Changes in Winter Warming Events in the Nordic Arctic Region

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ABSTRACT

In recent years extreme winter warming events have been reported in arctic areas. These events are characterized as extraordinarily warm weather episodes, occasionally combined with intense rainfall, causing ecological disturbance and challenges for arctic societies and infrastructure. Ground-ice formation due to winter rain or melting prevents ungulates from grazing, leads to vegetation browning, and impacts soil temperatures. The authors analyze changes in frequency and intensity of winter warming events in the Nordic arctic region—northern Norway, Sweden, and Finland, including the arctic islands Svalbard and Jan Mayen. This study identifies events in the longest available records of daily temperature and precipitation, as well as in future climate scenarios, and performs analyses of long-term trends for climate indices aimed to capture these individual events. Results show high frequencies of warm weather events during the 1920s–30s and the past 15 years (2000–14), causing weak positive trends over the past 90 years (1924–2014). In contrast, strong positive trends in occurrence and intensity for all climate indices are found for the past 50 years with, for example, increased rates for number of melt days of up to 9.2 days decade^{-1} for the arctic islands and 3–7 days decade^{-1} for the arctic mainland. Regional projections for the twenty-first century indicate a significant enhancement of the frequency and intensity of winter warming events. For northern Scandinavia, the simulations indicate a doubling in the number of warming events, compared to 1985–2014, while the projected frequencies for the arctic islands are up to 3 times higher.

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1. Introduction

Changes in extreme weather events will lead to increased stress on human and natural systems and a propensity for serious adverse effects in many places around the world (Maskrey et al. 2009, 2011). Recent worldwide assessments of changes in climate extremes

show great variability since 1950 across different regions (Seneviratne et al. 2012).

The substantial arctic warming observed to have occurred since the midtwentieth century (Bindoff et al. 2013), which has intensified in the past decade (Walsh et al. 2011), is much greater than for global or Northern Hemisphere averages and is strongest for autumn and winter seasons (Dicks et al. 2012; Cohen et al. 2014). The reduction of sea ice and snow cover has especially contributed to the high-latitude warming (Walsh 2014). Of great concern is that this arctic amplification is projected to result in more winter warming events and, in particular, more frequent and intensified rain-on-snow (ROS) events (e.g., Rennert et al. 2009; Putkonen et al. 2009). Such events can lead to the formation of thick internal ice layers in the snowpack or ground ice, impacting the ground vegetation and restricting access to winter fodder for overwintering herbivores (e.g., voles, reindeer, or musk ox; e.g., Forchhammer and Boertmann 1993; Putkonen and Roe 2003; Kausrud et al. 2008; Bokhorst et al. 2009; Hansen et al. 2013; Bjerke et al. 2014). For arctic societies, such events may also have major impacts on, for example, transportation and infrastructure (e.g., Hansen et al. 2014; Stewart et al. 2015).

Although a number of studies have examined the impact of these extreme events on environment and society, analyses of trends in such events in the arctic region appear challenging. The meteorological station network in the Arctic is sparse, and there are relatively few long-term records available of daily temperature and precipitation measurements that can be used to detect extreme events at higher latitudes (e.g., Moberg et al. 2006; Rennert et al. 2009; Bokhorst et al. 2016). In addition, precipitation measurements in the Arctic are strongly influenced by wind-induced bias, which may cause fictitious trends (Førland and Hanssen-Bauer 2000; Przybylak 2003).

A number of trend studies on warm winter events have been performed on historical data, both observations and reanalysis data. Cohen et al. (2015) found weak trends in ROS events over the Northern Hemisphere using reanalysis data from 1979 to 2014. Groisman et al. (2003) assessed 50-yr trends in small ROS events in the arctic winter and spring to find an increasing trend in western Russia and a decrease in western Canada. In Greenland, Pedersen et al. (2015) reported large year-to-year variability in the number of ROS events from 1979 to 2013, with the highest frequency in southwest Greenland where the events are linked to foehn winds. Shabbar and Bonsal (2003) found significant increases in both the frequency and duration of warm spells over Canada during the second half of the twentieth century. Hanesiak and Wang (2005) inferred

an increase in freezing rain occurrence in parts of the Canadian Arctic. Tuomenvirta et al. (2000) analyzed a comprehensive dataset of monthly mean daily maximum temperatures in the Nordic arctic region (NAR) and found mainly positive trends during the period 1950–95. On Svalbard, and more recently, Wei et al. (2016) found a positive trend in warm extremes between 1975 and 2014 and Tomczyk and Bednorz (2014) reported a considerable increase in the number of warm days in the last decade (2001–10). Using a remote sensing dataset for the winters 2000/01–2008/09, Bartsch et al. (2010) estimate an average of one to three strong wintertime melt events per season (November–February) in northern Scandinavia and most areas on Svalbard.

However, there are few recent studies that have analyzed both long-term historical trends and future projected trends in winter warming and ROS events, particularly in the Arctic. Sillmann et al. (2013) used projections from global climate models (GCMs), but no regional climate model (RCM) data, to study future changes in extremes, and only part of the Arctic was included (Greenland). Given that the Arctic is projected to experience the greatest temperature change during winter months (Dicks et al. 2012; Koenigk et al. 2012; Manabe and Stouffer 1980; Overland et al. 2014), it is likely that the Arctic will experience more winter warming events in the twenty-first century. A better understanding of extreme winter events in the Arctic is then required, as stated by Dicks et al. (2012) and Bokhorst et al. (2016).

In this paper, we identify and analyze changes in intensity and frequency of winter warming events over the past 50–100 years, the present 15 years (2000–14), and the future (twenty-first century) in the NAR. The NAR is defined geographically as those parts of Norway, Sweden, and Finland that are north of the Arctic Circle (66.5°N), as well as the arctic islands of Svalbard and Jan Mayen (Fig. 1). A number of long-term continuous climatic monitoring series are available in the NAR (e.g., Kohler et al. 2006; Nordli et al. 2014), comprising a unique record for studies related to Arctic climate change and variability during winter. The region is a primary pathway for the transport of atmospheric energy into the Arctic (Serreze et al. 2007) and is situated in a projected hot spot area with increased heat fluxes from the Atlantic water masses (e.g., Årthun et al. 2012), the retreat of winter sea ice (Onarheim et al. 2014), and a decrease in snow cover (e.g., Irannezhad et al. 2015). These processes are connected with a relatively large transition to more frequent temperatures above 0°C (e.g., Førland et al. 2011) and an increase in precipitation (e.g., Fleig et al. 2015) and heavy rainfalls during winter (e.g., Hansen et al. 2014). This has
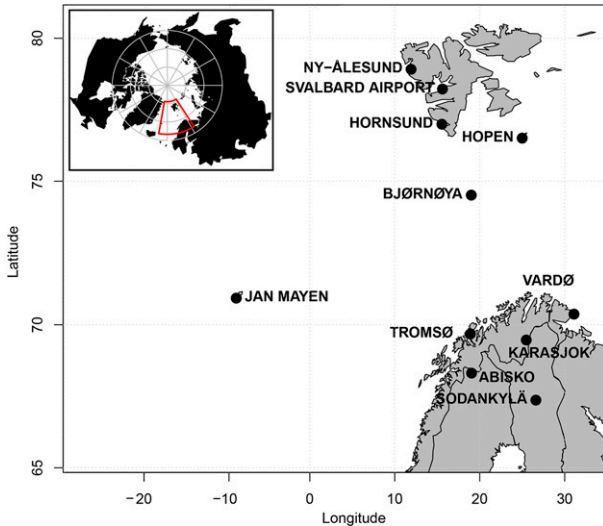
FIG. 1. Map of the Nordic arctic region and its location in the Arctic (red line in the inset). Weather stations used in the analysis are shown as black dots.

triggered extensive international environmental research, where many studies document the ecological effects of winter warming events and ROS in the NAR (e.g., Kohler and Aanes 2004; Hansen et al. 2013, 2014; Stien et al. 2010, 2012; Hansen and Aanes 2012; Cooper 2014; Bjerke et al. 2014, 2015; Vikhamar-Schuler et al. 2013; Kivinen and Rasmus 2015; Rasmus et al. 2016), and provides the motivation in this study for analyzing both the past and future projected trends of such extreme events.

To be relevant for the interdisciplinary environmental research ongoing in the NAR, and as an arctic modification to the climate indices defined by the Expert Team on Climate Change Detection and Indices (ETCCDI; Karl and Easterling 1999; Klein-Tank et al. 2009; Sillmann et al. 2013), we define warming events as extraordinarily warm weather episodes occurring during the winter season, occasionally combined with intense rainfall. We define five different climate indices, described in detail in section 2, to detect the occurrence of winter warming events. The winter season is defined here as comprising the months October–April. The total duration of this winter season corresponds closely to the period during which mean monthly temperatures lie below 0°C, the climatological definition of winter (Birkeland 1936, p. 25). Using this definition, the winter season is slightly longer at the arctic islands (Fig. 2b) than at the arctic mainland stations (Fig. 2a), but we choose to use a consistent season duration to facilitate climate comparisons across all stations. Plant species under the snow cover have been observed to respond differently to extraordinary warming events, depending on the timing of
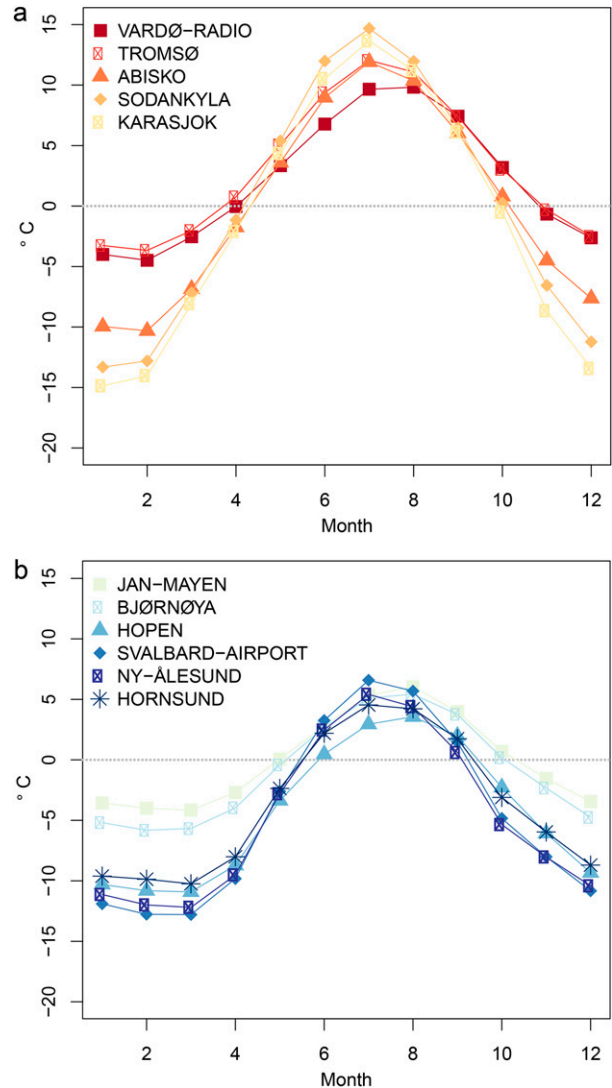

FIG. 2. Mean monthly temperature for the recent period 1985–2014 at (a) the arctic mainland stations and (b) the arctic stations. Monthly values below 0°C (gray line) are climatologically defined as winter.

their occurrence during the winter season (Bokhorst et al. 2010, 2011; Preece and Phoenix 2014). Therefore, we also consider three subperiods: 1) early winter (October–November), 2) midwinter (December–February), and 3) late winter (March–April). Throughout this paper, the year denotes the year of the late winter season (e.g., the 2014 winter refers to October 2013–April 2014).

2. Data and study area

a. Weather station data

We selected data from a geographical distribution of weather stations in the NAR that can capture the

TABLE 1. Metadata for the daily observation series at the weather stations.

Station	Region	Temperature	Precipitation
Tromsø	Troms, Norway	1867–present	1867–present
Vardø	Finmark, Norway	1867–present	1894–present
Karasjok	Finnmark, Norway	1877–present	1877–present
Abisko	Norrbottens Län, Sweden	1913–present	1913–present
Sodankylä	Lapland, Finland	1908–present	1908–present
Svalbard Airport	Svalbard	1957–present	1957–present
Ny-Ålesund	Svalbard	1974–present	1974–present
Hornsund	Svalbard	1982–present	1982–present
Hopen	Svalbard	1945–present	1945–present
Bjørnøya	Svalbard	1918–present	1920–present
Jan Mayen	Jan Mayen	1922–present	1922–present

inherent variability from both maritime to continental climates and feature long and high-quality observational series. For computing statistics of the climate indices it is crucial that the meteorological time series are homogeneous. Various nonclimatic factors can cause discontinuities and leave erroneous trends. Such factors include relocation of stations, changes in observing procedures, or new instruments.

A considerable number of weather stations within the NAR are not appropriate for this study as they only have short-term records of digitally available daily temperature and precipitation measurements, have significant periods with missing data, have only single-parameter observations, or have been relocated. For this analysis, we selected the 11 longest available high-quality observation series with daily temperature and precipitation data (Table 1). These stations represent well the climatic variability of the study area (Førland et al. 1997) and have been subject to extensive quality control and inspection of metadata and have been homogenized using modern statistical techniques (Frich et al. 1996). Furthermore, the series are relatively long; seven stations have more than 90 years of daily temperature and precipitation data.

Data from the Norwegian stations (Tromsø, Vardø, Karasjok, Svalbard Airport, Ny-Ålesund, Hopen, Bjørnøya, and Jan Mayen) are freely available from the climate database of the Norwegian Meteorological Institute (eKlima 2016). Note that the Svalbard Airport temperature series, starting in 1898, is the only composite series, which has been established by quality checking and homogenizing the local series with the principal series from Svalbard Airport (Nordli 2010; Nordli et al. 2014). The Sodankylä dataset (Klein-Tank et al. 2002) can be freely downloaded from the European Climate Assessment and Dataset (European Climate Assessment and Dataset 2016). The Abisko data series starts in 1913 (Kohler et al. 2006; Callaghan et al. 2010), while the records from Hornsund and Ny-Ålesund stations are rather

short, with observations starting in 1982 and 1974, respectively. These stations are included in the analysis to extend the number of arctic stations.

Daily mean temperature values are used in our analysis. While daily maximum temperatures may be more suitable for identifying single warming events, digitized values of daily minima and maxima exist only for the latest 40–80 years. Despite different methodologies used to calculate daily mean temperature, both through time and for the different Nordic countries (Ma and Guttorp 2013; Nordli and Tveito 2008), we consider the daily mean temperature data series to be comparable for the statistical evaluation.

Precipitation values are not homogenized. From 1876 to 1915, daily precipitation was measured at 0600 UTC for the longest Norwegian time series—Tromsø, Vardø, and Karasjok. During this period, the measured rainfall was recorded at the previous day, except when the observer was confident that all the rainfall had fallen after midnight. In such cases, the rainfall amount was recorded in the same day as it was measured (Harbitz 1963). From 1916 to the present rainfall amount was recorded on the day it was measured (0600 UTC). The changes in observational practices before and after 1916 for the three Norwegian series are thought to introduce only a small bias in the dataset.

b. Regional climate model projections

We extracted daily mean temperature and precipitation from RCM simulations covering the study area (Table 2). For the arctic mainland areas, RCM data are available from the project ENSEMBLES (van der Linden and Mitchell 2009). We selected 14 simulations performed on a 25-km grid covering the time period 1961–2100. The ENSEMBLES simulations cover a combination of four GCMs, seven regional climate models, and two emission scenarios (IPCC 2000).

The northern border for the ENSEMBLES domain lies just north of the Norwegian mainland, so the domain

TABLE 2. RCM simulations from the ENSEMBLES project [notation adopted from Table 5.1 in van der Linden and Mitchell (2009)] and the NorACIA project [below the blank line; notation adopted from Førland et al. (2009, 2011)]. Max Planck Institute (MPI), Met Office Hadley Centre (HC), Nansen Environmental and Remote Sensing Center (NERSC), Centre National de Recherches Météorologiques (CNRM), Royal Netherlands Meteorological Institute (KNMI), Swedish Meteorological and Hydrological Institute (SMHI), Danish Meteorological Institute (DMI), Community Climate Change Consortium for Ireland (C4I), and Norwegian Meteorological Institute (METNO). (Acronym expansions are available online at http://www.ametsoc.org/PubsAcronymList.)

GCM institute/model	RCM institute	RCM model	Emission scenario	Control	Scenario	Name
				Period		
MPI/ECHAM5	MPI	REMO	SRES A1B	1961–2000	2001–2100	ENSEMBLES
MPI/ECHAM5	KNMI	RACMO	SRES A1B	1961–2000	2001–2100	
MPI/ECHAM5	SMHI	RCA3	SRES A1B	1961–2000	2001–2100	
MPI/ECHAM5	DMI	HIRHAM5	SRES A1B	1961–2000	2001–2100	
MPI/ECHAM5	C4I	RCA3	SRES A2	1961–2000	2001–50	
NERSC/BCM	SMHI	RCA3	SRES A1B	1961–2000	2001–2100	
NERSC/BCM	METNO	HIRHAM	SRES A1B	1961–2000	2001–2050	
CNRM/ARPEGE	DMI	HIRHAM5	SRES A1B	1961–2000	2001–2100	
HC/HadCM3, low	SMHI	in RCA3	SRES A1B	1961–2000	2001–2100	
HC/HadCM3, std	HC	HadRM3	SRES A1B	1961–2000	2001–2100	
HC/HadCM3, low	HC	HadRM3	SRES A1B	1961–2000	2001–2100	
HC/HadCM3, high	HC	HadRM3	SRES A1B	1961–2000	2001–2100	
HC/HadCM3, high	C4I	RCA3	SRES A1B	1961–2000	2001–2100	
HC/HadCM, std	METNO	HIRHAM	SRES A1B	1961–2000	2001–2100	
MPI/ECHAM4	METNO	HIRHAM	IS92a	1981–2010	2021–50	MPI92b
MPI/ECHAM5	METNO	HIRHAM	SRES B2	1961–90	2071–2100	MPIB2
HC/HadAM3H	METNO	HIRHAM	SRES A2	1961–90	2071–2100	HADA2
HC/HadCM3, std	METNO	HIRHAM	SRES B2	1961–90	2071–2100	HADB2
HC/HadCM3, std	METNO	HIRHAM	SRES A1B	1961–90	2021–50	HADA1b
HC/HadCM3, std	METNO	HIRHAM	SRES A1B	1961–90	2071–2100	HADA1c

does not include the arctic islands. There instead we used selected data from the Norwegian Arctic Climate Impact Assessment (NorACIA) RCM simulations, which cover the entire NAR study area, also on a 25-km grid, and which have shown good results for daily temperature and precipitation (Førland et al. 2009, 2011). We selected six NorACIA RCM simulations with 30-year time blocks covering the time periods 1961–90, 1981–2010, 2021–50, and 2071–2100 (Table 2, below the blank line). The simulations cover a combination of one RCM, four GCM and four emission scenarios. Both the ENSEMBLES and NorACIA RCM simulations used in this study were forced by global climate model data used for analysis in previous IPCC reports (Cubasch et al. 2001; Meehl et al. 2007).

The imperfect GCM and RCM representations may lead to unrealistic climate signal results. Therefore, the coarse-resolution RCM data need to be statistically processed to local stations using a bias-correction method before carrying out the climate analysis (e.g., Takayabu et al. 2015). On one hand, this bias correction unfortunately leads to loss of physical consistency between variables, but the present-day climate is much closer to reality, which for impact studies has very high priority (Sorteberg et al. 2014). To use our RCM data

for specific locations in the NAR, the data were bias corrected and downscaled. Temperature and precipitation values were interpolated from the model grid to station locations and adjusted for each site, using a quantile-mapping procedure for each variable separately (Gudmundsson et al. 2012). The correction procedure takes into account new extremes in the tail of the local climate distribution (e.g., increase in extreme precipitation). Quantiles of the RCM data for the 1961–2000 control period were mapped to those of observations from 1985–2014 (the most recent 30-yr reference period used throughout this paper; Table 1). The transfer function obtained was applied to correct the daily RCM temperature and precipitation values. The present procedure is evaluated and compared to other bias correction methods in Sorteberg et al. (2014).

c. Study region climate

The climate of the NAR is thoroughly described by Førland et al. (1997, 2009). Briefly, the NAR is exceptionally warm for its latitude, especially during winter. The mild winters are mainly caused by two factors. First, the region is frequently influenced by extratropical cyclones associated with the North Atlantic cyclone track. Second, the Norwegian Atlantic Current acts as a conduit

for warm and saline Atlantic Water from the North Atlantic to the Barents Sea and Arctic Ocean (Skagseth et al. 2008). About one-third of this flow continues east on the Barents Sea shelf, while the larger portion, the West Spitsbergen Current, flows toward Spitsbergen (Schauer et al. 2004). The branches of the Norwegian Atlantic Current lose heat to the atmosphere until their upper parts merge with and subduct below the colder and fresher Arctic surface water in the Arctic Ocean and create the northernmost area of open water in the Arctic (Polyakov et al. 2005). The frequent cyclones, the Atlantic Ocean, and the nearby coastal waters have a moderating effect on the climate, especially in the maritime regions of northern Norway. Tromsø and Vardø are coastal stations with mean monthly midwinter (December–February) temperatures higher than −5°C, while the Abisko, Karasjok, and Sodankylä stations are characterized by more continental climates (midwinter temperatures below −10°C). The stations at the arctic islands also represent two types of climate (Fig. 2b). Bjørnøya and Jan Mayen are warmer than Hopen, Svalbard Airport, Ny-Ålesund, and Hornsund, with midwinter temperatures higher than −5°C.

Winter precipitation is relatively variable in the study area. The maritime stations (e.g., Tromsø) receive more precipitation in winter than in summer, while the continental stations (Abisko, Karasjok, and Sodankylä) receive less precipitation in winter than in summer (Fig. 3a). Precipitation is distributed more evenly through the year for the arctic islands but with a minimum amount in summer, just as for the maritime arctic mainland stations (Fig. 3b).

Decadal temperature variability in the study area (Fig. 4) shows annual mean temperature values smoothed with a 10-yr Gaussian filter (Janert 2010). It is clear that the arctic island stations have larger decadal temperature variability than the arctic mainland stations. Furthermore, the long-term record can be broken up into four basic periods characterized by 1) minimum temperatures in the 1910s, 2) maxima in the 1930s and 1950s, 3) another minimum in the 1960s, and 4) a general increase in the most recent decades. The strong temperature increase in the period from 1910 to the 1930s, often referred to as the early twentieth-century warming (EW20; Yamanouchi 2011), is strongest at Svalbard Airport (Nordli et al. 2014). Wood and Overland (2010) review the various theories on the causes of the EW20, settling on natural climate variability combined with anthropogenic forcing as the most likely factors, while Yamanouchi (2011) attributes the EW20 mostly to natural climate variability.

The most recent temperature increase at the arctic island stations is much greater than that of the arctic mainland
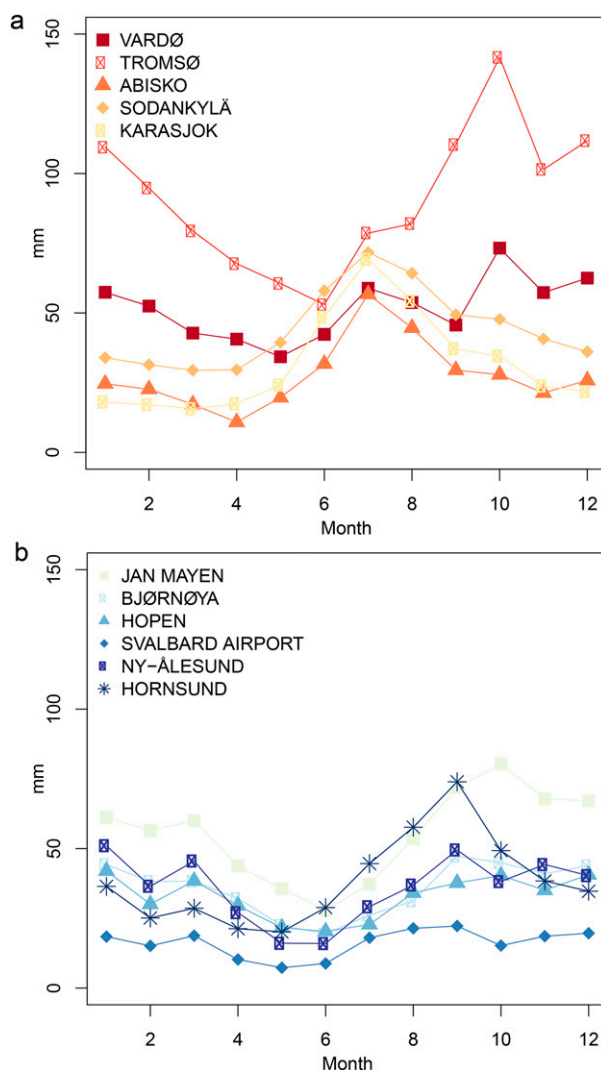

FIG. 3. Mean monthly precipitation sum for the recent period 1985–2014 at (a) the arctic mainland stations and (b) the arctic stations.

stations. Present temperatures are even significantly higher than during any of the earlier periods at Svalbard Airport (Førland et al. 2011; Nordli et al. 2014), while they are slightly higher or at the same level as the 1930s maxima for the arctic mainland stations.

3. Data analysis

a. Winter warm event indices

We defined five climate indices (Table 3) to identify warming events. Indices 1–3 use only a temperature threshold to identify warm days, while indices 4 and 5 additionally employ a precipitation threshold to identify days that are both warm and wet.
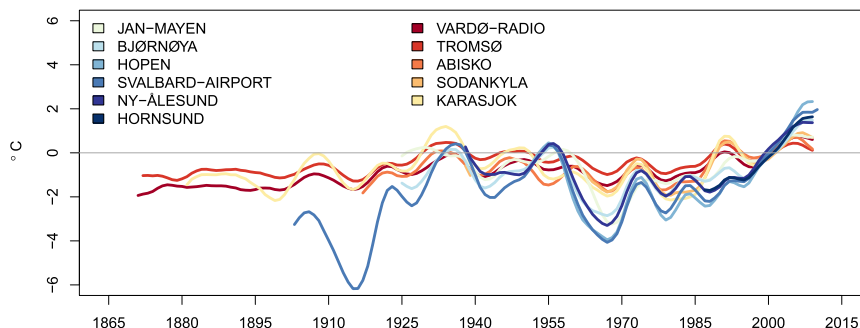
FIG. 4. October–April mean temperature deviation from the 1985–2014 reference period for each station. Data are extracted from homogeneity-tested monthly temperature series and filtered with a 10-yr Gaussian filter. These monthly series are longer than the digitized daily data for the same stations. Arctic stations are shown in blue colors, while arctic mainland stations are shown in red-yellow colors.

- Index 1 counts the number of warm days (WD) in a winter using a location-specific threshold temperature defined as the 90th percentile (Beniston 2005; López-Moreno et al. 2014) of the winter (October–April) distribution for the most recent 30-yr reference period (1985–2014) at each station.
- Index 2 counts the number of melt days (MD) in a winter using a fixed threshold temperature of 0°C, corresponding to the melting temperature for atmospheric conditions.
- Index 3, the positive degree-day sum (PDD), is the sum over the winter season of temperatures values above the 0°C threshold and represents a measure of the intensity of the seasons warm events.
- Index 4 is the number of melt and precipitation days (MPD), similar to MD but with the additional constraint that precipitation $P > 0$ mm.
- Index 5 accumulates the total winter precipitation amounts (MPD$_{sum}$) for the MPD.

Each index is computed from daily values in both the observational and RCM datasets. Annual winter season values of frequency and intensity are summarized for each station.

To identify warming events with rainfall we used a fixed threshold temperature of 0°C (indices 4 and 5; Table 3). In reality there is no constant or exact temperature threshold differentiating precipitation falling as rain or snow; this varies with atmospheric and local conditions (Marks et al. 2013). To test the assumption of a fixed threshold temperature, we evaluated available precipitation records where measured 12-h precipitation has been visually classified as rain by the observers in Tromsø (maritime) and Karasjok (continental) between 1960 and 2000. Results show that 99% of winter rain events in Tromsø occurred at temperatures above 0°C, while in the more continental climate of Karasjok, 76% of the wintertime rain events occurred above 0°C.

b. Trends

To study trends, linear regressions of the indices are analyzed over the past 50, 90, and 120 years, as well as for the future 50–100 years. For comparison of the stations, trend values were expressed as absolute change per decade for all periods, in addition to the change (%) relative to the reference period 1985–2014 for the future projections. Regression time periods were selected to include a maximum number of stations; nine stations have more than 50 years of observational data, seven stations have more than 90 years of data, and four stations have more than 120 years. Trends for the past 90 years include both the recent warming period and the

TABLE 3. Climate indices used to analyze winter warming events. Index 1 uses variable threshold temperature for each station, while indices 2–5 apply a fixed threshold temperature. The variable P is daily precipitation sum and T is daily mean temperature.

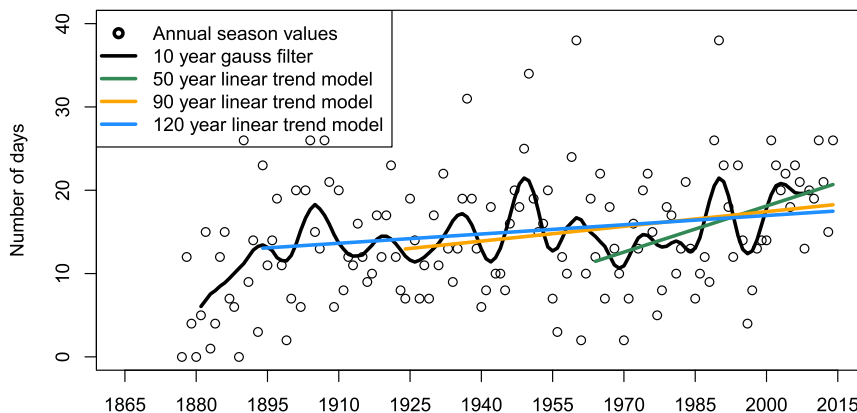| Number	Abbreviation	Name	Description	Type
1	WD	Warm day	$T > T_{90\text{percentile}}$	Frequency
2	MD	Melt day	$T > 0°C$	Frequency
3	PDD	Positive degree-day sum	$\sum_{\text{days}=1}^{n}(T > 0°C)$	Intensity
4	MPD	Melt and precipitation day	$T > 0°C$ and $P > 0$ mm	Frequency
5	MPD$_{sum}$	Precipitation sum for MPDs	$\sum_{\text{days}=1}^{n}(T > 0°C$ and $P > 0$ mm$)$	Intensity

FIG. 5. Illustration of the data analysis. Computation of annual October–April warm days at Karasjok station, using index 1. The plot shows linear trends for 50-, 90-, and 120-yr periods, and a 10-yr Gaussian-filter smoothed line.

warm winters of the 1920s and 1930s. Trend values were tested at a 5% significance level using the nonparametric Mann–Kendall test, widely used for trend analysis of climatological and hydrological time series (Yue and Pilon 2004). The Mann–Kendall test does not require a normal distribution of the data.

Decadal variability is studied by first computing change (%) relative to the reference period 1985–2014 and then applying a Gaussian 10-yr smoothing filter. Figure 5 illustrates, as an example, both the trend and the decadal analysis for the historical data for Karasjok using index 1, the annual October–April number of warm days.

c. Top five extreme winter warming years

To compare the current frequency of winter warming events with that of the past, we identified the top five extreme winters over the past 90 years for each climate index and station (Table 4). We subdivided the 90-yr period into 15-yr intervals and counted the occurrences of extreme years in each of the intervals (Fig. 6). This analysis is based on October–April periods, and subseasons were not considered.

4. Results

a. Winter warming events over the last 15 years (2000–14) versus previous 15-yr periods

Figure 6 shows a histogram of the top five extreme winters over the past 90 years. The stacked columns show the contribution of each index to each 15-yr period. The sorted lists for each index are presented in the Table 4. The highest number of top five extreme winters (37%) occurred in the most recent 15-yr period (2000–14 winter seasons), followed by the 15-yr period of 1925–39 (20% of top five extreme winters). The lowest number of

top five extreme winters occurred during the 15-yr period of 1970–84 (5%). For a uniform frequency, one would expect 17% of the events to fall into each 15-yr period. The histogram demonstrates the high frequency of extraordinary winter warming events occurring in the present climate, compared to the past 90 years.

The percentage of 2000–14 years occurring on each of the top five lists, individually, are 51% for melt and precipitation days (index 4), 46% for melt days (index 2), 43% for positive degree days (index 3), 25% for warm days (index 1), and 17% for precipitation sum for melt and precipitation days (index 5).

The individual years appearing most often among the top five years are 2006 (12 times), 1960 (10 times), 1990 (9 times), 1950 (8 times), and 2012 (7 times).

b. October–April winter warming events over the last 50–120 years

Trend analysis results are summarized in Table 5 for the past 50 years (1964–2014), 90 years (1924–2014), and 120 years (1894–2014).

1) LINEAR TRENDS FOR THE PAST 50 YEARS (1964–2014)

Overall all five winter warming indices show positive trends for the past 50 years, with only a few exceptions, and all are statistically significant (Table 5). In particular, index 1 has increased strongly for all arctic island records, and the smallest increases, still significant, occurred at the arctic mainland stations. The rate of increase in warm days for the arctic islands varies from 3.2 days decade^{-1} at Hopen to 5.5 days decade^{-1} at Jan Mayen. The rate of increase in warm days for the arctic mainland stations varies from 2.2 (Karasjok and Tromsø) to 3.1 days decade^{-1} (Vardø).

TABLE 4. Top five list of extreme years over the past 90 years. Index 1: number of warm days; index 2: number of melt days; index 3: positive degree-day sum; index 4: number of melt and precipitation days; and index 5: precipitation sum for melt and precipitation days. Years 2000–14 are in boldface font.

Station	Index 1: Warm days					Index 2: Melt days					Index 3: PDD					Index 4: MPD					Index 5: MPD$_{sum}$				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Vardø	1990	**2006**	1950	**2004**	1960	**2006**	**2014**	**2012**	**2007**	1930	**2011**	**2008**	**2013**	**2004**	1938	**2014**	**2006**	**2012**	**2007**	**2008**	**2011**	**2008**	1959	1938	1932
Tromsø	**2004**	1930	1937	1960	1950	1930	**2005**	1932	1959	**2006**	1987	1957	1934	1961	**2013**	1934	1949	1992	**2014**	1933	1987	**2005**	1957	1947	1959
Karasjok	1960	1990	1950	1937	1989	1990	1960	1950	1937	**2002**	1960	1937	**2013**	1938	1934	**2006**	**2007**	1949	**2014**	**2012**	1982	1992	1964	1932	1974
Sodankylä	1990	**2006**	**2011**	1950	1960	1990	**2007**	1989	**2005**	**2014**	1987	**2013**	**2011**	1960	1938	1930	1950	1990	**2000**	1939	1987	1992	1932	1954	1974
Abisko	1990	**2002**	1925	1950	1959	1990	1959	1925	**2002**	**2003**	**2013**	1937	1950	**2002**	**2011**	**2012**	1925	1990	1959	1989	**2004**	1983	**2012**	1999	1952
Bjørnøya	**2006**	1954	1957	**2010**	1960	**2006**	1954	**2010**	1957	1960	**2013**	1934	**2004**	**2006**	1937	**2006**	1954	1957	**2010**	**2012**	1934	1964	1974	**2005**	1970
Jan Mayen	1939	**2003**	1947	1954	1955	**2003**	1939	1930	**2006**	1994	1939	1934	**2002**	1953	1960	**2003**	1939	**2006**	**2012**	1930	1976	1988	1961	1963	1973

The temperature threshold for index 1 varies for each station and emphasizes therefore local changes in extremes. Indices 2–5 are all based on fixed temperature and precipitation thresholds (0°C and 0-mm precipitation) and generally show similar results, with the strongest positive trends for stations with average winter temperatures near 0°C (Jan Mayen, Vardø, Bjørnøya, and Tromsø; Figs. 2a,b). With increasing winter temperatures, the probability for winter days above 0°C is more likely to increase, compared to colder stations.

Jan Mayen has the strongest trends for both the frequency indices 2 and 4 and the intensity indices 3 and 5. The station experienced an increase by 9.2 melt days per decade and an increase by 7.5 melt days with precipitation per decade. On Jan Mayen, seasonal temperature variations are very small with average winter temperatures a few degrees below 0°C. Thus, a general temperature increase will have a significant impact on the frequency and intensity in winter warming events. In addition, because of the island's location at the border between the relatively warm Norwegian Sea and the cold Greenland Sea, temperatures and precipitation patterns are sensitive to changes in oceanic and atmospheric circulation patterns. The smallest changes for indices 2–5 were found for Svalbard Airport, Hopen, and Abisko.

Winter warming events are getting not only warmer but also wetter (Table 5). At all stations, winter warm precipitation sums are increasing, with Jan Mayen and Tromsø stations having the strongest positive trends. These two stations also have the largest winter precipitation among the island and mainland stations, respectively (Fig. 3).

2) LINEAR TRENDS FOR THE PAST 90 (1924–2014) AND 120 (1894–2014) YEARS

There are weak positive trends for most stations for all five indices in the past 90 years. However, only a few trends are significant. Jan Mayen even exhibits weak negative trends (not significant) over the past 90 years for two of the five indices (indices 1 and 3; Table 5). Winters during the 1920s–30s were warm throughout the NAR, representing a period that most closely resembles the present (Fig. 4).

Vardø, Tromsø, and Karasjok are the only stations with more than 120 years of observations. Trend values for changes in warming events at these stations show weak positive trends for all indices. However, Vardø is the only station with significant positive trends for both frequency and intensity indices over the past 120 years.
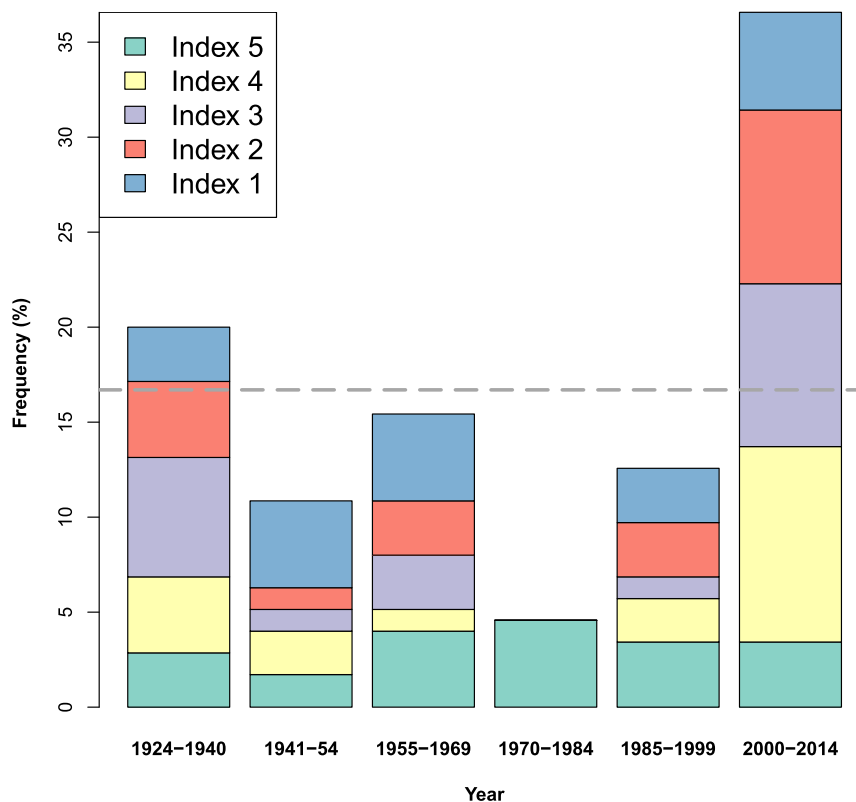
FIG. 6. Histogram of the top five extreme winters summarized for the five climate indices occurring in six 15-yr periods from 1924 to 2014. The stacked columns show the contribution of each index to each 15-yr period. For a uniform frequency one would expect 17% (gray line) of the events to fall into each 15-yr period. Of the top five years, 37% occur in the most recent 15-yr period.

c. Early, mid-, and late winter warming events over the last 50–120 years

Early winter (October–November), midwinter (December–February), and late winter (March–April) warming events over the past roughly 100 years for the five indices are shown in Figs. 7–11.

For early winter, some arctic stations have a maximum period in the 1950s (index 1: Jan Mayen, Hopen, and Bjørnøya), while the other stations and indices follow the general trends in the long-term temperature development (Fig. 4).

For midwinter the results for all indices show that the frequency and intensity of warming events during the 1930s were high and at approximately the same maxima level as the present level (last 15 years), both for arctic island and arctic mainland stations. In addition, mainland stations reached a maximum in the 1990s, which is not observed for the arctic islands. Several stations experienced a period of minimum midwinter warming events from approximately 1965 to 1970.

The trends in frequency of late winter warming events follow the general long-term temperature development

with an increase over the past 50 years (Fig. 4). For some of the stations there are large deviations—for example, for Ny-Ålesund in the 1970s and 1980s and for Hopen in the 1980s where both have peaks during late winter with large amounts of precipitation during the warming events (Fig. 11). Most stations have a maximum period around 2005 for all five indices.

d. Winter warming events over the next 50–100 years

Linear trends of winter warming events for the five indices from 2000 to 2100 are summarized in Table 5. All stations show positive future trends equal to or higher than the observed trends during the last 50 years. For all indices, the largest relative change will take place at the six arctic island stations, ranging from 317% (Hopen) to 201% (Svalbard Airport) for index 1. The relative increase for the arctic islands is larger for index 2, ranging from 402% (Hopen) to 118% (Jan Mayen). For the same indices, the relative change is smaller for the arctic mainland stations, ranging from 211% (Vardø) to 115% (Abisko) for index 1 and from 113% (Vardø) to 64% (Tromsø) for index 2. Roughly

TABLE 5. October–April change per decade in 1) number of days (indices 1, 2, and 4), 2) positive degree-day sum (index 3), and 3) precipitation sum (index 5). The columns show the linear trend per decade for the last 50, 90, and 120 years, as well as the next 100 years (21C) from 2000 to 2100. Last column shows the relative increase (%) of future model spread are shown in parentheses. Significant trend values are marked in boldface on historic data. Stations are ordered by latitude from north to south, with arctic mainland stations in italic font.

Station	Index 1: Warm days					Index 2: Melt days					Index 3: PDD (°C decade^{-1})					Index 4: MPD					Index 5: MPD$_{sum}$ (mm decade^{-1})				
	50	90	120	21C	21C (%)	50	90	120	21C	21C (%)	50	90	120	21C	21C (%)	50	90	120	21C	21C (%)	50	90	120	21C	21C (%)
Ny-Ålesund	—	—	—	5.5	219 (178, 254)	—	—	—	4.2	322 (261, 370)	—	—	—	12.1	585 (461, 712)	—	—	—	2.4	262 (186, 324)	—	—	—	11.3	250 (147, 340)
Svalbard-A.	**3.6**	—	—	5.2	201 (150, 243)	**2.1**	—	—	4.3	263 (191, 316)	3.5	—	—	13.6	472 (321, 585)	**1.3**	—	—	2.0	225 (167, 280)	2.6	—	—	4.2	245 (183, 307)
Hornsund	—	—	—	6.5	252 (219, 293)	—	—	—	6.2	280 (245, 323)	—	—	—	17.5	582 (472, 682)	—	—	—	3.8	206 (150, 261)	—	—	—	14.4	196 (152, 252)
Hopen	**3.2**	—	—	9.4	317 (294, 358)	**2.1**	—	—	8.8	402 (367, 457)	**2.8**	—	—	31.1	1064 (844, 1222)	**1.5**	—	—	4.4	300 (258, 346)	**2.4**	—	—	13.5	514 (438, 607)
Bjørnøya	**3.4**	0.6	—	9.3	300 (230, 353)	**6.7**	**1.5**	—	9.4	177 (147, 207)	**10.2**	1.3	—	46.5	535 (327, 687)	**5.1**	**1.5**	—	4.4	122 (107, 143)	**14.1**	**1.6**	—	12.3	173 (157, 194)
Jan Mayen	**5.5**	−0.6	—	7.8	250 (207, 280)	**9.2**	0.2	—	7.8	118 (106, 126)	**17.7**	−1.5	—	31.8	268 (199, 320)	**7.5**	0.9	—	4.0	86 (83, 90)	**20.8**	1.5	—	16.0	119 (118, 124)
Vardø	**3.1**	0.8	**0.9**	7.9	211 (193, 248)	**7.2**	**2.2**	**2.1**	8.8	113 (106, 134)	**16.3**	**4.4**	**4.3**	49.2	243 (211, 271)	**6.1**	**2.1**	**2.4**	5.2	117 (91, 130)	**11.9**	**3.7**	**3.1**	18.7	190 (164, 218)
Tromsø	**2.2**	0.2	0.3	4.9	152 (135, 165)	**5.1**	0.6	**0.7**	5.7	64 (60, 68)	**17.8**	1.6	2.0	36.6	139 (116, 160)	**3.2**	0.4	**1.3**	3.1	57 (50, 68)	**20.5**	3.5	0.4	17.8	69 (55, 87)
Karasjok	**2.2**	**0.7**	**0.4**	4.2	134 (118, 147)	**2.5**	**0.8**	**0.6**	4.6	115 (102, 125)	**6.7**	**2.7**	1.2	21.4	207 (158, 243)	**2.3**	**0.8**	**0.8**	2.2	115 (100, 119)	**2.9**	0.2	**0.7**	5.6	180 (137, 196)
Abisko	**2.6**	0.4	—	3.7	115 (106, 132)	**3.2**	0.6	—	4.2	89 (86, 101)	**9.4**	1.2	—	20.0	162 (132, 194)	**1.5**	0.2	—	1.9	98 (98, 108)	1.3	0.1	—	6.0	171 (155, 164)
Sodankylä	**3.0**	**0.8**	—	4.1	126 (116, 138)	**3.1**	**1.2**	—	4.5	103 (99, 111)	**9.2**	0.3	—	21.6	184 (157, 216)	**1.3**	**0.6**	—	2.3	103 (90, 118)	**11.9**	**1.4**	—	8.3	153 (132, 173)

speaking, the relative increase is more than double for the arctic mainland stations and up to 3 times for the arctic island stations by 2100.

Detailed downscaled scenarios for melt days and precipitation sum are shown in Figs. 12a–d for the northernmost (Ny-Ålesund) and the southernmost (Sodankylä) stations in our study area. The spread in the ENSEMBLES RCM data is described by the minimum and maximum, the 10th and 90th percentiles of all members, while the NorACIA RCM data are plotted as annual values. Figures 12e,f show the temperature and precipitation data used for the computation of the indices for Sodankylä, where both sources of model data are available. The spread and main trend of the observations are well captured by the model ensemble for the historical period 1961–2014, but a year-to-year correspondence of modeled and observed data is not expected. Based on these results, we consider the locally downscaled scenarios to have reasonable quality to perform weather statistics and trend analysis using the indices.

5. Discussion

a. Winter warming trends in the twentieth century

1) SEASONAL AND DECADAL VARIABILITY

There is a strong maximum in winter warming events for the midwinter period during the 1930s, across all stations; however, this is less pronounced for the early and late winter trends. This is the signature of the EW20 (Brönnimann 2009; Wood and Overland 2010; Yamanouchi 2011) discussed in section 2c.

The 1990s had a midwinter warming maximum period at arctic mainland stations but not at arctic island stations. During this period, many maritime glaciers in Norway advanced, while most glaciers worldwide retreated (Andreassen et al. 2005; Chinn et al. 2005). The glacier advance was caused by a series of precipitation-rich winters. Chinn et al. (2005) related the increase of winter precipitation to stronger westerly atmospheric circulation transporting more moist air toward land. Since only arctic mainland stations and not the arctic islands experienced a maximum in winter warming events in this period, the results may be related to more southern storm tracks affecting the arctic mainland of the Nordic arctic region.

Around 2005/06 there is a maximum in warm events for most of the stations for all the indices (except index 5) and for all seasons. The maximum is generally slightly stronger for the arctic island stations than the arctic mainland stations. The winter of 2006 also appears most often in the list of top five extreme winters
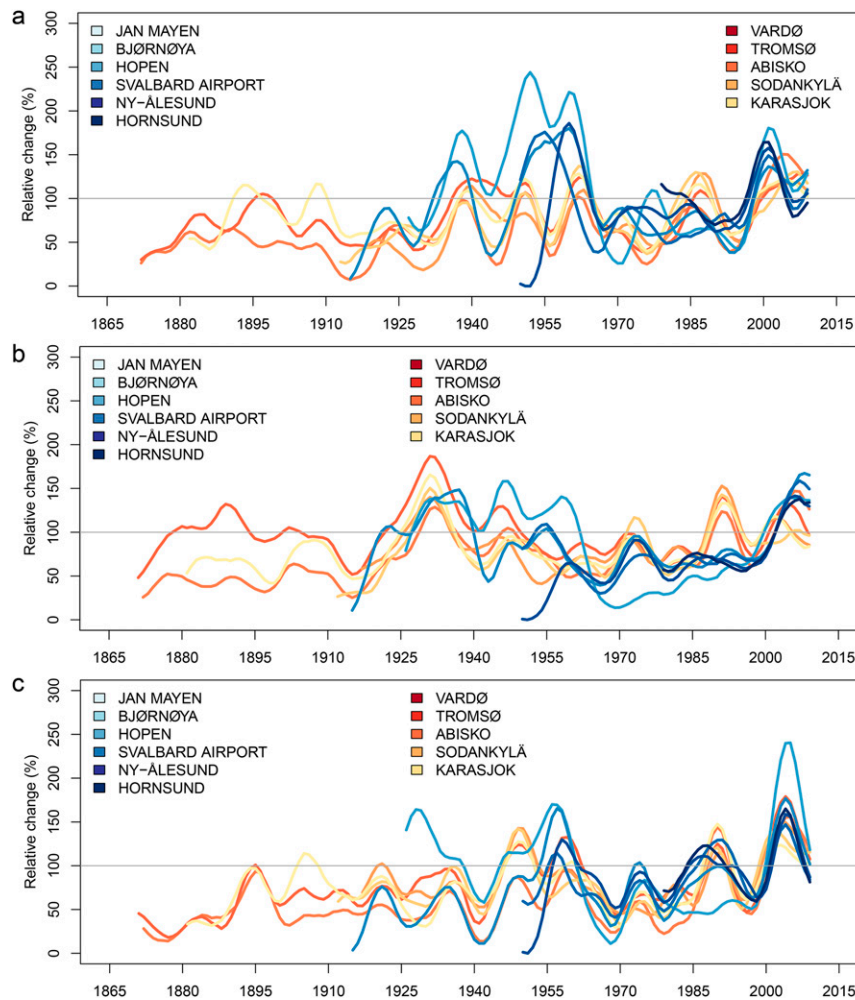
FIG. 7. Change (%) in number of warm days (index 1) relative to the 1985–2014 mean. Arctic stations in blue and arctic mainland stations in red–yellow. (a) Early winter, (b) midwinter, and (c) late winter.

(12 occurrences in Table 4). During this particular winter the NAR experienced an unusual synoptic situation with long periods of strong, mild southerlies. Sea temperatures were unusually high with anomalous ocean heat transport observed west of Svalbard (Walczowski and Piechura 2011). The normal cycle of sea ice formation was interrupted, causing unusually large regions with open water around Svalbard (Cottier et al. 2007). The associated high moisture flux resulted in, for instance, exceptionally high winter accumulation at Austfonna, the largest ice cap at Svalbard (Dunse et al. 2009). During this winter a distinct shift of the sea ice cover on two fjords near Svalbard Airport and Hornsund was observed, from generally ice-covered fjords before 2006 to ice-free fjords after 2006 (Muckenhuber et al. 2016). In turn, high temperatures, including winter warming events,

were then recorded on land. Mean air temperature from December 2005 to May 2006 at Svalbard Airport was 8.2°C above the 1961–90 average, representing the warmest temperature anomaly since the start of this time series (Isaksen et al. 2007).

The observed seasonal and decadal changes shown here are probably a consequence of how the winter sea ice extent is tied to temperature and precipitation at the arctic islands stations. Cold and dry winters are associated with increased sea ice extent near the stations, while ice-free winters are typically mild and humid (Førland et al. 2009). North of Svalbard, sea ice cover has been reduced more in winter (-10% decade^{-1}) than in summer (-6% decade^{-1}) since 1979 (Onarheim et al. 2014). This is in contrast to the entire Arctic where the largest seasonal reduction in sea ice extent is observed in September, a 13% reduction per decade since 1979
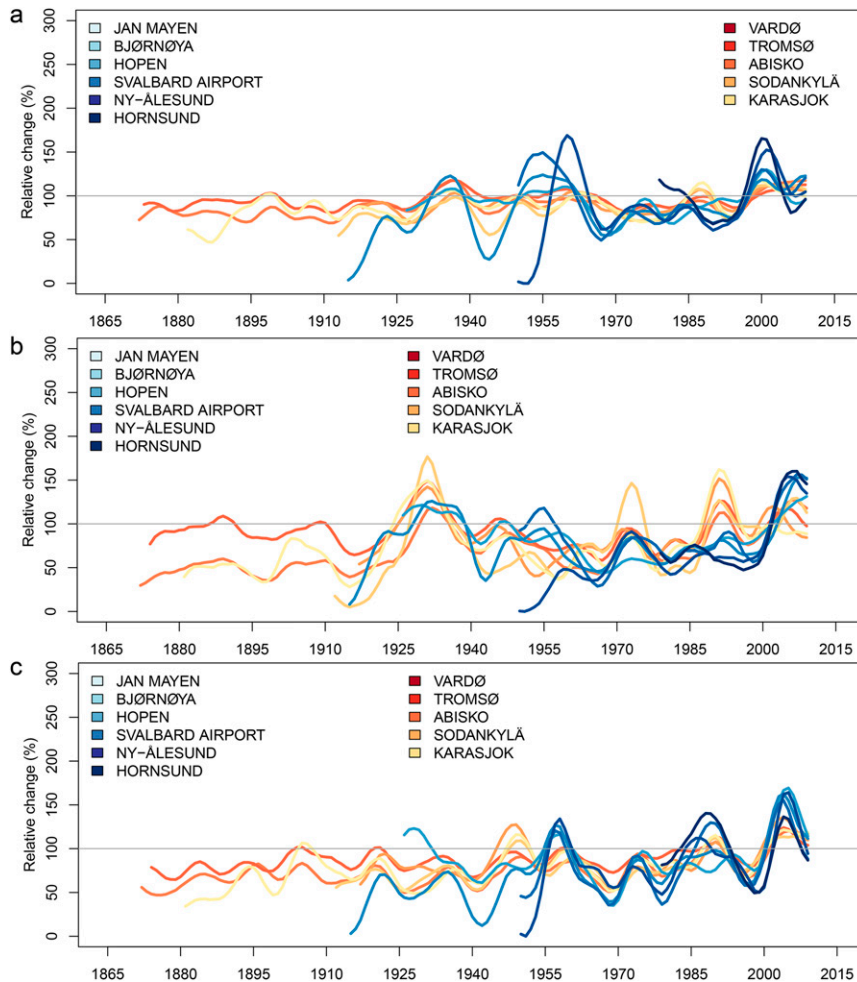
FIG. 8. As in Fig. 7, but for melting days (index 2).

(Stroeve et al. 2007, 2012). Although there is a general negative trend in sea ice extent, the interannual variability is largely due to variations in ocean and atmosphere circulation and heat transfer.

2) STRONG 50-YR TRENDS AND WEAK 90- AND 120-YR TRENDS

Regardless of the season (early, mid-, and late winter), our results showed weak winter warming trends over the past 90 years (from 1924 to 2014) and 120 years (1894–2014), while strong trends are found for all stations over the past 50 years (from 1964 to 2014). The 50-yr trends are clearly increasing with latitude within our study area and are probably linked to the general temperature development in the area. Arctic temperatures increased by 0.09°C decade^{-1} for the twentieth century, which is more than the temperature increase of 0.06°C decade^{-1} for the entire Northern Hemisphere over the same period (Berner et al. 2005). Limiting the

period to the past 50 years, the arctic temperature increase was much stronger. The Arctic is now warming at more than twice the rate of lower latitudes, and mean annual air temperature has increased by 2.3°C since the 1970s (0.5°–0.6°C decade^{-1}; Overland et al. 2015). This is also clearly observed the past two decades at Svalbard with the strongest temperature increase in winter, by 2°–3°C decade^{-1} (Førland et al. 2011).

Our results show that the 1930s, the 1990s, and the recent 15-yr period are maxima in the Arctic. The causes of the two latter periods are thought to be different from the first. The EW20 presumably was governed by natural variability (Wood and Overland 2010; Yamanouchi 2011). In contrast, the recent warming is associated with increased anthropogenic greenhouse gas forcing, resulting in increased cyclone activity in the NAR (Sorteberg and Walsh 2008; Førland et al. 2009). Both the number and the intensity of cyclones crossing 70°N increased from 1950 to 2007, particularly during
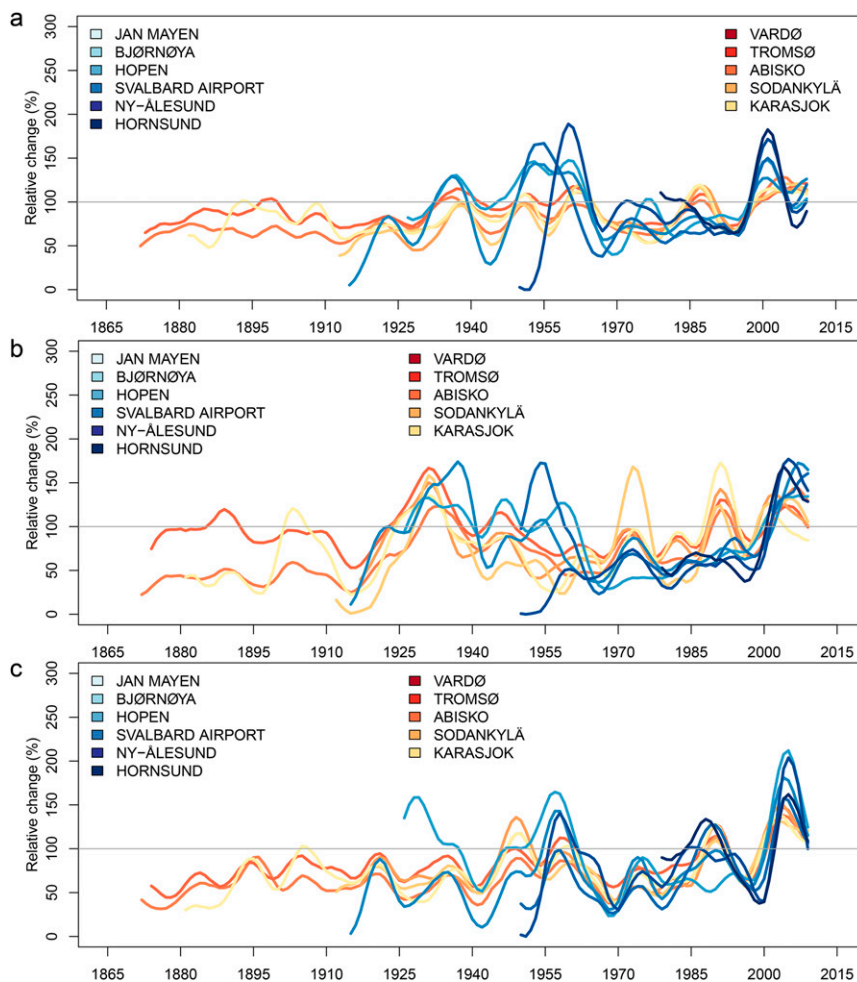
FIG. 9. As in Fig. 7, but for positive degree-day sum for the melt days (index 3).

midwinter (December–February), where positive trends were found for both the mean intensity of the cyclones and the intensity of the most extreme cyclones.

3) WARMER AND WETTER AFTER YEAR 2000?

As discussed in the previous section, the arctic temperature amplification has been strong over the past 15 years (2000–14), particularly during autumn and winter (Serreze and Barry 2011; Serreze and Stroeve 2015). Our analysis is in line with these observations showing that the highest number of top five extreme winter warming years have occurred within the most recent 15-yr period (2000–14), particularly the climate indices 2–4 (Fig. 6).

b. Winter warming trends in the twenty-first century

For future scenarios, the large increase in winter warming events for the arctic island stations is probably strongly influenced by the GCM modeled sea ice extent, which is shown to exert a significant control on the climate of Svalbard (e.g., Benestad et al. 2002; Day et al. 2012). In addition, the predicted large relative increase of warming events in winter for the arctic islands is also a result of normalizing using current conditions, which feature relatively few events per year, even if the absolute increase in events predicted is not too different from projections for the arctic mainland stations.

Another possible explanation for larger increases predicted for the arctic island stations is that the ensemble is based on fewer realizations (only NorACIA data) than for the mainland region (both ENSEMBLES and NorACIA data). A smaller ensemble is usually associated with a smaller spread in the results. But here the NorACIA simulations include both moderate and more extreme emission scenarios (e.g., SRES A2), whereas the ENSEMBLES data are mainly based on one emission scenario (SRES A1B; van der Linden and Mitchell 2009; Førland et al. 2009, 2011).
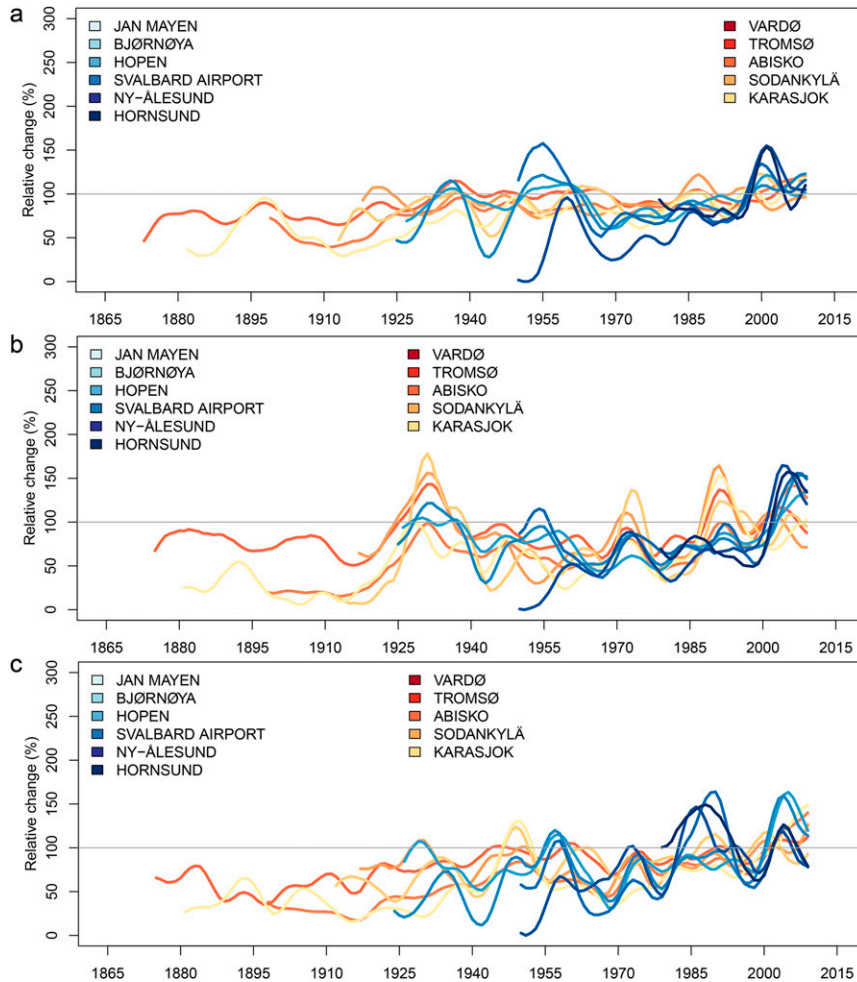
FIG. 10. As in Fig. 7, but for the number of melt and precipitation days (index 4).

The tabulated indices for the twenty-first century were based on bias-corrected model data, with calculation of combined indices from independently modified parameters. The analysis was repeated from uncorrected model data in order to check the sensitivity to the quantile-mapping procedure. Although the quantitative responses slightly differ for some of the stations, the major conclusion is that both analyses (corrected vs original data) show large increases for arctic islands stations. On the other hand, the simulation of the climate at arctic islands stations is influenced by the quality of the forcing data from the global climate models and their ability to model arctic sea ice and sea surface temperature as well as relatively low-resolution forcing data over sea. The ability of the regional climate models to simulate temperatures around the threshold temperature (0°C) can also influence the results. Nevertheless, trends for all indices are similar for both datasets (NorACIA and

ENSEMBLES), and the expected large increase predicted for the twenty-first century is likely due to the response in the forcing GCM data.

c. Impact of warmer wetter winters on ecosystems, soil, and society

Warmer and wetter winters will have major implications for northern European, arctic biomes and societies. Northern terrestrial ecosystems are adapted to a long-lasting snow cover. Hence, in regions where climate change will lead to reduced snow cover, especially plants and animals in the subnivean environment will be particularly adversely disturbed (Bjerke et al. 2014; Williams et al. 2015). Organisms overwintering above the snow will also be severely impacted in various ways (Bjerke et al. 2014; Hansen et al. 2014). Records from warm, wet years in the NAR illustrate these impacts. The winter of 2006 was the individual winter appearing most often among the top five extreme winters in our
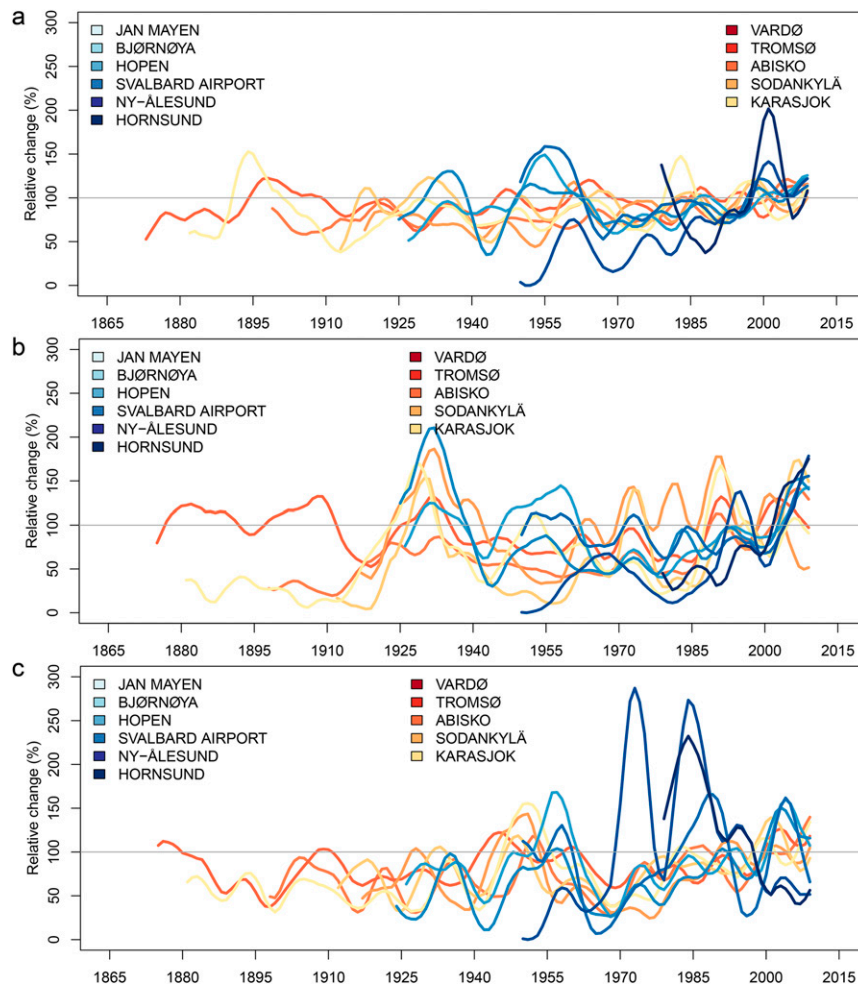
FIG. 11. As in Fig. 7, but for the precipitation sum for melt and precipitation days (index 5).

data. In their online supplementary information, Bjerke et al. (2014) summarized the biological impacts of weather events this winter on the mainland: there was extensive damage to evergreen plants, both dwarf shrubs and coniferous trees, due to frost drought, which probably took place during a cold late winter period after the winter warming events. The warming events this winter were associated with strong winds; wind-borne salt spray caused some damage to plants, and wind felling was also widespread. In Svalbard, ROS events this winter led to ground-ice accumulation and population crashes of reindeer and voles (Stien et al. 2012). The winter of 2012 also appears on the top-five list in our analysis. Hansen et al. (2014) show that the warm weather this winter led to a similar situation as in 2006 with numerous ROS events, ground-ice accumulation, and starvation-induced mortality in all monitored populations of wild reindeer by blocking access to the winter food source. Similar population crashes to

semidomesticated reindeer caused by ground ice are also known from other northern regions and years (Riseth et al. 2011; Vikhamar-Schuler et al. 2013; Rasmus et al. 2016). Ground ice has a negative impact on vegetation encased in ice (Gudleifsson 2009; Bjerke et al. 2011; Preece et al. 2012). The winter of 2012 also led to negative plant responses, similar to those recorded after the 2006 winter (Bjerke et al. 2014). Similar negative impacts on plants and animals were also reported during the EW20 in the late 1920s and the 1930s (Langlet 1929; Printz 1933; Bathen 1935; Ruong 1937). Other years appearing in the top-five list are 1950, 1960, and 1990. There are indications that weather during these winters also had negative impacts on plants and animals (e.g., Solberg 1991; Päiviö 2006; Riseth et al. 2011), but available reports are few.

As discussed earlier, increased occurrence of open water in the Svalbard region since the winter of 2006 probably caused an amplifying recent warming (Cottier
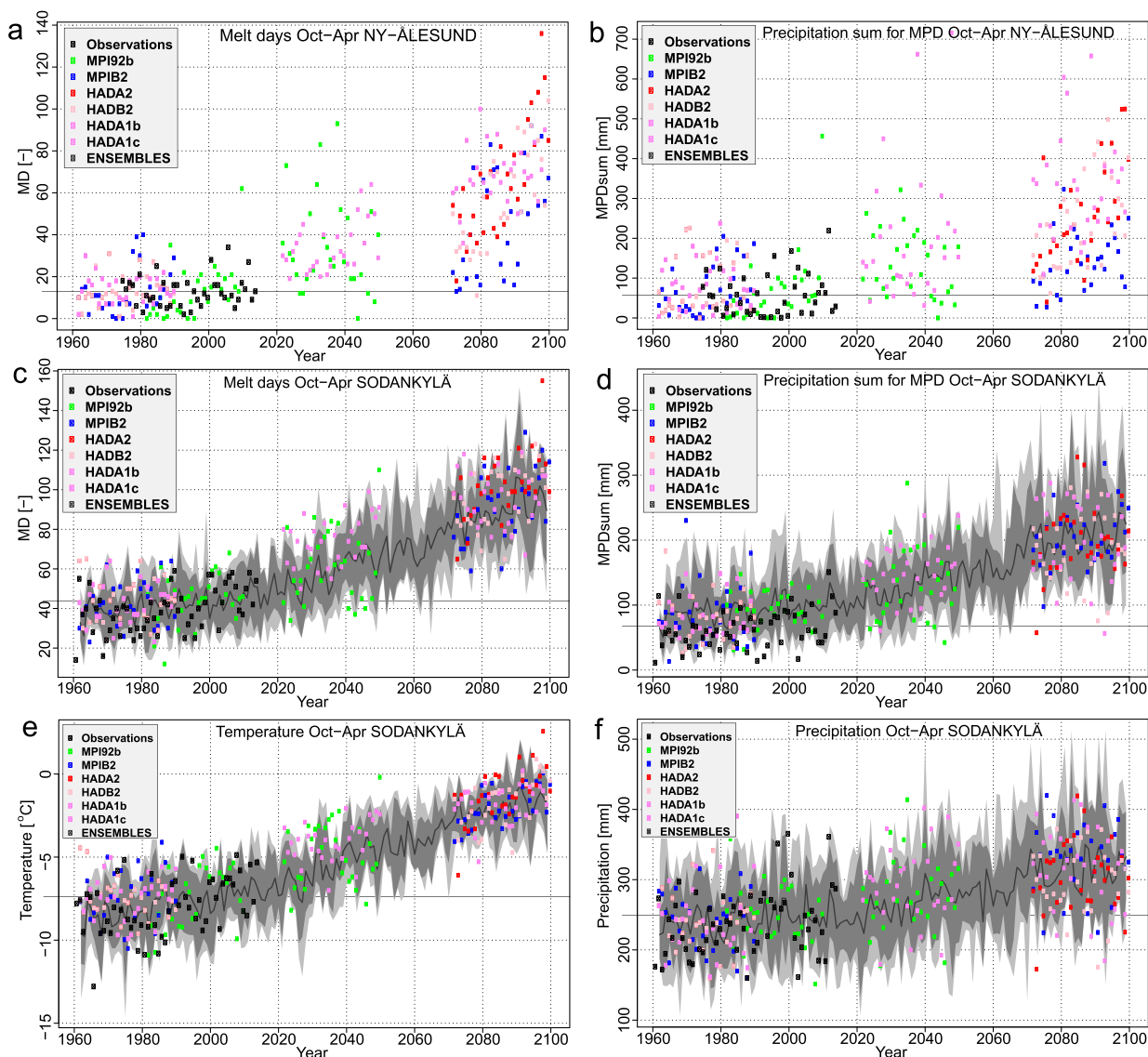
FIG. 12. Regionally downscaled scenarios for the season October–April from 1961 to 2100. MD for (a) Ny-Ålesund and (c) Sodankylä. Precipitation sum for melt and precipitation days (MPDsum) for (b) Ny-Ålesund and (c) Sodankylä. Sodankylä (e) mean temperature and (f) precipitation sum. Observations as black points and NorACIA RCM data as colored points. ENSEMBLES data as gray shading (outer light shading showing minimum and maximum values, dark shading showing 10th–90th percentiles, and gray line showing ensemble mean).

et al. 2007). Warmer ocean temperatures and increasing frequency of ice-free fjords have led to increasing northward migration of North Atlantic species (Berge et al. 2015; Ingvaldsen et al. 2015).

Warmer wetter winters also affect soil temperatures. During the extreme winters of 2006 and 2012, permafrost soil on Svalbard was much warmer than during normal winters, and the thermal response was detectable to a depth of 5–15 m (Isaksen et al. 2007; Hansen et al. 2014). Multiannual simulations by Westermann et al. (2011) project that ROS events can

significantly accelerate the warming of soil temperatures in permafrost areas and that initially stable permafrost systems may in certain areas start to thaw if environmental conditions such as those observed on Svalbard in 2006 and 2012 return for several consecutive winters. Resulting increases in active-layer thickness may in certain areas be associated with unprecedented thaw settlement as ice-rich soils in the upper-permafrost-layer melt (Nelson et al. 2001), leading to a marked increase in slope instability (Harris et al. 2001).

Warmer wetter winters will affect human societies in various ways. Extreme winters have proven that ROS events followed by ground-ice accumulation lead to more road icings, airport closures, bone fractures, damage to buildings due to burst from frozen pipes, and reduced profits from nature-based industries due to winterkill of reindeer and agricultural grasslands (Helle and Säntii 1982; Riseth et al. 2011; Vikhamar-Schuler et al. 2013; Hansen et al. 2014; Bjerke et al. 2014, 2015; Rasmus et al. 2016; Bokhorst et al. 2016). Higher atmospheric humidity at near-zero temperatures may also lead to increased icing formation, which can be hazardous to high seas fishery, forestry, and manmade infrastructure (Bulygina et al. 2015). We show here that warm events will most likely become more frequent in the NAR in the future, which can in turn have negative consequences for the winter tourism industry, as reported from the European Alps (Rixen et al. 2011), northern Sweden (Moen and Fredman 2007), and Svalbard (Hansen et al. 2014). Moreover, most local residents prefer some snow during the polar night, as it lightens up the landscape. Northern residents tend to be more depressive and have more sleep disorders during the darkest period of winter (Hansen et al. 1998; Johnsen et al. 2012), which may become more frequent during rainy winters.

6. Conclusions

In this study, we analyze changes in the intensity and frequency of extraordinarily warm weather episodes occurring during the winter season for the Nordic arctic region. Long-term trends were evaluated for a set of climate indices aimed to capture these individual events based on data from the longest available observational time series in the region, as well as future climate scenarios based on regional climate model simulations. The main findings are as follows:

- Weak positive trends in winter warming events are found over the past 120 years for the arctic mainland stations, Karasjok (significant for all indices) and Tromsø.
- Weak positive trends in winter warming events are found over the past 90 years as well. This is due to the warm winters of the 1920s and 1930s, the period most similar to the present (2000–14) in terms of winter climate. Midwinter warming events were more frequent during the 1920s and 1930s, similarly to the present. However, early and late winter have a clearer increasing trend over the past 90 years.
- For the past 50 years, we find strong increasing trends in occurrence and intensity for all climate indices, all statistically significant. The main pattern follows the general

temperature development of arctic areas. The trends are stronger to the north, with the largest trends at the arctic islands. Here, the rate of melt days (index 2) in winter increased by up to 9.2 days decade^{-1}. For melt days with precipitation (mainly as rain; index 5) the increase in precipitation sum is up to 20.8 mm decade^{-1} (for the arctic island Jan Mayen).

- During the past 15 winters (2000–14), warming events have become more frequent and intense, seen in a 90-yr perspective. Of the top five extreme winter warming years, 37% occurred within the most recent 15-yr period, followed by the 15-yr period from 1925 to 1939, which had 20% of the top five extreme winter warming years.
- Regional climate model simulations over the next 50–100 years indicate that the strong past 50-yr trends will continue. In northern Scandinavia, simulations indicate a doubling in the number of warming events while the arctic islands may see a threefold increase in the number compared to the 1985–2014 reference period.

These results are valid for stations in the NAR and hence obtained from a dataset of limited spatial coverage. To evaluate the representativeness of this analysis in a broader geographical perspective, it is recommended that a similar study is carried out using reanalysis data for the entire panarctic region, elucidating possible variability in extreme events occurring in continental and maritime climates of the arctic region. We also suggest carrying out this study with a larger ensemble of regionally downscaled projections covering the Arctic (e.g., CORDEX Arctic). A larger spread of simulations will provide even higher trust to the findings of future changes.

The findings in this study have improved our understanding of the regional climate variability in the NAR. The information is important for predicting the impact of climate change in the arctic environments, as well as for developing adaptation strategies to deal with these changes.

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