Half-Year Report:
Seasonal Varying Phenology for COSMO-CLM

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October 30, 2019

1 Introduction

The phenology of plants plays an important role in the climate system. The vegetation interacts with the atmosphere through mainly 3 different methods [Bonan, 2015]. Those are surface energy fluxes, hydrology and the carbon cycle. How intensive this interaction is depends on the state of phenology, what means the seasonal cycle of the phenology throughout the year. This state is measured by the variable leaf area index (LAI). The LAI is defined as the leaf area per unit of land [Watson, 1947].
The annual cycle of LAI is represented in different climate models with huge differences. But the more precise the calculation of the phenology is the more uncertainties come up and the higher are the computational costs. In the COSMO-CLM model itself the LAI is not calculated explicitly but it is pre-calculated by the interpolation program INT2LM. Consequently the LAI does not depend on the actual state but only depends on the geographical location (latitude and altitude) and the day of the year. The cycle is annually recurring and does not change over time.
This can not represent the reality. In reality the LAI changes from year to year. This gets even more important taking into account the climate change. The shape of the annual LAI already changed in the last decades especially in Europe [Jeong et al., 2011].
Therefore, a new calculation of phenology in the COSMO-CLM model should be taken into consideration. Here, an existing approach by is adjusted to and implemented in the COSMO-CLM model [Knorr et al., 2010]. Former developments are used as basis for threshold values [Schulz et al., 2014].
With the new calculation of the phenology the LAI is expected to have a higher correlation to observations. This means that the highest values are expected to be in late spring or early summer (May-June) and decrease in summer because of less water availability in mid-latitudes. Compared to former simulations the LAI should therefore be lower during summer. This would cause a lower latent heat flux because of less transpiration. This again would lead to less humidity and higher temperatures in theory.

2 Methods

To improve the phenology in the COSMO-CLM model the following procedure is used. To evaluate some of the results the method of standardization is used. This is also explained in this section.

Table 1: Parameters of the Phenology Model

Symbol	Description	Units
Λ	leaf area index	-
r	growth rate	$days^{-1}$
T	phenology temperature	$^\circ C$
T_{on}	threshold temperature	$^\circ C$
t_d	day length	hours
t_{on}	threshold day length	hours
τ_m	averaging time for temperature	days
τ_s	averaging time for water availability	days
Λ_T	LAI depending on temperature and day length	-
Λ_W	LAI with water dependency	-
Λ_S	LAI with smoothed water availability	-

2.1 Implementation of the New Phenology

The new phenology depends on the temperature, the day length and the water availability [Knorr et al., 2010]. At first, there is an equation for the LAI that depends on the temperature

$$\Lambda_T(t+\Delta t) = \begin{cases} \Lambda_{max} - e^{-r\Delta t} \cdot (\Lambda_{max} - \Lambda_T(t)), & \text{if } T \geq T_{on} \\ \Lambda_{min} - e^{-r\Delta t} \cdot (\Lambda_{min} - \Lambda_T(t)), & \text{else} \end{cases} . \tag{1}$$

where the growth rate is chosen to be $r = 3.36\ days^{-1}$ and the threshold temperature is set to $T_{on} = 5^\circ C$ [Schulz et al., 2014]. All other variables are explained in table 1. Because the temperature changes very rapidly and can even reach very high values in winter, the realy measured temperature can not be used as indicator for the phenology. Therefore, an phenology temperature with a memory of a chosen time is introduced [Knorr et al., 2010].

$$T(t+\Delta t) = T(t) \cdot e^{-\Delta t/\tau_m} + T_{2m}(t) \cdot (1 - e^{-\Delta t/\tau_m}) . \tag{2}$$

Here the memory of the temperature is chosen to be $\tau_m = 15\ days$ and the phenology temperature is calculated from the 2m temperature T_{2m} [Schulz et al., 2014]. Simulations with with this calculation of LAI are denoted as $\_T$.

Now the day length is implemented in addition. Plants need a critical day length or photoperiod to grow [Vegis, 1964, NOODÉN and WEBER, 1978]. To have at least a day length that corresponds to the minimum day length in Central Europe from February to October it is set to $t_{on} = 10$h. Now the LAI calculates as follows

$$\Lambda_T(t+\Delta t) = \begin{cases} \Lambda_{max} - e^{-r\Delta t} \cdot (\Lambda_{max} - \Lambda_T(t)), & \text{if } T \geq T_{on} \text{ and } t_d \geq t_{on} \\ \Lambda_{min} - e^{-r\Delta t} \cdot (\Lambda_{min} - \Lambda_T(t)), & \text{else} \end{cases} . \tag{3}$$

The simulations where LAI depends on the temperature and the day length are denoted as $\_TD$.

As a last step, the water availability is implemented in the model as well. The water available in the soil is very important for the growth and for the transpiration of the plants [Gardner and Ehlig, 1963]. Required here is the water content W_c that can be reached by the plants and the maximum available water content W_{max} that can be calculated as the difference between the field capacity $FCAP$ and the permanent wilting point PWP. Now the water dependent leaf area index Λ_W can be calculated

$$\Lambda_W = \Lambda_T \cdot \frac{W_c}{W_{max}} . \tag{4}$$

This is implemented as a smoothed minimum function [Knorr et al., 2010]

$$\Lambda_S = \frac{\Lambda_T + \Lambda_W - \sqrt{(\Lambda_T + \Lambda_W)^2 - 4\eta\Lambda_T\Lambda_W}}{2\eta}\,, \tag{5}$$

where Λ_S is the smoothed water available leaf area index and $\eta = 0.99$. With the help of the smoothed water available LAI and the former calculated LAI_T one can calculate the whole LAI:

$$\Lambda(t + \Delta t) = \Lambda_T \cdot e^{-\Delta t/\tau_s} + \Lambda_S \cdot (1 - e^{-\Delta t/\tau_s})\,. \tag{6}$$

The simulations with the implementation of the water availability in addition to the temperature and day length dependency are denoted with $\_TDW$. The new modue for phenology is called by the model right before the call of the surface model TERRA in the code. So the new LAI is used to calculate for example the surface fluxes and therefore the turbulent fluxes. In this way the atmospheric parameters are influenced by the phenology as well.

2.2 Standardization

In order to find extreme years of phenology, the years are also expected to be extreme either in temperature or in precipitation [Shen et al., 2011]. When a year starts with an enormous warm spring, the vegetation should also start growing earlier than in average or cold years [Chmielewski and Rötzer, 2002]. On the other hand the growing season should start later when spring is very cold. And on the opposite hand the end of growing season should be earlier when the late summer or autumn is outstanding cold. And later when it is warm.
The precipitation influences the reduction of LAI especially in summer during the growing season [Currie and Peterson, 1966]. The more precipitation there is the more water is available for the plants and vice versa. This means in a year with less precipitation there is less water available what means more reduction.
Therefore, one needs to find the years that differ from the average most. This is here done with the help of the standardization of temperature and precipitation data. The standardized form z of a variable x is calculated as

$$z(x) = \frac{x - \mu}{\sigma}\,, \tag{7}$$

with the mean μ and the standard deviation σ. The higher the absolute value of z the more extreme is the variable x.

3 Material

The simulations are done with the COSMO-CLM version 5.0 with clm15. The forcing data is ERA-Interim and the external data is modified with values for only grass as plant functional type. Simulated is the period from 1999 to 2015. More details to the experimental setup are given in table 2.

The observations used for the evaluation of the simulations are obtained from different sources. For all domains the gridded SPOT/PROBA-V LAI data is used [Baret et al., 2013, Camacho et al., 2013]. For the meteorological data in Lindenberg the DWD (German Weather Service) information at the station 03015 (Lindneberg) is used. In Linden close to Gießen the measurements of the University of Gießen in the GiFACE project are used. And in Selhausen close to the Forschungszentrum Jülich the data of CRC/TR32 database

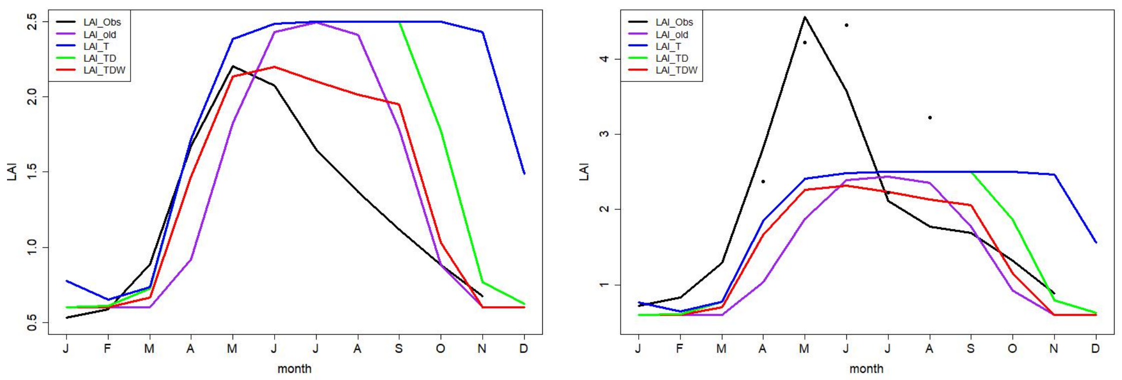
Table 2: Experimental Setup

Model	COSMO-CLM-v5.0 clm15
Interpolation	INT2LM-v2.05 clm1
Forcing	ERA-Interim
External data	ASTER, Orographic Filtering, no Subgrid-scale Slope, GLC2000, FAO DSMW, NASA GISS, MODIS12 vis, only grass as land cover type
Spatial resolution	3 km (0.0275 °) with 25 x 25 grid points
Domain	1 grid point at Lindenberg (Lat=52.220 °, Lon=14.135 °) 1 grid point at Linden (Lat=50.531 °, Lon=8.704 °) 1 grid point at Selhausen (Lat=50.855 °, Lon=6.439 °)
Time Series	1 January 1999 - 1 January 2016
Time Integration	2 time-level Runge-Kutta scheme
Model time step	25 seconds
Convection	Shallow convection based on Tiedtke scheme
Observations	SPOT/PROBA-V LAI data with 1 km horizontal and 10 days temporal resolution ([Baret et al., 2013], [Camacho et al., 2013]) DWD CDC hourly temperature and precipitation at station 03015 (Lindenberg, Brandenburg)

are used.
A special attention is paid to measurements of LAI because they are very sparse and there are different methods to measure. The direct method is to collect the leaves and have the real mass of the leaves. With this method you can directly derive the LAI and this is why this method is supposed to give the best results [Cutini et al., 1998]. The second method is the indirect. Indirect measurements are based on radiation measurements. They are not as precise as the direct measurements but can easily be automated and are less expensive and complex [Cutini et al., 1998]. One of the common methods here is the plant canopy analyzer LAI-2000 [Li-Cor, 1992]. Here the radiation is measured above and below the canopy to get the influence of the canopy and so the radiation.
In satellite data the LAI is calculated from the satellite product of SPOT and PROBA-V [Smets et al., 2019]. The LAI is derived from the normalized reflectance of red, near-infrared and shortwave-infrared radiation [Verger et al., 2014]. Because the vegetation is not distributed equally in reality and it comes to clumping, the product uses a method to distribute the vegetation equally in the resolved grid [Chen et al., 2005].
The other meteorological variables like temperature and precipitation are measured as usual and following the instructions of the World Meteorological Organization (WMO) with thermometers and rain collectors that provide automated data.

4 Results

The results in the following are for each location four or rather five different simulations. The first one is the reference simulation with the common phenology of the COSMO-CLM. It is called *_old*. The simulations with the new phenology are called as mentioned before *_T*, *_TD* or *_TDW* depending on the dependencies used. When there are available also the observations are shown and called *_Obs*. At the moment there are only results for the locations Lindenberg and Linden. The results at Selhausen follow as soon as possible.



(a) Lindenberg (b) Linden

Figure 1: Mean (1999-2015) annual cycle of LAI. In black are the observations (satellite-lines and in-situ-dots) and coloured the simulations.

4.1 Annual Cycle

The mean annual cycle of the phenology can be seen in the following. In figure 1 are shown the annual cycles of Lindenberg and Linden as a mean over the whole period from 1999 to 2015. It can be seen that the simulations with the new phenology at first got further away from the observations compared to the old version. This changed with implementing the water availability. The peak of LAI is with the new phenology very close to the peak in the satellite observations between May and June. The start of the growing season is also improved. With the old version the start was to late. One big difference between the simulations and the observations is the LAI in late summer. The simulations show much higher values than the observations. Another obvious difference is the maximum value of LAI in Linden. It is much higher in the observations.
The correlations between the simulations and the observation are the following. The Pearson correlation is used here where the correlation means the Pearson's correlation coefficient r [Pearson and Filon, 1898].

simulation	*LAI_old*	*LAI_T*	*LAI_TD*	*LAI_TDW*
correlation Lindenberg	0.69	0.52	0.74	0.80
correlation Linden	0.62	0.47	0.69	0.76

The correlations are significantly higher comparing the old to the new phenology. Fisher's z is in Lindenberg -2.4940 and in Linden -2.6985 [Fisher, 1925]. Now assuming the new phenology to be higher, the p-value in Lindenberg is 0.006 and in Linden 0.003. This means that the improvements at both locations are < 0.01 meaning highly significant.

4.1.1 LAI Measurements Linden

In Linden near Gießen are two different LAI values available. For the above comparison the satellite data is used because here the dataset is complete for the whole period. The in-situ measurements are done irregularly in only a few years. Anyhow the different LAIs can be compared between the satellite and the in-situ measurements. The in-situ measurements are done over grass in an experimental area of a size of about $100\,m$ x $200\,m$. The satellite

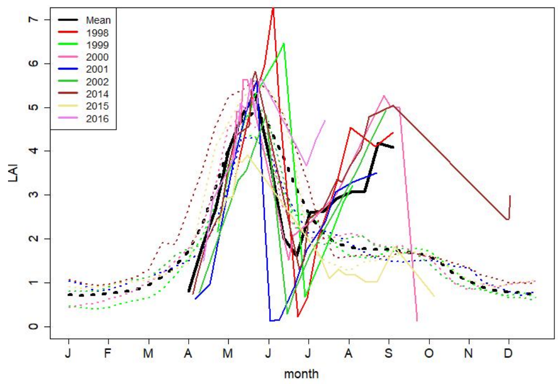


Figure 2: LAI observations: dotted-Satellite and lines-In-situ.

data in contrast is the data of a pixel with size $1000\,m$ x $1000\,m$. In this pixel is not only grass but also agricultural land as well as urban areas and forests.

The in-situ measurements show two peaks per year. One is in June and a second one is in September. This comes because at each peak the grass of the experimental area is cutted what causes the decrease of LAI. In some years the peak of the in-situ measurements is higher then the satellite data, but in general the first peak is more or less the same in both data. But the second peak only shows up in the in-situ measurements.

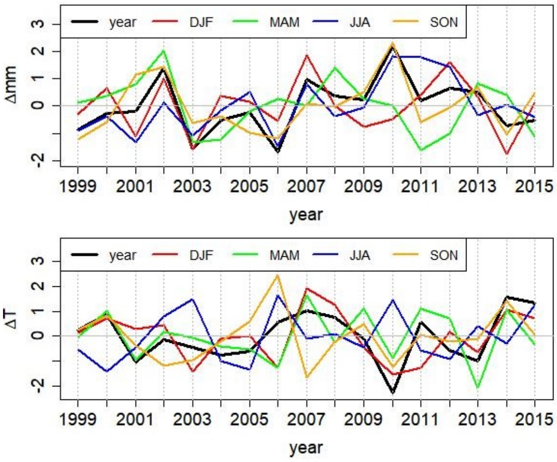
4.2 Extreme Events

The change of phenology is most obvious in extreme years. This means in years with very high temperatures in spring, that causes an early start of the vegetation period or with high temperatures in autumn causing a late end of the growing season and vice versa. Another important factor changing from year to year is the precipitation. Precipitation is used as source for soil water and therefore as water available for the plants. What means the higher the precipitation the less is the reduction of LAI due to water and vice versa.

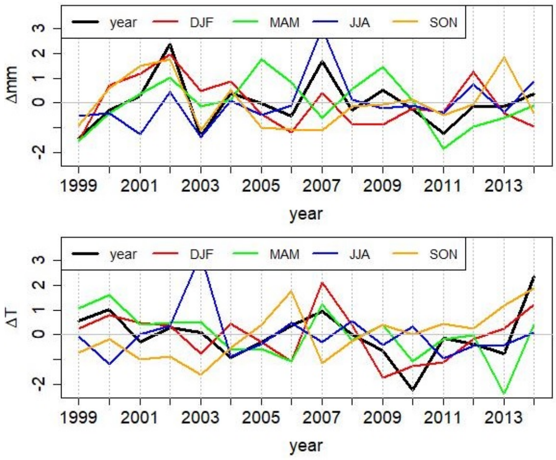
What should especially be seen with the new implemented phenology is the early start of the growing season in extraordinary warm springs and the lower amplitude of LAI in extraordinary dry summers. For this reason all simulated years and seasons are standardized in order to find the extreme events. This is done for Lindenberg and Linden and can be seen in figure 3.

In Lindenberg the driest summer and driest year in general is 2006. The warmest winter and spring is in 2007. Those are the years that are taken under further examination. In Linden the driest summer and again also year is 2003. The year with the warmest winter and spring is again 2007. The LAI of the specific years can be seen in figure 4.

As expected the LAI of the dry years is reduced in the observations and in the simulations with the new phenology compared to mean values. In Lindenberg this can be seen very clearly, whereby the reducing in the observation is even higher than in the simulation. In Linden the improvement can only hardly be seen because of the very high observed values. But compared to the mean values the observation and the simulation with new water-availability dependent phenology both show reduced values. The early onset of the growing season in extraordinary the warm beginning year 2007 can be seen very explicitly in the observations as well as in all simulations with newly implemented phenology for both tested locations.

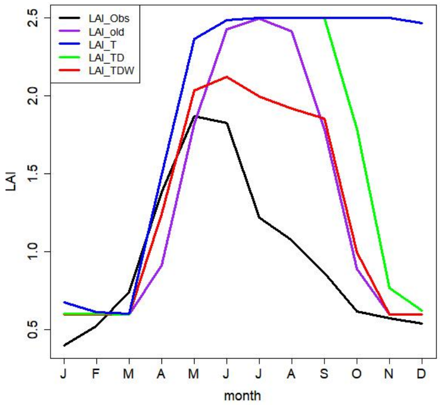


(a) Lindenberg

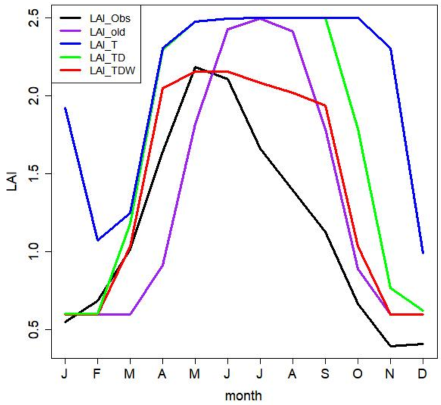


(b) Linden

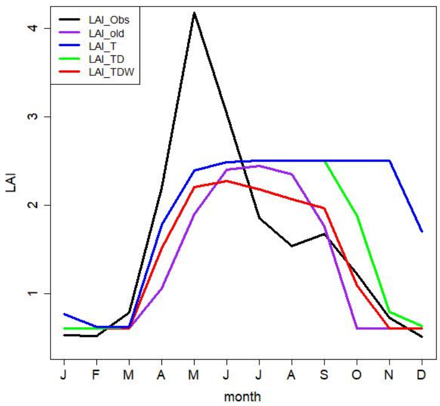
Figure 3: Standardized precipitation (top) and temperature (bottom) for each year with the mean value in black and the different seasons with colors.



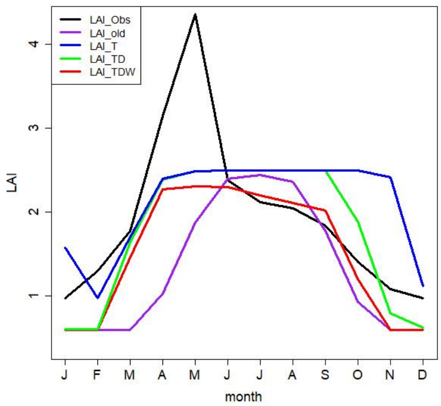
(a) Lindenberg 2006



(b) Lindenberg 2007

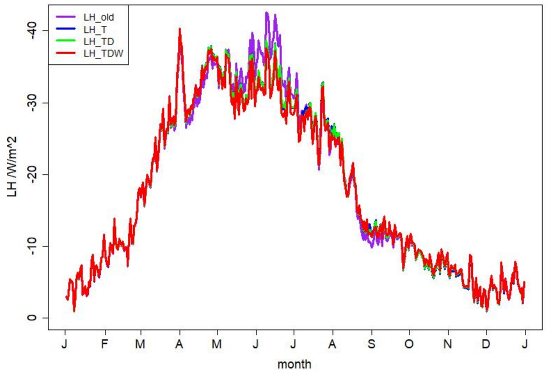


(c) Linden 2003

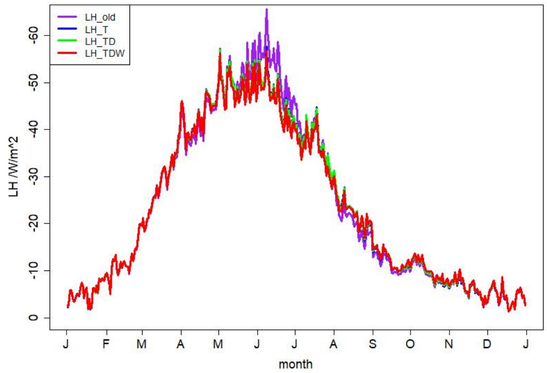


(d) Linden 2007

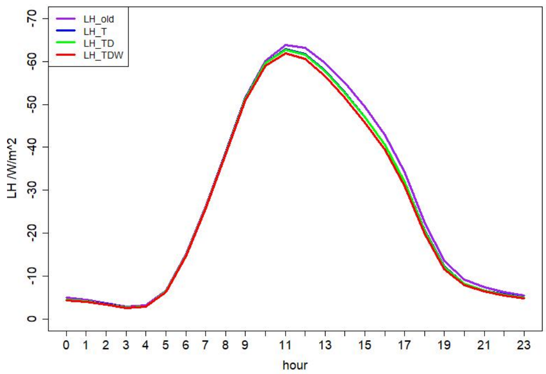
Figure 4: LAI of the extreme dry years (a+c) and the extreme warm springs (b+d).



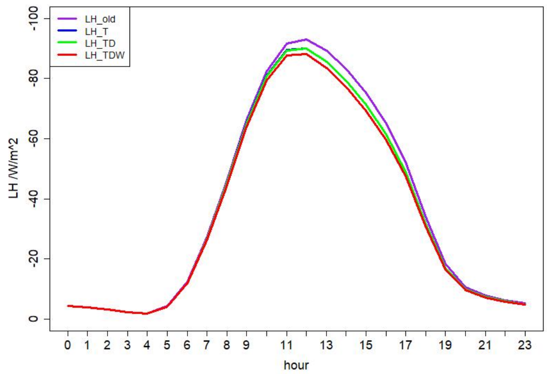
(a) Lindenberg



(b) Linden



(c) Lindenberg



(d) Linden

Figure 5: Mean (1999-2015) annual cycle of latent heat flux (a+b) and mean (1999-2015) daily cycle in the summer months (June-August) (c+d).

4.3 Latent Heat Flux

The vegetation is one important factor that influences latent heat flux because of transpiration. Therefore, it can be expected that the latent heat flux of the model should be reduced in summer because of less vegetation.
This can be seen in figure 5. As expected the latent heat flux reduces in summer. But in spring the latent heat flux in the simulations with the new phenology is higher because of the higher LAI. The same can be seen in autumn. Nevertheless, the greatest difference is in summer, where the simulation with the old phenology show higher values. Looking at the daily cycle of the latent heat flux it can be seen that this accounts especially during the daytime, what was also expected.

5 Discussion

The so far shown results are very close to what could have been expected. The annual cycle of LAI seems to be much closer at the observations. The greatest difference between the simulations with the new phenology and the observations in Lindenberg show up from July to September. Even though the LAI is much closer at the observations than the simulation with the old phenology, it is still too high compared with satellite observations.

There are two explanations for that. The first is that the water availability in reality is even higher than the now implemented one or rather there is another reducing factor. This is the more unlikely explanation because in that way the reduction in spring would also be higher, what is not reasonable. The second and more convincing explanation is that human activities have an influence on the observations. This means for example by cutting the grass, the LAI is reduced artificially.

The second theory is supported by the comparison of the satellite and the in-situ measurements of LAI in Linden. In the in-situ measurements the cutting of grass can be seen very harshly two times a year. The satellite data do not show the second peak of LAI after the first cut, that can be seen in the in-situ measurements. Most important to understand that fact is that the in-situ measurements are done over a measurement area of about 100 m x 200 m with only grass as vegetation. In contrast the satellite data is only one pixel of a gridded data set with 1 km x 1 km grid size. In this grid the vegetation is evenly distributed with the measured values. So the LAI from satellite observations show a value of mixture between all surface possibilities in this grid. This is for example grass, different forests, urban areas and crops. Potentially, because there is a lot of agricultural used land at both locations, the main land-use class in those pixels is crop. This would explain why there is no second peak. After the harvest the plants do not grow again in the same way as before, how it is with the grass in the in-situ measurements. All in all, this underlines that the difference in LAI in summer between the new simulation and the observation is caused by human activity.

Another obvious difference can be seen at the location Linden. Here the maximum value of LAI in the observations is about double the value of the simulations. The maximum and minimum values of the simulations are prescribed in the external data. Those given values are chosen to be at first close to reality but second are not too extreme to not influence the energy fluxes in an unrealistic way. Therefore, the simulations cannot reach the maximum of the observations. Those boundaries have to be taken into account when evaluating the results. It is recommended to not evaluate the exact values, but to evaluate the shape of LAI in general. Looking at the correlations shows that this really makes sense.

In years with a very warm beginning, what means winter and spring are extraordinary warm, the LAI starts to increase earlier in the simulation with the new phenology. The start of the growing season now fits very well to the observations. The end of the growing season also fits in general, but the decay is different. This again can be explained as above. This is the same for the very dry years. But here are differences for the two locations. In Lindenberg the observations show even lower LAI and in Linden again the absolute values are much higher. So an overall applicable statement whether the influence of the water availability in the model should be higher or not can not be given.

The latent heat flux at both locations show an almost similar annual cycle. They only differ in absolute value. The maximum values in summer at Linden are about 50 % higher than at Lindenberg. Regarding this fact it is even more useful to limit the maximum values of LAI in the external data. Having much higher values of LAI in the simulations, the latent heat flux at Linden would be even higher.

The latent heat flux of the different simulations are about the same during winter. Then in April and March the simulations with the new phenology have higher latent heat flux because the growing of vegetation starts earlier and harsher. In summer from June to August the latent heat flux is clearly lower than in the simulations with the old phenology because the reduction due to water availability comes into play. And from August to September again the new phenology is slightly higher. This can not be explained easily

with the vegetation, but needs to be examined further.
The daily cycle of latent heat flux in summer also differs between the different simulations but beside the maximum values not between the locations. The latent heat flux is higher in the simulations with the old phenology because there the LAI in summer is higher and more vegetation causes a higher latent heat flux.
All in all, the results are as expected and the simulations with the new phenology show LAI values much closer to reality. Extreme events can be displayed and so climate change effects on phenology are also possible in the climate model COSMO-CLM as well.

6 Outlook

To continue the so far promising approach further simulations are planned. Those are at first simulations on a third location as described in Material in Selhausen which is close to Jülich. Additionally simulations at the same locations but with a different albedo calculation are planned [Tölle et al., 2018].
Afterwards the newly implemented phenology should be extended to different vegetation types. Those are deciduous and coniferous forest and summer as well as winter crop. Idealized test cases with each of the vegetation types are planned over a domain in Central Europe including Germany, Austria, the Benelux and the Alps. From those results one can derive the influence of the different vegetation on the climate system.
As a next step the new phenology model should be implemented in the new ICON-CLM and with the different vegetation types in parallel. This should give a more realistic presentation of the vegetation in the climate model COSMO-CLM or rather ICON-CLM over a larger domain in Central Europe.

Acknowlegdements

For temperature and precipitation data we acknowledge DWD Climate Data Center (CDC): Historical hourly station observations of 2m air temperature and humidityfor Germany, version v006, 2018 and DWD Climate Data Center (CDC): Historical hourly station observations of precipitation for Germany, versionv006, 2018. The SPOT/PROBA-V LAI data product was generated by the land service of Copernicus, the Earth Observation programme of the European Commission. The research leading to the current version of the LAI product has received funding from various European Commission Research and Technical Development programmes. The product is based on SPOT/VGT 1km data ((c) CNES / PROBA-V 1km data ((c) ESA and distributed by VITO), last access date: 28/9/2018. The LAI measurements at Linden were produced in the GiFACE project by Claudia Kammann and Ruben Seibert at the Justus-Liebig-University Gießen. Computational resources were made available by the German Climate Computing Center (DKRZ) through support from the Federal Ministry of Education and Research in Germany (BMBF). We acknowledge the funding of the German Research Foundation (DFG) through grant nr. 401857120.

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