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Spring initiation and autumn cessation of boreal coniferous forest CO_2 exchange assessed by meteorological and biological variables

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ABSTRACT

We studied the commencement and finishing of the growing season using different air temperature indices, the surface albedo, the chlorophyll fluorescence (Fv/Fm) and the carbon dioxide (CO_2) tropospheric concentration, together with eddy covariance measurements of CO_2 flux. We used CO_2 flux data from four boreal coniferous forest sites covering a wide latitudinal range, and CO_2 concentration measurements from Sammaltunturi in Pallas. The CO_2 gas exchange was taken as the primary determinant for the growing season to which other methods were compared.

Indices based on the cumulative temperature sum and the variation in daily mean temperature were successfully used for approximating the start and cessation of the growing season. The beginning of snow melt was a successful predictor of the onset of the growing season. The chlorophyll fluorescence parameter Fv/Fm and the CO_2 concentration were good indicators of both the commencement and cessation of the growing season. By a derivative estimation method for the CO_2 concentration, we were also able to capture the larger-scale spring recovery. The trends of the CO_2 concentration and temperature indices at Pallas/Sammaltunturi were studied over an 11-yr time period, and a significant tendency towards an earlier spring was observed. This tendency was not observed at the other sites.

1. Introduction

Climate change introduces alterations to the timing and length of the spring and autumn periods, which in turn can have significant effects on vegetation, and in general spring temperatures are increasing (Trenberth et al., 2007). Despite this, some regions may still experience late severe night frosts leading to frost damage (Jönsson et al., 2004; Gu et al., 2008). Higher temperatures in autumn increase soil respiration and, as the photoperiod simultaneously limits photosynthesis, changes in the carbon balance may well be introduced (Falge et al., 2002; Piao et al., 2008). Increasing levels of carbon dioxide (CO_2) in the atmosphere also influence the behaviour of the plants during these transition periods (Repo et al., 1996; Taylor et al., 2008).

To estimate the carbon balance in a changing climate, it is important to properly simulate the seasonality of the carbon cycle in global climate models. CO_2 fluxes are widely measured with the eddy covariance (EC) method, which provides direct and continuous information about local CO_2 fluxes (Baldocchi, 2003). The disadvantages of this method include, for example, its high expense. Since the number of EC sites remains limited, it is important to generalize the information about carbon cycle dynamics that these sites provide, in order to better improve global climate models.

Because of their large size, northern boreal forests play an important role in the global carbon cycle. The activity of the boreal vegetation is more linked to temperature than to water availability (Tanja et al., 2003; Yuan et al., 2008). In this region the transition periods between winter and summer are clearly distinguishable. Air temperature has been considered to be a very important factor in the spring recovery of the boreal forests (Leinonen et al., 1997; Tanja et al., 2003; Arneth et al., 2006). Night frosts (Bergh and Linder, 1999; Ensminger et al., 2004) and low soil temperatures (Ensminger et al., 2008) have also been shown to influence this transition period.

The growing season of the ecosystem starts when vegetation begins to absorb CO_2 from the atmosphere. It has been argued that the length of the growing season can have a significant effect

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on the carbon balance of a coniferous boreal forest (Churkina et al., 2005; Monson et al., 2005), but opposing evidence has also been offered (Dunn et al., 2007; Welp et al., 2007).

Since the spring recovery and autumn decline of the forest are closely related to air temperature (Tanja et al., 2003; Lagergren et al., 2008), different temperature indices have been developed to describe the forest's photosynthetical status. The use of the temperature sum and the thermal growing season are traditional methods (Venäläinen and Nordlund, 1988; Solantie 2004) used extensively in ecology, agriculture, forestry and hydrology. Lately more sophisticated indices have also been developed (Mäkelä et al., 2004; Lagergren et al., 2005) using direct CO_2 gas exchange measurements.

The measurement of chlorophyll fluorescence is a standard method in plant physiology, providing reliable information about the photochemistry (Baker, 2008). It therefore provides suitable parameters for estimation of the functioning of plants, for example, the end of winter dormancy in conifers (Ensminger et al., 2004; Louis et al., 2005) or frost damage estimation (Woldendorp et al., 2008). Remote sensing methods to detect chlorophyll fluorescence have been developed (Ananyev et al., 2005; Meroni and Colombo, 2006). The beginning of the growing season has also been found to coincide with the start of the snow melt (Kimball et al., 2004; Bartsch et al., 2007); the dynamics of the snow melt, such as its beginning day, can be assessed from the surface albedo.

The CO_2 concentration is measured globally within the Global Atmospheric Watch (GAW) network organized by the World Meteorological Organization. The ecosystem-scale CO_2 exchange observed by the EC method is reflected in the atmospheric CO_2 concentrations in an integrative way, because the footprint of the background CO_2 concentration measurement is much larger than the footprint of the EC measurements (e.g. Gloor et al., 2001; Denning et al., 2003). In these concentration data the yearly cycle is clearly visible and thus it is possible to use it in an estimation of the growing season (Keeling et al., 1996; Higuchi et al., 2003; Piao et al., 2008).

Our aim was to study different proxies for estimating growing season dynamics, using the EC measurements as a reference. Our study comprises four coniferous forests (Kenttärova, Sodankylä, Hyytiälä, Norunda) spanning a wide latitudinal range in the boreal zone. To estimate the growing season we used temperature indices, CO_2 concentration, albedo and chlorophyll fluorescence measurements. The comparison of these different methods provides tools for use in larger-scale estimates, as well as in the modelling of the carbon cycle. Data available over a number of years also gave us the opportunity of detecting trends.

2. Materials and methods

2.1. Measurements

2.1.1. Measurement sites. We studied four conifer forests located in the boreal zone. Two of the sites, Kenttärova and Sodankylä, are situated in Finland north of the Arctic Circle in the northern boreal zone (Solantie, 2005). The site at Sodankylä is a naturally regenerated Scots pine (*Pinus Sylvestris*) forest representing pine-dominated areas in central Lapland. The site at Kenttärova is a homogenous Norway spruce (*Picea abies*) forest in the Pallas-Yllästunturi National Park, located 6 km from Sammaltunturi, where the CO_2 concentration measurements were made. Kenttärova was the only spruce forest used in the study. Pallas is located at the northern limit of the boreal forest zone in a sparsely populated region characterized by patches of forests, wetlands and lakes. Hereafter the forest site at Pallas will be referred to as Pallas/Kenttärova and the CO_2 concentration measurement site as Pallas/Sammaltunturi.

The Scots-pine-dominated forest at Hyytiälä in Finland is located in the southern boreal zone. Pine seedlings were planted in 1962 after a prescribed burning. The southernmost site, Norunda, is situated in the hemi-boreal zone in the central part of Sweden. Norunda is a mixed Scots pine/Norway spruce coniferous forest (Grelle et al., 1999). More detailed descriptions of the forest sites can be found in Table 1, while their locations are shown

Table 1. Characteristics of the measurement sites

Site	Location	Forest type	LAI (m^2 m^{-2}) (total, annual)	Mean annual temperature (°C) and precipitation (mm) (30 yr average)	References
Kenttärova	67°59′N 24°15′E	Norway Spruce	6.6	−1.7 450	Aurela (2005) Finnish Meteorological Institute (1991)
Sodankylä	67°21′N 26°38′E	Scots pine	3.6	−1.0 500	Aurela (2005)
Hyytiälä	61°51′N 24 °17′E	Scots pine/ Norway Spruce	8.0[a]	3.0 709	Markkanen et al. (2001) Vesala et al. (1998, 2005)
Norunda	60°5′N 17°28′E	Scots pine/ Norway spruce	13.5	5.5 527	Grelle et al. (1999)

[a]Thinning in spring 2002 reduced the LAI from 8 to 6 m^2 m^{-2}, after that a 0.3 m^2 m^{-2} increase yearly (P. Kolari, personal communication).

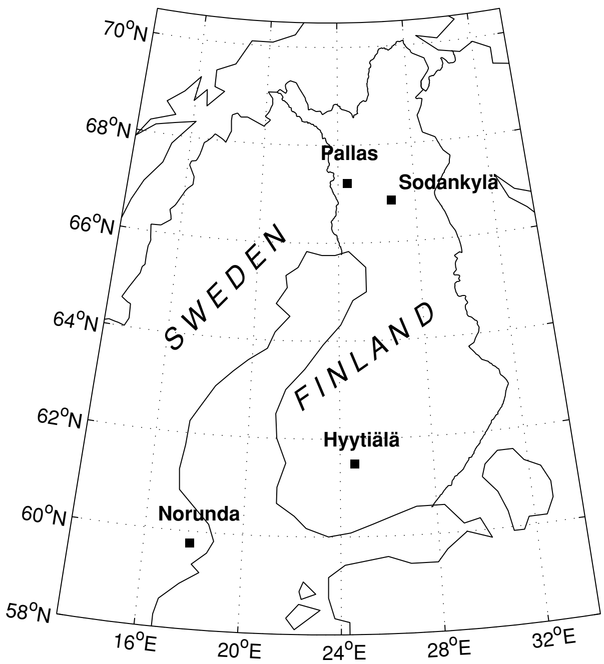

Fig. 1. Locations of the measurement sites.

on the map in Fig. 1. Except for Pallas/Kenttärova, the sites are part of the CARBOEUROPE flux network (www.carboeurope.org).

We used 3–7 yr of data from each of the four sites: Hyytiälä 2000–2005, Sodankylä 2001–2007, Norunda 1999, 2001 and 2002 and Pallas/Kenttärova 2003–2006.

Temperature measurements at Sodankylä and Helsinki (60°11′N, 24°57′E) were used for trend analysis of the time period 1908–2005. Details of how the measurement data have been adjusted are to be found in Linkosalo et al. (2008).

2.1.2. Measurement techniques. The micrometeorological EC method is based on high-frequency observations of wind components and trace gas concentrations. The direct CO_2 and H_2O fluxes between the ecosystem and the atmosphere were calculated as covariances between variations in the rotated vertical wind component and trace gas concentrations (Moncrieff et al., 2004). More details of the data manipulation and corrections made can be found in Aurela (2005), Grelle et al. (1999) and Markkanen et al. (2001).

The measurement equipment for each site consisted of a fast-response 3-D anemometer and a CO_2/H_2O-analyser. At Norunda and Hyytiälä, the anemometers were Gill Solent 1012-R2 (Gill Instruments Ltd, Lymington, UK), while the CO_2/H_2O concentrations were measured by an LI-6262 (Li-Cor Inc., NE, USA). At Sodankylä and Kenttärova, the CO_2/H_2O monitors were LI-7000. The anemometers at Sodankylä and Kenttärova were SATI/3Sx (Applied Technologies Inc., CO, USA) until June 15, 2003 at Sodankylä and September 15, 2003 at Kenttärova, after which they were replaced by METEK USA-1 (METEK GmbH, Elmshorn, Germany). In this study, a negative CO_2 flux denotes uptake of CO_2 by the vegetation, while a positive CO_2 flux denotes release of CO_2 into the atmosphere.

At Pallas/Kenttärova and Sodankylä the snow depth was measured by a snow depth sensor. At Hyytiälä the snow depth was measured weekly at seven different locations manually. The final day of the snow melt was estimated as the weighted average of the manual measurements. At Sodankylä and Norunda the albedo was estimated from incoming and reflected Photosynthetic Photon Flux Density (PPFD). At Hyytiälä measurements of global radiation were used. Henceforth albedo measured at ground level will be referred to as A_{GR}. For the spaceborne measurement of albedo we used a MODIS/Terra+Aqua product with 1 km resolution (ORNL DAAC, 2006), hereafter referred to as A_{MOD}. The final day of snow melt at Norunda was estimated from albedo measurements.

Maximum photochemical efficiency (Fv/Fm) measurements were started at Sodankylä in 2001. Fv/Fm has been measured there approximately twice a week with a portable fluorometer (Hansatech PEA) on four Scots pine trees. The measurements are made on dark-adapted samples. During spring 2002 Fv/Fm was measured almost daily from late April until early June.

In the Pallas region, CO_2 concentrations were measured on the treeless top of the arctic Sammaltunturi fell (67° 58′N, 24° 06′E), which is a background GAW observation site 565 m above sea level. The measurement was made continuously with an LI-6252 infrared gas analyser (Li-Cor Inc., NE, USA), calibrated using gases of known concentrations. The measurement system was calibrated once every 2.5 h against three working standard gases spanning the ambient concentration range. In addition, a reference gas with a concentration below the ambient range was measured every 7.5 h. These gases were calibrated every 3 months against WMO/CCL (NOAA/ESRL) standards on the WMO-2007 scale. The accuracy of the measured CO_2 concentrations was better than 0.1 ppm. The measurements are described in more detail in Hatakka et al. (2003).

2.2. Growing season indices

In the following we introduce variables that can be used independently to estimate the timing of the growing season. We also introduce indices that can provide the same information when used together with a primary determinant, that is, the ecosystem flux measurement, to set a threshold for the commencement and cessation of the growing season.

2.2.1. CO_2 flux measurements. EC measurements provide year-round information about the CO_2 gas exchange of the vegetation. To assess the seasonality of the carbon cycle, the approach developed by Suni et al. (2003) was chosen. In this, the growing season commenced when the daytime Net Ecosystem Exchange (NEE) exceeded by 20% a limit that was defined as the 10th percentile of all daily maximum uptake values from June and July. Similarly, the growing season ended when this limit was fallen below. This time period is hereafter called the growing season, and is denoted as the Flux Growing Season (FGS). To estimate the maximum uptake values, all the years of available data were used. The 20% threshold for the FGS was chosen by Tanja et al. (2003) because thresholds of 13–22% produced predictions similar to those of the temperature index, while a threshold above 25% lead to disintegrating predictions. A similar behaviour was noted in our study. EC measurements were then used as a reference measurement for the growing season to which the other methods were compared.

2.2.2. Thermal growing season. The more traditional way of defining the growing season is to use the thermal growing season (TGS). TGS starts when the daily average temperature on five consecutive days exceeds 5 °C and snow cover is absent, and ends when the average daily temperature is less than 5 °C on five consecutive days (Venäläinen and Nordlund, 1988). Unlike the other temperature-related indices, TGS is not dependent on the CO_2 fluxes. It thus provides an independent estimate of the timing of the growing season.

2.2.3. Temperature sum. The biotemperature is the sum of diurnal mean temperatures above the freezing point (Holdridge, 1967). We used this definition as our temperature sum (TS). Also often used to measure vegetation development is the effective temperature sum. This is defined as the sum of positive differences between the diurnal mean temperatures and 5 °C (Solantie, 2004). To predict the start of the growing season, the value of the temperature sum on the first day of the FGS in 1 yr was set as a threshold value that was used to estimate the start of the growing cycle in other years. When setting the threshold value it was noted that the effective temperature sum was sometimes still zero well after start of FGS, and that the biotemperature yielded better results. The temperature sum was only used for estimating the beginning of the FGS. At Sodankylä, Hyytiälä and Norunda the threshold values for the temperature indices were estimated from measurements in 2001. At Pallas/Kenttärova the year 2003 was used.

2.2.4. Five-day running mean temperature. The five-day running average temperature (5Dave) was shown by Tanja et al. (2003) to have the capability of indicating the spring recovery for various northern boreal sites. To predict the start of the growing season, the threshold for 5Dave was set similarly to TS. The threshold value of 5Dave for the end of the growing season was also determined from the FGS data in 1 yr, as explained above. The 5-d running mean was calculated linearly.

2.2.5. Seasonal factor. The seasonal factor (f) developed by Lagergren et al. (2005) rises from a winter value of zero to a summer value of unity according to the temperature sum of average daily temperatures with reductions caused by frost events. A daily value for f is calculated (subscript d) which is a function of a cumulative temperature sum (S_{spring}) with a threshold of 0 °C during springtime:

$$f_d = \begin{cases} 1, \; S_{\text{spring}_d} \geq 100 \\ 1 - \frac{100 - S_{\text{spring}_d}}{100 + S_{\text{spring}_d}}, \quad S_{\text{spring}_d} < 100 \end{cases} \tag{1}$$

$$S_{\text{spring}_d} = \begin{cases} \frac{S_{\text{spring}_{d-1}} + T_{\text{day}_d}}{1 + P_{\text{frost}_d}}, & T_{\text{day}_d} > 0 \\ \frac{S_{\text{spring}_{d-1}}}{1 + P_{\text{frost}_d}}, & T_{\text{day}_d} \leq 0 \end{cases}, \tag{2}$$

where T_{day} is the average daily temperature, differing from the original definition, which was based on average daytime temperature. Average daily temperature was used because daytime was not easily defined consistently for our sites located over such a large spread in latitude.

The reduction caused by frost events in eq. (2) is accounted for by P_{frost}:

$$P_{\text{frost}} = \begin{cases} 0, \; T_{\min} \geq -3 \\ 0.05(-3 - T_{\min}/5), \quad -8 < T_{\min} < -3 \\ 0.05, \; T_{\min} \leq -8 \end{cases}, \tag{3}$$

where $T_{\min}$ is the daily minimum temperature.

In the autumn the seasonal factor decreases due to the decreasing day length and subzero temperatures. The seasonal factor f was calculated by using a negative temperature sum (S_{aut}) with a threshold of 0 °C down to −50 d-degrees and an additive function of days from a starting date, set to 10 August (D_{sum}), as:

$$f_d = \begin{cases} 0, \; S_{\text{aut}_d} \leq -50 \\ \left(1 - \frac{D_{\text{sum}_d}}{10\,000}\right)\left(1 + \frac{S_{\text{aut}_d}}{50}\right), \quad S_{\text{aut}_d} > 50 \end{cases} \tag{4}$$

$$S_{\text{aut}_d} = \begin{cases} S_{\text{aut}_{d-1}} + T_{\min}, & T_{\min} < 0 \\ S_{\text{aut}_{d-1}}, & T_{\min} \geq 0 \end{cases} \tag{5}$$

$$D_{\text{sum}_d} = D_{\text{sum}_{d-1}} + D_{\text{DOY}_d} - 222, \tag{6}$$

where D_{DOY} is day of the year. This index was originally developed for Norunda, and the starting date (August 10) was also kept the same for the other three sites. The value of f on the first and last day of the FGS in 1 yrr were set as threshold values that were used to estimate the growing cycle in the other years.

2.2.6. State of acclimation. The state of acclimation (S; Pelkonen and Hari, 1980; Mäkelä et al., 2004) has been developed from shoot chamber measurements, and used in modelling to describe seasonality (Mäkelä et al., 2006). S describes the slow process of acclimation of photosynthetic capacity and follows the temperature with a certain delay (Mäkelä et al., 2004); it behaves somewhat like a temperature sum, but can also decrease during a cold period (Tanja et al., 2003). The threshold values for S were determined by using the FGS similarly to f and 5Dave.

2.2.7. Maximum photochemical efficiency. Chlorophyll fluorescence measures how light energy absorbed by the chlorophyll molecules in leaves is used in the plant (Maxwell and Johnson, 2000). We used measurements of dark-adapted needles. The chlorophyll fluorescence parameter Fv is the variable fluorescence, the difference between the maximal and minimal fluorescence, from a dark-adapted leaf, and demonstrates the ability of photosystem II (PSII) to perform photochemistry, that is, Q_A (primary quinone electron acceptor of PSII) reduction. Fm is the maximal fluorescence from a dark-adapted sample, and it is the level of fluorescence when Q_A is maximally reduced, that is, the PSII centres are closed. The ratio of these two, Fv/Fm, is the maximum photochemical efficiency that describes the maximum efficiency at which light absorbed by PSII is used for the reduction of Q_A (Baker, 2008). We used measurements of Fv/Fm to give a relative measure of a plant's photosynthetic performance.

During winter Fv/Fm has a low value (about 0.1), while during summer it has a value higher than 0.8. The increase in spring towards the summer level occurs concurrently with the start of CO_2 assimilation, and the reduction towards the wintertime value starts after the first night frosts of the autumn. For the determination of the growing season, the threshold values for Fv/Fm were obtained similarly to *f* and 5Dave using FGS. The value of Fv/Fm on the commencement day of FGS in 2001 at Sodankylä was 0.20, and this was taken as the threshold value to be used in other years. Similarly, the ending day of FGS in 2001 was used; the threshold value for Fv/Fm then was 0.63. To estimate the beginning and end of the growing season in other years, the day when these thresholds were crossed was recorded. Since measurements were usually only biweekly, data points were interpolated to estimate the date of the threshold crossing.

2.2.8. Dynamics of snow melt. The albedo of the forest surface changes considerably as spring advances due to the disappearance of the snow cover. This change is reflected in both the PPFD and the global albedo. For the albedo measurements, both ground-based and remote sensing, the beginning of the growing season was estimated as the date when the albedo started to decline from its wintertime level. This day is henceforth called BSnow (Beginning day of Snow melt). The observations of the final snow melt date were compared to the albedo measurements and the corresponding flux values. The day of the final snow melt from now on is referred to as FSnow (Final day of snow melt).

2.2.9. CO_2 concentration. We studied how the background CO_2 concentration can be used as a proxy for the beginning and the end of the growing season. The concentration data contain signals that originate not only from the local forest, but also due to long-range transport from forests possibly experiencing quite different weather conditions. The growing season was therefore determined in two different ways, one trying to follow the local changes in CO_2 exchange and the other reflecting more large-scale phenomena.

The background CO_2 growth trend (see Thoning et al., 1989) was first removed from the time series, leaving only the seasonal variation in concentrations. For a more local estimate of the growing season, the CO_2 concentration was used similarly to the temperature indices by estimating threshold values for spring and autumn using 1 yr of EC measurement data, and then applying these threshold values to the other years. In order to decrease the amount of noise and to be able to uniquely determine the date when the threshold is achieved, calculated 5-d running daily averages of the concentrations were used. To some degree, averaging would also level out short non-biospheric episodes, if such were to exist. The threshold method used is comparable to that in the work of Piao et al. (2008). In our work the threshold relative to the background concentration was 5.3 ppm in springtime and −3.8 ppm in autumn, determined from the local forest uptake. The beginning and end of the local forest uptake were estimated with the method of Suni et al. (2003). This estimation method is henceforth denoted as CO_2 MR. At Pallas/Kenttärova we only had EC data during both spring and autumn for the years 2003 and 2006; since the development of the CO_2 concentration was more straightforward in the spring of 2006, that year was used to estimate the thresholds.

In order to gain a large-scale estimate of the growing season, we aimed at capturing the start of the strong annual drop in concentrations towards the summer minimum, as well as the end of the annual increase towards the winter maximum. A linear fit was made using a running 2-month data window of the daily averages. The slope of the fit had a distinct minimum in early summer, and a maximum during autumn before the winter dormancy. The growing season began when the slope decreased permanently below zero in spring, and ended when the slope passed its maximum values in late autumn. This derivative approach provided a larger-scale estimate, since it also recorded the start of the annual drop; hereafter it is denoted as CO_2 D0. The threshold method provided a regional estimate, since it was tied to the emergence of the local CO_2 flux.

3. Results

3.1. Pallas

3.1.1. Growing season dynamics. The CO_2 concentration measurements from Pallas/Sammaltunturi are shown in Fig. 2 with the CO_2 flux measurements and temperature indices from Pallas/Kenttärova for the year 2006. The drop in the CO_2 concentration already started some weeks earlier than the commencement of local CO_2 assimilation. On the other hand, the lowest value of the CO_2 concentration was reached during late July–mid August [Day-Of-Year (DOY) 210–230], whereas the maximum assimilation levels at Pallas/Kenttärova had already been attained by mid-July (DOY 196). The CO_2 concentration did not reach its winter level before mid-November (DOY 320), even though

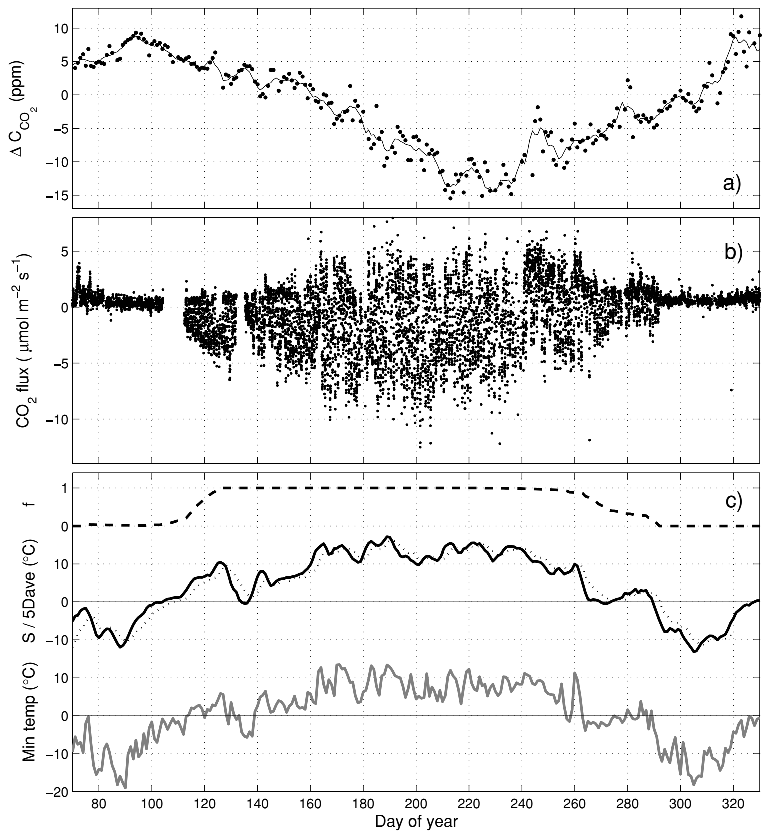

Fig. 2. CO_2 concentrations, fluxes and temperature indices at Pallas during the period March 11–November 26 (DOY 70–330) 2006. (a) The 5-d running average of trend-removed CO_2 concentration at Pallas/Sammaltunturi (solid line) and the daily averages (points). (b) The half-hourly eddy covariance flux measurements from Pallas/Kenttärova. (c) Seasonal factor *f* (dashed line), 5-d running average of daily mean temperature 5Dave (solid black line), state of acclimation S (dotted black line) and minimum daily temperature (grey line) for Pallas/Kenttärova in 2006.

the local CO_2 assimilation had already ceased by mid-October (DOY 290).

The seasonal factor *f* increased to its summer level between mid-April and mid-May (DOY 105–130 in Fig. 2c). Some night frosts occurred after reaching this summer value but these did not affect *f*. The drop to the winter level took place from mid-September until mid-October (DOY 260–290), and was caused by night frosts. The 5Dave of the air temperature and the state of acclimation S were closely related to each other (Fig. 2c). They can both cross a certain threshold several times during spring and autumn. The minimum temperature at Pallas/Kenttärova is also shown in Fig. 2c.

3.1.2. Background CO_2 concentration. At Pallas/Sammaltunturi the commencement day for the growing season was determined from the atmospheric CO_2 concentration measurement there. To estimate the amount of southerly airstreams, trajectory analysis similarly to Aalto et al. (2002) was done. In these southerly airstreams, warmer air entered the area from the south, and since the growing season had already started there, the arriving air parcels had a lower CO_2 concentration. This effect was clearly seen in late April 2005, after DOY 140, when air parcels from southern regions reached Pallas (Figs. 3a and c). There was a simultaneous increase in temperature (Fig. 3b). In addition to the lowering of the background CO_2 level, there was a daytime fall in the CO_2 concentration occurring simultaneously with modest local CO_2 assimilation (Fig. 3d). Since this local CO_2 assimilation had already been at the same level before DOY 140, the lowering of the CO_2 concentration is most probably caused by the warm air arriving from the south. The relative flattening between DOY 145 and 160 is probably caused by a northerly air mass that lowered the air temperature and had a higher CO_2 concentration. These cold air intrusions inhibit increases in local CO_2 assimilation.

Pallas/Kenttärova EC data from the year 2006 were used to determine the threshold values for CO_2 concentrations, and the growing season days were estimated using 5-d running mean CO_2 concentrations (CO_2 MR). In spring 2005, DOY 132 was the last day when the threshold was crossed, but it had also been temporarily crossed around DOY 115, as is seen in Fig. 3c. For the DOY 115 crossing, however, there was no corresponding daily variation or local CO_2 assimilation (Fig. 3d), and the air masses originating in the north (Fig. 3a). The above-zero temperatures were observed in very-slowly moving air masses. This period of low CO_2 concentrations was therefore considered to be a clean (arctic) air episode, typical of winter.

The commencing days of the 2005 growing season, as estimated from the CO_2 flux measurements, are shown in Fig. 3d for Hyytiälä and Sodankylä. For Pallas/Kenttärova that day could not be defined in 2005, due to missing EC data. Hyytiälä is

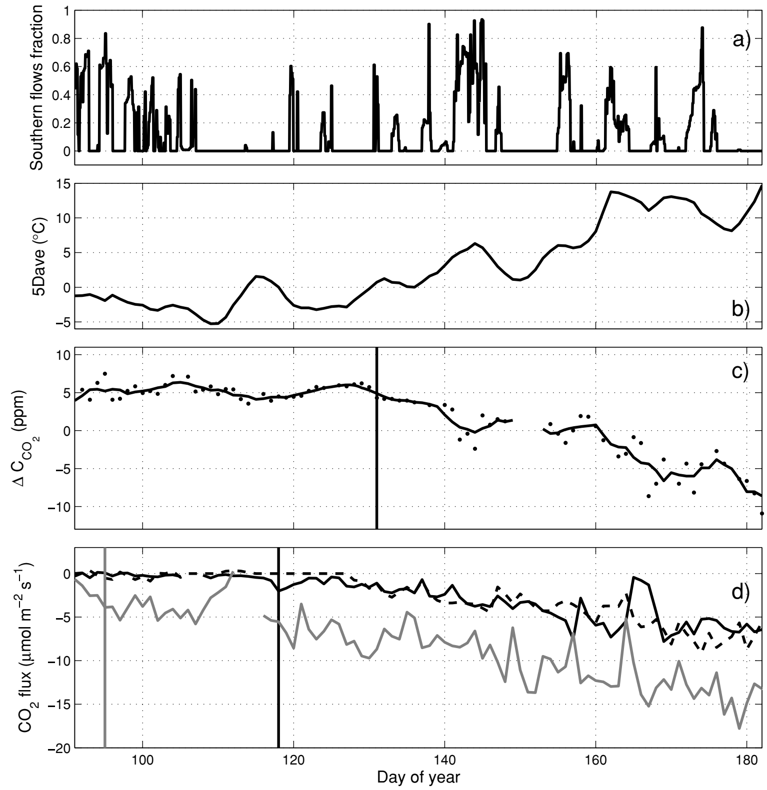

Fig. 3. Fraction of southerly airstreams, air temperature and CO_2 concentration at Pallas/Sammaltunturi, and CO_2 exchange at Pallas/Kenttärova, Hyytiälä and Sodankylä during April–June (DOY 91–181) 2005. (a) The fraction of southerly airstreams, i.e. the number of hours an air parcel had spent crossing a continental region south of Pallas expressed as a fraction of the total length of its 5-d backtrajectory. (b) Five-day running average of daily mean temperature (5Dave) at Pallas/Sammaltunturi. (c) Five-day running average of trend-removed CO_2 concentration (solid line) and daily values (points) at Pallas/Sammaltunturi. The vertical line denotes the beginning day of the growing season as estimated from the CO_2 concentration by a threshold method. (d) The highest CO_2 uptakes (mean of the five maximum values) for Pallas/Kenttärova (dashed line), Sodankylä (solid black line) and Hyytiälä (solid grey line). The vertical black line denotes the commencement of the growing season at Sodankylä and the vertical grey line that at Hyytiälä.

the southernmost of these three sites, and there the start of the growing season already took place in early April (DOY 95). In comparison to Sodankylä, the 20% level of the maximum summer-time fluxes was about 80% higher. The start of the growing season occurred 23 d earlier at Hyytiälä than at Sodankylä. The development in the CO_2 fluxes at Sodankylä and Pallas/Kenttärova appears to be quite similar.

3.1.3. Temperature indices. The starting and ending days of the growing season in the case of the temperature indices were defined from flux measurements (FGS), using 1 yr to set the threshold and then estimating the growing season for the other years using this threshold. For the Pallas/Kenttärova site, the commencement of the FGS in spring was only defined in 2003 and 2006; to estimate cessation of the FGS in autumn, the year 2004 was also available. The FGS started in 2003 on DOY 108 and in 2006 on DOY 114. The cessation days for the years 2003, 2004 and 2006 were 288, 278 and 290, respectively. 2003 was used to estimate the thresholds for the temperature indices.

Figure 4a shows how the temperature indices estimate the commencement of the FGS. The positive numbers on the *y*-axis are the number of days that overestimate the beginning of the FGS, while the negative numbers denote how many days too early the estimation is. TGS gives approximately four weeks later estimates for the commencement of the FGS, whereas other temperature indices succeed well in 2006. Figure 5a is a similar figure for autumn and the cessation of the FGS. All the estimates predict too early an end to the FGS. In 2006 there was a warm spell in autumn, and CO_2 assimilation continued even though the thresholds were crossed for the first time.

3.2. Sodankylä

3.2.1. Growing season dynamics. The maximum photochemical efficiency (Fv/Fm) and the albedo at Sodankylä in spring 2002 are shown together with the CO_2 flux measurements in Fig. 6. During spring, Fv/Fm increased from its wintertime value of 0.1 to its summer value of 0.83. The growing season defined from the albedo started when the values clearly began to decline. In 2002 this day was estimated to be DOY 116 (April 26).

In Fig. 7, differences between estimates for the start and the end dates of the growing season derived from the maximum photochemical efficiency (Fv/Fm) and FGS are displayed. As can be seen, these differences are small. Fv/Fm was a good estimator of the final day of the FGS, the difference being 4 d at the largest, except in 2007. In 2007 the difference was 22 d; this was caused by a warm spell in autumn.

In addition, results from the other estimation methods for the growing season at Sodankylä are illustrated in Fig. 7. The FGS is the standard to which the other days are compared, TGS and 5Dave are temperature-based indices, A_{GR} and A_{MOD}

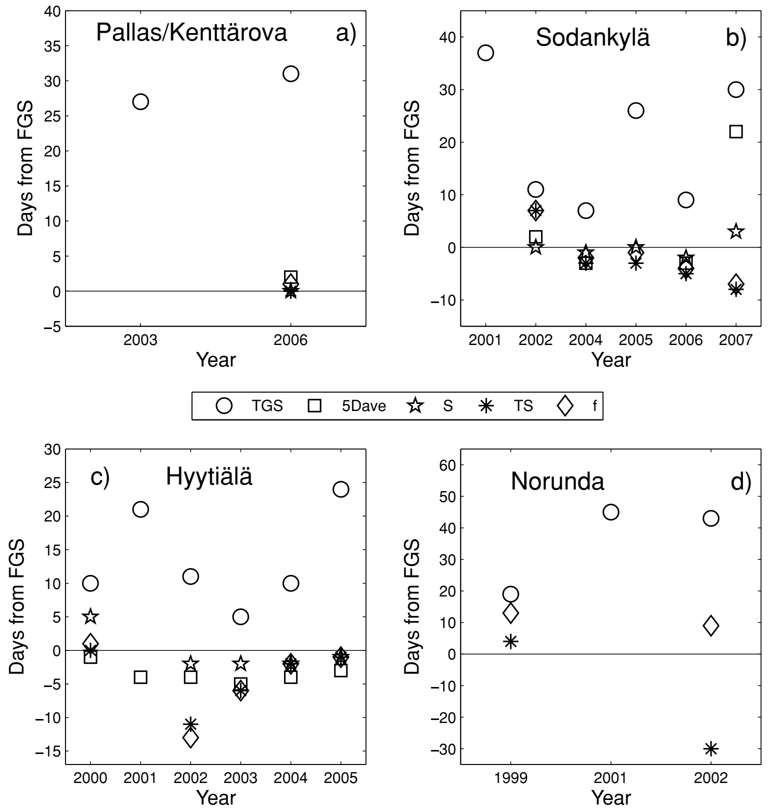

Fig. 4. The differences between growing season's beginning days as defined by temperature-based indices and FGS shown for (a) Pallas/Kenttärova, (b) Sodankylä, (c) Hyytiälä and (d) Norunda. FGS is the growing season start as defined from the CO_2 flux according to Suni et al. (2003). TGS is the thermal growing season, S is the state of acclimation, 5Dave is the 5-d running temperature and TS is the temperature sum.

represent two different albedo measurements and CO_2MR is the estimate from the CO_2 concentration measurement at Pallas/Sammaltunturi. The day of final snow (FSnow) melt is also shown.

3.2.2. Temperature indices. The first days of the FGS at Sodankylä are shown in Table 2. Between 2001 and 2007, the final days of the FGS were between DOY 282 and 296. In 2003 the first day of the FGS and in 2002 its final day were undefined. Figure 4b demonstrates the differences between the first day of the FGS and corresponding estimates based on temperature indices. TGS gives predictions that are too late, whereas the other temperature indices give good estimates. In 2007 5Dave gives a later estimate. At Sodankylä in 2007 the thresholds were already passed for the first time on DOY 105–107. The CO_2 fluxes, however, emerged only on DOY 113, due to severe night frosts on the previous days. S crossed the threshold for the second time then, while it took 5Dave two more weeks to cross the threshold.

Figure 5b shows the corresponding estimates for autumn. In three years TGS gives too early cessation days, otherwise the indices give quite good estimates, except parameter *f* in 2006. In 2005 and 2007 there was a warm spell during November at Sodankylä, and the thresholds for S and 5Dave were crossed again. In Fig. 5b only the first crossings of the threshold are shown.

3.2.3. Snow melt and albedo. Springtime changes in albedo (BSnow) and the timing of the snow melt (FSnow) were studied together with TGS and FGS to see how they relate to the start of the growing season and whether they can explain the observed differences. Table 2 shows the dates on which the snow had finally melted (FSnow) together with the percentages of the CO_2 fluxes reached by that date compared to the maximum summertime CO_2 assimilation. The corresponding values are also given for TGS. The first day of FGS is also shown.

Overall, the CO_2 assimilation had attained 40% level of its summertime maximum level when the snow had melted (Table 2). In 2006 the snow had melted at Pallas/Kenttärova on day 145 (FSnow), and by this time the CO_2 assimilation had reached 66% of its summertime maximum level. When this day is compared to the commencement of FGS, a difference of 31 d is seen. At Sodankylä the biggest difference between the commencement of FGS and FSnow was 26 d.

For surface albedo, we used measurements from both ground level and space. The start of FGS was estimated to occur when the decline from the wintertime level of surface albedo began (BSnow). These days are shown for Sodankylä in Table 2. The albedo measured at ground level succeeded well in estimating the first day of FGS: for 4 yr the estimate was within 3 d of the FGS value. The MODIS/Terra+Aqua estimations for the start of FGS were also successful for Sodankylä. 19 d was the largest

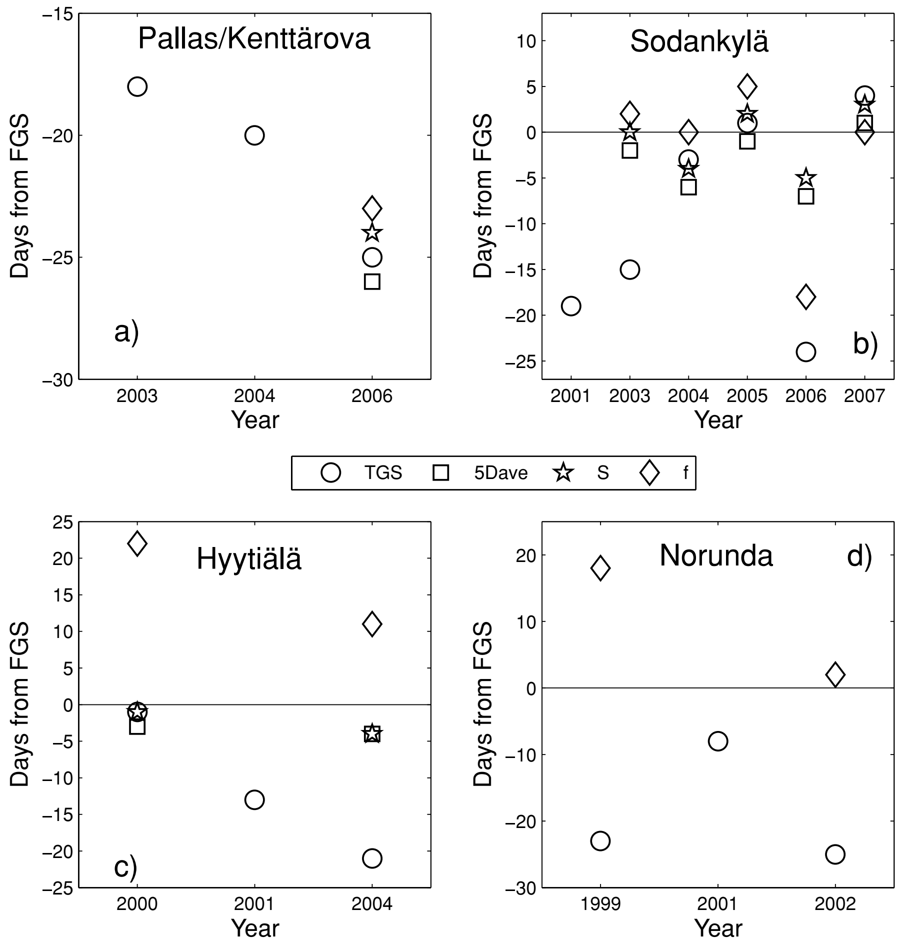

Fig. 5. The differences between the growing season's ending days as defined by temperature-based indices and FGS shown for (a) Pallas/Kenttärova, (b) Sodankylä, (c) Hyytiälä and (d) Norunda. FGS is the growing season ending as defined from the CO_2 flux according to Suni et al. (2003). TGS is the thermal growing season, S is the state of acclimation, 5Dave is the 5-d running temperature and TS is the temperature sum.

difference from the flux measurement estimations, otherwise the range was within 8 d.

3.3. *Hyytiälä*

3.3.1. Temperature indices. For Hyytiälä the threshold for the 5Dave in 2001 was adapted from the literature (Tanja et al., 2003). When severe night frosts occurred (below −5 °C), the first crossing of the threshold for the 5Dave was ignored, and only the second crossing was taken into consideration, as was also done by Tanja et al. (2003). This was carried out at Hyytiälä in 2002 and 2003. This same approach was also adopted for the seasonal factor *f* in 2003.

The beginning days for FGS at Hyytiälä are given in Table 2. The cessation days for the years 2000, 2001 and 2004 were 305, 309 and 308, respectively. In most years the start of the FGS occurred later at the northern sites than at the southern sites. In 2003 the start of the FGS exceptionally took place at Pallas/Kenttärova and Hyytiälä on the same day. TGS provides estimates for the beginning of FGS that are too late, whereas the other temperature indices give good estimates (Fig. 4c). In 2002, however, TS and *f* give too early estimates. This was due to a delay in the emergence of the CO_2 fluxes due to severe night frosts; these were accounted for by S and 5Dave. In the autumn TGS gives too early predictions for the cessation of the FGS of 2 yr and *f* estimates that are too late (Fig. 5c). 5Dave and S provide better estimates.

3.3.2. Snow melt and albedo. Similarly to Sodankylä, the CO_2 assimilation at Hyytiälä had attained 40% level of its summertime maximum level by the time the snow had melted (Table 2). The timing of FGS was compared to the first changes seen in the albedo measurements, that is, BSnow, which is the day when the snow starts to melt. In this comparison, there are 4 yr when the difference was about 10 d (Table 2). For Hyytiälä, the MODIS/Terra+Aqua measurement provided better estimates, even though the data are available only at 8-d intervals. The only estimate that erred by more than 10 d was in 2004 (Table 2).

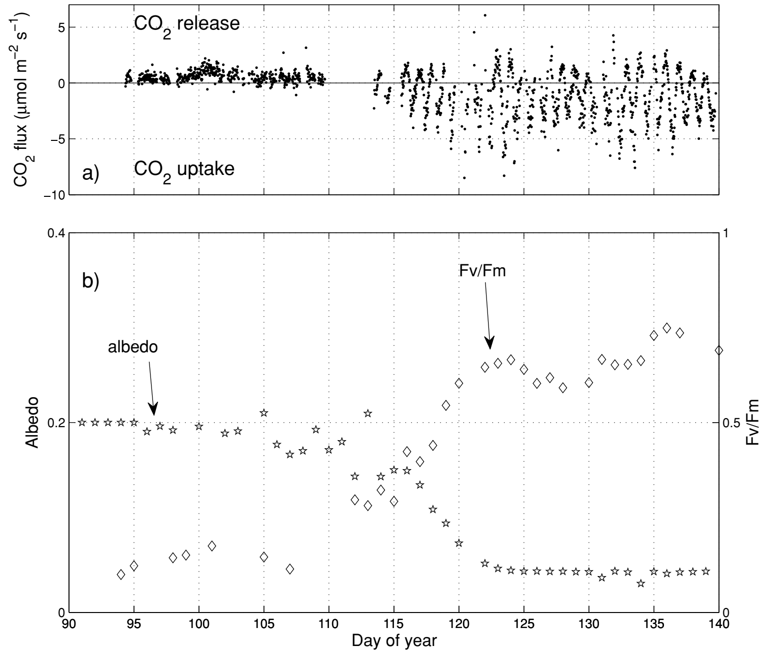

Fig. 6. (a) The CO_2 flux measured by eddy covariance and (b) the maximum photochemical efficiency Fv/Fm (diamonds) and albedo (stars) at Sodankylä in spring 2002 (March 31–May 20).

To conclude, the change in albedo, if taken from the time when the albedo starts to decrease, describes well the beginning day of the FGS. The day of the final snow melt that occurs later is close to or coincident with the start of the TGS.

3.4. Norunda

3.4.1. Temperature indices. For Norunda it was not possible to define S and 5Dave uniquely because of their large fluctuations

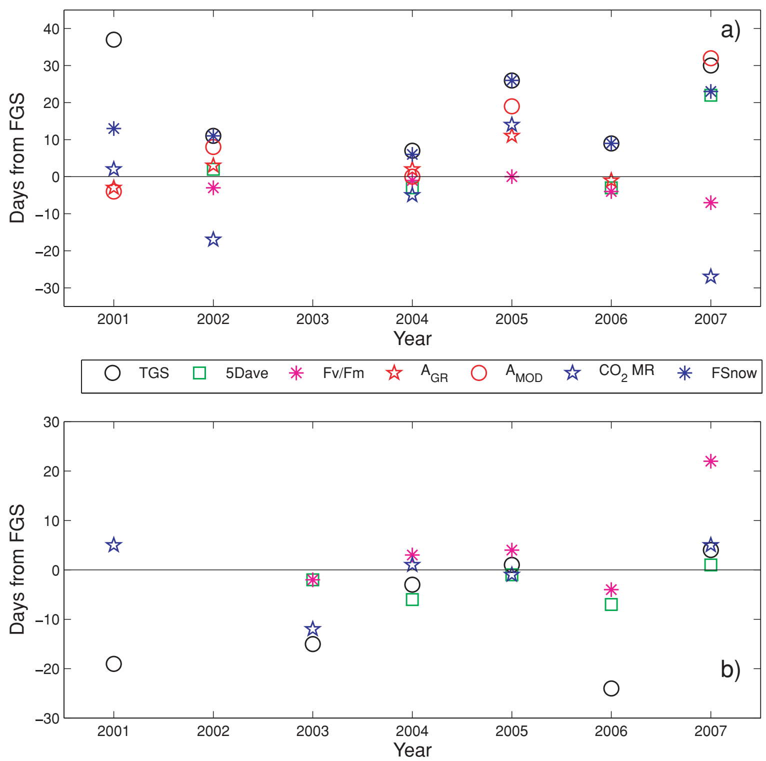

Fig. 7. The difference between the start of the growing season (a) and the end of the growing season (b) at Sodankylä by different methods compared to FGS. FGS is the growing season start and ending as defined from the CO_2 flux according to Suni et al. (2003). TGS is the thermal growing season, 5Dave is the 5-d running temperature, Fv/Fm is the chlorophyll fluorescence, A_{GR} is albedo measured at ground level, A_{MOD} is albedo measured from the MODIS satellite and FSnow denotes the final day of the snow melt. CO_2 MR is a threshold defined from the 5-d average CO_2 concentration at Pallas/Kenttärova.

Table 2. Days of final snow melt (FSnow) at Hyytiälä and Sodankylä

Site	Year	FGS	FSnow%	$Flux_{FSnow}$	TGS%	$Flux_{TGS}$	A_{GR}	A_{MOD}
Hyytiälä								
	2000	103	111	47%	113	60%	93	97
	2001	97	118	35%	118	35%	96	97
	2002	103	113	32%	114	33%	93	*
	2003	108	111	22%	113	39%	97	105
	2004	101	111	43%	111	43%	101	113
	2005	95	114	35%	119	42%	87	97
Sodankylä								
	2001	117	130	25%	154	55%	114	113
	2002	113	124	73%	124	73%	116	121
	2003	*	133	*	136	*	122	121
	2004	121	127	38%	128	42%	123	121
	2005	118	144	43%	144	43%	129	137
	2006	117	126	55%	126	55%	116	*
	2007	113	136	41%	143	41%	*	145

Notes: The start of the growing season as defined by Suni et al. (2003) is denoted by FGS.%$Flux_{FSnow}$ denotes the percentage of the maximum summertime assimilation reached on the day of snow melt. TGS is the first day of the thermal growing season and%$Flux_{TGS}$ is the percentage of maximum summertime fluxes reached on TGS. The day of change in albedo towards its summertime value from ground measurements is denoted by A_{GR} and that from MODIS-data by A_{MOD}. An asterisk (*) denotes values that were undefined due to insufficient data.

close to the FGS commencement and ending days. Therefore only *f* and TGS were studied. In spring, TGS gives too late estimates and in spring 2002 TS gave too early an estimate. The parameter *f* provides the best predictions in spring (Fig. 4d). In autumn TGS gives too early estimations. In 1999 the parameter *f* gives too late a prediction, but in 2002 it works well (Fig. 5d).

At all the sites the seasonal factor *f* reached its summer value before the last night frosts occurred. TGS always predicted later commencement days, differing from three up to 43 d from that of FGS. The temperature sum had smaller values at the two southern sites than at the northern sites at the commencement of the growing season. In the south, the temperature sum varied between 2 and 34 °C d, while in the north it took values between 15 and 40 °C d. At this time, 5Dave also had smaller values in the south than at the northern sites. FGS terminated every year at the two northern places before October 24 (DOY 297), while at the southern sites it finished every year in November.

Overall, the temperature indices were able to satisfactorily predict the beginning of the FGS. In autumn S and 5Dave provided the most reliable estimations, with some difficulties occurring during late warm spells. At all the sites FGS started before the rapid rise of soil temperatures through 0 °C.

Table 3. The commencement and cessation of the growing season at Pallas/Sammaltunturi as estimated from the CO_2 concentration

Year	Spring (CO_2 MR)	Spring (CO_2 D0)	Autumn (CO_2 MR)	Autumn (CO_2 D0)
1997	*	*	308	323
1998	*	*	281	308
1999	135	62	282	309
2000	116	99	274	322
2001	119	76	294	322
2002	96	77	292	318
2003	127	104	274	316
2004	116	80	289	322
2005	132	110	290	318
2006	-	97	-	323
2007	86	55	287	316

Notes: CO_2 MR denotes the threshold method and CO_2 D0 the derivative method. A hyphen (-) denotes data used for setting the threshold values and an asterisk (*) denotes undefined values.

3.5. Trends in growing season length

3.5.1. Pallas. The 11-yr-long Pallas/Sammaltunturi time series of CO_2 concentrations and temperatures enables the study of trends in the growing season beginning and ending days. The days for the commencement and ending of the growing season as estimated from the CO_2 concentration at Pallas/Sammaltunturi are shown in Table 3 for the years 1997–2007. The local starting days (CO_2 MR) usually extended from April to May, whereas the large-scale derivative approach (CO_2 D0) gave earlier estimates, varying from March to April. In 2007 the growing season already

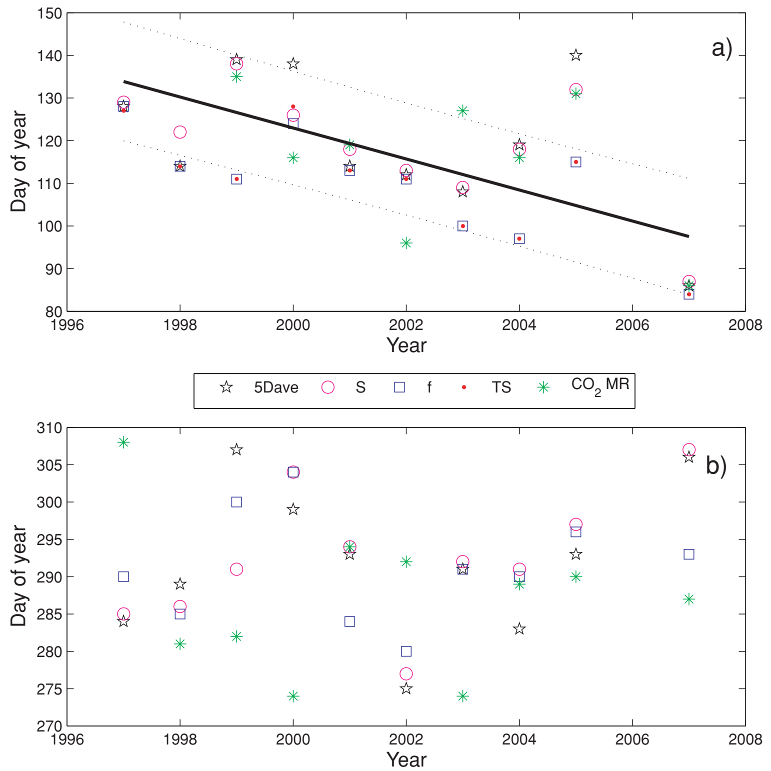

Fig. 8. The start (a) and cessation (b) of the growing season as estimated from temperature indices and the CO_2 concentration at Pallas/Sammaltunturi. In (a) a line is fitted to all the data points shown ($r^2 = 0.336$, $p = 0.0001$). The dashed error lines show the area that contains at least 50% of the predictions. CO_2 MR is a threshold defined from the 5-d average CO_2 concentration.

started in late February (CO_2 D0). The ending of the growing season had less interannual variability, occurring mostly in October according to CO_2 MR and in November according to CO_2 D0. The CO_2 MR results were in line with the Sodankylä and Pallas flux (FGS) results (differences being 10–19 d) and CO_2 D0 correlated correspondingly with Norunda FGS (differences being 1–12 d).

To study whether similar results can be obtained with temperature indices for this same time period, Pallas/Kenttärova EC data from the year 2006 were used to determine the threshold values, and the growing season beginning and ending days were re-estimated by the temperature indices using the Pallas/Sammaltunturi temperature data. The results for the commencement days estimated with four temperature indices (5Dave, S, *f* and TS) and CO_2 MR are displayed in Fig. 8a. TGS is not shown here due to its large deviation from the FGS results, as discussed above. The temperature indices yielded differing results in 1999, 2004 and 2005 but during the other 5 yr their results were consistent. The parameter *f* agreed best with TS and 5Dave with S. The CO_2 concentration (CO_2 MR) had the largest dissimilarity to the temperature indices in 2002 and 2003, the disagreement being over two weeks in these 2 yr. Otherwise the predictions were slightly more consistent with 5Dave and S than with *f* and TS.

There was a statistically significant trend towards earlier spring recovery when calculated by the three temperature indices 5Dave ($p = 0.0615$), S ($p = 0.00110$) and *f* ($p = 0.0015$) separately or with all four temperature indices (5Dave, S, *f*, TS) and CO_2 MR together ($p = 0.0001$). A linear fit was made to the combined temperature indices (5Dave, S, *f*, TS) and CO_2 MR results, showing a trend of 3.64 (standard error 0.82) days per year towards an earlier growing season commencement (Fig. 8a).

The ending days of the active period of vegetation are shown in Fig. 8b for Pallas/Sammaltunturi. TGS always gave the earliest assessments, mostly occurring in September, twice even in August. The three temperature indices 5Dave, S and *f* gave mutually quite similar estimates for the ending days, the largest difference being 16 d in 1999. A clear trend in time was not seen in these values. The finishing days estimated from the CO_2 concentration (CO_2 MR) stayed at quite a constant level after the year 2000. The large-scale estimate CO_2 D0 did not show a significant trend either in the ending or beginning days.

The time series of the temperature indices at Hyytiälä were investigated, but no significant trend was found during either spring or autumn. We also tried to estimate CO_2 MR by using the Hyytiälä flux data together with the Pallas/Sammaltunturi CO_2 concentration, but the results were not applicable because of too large a difference in the influence regimes.

3.5.2. Sodankylä. Trends at Sodankylä were calculated for all the growing season estimation methods. The growing season length was estimated by 5Dave for the years 1908–2005. A trend toward an earlier spring was found (10.78 d in 98 yr, $p = 0.0040$). A similar trend was also found for Helsinki. No trends in autumn were seen.

Temperature indices were also calculated for the time period 2001–2007 at Sodankylä. No trends in these indices were noticed, neither in snow melt date or ground based albedo measurements during spring. The only trend in spring was that towards a later start of the growing season by airborne albedo measurement ($r^2 = 0.8891$, $p = 0.0048$). Trends were also calculated for autumn. A trend toward a later cessation of FGS is seen in the Fv/Fm estimates ($r^2 = 0.8493$, $p = 0.0090$). No other autumn trends were found for Sodankylä.

A statistical *t*-test, assuming independency of the samples, was performed for growing season estimations at Sodankylä. According to this test, the start dates derived from four temperature indices (5Dave, S, *f*, TS), two albedo-based estimates (A_{GR}, A_{MOD}), Fv/Fm and CO_2MR agree with FGS at the 5% significance level. Only FSnow and TGS did not agree with FGS. During autumn, the estimated cessation dates of three temperature indices (5Dave, S, *f*), Fv/Fm and CO_2MR agree with FGS at the 5% significance level. Similar results for springtime were obtained for Hyytiälä; the autumn-time correlation was not possible to calculate with the *t*-test because of the few years available.

To compare the different estimation methods we calculated how successful they are at Sodankylä, using the mean of the deviations from the value given by FGS. In spring the best estimator was the temperature index S [average deviation (AD) = 1.2 d], while the second-best was Fv/Fm (AD = 3 d). The temperature index S was also the most successful in predicting the end of the FGS in autumn (AD = 2.8 d), 5Dave coming second (3.4 d).

4. Discussion

4.1. Prediction of the growing season

The vegetation of a boreal forest has a clear seasonal cycle in activity, and this can be tracked with several variables. The various variables describe the transition period from winter to summer differently. As the air temperature increases, the snow starts to melt and the albedo of the snow declines. The plants no longer need to protect their photochemical apparatus from frost events and the photochemical efficiency starts to increase. Thus, the level of CO_2 assimilation increases, resulting in a lower atmospheric CO_2 concentration.

We predicted growing season dynamics by various environmental variables: temperature indices, CO_2 concentration, surface albedo and chlorophyll fluorescence. Most of the temperature indices succeeded in a prediction of the growing season at the Finnish sites, but were not so successful in the more temperate climate of Norunda. The difficulty with the 5Dave and S indices was that they were not uniquely defined. This was not true of the temperature sum, but that estimate was applicable only during the spring time: during autumn the use of 5Dave and S was necessary. With exceptions caused in 2 yr by late warm spells, the latter also functioned properly in autumn, making them the most applicable of these indices. The seasonal parameter *f* was uniquely defined during both autumn and spring, but did not provide as good estimates for the FGS as did 5Dave and S. The CO_2 concentration (CO_2 MR) suffered from the same problem as 5Dave and S, being not always uniquely defined. However, it also succeeded in the estimation of the growing season.

TGS did not describe the onset period of the CO_2 fluxes but rather the time when the vegetation is already closer to its summer state. If TGS were to be used to estimate the active phase of vegetation, a significant part of the annual gas exchange might be missed. This might cause a bias in annual carbon balance estimates.

Bud burst has been traditionally modelled by temperature-related indices (Hänninen and Kramer, 2007), and some sophisticated methods linking temperature and bud burst have been developed (Schleip et al., 2008). Even though the bud burst is a significant event in a tree's phenology, coniferous forests already have a considerable carbon uptake before bud burst (Leinonen and Kramer, 2002). For this reason, we did not consider this phenomenon to be very important when developing methods to improve carbon cycle modelling in coniferous forests. Proper modelling of the bud burst is, however, significant when assessing frost damages during spring (Jönsson et al., 2004).

Detection of the chlorophyll fluorescence signal by remote sensing is advancing (Evain et al., 2004; Moya et al., 2004; Louis et al., 2005). Chlorophyll fluorescence is an optical and non-destructive method for studying the photochemical state of a plant. Its relationship to photosynthesis has been widely studied (Rosema et al., 1998; Flexas et al., 2002). We made active measurements of Fv/Fm, which has been shown to explain the spring recovery at a Siberian Scots pine site (Ensminger et al., 2004). Our multiple-year data proved that Fv/Fm is a reliable indicator of the growing season at a Finnish northern boreal site. It was also feasible to use it to estimate the cessation of the growing season, even though at this time it was at a much higher level than during the onset of the growing season. In autumn 2007 it gave a later prediction for the cessation of the growing season than the CO_2 flux measurement, in line with two temperature indices. This indicates that the forest still had the physiological potential for photosynthesis, but the meteorological conditions, in this case lack of radiation, inhibited this.

4.2. Differences in southern and northern forest sites

The southern sites of Hyytiälä and Norunda had a characteristically different behaviour to the two Finnish Lapland sites in several respects. In the south, the temperature sum and the 5Dave were smaller during the emergence of the CO_2 fluxes than in the north. This agrees with Kolari et al. (2007) whose study sites were Hyytiälä and Värriö in Finnish Lapland. This might show that the frost hardening is more effective at the northern sites, which might have a stronger genetic adaptation to late night frosts. A warming climate might cause more frost damage to needles because of a decreased frost hardening (Leinonen et al., 1997; Ögren, 2001; Jönsson et al., 2004).

The difference might also be connected to soil temperatures. Recently, it has been shown that cold soils inhibit the recovery of photosynthesis (Ensminger et al., 2008). Soil water was not a limiting factor at our sites, as was shown by Tanja et al. (2003). As the snow melt begins, water becomes available for photosynthesis (Arneth et al., 2006). At all the Finnish sites the assimilation started after the beginning of snow-melt, but nevertheless still in the presence of a snow cover, similarly to the central Siberian Scots pine forest at Zotino (Arneth et al., 2006) and the black spruce forest in Alaska (Ueyama et al., 2006). According to our results, CO_2 assimilation might already be at a significant level by the time of complete snow melt (FSnow). The start of snow melt (BSnow) can be estimated from surface albedo measurements. In our study the ground and satellite measurements of albedo succeeded in estimating the onset of the growing season. This phenomenon can be observed with satellite radars that are not sensitive to cloud cover (Kimball et al., 2004; Bartsch et al., 2007).

4.3. *Trend toward an earlier growing season*

A higher autumn temperature may not increase the photosynthetic gain, because of the photoperiod control of dormancy. Instead of increasing carbon uptake, the effect might be the opposite due to an increased respiration rate and decreased maximum capacity for carbon uptake (Busch et al., 2007). Similar conclusions were drawn by Piao et al. (2008) in their large study based on CO_2 concentration measurements and EC data.

For Hyytiälä the most important factor for the cessation of the growing season has been shown to be the photoperiod (Suni et al., 2003). For the two northern sites, this also seemed to apply, since the ending days were close to each other, with the exception of a 9 d difference at Kenttärova. At Norunda the interannual variation was more pronounced. There the amplitude of the annual photoperiod variation is not as large as at the more northern sites, and therefore other factors may also be important in the diminishing of the assimilation. Lagergren et al. (2008) found air temperature to be the most determinant factor in the ending of photosynthesis; their study included Hyytiälä and Norunda.

Since there was no change in the relationship between temperature indices and CO_2 concentration at Pallas/Sammaltunturi during autumn in our time series, our measurements do not confirm an increase in respiration and a warming of the autumn. This result is in contrast to the study by Piao et al. (2008) but in line with the results of Higuchi et al. (2003). This might be due to the longer time series that Piao et al. (2008) used compared to the other studies. The only trend we found toward a later autumn was in our chlorophyll fluorescence measurements at Sodankylä.

The earlier commencement of the growing season at Pallas/Sammaltunturi as estimated by the temperature indices and the CO_2 concentration agrees with the general trend in Finland of rising spring temperatures (Tuomenvirta et al., 2000) and with the trend in CO_2 concentration observed in northern latitudes (Randerson et al., 1999). This was not confirmed by our Sodankylä data for 2001–2007 that were 2 yr shorter than the Pallas/Sammaltunturi time series. However, a trend of an earlier beginning of the growing season as assessed by 5Dave was found when a 98-yr-long time series at Sodankylä was used.

Overall, the methods used here are best applicable to northern ecosystems where the changes are most clearly seen, because there large changes in temperature and in the activity of the vegetation take place during the spring.

5. Conclusions

The connections between forest CO_2 exchange and some meteorological and biological variables were studied during spring and autumn at four boreal sites, Pallas, Sodankylä and Hyytiälä in Finland, and Norunda in Sweden. Air temperature is a variable driving the spring recovery of a forest, and the start of the snow melt is a result of higher air temperature. Fv/Fm provides direct information about the photochemistry of a plant, and the CO_2 concentration is influenced by the CO_2 fluxes. Some of these variables have remote sensing potential, whereas temperature indices can be used to detect trends in long time series.

The various different temperature indices all succeeded well in estimating the start of the growing season at the Finnish sites. At Norunda two indices (5Dave and S) were not usable, but the temperature sum and the seasonal factor gave reasonable results in spring. The final day was harder to predict at all sites, but 5Dave and S provided good estimates where they were applicable. The utility of the temperature indices was thus better in colder climatic conditions, making these methods feasible for studying the responses of northern ecosystems to a warming climate.

The thermal growing season and the final disappearance of snow (FSnow) did not serve as good estimates for the beginning of CO_2 assimilation, but rather they indicate a later state of the growing season. Instead, the start of the snow melt (BSnow) estimated from the surface albedo appeared to be a good estimator of beginning of the active period of the vegetation, also from satellite-borne measurements. The maximum photochemical efficiency (Fv/Fm) functioned properly also for estimating the commencement and finishing of the growing season.

Our results agree with Bartsch et al. (2007) that the start of snow melt coincides with the start of CO_2 assimilation in boreal forests. Using a widespread EC measurement network, it would be possible to study whether this can also be detected in more temperate regions, or is this phenomenon only typical of boreal regions where the spring recovery takes place at a fast pace.

The CO_2 concentration also appeared to be a good estimator for the growing season on the local scale. It can also be used in larger-scale estimates. The difficulty in using the CO_2 concentration to predict the growing season comes from the large advective influence (Eneroth et al., 2005; Murayama et al., 2007) caused by the large source area of the measurement.

The processes associated with the emergence of the CO_2 fluxes in spring and the cessation of the CO_2 fluxes in autumn are non-linear and have complex dependencies on changes in the physical environment. It is therefore problematic to linearly associate various variables, such as temperature indices, to the seasonal evolution of plant metabolic activity. Our results provide some simple tools with which to approach this matter. The non-linearity of these processes we are tracking causes ambiguity in the results. In this study some understanding is obtained as to how useful these methods are.

The CO_2 concentration and temperature indices at Pallas/Sammaltunturi showed a trend toward an earlier spring, but no trends in autumn were seen, except in the Fv/Fm time series. A 98-yr-long time series also yielded a similar trend in spring at Sodankylä, as assessed by the 5Dave.

Our results for the different estimation methods can be used to improve modelling of the boreal forest phenology in carbon cycle models. The temperature indices have been successfully used in a modelling study to improve the seasonality of the CO_2 exchange at the canopy scale (Thum et al., 2008). Other estimation methods introduced here can also be used in modelling. The CO_2 concentration provides information on a larger scale, whereas remote sensing applications enable the use of albedo and chlorophyll fluorescence measurements in global simulations.

6. Acknowledgments

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