Spring phenology in boreal Eurasia over a nearly century time scale

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Abstract
It has been widely reported that tree leaves have tended to appear earlier in many regions of the northern hemisphere in the last few decades, reflecting climate warming. Satellite observations revealed an 8-day advance in leaf appearance date between 1982 and 1991 in northern latitudes. In situ observations show that leaf appearance dates in Europe have advanced by an average of 6.3 days from 1959 to 1996. Modelling of leaf appearance on the basis of temperature also shows a marked advance in temperate and boreal regions from 1955 to 2002. However, before 1955, reported studies of phenological variations are restricted to local scale. Modelling, ground observations and satellite observations are here combined to analyse phenological variations in Eurasian taiga over nearly a century. The trend observed by remote sensing consists mainly in a shift at the end of the 1980s, reflecting a shift in winter and spring temperature. In western boreal Eurasia, a trend to earlier leaf appearance is evident since the mid-1930s, although it is discontinuous. In contrast, the strong advance in leaf appearance detected over Central Siberia using satellite data in 1982–1991 is strengthened by late springs in 1983–1984; moreover, in this region the green-up timing has displayed successive trends with opposite signs since 1920. Thus, such strong trend is not unusual if considered locally. However, the recent advance is unique in simultaneously affecting most of the Eurasian taiga, the leaf appearance dates after 1990 being the earliest in nearly a century in most of the area.

Keywords: boreal, climatic change, Eurasia, in situ, leaf appearance, modelling, NDVI, phenology, remote sensing, Russia, spring, taiga, time series, trend

Introduction
Satellite observations revealed an 8 ± 3 day-advance in spring phenology in Northern latitudes from 1982 to 1991 (Myneni et al., 1997), and a 6.4-day advance in 1982–1999 in Eurasian forests (Zhou et al., 2001). This advance was shown to be related to an increase in the vegetation net primary productivity (Lucht et al., 2002) and to changes in the seasonal cycle of atmospheric CO₂ concentration (Myneni et al., 1997) previously reported (Keeling et al., 1996), as leaf phenology is a key factor in the annual vegetation carbon uptake (White et al., 1999; Baldocchi et al., 2001). However, remote sensing methods have a fundamental drawback: they can be applied only since 1982, the year suitable satellite observations became available. Moreover, what is actually measured is uncertain: different remote sensing metrics proposed in the literature are difficult to relate precisely to a particular phenological stage (Badeck et al., 2004) and can give substantially different results (Schwartz et al., 2002). Thus, the magnitude of the changes found from satellite observations has been so far uncertain (Zhou et al., 2001). Furthermore, because the satellite observations commonly used to measure vegetation phenology
are sensitive to snow (Moulin et al., 1997), variations found in the boreal regions and attributed to phenological changes may be partially related to snow melt timing variations (Shabanov et al., 2002; Dye & Tucker, 2003).

In contrast, ground observations are precisely related to leaf appearance. They revealed an advancing trend in Europe in the last few decades (Menzel & Fabian, 1999; Menzel et al., 2006), although the variations are spatially heterogeneous with 4 weeks advance in Germany and 2 weeks delay in the Eastern border of Europe since 1951 (Ahas et al., 2002), while Kozlov & Berlina (2002) showed a slight delay trend in Fennoscandia since 1930. At regions such as South Germany, the advance found in the last two decades is not a unique event during the 20th century (Schaber & Badeck, 2005). However, despite their exactness in measuring interannual changes, such records exist only for a limited number of stations in the world, primarily concentrated in Europe, and thus do not allow large-scale studies.

A third approach, which allows both the spatial and temporal extent of phenological analysis to be extended, is empirical modelling based on climatic records. The suite of models and climatic indicators proposed in Schwartz et al. (2006) confirmed a large-scale trend to earlier spring since 1961 in northern latitudes. Such models require reliable daily temperature records, which exist only locally in the long term. For example, such long-term data exist in North East America, for which empirical modelling indicates that periods with trends to earlier leaf appearance are not confined to the last few decades of the 20th century (Schwartz, 1998).

In this study, we integrate the three approaches in order to analyse phenological variations since 1920 in Central Siberia and since 1936 for all the Eurasian taiga. We first developed a new remote sensing methodology that estimates the green-up dates in boreal regions for 1982–2005. These differ from the in situ measurements of the leaf appearance date by 8 days RMS (Delbart et al., 2005, 2006), and which are free of snow effects on the signal. These satellite-derived green-up dates were used to calibrate a green-up model (Picard et al., 2005) based on the Spring Warming approach (Chuine et al., 2003) which has a precision of 7 days RMS. The model is applied to a global temperature dataset for 1958–2002, and to station temperature records for 1936–1989. We analyse jointly the ground observations of leaf appearance and the modelled and satellite green-up dates, combining the advantages of each dataset to reach a robust representation of the interannual variations in leaf appearance timing at the continental scale, over a much longer period than was previously possible.

Materials and methods

Study area

The study area was selected from the GLC2000 map (Bartholomé & Belward, 2005). The original resolution of this map is about 0.0089°. We selected all 0.1° grid cells dominated either by deciduous needleleaf forests, deciduous broadleaf forests, or mixed (evergreen/deciduous) forests (Fig. 1). Deciduous needleleaf forests are essentially located east of 100°E, and are dominated by larch (Larix gmelinii) which forms continuous forests either as pure stands or associated with Pinus sibirica, Pinus silvestris or Betula sp. (Helmisaari & Nikolov, 1989). Larix sibirica is also a dominant species from approximately 80–100°E. West of 80°E, deciduous forests are essentially dominated by birch (Nilsson et al., 2000) [i.e. Betula pubescens and Betula pendula, often in association with aspen (Populus tremula)]. Other important but not dominant deciduous species are present mainly in the western part of the study area, such as other Larix species, oak (Quercus robur) and beech (Fagus sylvatica).

In western Russia, deciduous species are often associated with evergreen species to form mixed type forests. Note, some areas classified as mixed forest in the GLC2000 are classified as evergreen forest in other land cover products, such as the MODIS MOD12 map (Strahler et al., 1999) (Fig. 1).

In situ measurements of leaf appearance

Leaf appearance dates are from 14 sites, obtained from various sources such as hydrometeorological stations or nature reserves. The locations and sources are shown in

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Fig. 1 Study area, defined from GLC2000 (Bartholomé & Belward, 2005). Dark grey pixels show larch forests, light grey pixels show deciduous broadleaf forests and mixed forest. The black line contours the area dominated by evergreen forests according to the MOD12 landcover map (Strahler et al., 1999).
Unfortunately, this methodology cannot be applied before 1998: the SPOT-VGT dataset starts in April 1998, and the existing long-term remote sensing archives, such as the Pathfinder AVHRR Land (PAL) data (James & Kalluri, 1994), available for years since 1982, do not offer the short wave infrared band necessary to calculate NDWI. Thus, we developed another methodology (Delbart et al., 2006) to measure \( t_{rs} \) from PAL-NDVI. The green-up dates obtained for 1998–2001 from the SPOT-VEGETATION data are used to calibrate PAL-NDVI threshold specifically for each pixel. From 1992 to 1997 (and in 1999), green up is assumed to occur when the PAL-NDVI reaches the threshold value (Delbart et al., 2006).

Both methodologies give consistent results in common years (1998–2001), and similar agreement with ground observations of birch leaf appearance date. The dates measured by remote sensing show no bias when compared with in situ measurements of the leaf appearance date of birch, and an RMS difference of 8 days (Delbart et al., 2006). This error, which is smaller than the interannual variation, comes mostly from the compositing procedure used to reduce cloud contamination in the satellite data, from the heterogeneity of phenology (due to species coexistence or altitude gradients for example) within the remote sensing pixels, and from the coexistence of diverse land cover types within the remote sensing pixel. The two methodologies are applied at the 0.1° resolution (Delbart et al., 2006).

### Phenology model

Satellite green-up dates were used to calibrate a green-up model (Picard et al., 2005) based on the Spring Warming model (Robertson, 1968; Chuine et al., 2003). The Spring Warming model assumes that air temperature drives the development towards budburst. The modelled green-up date \( t_{rs} \) is the smallest value such as

\[
\sum_{t_0}^{t_m} \max(\theta - \theta_0, 0) \geq F^*,
\]

where \( \theta \) is the daily temperature, \( t_0 \) is the start date (1 January), and \( \theta_0 \) and \( F^* \) are, respectively, the base temperature and the threshold for the cumulative thermal forcing rate. Here, \( \theta_0 \) and \( F^* \) are calibrated using \( t_{rs} \) obtained from SPOT-VEGETATION in 1998–2002 for the deciduous forests in Central Siberia (Picard et al., 2005). Daily temperature is from the ECMWF ERA40 reanalysis dataset, scaled to 0.1° resolution by bilinear interpolation and with a lapse rate of 0.006 °C m⁻¹ to account for altitude differences. The best agreement with \( t_{rs} \) is found for \( \theta_0 = 4.1 \) °C and \( F^* = 65 \) °C day⁻¹. Models with a chilling requirement gave no significant

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**Table 1** Description of in situ phenological records: location, species and source

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Longitude</th>
<th>Species</th>
<th>Source, documentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 53.9000</td>
<td>92.7000</td>
<td>Birch</td>
<td>Komarov Russian Academy of Sciences.</td>
</tr>
<tr>
<td>2 63.1000</td>
<td>88.0000</td>
<td>Academy of Sciences.</td>
<td></td>
</tr>
<tr>
<td>4 66.5000</td>
<td>67.8000</td>
<td>Delbart et al. (2006)</td>
<td></td>
</tr>
<tr>
<td>5 54.0000</td>
<td>81.0000</td>
<td>Delbart et al. (2006)</td>
<td></td>
</tr>
<tr>
<td>6 52.7000</td>
<td>90.0000</td>
<td>Delbart et al. (2006)</td>
<td></td>
</tr>
<tr>
<td>7 57.2000</td>
<td>94.8000</td>
<td>Delbart et al. (2006)</td>
<td></td>
</tr>
<tr>
<td>8 56.0000</td>
<td>93.0000</td>
<td>Delbart et al. (2006)</td>
<td></td>
</tr>
<tr>
<td>9 58.5000</td>
<td>92.2000</td>
<td>Delbart et al. (2006)</td>
<td></td>
</tr>
<tr>
<td>10 67.6500</td>
<td>32.6200</td>
<td>Birch</td>
<td>Kozlov &amp; Berlina (2002)</td>
</tr>
<tr>
<td>11 55.5000</td>
<td>60.5000</td>
<td>Birch</td>
<td>Ahas et al. (2002)</td>
</tr>
<tr>
<td>12 58.3700</td>
<td>24.5200</td>
<td>Ahas et al. (2002)</td>
<td></td>
</tr>
<tr>
<td>13 50.3300</td>
<td>28.6700</td>
<td>Ahas et al. (2002)</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. For 13 sites, the measurement is the date of appearance (or unfolding) of birch leaves. For the easternmost site (site 14), the measurement is the date of needle appearance of larch.

Leafing phenology of the dominant deciduous tree species in the boreal forest displays much less variation than in the temperate zone, when the whole community is considered (Lechowicz, 1984). *Larix*, *Betula* and *Populus* belong to the early spring group of Lechowicz (1984) study. For sites 3, 4, 5, 7, 8 and 9, observations of leaf appearance of larch (*L. sibirica*) are also available, whereas on sites 1, 5, 8 and 9 observations are available for aspen (*P. tremula*). The average difference between the appearance of larch needles and birch leaves is zero days (SD of 4.2 days), whereas aspen leaves appear on average 3 days (SD 4.7 days) after those of birch (Delbart et al., 2005).

**Remote sensing of the green-up date**

We define the remote sensing green-up date \( t_{rs} \) as the date on which the satellite image grid-cell starts to green up. For 1998–2005 (except 1999, where deficiencies in the SPOT-VEGETATION middle infrared sensor affected our results, Delbart et al., 2005), \( t_{rs} \) is taken as the date on which the normalized difference water index (NDWI) starts to increase, since NDWI decreases with snowmelt and increases with foliage development (Delbart et al., 2005). Here, \( \text{NDWI} = (\text{NIR} - \text{MIR})/ (\text{NIR} + \text{MIR}) \), where NIR and MIR refer to the near and middle infrared reflectance measured by the SPOT-VEGETATION sensor.
From 1966 onward, this bias is not present as the daily temperature, estimated from daily temperature time series recorded at former USSR meteorological stations (Razuvaev et al., 1993). Before 1936, the daily temperature is the average of three diurnal measurements. The model is, therefore, not applied before 1936 in order to avoid the bias introduced into the daily temperature by the lack of night-time measurements. From 1936 to 1965, daily temperatures are the average of four diurnal or night-time measurements. This low number of daily measurements results in a bias in daily temperature, estimated to be 0.2°C (Razuvaev et al., 1993), giving a 0.66-day bias in the modelled green-up date (Picard et al., 2005). From 1966 onward, this bias is not present as the daily temperatures are the average of eight diurnal and night-time measurements (Razuvaev et al., 1993). Temperatures from NDP-040 are affected by heterogeneities: the records are incomplete, and many stations were relocated during the observation period. However, most of the moves were small enough (often within 1 km) not to affect the model estimates strongly. We use stations for which records are available since 1936, excluding the urban stations, to avoid the heat island effect.

Previously, Botta et al. (2000) also used phenological dates derived from remote sensing to calibrate phenological models at the global scale. However, the green-up timing was taken as the day at which NDVI starts increasing (Moulin et al., 1997), with no correction for snowmelt in the boreal regions. Consequently, the phenological models for the boreal regions were calibrated over snow melt timing (Moulin et al., 1997).

**Results**

The spatial patterns of changes (in days) computed from the linear regression of the time series of $t_{rs}$ (Fig. 3a) and $t_m$ (Fig. 3b) in 1982–2002 display common features: they both reveal an advancing trend (negative) for all regions from the Baltic to the Lake Baikal, this trend being especially strong over Central Siberia (Fig. 3a) where it is significantly different from zero at the 95% confidence level (Fig. 4), and a nearly null trend in the Yakutsk region (125–135°E, 58–63°N). Nevertheless, the absolute values of the trend differ, the trend in $t_{rs}$ being generally more strongly negative than the trend in $t_m$, especially in Western Russia and in the Baltic region (Fig. 5). The average rate of change is $-0.38$ days yr$^{-1}$ for $t_{rs}$ and $-0.32$ days yr$^{-1}$ for $t_m$ when averaged over the whole area.

The trend over the satellite era results from two distinct periods. The advancing trend occurs only in 1982–1991 (Fig. 3c), whereas 1991–2005 (Fig. 3d) is characterized by a slight delay trend: the spatially averaged rate of change in $t_{rs}$ is $-0.92$ days yr$^{-1}$ in 1982–1991, and $+0.04$ days yr$^{-1}$ in 1991–2005.

Before the beginning of the satellite observation period (1982), trends can be computed for $t_m$ only. Over 1958–1982 (Fig. 3e), slightly negative trends are found over southern Siberia and north-east Siberia (excluding the Far East), which do not display negative trends in the following 1982–2002 period (Fig. 3a and b). The rest of Eurasia displays low amplitude or slightly positive trends, not statistically different from zero (Fig. 4). Over the whole 1958–2002 period (Fig. 3f), nearly all regions except the Far East display an advancing trend, and the rate of change is significantly different from zero (at the 95% confidence level) for 49% of the pixels (Fig. 4).

The spatially averaged time series of $t_{rs}$ and $t_m$ are very close (Fig. 6), except in 1994 and 1997 for which they differ by 8 and 6 days, respectively. According to modelling, during 1958–2002, the earliest green-up

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**Fig. 2** Modelled leaf-out dates vs. *in situ* leaf appearance dates.

**Fig. 3** Linear regression of the green-up date from remote sensing and modelling (based on ERA40). Each map gives the change (in days) computed as the rate of change from the linear regression (least squares) multiplied by the number of years. (a) 1982–2002, from remote sensing, (b) same period 1982–2002 from modelling, (c) first half of remote sensing period 1982–1991, (d) second half of remote sensing period 1991–2005, (e) 1958–1982, from modelling, (f) 1958–2002, from modelling. Pixels with rate of change significantly different from zero at the 95% level are shown in Fig. 5.
dates occurred in 1967, 1989, 1990, 1991, 1997, 1999, 2000, 2001 and 2002. Moreover, after 1987, the average $t_m$ never exceeds the day of year number 147, whereas before 1987 it exceeds 147 nearly every second year. Consequently, the 1990–2002 period had the earliest green up in nearly half a century (Fig. 6): it occurred
4.5 days earlier in 1990–2002 than in 1958–1980 on average over the whole region. At the continental scale, the trend to earlier green-up principally consists of a large shift from 1987 to 1991. Before 1987 and after 1991, green-up dates does not present any notable trend.

In order to explore a longer timescale, the model was also applied to the temperature records from the meteorological stations available since 1936 (Fig. 7). In 1936–2002, only western boreal Eurasia and south-eastern Siberia exhibit a trend to earlier green up (Fig. 7a), and no significant trend is observed in the central regions. The reason for this is that in the first decades after 1936, green up occurred progressively earlier in the Western regions and progressively later in the Eastern regions, this contrast maximizing in 1936–1960 (Fig. 7b). From 1960, green-up modelled at meteorological stations exhibits a trend towards earlier spring, consistent with the gridded model (Fig. 3e).

Model results are corroborated by in situ data collected: \( t_m \) and \( t_{rs} \) show a good agreement with the ground observations of leaf appearance timing for the three sub-regions shown in Fig. 8.

The Baltic region (Fig. 8a) is characterized by two distinct periods of advance trends (1940–1950 and 1978–2005) display advancing trends, resulting in an average 10.4-day advance in 1990–2002 relative to 1936–1949. The advance found over 1940–1950 is partially due to remarkably cold temperatures in March and April 1940–1942 (Fig. 9a), which caused late leaf appearance.
As in Central Europe (Chmielewski & Rötzer, 2001; Scheifinger et al., 2002), the earliest leaf appearance dates are found in 1989 and 1990.

In Western Siberia (Fig. 8b), leaves appeared on average 6.2 days earlier in 1980–2002 than in 1960–1969, and 1.8 days earlier in 1960–1969 than in 1940–1949. No trend is visible from satellite observations as the leaf appearance remained stable after 1978 in this region.

In Central Siberia (Fig. 8c), ground observations and modelling reveal that leaf appearance has been progressively delayed from 1944 to 1960. This delay is also found by modelling for all meteorological stations east of the Ob river (longitude > 70°E). Before 1944, a trend to earlier leaf appearance is found in 1936–1944, and is similar in amplitude to the trend found in 1982–1991. This advancing trend in 1936–1944 is detected for all Central and Eastern Eurasian regions. Despite these successive trends of opposite signs, both ground observations and modelling show that the leaf appearance dates observed in the 1990s in Central Siberia are on average the earliest observed over the whole 1920–2005 period despite past occurrences of very early leaf appearance (e.g. 1943). The earliest spring green up occurred 1997, while the latest leaf appearance dates occurred in 1928–1936 and in 1983–1984. As a result, the strong advancing trend detected in Central Siberia with satellite observations, which is the strongest over the whole Eurasian taiga, is not only due to very early leaf appearance in the most recent years, but also to extremely late leaf appearance in the first years for which satellite data were available, due to cold temperatures in the 2 months preceding leaf appearance in 1983 and 1984 (Fig. 9b).

Discussion

Previously, other studies used satellite data to quantify the changes in the timing of the greening onset. The average rates of change previously determined from satellite observations (Myneni et al., 1997; Zhou et al., 2001) were close to those we present, when averaged over the continental scale, as we find a 7.1-day advance instead of the 6.4 days found by Zhou et al. (2001) in 1982–1999, although over a slightly different area. However, the previous methodology only studied the inter-annual changes in NDVI by using a set of threshold values having unclear phenological meaning, some of
them being related to snow melt. Thus, it was appropriate to show the general direction of changes, but their magnitude could not be safely ascribed to plants (Zhou et al., 2001). In contrast, our remote sensing methodology is unaffected by snowmelt and is shown to be related the actual date of leaf appearance. Consequently, our results confirm previous work and reduce the uncertainty in the value of the trend.

The uncertainty on the value of the trend in the green-up timing is further reduced by the agreement with modelling. Comparing the trends from each methodology permits identification of discrepancies, such as in the Baltic region, and also allows to increase the confidence in the results where the two methods agree, such as Central Siberia where a strong trend to earlier green up is identified after 1982. In order to
statistically evaluate the difference between the rates of change from $t_r$ and $t_m$, we associated confidence intervals to the rates of change of Fig. 3a and b at the 95% confidence level based on a Student’s test. For most pixels, except for isolated pixels located in the East of the Lake Baikal and in the Far East, the hypothesis that the rates of change from $t_r$ and $t_m$ differ can be rejected, as the confidence intervals overlap. However, the difference in the calculated rates of change can exceed 0.5 days yr$^{-1}$ (over 20 years) locally (Fig. 5). Different reasons may explain residual differences in the rates of change in $t_r$ and $t_m$: 1. The remote sensing methodology is more accurate for high signal-to-noise ratio. The magnitude of the increases in NDVI or NDWI in spring increases with the proportion of deciduous vegetation in the pixel. However, in the western part of our study area, some regions classified as deciduous or mixed forest in GLC2000 are classified as evergreen forest in MOD12 (Fig. 1), and may have a low signal-to-noise ratio. 2. In the case of the Baltic region (Fig. 8), the rate of change in $t_r$ is $-0.73$ and $-0.31$ days yr$^{-1}$ for $t_m$. The two rates of change become, respectively, $-0.65$ and $-0.46$ days yr$^{-1}$ when removing 1983 from the regression: in this year $t_m$ is 12 days earlier than the ground observations. In this case, a modelling error in only 1 year is responsible for one-third of the difference between the rates of change calculated from $t_r$ and $t_m$. More generally, the error affecting...
In addition to the cross-checking of the trends in the green-up dates from remote sensing and modelling, combining the two methodologies presents a strong advantage: as suggested by Schwartz (1998), it provides a longer term context for the remote sensing-based studies. Modelling shows that the period which is accessible by remote sensing has been preceded by a period in which the date of leaf appearance did not display any strong trend noticeable at the large scale. Applying the model to temperature records from meteorological stations reveal that a delaying trend existed in the whole Central and Eastern Siberia over the 1944–1960 period.

The ground observations have been used first for validating the remote sensing methods and the model. The result of these validations, and the agreement between the time series from the three sources of information (Fig. 8), indicate that the remote sensing methods and the model both produce green-up dates that are close to actual leaf appearance dates, and that the three sources of information can be analysed jointly. Where available, they also allow evaluation of whether \( t_m \) or \( t_{rs} \) is wrong when the rates of change from these two methodologies differ, such as in the Baltic region in our study. In addition, ground observations further extend the study period, although this is applicable at the local scale. However, the agreement of the ground observations with \( t_{rs} \) and \( t_m \) that are averaged regionally (Fig. 8) also indicates that the ground observations can be used to study phenology at the regional scale and not only at the specific location where they were made. In other words, the ground observations allows increasing our confidence in the temporal changes of the timing of green up and meanwhile, the agreement between the gridded data \( (t_{rs}, t_m) \) and the local measurements allows to extent the area for which the ground observations are representative, and thus replace this gridded information in a longer term context. Such combination revealed a previous trend to earlier green up in the 1930s in Central Siberia. We note that such a unified analysis is usually considered difficult (Badeck et al., 2004; Fisher et al., 2007), probably because these previous studies were conducted over temperate forests, which often form complex mosaics with crop-lands of readily different phenology. Temperate forests themselves consist of more numerous deciduous species, displaying a large range of leaf appearance timing at the local scale (Lechowicz, 1984; Fisher et al., 2006). In these regions the green-up dates detected from satellite observations are more difficult to relate to in situ observations from one species than in the boreal regions. Overall, although further improvements in the model and the remote sensing method may be possible, the combination of remote sensing, model and historical in situ data allows to portray Eurasian phenology at a nearly century scale.

Conclusion

The greening trend observed by remote sensing consists essentially in a large-scale shift at the end of the 1980s. After this shift, there is no strong trend in the timing of leaf appearance, and thus the trend should not be extrapolated. This shift in the late 1980s was also observed in the leaf appearance timing in Central Europe (Chmielewski & Rötzer, 2001; Scheifinger et al., 2002), and may be an indicator of the decadal shift in the climate of the Northern hemisphere that occurred in winter 1989 (Watanabe & Nitta, 1999; Yasunaka & Hanawa, 2002) and affected surface temperatures. In eastern and Central Siberia, as well as in Germany (Schaber & Badeck, 2005) and in North East America (Schwartz, 1998) previous instances of advancing and delaying trends were found; in the context of a nearly century time scale, greening trends such as the one revealed by satellite observations over 1982–1991 is not unusual if considered locally. Moreover, the strong trend found in Central Siberia, which is the strongest for the whole study area, was accentuated by late leaf appearance at the beginning of the period for which remote sensing data were available. However, the leaf appearance dates after 1990 are the earliest since 1958 at the continental scale, the earliest since 1936 in the Baltic region, and the earliest since 1920 in Central Siberia, (i.e. since the beginning of the observation or modelling period for each region or subregion). The greening trend measured using satellite observations...
since 1982 is consequently unprecedented because it simultaneously affected a large part of boreal Eurasia, indicating a large scale spring temperature increase.

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