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Towards the use of dynamic growing seasons in a chemical transport model

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Abstract

Chemical transport models (CTMs), used for the prediction of, for example, nitrogen deposition or air quality changes, require estimates of the growing season of plants for a number of reasons. Typically, the growing seasons are defined in a very simplified way in CTMs, using e.g. fixed dates or simple functions. In order to explore the importance of more realistic growing season estimates, we have developed a new and simple method (the “T5” method) for calculating the start of the growing season (SGS) of birch (which we use as a surrogate for deciduous trees), suitable for use in CTMs and other modelling systems. We developed the “T5” method from observations, and here we compare with these and other methodologies, and show that with just two parameters “T5” captures well the spatial variation in SGS across Europe.

We use the EMEP MSC-W chemical transport model to illustrate the importance of improved SGS estimates for ozone and two metrics associated with ozone-damage to vegetation. This study shows that although inclusion of more realistic growing seasons has only small effects on annual average concentrations of pollutants such as ozone, the metrics associated with vegetation-risk from ozone are significantly affected.

This work demonstrates a strong need to include more realistic treatments of growing seasons in CTMs. The method used here could also be suitable for other types of models which require information on vegetation cover, such as meteorological and regional climate models. In future work, the “T5” and other methods will also be further evaluated for use with agricultural and grassland land-covers, which are important for emissions and deposition of reactive nitrogen compounds.

1 Introduction

For forest trees, the start of the growing season (SGS) is associated with changes in key biogeochemical processes such as photosynthesis, transpiration and especially CO₂ uptake. The growing season is usually determined by environmental factors,

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including air and/or soil temperature, daylight length, precipitation and altitude (Mahall et al., 2010; Pinto et al., 2011).

In particular, SGS is highly sensitive to temperature (Polgar and Primack, 2011; Rybski et al., 2011; Doi and Katano, 2008), and hence to the effects of climate change.

Several studies have shown the impact of climate change on SGS and the end of the growing season (EGS), for example Menzel and Fabian (1999); Menzel et al. (2006); Penuelas et al. (2009) and Wiedinmyer et al. (2004). Menzel and Fabian (1999) reported that the average annual growing season has lengthened by almost 11 days since the early 1960s. Chmielewski and Rotzer (2001) reported that the warming in early spring in the last 30 yr caused an earlier start of growing season by 8 days. Further, Myeni et al. (1997) published the effect of seasonality of start of growing season on seasonality of CO₂ in the atmosphere.

A number of different types of models try to predict or require information on SGS. These studies include ecosystem models such as the Lund-Potsdam-Jena (LPJ) family of codes (Sykes et al., 1996; Smith et al., 2001), which simulate the growth of vegetation on multi-annual time scales, often on global scales. The LPJ-GUESS version of this code (Smith et al., 2001) has also been used in combination with regional climate models (Smith et al., 2011), and for the estimation of emissions of “biogenic” volatile organic compounds (BVOC) such as isoprene or monoterpenes from vegetation (Arneth et al., 2007; Schurgers et al., 2009).

Chemical transport models (CTMs), which are used to predict concentrations of air pollutants such as ozone or particulate matter (PM), or to predict depositions of e.g. sulphur and nitrogen, also require assumptions about SGS and EGS for dealing with biosphere-atmosphere interactions. Of particular interest for this study, the CTM (Simpson et al., 2012) of the European Monitoring and Evaluation Programme, Meteorological Centre-West (EMEP MSC-W, www.emep.int) requires SGS and EGS for many important processes. These include calculations of the dry-deposition of pollutants, including oxidised and reduced nitrogen (Simpson et al., 2006), and for emissions of biogenic volatile organic compounds (BVOC) which are important for ozone and organic

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aerosol (Simpson et al., 1999, 2007; Bergström et al., 2012). The EMEP model is important for the development of policy in Europe, as results from the model underpin the integrated assessment approach which has been the basis for Protocols developed under the United Nation Economic Commission for Europe for more than thirty years (Sliggers and Kakebeeke, 2004), and within the European Union's Clean Air for Europe programme (Amann et al., 2011). The model has also been used recently to help untangle the connections between nitrogen-deposition and forest carbon sequestration (Sutton et al., 2008).

Similarly, numerical weather prediction (NWP) models and general climate models (GCMs) use SGS in their predictions of water and heat fluxes, again often using very simplified treatments of vegetation and growing seasons. For example, the weather research and forecasting (WRF) model (Skamarock and Klemp, 2008) is a well regarded meso-scale NWP model, widely used also in air quality modelling (e.g. Grell et al., 2005; Zhang, 2008; Foley et al., 2010; Vieno et al., 2010; Zhang, 2008). Vegetation characteristics are mainly prescribed by the input of monthly fields of leaf area index, implying no year-to-year variation. As another example, a revised land surface model (TESSEL), which is implemented in the European Centre for Medium-Range Weather Forecasts (ECMWF) model, uses a constant day (e.g. 26 March) for the start of the growing season for surface Exchange over Land (Wipfler et al., 2011).

There are several models which calculate SGS as a function of air temperature. The most common approaches use the so-called **Growing Day Degree** (GDD) method, based on daily average temperature to predict SGS (e.g. Smith et al., 2001; Villordon et al., 2009). GDD is defined as the number of temperature degrees above a certain threshold base temperature, and is often used to predict phenological features such as SGS, flowering time or start of pollen prediction time.

Other models use NDVI (**N**ormalized **D**ifferenced **V**egetation **I**ndex) from satellite data to define the start and end of growing seasons (e.g. Steltzer and Post, 2009; Going Dao-Yi, 2003; Cox, 2001; Myeni et al., 1997).

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As will be discussed in more detail in Sect. 2.1, the EMEP MSC-W model uses a latitude equation to model SGS and EGS. This simplified method has actually been found to work quite well compared to more complex methods (Tuovinen et al., 2009), but has obvious deficiencies. Not least, it pays no regard to year-to-year variations, and cannot account for the differences between locations at the same latitude, but with different climates. This methodology is obviously not ideal for looking at long-term (e.g. decadal or 100 yr) trends of air pollution, especially when linked to expected climate change impacts. In order to improve the ability of the EMEP model to capture year-to-year variations in SGS and EGS, we have tested several methodologies, and developed a new dynamic method which depends only on daily average temperature. The methodology has been developed and tested for birch (*B. pubescens*). Although we focus on this one particular species, SGS from *B. pubescens* is thought to serve a reasonable surrogate for other deciduous trees in our CTM model.

In this study, we have postulated some simple temperature dependent equations, and compared these and a few other methods for calculating SGS against observed data. We also compare some existing EGS methods to observations. We also investigate the sensitivity of the EMEP CTM model results to the choice of method, in order to quantify the impacts of changes in growing season on a few illustrative metrics of air quality.

There are several different definitions for SGS, including start of budburst (Duchemin et al., 1999), start of leaf unfolding (Beck et al., 2007; Kross et al., 2011; O'Connor et al., 2012), or cambial growth after winter dormancy (Krepkowski et al., 2011; Jyske et al., 2012), and it is often unclear which definition is used in different studies. In this study, we define SGS as the time of start of leaf unfolding by the plants.

2 Methods for SGS and EGS

In this paper we compare SGS values calculated using four different methods, and EGS values with two methods. One method will use monthly average temperatures,

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typical of ecosystem usage, and two will use daily temperatures, from EMEP MSC-W input fields. Sects. 2.1–2.4 below describe the methods used. In principal daily temperatures are of course more realistic, but in practice many ecosystem and other models have to rely upon archived monthly data, and typically daily temperature values are generated using interpolation between these monthly values. In particular, many models (including LPJ-GUESS) make use of the CRU (Climatic Research Unit) climate database. The database provides long term monthly average temperatures gridded at 0.5° longitude/latitude resolution for the period 1901–2009, and has thus proved an invaluable resource for vegetation modelling.

Figure 1 illustrates the differences inherent in using temperature from an NWP model or from monthly CRU data. The averages of the NWP method (monthly values not shown) and the CRU data are actually quite close, especially in the first half of the year, but the day-to-day change in temperature is of course much more variable using direct daily NWP data. Interestingly, this figure shows several examples where daily average temperatures from the NWP model exceed 5°C, a threshold which is often used alone to define growing seasons. Using interpolated data from monthly averages, this 5°C would only be exceeded after about 3 months, but in the NWP data the first exceedences occur in January.

2.1 “LAT” method

The default latitude-based method of the EMEP model. The calculation of SGS and EGS in the EMEP model is a function of latitude, not climate. The equations used are:

$$d_{\text{SGS, LAT}} = d_{\text{SGS, 50}} + \Delta_{\text{SGS}} (\phi - 50) \quad (1)$$

where $d_{\text{SGS, LAT}}$ is the ordinal day of SGS, $d_{\text{SGS, 50}}$ (= 100 for deciduous trees) defines the start of the growing season at 50° North, ϕ is latitude in degrees, and Δ_{SGS} is the increase in SGS per degree N, set as 1.5 days/degree for deciduous trees. For the end of the growing season, we use:

$$d_{\text{EGS, LAT}} = d_{\text{EGS, 50}} + \Delta_{\text{EGS}} (\phi - 50) \quad (2)$$

where $d_{\text{EGS},50}$ and Δ_{EGS} define the end of the growing season in an analogous way to the SGS terms.

These equations were loosely developed to fit data presented in Zhang et al. (2004), although modified in consultation with European forest experts from the UNECE “Mapping Manual” process (LRTAP, 2009). These equations have been found to fit a wide range of data (Emberson, 2009), and have often been found to perform better than more complex methods (see e.g. Tuovinen et al., 2009).

2.2 “LPJ-CRU”

LPJ-GUESS is an object-oriented, modular framework to model the dynamics of ecosystem structure and functioning from the patch-scale to the globe (Smith et al., 2001). Standard LPJ-GUESS uses the CRU climate database as noted above. In default usage, the daily average temperatures are approximated by using interpolation functions to estimate daily temperatures from these monthly average data. These estimated daily temperatures are then used for the calculation of growing degree days (GDD). A detailed documentation of the interpolation function is found in Smith et al. (2001). In the model from Smith et al. (2011), the growing degree days to budburst (GDD⁰) are first calculated as a function of the length of the chilling period (Sykes et al., 1996), using:

$$\text{GDD}^0 = a + b \cdot e^{-k \cdot C} \quad (3)$$

where C is the number of days over the winter period¹ with the temperature $< 5^\circ$ (chilling days) and a , b and k are species specific constants (for *Betula pubescens* $a = 0$, $b = 350$ and $k = 0.05$). The growing degree days until a specific ordinal day j are calculated

¹As defined in the LPJ-GUESS code, chilling days start to be accumulated once the running 31-day average temperature in Autumn/Winter drops below 5°C .

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with:

$$\text{GDD}_{5,LPJ}^j = \sum_{i=1}^{i=j} \max(0, T_i - 5) \quad (4)$$

where T_i is the daily average temperature in °C on day i , and the max function returns the value $T_i - 5$ where $T_i > 5$, otherwise zero. The SGS is then calculated with:

$$d_{\text{SGS}, LPJ} = \text{First day } i \text{ where } \text{GDD}_{5,LPJ}^i > \text{GDD}^0 \quad (5)$$

The modeling of EGS begins after the start of growing season in a location. First we calculate the sum of daily fractional leaf cover (equivalent number of days with full leaf cover) so far this growing season:

$$A_{LPJ}^j = \sum_{i=d_{\text{SGS}, LPJ}}^{i=j} \min \left(1, \frac{\text{GDD}_{5,LPJ}^i - \text{GDD}^0}{\Delta \text{GDD}_5} \right) \quad (6)$$

where ΔGDD_5 ($= 200$) is the the GDD needed on 5°C base to attain full leaf cover. EGS is then calculated as:

$$d_{\text{EGS}, LPJ} = \text{First day } i, \text{ after } d_{\text{SGS}, LPJ}, \text{ where } A_{LPJ}^i > A_{LPJ}^{\text{max}} \quad (7)$$

where A_{LPJ}^{max} ($= 210$) is the maximum number of equivalent days with full leaf cover per growing season.

2.3 “TTM” method

The Thermal Time Model was developed by Linkosalo et al. (2008) and Sofiev et al. (2012) to calculate leaf bud burst for birch. The calculation of SGS using TTM begins with a modified heat sum

$$\text{GDD}_{3.5, \text{TTM}}^j = \sum_{i=t_0}^{i=j} \max(T_i - T_{\text{crit}}, 0) \quad (8)$$

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where $GDD_{3.5,TTM}^j$ is this modified heat sum ($H(t)$ in the notation of Sofiev et al., 2012), t_0 the first day of counting ($t_0 = 60$, ~ 1 March, as in Sofiev et al., 2012), and T_{crit} is the critical temperature threshold (3.5°C). Sofiev et al. (2012) used the TTM to predict onset and duration of flowering. In this work, we assume that the start of flowering and start of leaf bud burst are quite close (usually a reasonable assumption within some days uncertainty, M. Sofiev, personal communication, 2012), and calculate our SGS using the same criteria as Sofiev et al. used for flowering:

$$d_{\text{SGS, TTM}} = \text{First day } i \text{ where } GDD_{3.5,TTM}^i > H_{fs} \quad (9)$$

H_{fs} is a temperature sum threshold for the start of the season, which varies by location. We used maps of H_{fs} calculated by Sofiev et al. (2012) (as available at <http://silam.fmi.fi/MACC/>).

Sofiev et al. (2012) also present methods of calculating the end of the pollen season, but this is physiologically different to the EGS required in this work, so we use TTM only for SGS calculations.

2.4 “T5” method

A new method tested here, designed to make use of one simple parameter, near-surface temperature from the NWP model, but accounting for geographical differences in plant response.

The T5 method considers that the plant in warm regions need more days in which the daily average temperature continuously more than 5°C than in cold regions. This is loosely consistent with the assumption that the heat sum requirement in warm regions is greater than in cold regions (cf. Sofiev et al., 2012), and with experimental results that the days needed to bud-burst is often related to the number of chilling days (which is usually related to the duration of winter). For example, Myking and Heide (1995) and Myking (1999) found that the days to bud burst for *Betula pendula* Roth and *B. pubescens* seedlings decreased with increased duration of chilling.

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Thus, we assume that birch needs a particular time range in which the daily average temperature is always more than 5°C to start unfolding of leaves, and that this time-range is shorter in colder conditions. We have developed the following two equations to express this dependency:

$$D_{u,i} = \alpha - \beta i \quad (10)$$

$$d_{\text{SGS}, T5} = \text{First day } i \text{ where all } T_{i-D_{u,i}} \cdots T_i \geq 5^{\circ}\text{C} \quad (11)$$

where $D_{u,i}$ is the required number of days for the starting of the unfolding of the leaves for a given ordinal day i , α ($= 39$) and β ($= 0.2$) are empirical constants, and SGS is defined as the first day where a number, $D_{u,i}$, of previous days have daily average temperatures exceeding 5°C . We test Eqs. (10)–(11) for all days i starting at $i = 1$ until Eq. (11) is satisfied. Figure 2 illustrates how $D_{u,i}$ varies with day number. The parameter values ($\alpha = 39$, $\beta = 0.2$) in Eq. (10) were found by optimising against the observed SGS data, in terms of regression slope and correlation coefficient, using meteorological data from the year 2008. The index of agreement and mean absolute error discussed below were not part of the optimisation. This procedure is further commented on in Sect. 5.1.

As an example of usage, to end up with $d_{\text{SGS}, T5}$ around day 100, we have $D_{u,100} = 19$, so temperatures must have been $\geq 5^{\circ}\text{C}$ from days 81 to 100. For much colder regions, where we ended up with $d_{\text{SGS}, T5} = 180$ say, then $D_{u,100} = 3$, so only days 178–180 above 5°C were needed before the growing season is assumed to start.

The T5 methodology is deliberately simple, but has a number of advantages:

- A single temperature threshold is used across Europe, but the methodology accounts in a natural way for the differences between cold and warm climates, with plants in e.g. northern Europe (or at high altitude) requiring only a few days with temperatures exceeding 5°C , whereas plants in warmer areas require longer period of warmth before growth starts.

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- The methodology is self-consistent and can be applied for any model resolution, and is not dependent on external data (e.g. no specification of heat-sum thresholds is needed).
- SGS can be calculated from current-year temperature fields only; it avoids the need for data from previous winters for example.

Of course, the methodology has disadvantages too. It does not explicitly account for chilling-events, and is less sophisticated than methods such as those of Myking and Heide (1995) and Hanninen (1990). The methodology is empirical, rather than biologically-based, and thus cannot account for some aspects of climate change. However, we will show that the methodology can be quite successful in reproducing the spatial variation in SGS seen across Europe, and thus it serves as a useful first step to improving the treatment of growing seasons in the EMEP model. This also allows us to explore the importance of more accurate estimates of growing season for some air quality indicators associated with biosphere-atmosphere exchange.

3 Observations and statistical approach

To develop the “T5” method, and evaluate this and other SGS and EGS methods described above, we compare with the PAN European Phenological Database (PEP) (PAN, 2011). The PEP database includes observation data from 31 European countries, and has in total collected data from 18 687 stations.

We found 2029 observed data records from 122 stations in 23 European countries about the start of the growing season for *B. pubescens*. Most observation stations (77 of 122) are located in Finland, Germany and the Netherlands. The data records for SGS were mostly taken between 1971 and 1991, but records up to 2009 were available at some sites. The earliest observed SGS values were day 56 in the Netherlands, and the latest day 175 in Finland. Most stations (107 of 122) were located below 500 m above sea level. The highest station is located at 1550 m above sea level in Greece. For

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the end of the growing season (EGS), we found suitable data sets at 55 stations. Table 1 summarises the available data for SGS, and Tables S1 in the Supplement provides details of SGS for each location.

In Sect. 5.1 we will present comparisons between the estimated and observed SGS and EGS. However, two important complications in making this comparison are (i) differences in the altitude of the observed SGS and modelled temperature data, and (ii) differences in the years available for comparison.

The effect of altitude on temperature and the vegetation has reported in the many studies (e.g. Beals, 1969; Caprio, 1993; Klimes, 2003; Luo et al., 2004; Korner, 2007). A 100 m increase in altitude causes a temperature of about 0.6 °C. In principal we could account for this, but the NWP and CRU data are also applicable to a given altitude, and their interpretation is problematic. For example, the NWP data input to the EMEP model is provided in terrain-following coordinates, for grid-cells of ca. 50 km × 50 km in extent. The NWP model's near-surface temperature is in some senses a temperature applicable to an average terrain height, but at the same time it has been derived through assumptions applicable only to flat homogeneous terrain. In order to avoid some of the problems which are inevitably introduced when comparing data in mountain regions, we restrict our analysis to sites where the difference in the NWP model's (or CRU-data) terrain height and the observation site are within 100 m.

Direct year to year comparison between observed SGS, EGS and estimated values is also problematic. Most observed SGS and EGS were recorded between 1971 and 1994. In a few locations, the SGS were observed between 2005 and 2009. We have daily ECMWF NWP data from the EMEP system available only for 2005 onwards. It was therefore not possible to make a comparison of the observed SGS and modelled SGS year by year except over a very limited data-range. The CRU data could have been used in principal, but as discussed above, the use of interpolated data from monthly records can be misleading when comparing to daily temperature thresholds, and we are primarily seeking a method for use with CTMs which can make use of detailed temperature data. Therefore we calculated the average SGS of each station

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and compared with average modelled SGS for 5 yr. This approach ignores therefore year-to-year variability at particular stations, and indeed the effects of climate trends, but is aimed at capturing the larger geographical differences which the PAN database provides.

However, for 23 stations we were able to compare estimates of average SGS made from all the data with average SGS made from 2005–2009 values (where at least three of these years were available), and the differences were found to be rather small. As expected, SGS values from the recent years were somewhat earlier than from the longer-term averages, but by only 3.1 days on average, with a biggest discrepancy of less than eight days.

For each station, we thus extract the temperature from the NWP and/or CRU climate data bases for each year between 2005 and 2009. We will illustrate the comparison between the estimates and observed SGS and EGS. As well as calculating the regression lines, and correlation coefficient between the observed and modelled SGS and EGS, we also calculated the mean absolute error (MAE) and index of agreement, d , (Willmott, 1982) for the validation of the results of the models:

$$\text{MAE} = \frac{1}{n} \sum_{i=1}^n |P_i - O_i| \quad (12)$$

$$d = 1 - \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n ((|P_i - \bar{O}|) + (|O_i - \bar{O}|))^2} \quad (13)$$

where P is the simulation and O is the observation data, i a particular sample, n the number of samples, overbar represents mean values, and d is the index of agreement, respectively.

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4 Modelling studies

As noted in Sect. 1, the EMEP model is used to provide estimates of a number of pollutants, and metrics associated with health and vegetation effects. Some metrics, such as sulphur and nitrogen deposition, are not expected to be very sensitive to SGS and EGS, since deposition is largely related to emissions, and these are almost entirely from combustion sources. Here we focus on ozone-damage indicators which are expected to be sensitive to SGS, since at many sites (especially in Northern Europe) ozone concentrations peak in springtime, usually the period where the growing season starts (e.g. Monks, 2000; Karlsson et al., 2007; Scheel et al., 1997). The EMEP model is described briefly in Sect. 4.1 and the selected metrics for this study described in Sect. 4.2. An illustration of the performance of the EMEP model for some selected stations in Europe is given in Fig. 3. This figure illustrates that the EMEP model usually performs well for ozone in very different parts of Europe. It also illustrates the important of springtime ozone at many of these sites.

In Sect. 5.2 we will illustrate the the effect of using a dynamic growing season on these selected metrics, using two runs of the EMEP model. In the “base” run, we run the EMEP model with the standard latitude method for SGS and EGS. In a second test scenario, we run the EMEP model with the “T5” method for the modeling of SGS, preserving the standard EMEP method for EGS.

4.1 The EMEP MSC-W model

The EMEP MSC-W chemical transport model used in this work (Simpson et al., 2012) is a development of the 3-D CTM of Berge and Jakobsen (1998), extended with photo-oxidant and inorganic aerosol chemistry. The model domain used in this study covers the whole of Europe, and includes a large part of the North Atlantic and Arctic areas. The standard grid system of the EMEP model is based on a polar-stereographic projection, with a horizontal resolution of 50 km × 50 km at latitude 60°. The model includes 20

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vertical layers, using terrain-following coordinates, and the lowest layer has a thickness of about 90 m.

The model is capable of using various meteorological data inputs, but in standard use and here we use meteorological fields derived from the European Centre for Medium Range Weather Forecasting Integrated Forecasting System (ECMWF-IFS) model (<http://www.ecmwf.int/research/ifsdocs/>). These data have 3-hourly resolution, and include the near-surface (2 m) temperature (T_2) that we will use in this study.

As noted in Sect. 1, the EMEP model is one of the key tools in the development of air pollution emissions policy in Europe. The model has to be both state-of-the-art in terms of model performance when compared to measurements, but also very efficient in computer processing in order to conduct literally thousands of scenario runs. This means that modelling of pollution transfer between the atmosphere and biosphere needs to be simple enough to ensure reasonable model run times, yet complex enough to incorporate the key drivers of for example O_3 or nitrogen deposition fluxes at the European scale. The application of the model across such a large spatial region also means that the complexity of the model has to be balanced against the availability of spatial data characterising the important physical and environmental conditions that will influence for example ozone concentrations or nitrogen deposition across Europe (e.g. land cover, species distribution, soil type, root depth and meteorological information).

4.2 Model outputs

Some specific outputs of the EMEP model are of interest for this work. Firstly, we have two metrics commonly used to indicate risks of ozone damage to vegetation in Europe, AOT40 and POD_1 . These metrics have been described in details elsewhere (LRTAP, 2009), but can be briefly summarised:

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(i) POD_Y

Phyto-toxic ozone dose, is the accumulated stomatal ozone flux over a threshold Y nmole O_3 $m^{-2} s^{-1}$, i.e.:

$$POD_Y = \int \max(F_{st} - Y, 0) dt \quad (14)$$

5 where the stomatal flux F_{st} , and threshold, Y , are in nmole O_3 $m^{-2} s^{-1}$ (per projected leaf area). This integral is evaluated over time, from the start of the growing season (SGS), to the end (EGS). The flux F_{st} is calculated using the so-called DO3SE model (Emberson et al., 2000, 2001; Simpson et al., 2001, 2003; Tuovinen et al., 2009). Details of the method and parameters have changed over the years, but the latest version
10 is documented in Simpson et al. (2012).

(ii) AOT40

AOT40 is the accumulated amount of ozone over the threshold value of 40 ppb, i.e.:

$$AOT40 = \int \max(O_3 - 40 \text{ ppb}, 0) dt \quad (15)$$

This integral is also taken over time, namely the relevant growing season for the vegetation concerned. The corresponding unit are ppb hours (abbreviated to ppb h). The usage and definitions of AOT40 have changed over the years though, and with different applications. Here we use AOT40 calculated from ozone values at the top of the canopy, during daylight hours, consistent with Mapping Manual recommendations (LRTAP, 2009).
15

20 In recent effects work, POD-type metrics are clearly preferred to AOT40 for forest and crop species, but we present AOT40 here as the definition is conceptually simpler than POD, and AOT40 is still relevant for semi-natural vegetation (LRTAP, 2009).

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AOT40 is also rather similar to the so-called SOMO35 metric which is recommended as the relevant ozone indicator by WHO (2004). SOMO35 is calculated as the sum over the year of the daily 8-h maximum ozone concentrations in excess of a 35 ppb threshold. The POD metric was previously denoted AFstY (accumulated stomatal flux over threshold Y), and has been compared to AOT40 over Europe by Simpson et al. (2007).

Our third metric is the annual average concentration of ozone, primarily in order to compare with the two effects metrics above which are based upon O_3 . Also, ozone is a key oxidant in tropospheric chemical cycles (Monks et al., 2009), an important greenhouse gas, and highly coupled to carbon sequestration (e.g. Sitch et al., 2007).

5 Results

5.1 Evaluation of SGS and EGS methods

Figure 4 compares the SGS predictions of the four SGS methods (Sect. 2) against observed values from the PAN database. Actual values are given in the Supplement, Table S1. (As noted in Sect. 2, we restrict our analysis to situations where the difference in the NWP model's terrain height and the observation site are within 100 m.) The regression line, 1 : 1 line, correlation coefficients (r^2), mean absolute error (MAE), and index of agreement (d) are also given on these plots.

The r^2 values range between 77 % to 88 %, indicating quite good performance for all methods. The very simple "LAT" method correlates quite well with the observations ($r^2 = 0.77$), but the regression line has a slope of just 0.48, and large intercept of 51 days. The modelled SGS with the "LAT" method covers a much smaller range of values than the observed. The poorest index of agreement is found for the LPJ-CRU method ($d = 0.74$), which uses monthly average temperature, but the correlation ($r^2 = 0.84$) is much better than the "LAT" method. There is a clear tendency for the method to predict an SGS values earlier than the measurements, with the largest MAE of about 22 days.

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This difference compared to the other models is likely due to the fact that LPJ-GUESS is designed for global scale usage, whereas the other methods were optimised for European application. (Further, in the LPJ-GUESS model the development of birch leaves at the start of the season extends over a long period, which will partly compensate for this early start of SGS.) The TTM method performs well with this dataset, with $r^2 = 0.88$ $d = 0.94$, although with a slope of 1.28 and quite large (36 day) intercept. Mean absolute error is within 9 days. TTM is thus significantly better than the default latitude method.

Finally, the simple “T5” method performs rather well, with best index of agreement ($d = 0.95$), lowest MAE (5.4 days), and a regression line which is almost co-incident with the 1:1 line. The correlation coefficient ($r^2 = 0.83$) is not so high as with LPJ-CRU or TTM, but still good. Of course, much of this good agreement stems from the fact that the parameters of the “T5” method were obtained by fitting this data-set (optimising for r^2 and slope), but this fitting was done for one year of meteorology only, whereas here we use results from five meteorological years. The fact that all three statistical measures fit so well suggests that the underlying model has a good structure. (We have also tested the use of a simpler model with fixed values for the $D_{u,i}$ parameter; results were not as good, however, see Supplement, Fig. S1.)

Figure 5 compares EGS estimates from the two available methods with observations. It is clearly seen that both methods perform poorly in reproducing observed EGS values. The range of observed EGS is quite small, with most values between days 290–320, suggesting that factors other than temperature control this phase of the growing season. It could be said that the EMEP model’s current assumption of a latitude-dependent (and hence implicitly, photo-period dependent) EGS is no worse than the more physiologically based LPJ methods. This would be partly consistent with Partanen et al. (1998) who suggested that the day length and photo-period could be the drivers for leaf colouring and end of growing season in boreal and temperate environments. One could also argue for a simpler fixed-date system however, since the correlation is essentially zero for both methods.

5.2 EMEP model simulations

As discussed in Sect. 4.2, we have selected three outputs from the EMEP model to illustrate the importance of variations in SGS and EGS: the two ozone-effects metrics $POD_{1,DF}$ and $AOT40_{DF}$, and annual mean ozone concentration.

We have run the EMEP model using the two growing-season methods (“LAT” and “T5”) and taken the difference between the scenarios to find out the effect of the changing of the growing season on the four output metrics. Figures 6 and 7 illustrates the estimated distribution of SGS and EGS obtained the EMEP “LAT” method, and SGS as estimated by the “T5” method. The “T5” SGS values are obviously much more complex than those obtained with the “LAT” method, reflecting both climate differences across Europe and topographic effects. Fig. 7b shows significant differences between the two methods, with “T5” SGS values frequently more than a month later than the “LAT” values (e.g. in the Alps, western Norway, Turkey).

Figure 8 shows the modelled $POD_{1,DF}$ across Eurasia when using the “LAT” method for the year 2009. Highest values, of around 30 mmole m^{-2} are found in southern Europe, but values exceed 10 mmole m^{-2} over much of the continent. (These values are all well in excess of the recommended critical levels of 4 mmole m^{-2} for deciduous forests, cf. Mills et al. 2011.) Figure 8b shows the difference in modelled $POD_{1,DF}$ when using the “T5” methodology. The effect of the different SGS methods is different in different parts of Europe. In many parts of southern Europe, $POD_{1,DF}$ using the “T5” method is significantly higher than in the base-case run (“LAT”). In other parts, especially northern and eastern Europe, and mountain areas, $POD_{1,DF}$ with “T5” is lower than in the base-case. These changes are as expected: delayed SGS means less exposure to the spring peak in ozone in many parts of Europe. Changes are of order $2\text{--}5 \text{ mmole m}^{-2}$, corresponding to about 10 % of the base values in many areas.

The modelled values of $AOT40_{DF}$ are illustrated in Fig. 9a. As shown and discussed already in Simpson et al. (2007), modelled $AOT40$ values shows much stronger

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gradients than those of the flux indicator $POD_{1,DF}$. Highest values (over 40 000 ppb h) are seen in the Alps and northern Italy.

The implementation of the “T5” method lowers $AOT40_{DF}$ in many parts of Europe, with largest changes of ca. 10 000 ppb h in mountain areas. This method leads to moderate increases in parts of the United Kingdom, Denmark, in eastern France and also in some regions in Southern Europe. Elsewhere (e.g. over much of central and Eastern Europe) changes are much smaller, typically with “T5” leading to reductions in $AOT40_{DF}$ of around 1–2000 ppb h, about 10 % of the values given by the “LAT” method.

The surface O_3 prediction by using EMEP standard model and the effect of implementation of the “T5” method on the surface O_3 concentrations is shown in Fig. 10. The distribution of ozone reflects well-known patterns, with a general north-south gradient (e.g. Scheel et al., 1997), and higher levels over sea-areas where ozone deposition is very low. The gradients in ozone are also much smaller than those of $AOT40_{DF}$ or $POD_{1,DF}$, a result of the thresholds used in these ozone metrics which amplify the importance of the higher end of the ozone (or ozone-flux) frequency distributions (Tuovinen et al., 2007; Sofiev and Tuovinen, 2001).

Figure 10 shows that the impact of the changing SGS values are quite small on mean ozone levels, with changes being smaller than 0.5 ppb almost everywhere.

Finally, we have explored the response of other outputs of the EMEP model to this change in SGS, but such responses are generally very small. For example, use of the “T5” method instead of “LAT” produces changes in the modelled fields of nitrogen dry-deposition of up to a few $mg(N) m^{-2}$, less than one percent of the base-case deposition values of several hundred $mg(N) m^{-2}$ (see e.g. Simpson et al., 2006).

6 Discussion

As discussed above, the use of the “T5” methodology as introduced here results in differences in SGS of deciduous forests (DF) of typically 10–30 days in many parts of Europe, sometimes more (cf. Fig. 7), with the SGS generally delayed compared to

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that of the default EMEP “LAT” method. The results of the EMEP model simulations discussed in Sect. 5.2 show that differences in SGS estimates can have significant effects on the two ozone metrics $POD_{1,DF}$ and $AOT40_{DF}$. On the other hand, ozone itself was shown to be very insensitive to these SGS changes. Other metrics such as nitrogen deposition were also found to be very insensitive to these SGS experiments.

There are several reasons for these strong differences in response. Firstly, it is important to remember that here we change SGS only for deciduous forests. Thus, growing seasons are unchanged for coniferous forests, crops, grasslands, seminatural and all other land-cover classes in the EMEP model. The $POD_{1,DF}$ and $AOT40_{DF}$ metrics are directly linked to deciduous forests, whereas most other metrics (e.g. ozone concentrations) are under the influence of all land-cover categories.

Further, ozone concentrations frequently show peaks in springtime (Monks, 2000; Karlsson et al., 2007; Scheel et al., 1997) (see also Fig. 3). Metrics such as $AOT40_{DF}$ and $POD_{1,DF}$ are accumulated over a relatively short time-period, which is defined by SGS and EGS, and shifts in this time period can significantly affect the accumulated ozone exposure or dose.

Other metrics are rather insensitive to vegetation characteristics in this springtime period. For example, those aspects of biosphere-atmosphere exchange that most affect ozone are deposition processes and biogenic VOC emissions (BVOC). Ozone deposition occurs to all vegetative canopies, so a change in just DF only affects a fraction of the total deposition. Further, in springtime much of ozone deposition is through the non-stomatal rather than stomatal pathways (Fowler et al., 2009), and even stomatal fluxes are quite low until temperatures rise well above 5°C , so emergence of leaves has only a limited impact on the total deposition sink. Biogenic VOC are also strongly temperature dependent (Guenther et al., 2006), so again changes in leaf-area at the beginning of the growing season have only limited effect.

The small sensitivity of the modelled nitrogen-deposition to the SGS changes shares some of these features. In this case, the non-stomatal contributions to deposition are even larger than for ozone (e.g. Burkhardt et al., 2009; Flechard et al., 2011; Fowler

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et al., 2009; Sutton et al., 2007), and to a large extent the deposition of nitrogen has to match the emissions input - and in Europe most emissions of reactive nitrogen are from anthropogenic combustion sources.

On the other hand, a natural extension of this work will be to evaluate the “T5” and other methodologies for other land-use categories, including those associated with agriculture. Further work is needed to explore the extent to which dynamic SGS values over other vegetation canopies might affect biosphere-atmosphere exchange in this case. For example, emissions and deposition of oxidised and reduced nitrogen compounds from agricultural areas depends on the growing seasons of for example crops and pastures (e.g. Fowler et al., 2009; Skjøth et al., 2011). Indeed, the timing of key agricultural activities is linked to local knowledge of growing-seasons. This influences for example fertiliser application and cutting times, which can strongly influence biosphere-atmosphere exchange of NH₃ (e.g. Loubet et al., 2002).

7 Conclusions

In order to explore the importance of using more realistic growing season estimates in chemical transport models, we have developed a new and simple method (the “T5” method) for calculating the start of the growing season (SGS) of birch (which we use as a surrogate for deciduous trees). This method is intended as a first step to the introduction of dynamic growing seasons in the EMEP MSC-W chemical transport model. The simple requirements of the “T5” method also make it suitable for use in other CTMs and other modelling systems.

The “T5” method is empirical, based upon a simple equation with just two free parameters. We show that with this formulation a very good fit to the observed SGS values is attained, in terms of the regression statistics, mean absolute error, and index of agreement.

We developed the “T5” method with observations from the PAN European Phenological Database, which provided appropriate data from 122 stations for SGS (and 55 for

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EGS). We also compared with the simple latitude-based scheme currently used in the EMEM MSC-W model, the LPJ-GUESS scheme using monthly CRU data, and with the Finnish thermal-time system which is used for pollen-modelling. All methods performed quite well for the start of the growing season, especially those developed specifically for Europe (TTM and “T5”), and driven by daily meteorological data. The LPJ-GUESS code, driven by monthly data, also gave good correlation but predicted SGS too early compared to the other methods. (This is partly compensated in the LPJ-GUESS code by a long development time for LAI for birch, but may also reflect that LPJ-GUESS has a more global focus than the other methods; parameters are not optimised for European conditions.) For the end of the growing season, the two available methods performed poorly, but uncertainties about the end of the growing season have little impact on CTM results.

The SGS values generated by “T5” can be significantly different from those of the simple default latitude function used in the EMEP model, with differences of 10–30 days over many parts of Europe. The “T5” values present a much more realistic picture of the variation of SGS across Europe.

We have used the EMEP MSC-W chemical transport to illustrate the importance of improved SGS estimates for ozone and two metrics associated with ozone-damage to vegetation. This study shows that although inclusion of more realistic growing seasons has only small effects on annual average concentrations of pollutants such as ozone, the metrics associated with vegetation-risk from ozone are significantly affected. The ozone-flux metric $POD_{1,DF}$ showed reductions of almost 50 % in some areas

In this study, the impacts of a dynamic SGS applied to deciduous forests on other long-term pollution metrics such as nitrogen deposition are small. We have presented a number of reasons for this, but an important need is to explore the impact of improved SGS for other types of vegetation, including agricultural. This work demonstrates a strong need to include more realistic treatments of growing seasons in CTMs.

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Supplementary material related to this article is available online at:
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bgd-9-12137-2012-supplement.pdf](http://www.biogeosciences-discuss.net/9/12137/2012/bgd-9-12137-2012-supplement.pdf).

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Table 1. Summary of the observation stations with data records for SGS in the PAN database. Note that countries can have several stations, taking observations for different years.

Country	Number Sites	Number Obs.	Years	Range in SGS (days)	Altitude range (m asl)
AT	3	50	1971–1999	79–134	150–900
BA	1	21	1971–1991	104–143	1000
BE	2	46	1971–1997	79–135	15–500
CH	1	29	1971–2000	90–122	600
DE	22	482	1971–2000	80–166	13–1370
DK	4	49	1971–1994	92–135	5–40
FI	37	693	1971–2009	113–175	5–335
FR	1	9	1978–1988	91–135	70
GR	1	9	1973–1982	110–125	1550
HR	2	35	1971–2000	74–118	64–146
HU	2	21	1974–1994	90–134	90–220
IT	5	135	1968–2009	63–129	14–80
ME	1	18	1975–1993	69–120	5
MR	1	3	1975–1994	98–116	240
NL	18	71	1868–1978	56–125	0–25
NO	5	144	1965–2005	105–144	25–95
PL	2	33	1971–2000	87–128	74–127
PR	1	9	1971–1979	64–95	30
RS	2	37	1975–1993	82–121	90–121
SE	6	32	1971–2007	105–149	33–320
SK	2	58	1971–2000	86–132	180–540
SL	1	29	1971–2000	93–121	310
UK	2	16	1971–2009	88–117	64–84

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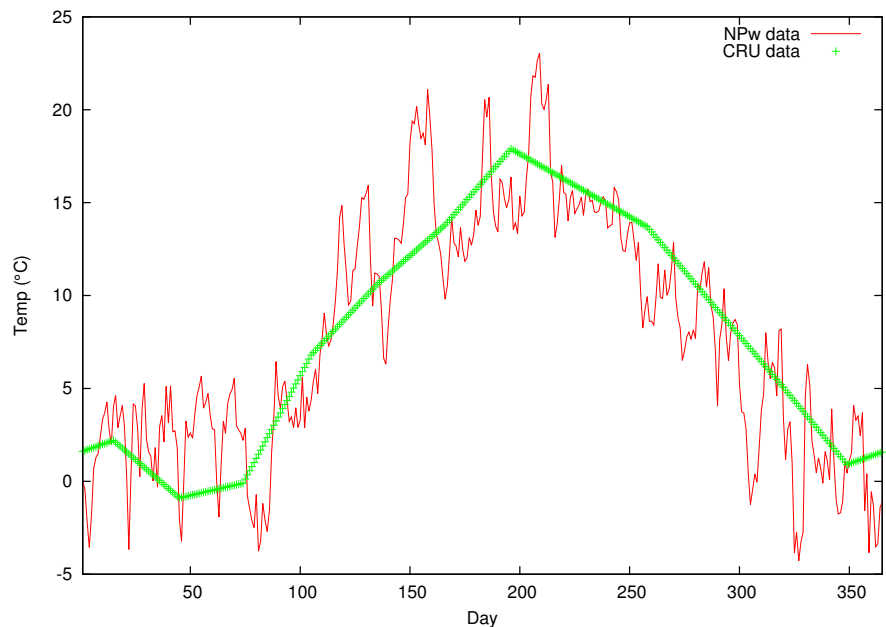


Fig. 1. The daily average temperature from the ECMWF numerical weather prediction model (as input to the EMEP model) and as interpolated from the CRU climate database for a low-altitude location in Northern Germany.

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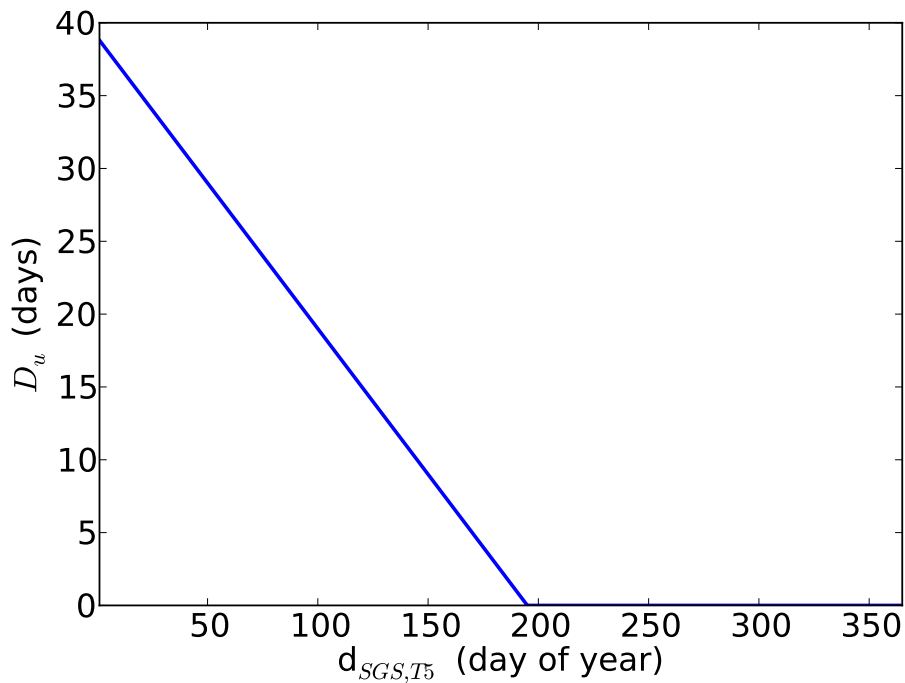


Fig. 2. The required number of days to start leaf unfolding by birch as a function of the start of growing season.

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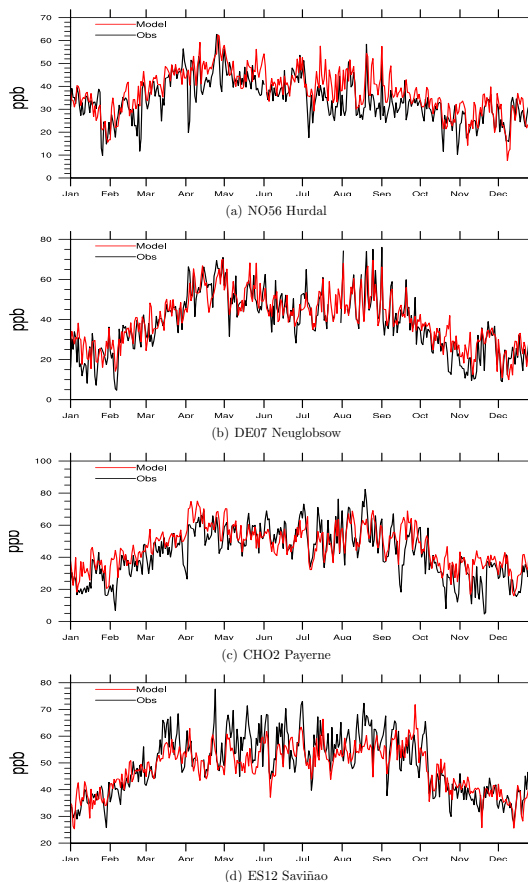
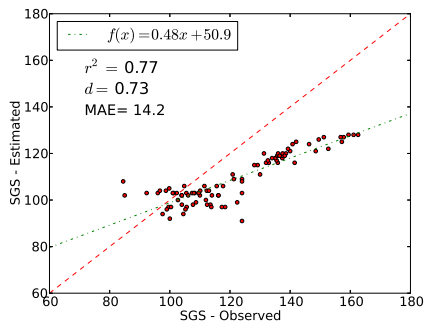
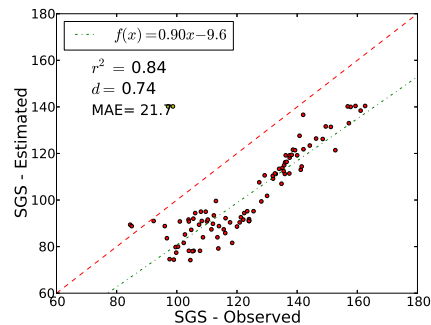


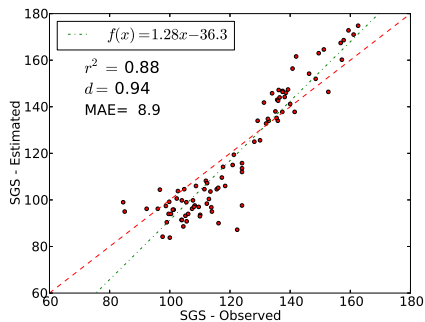
Fig. 3. Comparison of modelled and observed daily maximum ozone (ppb) values at four European sites: **(a)** Hurdal, Norway (NO56), **(b)** Neuglobsow, Germany (DE07), **(c)** Payerne, Switzerland (CH02) and **(d)** O Saviñao, Spain (ES12).



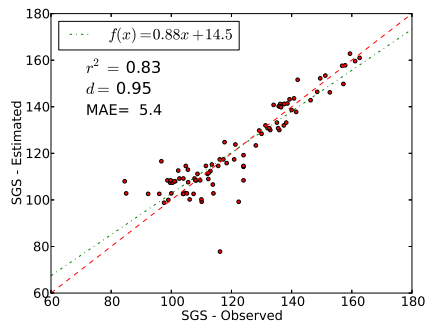
(a) LAT



(b) LPJ-CRU



(c) TTM



(d) T5

Fig. 4. Comparison of estimated and observed SGS (day number) using the methods “T5”, “LPJ-CRU”, “TTM” and “LAT”. The regression and 1:1 lines are also indicated, along with correlation coefficient (r), mean absolute error (MAE) and index of agreement (d). For LPJ-CRU two stations (marked in yellow) are obvious outliers and have been excluded from the statistics.

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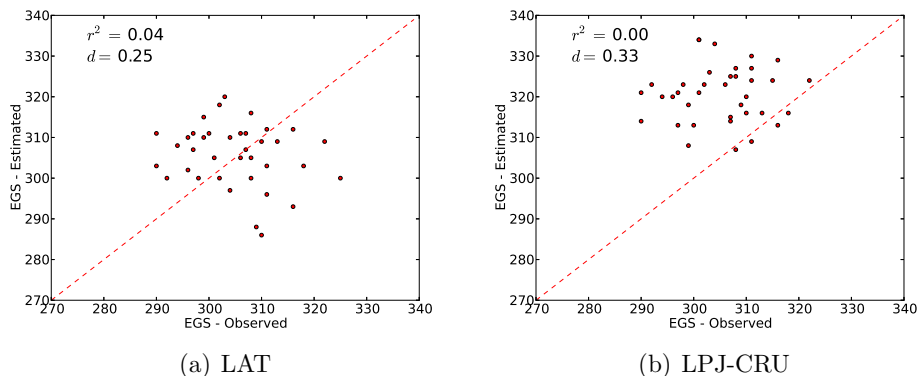


Fig. 5. Comparison of observed and estimated EGS (day number) using the methods “LPJ-CRU” and “LAT” (= EMEP default) at stations from PAN database. Regression lines are not given since neither method shows significant correlation with the data.

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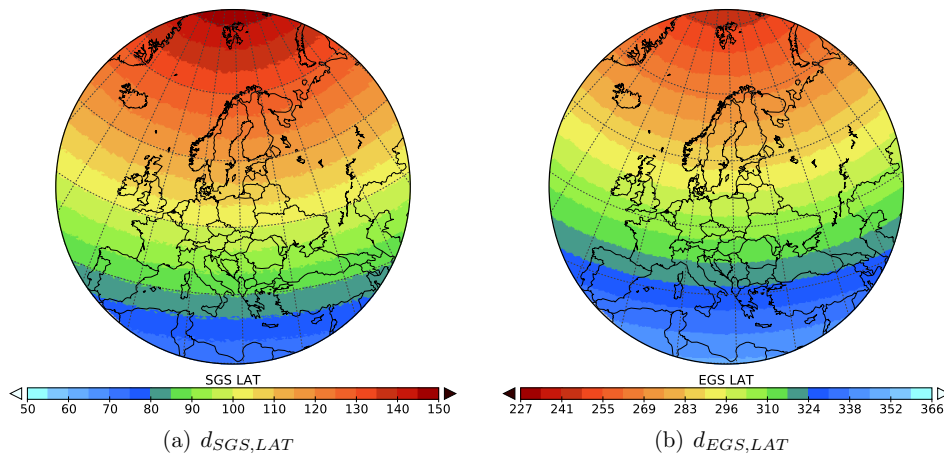
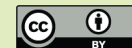


Fig. 6. Estimated start and end of growing season in Eurasia, using the standard EMEP “LAT” method.

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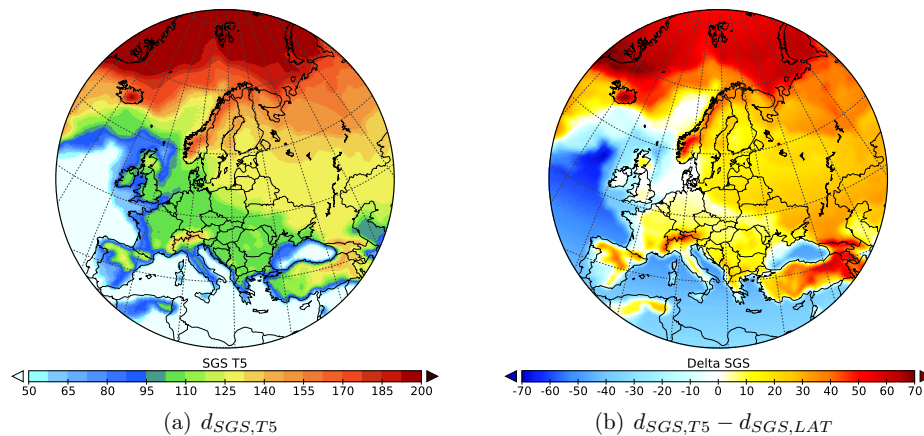


Fig. 7. (a) Estimated start of the growing season using the “T5” method, and (b) the difference between the “T5” and LAT methods.

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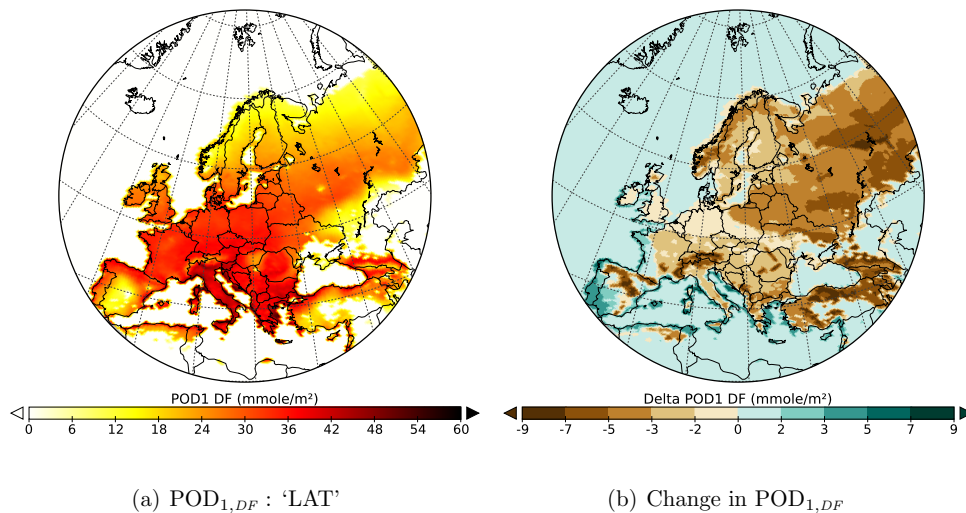


Fig. 8. Modelled values of **(a)** $POD_{1,DF}$ (mmole m^{-2}) using the EMEP “LAT” method, and **(b)** the difference (T5 minus LAT) in modelled $POD_{1,DF}$ when using the “T5” method.

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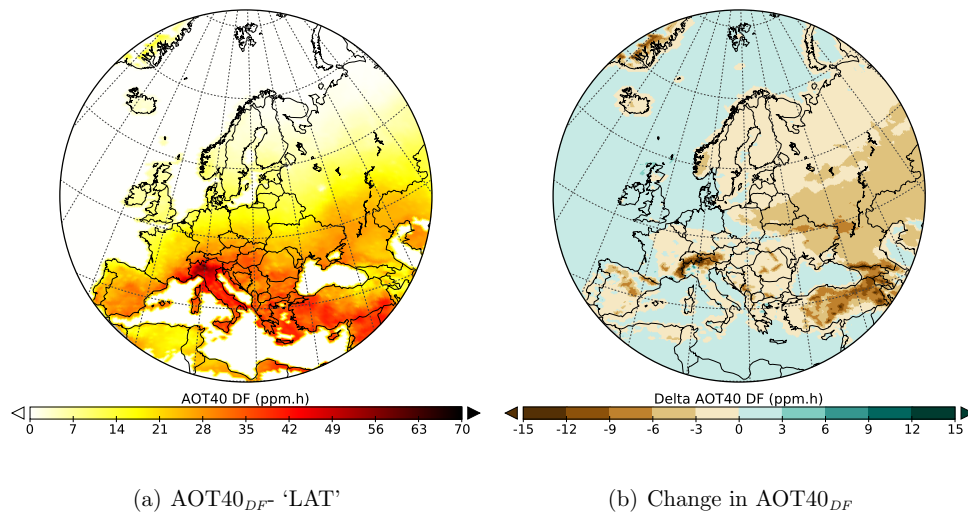


Fig. 9. Modelled values of **(a)** AOT40_{DF} (units: ppm h) using the EMEP “LAT” method, and **(b)** the difference (T5 minus LAT) in modelled AOT40_{DF} when using the “T5” method.

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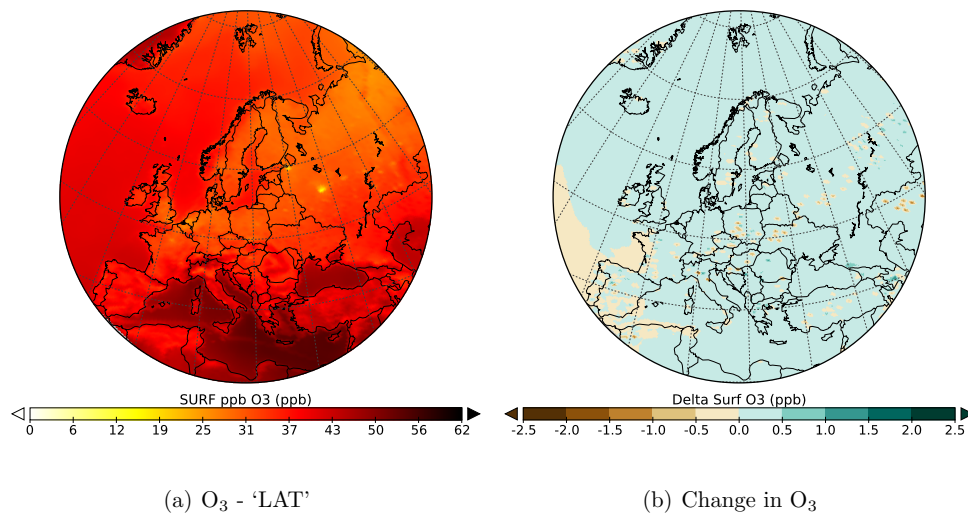


Fig. 10. Modelled values of **(a)** O_3 (units: ppb) using the EMEP “LAT” method, and **(b)** the difference (T5 minus LAT) in modelled O_3 when using the “T5” method.