
Nicolas Delbart a,b,*, Thuy Le Toan a, Laurent Kergoat a, Violetta Fedotova c

a Centre d’Etudes Spatiales de la Biosphère, CNRS-CNES-UPS-IRD, Toulouse, France
b Ecosystem Change Research Program, JAMSTEC Frontier Research Center for Global Change (FRCGC), Yokohama, Japan
c Institute of Botany, Komarov Russian Academy of Science, Saint-Petersburg, Russia

Received 20 May 2005; received in revised form 10 November 2005; accepted 26 November 2005

Abstract

Measurements of spring phenological dates in boreal regions using NDVI can be affected by snowmelt. This impacts the analysis of interannual variations in phenology and the estimates of annual carbon fluxes. For these two objectives, snowmelt effect must be removed from the phenological detection. We propose a methodology for determining the date of onset of greening in the 1982–2004 period using SPOT-VEGETATION (VGT) and NOAA Advanced Very High Resolution Radiometer (AVHRR) data. From 1998 onwards, the date of onset of greening is taken as the date at which the Normalized Difference Water Index (NDWI), calculated from SPOT-VGT near and short-wave infrared bands, starts increasing. This index decreases with snowmelt but increases with vegetation greening. For the 1982–2001 period, the date of onset of greening is the date at which AVHRR-NDVI equals a pixel specific threshold (PST), determined using the results of the NDWI method in the years common to the two datasets. The methods are validated using in situ measurements of the dates of leaf appearance. RMSE of 6.7 and 7.8 days, respectively, is found using NDWI-VGT and PST-NOAA methodologies, and the difference between the two methodologies in the common years is small. Very importantly, the dates are not biased. The interannual variations of the 23-year spring phenology dataset on the study area in northern Eurasia are analysed. In average over the study area, an advance of 8 days and a delay of 3.6 days are, respectively, found over the periods 1982–1991 and 1993–2004. These results confirm and complete previous studies about the greening trend, remove the uncertainty due to snow, and may improve carbon budget calculations.

© 2006 Elsevier Inc. All rights reserved.

Keywords: Phenology; Snow; Boreal; Siberia; SPOT-VEGETATION; NOAA-AVHRR; Leaf appearance; NDVI; NDWI; Spring

1. Introduction

Phenology of many organism types in terrestrial ecosystems has been clearly identified to be disturbed by climatic changes (Parmesan & Yohe, 2003; Root et al., 2003; Walther et al., 2002). In recent years, remote sensing satellite data have been used at regional and global geographic scales as an objective means to assess the interannual variations in the phenology of deciduous vegetation foliage, i.e. the timing of foliage appearance and senescence. In particular, the time series of the Normalised Difference Vegetation Index (NDVI) from the NOAA Advanced Very High Resolution Radiometer (AVHRR) has been used to demonstrate a trend of earlier greening in the northern latitudes since 1982 (Myneni et al., 1997, 1998; Slayback et al., 2003; Tucker et al., 2001; Zhou et al., 2001). The statement was based on the trend in the timing of the NDVI increase in spring. However, in boreal regions, where strong impacts of climatic change on vegetation phenology are expected, NDVI also increases during snowmelt (Moulin et al., 1997). Consequently, an earlier NDVI increase could be due either to an earlier vegetation onset or to an earlier snowmelt (Dye & Tucker, 2003; Shabanov et al., 2002). Since both snowmelt and greening events are driven by temperature, a trend in the dates of NDVI increase indicates a general warming or cooling effect, without giving any specific information on the related surface processes.

Recently, several approaches have been used to detect spring phenology in boreal regions, accounting for the presence of snow. Zhang et al. (2004) replace any record at which snow...
is detected by a snow free record, using MODIS data. Alternatively, the onset of greening has been estimated as the date at which NDVI exceeds a threshold. Suzuki et al. (2003) consider that the budburst occurs when the NOAA NDVI exceeds 0.2, assuming that above this threshold snow is not present. White et al. (2005) consider that removing the snow effects from the signal is of primary importance for the analysis of phenological variations from NDVI.

In a previous paper, a method was proposed to retrieve the date of onset of greening using a remote sensing index (different from NDVI) which excludes snow effects (Delbart et al., 2005). The index used in this method is a combination of near and middle infrared reflectances. Such combination was proposed by Hardisky et al. (1983) and was adapted to the SPOT-VEGETATION (VGT) spectral bands by Xiao et al. (2002) under the name of Normalized Difference Water Index (NDWI), first proposed by Gao (1996) to designate a slightly different spectral index. The detection algorithm by Delbart et al. (2005) relies on the fact that NDWI first decreases with snowmelt and then increases during the vegetation greening. The method (referred to as the NDWI-VGT method) was applied to VGT data from 1998 to 2002 over central Siberia and its results agreed well with in situ dates of leaf appearance. The RMS error over 19 data points was of 8.7 days and the bias, 0.7 day, whereas using NDVI, the RMSE were about 9.7 days and the bias, non-uniform spatially, varied from 5.6 days to more than 10 days. Both methods could give equivalent results in the trend analysis, however, only the NDWI-VGT method can provide an accurate and precise determination of the dates of onset of greening (Delbart et al., 2005).

Long time series of accurate and precise spring phenology dates cannot be provided by neither VGT, which has been operating since 1998, nor NOAA-AVHRR which does not have the equivalent middle infrared band needed for the NDWI method. To make use of the long time series of NOAA-AVHRR, the alternative proposed in this paper consists of using NDWI-VGT results from 1998 to 2001 to determine pixel specific thresholds (PST) from NOAA-AVHRR NDVI time series. The PST value is then the NDVI value at which onset of greening is expected to occur for all years at a particular pixel. The method (referred to as the PST-NOAA method) is applied to the 1982–2001 Pathfinder AVHRR Land (PAL) NDVI dataset, on a large area in Northern Eurasia. The greening-up dataset is then constructed from 1982 to 2004, using PST-NOAA results for 1982–1997 and NDWI-VGT results for 1998–2004. All results are compared to in situ dates of leaf appearance from eight validation sites. The temporal evolution of spring phenology in the study area since 1982 to present is analysed. Finally, the method is discussed in regard to the sources of uncertainty, the calculated trends in phenology are compared with those from other studies, and the significance of our results for carbon budget calculation is discussed.

2. Study area and data

2.1. Study area

The study area is in northern Eurasia, located between latitudes 50°N and 72°N and longitudes 45°E and 180°E. Fig. 1 shows the land cover map of the study area, adapted from the Global Land Cover 2000 (GLC 2000) map (Bartholomé & Belward, 2005) to highlight evergreen and deciduous vegetation covers, and herbaceous covers in the North (tundra) and South (steppe). Bare areas and agricultural covers are not considered in the study and are shown in black. Fig. 1 shows that deciduous vegetation covers a large proportion of the area, in particular at latitudes beyond 90°E, where the main tree species is larch.
2.2. SPOT-VGT S10 data

The SPOT-VGT data used in the study are 10-day-composite data (S10) at the resolution of 0.008928° (about 1 km) in plate-carree geographic projection available from http://free.vgt.vito.be/ for years 1998 to 2004. The data consist of reflectances in spectral bands B0, B2, B3 and SWIR, which correspond, respectively, to the blue (0.43–0.47 μm), red (0.61–0.68 μm), near-infrared (0.78–0.89 μm) and short-wave infrared (1.58–1.75 μm) domains.

One pixel record of S10 data corresponds to the record the least affected by atmospheric noise in the 10-day period, selected based on the Maximum Value Composite technique (Holben, 1986). One record comprises the recording date and reflectance values in each of the spectral bands. The SPOT-VGT SWIR sensor being sensitive to collisions with protons, some deficiencies have been observed in a number of records. The SPOT-VGT S10 data, only one NDVI measurement is retained on each 10-day period using the Maximum Value Composite technique. However, the date of the selected data is not given, and in this study, we define it as the midpoint of the 10-day period.

2.3. NOAA Pathfinder AVHRR Land (PAL) 10-day-composite NDVI

The Pathfinder (James & Kalluri, 1994) 8 km resolution NDVI data set (downloaded from http://daac.gsfc.nasa.gov/) was built from data from NOAA satellites (NOAA 7, 9, 11 and 14). NDVI is calculated as follows:

\[ \text{NDVI} = \frac{\text{channel2} - \text{channel1}}{\text{channel2} + \text{channel1}} \]  

where channel1 and channel2 are the reflectance values measured at 0.58–0.68 (red) and 0.73–1.10 μm (near infrared), respectively. Similarly to the SPOT-VGT S10 data, only one NDVI measurement is retained on each 10-day period using the Maximum Value Composite technique. However, the date of the selected data is not given, and in this study, we define it as the midpoint of the 10-day period.

2.4. In situ phenological records

The phenological records used for validating the retrieval algorithms are from the eight sites detailed in Table 1 and indicated geographically in Fig. 1. Records 1 to 6 were compiled by the Komarov Botanical Institute, Saint Petersburg, and originate from various sources, such as hydrometeorological stations, agricultural stations and nature reserves (Fedotova, 2000). Methodologies for phenological observations are described for instance in Bulygin (1976) and Elagin (1975). The records contain the dates of leaf appearance for birch and larch, obtained through visual observations. The temporal coverage, up to 2002, is different for each site. Record 7 consists of one observation made in 2004, and was presented by Miyahara et al. (2004). The authors give the date of larch leaf appearance as mid May. We consider it as day-of-year (DOY) 135. Record 8 gives the date of larch leaf appearance as given in Ahas et al. (2002). It is noted that the validation sites are not well distributed geographically: records 1 to 5 are in southern taiga, record 6 represents northern latitudes, and records 7 and 8 are, respectively, the only ones in the East and the South West of the study area.

3. Methodologies

3.1. Data pre-processing

Before the phenological retrieval algorithms are performed, SPOT VGT and PAL NDVI datasets are processed to have similar 0.1° plate-carree (geographic) projection, and to reduce the cloud and atmospheric effects.

SPOT-VGT reflectance maps are averaged to the 0.1° resolution. For each 0.1° × 0.1° pixel, the day of acquisition is taken as the day having the maximum occurrence among the original pixels. The 0.1° resolution reflectance maps are combined to calculate NDWI as:

\[ \text{NDWI} = \frac{\text{B3} - \text{SWIR}}{\text{B3} + \text{SWIR}} \]  

PAL NDVI maps are projected to a 0.1° plate-carree. The Best Index Slope Extraction (BISE) algorithm (Viovy et al., 1992) is then applied to the whole series of PAL NDVI in order to reduce cloud and atmospheric effects. BISE replaces acquisitions affected by quick and non-persistent NDVI increases or decreases by the average of previous and next NDVI acquisitions. In order to further remove late spring and summer atmospheric and cloud effects we apply a second filter. This consists in cancelling NDVI decreases after it has reached 80% of its amplitude (defined as the difference between the maximum NDVI and the average NDVI in March). These two filters together allow retaining the external envelope of the ascending part of the NDVI course.

3.2. Retrieval of the date of onset of greening with NDWI-VGT in 1998-2004

The spring phenology date in years 1998–2004 is estimated using the method described and validated in Delbart et al. (2005). Using this method, the date of onset of greening is taken as the day at which NDWI starts increasing, determined as the last date at which NDWI is lower than the minimum NDWI increased by a quantity \( \varepsilon \), taken as 20% of the NDWI spring amplitude.
3.3. Retrieval of the date of onset greening with PST-NOAA in 1982–2001

We use the threshold method which considers the greening up date as the date at which PAL NDVI is equal to a threshold. It is understood that the threshold value depends on the vegetation type and on climatic and environmental factors. This means that the threshold value should vary both in space and in time. However, the interannual variations of the threshold are assumed to be smaller than its spatial variations. In Schwartz et al. (2002), the threshold called Seasonal Midpoint NDVI (SMN) (White et al., 1997) is defined as the NDVI value at half its seasonal increase amplitude averaged on several years, meaning that the threshold value varies spatially, but is fixed interannually. The authors also tried to redefine it annually, but the results were less satisfying because of large interannual variations in the minimum NDVI mostly due to partial snow and cloud cover.

In our study, we use the same assumption of small interannual variations of the threshold. The threshold value is determined for each pixel, from years 1998, 2000 and 2001 for which both PAL NDVI and SPOT-VGT data exist (data in 1999 are discarded because of SWIR sensor deficiencies). For each year, the threshold is determined for each pixel as the PAL NDVI value found at the date of onset of greening estimated using the NDWI-VGT method. As shown in Fig. 2, a linear regression is applied to the three PAL NDVIs which are the closest in time to the date of onset of greening (or to the 2 closest if the date of onset of greening is just at the middle of two PAL NDVI records). The single-year threshold value is the value of the regressed NDVI found at the date of onset of greening. The Pixel Specific Threshold (PST) value is the average of the three single-year thresholds.

Once the PST value is determined, the date of onset of greening is estimated from the 1982-2001 PAL NDVI as the date at which NDVI (interpolated) is equal to the PST. We assume that the onset of greening occurs between 1st April (DOY 90) and 19th July (DOY 200). If NDVI is equal to the PST at several dates, for example because of early spring variations, the last date among those several dates is given. This provides a conservative estimate of the actual date of onset of greening. If NDVI is never equal to the PST, no date is provided.

4. Results

4.1. Maps of phenological dates and validation

Fig. 3 presents the dates of onset of greening determined using PST-NOAA in 1982-2001 and using NDWI-VGT in 1998–2004. Three main points should be noted from these results. Firstly, the date of onset of greening displays for all years a marked North–South gradient up to three months, with the earliest dates found in the South West (1st to 20th April), and the latest dates found in the North (end of June). Secondly, the interannual variations are important: at one location the date varies on average from –19 to +19 days around the average date. This is consistent with the variations estimated from the in situ records: from –15 to +15 days (Delbart et al., 2005). Extreme years are noticeable, e.g. latest onset of greening in 1987 and earliest in 1997. Thirdly, the mean absolute difference between the dates obtained using NDWI-VGT and PST-NOAA is of the order of a week (7.3 days in 1998, 6.8 days in 2000, and 8.6 days in 2001), which is much smaller than the interannual variations.

Fig. 4 presents the dates of onset of greening obtained using PST-NOAA and NDWI-VGT from 1982 to 2004 and the available in situ dates of leaf appearance at the eight validation sites. For the comparison, the remote sensing greening dates are taken on the pixel of deciduous forest which is the closest to the in situ coordinates (Table 1), in order to avoid water pixels (close to site 9), urban pixels (close to site 5), agricultural pixels (close to sites 2 and 3), and mixed forest (close to site 1). The largest shift in space is 0°25’westwards shift at site 3.

Fig. 4 shows that a) the remote sensing retrieved dates are close to the in situ dates, and b) the interannual variations are in most cases correctly represented. Fig. 5 presents the dates of onset of greening obtained with the two remote sensing methods plotted against the in situ dates, and Table 2 presents the associated measures of the agreement between the retrieved dates and the in situ dates. Despite the difference in the number of records (number of sites multiplied by the number of years), very similar results have been obtained with the two remote sensing methods. There is no systematic error in the retrieval, as indicated by small MBE values found with both methods (0.55 and 0.33 days) and by the small RMSE values (0.97 and

![Graph](image-url)
1.54 days). With both methods, the RMSE is of the order of a week (6.7 days with NDWI-VGT and 7.8 days with PST-NOAA), and is nearly equal to its unsystematic component $\text{RMSE}_{u}$, which accounts for errors caused by the temporal resolution of the radiometric data, and by factors such as the variability in the threshold, the type of vegetation, or the landcover changes. The correlation between the retrieved dates and the in situ dates is high ($r^2 \approx 0.8$) and statistically significant ($p < 0.0001$).

The small difference between the dates found with the two methods, and the similar agreement with the in situ records, show that the PST-NOAA method correctly reproduces the results obtained with the NDWI-VGT method, although it uses different spectral bands, and that the effect of snow in this retrieval is low.

### 4.2. Variations in NDVI value at spring phenology date

Fig. 6 present maps of the NDVI values at the onset of greening obtained for years 1998, 2000 and 2001 (Fig. 6a to c), their temporal average (Fig. 6d), and their temporal range (Fig. 6e) for the study area. Fig. 6a to d show that the NDVI value at the greening onset is higher on forest covers than on shrub and herbaceous covers. It is also higher on evergreen forest than on deciduous forest. This can be explained by the fact that for evergreens, the NDVI is already high when the understory, grass, or sparse deciduous trees in the pixel start greening.

Fig. 6e shows the temporal range of NDVI values found at the onset of greening. Some of the temporal variations are due to errors in the retrieval of the dates measured with NDWI, and
to noise in the NDVI time series. Averaging the three single-year-thresholds reduces these errors. Another component of the temporal variations may be due to the amount of grass, shrubs, and to the snow cover remaining at leaf flush, all of which may vary from one year to another. The assumption of fixed threshold in the PST-NOAA method does not account for such variations. However the good agreement between the retrieved dates and the in situ records shows that these variations must be small enough not to impact drastically the retrieval.

Table 2
Quantitative measures of the agreement between the dates of onset of greening retrieved using the NDWI-VGT method and the PST-NOAA method (estimations) and the in situ dates of leaf appearance (observations): number of in situ records ($N$), Mean Bias Error (MBE), variance of the distribution of the error ($s^2$), Mean Absolute Error (MAE), Root Mean Square Error (RMSE), slope ($a$) and intercept ($b$) of the regressed function, Root Mean Square of the Unsystematic Error (RMSEu) and of the Systematic Error (RMSEs), degree of agreement ($d$), determination coefficient ($r^2$), and $p$ value

<table>
<thead>
<tr>
<th></th>
<th>NDWI-VGT</th>
<th>PST-NOAA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>21</td>
<td>81</td>
</tr>
<tr>
<td>MBE (days)</td>
<td>0.55</td>
<td>0.34</td>
</tr>
<tr>
<td>$s^2$ (days)</td>
<td>6.79</td>
<td>7.79</td>
</tr>
<tr>
<td>MAE (days)</td>
<td>5.50</td>
<td>6.25</td>
</tr>
<tr>
<td>RMSE (days)</td>
<td>6.65</td>
<td>7.75</td>
</tr>
<tr>
<td>$a$</td>
<td>0.94</td>
<td>0.91</td>
</tr>
<tr>
<td>$b$ (days)</td>
<td>6.96</td>
<td>12.64</td>
</tr>
<tr>
<td>RMSEu (days)</td>
<td>6.57</td>
<td>7.60</td>
</tr>
<tr>
<td>RMSEs (days)</td>
<td>0.95</td>
<td>1.54</td>
</tr>
<tr>
<td>$d^2$</td>
<td>0.83</td>
<td>0.75</td>
</tr>
<tr>
<td>$r^2$</td>
<td>$1.2 \times 10^{-8}$</td>
<td>$7 \times 10^{-20}$</td>
</tr>
</tbody>
</table>

The term error relates for difference between the estimation and the observation. Description and formulation of MBE, $s^2$, MAE, RMSE, RMSEu, RMSE, and $d$ are given in Willmott (1982).
4.3. Retrieval in evergreen forest

Fig. 7 presents the NDVI variations for a deciduous forest (Fig. 7a) and for an evergreen forest (Fig. 7b), with their respective thresholds. In the deciduous forest, snowmelt induces a marked and continuous increase in NDVI, so that the PST value is significantly larger than the average winter NDVI, which is low because of snow and because of the absence of green leaves.

Fig. 7b gives the NDVI variations on the same evergreen forest in two consecutive years. In the curve corresponding to year 1993, the PST value is only slightly higher than the mean winter NDVI, which is high because of the presence of the leaves and because the leaves hide the snow lying on the ground. The increase in NDVI with snowmelt is less important than in deciduous pixels, making the PST value closer to the mean winter NDVI, although it is higher than in deciduous forests. In year 1994, NDVI is higher than in 1993, and exceeds the threshold very early during the year. As described in Section 5.2, the NDVI value at the onset of greening fluctuates from one year to another, which is not considered in the PST-NOAA method. In year 1994 the PST value is too low, inducing an underestimation of the date of onset of greening. This indicates that the retrieval of the phenological date of deciduous trees is more difficult for forests dominated by evergreen trees.

4.4. Analysis of onset of greening up time series: 1982–2004

The dataset is used to analyse the interannual variations and the trend in spring phenology dates. In this analysis, we discard the dates which differ from the interannual mean by more than 30 days (twice the range of variations found from the in situ data) at a pixel.

Fig. 8 shows the interannual variations of the onset of greening date averaged over the study area during the 23 year period. To study the trend, a linear regression is fitted to the greening dates for each pixel of the study area, from 1982 to 2004. Fig. 9a gives the map of the number of days of advance (negative) or delay (positive) of the onset of greening, taken as the slope of the regression multiplied by the number of years. The black line represents the 95% confidence level on the sign of the slope. Over the study area and for the entire period, the average trend corresponds to an advance in the spring phenology of 3.5 days. However, the trend is spatially and temporally heterogeneous.

Two regions display a strong advance in the spring phenology. The first region is a larch taiga in the North East. The second region spreads from Lake Baikal towards the Ob river’s mouth, and contains most of the sites used in the validation. Other regions display no trend (close to zero), and in regions such as the Yakoutia region, the onset of greening tends to be delayed. Different trends can be found if we break down the time series in specific periods.

From 1982 to 1991 (Fig. 9b), we find an advance of 7.8 days in average over our study area. In particular, the 1985–1991 period is characterized by an average advance of 11 days. This 1982–1991 result is consistent with the advance found by Myneni et al. (1997), Zhou et al. (2001), Tucker et al. (2001) and Shabanov et al. (2002) in northern Eurasia and northern latitudes for the same period. After 1991 the average date varies irregularly until 1999, and increases continuously between year 2000 and year 2004. Spring phenology is found to occur late in 1992, due to the cooling induced by the Pinatubo eruption in June 1991 (Tucker et al., 2001), and the earliest greening of the whole dataset is found in 1997. To identify general climate related trends, we discard year 1992, and we proceed to the trend analysis in the 1993–2004 period (Fig. 9c). Despite 1997, this period is characterised by a delay of the date of onset of greening of 3.6 days in average on the
study area. Specifically, the delay in the period 2000–2004 is found to be of 7 days. The overall results show that the greening trend observed in the 1982–2004 period is essentially dominated by the advance in 1985–1991.

5. Discussion and conclusions

In this paper, we have presented a remote sensing method to determine the date of onset of greening in boreal ecosystems, which reduces the uncertainty due to the effect of snow in the remote sensing signal. From 1998 onwards, the date of onset of greening up is taken as the date at which NDWI calculated from SPOT-VGT data starts increasing, as this index decreases with snowmelt and increases with vegetation greening up (Delbart et al., 2005). In the 1982–2001 period, the date of onset of greening up is the date at which PAL NDVI equals a threshold, which has been determined for each pixel using the results of the NDWI-VGT method. The pre-requisite to apply this method is to eliminate the noise affecting NDVI. Consequently, the BISE filter has been used to retain the external envelope of the NDVI curve, as atmospheric noise generally induces a decrease in NDVI. Alternative methods could be used: Chen et al., 2004 proposed a Savitsky–Golay filter, Sakamoto et al. (2005) used a wavelet-based filter. The use of BISE with a second filter, which eliminates drastically the summer noise, yielded an NDVI time series adapted to phenology detection. Noise in the summer period would significantly affect our phenology retrieval because our algorithm returns the last date at which NDVI equals the threshold value.

In Delbart et al. (2005), it was shown that the retrieval of the date of onset of greening using the NDWI-VGT method was more difficult in forests dominated by evergreen trees. Present results indicate that this is also true for the PST-NOAA method. This method may also have other limitations. The first potential limitation comes from the use of the PAL dataset. Successive NOAA satellites are differently calibrated, and their equatorial crossing time changes with satellite ageing, leading to illumination variations. It was found that the effect of acquisition geometry on NDVI is low on vegetated areas (Kaufmann et al., 2000), and it is lower at high latitudes than at low latitudes (Slayback et al., 2003), and nearly insignificant in Eurasia (Zhou et al., 2003). In our study, the good agreement between in situ data and the retrieved dates shows that if errors due to illumination variations exist, they are smaller than errors such as those induced by the temporal variations of threshold or by the composite aspect of data. However, NOAA 14 westward drifting leads to a significant decay in NDVI in 2000 and 2001. In 2001, NDVI in desert areas was found to be lower by about 0.05 than the multi year average (Stöckli & Vidale, 2004). In the determination of the threshold value, using year 2001 may degrade the retrieval performance. In order to quantify the effect of 2001 data, threshold averaged only from years 1998 and 2000 has also been tested for the retrieval, but the resulting RMSE with in situ data is 9.8 days instead of 7.8 days. We conclude that the effect of satellite transition, ageing and drifting is negligible in the retrieval using the PST-NOAA method.

The second potential limitation comes from the use of a threshold which is constant in time. In the Results section, it was stated that interannual fluctuations in the threshold value do not strongly affect the retrieval using the PST-NOAA method. However, potential landcover changes that occurred before 1998 may affect it. The threshold value is not valid for all years prior to deforestation or fire. Similarly, NDVI of a regenerating forest is lower in 1982 for example than in 1998–2001. Moreover, a change in the proportion of the plant functional types in a regenerating forest, especially the proportion of deciduous/evergreen, can gradually modify the value of the threshold. However, at 0.1° resolution, the effect is in general expected to be small, because deforestation and forest regeneration may compensate each other, except where fires or deforestation affect large areas.

Overall, the comparison of the dates obtained from these two remote sensing methods with phenological in situ records at eight validation sites gives RMS errors of 6.7 and 7.8 days with NDWI-VGT and PST-NOAA methods, respectively, and a negligible bias. The relatively good precision and accuracy of these spring phenological dates indicate that a) the snow effect has been decoupled in the signal, and b) the remote sensing onset of greening corresponds well to the leaf appearance observed in situ. By decoupling the snow and the vegetation spring events, the present results remove the ambiguity stressed by Dye and Tucker (2003) and by Shabanov et al. (2002) and allow studying the interannual variations in phenology with no confusion with those of snow. Trends of variations in spring phenology derived in the 1982–1991 period are in good agreement with previous studies and confirm the greening trend. This is a surprising result, as these studies did not take into account the effect of snow on the retrieval of phenology. There may be two main reasons for that. Firstly, studies by Myneni et al. (1997, 1998), Zhou et al. (2001) and Shabanov et al. (2002) used a set of thresholds to study the interannual variations in the seasonality of NDVI instead of attempting to measure phenology. Some of these thresholds were above our threshold value so that the retrieval was not affected by snow. Secondly, both snowmelt and spring phenology are driven by temperature, so that the interannual variations must be partially correlated.

The method allows studying the variations in phenology on a longer period than the previous studies, which stopped either at 1991 or at 1999, and will allow continuing this analysis in the future with SPOT-VGT or MODIS. The current results show that the greening trend has slowed down after 1991. In particular the 2000–2004 period is characterised by a continuous delay in spring phenology, so that over the 1982–2004 period the advance is only 3.5 days on average over the study area. To allow more general observation of the warming or cooling effect on boreal phenology, an extension of the present results in the future with SPOT-VGT or MODIS. The current results can also strongly contribute to the calculation of the carbon budget of deciduous forests, in which photosynthesis and carbon uptake start with leaf appearance. The duration of the growing season, taken as the season during...
which leaves are present, influences the annual carbon uptake. CO₂ flux measurements over ten forest sites show that the net ecosystem CO₂ exchange increases on average by 5.7g C m⁻² for each day that the length of the growing season increases (Baldocchi et al., 2001), and that the variations in the length of the growing season account for 83% of the variance of CO₂ exchanges. White et al. (1999) estimate that a one-day change in the growing season length can result in a variation of 0.53% of the annual GPP (Gross Primary Productivity), and 1.6% of the annual NEP (Net Ecosystem Productivity), with potentially higher values in northern latitudes where the growing season is shorter. Botta (1999) declares that a 20-day shift in spring phenology induces a 30% change in the gross primary productivity of Eurasian taiga. Consequently, phenology appears to be a key factor in the calculation of annual carbon exchange between deciduous forests and the atmosphere. This idea should be moderated as it seems that the increase of carbon uptake with a lengthening of the growing season may occur only if water is available (White & Nemani, 2003), and that the increase of carbon uptake with a lengthening of the growing season because of warming could be cancelled by an increase of soil respiration also induced by warming (Goulden et al., 1998). Nevertheless, accurate and precise estimates of phenology are required when calculating the carbon budget of boreal forests. By removing the effect of snow on the remote sensing signal, the methodology described in this article yields non-biased and relatively precise estimates of phenology which could be used for estimating the carbon budget of boreal deciduous ecosystems.

Acknowledgements

This work was conducted in the framework of the Siberia II project (Multi-sensor concepts for Greenhouse Gas Accounting of Northern Eurasia), EC Framework 4 Contract: EVG1-CT-2001-00048.

First author is very grateful to the Japanese Society for Promotion of Science (JSPS) for the financial support.

References


Elagin, I. N. (1975). Methodology for collecting and processing data of phenological observations on trees and shrubs. In I. N. Elagin, & T. N. Bytotorina (Eds.), Phenological methods for studying the forest biocenoses (pp. 3–20). Krasnoyarsk: Institute of Forest and Wood of Siberian Branch of Academy of Sciences of USSR.


