A simple and effective method for detecting phenological change from time series of vegetation index

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1. Introduction

Plant phenology, defined as the timing of seasonal activities manipulated by periodic changes in climate, is expected to be one of the most sensitive and directly observable indicators of terrestrial ecosystem in response to climate change (Badeck et al., 2004; IPCC, 2007) Remote sensing technique provides a valuable way to retrieve spatially continuous information on phenological changes (e.g. Cong et al., 2012; Delbart et al., 2006; Shen et al., 2011; Zhou et al., 2001) . As a widespread result of these studies, the advance of green-up onset (GUD) and extension of growing season length were observed by time series of vegetation index in many areas (e.g. Zhang et al., 2006; Zhou et al., 2001). Current methods for extracting plant phenology and detecting its change from remote sensing time series data have several limitations, particularly their requirements for the data quality and the prior knowledge like the pre-defined fitting function of the VI curve or the thresholds (White et al., 2009; Zhang et al., 2006)..

To alleviate the limitations of the existing methods, we proposed a method to detect phenological change based on weighted Cross-correlogram Spectral Matching (CCSM-P). CCSM-P determine the phenological change by maximizing the weighted cross correlation between the annual VI profile of reference year and target year.

2. Methods

The cross-correlogram spectral matching method was firstly proposed by van der Meer and Bakker (1997) to match key absorption features of the spectrum. In general, phenological change can be considered as a date shift of a phenological event from a year to another year annual VI time-series data.

In the study, MODIS EVI products were selected as data source for phenology extraction. In order to get accurate phenology estimation, the VI profile should be filtered by Savitzky-Golay filter (Chen et al., 2004) and interpolated to one day scale by the spline interpolation method (Cong et al., 2012; White et al., 2009). Usually, reference VI profile is generated by averaging the VI profile of all target years. It also could be manually selected by data quality if the filed phenological observations are available. Then, a reference phenology date (t_R) is identified according to reference profile using either remote sensing methods or filed observations. After that, the cross-correlogram is constructed.

In original CCSM method, correlation coefficients are calculated at different match positions. In detail, the correlation coefficient at match position *m* is calculated by fixing the reference profile (VI profile in the reference year) and shifting the target profile (VI profile in target year) with *m* units (day in the study). Different from the original CCSM method, we introduce the weighted correlation coefficient ($R_{m,w}$, equation (1)) into the CCSM method because the phenological change is usually small and the observations should have different weights to define their contributions.

$$R_{w,m} = \frac{\sum_{i=1}^{n} w_i \left(\lambda_{t,i} - \overline{\lambda}_t^w\right)\left(\lambda_{r,i} - \overline{\lambda}_r^w\right)}{\sqrt{\left[\sum_{i=1}^{n} w_i \left(\lambda_{t,i} - \overline{\lambda}_t^w\right)^2\right]\left[\sum_{i=1}^{n} w_i \left(\lambda_{r,i} - \overline{\lambda}_r^w\right)^2\right]}} \tag{1}$$

where *n* is the number of the overlapping day between the reference profile curve and the test profile curve, $\lambda_{i,r}$ and $\lambda_{i,t}$ are VI values at the *i* th overlapping day of reference profile curve and test profile curve, w_i is the weight of the *i* th overlapping point in both reference and test curve, while $\overline{\lambda}_r^w$ and $\overline{\lambda}_t^w$ are the weighted average of reference and test curve segment respectively. Then, the cross-correlogram is constructed by plotting $R_{m,w}$ against match position (*m*) (Fig. 1).Moreover, weights are negatively correlated with the time distance from reference date on the reference profile.

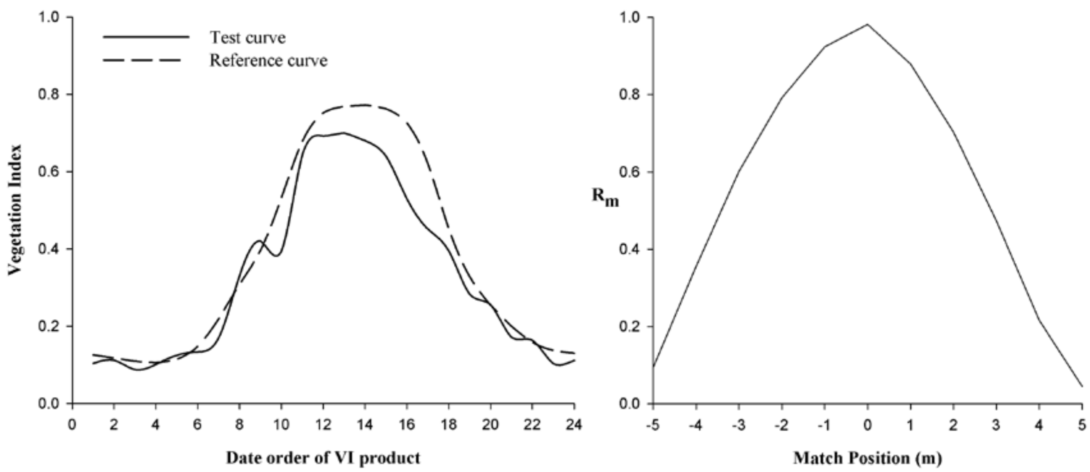

Figure 1. The concept of the vegetation index based cross-correlogram spectral matching.

By maximizing $R_{m,w}$, we can obtain phenological changes (m_p) between reference profile and target profiles. Then the phenology date of target years are calculated as equation (2),

$$t_p = t_R - m_p \tag{2}$$

3. Experiments and results

3.1 Test on simulation data

In order to test the ability of proposed method to catching both year-to-year variations and the long term trend in phenology, we generated several groups of simulation data.

The data was generated by being shifted and adding 10% Gaussian noise. Fig. 2 demonstrated that estimations by CCSM are better than all non-CCSM method.

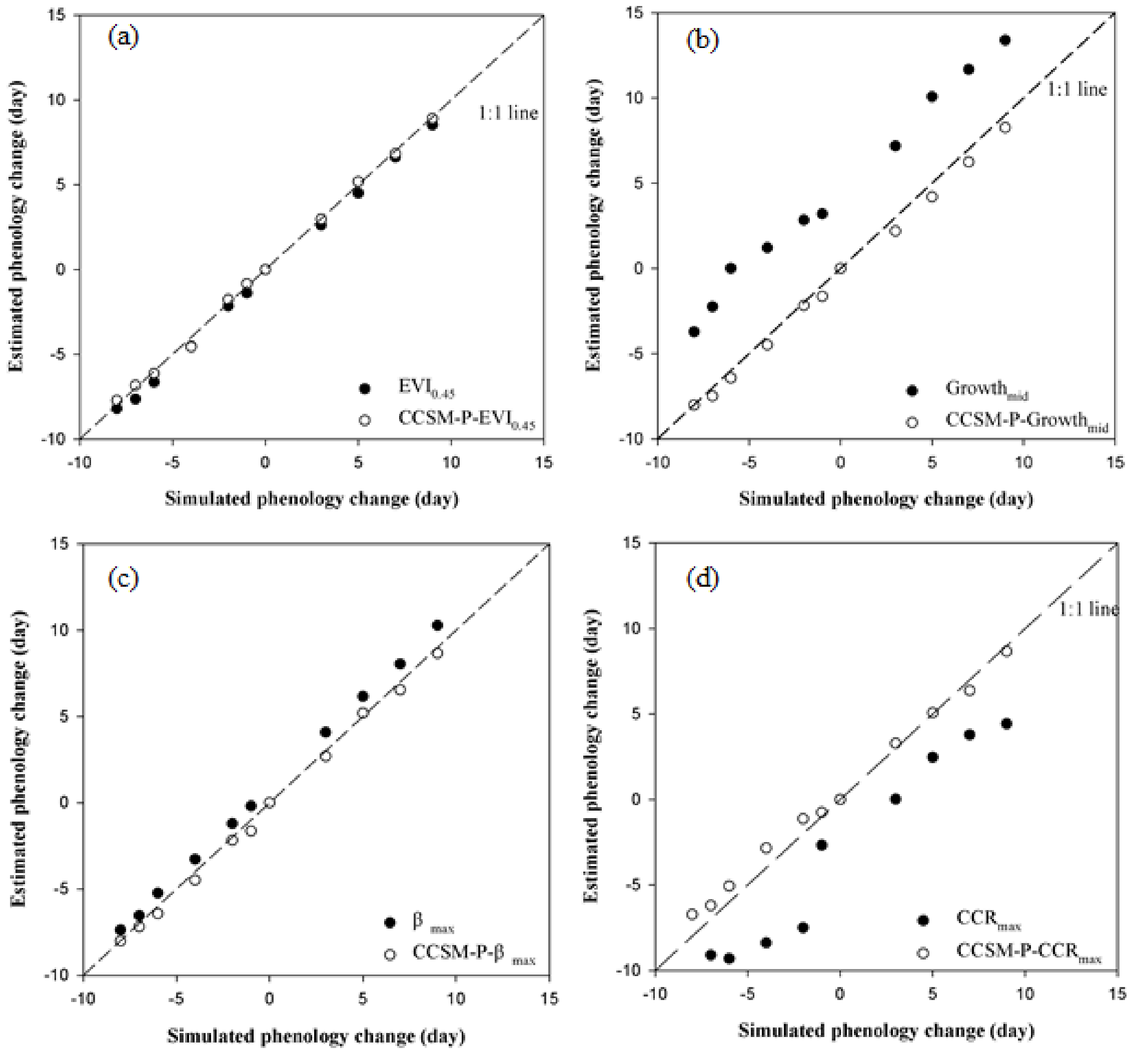

Figure 2. The scatter plots of estimated GUD against simulated GUD with 10% Gaussian noise in EVI curves.

Fig. 3 exhibited the performance of CCSM and non-CCSM methods on capturing the long-term trend of phenology events. All CCSM estimations have passed the identical test with a significance level of 0.01 while all non-CCSM estimations except $EVI_{0.45}$ failed the statistical test with $p<0.01$. The results indicate that CCSM could obtain accurate year-to-year variations and capture long-term trend at the same time.

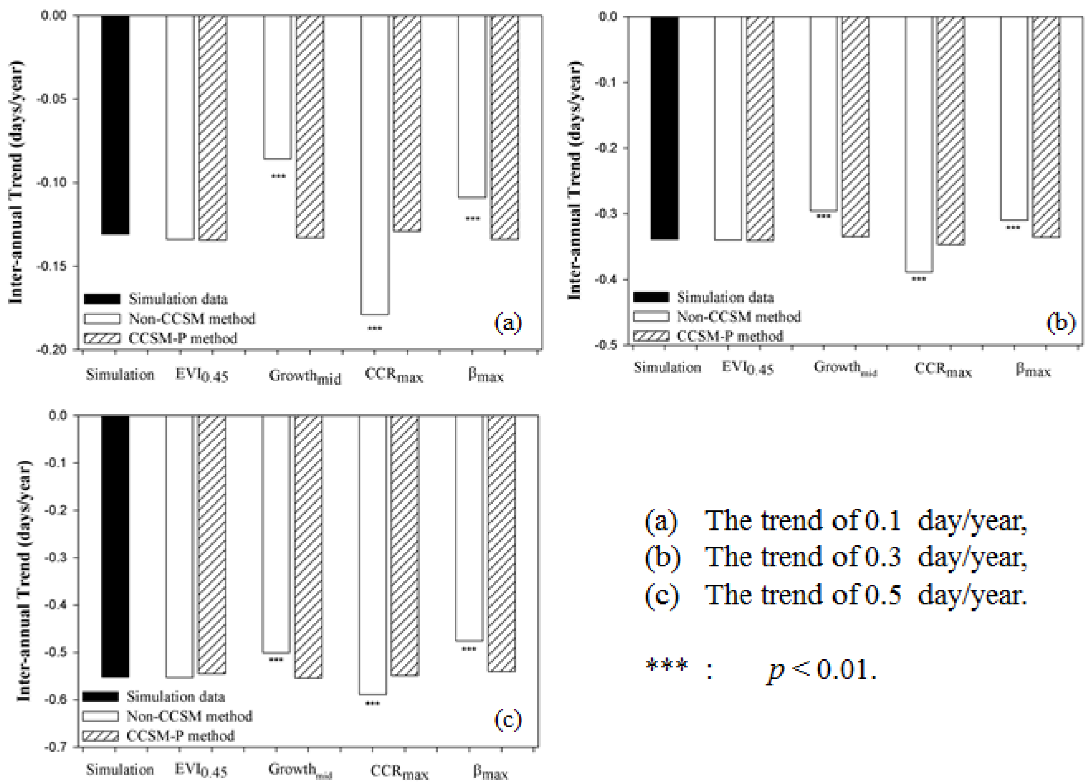

Figure 3. The inter-annual trend comparison between CCSM-P methods and the other non-CCSM methods under three given trend situation.

3.2 Test on filed observations in Harvard Forest

To test the compatibility of CCSM-P method with filed phenological observations, the Harvard Forest (42.53°N-42.54°N, 72.18°N-42.54°W) was used as study area. Three filed phenological metrics (i.e. BBRK, L75 and L95, O' Keefe, 2000) were used to be integrated with MODIS EVI derived from the Nadir BRDF-Adjusted Reflectance products. Table 1 gave a direct comparison between the CCSM-P method integrating field observations and non-CCSM methods. The mean absolute difference (MAD) exhibited that CCSM-P only has little bias with the field observations.

		2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Mean Absolute Difference(Days)
	BBRK	122.7	122.1	133.9	125.9	127.4	127.8	129.2	124.3	121.9	113.2	-
Observation	L-75	138.9	148.3	153.2	141.4	155.5	150.1	145.9	149.0	144.1	135.9	-
(unit: DOY)	L-95	152.0	156.9	160.6	151.4	161.6	156.9	156.3	158.4	152.2	146.2	-
Absolute	BBRK	16.3	27.9	21.1	11.1	23.6	19.2	14.8	23.7	19.1	17.8	19.5
Difference	L-75	0.11	1.7	1.8	4.4	4.5	3.1	1.9	1.0	3.1	4.9	2.7
(Days) for	L-95	13.0	6.7	5.6	14.4	10.6	9.9	12.3	10.4	11.2	15.2	10.9
$EVI_{0.45}$												
Absolute	BBRK	18.1	27.4	20.1	14.4	22.9	21.6	16.4	23.5	18.8	22.7	20.6
Difference	L-75	2.0	1.2	0.8	1.1	5.1	0.7	0.3	1.3	3.4	0.0	1.6
(Days) for	L-95	11.1	7.4	6.6	11.1	11.3	7.5	10.8	10.7	11.5	10.3	9.8
$Growth_{mid}$												
Absolute	BBRK	2.3	7.9	2.1	2.9	7.6	2.2	1.8	6.7	5.1	0.8	3.9
Difference	L-75	13.9	18.3	17.2	18.4	20.5	20.1	14.9	18.0	17.1	21.9	18.0
(Days) for	L-95	27	26.9	24.6	28.4	26.6	26.9	25.3	27.4	25.2	32.2	27.0
CCR_{max}												
Absolute	BBRK	11.3	32.9	22.1	6.1	25.6	17.2	16.8	23.7	10.1	10.8	17.7
Difference	L-75	4.8	6.7	2.8	9.4	2.5	5.1	0.1	1.0	12.1	11.9	5.7
(Days) for	L-95	18.0	1.9	4.6	19.4	8.6	11.9	10.3	10.4	20.2	22.2	12.7
β_{max}												
Absolute	BBRK	0.4	7.0	1.7	4.8	1.7	1.3	0.0	4.9	1.2	1.0	2.4
Difference	L-75	0.0	5.6	2.7	6.6	3.6	5.3	0.0	1.2	0.3	9.1	3.4
(Days) for	L-95	2.4	5.5	4.7	2.9	0.7	2.6	0.0	0.0	1.1	7.2	2.7
CCSM-P												

Table 1. Comparison between ground based observations and EVI derived Green-up Day.

3.3 Test on MODIS EVI images in XilinGol grassland

To test ability for practical applications of CCSM-P method, a case study was conducted in Xilin Gol (41.5°-46.9° N, 111°-120° E), China. For the study area, MODIS EVI products (MOD13Q1) from 2001 to 2010 were collected. Fig. 4 shows the map of three related statistics of GUD (mean, standard deviation, and change trend) generated from the CCSM-P method, which show same spatial and temporal pattern with MODIS phenology products (MCD12Q2).

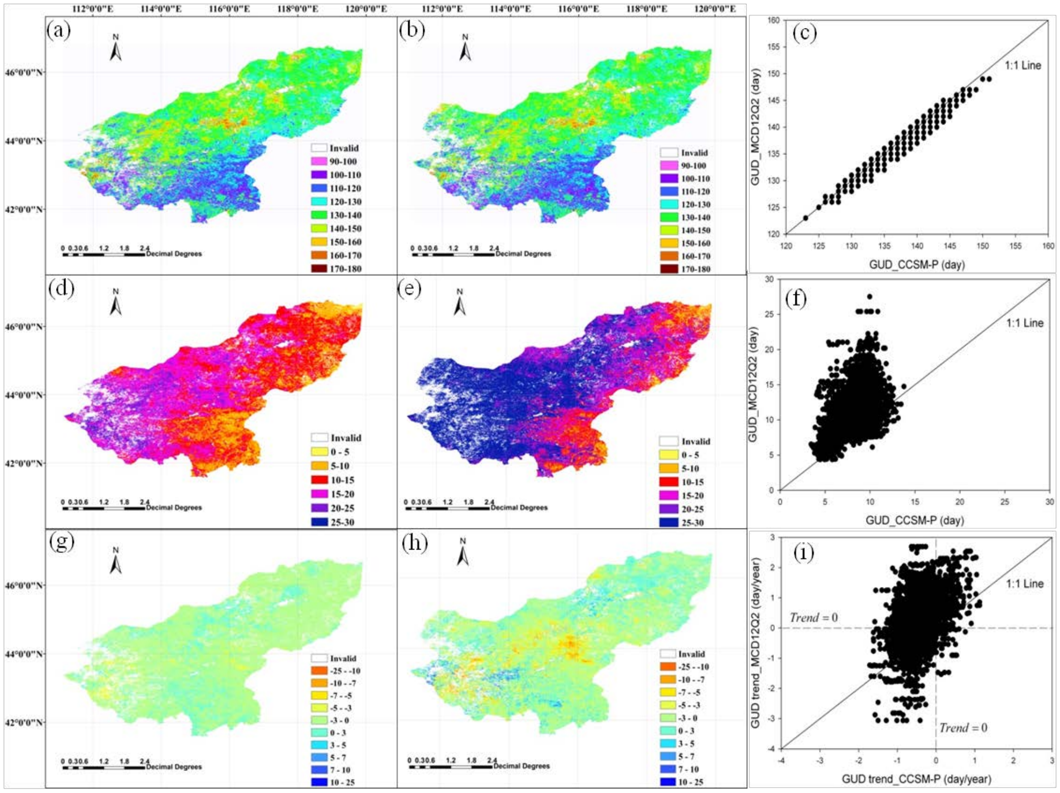

Figure 4. Comparisons of the Green-up Day (GUD) derived from the CCSM-P method and MODIS Land Surface Phenology Product (MCD12Q1)

4. Discussion and conclusions

In this study, we proposed a simple and effective method for detecting the phenological change using VI time-series datasets. CCSM-P compares the VI profile of target year with reference profile and then estimates the phenological change by maximizing the weighted correlation coefficient. As demonstrated in three experiments with both simulation data and the satellite data, CCSM-P method can not only obtain the year-to-year phenological variation but also capture long-term trend of the phenological change.

Compared with several widely used non-CCSM methods for identifying phenology, CCSM-P does not fit VI profile to a predefined function or manually define a threshold. CCSM-P method only needs to define a reference VI profile and reference phenological date before the correlation procedure. Moreover, the field observed phenological date can be used to define the reference phenological date, then the field observed information could be used to detect the phenological change through the matching procedure. However, the compatibility of CCSM-P and filed observations is based on a same scale of both data. All these advantages make CCSM-P a robust, effective and ecologically meaningful method to obtain an accurate phenological change detection result for the study of the global climate change and the terrestrial ecology.

5. Acknowledgements

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