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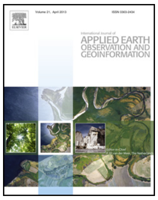

A simple smoother based on continuous wavelet transform: Comparative evaluation based on the fidelity, smoothness and efficiency in phenological estimation

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ABSTRACT

This study proposed a simple Smoother without any local adjustments based on Continuous Wavelet Transform (SCWT). And then it evaluated its performance together with other commonly applied techniques in phenological estimation. These noise reduction methods included Savitzky–Golay filter (SG), Double Logistic function (DL), Asymmetric Gaussian function (AG), Whittaker Smoother (WS) and Harmonic Analysis of Time-Series (HANTS). They were evaluated based on fidelity and smoothness, and their efficiencies in deriving phenological parameters through the inflexion point-based method with the 8-day composite Moderate Resolution Imaging Spectroradiometer (MODIS) 2-band Enhanced Vegetation Index (EVI2) in 2013 in China. The following conclusions were drawn: (1) The SG method exhibited strong fidelity, but weak smoothness and spatial continuity. (2) The HANTS method had very robust smoothness but weak fidelity. (3) The AG and DL methods performed weakly for vegetation with more than one growth cycle (i.e., multiple crops). (4) The WS and SCWT smoothers outperformed others with combined considerations of fidelity and smoothness, and consistent phenological patterns (correlation coefficients greater than 0.8 except evergreen broadleaf forests (0.68)). (5) Compared with WS methods, the SCWT smoother was capable in preservation of real local minima and maxima with fewer inflexions. (6) Large discrepancy was examined from the estimated phenological dates with SG and HANTS methods, particularly in evergreen forests and multiple cropping regions (the absolute mean deviation rates were 6.2–17.5 days and correlation coefficients less than 0.34 for estimated start dates).

1. Introduction

Vegetation phenology can be taken as an indication of vegetation health and global climate change (White et al., 1997; Ganguly et al., 2010). Remote sensing Vegetation Indices (VIs) time-series datasets have been widely applied for monitoring vegetation phenology dynamic trends (Ganguly et al., 2010; Qiu et al., 2013b; Walker et al., 2014; Wu et al., 2014). A smoothed VIs time-series is almost indispensable in most phenology studies (Atkinson et al., 2012; Zhang, 2015). However, it remains a challenge to obtain temporally and spatially continuous data with high quality due to various reasons such as the atmospheric contamination and inconsistency between different sensors (Hird and McDermid, 2009; Atkinson et al., 2012; Zhou et al., 2015). Considerable research efforts have concentrated on developing noise reduction methods (Eilers, 2003; Gang et al., 2015; Zhang, 2015). The commonly applied smoothing methods include the time-domain local filter methods such as the Savitzky–Golay filter (SG) (Meroni et al., 2014) and Asymmetric Gaussian function (AG) (Wu et al., 2014), the frequency-based methods such as Fourier decomposition (Roerink et al., 2000; Zhou et al., 2015) and the wavelet-based filter (Sakamoto et al., 2005; Lu et al., 2007).

Comparisons of their performances can be found in literatures (Schmidt and Skidmore, 2004; Hird and McDermid, 2009; Beurs de and Henebry, 2010; Atkinson et al., 2012; Ebadi et al., 2013; Kandasamy et al., 2013; Verger et al., 2013; Geng et al., 2014; Michishita et al., 2014). Although SG was one of the most recommended methods (Kandasamy et al., 2013; Geng et al., 2014; Michishita et al., 2014), the superior performance of other methods over SG was also indicated in several studies (Jönsson and Eklundh,

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2004; Hird and McDermid, 2009; Beurs de and Henebry, 2010; Julien and Sobrino, 2010; Atkinson et al., 2012). Despite the knowledge that choice of denoising and reconstruction models might lead to differences in derived information (Hird and McDermid, 2009; Atkinson et al., 2012), current literatures failed to provide consistent conclusions on their relative performance (Atkinson et al., 2012; Zhou et al., 2015). With the growing importance of the VIs time-series in global studies, there is a strong need for a more comprehensive understanding of current noise reduction methods (Hird and McDermid, 2009; Atzberger and Eilers, 2011a), in addition to differences resulting from the analysis of diverse satellite data sets (Atzberger et al., 2013).

In the time-series noise reduction research field, there are some aspects that need to be further investigated (Atkinson et al., 2012; Geng et al., 2014). First, too many parameters need to be estimated in current curve fitting models considering the limited number of observations per year (Beurs de and Henebry, 2010). Most smoothing techniques require an iterative approach to adjust the model parameters; and most of these adjustments are not static due to phenological variations within and across land cover classes (Dash et al., 2010). Regarding vegetation diversity and climate variability, it has been complicated to estimate a single set of parameters that fit across different regions (Beurs de and Henebry, 2010). Second, while many comparative studies focused on the fidelity to the observed signals, the merit of smoothness is often neglected (Hird and McDermid, 2009; Geng et al., 2014). Exceptions include Eilers (2003) and Kandasamy et al. (2013) among others. Third, few studies have focused on the application fields and most fitting models have been applied in higher latitudinal regions (Beck et al., 2006; Hird and McDermid, 2009; Geng et al., 2014). Complex signals from evergreen forests were deliberately excluded for analysis since the identification of seasonality was questionable (Kandasamy et al., 2013). Fourth, efficiency and accuracy were rarely evaluated in detecting vegetation phenology at the relatively large regional scale (Bridhikitti and Overcamp, 2012; Michishita et al., 2014). Most current smoothing and fitting approaches have evident limitations in detecting land surface phenology across complex environments (Beurs de and Henebry, 2010; Zhang, 2015).

The objectives of this paper are (1) to propose a simple Smoother without any local adjustments based on Continuous Wavelet Transform (SCWT) for estimation of phenological parameters based on VIs time-series; (2) to investigate the performance of SCWT together with five other denoising methods applied to tropical, subtropical and temperate regions based on metrics that measure both the fidelity and smoothness; and (3) to conduct a comprehensive analysis of the capability and reliability of these techniques in deriving phenological parameters across a large variety of vegetation types and climate conditions.

2. Study area and datasets

2.1. Study area

China is enriched with vegetation that extends from temperate to tropical regions. The vegetation landscape encompasses natural vegetation and agricultural crops with different cropping patterns (single, double or triple). There are large spatial variations in agricultural and rotation systems in China. We selected four typical regions: Northeast China (Fig. 1(a)), Henan Province (ranked first in food production over the past decade) (Fig. 1(b)), the Min-Gan region (ranked first in forest cover) (Fig. 1(c)) and Hainan Province (Fig. 1(d)), representing areas with temperate forests and single crops, temperate double crops, and subtropical and tropical agroforestry ecosystems, respectively (Qiu et al., 2013a, 2014) (Fig. 1).

2.2. Datasets

The 500 m 8-day composite MODIS surface reflectance products (MOD09A1) in 2013 were utilized. EVI2 was calculated using surface reflectance values from red (620–670 nm) and near-infrared (841–876 nm) (Jiang et al., 2008). EVI2 was selected since it eliminated most of the problems associated with sub-pixels and residual clouds (Jiang et al., 2008). There were 46 observations per year (https://ladsweb.nascom.nasa.gov/). Field survey data were collected in summer 2012 and 2013 in Henan province and Min-Gan region, in winter 2013 in Hainan Province, and in summer 2015 in Northeast China. Other datasets included the crop calendar observation data (provided by the National Meteorological Bureau of China) and 300 m GlobCover Land Cover Maps (Fig. 1) (provided by the Database of Global Change Parameters, Chinese Academy of Sciences, http://globalchange.nsdc.cn).

3. Methods

Fig. 2 summarized the overall procedure. First, a simple smoother without any local adjustments was proposed based on Continuous Wavelet Transform (CWT). Second, the MODIS EVI2 time-series were pre-processed and then smoothed by six methods respectively. Third, the smoothing effects were assessed. Fourth, three key phenological parameters were derived based on these techniques. Finally, their efficiencies in estimating vegetation phenology were evaluated. The following sections provided a detailed description of each procedure.

3.1. A simple smoother without any local adjustments based on CWT

Wavelet transformation methods could be categorized as Discrete Wavelet Transforms (DWT) and continuous wavelet transforms. Unlike the DWT, the CWT allowed transformation with continuous scales. The redundancy of the CWT makes the information available in signal characterization more detectible for interpretation. The CWT was widely used in agricultural and environmental research areas (Cheng et al., 2011; Qiu et al., 2014). However, differed from the commonly utilized DWT-based smoothers, the CWT-based smoothing methods was rarely applied to VIs time-series data, due to the conception that the wavelet coefficients through CWT were highly redundant and should be avoided for most practical applications (Schmidt and Skidmore, 2004). In this study, we wanted to reveal the efficiency of CWT-based smoothers for reconstruction of VIs time-series datasets. A detailed description and application of wavelet analysis could be found in related references (Daubechies, 1990; Torrence and Compo, 1998).

The procedure for CWT-based smoother was as follows (Fig. 3). First, CWT was performed on the daily VI time-series, in which the 2D wavelet scalogram could be obtained. The Morlet wavelet was selected for this purpose. Second, the proper scale range applied for signal reconstruction was selected from the wavelet scalogram. The scale range used for signal construction was determined as 10–40. Third, the values of 2D matrix of wavelet coefficients were set to zero outside this scale range. Finally, reverse wavelet transform was performed based on the 2D matrix of wavelet coefficients obtained in step 3 and the reconstructed signals were achieved.

The Matlab code for signal reconstruction based on CWT was:

```
S = {y,dt}
scale = {ss,ds,se,‘lin’};
WAV = {‘morl’,1};
SCWT = cwtft(S, ‘scales’, scale,‘wavelet’,WAV);
SCWT.cfs(1:LS,:) = 0;
```