia.

FREEZING SEASON

The length of the frost-free period is among the most carefully monitored variables in the Arctic (Groisman et al., 2003). To characterize the severity of the cold season, the sum of negative temperatures is often used. The thermal freezing season is in this study defined as the period of the year when the smoothed daily mean temperature (T_i) is below 0°C, while the freezing-degree-days (FDD) are the accumulated degree sum below a threshold temperature $\hat{T} = 0°\text{C}$:

$$FDD = \sum_{i=1}^{365} (T_i - \hat{T}), \quad T_i \leq \hat{T} \qquad (3)$$

where T_i is the daily mean temperature for day number i.

TABLE 3.

Length of heating season and sum of heating degree-days (HDD) 1901–2050 (The Δ-values are differences between actual period and standard normal period 1961–90)

	1961–1990				ΔLength					ΔHDD				
Station name	Start	End	Length (days)	HDD	1901–1930	1931–1960	1976–2000	1990–2002	2021–2050	1901–1930	1931–1960	1976–2000	1990–2002	2021–2050
Upernavik	—	—	365	8850	0	0	0	0	0	175	−309	101	127	−591
Ilullissat Airp.	—	—	365	7798	0	0	0	0	−23	223	−110	93	120	−658
Nuuk	—	—	365	6705	0	0	0	0	0	74	−238	126	120	−428
Narsarsuaq	7 Aug	07 Jul	335	5640	10	−13	−5	−10	−36	209	−260	86	44	−662
Tasilaq	—	—	365	6799	0	0	0	0	0	−50	−470	−102	−254	−126
Stykkisholmur	11 Aug	17 Jul	341	4750	9	−16	−10	−18	−35	135	−346	−97	−269	−720
Akureyri	17 Aug	26 Jun	314	4654	11	−6	−3	−5	−57	186	−263	−49	−145	−940
Teigarhorn	—	—	365	4849	0	0	0	0	0	69	−224	−63	−188	−469
Torshavn	28 Aug	26 Jun	312	3492	16	−18	−3	−10	−29	195	−217	−23	−140	−514
Karasjok	20 Aug	15 Jun	300	6751	5	−2	−1	−8	−18	−85	−307	−114	−403	−1351
Vardø	—	—	365	5707	0	0	0	−19	−53	89	−100	−65	−342	−1236
Tromsø	23 Aug	23 Jun	305	4933	11	−2	−1	3	−26	148	−120	−51	−102	−978
Bjørnøya	—	—	365	7050	—	0	0	0	0	—	−325	−190	−399	−1594
Svalbard Ap.	—	—	365	8618	—	0	0	0	0	—	−460	−260	−573	−1769
Jan Mayen	—	—	365	6711	—	0	0	0	0	—	−369	−230	−462	−729
Stensele	26 Aug	04 Jun	283	5631	7	0	0	−5	−22	160	−92	−73	−325	−1229
Kvikkjokk	21 Aug	12 Jun	296	6289	11	1	2	−6	−13	127	−98	−61	−328	−1246
Jokkmokk	27 Aug	05 Jun	283	6181	7	1	1	−2	−22	117	−92	−41	−244	−1312
Abisko	14 Aug	29 Jun	320	6212	—	−7	−3	−10	−11	—	−141	−123	−385	−1077
Karesuando	19 Aug	13 Jun	299	6647	5	1	0	−4	−29	39	−203	−92	−351	−1485
Kuusamo	25 Aug	07 Jun	287	6065	—	−3	2	−1	−18	—	−158	−48	−214	−1256
Sodankylä	23 Aug	07 Jun	289	6245	—	−2	1	−4	−14	—	−216	−51	−264	−1333
Reykjavik	18 Aug	02 Jul	319	4325	−2	−22	−5	−14	−34	55	−345	−2	−185	−690
Copenhagen	14 Oct	05 May	204	2708	12	4	−3	−5	−26	233	95	−84	−198	−502
Oslo-Blindern	19 Sep	13 May	237	3794	3	−4	−3	−6	−18	76	−50	−117	−290	−808
Helsinki	21 Sep	17 May	239	3972	9	0	1	0	−15	187	20	−61	−228	−920
Stockholm	28 Sep	13 May	228	3484	7	0	0	−2	−18	64	−16	−89	−273	−694

Time series of FDD indicate that the "severity" of the cold season has substantially decreased everywhere in the Arctic, except eastern Canada (Groisman et al., 2003). In terms of absolute values of FDD, the mean circumpolar decrease is 13% per 50 yr (Groisman et al., 2003).

The freezing season in the Nordic Arctic (Table 4) starts between 16 September (Svalbard Airport) and 10 December (Teigarhorn), and ends between 28 January (Teigarhorn) and 4 June (Upernavik and Svalbard Airport). In Torshavn there is no "freezing period" as the smoothed mean daily temperature is above zero for the whole year round (cf. Fig. 4). The length of the freezing period varies from zero days at Torshavn to 260 d at Svalbard Airport and Upernavik. For all Icelandic stations, the freezing period was shorter and the degree-day sums lower during 1931–1960 than for the latest decades.

The downscaled scenarios indicate a reduction of the freezing period at all stations except the eastern Greenlandic station Tasilaq. For several stations the scenarios imply a freezing season more than 50 days shorter than during 1961–1990. At Reykjavik and Stykkisholmur, there will be no "freezing period" during 2021–2050 according to the definition used in this study.

Discussion

As outlined above, different methods exist for estimating duration and degree-day-sums for growing, heating, and freezing seasons. Both daily and monthly temperatures are used as basis for the calculations (Quayle and Diaz, 1980; Carter, 1998). To avoid the influence of the day-to-day variability of daily values, the start and end of the growing season are often defined by the dates of steady (at least 5-d long) transition of mean daily temperatures across a threshold temperature (Venäläinen and Nordlund, 1988; Groisman et al., 2003). In the present study the estimates of growing, heating and freezing seasons were based on smoothed daily mean temperatures deduced from average monthly temperatures (cf. Fig. 3). A similar technique was applied by Carter (1998) for computing the growing season in the Nordic countries.

The different techniques for calculating start, end, duration, and degree-day-sums may give different estimates for the climatic indices. This particularly concerns series with weak average annual temperature amplitude, and where the temperatures are close to the threshold values for an extended period of the year. A comparison of growing season estimates based on observed daily temperatures ("daily method") and smoothed daily values deduced from monthly averages ("monthly method") was performed by Carter (1998) for Helsinki over the 1961–1990 period, and on average he found that the monthly method produced a slightly shorter (3 d) season than the daily method.

Table 5a shows estimates of growing and heating indices based on the daily and monthly methods for a few stations with digitized daily temperature series back to 1961. For the "daily method", the Finnish criteria (Venäläinen and Nordlund, 1988) were used for defining the start, end and length of the seasons. This implies that for the start of the growing season, the average daily temperature has to remain above +5°C for at least 5 d, and during the subsequent 5-d period the accumulated temperature above 0°C has to total at least 20 degrees. The growing season is defined to end in the first period in the autumn when the10-d running mean is below 5°C. For the "daily" method, the growing-degree-day sum is calculated within the defined growing season for each year. For comparison, also the annual total sum of degree-days and total number of days exceeding the threshold value are calculated ("Total method"). Similar considerations were used for the heating season.

TABLE 4.

Length of freezing season and sum of freezing degree-days (FDD) 1901–2050 (The Δ-values are differences between actual period and standard normal period 1961–1990)

	1961–1990				ΔLength					ΔFDD				
Station name	Start	End	Length (days)	FDD	1901–1930	1931–1960	1976–2000	1990–2002	2021–2050	1901–1930	1931–1960	1976–2000	1990–2002	2021–2050
Upernavik	20 Sep	04 Jun	258	3020	−6	−13	1	−1	−18	159	−244	118	164	−275
Ilullissat Airport	28 Sep	14 May	229	2266	0	−1	4	3	−9	203	−97	108	155	−213
Nuuk	9 Oct	11 May	215	1146	−3	−8	3	−1	−15	106	−101	109	122	−190
Narsarsuaq	17 Oct	17 Apr	183	862	−3	−8	−1	−9	−18	91	−133	135	190	−178
Tasilaq	9 Oct	11 May	215	1226	1	−14	1	−5	5	3	−295	−99	−208	−124
Stykkisholmur	28 Nov	01 Apr	125	109	6	−47	−10	−45	−125	26	−61	−3	−37	−109
Akureyri	11 Nov	01 Apr	142	210	14	−33	−1	0	−96	63	−92	−20	−54	−141
Teigarhorn	10 Dec	28 Jan	50	12	−12	−36	−10	−23	−28	−4	−11	−2	−7	−4
Torshavn	—	—	0	0	0	0	0	0	0	0	0	0	0	0
Karasjok	10 Oct	30 Apr	203	2182	4	1	−2	−2	−38	−146	−284	−93	−311	−948
Vardø	02 Nov	26 Apr	176	600	7	−9	−2	−4	−59	18	−73	−52	−140	−441
Tromsø	04 Nov	14 Apr	162	485	5	−9	−1	−3	−78	−46	−102	−44	−161	−417
Bjørnøya	10 Oct	29 May	232	1259	—	−12	−4	−7	−150	—	−276	−149	−297	−1200
Svalbard Airp.	16 Sep	04 Jun	262	2813	—	−4	−5	−10	−57	—	−433	−211	−461	−1535
Jan Mayen	16 Oct	24 May	221	951	—	−10	−5	−16	−45	—	−275	−186	−342	−563
Stensele	22 Oct	17 Apr	178	1389	7	1	1	−1	−33	40	−95	−71	−273	−841
Kvikkjokk	16 Oct	24 Apr	191	1805	8	6	1	1	−19	−17	−127	−69	−252	−908
Jokkmokk	18 Oct	22 Apr	187	1885	8	5	1	1	−16	−3	−126	−57	−238	−958
Abisko	17 Oct	1 May	197	1453	—	3	−2	−2	−24	—	−93	−87	−265	−772
Karesuando	9 Oct	3 May	207	2068	7	1	−1	−2	−32	−58	−225	−85	−299	−1017
Kuusamo	16 Oct	26 Apr	193	1687	—	0	0	0	−34	—	−141	−64	−220	−903
Sodankylä	14 Oct	26 Apr	195	1839	—	0	0	0	−47	—	−199	−62	−241	−999
Reykjavik	7 Dec	02 Feb	58	23	37	−10	−2	−6	−58	19	−8	7	3	−23
Copenhagen	—	—	0	0	22	37	0	0	0	4	10	0	0	0
Oslo-Blindern	18 Nov	18 Mar	121	371	7	−3	−8	−16	−100	−3	−20	−71	−180	−369
Helsinki	23 Nov	30 Mar	128	482	9	−3	−4	−7	−90	30	7	−59	−204	−459
Stockholm	3 Dec	16 Mar	104	215	1	−9	−8	−20	−103	−42	−5	−55	−170	−215

Table 5a demonstrates that for the growing seasons for Karasjok and Oslo-Blindern there is good correspondence between the daily, monthly, and total methods both concerning length and sum of degree-days. Also the main features of the differences between the time-slices are reproduced by all three methods. For Bjørnøya and Jan Mayen, where the temperatures during summer are close to the threshold value 5°C (cf. Fig. 3), there are differences in the estimates of L, ΔL, and GDD. However the ΔGDD values estimated by the three methods give quite similar results. The low GDD-values at these two locations imply that the thermal conditions for plant growth are marginal.

For the heating season (Table 5b), the three methods give largely consistent estimates of L and HDD for the period 1961–1990 as well as for the differences between the time slices. For Oslo-Blindern, however, the reduction in HDD for the period 1976–2000 is lower for the monthly method than for the daily and total methods, while for the 1990–2002 period the three methods give consistent values for ΔHDD.

Carter (1998) argued that because it employs smoothed temperatures, the monthly method provides a more consistent and reliable indicator of the general march of seasonal temperature than the daily method, enabling it to be applied in detecting general trends over the long term. The results in Table 5 support these conclusions, but also demonstrate that one should be careful in drawing conclusions for series with low degree-day sums. For studies of long-term variations, the present method of comparing estimates for different time-periods probably gives robust and consistent indices for thermal induced long-term variations in growing, heating and freezing conditions. For direct use in specific phenological, frost condition or energy consumption studies, more empirically based methodologies should be derived. It should also be emphasized that growing, heating and freezing conditions are determined by additional factors than those described by thermal indices.

Summary and Conclusions

The harsh climate places severe constraints on the living conditions in the Arctic. Important changes have occurred in the Nordic Arctic climate during the 20th century, and some of these changes imply considerable impacts on living conditions and ecosystems.

Global climate models generally project larger warming up to 2050 in the Arctic than in any other region on the globe. Few global climate models presently give an adequate sea-ice representation necessary for the projection of climate change in the Arctic. Climate change scenarios for the Nordic Arctic are consequently encumbered with large uncertainties, but to be able to compare future to observed climate changes tentative scenarios were estimated for selected localities in the Nordic Arctic.

Within climatology, 30-yr standard normal periods are commonly used as reference values for climatological conditions. In addition to air temperature, indices illustrating vegetation conditions (growing season), energy consumption (heating season) and frost conditions (freezing season) are analysed for the standard normal periods 1901–30, 1931–60, 1961–90 and the scenario period 2021–2050. Also, values for recent decades (1976–2000 and 1990–2002) are included. The estimates of climatic indices were based on smoothed daily temperatures derived from average monthly values for the specific time periods. The main conclusions are:

TABLE 5A.

Length (L (days)) and growing-degree-days (GDD) estimated by "Monthly" (M), "Daily" (D), and "Total" (T) method (see text). ΔL and ΔGDD are differences between the two time slices (1976–2000 and 1990–2002) and the standard normal period 1961–1990

	1961–1990						ΔL						ΔGDD					
	L			GDD			1976–2000			1990–2002			1976–2000			1990–2002		
Station	M	D	T	M	D	T	M	D	T	M	D	T	M	D	T	M	D	T
Karasjok	119	112	117	620	654	678	2	1	1	3	3	3	15	13	12	63	58	52
Bjørnøya	0	15	33	0	26	53	30	1	4	46	6	11	5	3	8	18	13	21
Jan Mayen	19	18	35	3	22	38	18	11	11	35	23	17	10	11	18	33	32	31
Oslo-Blindern	188	185	193	1388	1418	1440	1	0	3	4	2	8	16	18	22	76	84	90

TABLE 5B.

Length (L (days)) and heating-degree-days (HDD) estimated by "Monthly" (M), "Daily" (D), and "Total" (T) method. ΔL and ΔHDD are differences between the two time slices (1976–2000 and 1990–2002) and the standard normal period 1961–1990

	1961–1990						ΔL						ΔHDD					
	L			HDD			1976–2000			1990–2002			1976–2000			1990–2002		
Station	M	D	T	M	D	T	M	D	T	M	D	T	M	D	T	M	D	T
Karasjok	300	289	305	6751	6761	7086	−1	4	−2	−8	4	−6	−114	−112	−120	−403	−376	−391
Bjørnøya	365	365	365	7050	7055	7055	0	0	0	0	0	−1	−190	−190	−190	−399	−399	−399
Jan Mayen	365	365	365	6711	6710	6710	0	0	0	0	0	0	−230	−228	−228	−462	−462	−462
Oslo-Blindern	237	228	234	3794	3807	4175	−3	−4	−6	−6	−4	−6	−117	−322	−290	−290	−322	−290

- The normal period 1901–1930 was colder than the present normal period (1961–1990) at all stations except two continental stations in northern Fennoscandia. The length of the growing season was shorter, and the heating and freezing seasons were longer at a majority of the locations studied. The high heating-degree-day sums indicate a larger need for energy to heat buildings during 1901–1930 than for present conditions.
- During 1931–1960 the mean annual temperature was higher than the present normal values at all stations in the Nordic Arctic. The growing season was 2 to 3 wk longer at some locations, and the length of the heating and freezing seasons were lower than during 1961–90.
- The recent decades (1976–2000 and 1990–2002) have been warmer than the 1961–1990 normals in most of the region. An important exception is western Greenland, where all stations have experienced lower temperatures than during 1961–1990 and where the 1931–1960 values are substantially higher than the present level. In the rest of the region, the thermal growing conditions have improved, and the need for heating is reduced.
- The tentative scenarios for 2021–2050 indicate substantially higher temperatures than observed in the 20th century. The growing conditions will continue to improve; in large parts of the region the thermal growing period will last 3 to 4 wk longer than at present. Similarly the energy consumption for heating buildings will be substantially reduced. One exception is the eastern Greenlandic station Tasilaq, where the projected temperature for 2021–2050 is still lower than experienced during 1931–1960.

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