Review

Growing season changes in the last century

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Abstract

An increasing number of studies have reported on shifts in timing and length of the growing season, based on phenological, satellite and climatological studies. The evidence points to a lengthening of the growing season of ca. 10–20 days in the last few decades, where an earlier onset of the start is most prominent. This extension of the growing season has been associated with recent global warming. Changes in the timing and length of the growing season (GSL) may not only have far reaching consequences for plant and animal ecosystems, but persistent increases in GSL may lead to long-term increases in carbon storage and changes in vegetation cover which may affect the climate system. This paper reviews the recent literature concerned with GSL variability.
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1. Introduction

Over the 20th century, the global average surface temperature has increased by $0.6 \pm 0.2\ °C$, where most of the warming occurred between 1976 and 2000, and is projected to increase by 1.4–$5.8\ °C$ over the period 1990–2100 (IPCC, 2001). Furthermore, the IPCC (2001) stated that "most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations", where CO_2 has the strongest radiative forcing. Climate models of a warming world predict that a number of climate, weather and biological phenomena will be affected by the atmosphere's increasing CO_2 concentration. One such phenomenon is the growing-season length (GSL), i.e. the period between bud burst and leaf fall, which is expected to lengthen, especially at higher latitudes (EEA, 2004). The GSL has rendered substantial interest since it exerts a strong control on ecosystem function (White et al., 1999).

GSL variations are a useful climatic indicator and have several important climatological applications (Robeson, 2002). A decrease in GSL could result, for example, in alteration of planting dates determining lower yields of traditionally planting crops, which may not fully mature. Increasing GSL, however, may provide opportunities for earlier planting, ensuring maturation and even possibilities for multiple cropping (depending on water availability). Keeling et al. (1996) showed an association between surface air temperatures and variations in the timing and amplitude of the seasonal cycle of atmospheric CO_2. This is in agreement with the idea that warmer temperatures promote increases in plant growth in summer and/or respiration in winter. An increase of the annual amplitude of the seasonal CO_2 cycle by 40% in the Arctic (20% in Hawaii) since the early 1960s was linked to a lengthening of the growing season by about 7 days. Barford et al. (2001) found that seasonal and annual fluctuations of the uptake of CO_2 in a northern hardwood forest were regulated by weather and seasonal climate (e.g. variations in growing-season length). Myneni et al. (1997) showed that the increase in photosynthetic

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activity of terrestrial vegetation observed from satellite data during the period 1981–1991 suggested an increase in plant growth associated with a lengthening of the active growing season. Consequently, persistent increases in GSL may lead to long-term increases in carbon storage (White et al., 1999).

It is becoming evident that studies of the growing season of land vegetation have become an important scientific issue for research into global climate change (Chen et al., 2000). Most recent studies have utilized three main techniques to determine growing season change in the 20th century; phenology, the normalized difference vegetation index (NDVI) from satellite data, and surface air temperatures. This paper reviews some of the most important findings in recent GSL research, grouping them into three discussion areas. Table 1

summarizes the studies, which have quantified changes in growing season parameters. Furthermore, the implications of GSL change are briefly discussed.

2. Phenology

2.1. The importance of phenology in global change studies

Phenology can be defined as: "the study of the timing of recurring biological phases, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species" (Global Phenological Monitoring, http://www.dow.wau.nl/msa/gpm/). In temperate zones the reproductive cycles of plants is foremost controlled

Table 1
Observed changes in growing season parameters as seen in phenological records (P), normalized difference vegetation index (NDVI) from satellites, and climatological records (C)

Type	Time span	Geographic range	Number of sites	Change (days)			Reference
				Start	End	Length	
P	1980–2000	UK	1	−5.5			Sparks et al. (2005)
P	1991–2000	UK	1	−4.5			Fitter and Fitter (2002)
P	1951–1996	Germany	∼1000			9.2	Menzel et al. (2001)
P	1961–2000	Germany	22	−9.2			Chmielewski et al. (2004)
P	1952–2000	Spain	1	−16	13	29	Peñuelas et al. (2002)
P	1930–1998	NW Russia	1			−15 to −20	Kozlov and Berlina (2002)
P	1951–1996	Europe	80	−6.3	4.5	10.8	Menzel and Fabian (1999)
P	1951–1998	C & W Europe	104[c]	−28			Ahas et al. (2002)
P	1951–1998	E Europe		+7 to +14			Ahas et al. (2002)
P	1969–1998	Europe	∼50	−8			Chmielewski and Rötzer (2002)
P	1936–1996[a]	Canada	N.A.	−8			Beaubien and Freeland (2000)
P	1936–1998[b]	NE USA	1	−7			Bradley et al. (1999)
P	1970–1999	E USA	N.A.	−2.4			Abu-Asab et al. (2001)
P	1965–2001	NE USA	72	−2 to −8			Wolfe et al. (2005)
P	1922–2004	Korea	1	−13			Ho et al. (2006)
NDVI	1982–1993	China				∼17	Chen et al. (2005)
NDVI	1982–2000	Europe		−10.8		19.2	Stöckli and Vidale (2004)
NDVI	1981–1999	Eurasia		−7		18	Zhou et al. (2001)
NDVI	1981–1999	North America		−8		12	Zhou et al. (2001)
NDVI	1982–1991	45°N–75°N		−6		4	Tucker et al. (2001)
NDVI	1992–1999	45°N–75°N		−2		0.4	Tucker et al. (2001)
NDVI	1981–1991	Global		−8		∼12	Myneni et al. (1997)
C	1890–1995	Fennoscandia	9	−4 to −12	1–9	7–21	Carter (1998)
C	1951–2000	Greater Baltic Area	36	−6.3	1.3	7.4	Linderholm et al. (2006)
C	1950–2000	Germany	41	−6.5 to −12	12.5	5.5–24.5	Menzel et al. (2003)
C	1961–1990	Austria	20			11	Hasenauer et al. (1999)
C	1899–1982	NC USA	3[d]			∼14	Skaggs and Baker (1985)
C	1906–1997	EC USA	36			∼7	Robeson (2002)
C	1959–1993	China	147	−6	4	10	Schwartz and Chen (2002)
C	1964–1992	NH				∼7	Keeling et al. (1996)

[a] 1936–1961, 1973–1982 and 1987–1996.
[b] 1936–1947 and 1976–1998.
[c] C, W and E Europe.
[d] Average for three out of five stations used.

by temperature and day length (Menzel, 2002), while at lower latitudes rainfall and evapotranspiration must be taken into account (e.g. Spano et al., 1999). The timing of spring events in mid- to high-latitude plants, such as budding, leafing and flowering, is mainly regulated by temperatures after the dormancy is released, and a number of studies have found good correlation between spring phases and air temperatures (Menzel and Fabian, 1999; Wielgolaski, 1999; Abu-Asab et al., 2001; Chmielewski and Rötzer, 2002; Fitter and Fitter, 2002; Sparks and Menzel, 2002; Chmielewski et al., 2004). Thus phenological phases may serve as proxies for spring temperatures. While the climate signal controlling spring phenology is quite well understood, autumn phenology is less clearly explained in terms of climate (Walther et al., 2002), possibly because temporal changes in the autumn seem to be less pronounced and show more heterogeneous patterns (Menzel, 2002). Several studies have linked inter annual variability in phenology to large-scale weather features, such as the North Atlantic Oscillation (NAO) and El Niño-Southern Oscillation (ENSO) (D'Odorico et al., 2002; Stenseth et al., 2002; Menzel, 2003; Menzel et al., 2005). Changes in plant phenology are considered to be a most sensitive and observable indicator of plant responses to climate change. Unfortunately, there are few phenological records that extend beyond the instrumental records, e.g. the Marsham phenological record in the UK, spanning more than two centuries (Sparks and Carey, 1995), and the relationship between phenological records and temperature may be disturbed by other environmental factors (Menzel, 2003). Since non-climatic influences (e.g. land-use change) dominate local, short-term biological change, attributing recent biological changes to global warming is complicated (Parmesan and Yohe, 2003). However, there is a great potential for the use of phenological observations to assess ecological responses to climate change, and assembling data into phenological observation programs provides datasets to evaluate spatial and temporal impacts of climate on vegetation and animals (e.g. Chmielewski and Rötzer, 2002; Van Vliet et al., 2003). Furthermore, phenology has shown considerable promise to address questions in global modelling (e.g. downscaling), monitoring and impact assessments of climate change (Schwartz, 1999).

2.2. Observed phenological changes in the 20th century

The recent focus on phenology is partly due to the large number of studies that have documented long-term changes in phenology, which have been linked to global change. Because of the large quantity of phenological data available, as well as the establishment of data banks, there is a dominance of large-scale European phenological studies. However, due to the increased focus on phenology, more data are being analysed in other parts of the world. The following review of recently reported findings will mainly be focused on terrestrial plant phenology. However, there exist a large number of studies of changes in the phenology of animal species, e.g. migration (Bradley et al., 1999; Peñuelas et al., 2002; Cotton, 2003) and breeding (Crick et al., 1998; Forchhammer et al., 1998; Crick and Sparks, 1999), all which have indicated recent impacts of global change (see also McCarthy, 2001; Walther et al., 2002).

2.2.1. Local studies

2.2.1.1. Europe. To predict future responses of species to a changed climate, it is necessary to know how plants have responded to climate in the past. Unfortunately, few phenological records are of sufficient length to show responses to natural climate variability. There do, however, exist phenological records that extend beyond the 20th century. Sparks and Carey (1995) examined the Marsham phenological record (1736–1947). This is a record of the first dates of observations, or indications, of spring for 27 phenological events at the Marsham family estates in south-eastern England. The 27 phenological events came from taxa common to the British countryside. Clear relationships were found between phenological events and early spring weather. During the analysed period there had been a rise in temperatures, and the species responded to this, some by coming into leaf or flowering earlier, others by later coming into leaf or flowering. They also estimated how a future temperature increase of 3.5 °C in winter and 3 °C outside winter, together with increased precipitation would affect the observed species. The results suggested a dramatic change of species responses, with species appearing 2–3 weeks earlier than present. Ahas (1999) studied phenological time series (ranging from 132 to 44 years) from eight common plant, fish, and bird species at three different observation points in Estonia. It was concluded that Estonian springs had advanced 8 days on average over the 80-year study period, and that the last 40-year period has warmed even faster. Furthermore, spring was advancing about two times more rapidly in coastal regions than in inland areas. This difference was associated with the temperature regime and ice cover of the Baltic Sea, where a cold winter with a stable ice cover will cause the following

spring will be very late in the coastal region, while at the same time the inland areas warm up faster and spring will arrive much earlier, and vice versa. The resulting larger variations observed in the phenological data for a marine climate changes the hypothesis that the marine influence is a generally stabilizing seasonal factor. Menzel et al. (2001) analysed phenological seasons in Germany of more than four decades (1951–1996) and found clear advances in the key indicators of earliest and early spring (−0.18 to −0.23 days/year) and notable advances in the succeeding spring phenophases such as leaf unfolding of deciduous trees (−0.16 to −0.08 days/year). However, phenological changes were less strong during autumn (delayed by +0.03 to +0.10 days/year on average). In general, the growing season has been lengthened by up to 0.2 days/year, where the mean 1974–1996 growing season was up to 5 days longer than in the 1951–1973 period. Fitter and Fitter (2002) noted a major shift in first flowering date (FFD) in British plants from the 1980s after four decades of little variation. On average, FFD of the studied 385 plant species had advanced by 4.5 days; 16% showed an average advancement of 15 days. As the FFD is sensitive to temperature, the change in the 1990s was attributed to climate warming. Examination of a large number of phenological records kept by a farmer in Sussex, UK, from 1980 to 2000, showed that 25 out of 29 events were earlier in 1990–2000 than in 1980–1989 (Sparks et al., 2005). The average advancement of all events was 5.5 days, and more than half of the events were significantly related to temperatures of the 3 months preceding the mean event date.

2.2.1.2. North America. Over a 61-year period (1936–1947 and 1976–1998), 55 phenophases were studied in southern Wisconsin (Bradley et al., 1999). Approximately one-third of the phenophases appeared to advance in earliness over the period, and the mean trend for all 55 phenophases was −0.12 day/year. As springtime advanced, the number of phenophases increasing in earliness decreased, suggesting that the largest change in phenophases occurs in early spring. In Canada, where warmer winter and spring temperatures have been noted over the last century, first-bloom dates from Edmonton, Alberta, extracted from four historical data sets showed progressively earlier development in spring flowering (Beaubien and Freeland, 2000). The timing of the flowering was largely a response to temperature, with earlier blooms seen in years of higher spring temperatures. Correlations were found between stronger El Niño events, warmer ocean temperatures and warmer winter-spring temperatures and early

flowering. Over the last decades there was an 8-day trend to earlier flowering in central Alberta and the early blooming of *Populus tremuloides* showed a 26-day change in bloom time over the 20th century. Abu-Asab et al. (2001) investigated the trend of average ''first-flowering times'' (which was defined as the stage at which a mono- or diclinous flower begins anthesis or is receptive to pollen) for 100 selected plants from the Washington, DC, area. They found a significant advance of 2.4 days over a 30-year period and excluding 11 plants, which exhibited later first-flowering times, the remaining 89 species showed a significant advance of 4.5 days. The advancement of the first flowering in 89 species was directly correlated to increase in local minimum temperatures. Cayan et al. (2001) described fluctuations in spring climate, in the western USA, since the 1950s by examining changes in the Western Region Phenological Network data of first bloom of lilac and honeysuckle and the timing of snowmelt-runoff pulses. Both records showed year-to-year fluctuations (typically of 1–3 weeks), which were regionally consistent for most of the west. Analyses indicated that anomalous temperature had the greatest influence upon both inter-annual and secular changes in the onset of spring in these networks. The records showed earlier spring onsets since the late 1970s, where bloom-dates (and spring pulses) occurred 5–10 days earlier than in the previous part of the record, reflecting the unusual spell of warmer-than-normal springs in western North America during this period. The warm episodes were clearly related to larger-scale atmospheric conditions across North America and the North Pacific, but whether this is predominantly an expression of natural variability or also a symptom of global warming is not certain. Wolfe et al. (2005) evaluated the first leaf date (FLD) and FFD of woody plants (lilac, apple and grape) for the period 1965–2001 in the north-eastern parts of USA. They concluded that the general warming trend of the past several decades in north-eastern USA had resulted in an advance in spring phenology ranging from 2 to 8 days for the studied species.

2.2.1.3. Asia. Zheng et al. (2002) analysed the change of plant phenophase in spring and the impact of climate warming on the plant phenophase in China for the last 40 years, using plant phenology data from 26 stations in the Chinese Phenology Observation Network. They showed that the response of phenophase advance (or delay) to temperature change was non-linear. The rate of phenophase advance days decreases with temperature increase amplitude, and the rate of phenophase delay days increases with temperature decrease

amplitude. Since the 1980s, phenophases had advanced in north and north-eastern China, and the lower reaches of the Chang Jiang (Yangtze) River, and delayed in the eastern part of south western China and the middle reaches of the Chang Jiang River. Also, the rate of phenophase difference decreased with latitude. Using a simple phenological model driven by surface-level minimum–maximum temperatures, Schwartz and Chen (2002) found that the onset of spring growth in China had no apparent change over 1959–1993, which is in contrast to findings in North America and Europe. However, during that time last spring frost dates had become earlier (6 days), especially in the north eastern part of the country, and first frost dates had become later (4 days, especially in north-central China), resulting in an increase in the frost free period of 10 days, mainly over the northern part of the country. In Seoul, Korea, Ho et al. (2006) studied long-term (1922–2004) changes in the first bloom of five tree species. All species showed an advance in spring bloom (−1.4 to −2.4 days/decade for early spring flowering trees, and −0.5 day/decade for late-spring trees), associated with a 2 °C warming over the 83 years.

2.2.1.4. High latitude and altitude studies. A number of phenological variables in the northern Russian taiga were examined by Kozlov and Berlina (2002), to look for possible changes in the length of the growing season for the period 1930–1998. They found that snow-melt in spring occurred 16 days later and that the dates of permanent snow cover in the forests began 13 days earlier at the end of the study period than at its beginning. Furthermore, the duration of the snow- and ice-free periods in the forests decreased by 15–20 days over the 68-year period. It was concluded that the length of the growing season on the Kola Peninsula declined during the past 60 years, due to delayed spring and advanced autumn/winter. Similar findings were observed in the Colorado Rocky Mountains, USA, where Inouye et al. (2000) found no significant change in the beginning of the growing season over the 1975–1999 period. Here the beginning of the growing season is controlled by melting of the previous winters snowpack, and despite a trend for warmer spring temperatures, the dates for snowmelt had not changed, possibly due to an increase in winter precipitation. However, migrants and hibernators seemed to respond to increasing temperatures by arriving (American robins) and emerging (yellow-bellied marmots) earlier (14 and 38 days, respectively). The combination of changes in winter snowpack (starting earlier and lasting longer) and increased air temperatures at high altitudes could disrupt historical patterns for hibernating and migrating species.

2.2.2. Regional and global studies

Menzel and Fabian (1999) and Menzel (2000) analysed observational data from the International Phenological Gardens (IPG). The IPG is a Europe-wide network with a large spatial coverage (42°N–69°N, 10°W–27°E) which holds genetical clones from trees and shrubs, and dates for phases, such as leaf unfolding, flowering and leaf fall, have been collected since 1959. Analyses revealed that in the last four decades (1959–1996) spring events had advanced on average 6.3 days and autumn events had been delayed on average by 4.5 days, resulting in an average lengthening of the growing season by 10.8 days. The extension of the growing season was related to contemporary temperature increase. Chmielewski and Rötzer (2002) also utilised data from the IPG to investigate the beginning of the growing season (BGS) across Europe for the period 1969–1998. Using canonical correlation analysis, they established a relationship between air temperatures in February to April and BGS, where above (below) normal temperatures in whole Europe and advanced (delayed) BGS were related. In the last decade of their study period, early spring temperatures increased by approximately 0.8 °C, resulting in an advance in BGS of 8 days. Ahas et al. (2002) analysed data from the European phyto-phenological database (composed from different national databases of Eastern and Western Europe) for the time-period 1951–1998. Results suggested that the spring phase had advanced by 4 weeks in Western and Central Europe, because of intensified flow of warm Atlantic air masses in connection with a strong NAO. The advance in Eastern Europe was slighter, up to 2 weeks. There were some exceptions, with trends for delayed spring phase starts, in Eastern Europe, which were related to the Siberian high-pressure system. Root et al. (2003) calculated linear trends and analysed the regression slopes for a number of studies on spring phenology in the last 50 years. The analysis was based on 61 studies reporting results on 694 plant and animal species. A set of criteria was used to include the studies; the time series should have a length of at least 10 years, a change for at least one trait analysed should be found and, either a temporal trend in temperature or a strong association between the trait and site temperature should be found. The estimated mean number of days of advancement in the phenological phases per decade was 5.1 with a standard error (S.E.) equal to ±0.1. Because the warming trend is higher in higher latitudes, separate

analyses were performed for the latitudinal belts 32–49.9°N and 50–72°N that resulted in trends per decade of 4.2 (±0.2 S.E.) and 5.5 (±0.1 S.E.), respectively. Parmesan and Yohe (2003) quantitatively assessed 667 phenological shifts in species reported in the literature. Over a time-period range of 16–132 years, 62% showed trends towards spring advancement, while 9% showed trends toward delayed spring events. They performed a meta-analysis of trends in phenology for 172 species, for which time series of at least 17 years and observations over large geographical regions were available. Meta-analysis resulted in a mean advancement of spring phases by 2.3 days per decade (95% confidence interval, 1.7–3.2). As Badeck et al. (2004) noted, the differences in trend estimates provided by the two above studies could be related to differences in the relative number of observations in higher and lower latitudes, different taxa or groups of phases (flowering versus leafing; early versus late) and/or to the length of the time series analysed.

2.3. Phenological changes and large-scale weather phenomena

In the northern Atlantic region, a significant proportion of inter-annual climate variability is attributed to the dynamics of the North Atlantic Oscillation (NAO), which is a measure of the pressure difference between the Azores and Iceland and hence affects westerly winds blowing across the North Atlantic. Seasons of high positive NAO are associated with warming and increased rainfall over Northwest Europe (Hurrell, 1995). This relationship is most pronounced in winter and early spring and substantially weaker in summer (Rogers, 1990). Since the late 1960s there has been a strengthening of the wintertime NAO, with unprecedented strongly positive NAO index values since the 1970s (Hurrell, 1995). As the strengthening of the NAO coincides with late-20th century global warming, the influence of large-scale atmospheric circulation on a variety of ecosystems has gained increased attention in the North Atlantic region (e.g. Post and Stenseth, 1999; Weyhenmeyer et al., 1999; Mysterud et al., 2000; Linderholm, 2002; Solberg et al., 2002; Stenseth et al., 2002).

Chmielewski and Rötzer (2001) used leafing dates of trees from the International Phenological Gardens for the period 1969–1998, to define the beginning and the end of the growing season. A nearly Europe-wide warming in the early spring (February–April) over the last 30 years (1969–1998) led to an earlier beginning of growing season by 8 days. The observed trends in the onset of spring corresponded well with changes in air temperature and circulation (NAO-index) across Europe. In late winter and early spring, the positive phase of NAO increased clearly, leading to prevailing westerly winds and thus to higher temperatures in the period February–April. Since the end of the 1980s the changes in circulation, air temperature and the beginning of spring time were striking. The investigation showed that a warming in the early spring (February–April) by 1 °C causes an advance in the beginning of growing season of 7 days. The observed extension of growing season was mainly the result of an earlier onset of spring. D'Odorico et al. (2002) also examined the link between earlier onsets of the growing season in Europe and warmer winters associated with phase changes in the NAO. They found that spring phenology in Europe was significantly affected by the NAO, where high-NAO winters (warm) speeded up the occurrence of spring phenophases (budburst and bloom). Furthermore, the NAO could provide a partial explanation for both high- and low-frequency variability of plant phenology of the British Isles. Scheifinger et al. (2002) noted a relationship between inter-annual variability in NAO and the temporal variability in central European phenological events in 1951–1998. The trend in phenological time series from the late 1980s could largely be explained by the NAO. They showed that the influence of the NAO was strongest on early phases and decreased later in spring. The influence of the NAO was reduced with increasing distance from the Atlantic coast and also in mountainous terrain. Menzel (2003) investigated seasonal phases from the phenological network of the German Weather Service in relation to climate and NAO in 1951–2000. Using regression between phenological anomalies and NAO, she found a quite strong relationship between February and March NAO and spring phenological anomalies (R^2 ranging from 0.37 to 0.56), with early spring phases being more sensitive to NAO, and that January–February NAO explained ca. 40% of the variance in the length of the growing season. Similar results were obtained by Ahas et al. (2004) for Europe (data from the European plant phenology database). They studied relationships between start dates of spring phenological phases, for three species, and large scale circulation patterns in form of NAO and the Arctic oscillation, AO, defined as a nearly axisymmetric spatial pattern of inter-annual variability of Northern Hemisphere winter sea level pressure centred over the Arctic (Thompson and Wallace, 1998). In the period 1951–1998, the highest correlations between spring phenophases and NAO/AO were found during winter (December–March) and the three first

months of the year (January–March) over Europe, where correlations were particularly strong in the Baltic Sea region. In the eastern part of the studied area (near Ural Mountains) correlations were opposite of the rest of the study area.

Also in North America links between large-scale atmospheric conditions and changes in spring phenology have been suggested. Correlations of the spring flowering index with the incidence of El Niño events was found in western Canada (Beaubien and Freeland, 2000). Earlier onsets of spring since the late 1970s in western USA were related to shifts in the Pacific Decadal Oscillation (PDO, defined as the leading principal component of North Pacific monthly sea surface temperature variability; Mantua et al., 1997) in the study by Cayan et al. (2001).

3. Remote sensing

Land cover mapping produces archives that are used to parameterize global climate models, and since the progressive change of land cover over periods of decades is of interest, high-resolution remotely sensed data is needed (e.g. Wang and Tenhunen, 2004). In recent years, determining the growing season of large-scale land vegetation has become an important question in global climate change research. Because of the synoptic coverage and repeated temporal sampling satellites offer, remotely sensed data have a great potential for monitoring vegetation dynamics at regional to global scales (Myneni et al., 1997; Zhang et al., 2003). One of the most striking events in spring is the first appearance of foliage, generally called the ''green wave'' (e.g. Schwartz, 1998). This is a prominent event and can be well captured in satellite images, which then can be used to calibrate remote sensing data. To quantify the spatial and temporal variation in vegetation growth and activity, vegetation indices can be calculated from satellite images. One such vegetation index is the normalized difference vegetation index (NDVI), which will be described in the following part.

3.1. NDVI

NDVI data captures the contrast between red and near-infrared reflectance of vegetation, which indicates the abundance and energy absorption by leaf pigments such as chlorophyll (Zhou et al., 2001). NDVI is a general biophysical parameter and it provides an indication of the ''greenness'' of the vegetation, but not land-cover type directly. A time series of NDVI values can, however, separate different land-cover types based on their phenology or seasonal signals (Wang and Tenhunen, 2004). Because the NDVI is well correlated to the fraction of photosynthetically active radiation absorbed by plant canopies (and thus leaf area, leaf biomass and potential photosynthesis), it can be used as a proxy for the vegetation's responses to climate changes (Myneni et al., 1995). When investigating changes and variability in global vegetation activity, it is assumed that changes in NDVI yield information about the response of vegetation to climate. However, many factors unrelated to ecosystem variability, associated with the obtaining of remotely sensed data (e.g. satellite drift, calibration uncertainties, inter-satellite sensor differences, bidirectional and atmospheric effects and volcanic eruptions), may cause unrelated variability in NDVI which may be interpreted as real changes in NDVI (Zhou et al., 2001 and references therein). Much effort is thus placed on developing (and testing) corrections to provide consistent and calibrated time series for NDVI from satellite data. Previously, NDVI data was obtained from AVHRR (Advanced Very High-Resolution Radiometer) instruments carried by meteorological satellites in the NOAA/NASA Earth Observing System or the Global Inventory Monitoring and Modelling Studies (GIMMS). Recently, a new sensor system called MODIS (Moderate Resolution Imaging Spectroradiometer) has been developed, which offers improved calibration and atmospheric corrections, as well as higher spatial resolution, compared to AVHRR (Zhang et al., 2003; Beck et al., 2005). Usually, NDVI are of global extent, and the data has a spatial resolution of 1.1–8 km and a 10–15 day temporal frequency, while MODIS NDVI exist at spatial resolutions as high as 250 and 500 m for the entire globe (Beck et al., 2005).

3.2. Growing season change from satellite data

Myneni et al. (1997) explored two NDVI data sets (from NOAA and GIMMS) form July 1981 to end of June 1991 to evaluate the photosynthetic activity of terrestrial vegetation. This paper reported an increase in the photosynthetic activity for the period, and it was associated with a lengthening of the active growing season (AGS, the period when photosynthesis actually occurs). They estimated an advance in the AGS of ca. 8 days and a prolongation of the declining phase of the AGS by ca. 4 days, resulting in a total lengthening of the AGS by 12 days. Furthermore, the increase was greatest between 45°N and 70°N, an area where marked warming in spring have occurred due to earlier snowmelt. This result, together with that of Keeling

et al. (1996) (see above), indicates increased biospheric activity at high northern latitudes.

Zhou et al. (2001) extended the analysis period of NDVI data presented by Myneni et al. (1997) to December 1999. They found that ca. 61% of the total vegetated area between 40°N and 70°N in Eurasia showed a persistent increase in growing season NDVI from central Europe through Siberia to the Aldan plateau, an area which mainly consists of forests and woodland. The pattern was not that consistent in North America. Also, the growing season had increased by 18 days in Eurasia and 12 days in North America, caused by earlier spring and later autumn. NDVI decreases observed in northern North America and north-eastern Asia were interpreted as responses to temperature induced drought. Additional analyses of higher northern latitude NDVI by Tucker et al. (2001) for the period 1982–1999 yielded similar results as previous studies: an earlier start and increased length of the growing season which was a response to warmer temperatures. Furthermore, they noted that there was a delay in the start of the growing season in 1992, caused by the temporary global cooling resulting from the Mt. Pinatubo volcanic eruption in 1991. Furthermore, their analyses suggested greater gross photosynthesis in Eurasia than North America for the later 1990s than the 1980s.

Stöckli and Vidale (2004) used the NOAA/NASA Pathfinder NDVI data to create a continuous European vegetation phenology dataset (10-day temporal and 0.1° spatial resolution) for the years 1982–2001. They found strong seasonal and inter-annual variability in European land surface vegetation state. Phenological metrics indicated a late and short growing season for the years 1985–1987, in addition to early and prolonged activity in the years 1989, 1990, 1994 and 1995. Spring phenology was also shown to correlate particularly well with anomalies in winter temperature and winter North Atlantic Oscillation (NAO) index. Trends in the phenological phases revealed a general shift to earlier (−0.54 days/year) and prolonged (0.96 days/year) growing periods (statistically significant), especially for central Europe. Hogda et al. (2001) made a regional study of growing season changes in Fennoscandia, Denmark and the Kola Peninsula using the GIMMS NDVI dataset. During the period 1981–1998, they found a delay of spring in the alpine belts and the northern boreal zone, where the strongest delay occurred on the most continental parts of the northern boreal zone. In southern Fennoscandia and western Norway spring started earlier. Furthermore, autumn was delayed in the whole area, except for the most

continental part of northern Scandinavia. Thus, the GSL was prolonged for the whole area, except for the northern continental section. Beck et al. (2005) use MODIS NDVI data to map the onset of the spring 2000–2004 in Fennoscandia. During this short analysis period, they found large temporal and spatial difference within the area in the arrival of spring, varying by more than 2 months within the study area and more than a month between the years. Latitude, elevation gradients and distance from the seas appeared to be the determining factors.

Combining phenological and NDVI (from NOAA/NASA Pathfinder) data from 1982 to 1993 at seven sample stations in temperate eastern China, Chen et al. (2005) determined the growing season beginning and end dates at seven phenological sample stations for each year, and then made a spatial extrapolation of growing season parameters to all possible meteorological stations in the study area. The spatial patterns of growing season beginning and end dates correlated significantly with spatial patterns of mean air temperatures in spring and autumn, respectively. Unlike some results from similar studies in Europe and North America, their results suggested a significant delay in leaf coloration dates, along with a less pronounced advance of leaf unfolding dates from 1982 to 1993. The growing season in China had been extended by 1.4–3.6 days/year in the northern parts, 1.4 days/year averaged across the entire study area. The apparent delay in growing season end dates was associated with regional cooling from late spring to summer, while the insignificant advancement in beginning dates corresponded to inconsistent temperature trend changes from late winter to spring.

Kaufmann et al. (2004) attempted to answer the question of what the physiological significance of the findings by Myneni et al. (1997) and Zhou et al. (2001) was. They investigated the physiological effects of the elongation of the growing season and the increase in summer greenness on northern hemisphere forests by examining the relationship between NDVI and tree rings. They used NDVI time series and tree-ring data from 48 mid- to high-latitude sites in North America and Eurasia. They found correlations between NDVI and tree rings in June and July, but not for months at the start or the end of the growing season. This may imply that advances in spring and delays in autumn of the growing season are less important to the physiological status of trees. Thus, although changes in spring time may be easier to detect, summer-time changes may have bigger effects on the terrestrial carbon cycle.

4. The climatological growing season

4.1. Defining the climatological growing season

The climatological growing ''season'' can be viewed as the entire period in which growth can theoretically take place, and should be distinguished from the growing ''period'', which is the period of actual growth (Carter, 1998). There are a number of ways to define GSL. One definition of GSL is the period between the date of the last spring freeze and first autumn freeze (e.g. Robeson, 2002), where the frost may be determined by thresholds of daily minimum temperatures. Other investigations have used threshold temperatures in a predefined number of days to start and end the growing season, e.g. GSL can be defined as the period between when daily temperatures are $>5\,^{\circ}$C for >5 days and when daily temperatures are $<5\,^{\circ}$C for >5 days (Frich et al., 2002). The physiological significance of this period naturally differs among plant types, but at high latitudes it can be assumed to be relevant to perennial plants that are exposed to the weather throughout the year, e.g. trees and shrubs (Carter, 1998). In the literature, there exists a wide variety of growing season definitions, but only few comparisons have been made between different definitions on a single data set. Brinkmann (1979) compared differently defined growing seasons at four stations in Wisconsin, USA, over an 80-year period, using freeze criteria as well as temperatures averaged over a number of days as definitions of the growing season. The results showed that depending on definition, a variety of trends were obtained for one single station, meaning that the trend in the GSL is sensitive to the particular definition used. Walther and Linderholm (2006) examined a number of definitions of growing season parameters (start, end and length) from a large station network in the Greater Baltic Area, and they also found large differences in GSL trends depending on the definition used. The exclusion of a frost criterion in the definition could lead to erroneous GSL, especially in the south-western parts of the studied area. Consequently, it seems that, in order to be physiologically appropriate, regional GSL definitions should be used, so that finding one world-wide definition is quite unlikely. Furthermore, definitions of the GSL using temperatures may be considered valid in areas where the growing season is largely temperature-limited, but at lower latitudes other factors such as precipitation and evapotranspiration must be taken into consideration.

4.2. The growing season in relation to seasonal temperatures

Vedin (1990) compared the GSL in northernmost Sweden for two 10-year periods, where 1931–1940 was extraordinary warm and 1979–1988 was much colder. To his surprise, he found that the average GSL had been somewhat longer during the period 1979–1988 than during the warmer period 1931–1940. He reasoned that this was due to warmer springs and autumn in the latter period, but stated that a generally warm period may still be unfavourable with respect to the GSL. Jones and Briffa (1995) analysed daily mean temperatures during the growing season (here defined as days $>5\,^{\circ}$C) from ca. 200 stations in the former Soviet Union. They found that little change in a number of growing-season related variables had occurred in the last 110 years. Among other findings, they noted that there was little correlation between the duration of the growing season and the number of degree-days (above $5\,^{\circ}$C) in the season at station level. Consequently, a longer growing season does not automatically imply an increased number of warmer days. In a later study Jones et al. (2002) examined extreme temperatures, GSL and degree-days for four meteorological records, which extend back into the eighteenth century (Central England, Stockholm, Uppsala and St. Petersburg). They found that in northern Europe (Fennoscandia) growing seasons were clearly warmer before 1860, with only the late 1930s of recent times reaching the earlier levels. Similarly to the Russian study, they found that the duration of the growing season was only weakly correlated ($r \sim 0.2$–0.4) with seasonal temperatures (May through September) or number of degree-days, and therefore a warmer growing season need not necessarily be longer. In addition, the GSL was better correlated to annual temperatures than seasonal in all station records, and there was a strong (negative) relationship between GSL and number of cold days in a year.

4.3. Observed changes in the thermal GSL

4.3.1. Europe

Carter (1998) analysed parameters (start, end, duration and intensity) of the thermal growing season for the period 1890–1995 at nine sites in the Nordic region. He found that the GSL had increased considerably in the past century, between 1 and 3 weeks, but that the lengthening had been less pronounced since the 1960 in most parts. The absolute magnitude of lengthening showed a declining west–east

gradient between Denmark and Finland, and higher inter-annual variability at the western sites. Furthermore, the intensity (expressed by accumulated temperatures, the effective temperature sum above 5 °C) increased regionally between 1890 and 1960, but decreased slightly after 1960 at all sites except in southwestern Finland. Linderholm et al. (2006) investigated 20th-century thermal growing season trends in the Greater Baltic Area. Yearly dates for the start, end and length of the growing season were computed for 49 stations in the studied area, using daily mean temperature measurements. Analyses of trends and tendencies of the growing season components showed a general increase in the length of the growing season in the whole region. Averaged over the 1951–2000 period, the growing season had increased by 7.4 days, where the largest change had occurred during spring (6.3 days earlier growing season start). The largest increases were found at stations adjacent to the Baltic Sea and Skagerrak/Kattegatt, where the Danish stations showed an increase in GSL of more than 20 days in the 20th century. Furthermore, three long records (starting before 1850) from the region were examined, showing high inter-annual and decadal variability, far more prominent that the increasing trends. There were, however, tendencies for increased frequencies of longer growing seasons since the 1950s. Menzel et al. (2003) analysed the climatological growing season in Germany using data from 41 stations (1951–2000). The growing season was defined by single-value thresholds of daily minimum and mean air temperatures, and during this 50-year period they found a lengthening of the growing season of 0.11–0.49 days/year depending on the definition used. The greatest change was found in the frost-free period, due to observed stronger increase in daily minimum rather than maximum temperatures. Similar results of increased frost-free period were found in Austria, Switzerland (both 0.5 days/year) and Estonia (0.36 days/year). Furthermore, they noted that the trend was weakening at high-elevation stations (>950 m a.s.l.).

4.3.2. North America

In the 1980s, Skaggs and Baker (1985) studied fluctuations in GSL between 1899 and 1982 in Minnesota, USA. Temperature data from five rural stations were used. They found a general increase in GSL, where three stations showed increases of an average 14 days from 1899 to 1982. The increase in GSL came from combinations of earlier last freezes and later first freezes. At one station, however, the tendency was opposite, with a decrease in GSL. The patterns of

inter-annual variation in GSL duration was substantial among the stations, and it was concluded that care should be taken when extrapolating results of GSL studies in space and relating them to mean temperature fluctuations. Bootsma (1994) examined long term (ca. 100 years) trend for a wide range of agro-climatic variables from five stations across Canada, to determine if significant changes had occurred in climatic parameters that are important to agriculture. He found evidence for warming during the growing season for stations in western, but not in eastern, Canada. Warming of the growing season was accompanied by earlier dates of last spring frost, later dates of first autumn frost and longer frost-free periods. Only data from the westernmost station (Agassiz) showed a significant positive trend in GSL: at the other stations GSL fluctuated around the long term normal, although there were tendencies for increased number of above normal values in the last 60–20 years. There was no trend in GSL at the easternmost station (Charlottetown). In the state of Illinois, USA, Robeson (2002) examined temperature data from the Daily Historical Climate Network for trends towards earlier spring freezes in the period 1906–1997. Most of the 36 stations showed trends towards earlier spring freezes, however, there was no consistent trend in the network. The time series showed large interannual variability, but the results suggested that the GSL became ca. 1 week longer during the 20th century.

4.3.3. Global

Utilizing a new global dataset (daily, homogenised meteorological records from the Australian Climate Centre and National Climate Data Center), Frich et al. (2002) observed changes in climatic extremes in the second half of the 20th century. One of the observed parameters was GSL, and they found a significant lengthening of the thermal GSL throughout major parts of the Northern Hemisphere mid-latitudes, accompanying a systematic increase in the 90th percentile of daily minimum temperatures and a reduction in frost days. However, exceptions were found all over the Northern Hemisphere, most notably on Iceland (see Fig. 3 in Frich et al., 2002).

5. A short note on the limitations and possibilities of the described methods

It is evident that the methods of calculating GSL changes presented here all have their inherited limitations and possibilities. Phenological records have the benefit of providing information of biological phases with high temporal resolution. Presently,

however, the phenological records are limited in their spatial distribution and do not extend far back in time. This makes it difficult to assess 20th century changes in a longer time perspective. The recent focus on developing international observation networks is therefore encouraging. Satellite data have the advantage of high spatial coverage, allowing for studies of regional and global studies. Still, there are some problems associated with this method, e.g. the temporal resolution, problems with reflectance and calibration, and the short records that are available. Also, there is a problem how to relate the species-averaged information from satellite observations (over large and potentially diverse spatial areas) to species-level phenological events (Schwartz, 1999). Using the climatological growing season has the advantage of good spatial coverage (at least in parts of the world) of meteorological stations. Furthermore, numerous records cover the 20th century, or beyond, making it possible to study long-term changes in GSL variability and possible mechanisms behind that (e.g. changes in the atmospheric circulation). Nevertheless, there is no universal definition of the climatological growing season, mainly because large regional (and local) differences in climates, and there may be large discrepancies in GSL change depending on the definition used (Walther and Linderholm, 2006). Also, the climatological growing season is broadly defined, and may not truly represent the actual biological growing season, especially if only temperatures are used.

Ideally, combining the three methods discussed here would provide better information of temporal and spatial GSL variability. Calibrating the NDVI greenness values with corresponding phenologically derived growing season dates for different seasonal land covers will facilitate studies of growing-season greenness thresholds within different plant communities and vegetation types (e.g. Chen et al., 2000). This will facilitate spatial extrapolation of phenological point measurements through satellite data. Taking the climatological aspect into consideration is necessary when attempting to identify possible causes behind spatial changes in GSL (e.g. why opposite trends in spring phases have been observed in Western and Eastern Europe (Ahas et al., 2002; Linderholm et al., 2006)), and making temporal extrapolations of phenologically derived GSL data.

6. Implications of GSL change

Climate change is projected to increase the length of the growing season (e.g. IPCC, 2001; ACIA, 2004). Such an increase in GSL, together with a warmer growing season, is expected to advance the potential for crop production at high northern latitudes and increase the potential number of harvests and hence seasonal yields for perennial forage crops (ACIA, 2004). However, in warmer areas, increased warmth during the growing season may cause slight decreases in yields since higher temperatures speed development, reducing time to accumulate dry mater (ACIA, 2004). Effects in Fennoscandia could be elevated tree line and favourable conditions for growing of more southerly fruits (Wielgolaski, 2003), and in alpine areas with maximum precipitation during the growing season, lengthening of the growing season as a result of warmer temperatures could lead to improved forest productivity (Hasenauer et al., 1999). However, two recent studies have shown that recent warming has resulted in negative growth responses of trees at tree line sites in Alaska and the central Scandinavian Mountains (Linderholm and Linderholm, 2004; Wilmking et al., 2004). Consequently, a rapid climate change, occurring within the next 100 years, would have a large impact on already living trees, which would be less adaptive to the prevailing climate. Also, if tree species respond differently to climate change, then the competitive relationships between species will alter and hence, in the long run, the species composition of forests and possibly the geographical ranges of species (Kramer et al., 2000). The accelerated rates of change observed in the past three decades indicate that in a near future we will see large changes in ecosystems; latitudinal/altitudinal extension of species' range boundaries by establishment of new local populations and, consequently, extinction of low latitude/altitude populations; increasing invasion of opportunistic, weedy and/or highly mobile species; progressive decoupling of species interaction (e.g. plants and pollinators) because of out-of-phase phenology (e.g. Hughes, 2000; Peñuelas and Filella, 2001). However, ecosystems are dynamic systems that vary over time, even in the absence of human disturbance, and changes in geographic range, breeding and population size will occur even in the absence of climate change (McCarthy, 2001). Thus, in order to address important questions in global modelling, ecosystem monitoring and global change, increased knowledge of atmosphere–biosphere interactions, both spatially and temporally, is needed.

7. Concluding remarks

The research that has been reviewed here shows that the growing season has high inter-annual variability and that the most pronounced changes in growing-season

parameters has occurred in the last 30 years of the 20th century. The majority of phenological studies suggest that significantly advancing spring, as a consequence of warmer winters and springs and earlier last frosts, has been responsible for the most of the reported changes in the growing season. Phenological observations, NDVI from satellites and climatological data suggest links between recently observed changes in natural systems and 20th century climate change. However, several authors have found strong associations between large-scale weather phenomena (e.g. the NAO) and growing season variability, suggesting that global warming may not be the only explanation. Also, other factors like land use change may have been of importance. It must be kept in mind that the observed changes in GSL are not uniform; while increased GSL has been observed in low-to-mid latitudes, the GSL seems to decrease at some high latitude and altitude sites. Numerous studies reveal that an already significant impact on natural systems is associated with 20th century warming. Increased temperatures of 1.4–5.8 °C (globally) in the next century will most certainly have large consequences, where some species will benefit from warmer and longer growing season, while others will disappear.

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