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Nimeke Joitain Fennoskandian pohjoisosien talvi-ilmaston piirteitä

Tiivistelmä

Fennoskandian pohjoisosien talvi-ilmaston ankaruus luo erinomaiset edellytykset erilaisten laitteiden teknisen kestävyyden testaamiseen äärimmäisissä olosuhteissa. Autojen ja talvirenkaiden suorituskyvyn testaus talviolosuhteissa onkin ollut kasvava toimiala alueella. Myös alueen jatkuvasti kasvava matkailuelinkeino on vahvasti riippuvainen talvi-ilmastosta. Tietoa talvi-ilmaston alueellisesta vaihtelusta tarvitaan uusia investointeja suunniteltaessa. Tähän tarpeeseen vastataksemme olemme tutkineet valikoitujen, talven lämpötila- ja lumioloja kuvaavien ilmastollisten muuttujien alueellista vaihtelua Fennoskandian pohjoisosissa. Hilamuotoinen E-OBS aineisto lämpötilalle ja GlobSnow aineisto lumen vesiarvolle osoittautuivat käyttökelpoisiksi muodostettaessa kuvausta nykyilmastosta. Tämän lisäksi esitämme arvioita ilmastonmuutoksen vaikutuksesta termisen talven ja lumipeiteajan pituuteen lähitulevaisuudessa. Pisimpien ja lumisimpien talvien havaitaan esiintyvän Ruotsin luoteisosien vuoristoisilla alueilla, kun taas rannikkoalueilla talvet ovat lauhempia kuin muualla. Kaikkein matalimpia lämpötiloja vuorostaan esiintyy korkeimmilla alueilla vain harvoin.

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Abstract

The harsh winter climate of northern Fennoscandia creates an excellent environment for testing the technical durability of vehicles in extreme conditions. A growing economic activity in the region is testing the performance of cars and snow tyres in these winter conditions. Moreover, the continually-growing tourism industry of the region is highly dependent on the winter climate. When new infrastructures are planned, a spatial knowledge of winter climate is needed to determine the most favourable locations for the intended purposes. To respond to this demand, we have examined the spatial variation of selected climatological parameters describing winter temperature and snow conditions in northern Fennoscandia. The gridded high-resolution E-OBS data set for temperature and the GlobSnow data set for snow water equivalent were found to be suitable to construct a description of the present-day winter climate. In addition to presenting a description of the winter climate in the baseline period 1981–2010, we also give estimates of the effect of climate change on the length of the thermal winter and snow season in the near future. The longest and snowiest winters are found to occur in the mountainous areas of north-western Sweden, while in coastal areas winters are milder than elsewhere. In contrast, the lowest temperatures seldom occur in the highest areas.

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Contents

1. Introduction

Winters at high latitudes in northern Fennoscandia are long and snowy: winter conditions with sub-zero temperatures and snow cover typically prevail from October or early November to late April or May. The longest winters occur at the northern end of the Scandinavian mountains, where thermal winter lasts on average over seven months, i.e., well over half of the year. The cold and snowy climatic conditions also present a challenge to road maintenance, for example (e.g. Venäläinen and Kangas, 2003). On the other hand, these severe conditions create an excellent extreme environment for testing the technical durability of vehicles. Moreover, snow and ice are vitally important for the winter tourism of the region. The snow cover and numerous frozen inland lakes enable the efficient use of snowmobiles and make available traffic routes that are not possible during the summer.

The winter testing of cars and snow tyres is a growing economic activity in cold regions. Cars have to tolerate conditions that often are not experienced in the regions where they are designed and manufactured. Testing the performance of snow tyres also requires comprehensive verification. A well-functioning infrastructure is needed to make such testing feasible. Among other things, this requires good accessability to the test site. These requirements are fulfilled in northern Fennoscandia because the area is not logistically as remote as many other cold regions. Consequently, the region has become one of the leading winter test site regions in the world.

The importance of winter tourism also characterizes the economic structure of Lapland. Recently, the tourism industry in the area has been oriented around offering adventure holidays (Kairamo, 2006), for which the wild nature of the region and its unique winter conditions afford excellent possibilities. In the future, the region has been envisaged as becoming the primary sustainable tourism resort in Europe (Lapin liitto, 2010).

In spite of the general harshness of its winters, there is quite a considerable spatial variation in climatic conditions over northern Fennoscandia. The eastern parts of the region experience a more continental climate than the western side, where the strong influence of the Atlantic Ocean is felt. Furthermore, the Scandinavian mountains ranging along the border between Sweden and Norway as far as northern Norway have a strong impact on the region's climate (Vajda and Venäläinen, 2003; Aalto *et al*., 2013). The Bay of Bothnia also provides its own regional flavour to the climate of nearby areas. However, based on Köppen's climatic classification, northern Fennoscandia belongs almost entirely to the class of continental subarctic climate with cool summers (Peel *et al*., 2007). Only in the highest mountainous areas does a polar tundra climate prevail. By the end of the current century, the tundra climate is expected to disappear due to the projected increase in mean temperature (Jylhä *et al*., 2010). In addition, major changes in winter conditions are considered likely in northern Europe during the next decades, for instance. Temperatures are projected to rise and the duration of the snow season to shorten (e.g. Jylhä *et al*., 2004; Christensen *et al*., 2007; Räisänen and Eklund, 2012). Moreover, it has been suggested that, among other things, climate change might significantly affect to tourist flows in Europe (Ciscar *et al*., 2011).

Traditionally, climate analyses have been made for observation station locations. However, as a result of increasing international co-operation, continental and even global-scale data sets containing various climatological parameters have become available. In this study, we have employed the Europe-wide high-resolution ENSEMBLES Observations (E-OBS) gridded data set for temperature (Haylock *et al*., 2008) and global snow water equivalent products for snow cover (GlobSnow; Takala *et al*., 2009, 2011). The spatial variation of the climatological parameters characterizing the winter season in northern Fennoscandia approximately north of the latitude of 65°N have been examined to discover the locations with the most severe winter climate conditions. The parameters studied include the length of the thermal winter, the average dates for formation and melting of the snow cover, average snow depth and the number of cold and mild days during the winter. Additionally, the growth of lake ice thickness has been estimated based on a simple model using cumulative temperature sum as a predictor. The study period consists of the 30-year time span 1981–2010. In addition, the effect of climate change has been approximated with fixed wintertime warmings of 1, 2, 3 and 4 °C. The results of the study can be applied, for instance, when optimal sites for the winter testing of vehicles are sought and decisions on the construction of new infrastructure are made. In addition, this information is valuable from the point of forestry and the tourism industry. Furthermore, the study demonstrates the applicability of Europe-wide and global gridded data sets for benefiting various sectors of society.

2. Data and methods

2.1 Representation of the present-day winter climate

We have employed the E-OBS data set for temperature (Haylock *et al*., 2008). Calculations are based on version 7.0 of the data set released in early September 2012 on a regular 0.25° x 0.25° latitude-longitude grid. For the creation of the E-OBS data set an interpolation method known as global kriging was used. The choice of the interpolation method was based on a comparison of six alternative methods (Hofstra *et al*., 2008). Kriging takes into account external forcing, like terrain properties and altitude. Nevertheless, besides the density of the observation network, the terrain complexity and the form of the spatial variation of the variables affect the accuracy of the interpolation. Based on this daily data, we calculated the annual average length of the thermal winter, the occurrence of cold and mild winter days and the growth of lake ice thickness over the study period 1981–2010.

The definitions used for the above-mentioned parameters are described below. Thermal winter is that part of the year when the daily mean temperature on average remains below 0 °C. The average numbers of cold and mild winter days were calculated based on daily minimum and maximum temperatures. For instance, the average number of days with minimum temperature below -30 °C is simply the annual count of these days averaged over the 30-year study period. In calculating the average number of cold days, the whole calendar year was considered, while in calculating the average number of mild winter days only the period from November to March was taken into account.

The growth of lake ice thickness was estimated with a simple Stefan's type of equation (Stefan, 1890) which uses air temperature as a predictor:

$$lake\ ice\ thickness\ (cm) = -25 + \sqrt{625 - 8 * FS} \quad (1)$$

where *FS* is the cumulative frost sum in degree-days. According to Eq. (1) we determined the date when a lake ice thickness of 35 cm was achieved. This threshold was selected as a basis for the calculations because that thickness enables the safe use of frozen water areas for car-testing purposes. Compared to actual ice thickness measurements (Korhonen, 2005), Eq. (1) on average proved to somewhat overestimate the growth of ice thickness on most of the lakes. For example, on the largest lake of the study region, on Lake Inari, situated approximately at 69°N and 28°E, the modelled average annual maximum ice thickness in 1981–2010 surpassed the average observed value in 1961–2000 by over 20%. For some smaller lakes this overestimation in the ice thickness was considerably smaller.

Snow-related parameters were calculated based mainly on remote sensing measurements. In approximating the average formation date of a permanent snow cover and snow depth on certain dates, the snow water equivalent (SWE) product produced in the European Space Agency's GlobSnow project was employed (Takala *et al.*, 2011). This product combines satellite passive microwave measurements, weather station observations of snow depth, and forward simulations with a semi-empirical snow emission model in an assimilation scheme to map SWE. The conversion from SWE to snow depth was carried out with the following equation:

$$snow\ depth(m) = \frac{SWE(mm)}{\rho(kg/m^3)} \quad (2)$$

where ρ is the density of snow (a constant value of 240 kg/m^3 in the GlobSnow data). The average melting date of the snow cover was evaluated using space-borne microwave radiometer data (Takala *et al.*, 2009). The SWE product that we used has been found earlier to be superior to the available purely earth-observation-derived global SWE products (Hancock *et al.*, 2013).

2.2 Construction of climate change estimates

We present estimates for the effect of climate change on the length of the thermal winter and the snow cover duration time with fixed wintertime warmings of 1, 2, 3 and 4 °C. This has been done with a delta-change method. Because the beginning and ending of thermal winter are determined by the dates when the daily mean temperature on average passes 0 °C, the effect of warming on the length of the thermal winter was estimated by raising observed daily mean temperatures equally. However, as climate change scenarios indicate that temperatures will rise most in winter, the warming in other seasons was set to be one-third less compared to midwinter (December to February) months. This corresponds with the climate projections for northern Finland (Jylhä *et al.*, 2009).

To make projections of changes in snow cover duration time, we employed regional climate model (RCM) simulations conducted within the ENSEMBLES project (van der Linden and Mitchell, 2009). Thirteen simulations based on the Special Report on Emission Scenarios (SRES) (Nakićenović *et al*., 2000) A1B scenario were chosen. We chose the same simulations that were analysed by Räisänen and Eklund (2012), as they showed that in Finland the agreement between the multi-model mean with that particular model ensemble and observations is excellent for SWE and adequate for temperature. In addition, we included two more simulations. Eventually, the ensemble holds data from nine RCMs having boundary conditions provided by five global climate models (GCMs), counting separately the three GCM and RCM versions from the HadCM3/HadRM3 perturbed-parameter ensemble (Collins *et al*., 2011) (Table 1). All the days with SWE greater than 2.4 were considered as snowy days. This corresponds roughly to a snow depth of 1 cm.

To match the projected changes in snow cover with a fixed amount of warming, we calculated over northern Finland the area-averaged ensemble-mean change in midwinter temperature for every decade in the 21st century compared to the mean of 1981–2010. We then constructed four artificial time slices, each consisting of three decades, so that midwinter mean temperature of the periods in northern Finland were on average 1, 2, 3 and 4 °C higher compared to the mean of 1981–2010. Finally, the projections for changes in snow cover duration time were constructed based on the same time slices.

Table 1. The model simulations used to project changes in snow cover duration time. The first column indicates the driving global climate model, the second the regional climate model and the third the institution that conducted the simulations within the ENSEMBLES project (van der Linden and Mitchell, 2009).

Driving GCM	RCM	Institution
ECHAM5-r3	HIRHAM5	DMI
	RACMO2	KNMI
	RegCM3	ICTP
	REMO	MPI
	RCA3	SMHI
HadCM3Q3	RCA3	SMHI
	HadRM3Q3	Met Office
HadCM3Q0	CLM	ETHZ
	HadRM3Q0	Met Office
HadCM3Q16	RCA3	C4I
	HadRM3Q16	Met Office
BCM	HIRHAM5	DMI
	RCA3	SMHI

3. Results

3.1 Winter climate in 1981–2010

In northern Fennoscandia, the thermal winter in the period 1981–2010 lasted on average approximately half a year (Fig. 1). The longest winters occur in the mountainous regions of Swedish Lapland and in the very north-westernmost parts of Finland. There the onset of winter already takes place on average at the beginning of October, and winter does not turn into spring until early May. The onset of winter occurs on average in October over virtually the whole of Lapland; only locally on the coast of the Bay of Bothnia does winter not begin until in the beginning of November. Over most of Lapland, winter turns into spring on average during late April. In southern Lapland, winter typically ends already in mid-April, whereas in the mountainous regions the termination of winter is not usually experienced until early May. On the Norwegian coast, the climate deviates from other areas in northern

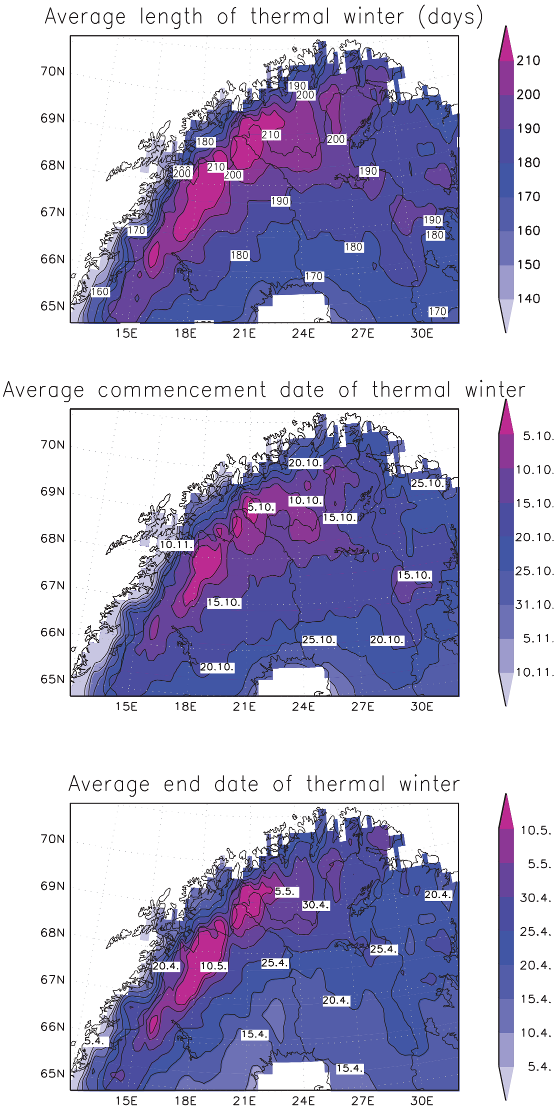

Figure 1. Average length (top), commencement date (middle) and end date (bottom) of thermal winter in 1981–2010.

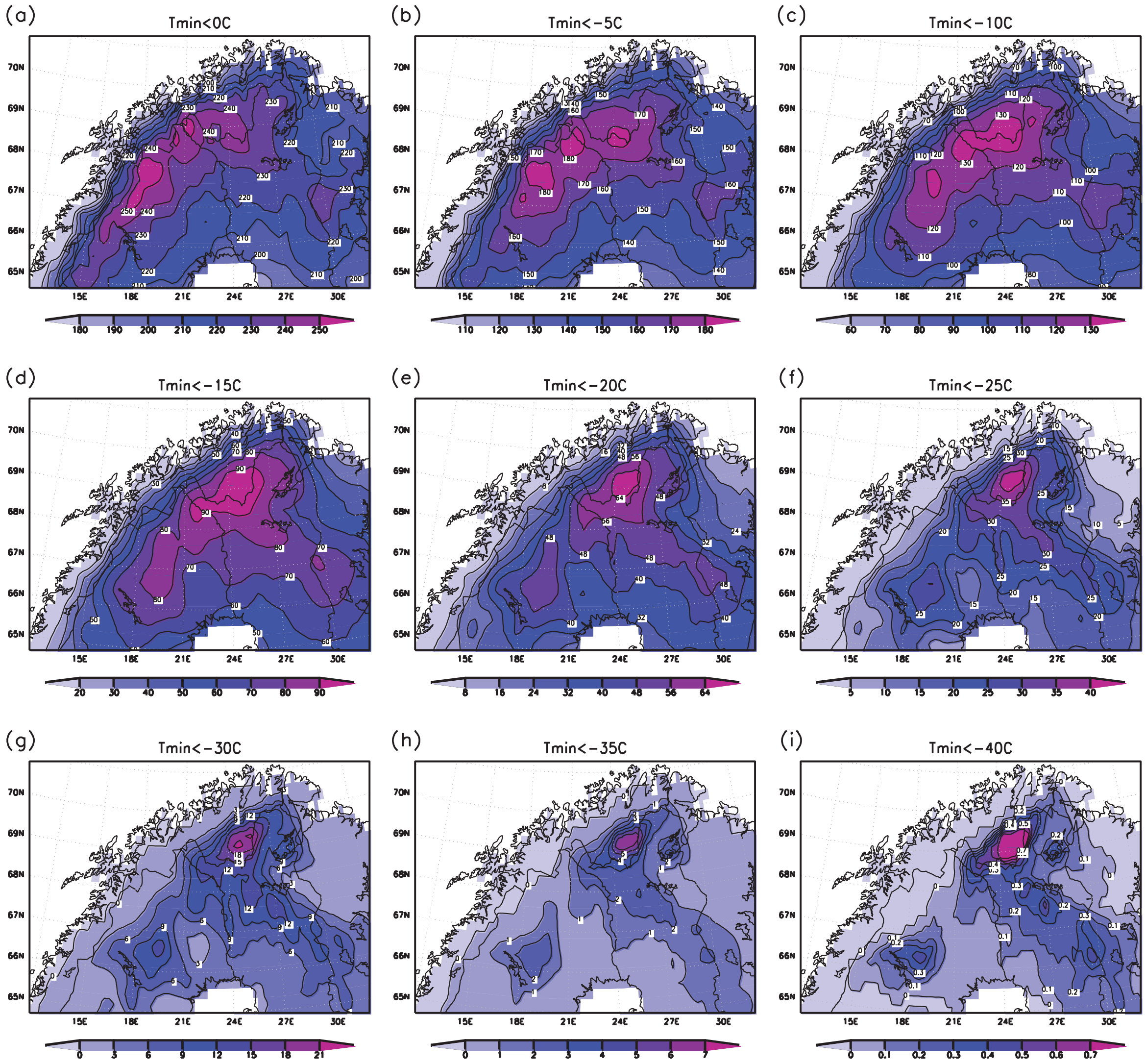

Figure 2. Average annual number of cold days with minimum temperature below (a) 0 °C, (b) -5 °C, (c) -10 °C, (d) -15 °C, (e) -20 °C, (f) -25 °C, (g) -30 °C, (h) -35 °C and (i) -40 °C in 1981–2010.

Fennoscandia. Typically winter there lasts from the end of November to the beginning of April, being much milder and shorter compared to that on the leeside of the Scandinavian mountains.

Frost days (daily minimum temperature < 0 °C) occur most commonly over the same areas where the thermal winter lasts longest (Fig. 2). The highest value for the annual average number of days for sub-zero temperatures to occur is over 250. On the coast of the Gulf of Bothnia, the number of such days remains typically below 200 per year, while an even smaller number of frost days occurs on the Norwegian coast. However, the occurrence of very low temperatures is centred somewhat differently. Most days with a minimum temperature below -20 °C occur in area extending from the Koillismaa region northwestwards towards the Swedish side of Lapland and the interior of Finnmark. Temperatures below -20 °C are reached over quite large areas on an average of 50–60 days annually, below -30 °C on approximately ten days and even below -35 °C on 1–5 days. Nowhere is -40 °C reached regularly every year.

Despite the cold winter climate in northern Fennoscandia, mild weather occasionally prevails even during the winter months. Over most of Lapland, there are an average of 15–30 thaw days (daily maximum temperature > 0 °C) between November and March (Fig. 3). During the same months on the coast of the Gulf of Bothnia, the number of thaw days in an average year reaches 50. On the Norwegian coast, thaw days are much more common even than this. However, in winter temperature rarely rises over 5 °C and only very occasionally over 10 °C. Along with the Norwegian coast, such exceptional high winter temperatures also occur more than elsewhere in the Torne Valley due to a foehn wind that occasionally blows down from the Scandinavian mountains.

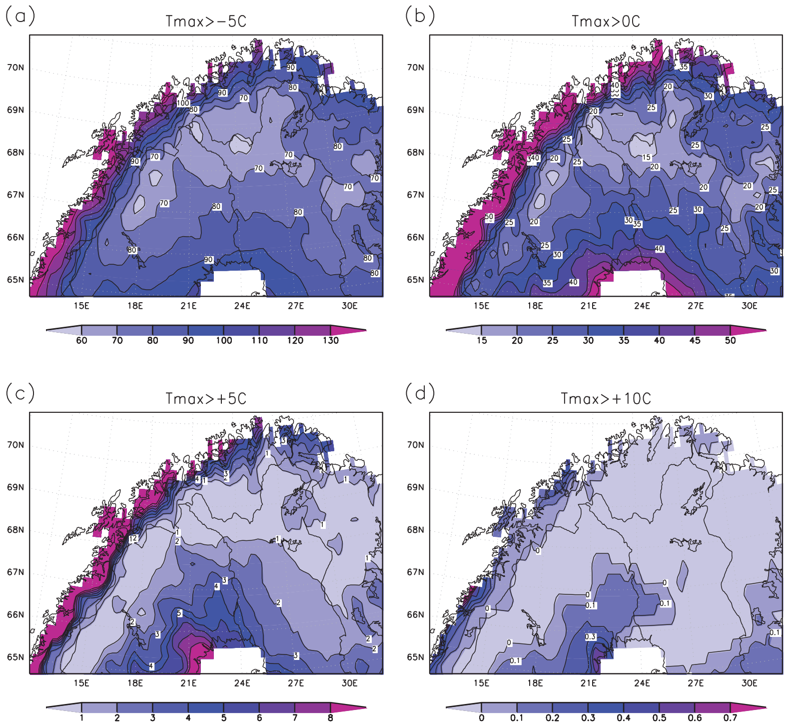

Figure 3. Average annual number of mild days with maximum temperature above (a) -5 °C, (b) 0 °C, (c) 5 °C and (d) 10 °C between November and March in 1981–2010.

Along with low temperatures, the winter climate in northern Fennoscandia is characterized by abundant snowfall. In the mountainous areas, a permanent snow cover typically forms in October and elsewhere in November (Fig. 4). Occasional snowfall episodes already occur earlier in the autumn. In spring, the snow cover typically disappears from some of the southernmost parts of Lapland and Norrbotten in late April and from elsewhere during May. The highest mountain regions are an exception, as there the snow does not usually melt until early June.

During a typical winter, the snow depth gradually increases until it peaks in March. Over most of Lapland, the ground in mid-March is covered on average with a 60–80 cm thick snow layer (Fig. 5). The most snow is to be found in the mountainous regions on the border

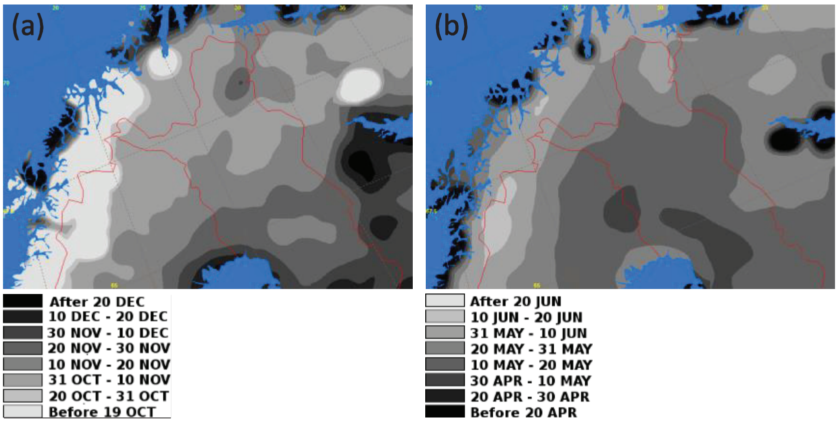

Figure 4. Average (a) formation date of permanent snow cover and (b) melting date of last snow cover in 1981–2010.

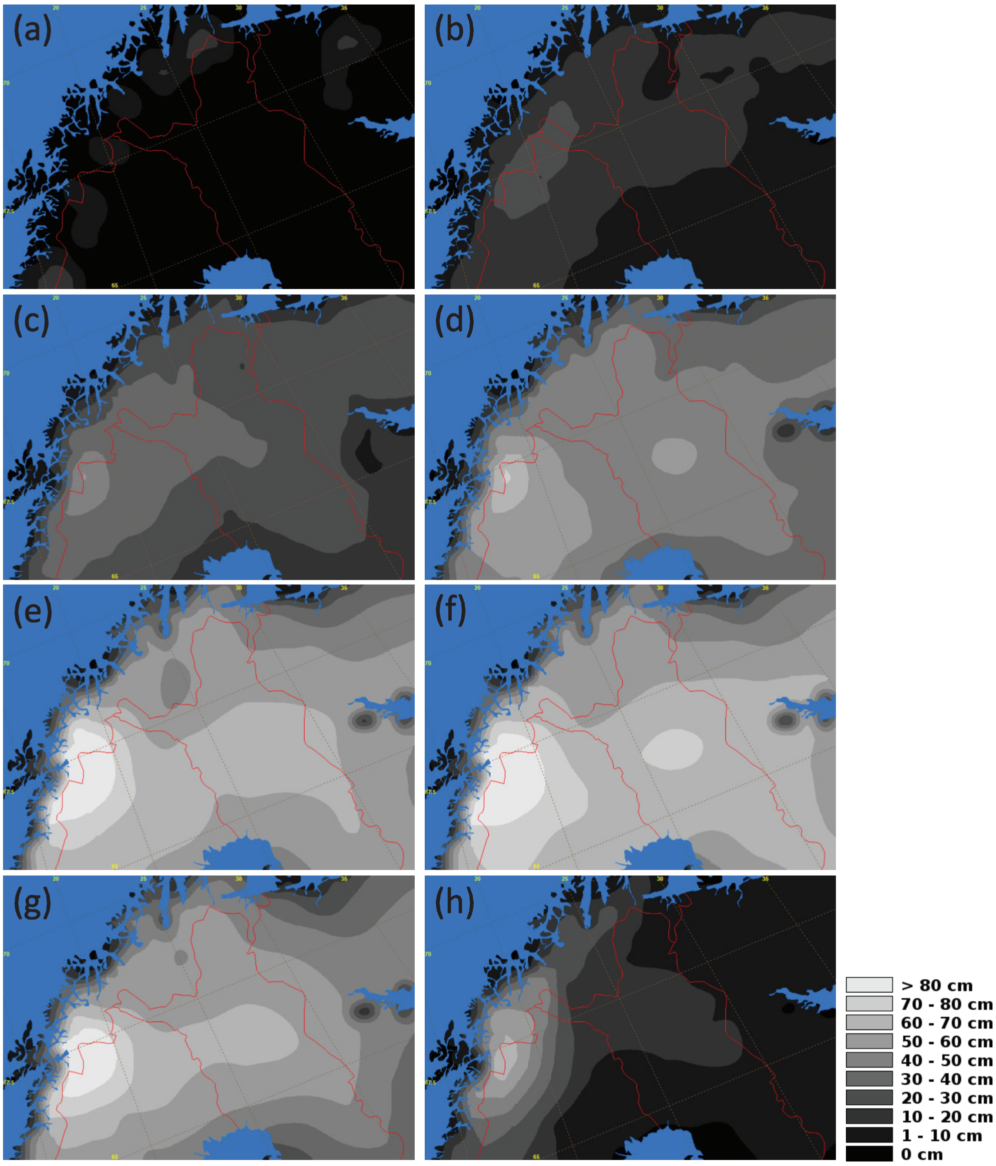

Figure 5. Average snow depth on (a) 15th October, (b) 15th November, (c) 15th December, (d) 15th January, (e) 15th February, (f) 15th March, (g) 15th April and (h) 15th May in 1981–2010.

between Sweden and Norway, where even in mid-May there is still an average of half a metre of snow on the ground.

Lake ice reaches its threshold thickness of 35 cm on average earliest in the mountainous regions, where the thermal winter lasts longest (Fig. 6). Except for the Norwegian coast, the modelled lake ice thickness reaches 35 cm everywhere in northern Fennoscandia on average within two months of the onset of thermal winter. Consequently, this date is in December, with the exception of coastal areas.

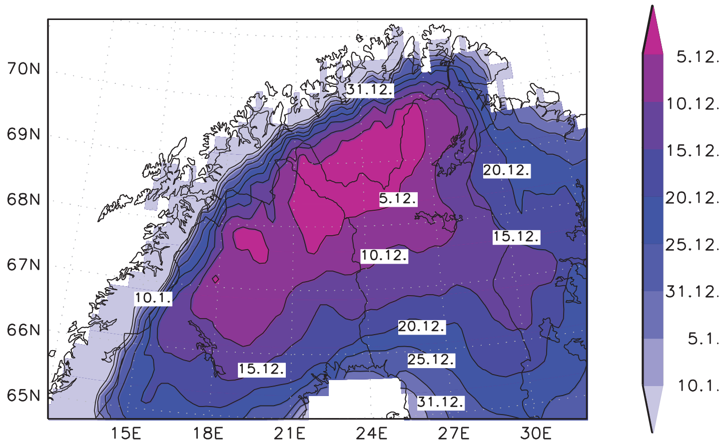

Figure 6. Date on which lake ice thickness on average reached 35 cm in 1981–2010 as estimated by Stefan's type of equation (Stefan, 1890).

3.2 The effect of climate change

The average lengths of the thermal winter with respect to a geographically-equal fixed midwinter warming of 1, 2, 3, and 4 °C are displayed in Fig. 7. Comparison with Fig. 1 reveals that a modest warming of 1 °C will shorten the thermal winter by only a couple of days. A warming of 2 °C brings about a contraction of about ten days in the length of the thermal winter, while with a 3 °C warming the thermal winter is predicted to shorten by almost three weeks. Depending on the location, a rise of 4 °C in midwinter temperatures would lead to a shortening of approximately 20–40 days in the length of the thermal winter. Thus, the thermal winter would on average then last only in the highest mountainous areas as long as it does in central Lapland at present, i.e., about six months. Correspondingly, the present conditions prevailing on the coast of the Gulf of Bothnia would be shifted approximately 200 kilometres northwards.

The impact of wintertime warming on the length of the snow season is rather similar to that on the length of the thermal winter. Owing to the warming, the annual count of days with snow cover is projected to diminish most in the coastal regions and least in the mountainous areas (Fig. 8). Nonetheless, the differences in the projections between different areas are not very remarkable, particularly with a smallish warming. The projected decrease in the number of snow-covered days is due to a shortening of the snow season from both ends.

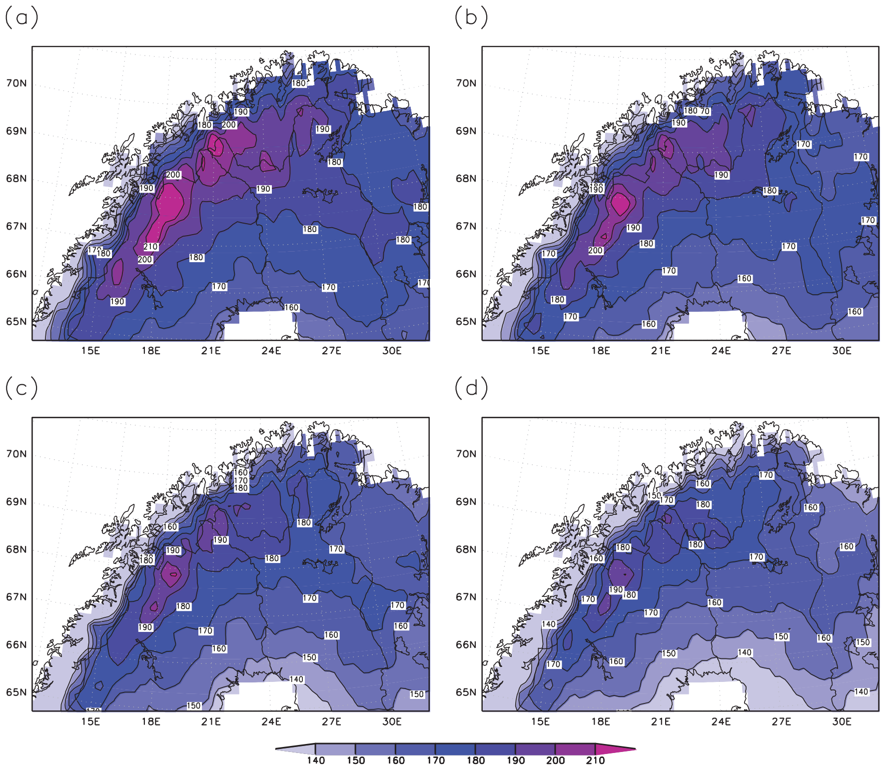

Figure 7. Average length (days) of the thermal winter when midwinter temperatures have risen (a) 1 °C, (b) 2 °C, (c) 3 °C and (d) 4 °C compared to the mean of 1981–2010.

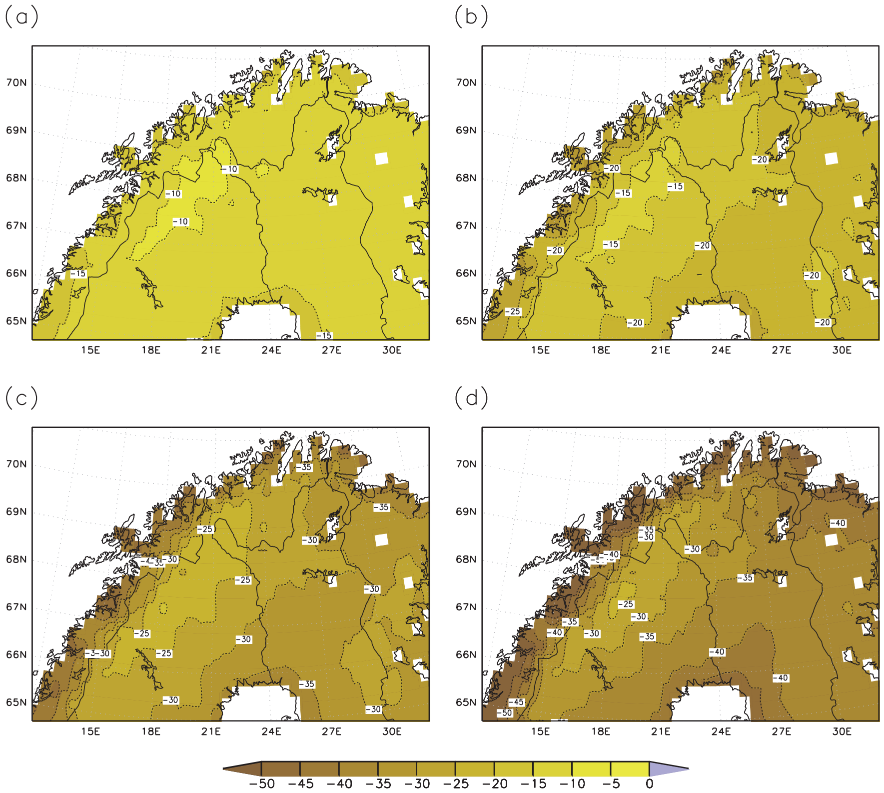

Figure 8. Projected multi-model mean change in annual average number of days with snow cover when midwinter temperatures have risen (a) 1 °C, (b) 2 °C, (c) 3 °C and (d) 4 °C compared to the mean of 1981–2010.

According to a best guess based on a large ensemble of climate model simulations under the SRES A1B scenario, midwinter temperatures in northern Finland will have risen 1 °C by about 2015, 2 °C before 2030, 3 °C by circa 2040 and 4 °C in the 2050s compared to the mean of 1981–2010 (Jylhä *et al.*, 2009). Differences in the projections between the different emission scenarios are rather small before the 2050s, but in the low-emission B1 scenario the projected warming will take place somewhat later, especially for a greater warming. When compared with the very recent climate projections based on the so-called representative concentration pathways (RCP) emission scenarios used in the Climate Model Intercomparison Project 5 (Taylor *et al.*, 2012) and in the fifth IPCC Assessment Report, the rate of wintertime warming in northern Fennoscandia will go ahead during the next few decades at a rather similar rate to that indicated by the older SRES scenarios. Even in the near future there is, however, a considerable amount of scatter among the different climate model projections regarding the rate of warming: in the next few decades, the 90% confidence level for the rate of projected temperature rise is approximately 4–5 °C wide (Jylhä *et al.*, 2009). To conclude, there is notable uncertainty about the timing for a certain amount of warming to be realized, but still the choice of the emission scenario is not very significant in the near future.

4. Discussion and conclusions

We have presented a mesoscale description of the winter climate in northern Fennoscandia in 1981–2010 based on gridded temperature data and space-borne SWE measurements combined with ground-based observations. In addition, the effect of climate change has been briefly estimated.

The data have proved to be suitable for our purposes. The most noteworthy problem was that satellite measurements had difficulties in detecting a thin snow cover, which most likely delayed the estimate for the average formation date of a permanent snow cover. On the other hand, misinterpretation of ice-covered lake or sea surfaces as snow-covered land in satellite measurements possibly caused some errors in estimating the average melting date of snow cover. Nonetheless, SWE-based estimates for average snow depth proved to agree very closely with station measurements in northern Finland (Pirinen *et al.*, 2012), particularly with snow depths of over 10 cm.

The results for the occurrence of very low temperatures show a somewhat suspicious feature in that these temperatures occur much more frequently in continental Finnmark compared to nearby areas (Fig. 2g-i). This might result from the interpolation of observations from some individual stations where low temperatures occur commonly. In any case, presenting the average occurrence of such low temperatures on a map of this resolution is slightly questionable, because the occurrence is strongly influenced by small-scale topographical features. Typically, a strong and shallow temperature inversion is present when the lowest temperatures are observed. Consequently, cold days occur much more regularly in depressions and river valleys than on hilltops. Although the kriging interpolation takes into account altitude differences, the occurrence of very low temperatures in a certain region in a gridded data set is influenced by the disposition of the observation stations used, especially when the observation network is scarce.

This study exemplifies the applicability of gridded data sets when inspecting the spatial variation of climate in a certain region. Moreover, the results have a wide range of practical applications from searching for winter tyre and car testing sites to the tourism industry. The harshest winter conditions are found to occur in the mountainous regions of north-western Sweden, in north-western Finland and in the highlands of continental Finnmark. In the areas bordering the Gulf of Bothnia, winters are milder and shorter compared to other areas east of the Scandinavian mountains. In coastal, Norway winters are vastly milder than elsewhere in northern Fennoscandia. When implementing these results in decision-making, it is noteworthy that the areas with the cruellest winters are just those that are logistically the most inaccessible.

While global warming continues, winters in northern Fennoscandia will become warmer. However, even with a 4 °C warming in midwinter, the thermal winter will still prevail on average for over five months in Fennoscandia in most areas north of the Arctic Circle; in the mountainous regions it will last no less than half a year. The snow season is projected to shorten most in the coastal regions and least in the mountainous areas, where snow already lies the longest nowadays. Over most of the study area, the snow season is projected to shorten by approximately one month in response to a 3°C midwinter warming.

As a final conclusion, the winter weather in northern Fennoscandia will on average continue to be favourable for tourism as well as for the testing the cars and snow tyres. The annual variation may become larger, however, under the changing climate, and this might imply challenges in strategic planning for car testing and tourism. This work serves as a good background for understanding the timeline of average changes and where to adjust in the long term.

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