Vegetation baseline phenology from kilometric global LAI satellite products

Aleixandre Verger a,b,c,*, Iolanda Filella a,b, Frédéric Baret c, Josep Peñuela a,b

a CREAf, Cerdanyola del Vallès 08193, Catalonia, Spain
b CSIC, Global Ecology Unit, Cerdanyola del Vallès 08193, Catalonia, Spain
c CREAF, Cerdanyola del Vallès 08193, Catalonia, Spain

A R T I C L E   I N F O

Article history:
Received 18 May 2015
Received in revised form 1 February 2016
Accepted 26 February 2016
Available online 8 March 2016

Keywords:
Climatology of land surface phenology
Mean annual seasonal cycle
Leaf area index
SPOT-VEGETATION
MODIS
Ground observations
Climatic drivers

A B S T R A C T

Land surface phenology derived from remotely sensed satellite data can substantially improve our macroecological knowledge and the representation of phenology in earth system models. We characterized the baseline phenology of the vegetation at the global scale from the GEOCLIM climatology of leaf area index (LAI) estimated from 1-km SPOT-VEGETATION time series for 1999–2010. The phenological metrics were calibrated over an ensemble of ground observations of the timing of leaf unfolding and autumnal colouring of leaves. The start and end of season were best identified using respectively 30% and 40% threshold of LAI amplitude values. The accuracy of the derived phenological metrics, evaluated using available ground observations for birch forests over Europe (and lilac shrubs over North America), improved as compared to those derived from MODIS-EVI and produced an overall root mean square error of 7 days (19 days) for the timing of the start of season, 15 for the end of season, and 16 for the length of season. The spatial patterns of the derived LAI phenology agreed well with those from MODIS-EVI and -NDVI, although the timing of the start, end, and length of season differed by about one month at the global scale, with higher uncertainties in areas of limited seasonality of the satellite signal and systematic biases due to the differences in the methodologies and datasets. The baseline LAI phenology was spatially consistent with the global distributions of climatic drivers and biome land cover.

© 2016 Elsevier Inc. All rights reserved.

1. Introduction

Phenology describes the timing of the several phases of life cycle of organisms including recurrent transitions of vegetation through states of dormancy, active growth, and senescence. Phenology is a key regulator of processes in terrestrial ecosystems, including carbon, water, and nutrient cycling (Richardson et al., 2013). Phenological feedbacks may alter the seasonal climate through their effects on biogeochemical processes (especially photosynthesis and carbon sequestration) and the physical properties (mainly surface energy and water balance) of vegetated land surfaces (Ball & Collins, 2015; Peñuelas, Rutishauser, & Filella, 2009). Land models coupled to global climatic models describe the exchanges of energy, water, and greenhouse gases between the land surface and the atmosphere using the leaf area index (LAI). Levis and Bonan (2004) highlighted the importance of accurate prognostic modelling of LAI dynamics for improving climatic simulations by atmospheric general-circulation models coupled to land-surface schemes.

The representation of phenology in state-of-the art models of the terrestrial biosphere, including the soil/vegetation/atmosphere transfer schemes used in earth-system models, tends to be poor (Richardson et al., 2012). Models usually overestimate mean annual LAI and predict too long growing seasons because of delayed ends of the growing seasons in all biomes (Anav et al., 2013; Murray-Tortarolo et al., 2013; Zhu et al., 2013). Phenological models are most deficient for subtropical and Mediterranean vegetation, with a temporal mismatch in spring green up of 1–2 months, because model parameters are often generalized from temperate vegetation to global scales (Stöckli et al., 2008). Models of widely studied temperate forests, however, tend to predict an excessively early start of season (one month or more) and a later end of season (up to two months), resulting in a substantially longer growing season than the actually observed one (Richardson et al., 2012). This overestimation produces large biases in the modelled seasonality of ecosystem processes and biosphere feedbacks to the climate system that are phenologically mediated (Richardson et al., 2013).

Vegetation phenology has been assessed through a variety of methods (White et al., 2009), including (1) ground observations of species-specific phenological events based on periodic visual inspection by scientists or by citizens (e.g. USA National Phenology Network wvw1, Pan European Phenology network wvw2, and Canadian PlantWatch project wwww3), (2) eddy covariance flux towers (Melaas et al., 2013), (3) phenology modelling (Chuine, Cambon, & Comtois, 2000), (4) close range remote sensing based on digital cameras and spectral radiometers (e.g. USA PhenoCam network wwww4, and
Phenological Eyes Network wwww5, and (5) satellite remote sensing such as this study. Satellite sensors with medium to coarse spatial resolution and frequent observations capture signals that can be exploited to improve our understanding on land surface processes including growth and in the representation of phenology in terrestrial biophysical models (Demarty et al., 2007; MacBean et al., 2015; Stöckli, Rutishauser, Baker, Liniger, & Denning, 2011) at the typical model grid cell spatial resolution (0.5 × 0.5°) where local ground-based data are more difficult to use (Penuelas, Rutishauser, & Filella, 2009). Land surface phenology derived from remotely sensed satellite data allows the modelling of spatially explicit phenological patterns related to climatic variability and provides a better understanding of the environmental drivers of phenology (De Beurs & Henebry, 2005; Zhang, Friedl, & Schaaf, 2006; Zhang, Tan, & Yu, 2014).

Satellite sensors with moderate spatial resolution, including AVHRR, SPOT-VEGETATION, and MODIS, provide long-term time series of observations that describe the patterns of land surface phenology at continental and global scales (Atzberger, Klish, Mattiuzzi, & Vuolo, 2013; Brown, de Beurs, & Marshall, 2012; Ganguly, Friedl, Tan, Zhang, & Verma, 2010; Maignan, Bréon, Bacour, Demarty, & Poisson, 2008; Sobrino, Julien, & Soria, 2013; Vrielings, de Leeuw, & Said, 2013; Zhang et al., 2003). A broad variety of strategies have been designed to extract phenological metrics from satellite time series based on thresholds (Myrneni, Keeling, Tucker, Asrar, & Nemani, 1997; White, Thornton, & Running, 1997), moving averages (Reed et al., 1994), first derivatives (Tateishi & Ebata, 2004; White et al., 2008), inflection points in empirical equations (Moulin, Kergoat, Viovy, & Dedieu, 1997), conceptual mathematical phenological models based on thermal time (De Beurs & Henebry, 2005; Kaduk & Heimann, 1996), maximum curvature of piecewise logistic functions (Zhang et al., 2003), spectral-frequency decomposition techniques (Bradley, Jacob, Hermance, & Mustard, 2007; Sakamoto et al., 2010; Verbesselt, Hyndman, Newnham, & Culvenor, 2010) and curve fitting (Jönsson & Eklundh, 2002; Julien & Sobrino, 2009), de Beurs and Henebry (2010) have comprehensively reviewed the current approaches for modelling land surface phenology. White et al. (2009) found large discrepancies of up to two months in the detection of the start of the season among several methods for extracting phenological timing.

In addition to the sensitivity to the phenological detection algorithm, the derived phenological metrics are also dependent on the sensor, processing chain, and satellite data set. Atzberger et al. (2013) reported large discrepancies in phenological metrics, particularly the start of season, derived from the GIMMS and MODIS data sets for normalized difference vegetation index (NDVI) using the same phenological detection algorithm. Extraction of phenological information is sensitive to the temporal (Zhang, Friedl, & Schaaf, 2009; Pouliot, Latifovic, Fernandez, & Olthof, 2011) and spatial (Fisher & Mustard, 2007; Kovalskyky, Roy, Zhang, & Ju, 2011) resolution of the satellite data. Noise and missing data due to cloud or snow contamination or to atmospheric or directional residual effects can also introduce significant uncertainties in the estimation of phenological metrics (Jönsson & Eklundh, 2002; Kandasamy, Baret, Verger, Neveux, & Weiss, 2013; Verger, Baret, Weiss, Kandasamy, & Vermote, 2013). The choice of the method for smoothing and gap filling the data can have a large impact on the accuracy of the phenology extracted from the reconstructed time series (Atkinson, Jeganathan, Dash, & Atzberger, 2012; Hird & McDermid, 2009; Kandasamy et al., 2013; Verger et al., 2013).

Most previous approaches for estimating phenological phases have been based on the use of spectral vegetation indices, which are proxies of vegetation biophysical variables. The different vegetation indices vary in their strength of phenological prediction across sites and plant functional types (Wu, Gonsamo, Gough, Chen, & Xu, 2014). White, Pontius, and Schaberg (2014) showed that the most commonly used NDVI and the enhanced vegetation index (EVI) outperformed other indices for the remote sensing of growing seasons in north-eastern American deciduous broadleaf and mixed forests, where the coincident timing of bud burst and snow melt may limit the use of the normalized difference water index (NDWI) and other indices based on mid-infrared wavelengths. The remote sensing of growing season in North American forests conducted by Wu et al. (2014), however, suggested that the NDVI and EVI had limited potential predictive strength for evergreen needleleaf forests, while indices sensitive to water (e.g. NDWI) or less influenced by soil (the optimized soil-adjusted vegetation index) were stronger predictors.

Unlike previous studies based on vegetation indices, the aim of this study is to characterize the baseline phenology of leaf development from remotely sensed estimations of LAI at the global scale. LAI is more sensitive than vegetation indices such as NDVI to larger amounts of vegetation (Baret & Guyot, 1991; Myneni & Williams, 1994). This is particularly important to characterize the later stages of canopy development and leaf maturity (Huete et al., 2002; White et al., 2014). LAI estimation is also expected to be more robust across sensors than are vegetation indices, which are dependent on the band characteristics of each sensor (Steven, Malthus, & Baret, 2015). This is a major issue for phenological studies because the asymmetric changes in leaf pigmentation (e.g. leaf senescence in autumn) during the year may accentuate the differences in the band settings between different sensors (Atzberger et al., 2013). This may be better handled by estimates of biophysical products such as LAI using radiative transfer model inversion techniques. Finally, the phenology derived from LAI is expected to be more closely related to actual ground observations because it is based on leaf development rather than on proxies provided by vegetation indices which are not driven solely by the amount of leaves but also by the canopy structure and the biochemical composition of the existing foliage (Richardson, Braswell, Hollinger, Jenkins, & Ollinger, 2009).

We used mean LAI seasonal values derived from the time series rather than focusing on a particular year of observation to mitigate the noise in satellite data and to avoid possible artefacts introduced by the use of curve-fitting or filtering methods. The climatology of the data defined as the mean annual seasonal cycle can better cope with high occurrence of missing data in the satellite time series, leading to improved estimation of phenological metrics (Guyon et al., 2011; Kandasamy et al., 2013; Verger et al., 2013). The climatology derived from time series of moderate spatial resolution sensors preserves the high temporal frequency mandatory for phenological studies (Guyon et al., 2011). We used the mean seasonal LAI values derived from 12 years of SPOT-VEGETATION observations at a spatial resolution of 1 km (actually 0.009° but termed 1 km resolution for the sake of simplicity) to characterize the baseline phenological patterns at a global scale. The main assumptions were that (i) the period of interest had no land-cover change or abrupt disturbance at the 1 km spatial resolution leading to a change in the phenological annual cycle and (ii) the time series were sufficiently long to encompass anomalies.

We will first describe the methodology for retrieving a global climatology of land surface phenology from SPOT-VEGETATION LAI. We will then assess the accuracy of the derived LAI-based phenological phases by comparison with available ground observations and the MODIS phenological products derived from the EVI and the NDVI, with due attention to the differences in the definitions of the phenological metrics. Finally, we will analyse the climatic drivers of the spatiotemporal patterns of the satellite and observed phenology.

2. Materials and methods

We used the GEOCLIM climatology of LAI (hereafter GEOCLIM-LAI) derived as the inter-annual means of 12-year of SPOT-VEGETATION observations (Verger, Baret, Weiss, Filella, & Peñuelas, 2015). We then computed specific phenological metrics based on the seasonal LAI development. The input data and the steps required to predict the climatology of land surface phenology are first described. The ground-based observations used for the validation of the GEOCLIM-LAI phenology, the MODIS phenological products, and the climatic data, are then
described. Finally, the approach for evaluating the methods and the associated metrics used is described.

2.1. GEOCLIM-LAI climatology: mean annual seasonal cycle

GEOCLIM (Verger et al., 2015), a global climatology of LAI, FAPAR, and fraction of vegetation cover (FCOVER), was derived as the interannual mean of the GEOV1 Copernicus Global Land time series of SPOT-VEGETATION biophysical products (Baret et al., 2013). GEOCLIM and the derived phenology take advantage of the improvements in accuracy and temporal consistency (smoothness) provided by GEOV1 over existing products (Camacho, Cernicharo, Lacaze, Baret, & Weiss, 2013). GEOV1 products are very little affected by the recently detected bug in Sun.-Earth distance calculation for SPOT-VEGETATION (Baret et al., 2013). This is clearly demonstrated for the bare soil situation where, as expected, no seasonality is observed (Verger et al., 2015). This is also supported by the fact that the biophysical products are actually more sensitive to the relative reflectance values (as are most vegetation indices that are ratios of reflectances) than to the absolute value as demonstrated by Verger et al. (2014).

The GEOCLIM-LAI product was here considered to describe the baseline characteristics of the seasonal cycle of the annual vegetation phenology for each pixel on the globe. GEOCLIM-LAI was computed every 10 days at a spatial resolution of 0.009° with a plate-carrée projection as the average for a given date across all years of the GEOV1 time series for 1999–2010 (Baret et al., 2013). A temporal smoothing and gap-filling (TSGF) technique (Verger, Baret, & Weiss, 2011) was applied in GEOCLIM-LAI to correct artefacts, especially when the LAI products were systematically unavailable across the years due to cloud coverage, which has a large impact on the accuracy of the derived phenological metrics (Kandasamy et al., 2013). Specific corrections based on the expected seasonality were applied to cloudy tropical evergreen broadleaf forests and high northern latitudes with poor levels of illumination where the low number of available observations compromised the reliability of the estimates (Verger et al., 2015).

GEOCLIM-LAI was demonstrated to be consistent, both spatially and temporally, with the climatologies of LAI derived from MODIS (Samanta et al., 2011), GIMMS3g (Zhu et al., 2013) and ECOCLIMAP (Champeaux, Masson, & Chauvin, 2005; Faroux et al., 2013). GEOCLIM-LAI showed absolute differences lower than 0.5 compared with MODIS (GIMMS3g) LAI for more than 80% (90%) of land pixels. Further details of the implementation and quality assessment of GEOCLIM-LAI are provided in Verger et al. (2015). We focus here on the climatology of land surface phenology as derived from GEOCLIM-LAI.

2.2. Computation of phenological metrics

The smoothed GEOCLIM-LAI annual time series were linearly interpolated at the daily time step for the computation of phenology in day units. The annual LAI time series were repeated three-times and we focused our analysis in the central period to prevent border effects in the beginning and the end of the year. A number of phenological metrics were computed from GEOCLIM-LAI (Fig. 1):

- The amplitude of GEOCLIM-LAI defined as the difference between the maximum and minimum LAI values over the growth cycle.
- The number of growing seasons per year was retrieved as the number of peaks identified in GEOCLIM-LAI. A point was considered as a maximum peak if it had the maximum value and was preceded by a value lower than $\delta$, where $\delta = \max(0.1, 0.3 \times \text{annual\_median\_GEOCLIM-LAI})$. For pixels with multiple growing seasons, we computed the phenological metrics for the growing season having the highest LAI amplitude. Phenological metrics were not computed for pixels with any growing season.
- The peak of the growing season corresponding to the timing of maximum foliar development (Brown et al., 2012; Jönsson & Eklundh, 2002) when GEOCLIM-LAI reached its maximum value over the annual cycle.
- The start of season (SoS) was defined as the date for which GEOCLIM-LAI rise to a given percentile of its amplitude (Jönsson & Eklundh, 2002; White et al., 1997), or the date of the maximum of the first derivative (White et al., 2009). The performances of these different definitions of the SoS will be compared with ground observations to select the most pertinent one. Results will be presented in Section 3.2.
- The end of season (EoS) was computed as the date for which GEOCLIM-LAI descent to a given percentile of its amplitude, or the date of the minimum of the first derivative.
- The length of season (LoS) was defined as the length of the period between the EoS and the SoS.

2.3. Ground data

The validation of GEOCLIM-LAI baseline phenology is particularly difficult since multi-annual ground-truth measurements of the same site and phenophase for the period 1999–2010 are rarely available. After an extensive review of the literature and exploration of the available phenology datasets, we used ground-based phenological observations for lilac (Syringa vulgaris) from USA National Phenology Network (open access data set at www1) and birch (Betula pendula) from the PEP725 Pan European Phenology data (www2). These data sets are unique in both its geographic and temporal coverages. They consist of data collected by volunteers on a weekly basis up to every day depending on the season (Koch et al., 2007; Olsson & Jönsson, 2014; Rosemartin et al., 2015). We only included sites with at least three years of measurements for 1999–2010. These ground measurements represent phenological phases for a limited number of individual plants that are not

![Fig. 1. Illustration of phenological metrics (amplitude, start (SoS), end (EoS), and length (LoS) of the growing season) computed from GEOCLIM-LAI over a cropland site at 45°N and 19°E (a) and a grassland site at 27°S and 27°E (b); DOY, day of year.](A. Verger et al. / Remote Sensing of Environment 178 (2016) 1–14)
necessarily representative of the areal coverage of the 1-km SPOT-VEGETATION satellite pixel (Liang, Schwartz, & Fei, 2011). The spatiotemporal-scale mismatch with field data is a major source of uncertainty in satellite phenological assessments (White et al., 2009). The phenology of each species influences the satellite signal depending on its abundance within the pixel sampling area but also on the timing of their phenophases (Delbart, Beaubien, Kergoat, & Le Toan, 2015). SoS based on remote sensing may mainly reflect the spring phenology of some early spring species in the study regions (Fu et al., 2014), so B. pendula was chosen because it is an early spring species with higher representation in the areas examined. Since vegetation phenology occurs in response to seasonal variations of climatic variables, land surface phenology can highly correlate with non-abundant species (Delbart et al., 2015). S. vulgaris was used because its phenology is strongly controlled by temperature (Schwartz & Reiter, 2000) although it is not a dominant species over large areas (Maignan et al., 2008). Similarly to Delbart et al. (2015), we excluded sites classified as pure agriculture or water, based on GLOBCOVER (Defourny et al., 2009) land-cover map.

The S. vulgaris dataset consists in leafing data collected across the continental United States from 1956 to 2014 (Rosemartin et al., 2015). We used data from 1999 for the full leaf phenophase, defined as the timing when nearly all (at least 95%) of the actively growing leaf buds have already leafed, and representing the SoS. The selected ground measurements of S. vulgaris in USA are distributed from the west coast to the east coast covering a south–north latitudinal gradient from 35.1° to 48.1° (Fig. 2a).

The ground measurements of B. pendula in Europe represented a south–north latitudinal gradient from 45.9° to 68.4° (Fig. 2b). We used observations from Finland, Lithuania, Germany, Slovenia, and Croatia (Fig. 2b). The German data set was extensive, so we selected randomly only 30 sites. The observations were (i) the day of budburst, defined as leaf unfolding on the first visible leaf stalk and representing the SoS (for Lithuania the observed phenophase representing SoS was the mouse-ear stage, i.e. the timing of the first leaves separating), and (ii) 50% autumnal colouring of leaves and representing the EoS. The LoS was computed as the length of the period between the EoS and the SoS.

2.4. MODIS phenology products

The MODIS-EVI phenology product (MCD12Q2 Collection 5) (Ganguly et al., 2010; Zhang et al., 2003) was used for comparison. MODIS-EVI provided yearly global vegetation phenologies at 500 m spatial resolution for the 2001–2010 period. The method used a series of piecewise logistic functions that were fitted once a year to the 16-day EVI data. More formally, the temporal variation of the EVI was modelled using a sigmoidal function:

\[ y(t) = \frac{c}{1 + e^{(a+bt)}} + d \]  

(1)

where \( t \) is time in days, \( y(t) \) is the EVI value at time \( t \), \( a \) and \( b \) are fitting parameters associated with the timing and rate of change in the EVI, respectively, \( c + d \) is the maximum modelled EVI value, and \( d \) is the initial background EVI value. The inflection points in the rate of change in the curvature of the fitted logistic model identified the phenological transition dates (Zhang et al., 2003). The MODIS-EVI phenology product provided the transition dates for vegetation activity and information about the EVI values on these dates for two growth cycles per year for each pixel. For each seasonal cycle, the onset of the increase in greenness (greenup), greenness maximum (maturity), greenness decrease (senescence), and greenness minimum (dormancy) were provided.

Note that the MODIS-EVI definition differs from the phenological metrics proposed here for GEOCLIM-LAI. The GEOCLIM-LAI SoS would correspond to the MODIS-EVI greenup, the EoS to the dormancy, and the peak would be within the maturity and the senescence but with no exact correspondence with the MODIS-EVI metrics. (Verger et al., 2015) showed that the peak of maximum leaf development from GEOCLIM-LAI occurred 14 days later than the MODIS-EVI maturity date due to the differences in the definitions and the use of LAI instead of EVI. We assessed the influence of the differences in the definitions of the phenological metrics in Section 3.3.

In addition to the MODIS-EVI phenology products, we used the MODIS-NDVI phenological parameters derived by Butt et al. (2011) using a double-logistic function fitted to seasonal NDVI trajectories for MODIS data. The MODIS-NDVI SoS is defined as the maximum of the second derivative, the EoS as the first date after maximum NDVI when the NDVI falls to 80% of its maximum value, and the LoS as the difference (in days) between the EoS and the SoS (Butt et al., 2011). We used the means of the SoS, EoS, and LoS for MODIS-NDVI phenological variables across the 2000–2010 period for 0.25° latitude bands in Sudano-Saharan West Africa as reported by (Butt et al., 2011). Results of the comparison between MODIS-NDVI and GEOCLIM-LAI latitudinal gradients of Sahelian phenology are presented in Section 3.4.

2.5. Temperature, short-wave radiation and rainfall data

To interpret phenological patterns observed with the possible climatic drivers, we used the WFDEI (WATCH Forcing Data methodology applied to ERA-Interim data) meteorological data, which is based on WATCH forcing data methodology applied to the ERA-Interim
reanalysis data (Weedon et al., 2014). We used the daily average air temperature at 2 m, the short-wave downwards surface radiation (W/m²) and the rainfall rate (cumulative mm) generated by using the Global Precipitation Climatology Centre (GPCC) precipitation totals (Schneider et al., 2014). WFDEI data were available for the global land surface at a spatial resolution of 0.5° from January 1979 to December 2012.

2.6. Evaluation approach

Because of the importance of the number of growing seasons and LAI amplitude for the understanding of LAI phenology, these two sub-products of the GEOCLIM-LAI will first be described (Section 3.1). The approach proposed for the evaluation of GEOCLIM-LAI phenology is based on three steps as sketched in Fig. 3. The several definitions of the SoS, EoS and LoS phenology metrics will be evaluated by comparison with the available ground measurements (Section 3.2). This will also provide some element of the validation of the phenology products proposed. Then these phenology products will be compared to those derived from MODIS (Section 3.3). Finally, the spatial patterns of phenological leaf development from satellite and ground data will be assessed with due attention to the latitudinal gradients in Europe and African Sahel and the possible climatic drivers (Section 3.4).

The climatology of land surface phenology derived from GEOCLIM-LAI was compared with the climatologies derived from ground and MODIS phenologies as the interannual means (Fig. 3). The assessment was performed from 1 km to 0.5° spatial resolutions. The comparison of GEOCLIM-LAI phenological metrics with ground observations (Section 3.2) was achieved at the original 1-km spatial resolution of VEGETATION-SPOT data. The latitudinal gradients of GEOCLIM-LAI phenological climatologies (Section 3.4) in the Sahel region were compared to the MODIS-NDVI transects available at 0.25° spatial resolution. Finally, the comparison with MODIS-EVI derived phenology (Section 3.3) and the analysis of climatic drivers (Section 3.4) were performed at a spatial sampling of 0.5° that corresponds to the typical resolution of global models.

For comparison purposes, we first computed a climatology of ground phenology based on the interannual average of ground-based values for SoS, EoS, and LoS (Fig. 3). Similarly, the yearly MODIS-EVI derived phenology data were averaged over the 2001–2010 period to provide a climatology of phenological stages. The MODIS-EVI 500-m original products were then projected on 1-km and 0.5° plate carrée system using the cubic convolution technique as implemented in the MODIS reprojection tool. We used the MODIS-NDVI climatology of Sahelian land surface phenology from 2000 to 2010 at 0.25° spatial resolution as proposed by Butt et al. (2011). We aggregated the 0.009° (about 1-km at the equator) GEOCLIM-LAI phenological products at 0.25° and 0.5° spatial resolutions for comparison with MODIS-NDVI and -EVI phenologies, respectively. Finally, we computed a climatology for air temperature, short-wave radiation and cumulative rainfall by averaging WFDEI daily data at 0.5° spatial resolution for the interpretation of the climatic drivers of the GEOCLIM-LAI phenological patterns.

3. Results and discussion

3.1. Number of growing seasons and LAI amplitude

The amplitude of GEOCLIM-LAI (Fig. 4a) reflected the expected regimes of vegetation at the global scale in agreement with the global distribution of biomes with maximum values around the mid-northern latitudes as well as around 10° latitude in Africa. Most of the other places showed LAI amplitude values lower than 2. The number of growing seasons (Fig. 4b) was set to zero in areas that exhibited null seasonality (Fig. 4a): deserts with LAI ~ 0 and evergreen broadleaf forests in the tropical belt with LAI ~ 5 throughout the year (Verger et al., 2015). Two growing seasons were identified in agricultural areas with two crop cycles per year (e.g. rice plantations in India, China, and the Nile delta) and in the Horn of Africa, which had a bimodal precipitation regime with two wet seasons per year (Vrieling et al., 2013). Bimodal LAIs also corresponded to areas where leaf development is constrained by both temperature in winter and water availability in summer (Julien & Sobrino, 2008). Other isolated areas with multiple growing seasons may indicate artefacts in the data set.

3.2. Comparison with ground data

The dates of SoS, EoS and LoS for GEOCLIM-LAI derived phenology products computed with several possible definitions were compared with the ground-based observations for birch (B. pendula) forests and lilac (S. vulgaris) shrubs. Note that the places where ground based measurements were taken (Fig. 2) correspond to single growth cycle areas (Fig. 4b). Results show that the best performances for SoS were obtained for the 30% threshold value that provided the smallest bias and root mean square error (RMSE) values (Table 1). However, this optimal definition of the SoS provided poorer performances in terms of RMSE for the EoS for which a threshold value of 40% better matched ground observations (Table 1) (Nagai et al., 2014). As a matter of facts, the ground data corresponded to 50% autumnal colouring of leaves.

![Fig. 3. Flow chart describing the approach for evaluating the climatologies (grey boxes) of phenological metrics derived from ground data, GEOCLIM-LAI, MODIS-EVI, MODIS-NDVI, and climatic variables (air temperature, rainfall and short-wave radiation). The original products are indicated in rectangular white boxes, the methods in ellipses. The horizontal and vertical arrows indicate the spatial and temporal scales, respectively.](Image)
Nevertheless, a higher variability across the canopy of the timing and rate of leaf development is expected in autumn than in spring (Richardson et al., 2009). This translates by a higher RMSE and lower correlation $R$ values for EoS as compared to the SoS (Table 1). The LoS computed as the distance between the EoS and SoS using, respectively, the 40% and 30% threshold values provided the best performances (Table 1) and it was retained as the proposed definition for GEOCLIM-LAI phenological metrics.

The agreement between GEOCLIM-LAI SoS date using the 30% threshold value (Fig. 5) with leafing ground observations of $B.\, pendula$ (respectively $S.\, vulgaris$) produced an overall RMSE of 7 (resp. 19) days, a bias of only 1 (resp. $-3$) day and correlated significantly (correlation coefficient $\sim 0.9$ (resp $-0.5$)) (Table 1). The performances decreased for the date of the EoS using the 40% threshold value, with an RMSE of 15 days and a positive bias (delay) of about 7 days. The performances for LoS (RMSE of 16 days) were mainly limited by those for EoS, with 6 days longer LoS for GEOCLIM-LAI as compared to the ground observations.

The higher uncertainty in the estimation of the date for EoS as compared to the SoS can be explained by multiple factors. The environmental (day length, temperature, rainfall) and internal (plant age, photosynthetic rate and other leaf traits) causes of the timing of leaf coloration in autumn are less understood and have a higher interspecific (and among individual plants) and interannual variability than leaf-out phenological phases (Archetti, Richardson, O’Keefe, & Delpierre, 2013; Estrella & Menzel, 2006; Richardson et al., 2009). Leaf colouring corresponds to various changes in chemical and structural properties, resulting in changes in spectral responses, which may start long before leaf abscission while leaf appearance is much more well defined in time (Delbart, Kergoat, Le Toan, Lhermitte, & Picard, 2005). In addition there is higher uncertainty associated both to ground measurements and satellite products for autumn phenology (Nagai et al., 2014). The timing of 50% of all leaves colouring is obviously more difficult to identify by ground observers than the timing of leaf unfolding or other spring phenophases (Estrella & Menzel, 2006). Finally, the satellite products and the derived phenology at high latitudes in autumn are affected for atmospheric effects, snow and poor illumination conditions (Delbart et al., 2005; Verger et al., 2015).

The phenological metrics derived from MODIS-EVI showed poorer agreement with ground observations, with higher RMSE and lower $R$ values (Table 1, Fig. 5). The MODIS derived phenology presented a negative bias (advance) of 12 (21) days for the timing of the SoS as compared to $B.\, pendula$ ($S.\, vulgaris$) ground measurements and a positive bias (delay) of about 25 days for the timing of the EoS which resulted in 38-day longer LoS.

### 3.3 Comparison with MODIS-EVI phenology

The SoS and EoS derived from GEOCLIM-LAI were globally consistent with those derived from MODIS-EVI with a correlation coefficient larger than 0.84 (Table 2) with however a RMSE of 30 days and a bias around 9 days later for GEOCLIM-LAI SoS and 12 days earlier for GEOCLIM-LAI EoS (Table 2). They vary widely as a function of space (Fig. 6) and biome type (Table 2). The analysis per class (Table 2) showed higher differences for shrubs-savannah and crops-grassland compared to forest classes. Crop and grassland biome types showed the largest RMSE.

Fig. 4. Maps of (a) the amplitude of GEOCLIM-LAI, and (b) the number of growing seasons derived from GEOCLIM-LAI. The dark grey areas correspond to pixels with missing data.
Table 1
Statistics of the comparisons between GEOCLIM-LAI derived phenologies for the start of season (SoS), end of season (EoS), and length of season (LoS) and the ground observations for different phenological metric definitions based on specific thresholds (10, 20, 30, 40, and 50%) of the LAI amplitude and the first derivative criteria (1st Der.). The statistics of the validation of the climatology of MODIS-EVI phenology are also indicated: \( n \): number of available ground observations. RMSE: root mean square error. Bias: average difference between GEOCLIM-LAI minus MODIS-EVI phenologies (negative (positive) bias indicates earlier (later) EoS (SoS) respectively, and the LoS is longer than the actual duration of the growing season). \( R \): correlation coefficient. * mark indicates significant correlations with \( p < 0.05 \) (** indicates \( p < 0.001 \)). Slope and offset of the regression line computed at \( p = 0.05 \). Numbers in bold refer to the selected method.

<table>
<thead>
<tr>
<th>Species</th>
<th>Metric</th>
<th>Definition</th>
<th>RMSE</th>
<th>Bias</th>
<th>( R )</th>
<th>Slope</th>
<th>Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>S. vulgaris</td>
<td>SoS</td>
<td>(n = 52)</td>
<td>10%</td>
<td>47.34</td>
<td>−16.38</td>
<td>0.26</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20%</td>
<td>27.56</td>
<td>−14.26</td>
<td>0.35</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30%</td>
<td>18.92</td>
<td>−2.69</td>
<td>0.5**</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40%</td>
<td>19.11</td>
<td>3.68</td>
<td>0.51**</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50%</td>
<td>21.01</td>
<td>10.32</td>
<td>0.52**</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>1st Der.</td>
<td>(n = 52)</td>
<td></td>
<td>22.07</td>
<td>10.19</td>
<td>0.49**</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>MODIS</td>
<td></td>
<td>28.22</td>
<td>−21.24</td>
<td>0.46**</td>
<td>0.46</td>
<td>40.1</td>
</tr>
<tr>
<td>B. pendula</td>
<td>SoS</td>
<td>(n = 59)</td>
<td>10%</td>
<td>27.82</td>
<td>−22.15</td>
<td>0.76**</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20%</td>
<td>34.61</td>
<td>−8.54</td>
<td>0.86**</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30%</td>
<td>7.22</td>
<td>0.66</td>
<td>0.95**</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40%</td>
<td>27.27</td>
<td>10.44</td>
<td>0.58**</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50%</td>
<td>14.78</td>
<td>13.08</td>
<td>0.95**</td>
<td>1.11</td>
</tr>
<tr>
<td></td>
<td>1st Der.</td>
<td>(n = 59)</td>
<td></td>
<td>15.78</td>
<td>13.44</td>
<td>0.94**</td>
<td>1.14</td>
</tr>
<tr>
<td></td>
<td>MODIS</td>
<td></td>
<td>17.59</td>
<td>−12.42</td>
<td>0.84**</td>
<td>1.04</td>
<td>−16.97</td>
</tr>
<tr>
<td></td>
<td>EoS</td>
<td>(n = 35,627)</td>
<td></td>
<td>44.84</td>
<td>43.03</td>
<td>0.88</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20%</td>
<td>33.49</td>
<td>31.72</td>
<td>0.81**</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30%</td>
<td>23.89</td>
<td>19.76</td>
<td>0.79**</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40%</td>
<td>15.00</td>
<td>6.59</td>
<td>0.72**</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>1st Der.</td>
<td>(n = 35,627)</td>
<td></td>
<td>17.59</td>
<td>13.44</td>
<td>0.94**</td>
<td>1.14</td>
</tr>
<tr>
<td></td>
<td>MODIS</td>
<td></td>
<td>59.64</td>
<td>24.78</td>
<td>0.12</td>
<td>0.34</td>
<td>202.23</td>
</tr>
<tr>
<td>LoS</td>
<td>10%</td>
<td>(n = 69)</td>
<td></td>
<td>69.61</td>
<td>65.19</td>
<td>0.84**</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20%</td>
<td>44.13</td>
<td>39.61</td>
<td>0.89**</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30%</td>
<td>33.89</td>
<td>19.11</td>
<td>0.93**</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40%</td>
<td>27.12</td>
<td>−3.85</td>
<td>0.76**</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50%</td>
<td>31.48</td>
<td>−23.54</td>
<td>0.82**</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>30–40%</td>
<td>(n = 35,627)</td>
<td></td>
<td>15.71</td>
<td>5.93</td>
<td>0.92**</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>1st Der.</td>
<td>(n = 35,627)</td>
<td></td>
<td>50.22</td>
<td>−25.49</td>
<td>0.61**</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>MODIS</td>
<td></td>
<td>68.05</td>
<td>37.6</td>
<td>0.42</td>
<td>0.73</td>
<td>78.95</td>
</tr>
</tbody>
</table>

Fig. 5. Direct validation of phenologies derived from GEOCLIM-LAI (top) and MODIS-EVI (bottom) for the start of season (SoS) (plots a, b, and f), end of season (EoS) (plots c and g), and length of season (LoS) (plots d and h) compared to available ground-based observations on the day of full leaf of lilac (S. vulgaris) in USA, and day of budburst and 50% autumnal colouring of leaves of birch (B. pendula) in Europe. See Fig. 2 for the location of the data and the legend. The statistics of the comparison are provided in Table 1.
exponential relationship proposed by Huete et al. (2002). Finally, the MODIS-EVI phenological metrics corresponding to the inflection points in the EVI time series, was compared to that of GEOCLIM-LAI corresponding to the 30%-percentile of LAI amplitude. Results (Fig. 7b) confirmed that the SoS phenological phase retrieved from the GEOCLIM-LAI was expected to occur later than the MODIS-EVI one and

Fig. 6. Global maps of the differences (in days) between the average phenologies derived from GEOCLIM-LAI and MODIS-EVI for the (a) start of season, (b) end of season, and (c) length of season. Red (blue) indicates a delay (advance) in phenological events or longer (shorter) seasons for GEOCLIM-LAI compared to MODIS-EVI. The light-grey areas correspond to pixels with any growing season (Fig. 4b). The dark-grey areas correspond to pixels with missing data.
that these positive differences increased for the pixels having low seasonality (rate of change near zero). Similar reasoning could be applied to the EoS stage.

The agreement between the phenology derived from GEOCLIM-LAI and MODIS-NDVI degraded for the LoS because of the combination of the uncertainties associated both with the SoS and the EoS. The LoS retrieved from GEOCLIM-LAI was thus shorter than the LoS retrieved from MODIS-NDVI (bias of −22 days, Table 2; the dominant blue tones in Fig. 6c indicate a negative bias).

### 3.4. Spatial patterns of satellite and ground-based phenology

The spatial pattern of the derived global phenology (Fig. 8) reflected the distributions of climatic drivers and biomes. The observed relationship between phenological patterns and latitudinal climatic drivers was not uniform but spatially dependent because of the interactions between climate, vegetation functioning, and the distribution of species (Forkel et al., 2014; Ito, Hikosaka, Anten, Nakagawa, & Ito, 2014; Verger et al., 2015; Zhang et al., 2004). In addition, latitudinal variation in the phenology of leaf development has a strong genetic component influencing the photosynthesis and carbon sequestration (Peñuelas et al., 2009; Richardson et al., 2013).

The cumulative annual rainfall was highly correlated with the LoS across latitudes of −40° (Fig. 9). The LoS in the Southern Hemisphere from 35°S to 0° increased from 150 to 230 days as the cumulative annual rainfall increased from 500 to 1500 mm. LoS decreased steeply from 0° to 15°N, corresponding to the negative south-to-north gradient in rainfall in the Sahel region where water availability is the main limiting factor of leaf development. The latitudinal pattern was more complex from 15°N to 40°N due to averaging the LoS of different phenological regimes driven by the conditions of climatic regions ranging from tropical to Mediterranean. LAI phenology for northern latitudes >40° was strongly dependent on the mean annual temperature, the short-wave radiation and the cumulative rainfall which are intrinsically correlated and decrease linearly with latitude. SoS (respectively EoS) had a clear and smooth negative (resp. positive) latitudinal gradient corresponding to a delay (resp. advance) in the timing of SoS (resp. EoS) (Fig. 8), which led to a decrease of LoS with latitude (Fig. 9).

The climatology of land surface phenology derived from GEOCLIM-LAI over the European continent (Fig. 10a) showed a good agreement with existing average phenologies derived from MODIS or AVHRR NDVI data (Atzberger et al., 2013). GEOCLIM-LAI phenology accurately reproduced latitudinal patterns provided by the ground observations, with a delay of 50 days in the SoS and a similar advance of 50 days in the EoS from 45° to 70° northern latitudes (Fig. 11a). This corresponds to a latitudinal gradient of LoS around 100 days (Fig. 11a) matching a temperature gradient of about 10 °C, i.e. a rate of change of 10 days/°C. The rate of change in the LoS in the European birch forests, estimated from both ground observations and satellite LAI, was about four days per latitude degree of latitude which resulted from symmetric variations of two days per latitude degree in the SoS and EoS.

LAI phenology in the African Sahel (Fig. 10b) reflected the negative south-to-north gradient in rainfall with later SoS and earlier EoS resulting in a steeply decrease of LoS with latitude (Fig. 11b). Good agreement was achieved between GEOCLIM-LAI and MODIS-NDVI latitudinal gradients of phenology in Sudano–Sahelian region from 12° to 17°N (Fig. 11b) with non-linear latitudinal pattern characterized by sharpest variations of SoS for the lower latitudes and a more limited variation of EoS with latitude. This results in a rate of change in the LoS of about 15 days per latitudinal degree. The systematic biases observed between GEOCLIM-LAI compared to MODIS-NDVI (Fig. 11b) are mainly due to the differences in the definition of phenological metrics as demonstrated previously (Section 3.2) and in agreement with Butt et al. (2011).

### 4. Conclusions

The baseline phenology of vegetation was described at the global scale from the mean annual seasonal cycle depicted by GEOCLIM-LAI — a global climatology of leaf area index (LAI) derived from the average values over twelve years of SPOT-VEGETATION observations at a spatial resolution of 1-km for 1999–2010.

The calibration of the phenological metrics over actual ground observations indicated that the 30% threshold on the LAI amplitude is optimal for the detection of the start of season while a 40% threshold is more appropriate for the end of season. The accuracy for the start of season evaluated using ground observations, produced an overall RMSE of 7 days for the date of leaf unfolding for European birch forests and 19 days for North American lilac shrubs. A higher uncertainty of
15 days was found for the end of season which resulted in deviations of 16 days for the length of season of birch forests. Further investigations should be pursued to better define the threshold values by including more ground observations with a wider range of species and a broader spatial extent in latitude and longitude. This should ultimately lead to propose a standardization of the phenological metrics.

The GEOCLIM-LAI phenology was highly spatially consistent and significantly correlated ($R > 0.8$) with the phenology derived from MODIS-EVI time series, but with differences of about one month in terms of RMSE for the start and end of season, and 40 days for the length of season. These differences were mostly driven by random errors in regions with limited seasonality (LAI amplitude ~ 0) but also by

---

Fig. 8. Maps of phenological metrics for the (a) start, (b) end and (c) length of season derived from GEOCLIM-LAI. Areas with any growing season are shaded in light grey. The dark-grey areas correspond to pixels with missing data. DOY, day of year.
systematic biases due to the differences in the methodologies and datasets. The phenology derived from GEOCLIM-LAI constituted an intermediate solution between those from MODIS-EVI and ground observations.

The GEOCLIM-LAI phenology reflected the expected regimes of the baseline annual cycle of the vegetation seasonality at the global scale, in agreement with the global distribution of biome land cover and climatic drivers. Phenological spatial patterns were complex at latitudes of $\pm 40^\circ$ due to the heterogeneity in the species composition and climate drivers, but the length of season was clearly correlated with the annual cumulative rainfall. Soil moisture is the main driver of phenology in water-limited vegetation, but evapotranspiration and soil characteristics that control water retention should be included for a better understanding of the vegetation dynamics in these regions. The timing of phenological leaf development at northern latitudes $N 40^\circ$ were highly correlated with the latitudinal decay in mean annual temperature, solar short-wave radiation and cumulative rainfall. Disentangling the contribution of climatic drivers and establishing the mechanisms that govern the latitudinal patterns of vegetation phenology at the global scale would require further analysis taking the interannual variations into account.

The latitudinal gradients of phenological leaf development from GEOCLIM-LAI and ground data in Europe agreed very well with a gradual decrease in the length of growing season of approximately four days per degree of latitude which resulted from symmetric variations of 2 days per degree in the start and end of season. The latitudinal pattern

![Fig. 9. Latitudinal transects at resolution of 0.5° of the average length of season (LoS) derived from GEOCLIM-LAI, mean annual air temperature (Tair), cumulative annual rainfall (Rainfall), and mean annual short-wave downwards surface radiation (SW). The LoS was not plotted when the fraction of the land pixels used to compute the average phenological metric was lower than 0.1% of the total land pixels.](image)

![Fig. 10. Maps of the start of season (SoS) derived from GEOCLIM-LAI in (a) Europe and (b) African Sahel. The dashed back box in Sudano-Sahelian West Africa covering much of the southern half of Mali corresponds to the study area for the evaluation of the latitudinal gradients of phenology (Fig. 11b). Areas with any growing season are shaded in light grey. DOY, day of year.](image)
of the derived phenology metrics also agreed with those from MODIS-NDVI in African Sahel showing a much stronger rate of change of the length of season with latitude of about 15 days per degree of latitude.

Our baseline phenology derived from kilometic global LAI satellite products is expected to contribute to improve our macroecological knowledge and the representation of phenology in earth system models.

Acknowledgements

This research was partially supported by the European Earth observation programme Copernicus, le Pôle Thématique Surfaces Continentales THEIA, and the FP7 geoland2 (218795), GIOBIO (32-566), and LONGOVE (32-594) projects. This research was also supported by the Spanish Government grant CGL2013-48074-P, the Catalan Government grant SGR 2014-274, and the European Research Council Synergy grant ERC-2013-SyG-610028 IMBALANCE-P. Alexandre Verger was the recipient of a Juan de la Cierva postdoctoral fellowship from the Spanish Ministry of Science and Innovation. The authors are indebted to Marie Weiss, the CNES, VITO and MODIS teams for providing access to the data. We also thank the volunteers that collected the phenology ground measurements and the teams who contributed to set up the PEP725 dataset.

References


Zhu, B., Li, J., Pan, Y., Ganguly, S., Anav, A., Xu, L., Myneni, R. (2013). Global data sets of vegetation leaf area index and fraction of photosynthetically active radiation (FPAR)3g derived from global inventory modeling and mapping studies (GIMMS)
normalized difference vegetation index (NDVI3g) for the period 1981 to 2011.

Further reading

www1: USA National Phenology Network

www2: Pan European Phenology Project PEP725

www3: PlantWatch project
https://www.naturewatch.ca/plantwatch (Accessed February 1st 2016)

www4: USA Phenocam Network
http://phenocam.sr.unh.edu/webcam (Accessed February 1st 2016)

www5: Phenological Eyes Network
http://pen.agbi.tsukuba.ac.jp/index_e.html (Accessed February 1st 2016)