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ORIGINAL PAPER

Variability of the start of the growing season in Fennoscandia, 1982–2002

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Abstract Fennoscandia is characterized by a large degree of climatic diversity. Vegetation phenology may respond differently to climate change according to the climatic gradients within the region. To map the annual and spatial variability of the start of the growing season (SOS) in Fennoscandia, the twice-monthly GIMMS-NDVI satellite dataset was used. The data set has an 8×8 km^2 spatial resolution and covers the period from 1982 to 2002. The mapping was done by applying pixel-specific threshold values to the NDVI data. These threshold values were determined form surface phenology data on birch (*Betula* sp.). Then, we produced NDVI based maps of SOS for each of the 21 years. Finally, the time differences between the SOS and the last day of snow cover, as well as dates of passing different temperatures, were analyzed for 21 meteorological stations. The analyses showed that 1985 was the most extreme year in terms of late SOS. In terms of early SOS, the year 1990 was by far the most extreme. Locally, the SOS has an average range of 1 month between the earliest and latest recorded SOS, with a trend towards a bigger range in the oceanic parts. The results indicate that a 1°C increase in spring temperatures in general corresponds to an advancement of 5–6 days in SOS. However, there is a clear trend according to the degree of oceanity, with a 1°C increase in the most oceanic parts corresponding roughly to 7–9 days earlier SOS, compared to less than 5 days earlier in the continental parts.

Keywords Fennoscandia · Phenology · Start of the growing season · NDVI · Air temperature

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Introduction

Fennoscandia is characterized by strong climate gradients running from the north to the south, from the west to the east, and from the lowlands to the mountains. Regional variation in vegetation is associated with these climatic contrasts and can be expressed in terms of vegetation zones and sections (Moen 1999). Vegetation zones are considered to mostly reflect temperature sums, whereas vegetation sections indicate oceanity gradients (Fig. 1). Hence, southern zones have an early start of the growing season (SOS) compared with northern zones. Likewise, in the oceanic sections, spring starts earlier than in the continental sections (Karlsen et al. 2006). To model future changes in the SOS under climate change scenarios, there is a need for knowledge of the spatial and temporal patterns in the SOS. For instance, a short growing season characterizes the boreal zones and the alpine belts within the continental sections (Karlsen et al. 2006). Hence, even small changes in the SOS may have a large impact on these ecosystems.

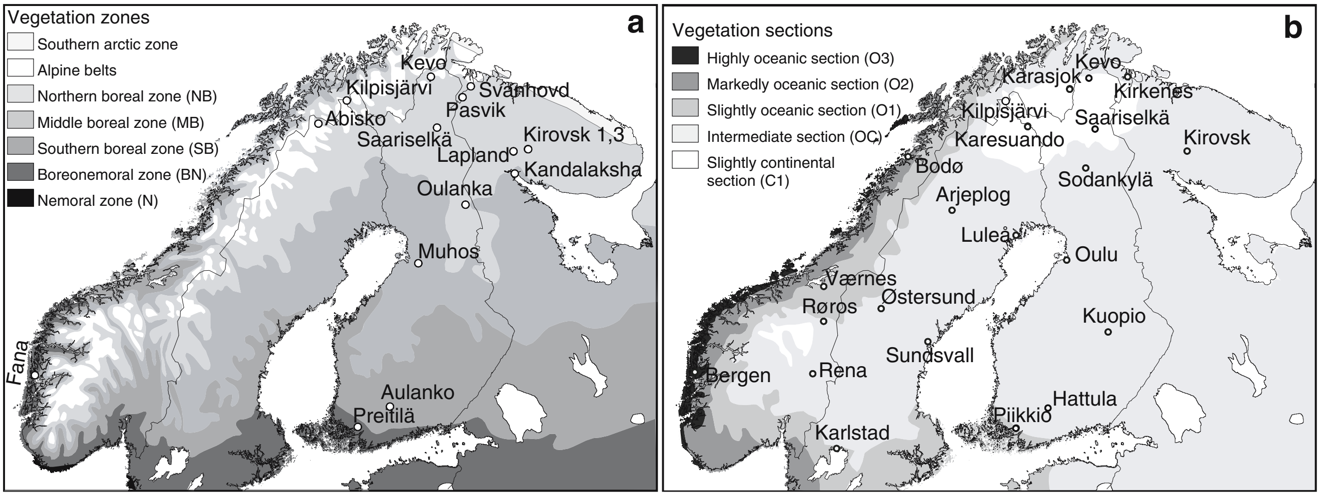


Fig. 1 Vegetation zones (**a**) and sections (**b**) in the study area, redrawn with permission from Moen (1999), along with the positions of the phenological (*left*) and meteorological (*right*) stations used in this study

The onset of plant phenological phases in spring at high latitude regions like Fennoscandia depends strongly on the spring temperature regime (e.g., Heide 1993; Wielgolaski 1999; Chmielewski and Rötzer 2001; Emberlin et al. 2002; Karlsson et al. 2003). However, one should be aware of the fact that the dependency of the SOS on temperature varies between species (Wielgolaski 1999; Schaber and Badeck 2003; Chmielewski et al. 2005), between ages of woody plants, and between development stages (Granier et al. 2002). The appearance of spring phenophases may also be influenced by other climatic factors, such as autumn temperature, air humidity, and soil moisture (e.g., Wielgolaski 2001, 2003; Heide 2003; Partanen et al. 2005). In boreal and arctic-alpine regions, the influences of these factors are generally minor compared with that of spring temperature. This is partly because different factors play a role at different spatial and temporal scales. In mountains, for example, the SOS is also linked to the timing of snowmelt, but locally and at a short time scale of days to weeks (Inouye and Wielgolaski 2003; Molau et al. 2005). On a longer time-scale (weekly to monthly), the mean temperature is the most important controller of spring phenophases, and the influences of other factors are therefore often overlooked. On an even longer time-scale, the mean temperature pattern follows the changes in the latitudinal global radiation distribution (cf. Wanner et al. 2001).

Satellite sensors are capable of measuring broad-scale changes in vegetation activity associated with phenological events such as the SOS. In particular, changes in the remote sensing based Normalized Difference Vegetation Index (NDVI) values are useful to map the SOS at a coarse spatial resolution (e.g., Schwartz et al. 2002; Beck et al. 2006, 2007). The NDVI is defined as: NDVI = (Ch2-Ch1)/(Ch2+Ch1), where Ch1 is red light reflectance and Ch2 represents near infrared reflectance. NDVI has evolved over two decades as the primary tool for monitoring changes in the vegetation activity. Numerous studies confirm the relationship between climate variability and fluctuation in NDVI values (e.g., Yang et al. 1997; Suzuki et al. 2001; Zhou et al. 2001; Gong and Shi 2003; Piao et al. 2003).

The data used in the present study is a 21-year (1982 to 2002) Global Inventory Monitoring and Modelling Studies (GIMMS) NDVI dataset (Tucker et al. 2001; Zhou et al. 2001; Bogaert et al. 2002). The dataset was earlier used in a bioclimatic study (Karlsen et al. 2006) to find the mean SOS in Fennoscandia (Fig. 2a). This study was based on correlation analyses between NDVI and surface phenological observations of the onset of leafing of birch (*Betula* sp.). The current study uses the same dataset and method in measuring the SOS year-to-year. In addition, the current study includes temperature and snow data from 21 meteorological stations.

The main objective of this paper is to map the broad pattern in the spatial and temporal variability of the SOS across Fennoscandia and neighbouring parts of NW Russia for the period 1982–2002 using the NDVI. A sub-objective is to identify the dates of passing different temperatures which correspond in time to the SOS, according to vegetation zones and sections. Finally, we briefly discuss potential changes in the SOS under climate change scenarios.

Materials and methods

Vegetation zone and section maps

Vegetation zones and sections have been defined by those botanic criteria (vegetation types, vegetation physiognomy and floristics) which are considered to show the strongest relationship with climate. Major classes of temperature sums lead to major classes of plant cover responses, which can be expressed as vegetation zones. Vegetation zones mainly vary

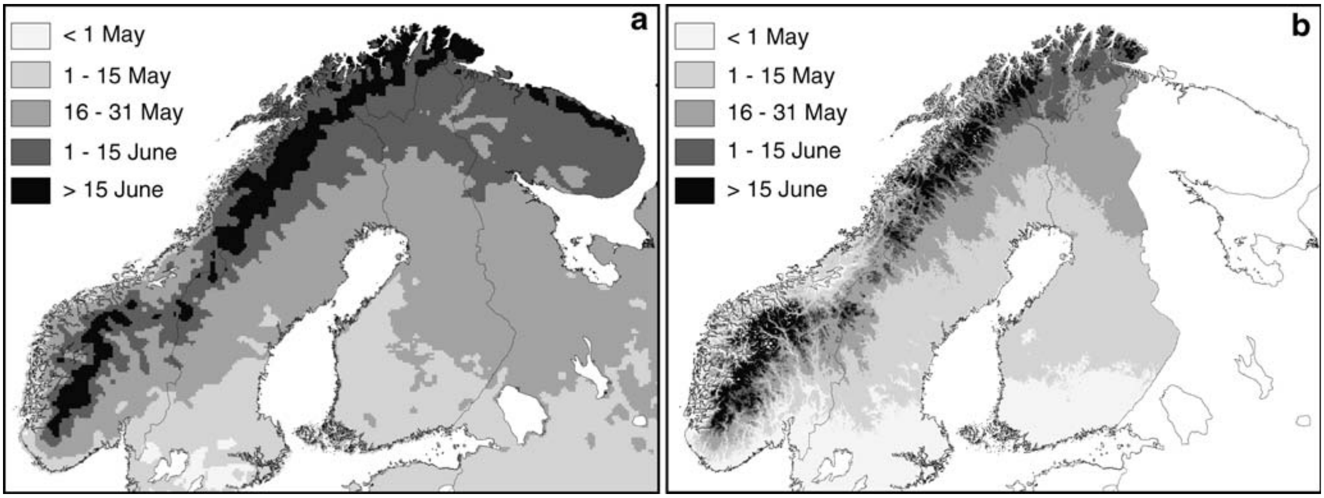


Fig. 2 (**a**) Date of the start of the growing season (SOS) as defined from the GIMMS–NDVI dataset. Mean values for the period from 1982 to 2002 are given. Redrawn and rescaled from Karlsen et al. (2006). (**b**) Date when the daily mean temperatures of the 1961–1990 normal period passes 5°C in spring. Redrawn and rescaled with permission from Tveito et al. (2001)

from north to south in Fennoscandia. The variation in vegetation sections depends on differences in oceanity, where air humidity, winter temperature (frost), and temperature differences between the coldest and the warmest month are important climatic criteria. Vegetation sections mainly show a pattern from the coast to the interior in Fennoscandia. The concept of vegetation zones and sections has a long tradition among Fennoscandian authors. The vegetation zone and section maps by Moen (1999) are used as a major reference here (Fig. 1), including 'region' as a combination of zonal and sectorial units. These maps are mainly a synthesis of earlier work by Fennoscandian investigators, such as Ahti et al. (1968), Dahl et al. (1986), and others.

In the study area, the northern boreal (NB), middle boreal (MB), and southern boreal (SB) zones are characterized by coniferous forests. The boreonemoral zone (BN) forms a transition between the nemoral zone (N), which is characterized by broad-leaved deciduous forest, and the typical coniferous forests. The highly oceanic (O3), markedly oceanic (O2), and the slightly oceanic (O1) sections are all characterized by a long growing season, high annual precipitation, and western species (Moen 1999). The intermediate oceanic section (OC) forms a transition between the oceanic and continental parts and occupies roughly three-quarters of the study area. The slightly continental section (C1) is characterized by a short growing season and low annual precipitation. The MB-OC region is the most common in the study area and occupies roughly a quarter of it, followed by the NB-OC region and the SB-OC regions, each occupying slightly less than one-fifth.

Climate data

We used air temperature data and snow data from 21 meteorological stations across Fennoscandia for the period 1982–2002 (Fig. 1b). The stations are operated by the meteorological institutes in the Nordic countries and by the Polar Alpine Botanical Garden Institute at Kirovsk in Russia. All stations are in the lowlands, except for Kirovsk (319 m a.s.l.). The meteorological stations were selected to cover the main vegetation zones and sections (Fig. 1). For various reasons, there are some missing values in the climate data series.

GIMMS-NDVI dataset

A NDVI dataset produced by the GIMMS group at NASA Goddard Space Flight Center was analyzed. The GIMMS dataset is produced by data from the AVHRR instrument onboard the afternoon-viewing NOAA satellite series (NOAA 7, 9, 11, 14, and 16). The dataset has an 8×8 km^2 resolution and is composed of the maximum NDVI values for twice-monthly periods between July 1981 and December 2002. The processing of the dataset includes calibration of the four different sensors, corrections for sensor degradation, and for atmospheric effects, such as Rayleigh absorption and scattering, and atmospheric correction for El Chichón and Pinatubo aerosols. Details of the dataset are described by Tucker et al. (2001), Zhou et al. (2001), and Bogaert et al. (2002). Different versions of the GIMMS data have been used in numerous studies investigating the relationship between climate and vegetation (e.g., Myneni et al. 1997; Bogaert et al. 2002; Kaufmann et al. 2003).

Estimating the SOS from the NDVI

In order to estimate the SOS, we applied a pixel-by-pixel based method, first used by Høgda et al. (2001) and described and discussed by Karlsen et al. (2006). Here, we use the same GIMMS–NDVI dataset, surface phenological dataset, and method for mapping the SOS as used by Karlsen et al. (2006). In the following, we give a summary of the method and the relevant results from the previous work for the current study. First, the NDVI values were calculated for a 3×3 pixel area centred on each of the 15 phenological stations. In some cases, the centre position of the 3×3 pixel area was adjusted by 1 pixel to avoid inclusions of pixels not representative for the area around a station, e.g. water, high altitude, and human impact areas. Topographical maps, a terrain model derived from MOD03 data (Guenther et al. 1998), and a vegetation map from the Baltic Sea drainage area (Malmberg 2001) were used in this adjustment process to find representative areas.

To link surface phenology with NDVI data to measure the SOS, we computed, for every pixel, a 21-year mean NDVI value (NDVI > 0) for the period 1982–2002. Only using NDVI values > 0 reduces the 'noise' from snow-covered ground and the period of polar night. As the date for the SOS, the last day in the half-month period during which a pixel-specific 21-year mean NDVI threshold was passed (upwards) was used. This threshold was chosen because it showed the highest correlation with the phenophase onset of leafing of birch. Other thresholds were tested, but gave results that were less correlated with the field data, and the one used was found by several iterations. Other methods that work on a pixel-by-pixel basis were also tried, for instance using the period of steepest increase in NDVI as the timing of SOS (White et al. 1997), but they gave low correlation when compared with field observations in our study area. An earlier comparison of the method chosen with other methods showed that it is most suitable for the GIMMS–NDVI dataset of the study area (Karlsen et al. 2006). However, it must be noted that the validity of the method depends on the calibration of the NDVI data with regard to the winter period.

We compared the NDVI-defined SOS with registrations of the onset of leafing of birch at 15 phenological registration sites across Fennoscandia (Fig. 1a). However, the registration sites are unevenly distributed, with most stations situated within the northern part of the study area. Most (13 out of 15) of the stations showed a moderately high correlation (r^2=0.22–0.65) between field data and the NDVI-defined SOS (Karlsen et al. 2006). Four of the stations had 20- or 21-year-long time-series. For these stations, the mean coefficient of determination (r^2) between the SOS and the onset of leafing of birch was 0.39 ($p<0.05$). For all stations (except for Preitilä in SW Finland), the mean time span between the NDVI-defined SOS and the onset of leafing of birch was less than 1 week, and the root mean square error between field data and NDVI data was less than 10 days for all stations.

While Karlsen et al. (2006) only calculated the mean SOS for the 1982–2002 period (Fig. 2a), this study goes further. Here, we map for each of the 21 years the deviation of the SOS from the mean SOS for the 1982–2002 period. To improve the cartographic presentation, a 4×4 median filter is applied to all the final NDVI based products.

Climate data analyses

The first step in the analyses was to calculate the yearly date of passing of 5, 7, and 10°C temperatures at each meteorological station. The 5 and 10°C passing temperatures were chosen because they are widely used by climatologists in Fennoscandia to characterize the start/end of spring and summer (Tuhkanen 1980; Tveito et al. 2001; Skaugen and Tveito 2004). The date of passing 7°C was chosen because in most cases 5°C was too early and 10°C too late compared with the dates of the NDVI-defined SOS. The last day of continuous snow cover was used to estimate the time from snowmelt to the date of greening. Especially in the most oceanic areas there are often mild periods even in winter when the daily mean temperatures exceed 5, 7, or even 10°C. To avoid such possible very early dates, the date of passing these temperatures is based on the 21-day moving average of the mean daily temperature. The passing-date is then defined as the first day when the moving average passed and stayed above these temperatures for at least 2 weeks.

The last day of continuous snow cover was defined as the first snow free day, without any periods of 5 days or longer with snow cover later during the spring. This criterion ensures that the date of 'general snow melt' is used, ignoring shorter snow-free periods in winter as well as exceptionally late snow fall.

The NDVI-defined SOS was calculated for a 3×3 pixel area centred on each of the 21 meteorological stations. In some cases it was adjusted by 1 pixel in a similar way as for the phenological data to avoid obvious ground-cover heterogeneity. The last step in the processing was to analyze the relationship between the climatic parameters calculated and the NDVI-defined SOS at each meteorological station.

Results

Annual and spatial variability

The year 1985 was generally the most extreme in terms of late NDVI-defined SOS. In this year, 62% of the study area showed a late or very late SOS, with only parts of northern and western Norway and southern Finland showing a SOS close to the average (Fig. 3). The SOS in 1982 was late in most of the study area (56%), but not in southern Norway and southernmost Finland. At the climate station in Bodø,

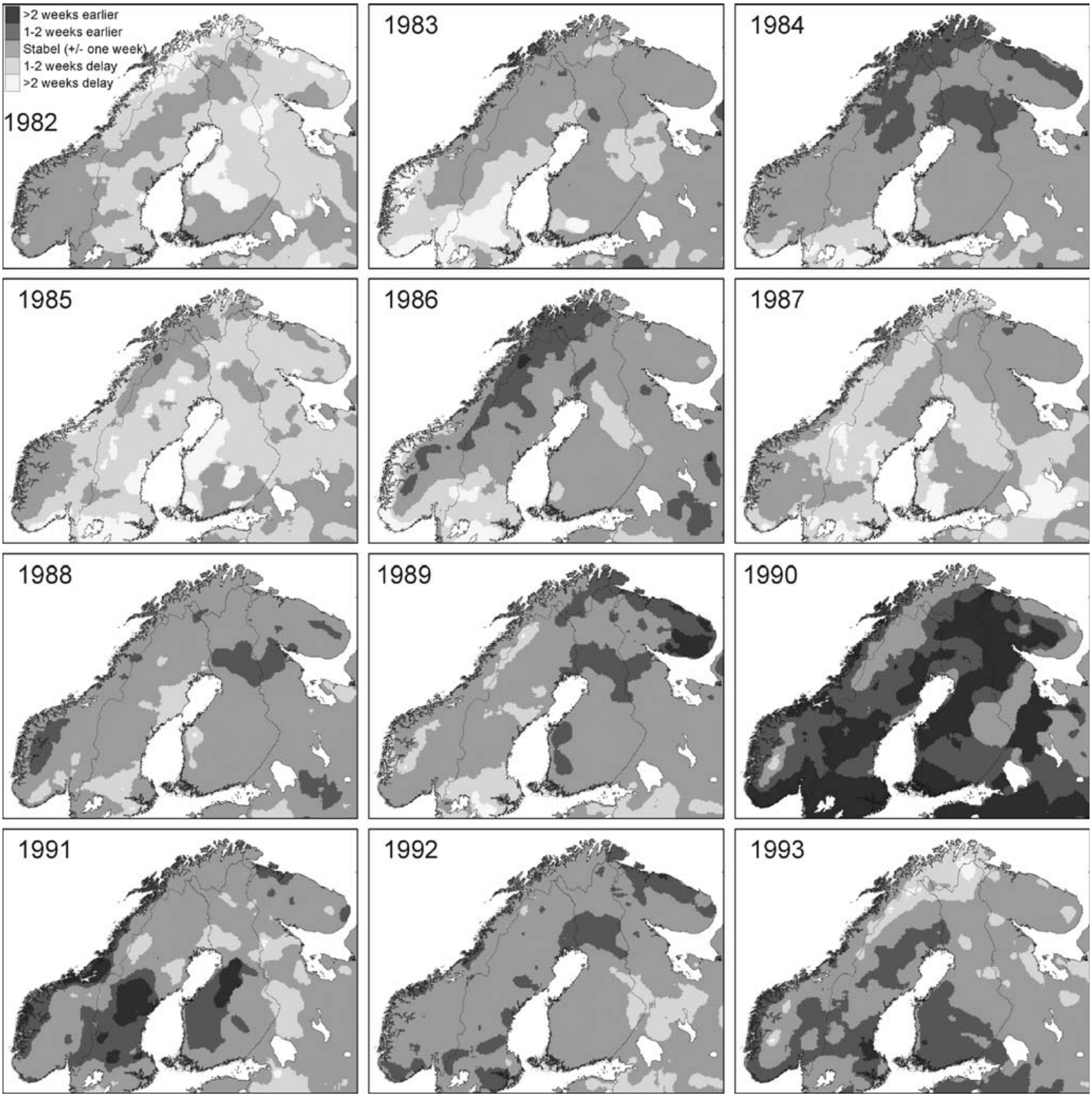


Fig. 3 Regional deviation in the start of the growing season (SOS) from the 1982–2002 average

for instance, the SOS occurred on 10 June in 1982, which is 15 days later than the average SOS for this station (Fig. 4). The year 1983 showed a late SOS in southern Norway and southern Sweden, while the years 1987, 1995, and 1997 showed a late SOS in most of central Fennoscandia, and the year 2000 a late SOS in the northern continental areas (the NB-C1 region; Fig. 1).

In terms of early SOS, the year 1990 was by far the most extreme, showing early or very early SOS in 72% of the study area (Fig. 3). In this year, the 5% of the study area with late SOS was found in very high altitude areas in southern Norway. At 13 of the 21 climate stations, the earliest NDVI-defined SOS of the analyzed period occurred in 1990 (Fig. 4). Most exceptional was the SOS at the climate station Piikkio in south-westernmost Finland, where the NDVI data showed a SOS 25 days earlier than the 21-year average (17 April vs 12 May). The spring in 2002 was early in 55% of the study area and the northern parts, in particular, showed a

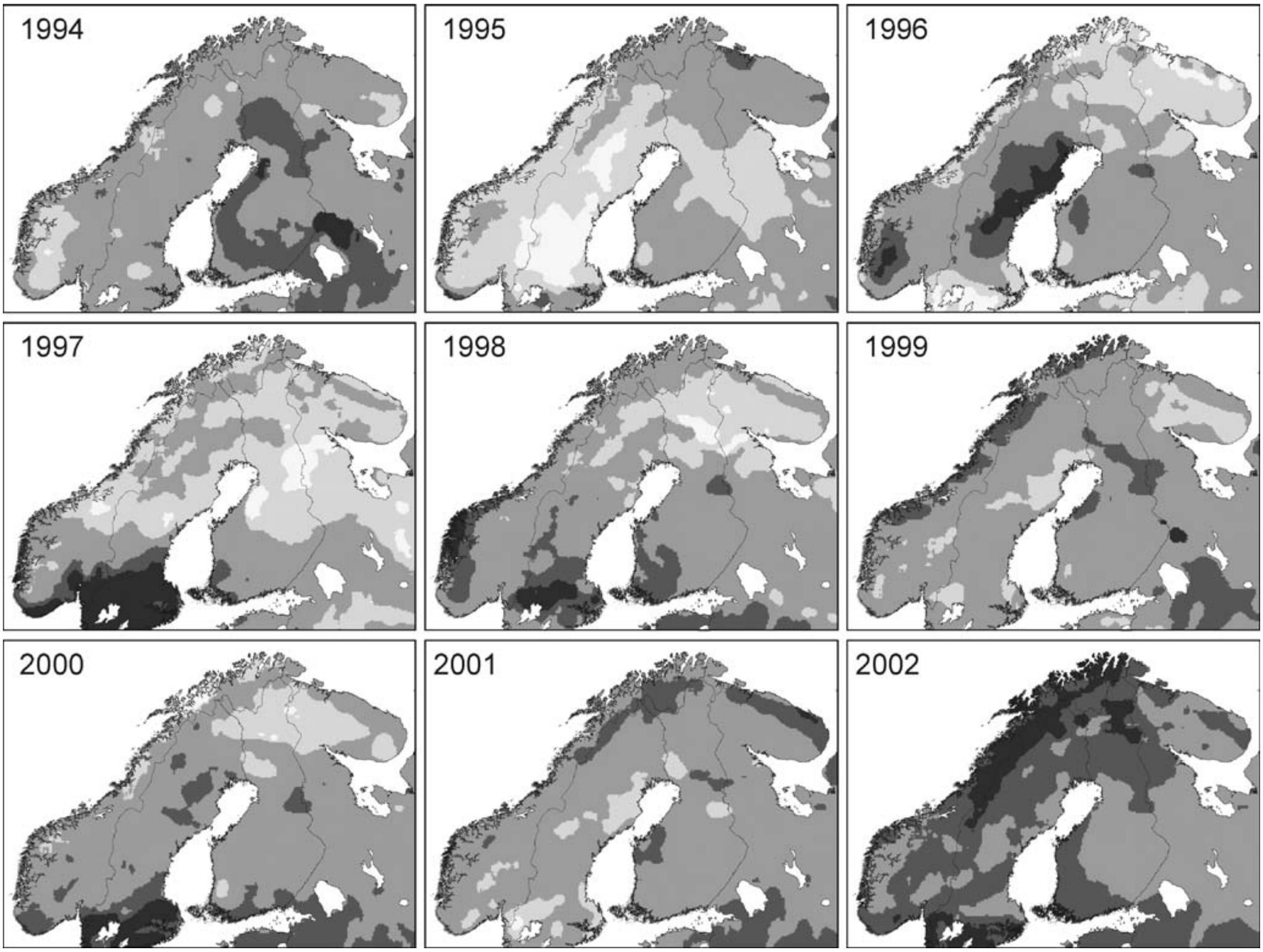


Fig. 3 (continued)

very early spring. The springs of 1984 and 1986 were early in the northern oceanic parts. Some other years, however, showed a very early SOS for small parts of the study area, and these spots are interpreted as outliers.

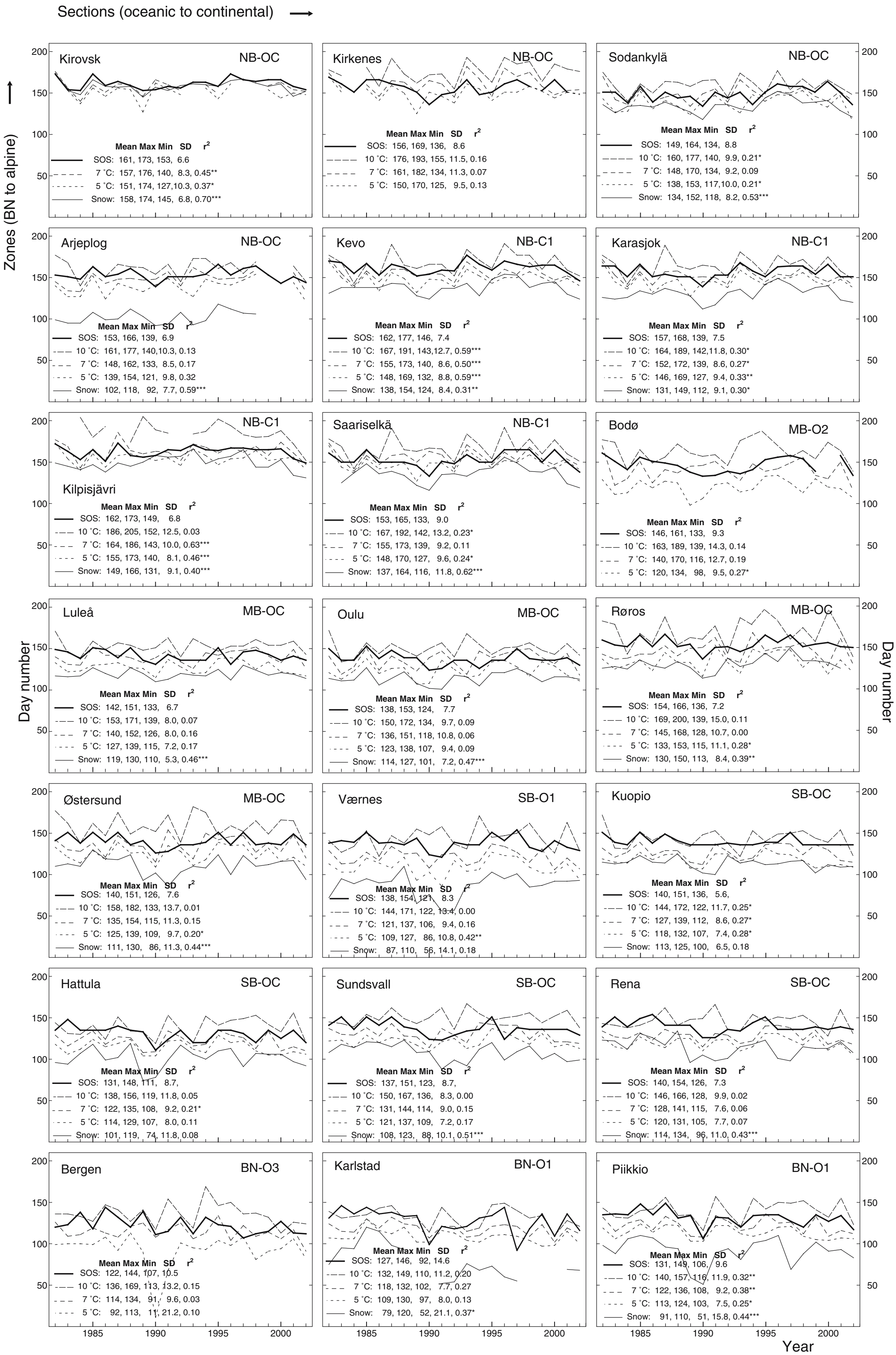
The years 1988, 1992, 1999, and 2001 each displayed an average SOS in more than 60% of the study area, and are useful as reference years when studying the effects of climatic change.

The average time span between the earliest and the latest NDVI-defined SOS at the 21 climatic stations is 1 month with a standard deviation (SD) of 8 days (Table 1). However, there is a clear spatial pattern as the oceanic sections have a much larger interannual variation. The O1/O2/O3 stations show an average variation of 39 days (SD 10.5 days) between the earliest and the latest SOS. The OC/C1 sections in contrast show an average variation of 27 days (SD 7.6 days) (Table 1). The high variability of 54 days in SOS at Karlstad in southern Sweden is due to the very early SOS in 1997 (2 April), which is interpreted as an outlier.

Relationship between the NDVI-defined SOS and climate parameters

Most stations show a moderately high correlation between the last day of continuous snow cover and the SOS (r^2-value ranges from 0.08 to 0.70 (Fig. 4), and has a mean of 0.39 (Table 1)). Ten of the 18 stations with snow data were significant at the 0.1 level. There is a trend of higher correlation between the last day of continuous snow cover and NDVI-defined SOS for northern stations, with the seven stations in the NB zone having a mean r^2-value of 0.48 (Table 1).

Fig. 4 Start of the growing season (SOS) as measured from NDVI data as well as the last day of continuous snow cover and the date of passing three different temperatures. Mean day number (*mean*), latest day number (*max*), earliest day number (*min*), and standard deviation (*SD*) are given, as are coefficient of determination values (r^2) between NDVI-defined SOS and climate variables, where * = significant at the 5% level, ** = significant at the 1% level, and *** = significant at the 0.1% level. Each meteorological station has a code for the ecogeographical region it belongs to (see Fig. 1) ▶



Sections (oceanic to continental)
Zones (BN to alpine)
Day number
Year
Kirovsk NB-OC
Mean Max Min SD r2
SOS: 161, 173, 153, 6.6
7 °C: 157, 176, 140, 8.3, 0.45**
5 °C: 151, 174, 127,10.3, 0.37*
Snow: 158, 174, 145, 6.8, 0.70***
Kirkenes NB-OC
Mean Max Min SD r2
SOS: 156, 169, 136, 8.6
10 °C: 176, 193, 155, 11.5, 0.16
7 °C: 161, 182, 134, 11.3, 0.07
5 °C: 150, 170, 125, 9.5, 0.13
Sodankylä NB-OC
Mean Max Min SD r2
SOS: 149, 164, 134, 8.8
10 °C: 160, 177, 140, 9.9, 0.21*
7 °C: 148, 170, 134, 9.2, 0.09
5 °C: 138, 153, 117,10.0, 0.21*
Snow: 134, 152, 118, 8.2, 0.53***
Arjeplog NB-OC
Mean Max Min SD r2
SOS: 153, 166, 139, 6.9
10 °C: 161, 177, 140,10.3, 0.13
7 °C: 148, 162, 133, 8.5, 0.17
5 °C: 139, 154, 121, 9.8, 0.32
Snow: 102, 118, 92, 7.7, 0.59***
Kevo NB-C1
Mean Max Min SD r2
SOS: 162, 177, 146, 7.4
10 °C: 167, 191, 143,12.7, 0.59***
7 °C: 155, 173, 140, 8.6, 0.50***
5 °C: 148, 169, 132, 8.8, 0.59***
Snow: 138, 154, 124, 8.4, 0.31**
Karasjok NB-C1
Mean Max Min SD r2
SOS: 157, 168, 139, 7.5
10 °C: 164, 189, 142,11.8, 0.30*
7 °C: 152, 172, 139, 8.6, 0.27*
5 °C: 146, 169, 127, 9.4, 0.33**
Snow: 131, 149, 112, 9.1, 0.30*
Kilpisjävri NB-C1
Mean Max Min SD r2
SOS: 162, 173, 149, 6.8
10 °C: 186, 205, 152, 12.5, 0.03
7 °C: 164, 186, 143, 10.0, 0.63***
5 °C: 155, 173, 140, 8.1, 0.46***
Snow: 149, 166, 131, 9.1, 0.40***
Saariselkä NB-C1
Mean Max Min SD r2
SOS: 153, 165, 133, 9.0
10 °C: 167, 192, 142, 13.2, 0.23*
7 °C: 155, 173, 139, 9.2, 0.11
5 °C: 148, 170, 127, 9.6, 0.24*
Snow: 137, 164, 116, 11.8, 0.62***
Bodø MB-O2
Mean Max Min SD r2
SOS: 146, 161, 133, 9.3
10 °C: 163, 189, 139, 14.3, 0.14
7 °C: 140, 170, 116, 12.7, 0.19
5 °C: 120, 134, 98, 9.5, 0.27*
Luleå MB-OC
Mean Max Min SD r2
SOS: 142, 151, 133, 6.7
10 °C: 153, 171, 139, 8.0, 0.07
7 °C: 140, 152, 126, 8.0, 0.16
5 °C: 127, 139, 115, 7.2, 0.17
Snow: 119, 130, 110, 5.3, 0.46***
Oulu MB-OC
Mean Max Min SD r2
SOS: 138, 153, 124, 7.7
10 °C: 150, 172, 134, 9.7, 0.09
7 °C: 136, 151, 118, 10.8, 0.06
5 °C: 123, 138, 107, 9.4, 0.09
Snow: 114, 127, 101, 7.2, 0.47***
Røros MB-OC
Mean Max Min SD r2
SOS: 154, 166, 136, 7.2
10 °C: 169, 200, 139, 15.0, 0.11
7 °C: 145, 168, 128, 10.7, 0.00
5 °C: 133, 153, 115, 11.1, 0.28*
Snow: 130, 150, 113, 8.4, 0.39**
Østersund MB-OC
Mean Max Min SD r2
SOS: 140, 151, 126, 7.6
10 °C: 158, 182, 133, 13.7, 0.01
7 °C: 135, 154, 115, 11.3, 0.15
5 °C: 125, 139, 109, 9.7, 0.20*
Snow: 111, 130, 86, 11.3, 0.44***
Værnes SB-O1
Mean Max Min SD r2
SOS: 138, 154, 121, 8.3
10 °C: 144, 171, 122, 13.4, 0.00
7 °C: 121, 137, 106, 9.4, 0.16
5 °C: 109, 127, 86, 10.8, 0.42**
Snow: 87, 110, 56, 14.1, 0.18
Kuopio SB-OC
Mean Max Min SD r2
SOS: 140, 151, 136, 5.6,
10 °C: 144, 172, 122, 11.7, 0.25*
7 °C: 127, 139, 112, 8.6, 0.27*
5 °C: 118, 132, 107, 7.4, 0.28*
Snow: 113, 125, 100, 6.5, 0.18
Hattula SB-OC
Mean Max Min SD r2
SOS: 131, 148, 111, 8.7,
10 °C: 138, 156, 119, 11.8, 0.05
7 °C: 122, 135, 108, 9.2, 0.21*
5 °C: 114, 129, 107, 8.0, 0.11
Snow: 101, 119, 74, 11.8, 0.08
Sundsvall SB-OC
Mean Max Min SD r2
SOS: 137, 151, 123, 8.7,
10 °C: 150, 167, 136, 8.3, 0.00
7 °C: 131, 144, 114, 9.0, 0.15
5 °C: 121, 137, 109, 7.2, 0.17
Snow: 108, 123, 88, 10.1, 0.51***
Rena SB-OC
Mean Max Min SD r2
SOS: 140, 154, 126, 7.3
10 °C: 146, 166, 128, 9.9, 0.02
7 °C: 128, 141, 115, 7.6, 0.06
5 °C: 120, 131, 105, 7.7, 0.07
Snow: 114, 134, 96, 11.0, 0.43***
Bergen BN-O3
Mean Max Min SD r2
SOS: 122, 144, 107, 10.5
10 °C: 136, 169, 113, 13.2, 0.15
7 °C: 114, 134, 91, 9.6, 0.03
5 °C: 92, 113, 11, 21.2, 0.10
Karlstad BN-O1
Mean Max Min SD r2
SOS: 127, 146, 92, 14.6
10 °C: 132, 149, 110, 11.2, 0.20
7 °C: 118, 132, 102, 7.7, 0.27
5 °C: 109, 130, 97, 8.0, 0.13
Snow: 79, 120, 52, 21.1, 0.37*
Piikkio BN-O1
Mean Max Min SD r2
SOS: 131, 149, 106, 9.6
10 °C: 140, 157, 116, 11.9, 0.32**
7 °C: 122, 136, 108, 9.2, 0.38**
5 °C: 113, 124, 103, 7.5, 0.25*
Snow: 91, 110, 51, 15.8, 0.44***

Table 1 Summary table of data from the 21 climate stations

Zone /sections	No st.	NDVI		Snow				5°C				7°C				10°C				Days /°C
		SD	Diff	B	r^2	SD	Diff	B	r^2	SD	Diff	B	r^2	SD	Diff	B	r^2	SD	Diff	
All stations	21	8.2	30.1	−27.3	0.39	10.2	38.3	−16.2	0.22	9.5	37.0	−5.7	0.17	9.4	34.0	11.3	0.10	11.7	44.1	5.4
NB	8	7.7	28.3	−21.1	0.48	8.7	34.1	−9.8	0.31	9.4	39.5	−1.6	0.24	9.2	35.1	12.7	0.18	11.7	44.3	4.2
MB	5	7.7	26.4	−25.0	0.44	8.1	31.8	−18.4	0.20	9.4	31.8	−4.8	0.09	10.7	38.4	14.6	0.08	12.1	46.0	6.6
SB	5	7.7	28.2	−31.2	0.26	10.7	39.4	−20.8	0.19	8.2	29.0	−11.4	0.16	8.8	28.2	7.2	0.02	11.0	41.0	5.5
BN	3	11.6	44.7	−44.0	0.40	18.5	63.5	−22.0	0.15	12.2	52.0	−8.7	0.19	8.8	33.7	9.3	0.22	12.1	45.3	6.3
OC/C1	16	7.6	27.4	−23.5	0.41	8.8	33.9	−13.7	0.23	9.0	33.9	−4.4	0.17	9.3	33.1	11.5	0.10	11.3	43.1	4.9
O3/O2/O1	5	10.5	39.0	−46.3	0.31	17.0	60.3	−24.2	0.21	11.4	46.6	−9.8	0.18	9.7	37.2	10.2	0.12	12.8	47.0	7.0

The information given in Fig. 4 is summarized according to vegetation zones and sections, where the sections are grouped in two groups, the oceanic and intermediate/continental one. *No st.* Number of climate stations within the vegetation zone / sections, *B* mean bias in days between last day of continuous snow cover / date of passing a temperature and the NDVI-based SOS, r^2 mean coefficient of determination value between last day of continuous snow cover / date of passing a temperature and the NDVI-based SOS, *SD* mean standard deviation, *Diff* mean differences in days between the earliest and latest recorded date of NDVI-based SOS / date of passing a temperature / last day of continuous snow cover. The mean difference in days/°C is calculated based on the difference in number of days between 5–7°C and 7–10°C

The average time span between last day of continuous snow cover and greenup (the NDVI-defined SOS) at the 21 meteorological stations is 27 days (Table 1). However, there is a clear pattern according to vegetation zones and sections. The meteorological stations in the NB zone shows on average 21 days (SD 8.7 days) from snowmelt to greenup versus 44 days (SD 18.5 days) in the BN zone. When comparing regions, the station Værnes (SB-O1 region) has on average 51 days from last day of continuous snow cover to greenup, while the mean value for the four stations in the SB-OC region is 26 days (Fig. 4). This also indicates a longer period from snowmelt to greenup in oceanic parts compared with continental parts.

The NDVI-defined SOS correlated slightly less well with the temperature passing-dates than with the last day of continuous snow cover. The mean r^2-values are 0.39, 0.22, and 0.10 for the dates of passing of 5, 7, and 10°C, respectively. Negative outliers in the NDVI-defined SOS estimates reduce these mean correlation coefficients. Figure 2 indicates that the SOS occurs 1–2 weeks later than when the daily normal temperature passes 5°C, except for the alpine areas. In the NB and MB zones, the SOS occurs on average less than 2 days and around 5 days after the date of passing 7°C, respectively (Table 1). This indicates that the SOS occurs around or slightly later than the date of passing 7°C in these northern zones. For the SB and BN zones, the SOS occurs approximately 10 days after passing 7°C and about 7 days before passing 10°C, suggesting it coincides with the date when the temperatures pass 8–8.5°C.

Number of days between passing different temperatures

Based on the differences in days between temperatures passing 5°C and 7°C and between temperatures passing 7°C and 10°C (Fig. 4), we estimated the effect of a difference of 1°C on the timing of the SOS. The overall mean is 5.4 days/°C (Table 1). However, there is a clear trend according to the degree of oceanity. At the most oceanic stations, the O2 and O3 stations Bodø and Bergen, 1°C corresponds with 9.0 days. For the stations within the sections O1, O2, and O3, the mean value is 7.0 days/°C (Table 1) versus 4.9 days/°C in the OC/C1 sections. The high average of 6.6 days/°C in the MB zone is due to the fact that the O2 station Bodø is located in this zone.

Discussion

The reliability of the NDVI-defined SOS maps

As summarized in Materials and methods, the phenological field data and the NDVI-defined SOS agreed well in most cases. Karlsen et al. (2006) also discussed the reliability of the mean NDVI-defined SOS map, compared the map with other phenological and climatic maps of the study area, and generally found high agreement. This indicates that we can expect the method in most cases to show the real SOS. However, since this study goes further and maps each year, we can additionally compare the results with other year-to-year data, and not only the mean dates as in Karlsen et al. (2006).

The results show both high spatial and annual variability in the SOS, and that the variability is higher in the oceanic areas than in the continental parts. The most extreme years in terms of SOS in the area are 1985 with a generally late SOS and 1990 with a very early SOS (Fig. 3). This is confirmed by the records of onset of birch pollen season at stations in Norway (Ramfjord and Brobakk 2004) and partly in Finland (Emberlin et al. 2002). In birch, budburst and the appearance of the first pollen are strongly correlated. The very early arrival of spring in 1990 is also well known from western and central Europe (e.g., Menzel 2000). Chmielewski and Rötzer (2002) have shown the annual and spatial variability of the SOS in Europe during the period 1969–1998. They mapped the timing of the SOS based on observations in the International Phenological Gardens (IPG). Five of the IPGs are located in our study area, and the IPG-maps cover Sweden, most of Norway and western parts of Finland. At a coarse spatial resolution, the NDVI-defined SOS agrees with the maps by Chmielewski and Rötzer (2002), both having 1985 as a late year and 1990 as the year with the earliest SOS in most parts of Fennoscandia. Contradictions between the results from the two studies are not found, but there are some differences in the size of the anomalies. For example, the NDVI-defined SOS shows 1988 as a generally normal year, while Chmielewski and Rötzer (2002) show it has moderately late SOS. On a more regional level, however, there are many disagreements. Our NDVI-defined SOS maps show more regional variation, and locally it even contradicts the maps by Chmielewski and Rötzer (2002), but this could be a result of different smoothing algorithms used.

The NDVI-defined SOS correlates well with the onset of leafing of birch across the study area, and the phenology data, the method used, and the reliability of the results are discussed in detail in Karlsen et al. (2006). However, this study suggests that some years the SOS can locally occur very early, which is not supported by the climate data. These outliers strongly influence the correlation between the SOS and the temperature data. Unfortunately, none of the areas with high disagreement have in-situ data on birch phenology. The SOS-map of 1991 indicates areas of very early SOS in both central parts of Norway, Sweden, and Finland. Several of the climate stations used here are located within these areas. At the station Østersund in central Sweden the r^2-value between the NDVI-defined SOS and the day of passing the 7°C temperature increases from 0.15 to 0.37 by removing 1991. However, at the same time the r^2-value with snow data decreases from 0.44 to 0.35. We can see a similar trend at the climate station at Sundsvall, Oulu, and to a certain extent at Værnes, in 1991. The SOS at these stations are negatively correlated with the temperature that year, but positively correlated with disappearance of snow. This is also the case for the climate stations at Oulu in 1994 and Luleå in 1996, located in central Finland and Sweden, respectively. The most extreme outliers occur in southernmost Sweden in 1997, where the NDVI data indicate a very early SOS. At the Karlstad station, located in this area, the NDVI-defined SOS is 2 April, which is 35 days earlier than the average for this station. At the same time, the temperature data indicate a normal year (Fig. 4). Also, the birch pollen records in the area indicate a normal SOS (Å. Dahl, personal communication). The early SOS is not supported by the map by Chmielewski and Rötzer (2002) either. If we remove the year 1997 then the r^2-value between NDVI and the day of passing the 7°C temperature increases from 0.44 to 0.66. The winter of 1997 had only scattered occurrence of snow, with 23 February being the last day with snow-cover, except for 1 cm recorded on 26 March.

The mentioned outliers in the NDVI-defined SOS indicate that our method deals rather poorly with some years with very irregular snow conditions. An explanation for this could be that the pixel specific threshold for determining the SOS is calculated from averaging each pixel over the whole 21-year period. If a year is extremely different from the average year (e.g., with a lack snow cover in areas where snow is the normal condition) the background NDVI value within 8×8 km^2 pixels may differ significantly from the normal situation. This will lead to higher NDVI values, especially in southern areas with sun in winter and large agricultural areas, causing the determination of the SOS to become inaccurate. In these exceptional years, the NDVI-defined SOS could be more related to the timing of snowmelt than to the onset of leafing of birch. However, possible errors in the GIMMS–NDVI data, due to long periods with cloud cover, could also provide an explanation. Other factors that could affect the results are cultivation procedures that distort NDVI values. The method is sensitive to changes in forestry and agriculture practices, and the results for such landuse areas should be interpreted cautiously. However, we believe that year-to-year landuse changes occur at a smaller scale than the NDVI dataset of 8×8 km^2 resolution is likely to detect.

The GIMMS–NDVI dataset has only a twice-monthly temporal resolution. This leads to a twice-monthly inaccuracy in the timing of SOS as shown by the maps (Fig. 3). However, the scale in the legend distinguishes between weeks and must thus be interpreted as a general trend, not exact values. Despite the local errors in some years, we believe that the NDVI-defined SOS is accurate in most of the years and in the major part of the area, because of its generally high correlation with both surface phenology and climate data.

Trends and variability in the NDVI-defined SOS maps

The interannual variation in the oceanic parts are larger compared with the continental part (Table 1). This is due to the fact that the annual differences in temperature are smaller in oceanic areas than in continental areas. It in turn leads to regular greening in continental areas, whereas small fluctuations in spring temperature in oceanic areas lead to larger interannual differences in SOS.

The SOS-maps have a useful spatial resolution for assessing regional trends. A study based on an earlier version of the GIMMS–NDVI dataset for the 1982–1999 period revealed a trend of an advancing SOS in the southern and oceanic parts, and a stable SOS in northern continental and alpine parts, of the study area (Høgda et al. 2001, 2007). The trend of earlier SOS in southern parts of Fennoscandia is clearly seen in our maps, with no years with generally early SOS in the 1982–1989 period (Fig. 3). A closer analysis of the trends and cycles in the study area is a topic for future studies with a greater emphasis on phenological in-situ data.

NDVI-defined SOS versus climate data

This study shows moderately high correlation (after removing outliers) between the dates of passing different temperatures and the NDVI-defined SOS. It also reveals that the NDVI-defined SOS corresponds in the NB/MB zones with the date on which temperatures exceed about 7°C, and with the date the temperatures exceed 8–8.5°C in the SB/BN zones. Tveito et al. (2001) used the date when the daily normal temperatures passed the 5°C as a definition of the SOS throughout the Nordic countries for the period 1961–1990 (Fig. 2b). The present study shows that the temperature passing-date for estimating the SOS varies within a climatically diverse area such as Fennoscandia. Accordingly, the results presented here are useful for climatologists who estimate the SOS based on climate data alone.

However, it should be stressed that a temperature passing date that correspond in time with the NDVI-defined SOS contributes little to explaining the growth and development behind the SOS. The threshold air temperature leading to renewed physiological activity occurs at a much lower temperature. For instance, Wielgolaski (1999) showed that in western Norway the threshold mean air temperature leading to new physiological activity and leaf-bud break is close to −5.9°C in bird cherry (*Prunus padus*), −1.7°C in downy birch (*Betula pubescens*), and 5.5°C in ash (*Fraxinus excelsior*).

This study, with the 8×8 km^2 resolution dataset, works at the ecosystem level and does not aim to explain the threshold air temperature leading to new physiological activity. An alternative parameter to be calculated is the sum of temperatures above a certain threshold to the SOS (known as growing degree days). This parameter has, for budburst of birch for example, shown correlation values in northern Fennoscandia in the range of r^2=0.25–0.74 (Karlsson et al. 2003). For a few stations, we calculated the growing degree days above 0°C to the SOS, but these values gave a lower correlation with the SOS than the temperature passing-dates used, and thereby reduce the credibility in estimating possible future changes in SOS. In addition, we found it very difficult to find a common starting date throughout the study area. This is due to the fact that winter chilling is necessary for growth to start in spring in at least some boreal and arctic-alpine plants (Heide 1993, 2003). As a result, Wielgolaski (1999) has found that, as an average for many plant species, 1 April can be used as the best starting date in western Norway, while Chmielewski et al. (2005) used 1 January in Saxony in southeastern Germany, which has a comparable climate to the southeastern part of our study area.

Possible future changes in SOS

The present study estimates that a 1°C increase in spring temperature corresponds with the SOS occurring about 5–6 days earlier, but with large differences according to vegetation zones and sections (Table 1). Karlsson et al. (2003) estimated that a 1°C increase in temperature would imply 3–8 days earlier budburst of birch in the northern Fennoscandia (NB-C1 region), and Shutova et al. (2006) found 4.6–5.5 days earlier budburst in the lowland and 7.6 days at an elevated site on Kola Peninsula in NW Russia (NB-OC region). Our results are within these ranges for the corresponding areas, with a mean of 4.9 days/°C increase in the OC/C1 sections (Table 1). However, our study has shown a clear trend according to the degree of oceanity, with 7–9 days/°C in the oceanic sections. To summarize, our results indicate that a rise of temperature of 1°C in spring would cause the SOS to advance by an average of 7–9 days in oceanic parts and by less than 5 days in more continental parts of Fennoscandia.

In the study area, an increase in spring temperature in the range of 2–4°C over the next 50–100 years is expected (Mearns et al. 2001; ACIA 2004), with a slightly higher increase in the continental north (Hanssen-Bauer et al. 2003). The present study shows that the SOS in the extreme years in the 1982–2002 period is within the range of the predicted warming. For instance, the meteorological station at Værnes, in the SB-O1 region of central Norway, had a mean April temperature of 4.5°C in the 1982–2002 period. This station had a mean April temperature of 7.2°C in 2002, a difference of 2.6°C above a normal year. This shows that the mapped extreme years could give a first indication of expected changes in SOS by the end of this century.

Based on the scenarios with increase in spring temperature and the present results, we can expect advances in spring in the range of 14–36 days in the oceanic parts, and about 10–20 days in the continental parts, this century. However, many components in the vegetation are resilient to changes, and one of the most challenging tasks is to predict the time needed for various ecosystems to respond to expected climate change. In addition, other factors besides temperature (e.g., precipitation and soil properties) are important for the SOS (Wielgolaski 2001).

Conclusions

The present and a previous study have found moderately high correlations between the NDVI-defined SOS, phenological field data and climatic data, and the mapped SOS is confirmed by other independent in-situ data, as well. This indicates that the SOS was mapped accurately in Fennoscandia in the 1982–2002 period, with a few local exceptions most likely due to highly irregular snow conditions.

The study indicates that the expected increase in spring temperature by the end of this century will lead to an advancement in the SOS which is much faster in the oceanic areas of Norway compared with the continental inland areas of Fennoscandia (7–9 days versus less than 5 days earlier per 1°C increase). In other words, the SOS in the continental inland of Fennoscandia is much more stable and resilient to future expected climate change compared with the oceanic coast of Norway.

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