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A noise reduction method for MODIS NDVI time series data based on statistical properties of NDVI temporal dynamics

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MODIS NDVI 시계열 자료의 통계적 특성에 기반한 NDVI 데이터 잡음 제거 방법

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Abstract Multitemporal MODIS vegetation index (VI) data are widely used in vegetation monitoring research into environmental and climate change, since they provide a profile of vegetation activity. However, MODIS data inevitably contain disturbances caused by the presence of clouds, atmospheric variability, and instrument problems, which impede the analysis of the NDVI time series data and limit its application utility. For this reason, preprocessing to reduce the noise and reconstruct high-quality temporal data streams is required for VI analysis. In this study, a data reconstruction method for MODIS NDVI is proposed to restore bad or missing data based on the statistical properties of the oscillations in the NDVI temporal dynamics. The first derivatives enable us to examine the monotonic properties of a function in the data stream and to detect anomalous changes, such as sudden spikes and drops. In this approach, only noisy data are corrected, while the other data are left intact to preserve the detailed temporal dynamics for further VI analysis. The proposed method was successfully tested and evaluated with simulated data and NDVI time series data covering Baekdu Mountain, located in the northern part of North Korea, over the period of interest from 2006 to 2012. The results show that it can be effectively employed as a preprocessing method for data reconstruction in MODIS NDVI analysis.

요 약 Multitemporal MODIS 식생 지수 (VI) 자료는 식생 활동의 프로파일을 제공하기 때문에 환경 및 기후 변화에 대한 식생 모니터링 연구에 널리 사용되고 있다. 그러나 MODIS 데이터에는 구름이나 대기 변동성 및 계측기 문제로 인해 노이즈가 발생하여 NDVI 시계열 데이터 분석과 애플리케이션 응용에 있어서 자료 정확성에 문제가 생기게 된다. 이러한 이유로, NDVI 자료를 이용한 VI 분석을 위해서는 잡음을 줄이고 고품질의 시계열 데이터 스트림을 재구성하기위한 전 처리가 필요하다. 본 연구에서는 NDVI 시계열 자료의 통계적 특성을 기반으로 불량 데이터 또는 미관측 데이터를 복원하기 위해 MODIS NDVI에 대한 데이터 재구성 방법을 제안하고 있다. 데이터 스트림 함수의 속성을 검사하면 급격한 증가나 감소와 같은 비정상적인 변화를 감지 할 수 있다. 본 연구에 제안하고 있는 방법은 정상적인 자료의 세부적 특징은 그대로 유지하면서 노이즈 자료만 수정하는 방향으로 자료를 복원할 수 있다. 제안된 기법은 시뮬레이션 데이터와 2006년부터 2012년까지의 북한지역 백두산을 대상으로 NDVI 시계열 자료를 사용하여 테스트하였고 시뮬레이션 테스트에서는 기존 wavelet이나 Gaussian 방법에 비해 본 방법이 에러율을 평균 70% 이상 줄일 수 있어 제안된 방법이 노이즈가 있는 시계열 자료의 데이터 재구성에 있어 효과적임을 입증하였다.

Keywords : Data reconstruction, Noise reduction, MODIS NDVI, Time series data, Vegetation index

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1. Introduction

Monitoring vegetation activity is an important means to understand environmental and climate change. The patterns of vegetation growth such as growing time, the vigor of plants, and vegetation composition are closely related to land-cover/use conditions and change. Multitemporal satellite data provide a profile of vegetation activity with the seasonal and annual dynamics of vegetation in the domain of time. Vegetation studies using remote sensing techniques generally require temporal observations at regular time intervals over a long period of time. Some satellite sensors such as NOAA/AVHRR (Advanced Very High Resolution Radiometer), MODIS (Moderate Resolution Imaging Spectroradiometer), and SPOT/VEGETATION have provided an adequate resource for research on global environmental and climate change due to their daily temporal resolution and global spatial resolution [**24, 25, 35**]. They have all proven to efficiently monitor vegetation activity at different spatial and temporal resolutions.

The normalized difference vegetation index (NDVI) is the most widely used vegetation index (VI) in vegetation studies, which is successfully used to monitor photosynthetic activity and compare seasonal and interannual changes in vegetation growth and activity [**24, 32**]. MODIS provides NDVI at varying spatial (250m, 500m, 1km) and temporal (16-day, monthly) resolutions from each of the Terra and Aqua sensors [**16**]. Multitemporal MODIS NDVI have been widely used for long-term vegetation monitoring in many applications locally and globally [**19, 25**].

Although the MODIS VI is pre-processed through 3 different stages for accuracy, NDVI data inevitably contain disturbances caused by cloud presence, atmospheric variability, aerosol scattering, and instrument problems [**8, 16, 18, 20, 26, 34**]. These error sources result in producing bad or missing observations. As a result, they impede the analysis of NDVI time series data and limit the application of NDVI because the availability of high-quality data is an important factor for accuracy and reliability of the analysis. For this reason, a number of filtering methods have been proposed to reduce noise and restore a continuous high-quality data stream. The reconstruction filters are generally categorized into two types of methods: frequency-domain methods such as Fourier and wavelet analysis [2, 3, **27**] and time-domain methods such as the best index slope extraction (BISE) [**33**], the mean-value iteration filter (MVI) [**25**], asymmetric Gaussian function [**19**], and Savitzky-Golay filtering [4]. In most methods, a filtering process is applied to the whole data set and thus there is a possibility of modifying the observed details even within the range of normal fluctuation. The most important thing in designing reconstruction filters is that filtering should remove noise that affects the accuracy of further NDVI analysis and preserve the detailed information of NDVI temporal dynamics at the same time [**25**].

In this paper, a filtering method is proposed to identify possible bad or missing observations using NDVI quality assurance (QA) data sets and the first derivatives of NDVI time series and then replace them with the estimated values based on the statistics of observed NDVI variation. The first derivatives show the monotonic properties of a function just to the left and right of a given point and thus enable us to examine the degree of change around the point. In the proposed method, noise is removed while the rest of the data are kept intact so that the detailed temporal dynamics are preserved in the filtering process. Ultimately, more reliable NDVI time series data can be reconstructed.

The proposed method was tested and evaluated using simulation data and MODIS/Aqua vegetation indices of 16-day L3 global 250 m SIN Grid(v005) (MYD13Q1) over the period of interest from 2006 to 2012. In section 2, we review some related previous work first and then address the filtering method, where we describe the process to reconstruct the qualitative

NDVI data stream. In Section 3, we conduct some experiments with the proposed method and evaluate its performance. Some conclusions and comments are presented in Section 4.

2. Filtering Methodology

2.1 Related Work

The wide-ranging data-reconstruction approaches are briefly described in many studies [8, **25**]. MODIS NDVI data are already processed by a Maximum Value Composite (MVC) method to get a higher percentage of clear-sky data [**15**]. Using the MVC data, several techniques based on interpolation of time series data have been proposed for noise reduction. Various polynomial function fitting techniques are compared in the research by Van Dijk et al. Viovy et al. developed BISE algorithm [**33**] and Lovell and Graetz suggested the modified BISE filtering [**22**]. The BISE method retains more valuable NDVI elements than the MVC. The BISE algorithm was employed in the research for extraction of seasonal metrics of vegetation phenology, classification of land cover types [**22, 34**] and development characteristics of various vegetation types. Noise reduction filters are developed in frequency-domain as well as in time-domain. Various Fourier-based and wavelet-based fitting methods were suggested to remove noise [2, 3, **23, 27**]. The Fourier-based fitting methods have been used in studies of land biosphere [5], canopy reflectance and photosynthesis [**31**]. An asymmetric Gaussian function fitting approach is more effective and demonstrates better performance over BISE and Fourier-based methods (Jonsson and Eklundh, 2002; Lee, 2011). They have been used for phenological studies [**19**]. Chen et al. modified a Savitzky–Golay filter and compared it to the fast Fourier transform technique [4]. Ma and Veroustraete compared a MVI method with a BISE algorithm and a Fourier-based method [**25**]. A double logistic function-fitting method shows better performance than Fourier-based methods [1]. Lu et al. suggested a wavelet-based method and compared it to BISE, a Savitzky–Golay filter and a Fourier-based filter [**23**]. They showed that the wavelet-based de-noising method enhances the ability to remove noise and some advantages such as independence of subjective parameter and threshold. Actually, a universal test standard does not exist to allow uniform comparisons of different methods. Each approach has its own advantages and has been successfully applied for some applications [4, **9-14**].

However, the common drawback of most noise reduction methods is that the adopted strategy is subjective and depends on the experience of the researcher. For instance, in the BISE algorithm, a sliding period and a threshold are to be empirically determined and in the asymmetric Gaussian function-fitting method, a consistent set of maxima and minima to which the local functions can be fitted is to be identified. The Savitzky–Golay method also requires empirical analysis to determine the width of the smoothing window and the degree of the smoothing polynomial. Fourier-based fitting methods may be problematic when applied to irregular or asymmetric NDVI data, since they depend critically on symmetric sine and cosine functions. In addition, they may generate spurious oscillations in the NDVI time series [8, **27-30**].

In most methods, we face a trade-off between removing noise and preserving details of the temporal dynamics. The goal of the proposed method is to remove noise and at the same time preserve the detailed information of NDVI temporal dynamics as much as possible. Unfortunately, there are no filtering methods which automatically allow noise reduction without some specific selection or pre-defined criterion according to the adopted strategy. In this study, the statistical information on temporal fluctuation observed from all NDVI data is employed instead of subjective parameters. As long-term time series data are analyzed, the possibility of identifying and restoring bad observations increases in the statistical point of view.

2.2 Data Description

MOD13Q1 product is one of MODIS NDVI products which have been used widely in areas such as land-cover/use change, vegetation conditions, crop monitoring and forecasting, climate change, and so on. It is a 16-day L3 Global 250 m SIN Grid (v005) VI data set and includes two VI products, NDVI and EVI(Enhanced Vegetation Index), with a QA data set indicating its quality. In this paper, MOD13Q1 time series for 7 years from 2006 to 2012, covering Bakdu Mountain located in the northern part of North Korea, were used to test and evaluate the performance of the proposed method.

2.3 Noise Reduction and Reconstruction

The noise-reduction method proposed in this study is based on the statistics of the observed oscillations in the temporal dynamics to reconstruct high-quality NDVI time-series. The erroneous observations due to cloud cover, snow, atmospheric variability, atmospheric correction errors, and sensor problems are usually presented as anomalous high (spikes) and low (drops) values in temporal data stream. That is, they suddenly increase or decrease compared with the adjacent values and return back to the values in accordance with the annual pattern of the vegetation in the region of a pixel. The first derivatives of NDVI data stream enable us to examine the monotonic properties of a function (data stream) just to the left and right of a given NDVI point in the time domain and to detect the anomalous spikes and drops. If the function abnormally switches from increasing to decreasing or vice versa at a given NDVI point and then gets back close to that point, there is a great possibility of noise occurrence at that point.

The monotonic fluctuation (oscillation) observed from the time series data statistically shows a pattern of normal distribution as in Fig. 1(a). Let D_i be the first derivative at the *i*th NDVI data in the time domain, which represents the amount of monotonic change between the values of the (*i*-1)th NDVI, $NDVI_{i-1}$andthe*i*th NDVI, $NDVI_i$. It can be assumed that D_i is normally distributed as follows,

$$D_i \sim N(\mu_{D,}\sigma_D^2) \tag{1}$$

where and are the mean and variance of all the derivatives, respectively. The points located outside of the normal distribution are likely to have noise occurrence. Then the threshold for anomalousness can be statistically specified with confidence interval. For example, 1.96s (or 2.58s) can be selected as a threshold value for noisy observation with a 95% (or 99%) confidence interval for mean of the first derivatives. This means that 95% (or 99%) of the first derivatives fall approximately within the range of 1.96 (or 2.54) standard errors of the mean [6].

In addition, a map of quality assurance (QA) given along with VI products, VI_QA Science Data Set, is also useful to find poor-quality data. It has a QA number related to the VI quality of each pixel. VI usefulness is usually decided by using bits 2-5 of the QA code with 16 bit values, where the highest quality corresponds to an index value of 0000 (QA flag 0) and the lowest quality to an index value of 1111 (QA flag 15). It is generally assumed that there might exist an observation error when the QA flag is larger than 5 (index value of 0101) [**16, 25**].

Then the observed values detected as bad-quality or missing data are to be replaced by the estimated values. Let *NDVI(t)* be the value at time *t* of temporal NDVI profile. It is assumed that *NDVI(t)* is closely related to the mean of the previous value, *NDVI(t-1)*, and the following value, *NDVI(t+1)*. When the NDVI data is analyzed over a large area, all the differences between the *NDVI(t)* and the mean of *NDVI(t-1)* and *NDVI(t+1)* within the normal range of temporal fluctuation can be assumed to be approximately normally distributed as in Fig. 1(b). Let be the difference at time *t* in pixel *i* between *NDVI(t)* and the mean of its previous and following NDVIs, which is defined as follows;

$$diff_i(t) = |NDVI_i(t) - (NDVI_i(t-1) + NDVI_i(t+1))/2| \quad (2)$$

$$diff_i \sim (t) N(\mu_{diff}, \sigma^2_{diff}) \quad (3)$$

Then the NDVI value for a bad-quality observation at time *t* in pixel *i* can be estimated using the following relationship;

$$(\widehat{NDVI})_i(t) = (NDVI_i(t-1) + NDVI_i(t+1))/2 + (\widehat{diff})_i(t) \quad (4)$$

The whole reconstruction process of MODIS NDVI time series can be summarized as in Fig. 2.

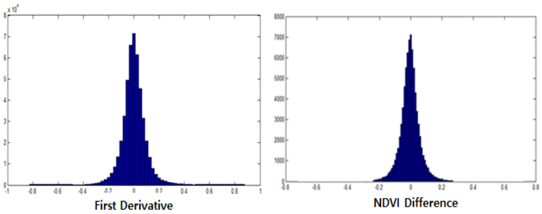

Fig. 1. Distribution obtained from sample pixels during 2006-2012 (a) first derivatives of multitemporal data (b) difference between the *NDVI(t)* and the mean of *NDVI(t-1)* and *NDVI(t+1)* within the normal range of temporal fluctuation.

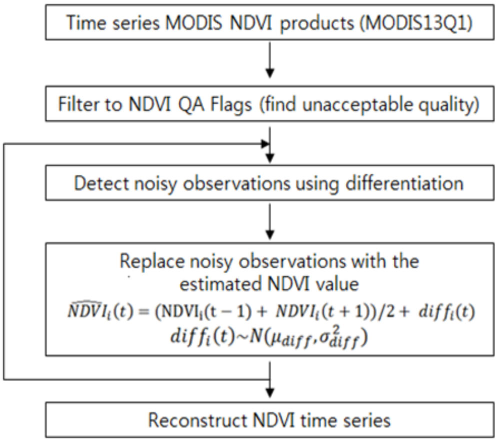

Fig. 2. Flowchart of reconstruction process of NDVI time series.

3. Experimental Results and Analysis

3.1 Evaluation of the Method

First, the method was tested and evaluated with simulated data. A simple wave pattern using the sum of two cosine functions and a harmonic signal over 7 years at the frequency of once per year was generated, respectively. Then random spiky noise was added to the original pattern as shown in Fig. 3(a). We calculated the first derivatives of the data stream and their statistics such as mean and standard deviation. Spiky points of the data stream were identified using the threshold based on the statistics, for instance, 95% confidence limits, and replaced with the estimated values. Fig. 3(b) shows the data stream restored by the proposed method, where all the spiky noises are corrected and relatively small ones are preserved. It is noted that only bad-quality points were restored while the rest of the data were kept intact. For comparison with other denoising methods, a median filter of three point smoothing and wavelet filter were applied to the same data set. The restored data stream obtained from those methods are shown in Fig. 3(c) and Fig. 3(d), respectively, where all the spiky noise is restored but the detail of the data stream is also modified because the process is applied to the whole data stream.

Then we compared the performance of the methods numerically using mean squared error (MSE). MSE enables us to quantify the difference between the true values of the original data and the restored values after denoising. In Table 1, MSE values calculated from four different filtering methods applied to the simulated data stream are compared. A smoothing method such as a mean or median filter is a temporal averaging technique and so it evenly smooths the data stream. For this reason, although MSE of median filter is the lowest, all the detailed dynamic information is integrated in the smooth trace. In contrast, a wavelet-based method relatively preserves details of temporal dynamics but tends to make spurious oscillations as expected from the highest MSE values.

In the case of the proposed method, only statistically identified noise is removed with most data being preserved and thus the restored data stream is closest to the pattern of the original data stream.

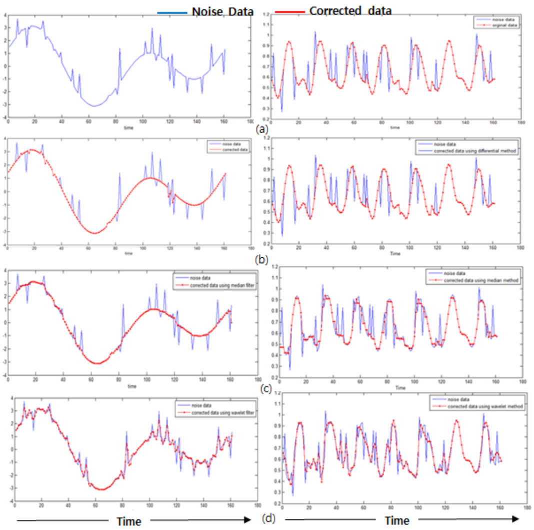

Fig. 3. Comparison of simulation tests: (a) a sample time series (b), (c), and (d) results of reconstruction by the proposed method, median filter, wavelet-based filter, respectively.

Table 1. Comparison of MSE values calculated from different filtering methods for each samples of Fig. 3.

Applied method	MSE (left column)	MSE (right column)
Proposed method	0.0331	0.0087
Median filter	0.0125	0.2181
Gaussian filter	0.1361	0.6832
Wavelet filter	0.1973	0.7908

Next, the proposed method was tested and evaluated with MODIS/Aqua 16-day L3 global 250m SIN Grid(v005) (MYD13Q1) VI data sets for 7 years from 2006 to 2012 covering Bakdu Mountain located at the northern part of North Korea. The size of the test image is 400x400 and thus a total of 160000 NDVI time series of 7 years were tested. Each pixel of the image has a NDVI time series of 161 observations since each pixel holds 23 observations per year. Fig. 4 shows an example of detecting bad-quality data points using the first derivatives based on the statistics of observed oscillations calculated from 160000 pixels with a 99.8% confidence interval.

Fig. 5(a) displays a sample image of the 125th NDVI obtained on May 1st, 2010 before data reconstruction and Fig.5(b) shows the result of noises reduction after application of the proposed method, where the image is noticeably cleaned by restoring bad-quality observations. Some sample areas with great improvement are shown within the circles.

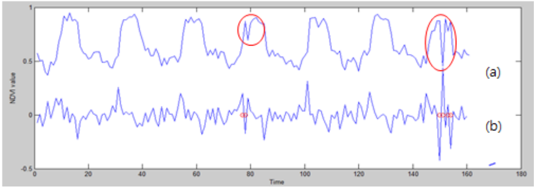

Fig. 4. Detection of bad-quality observations using 1^{st} derivatives: (a) one sample of NDVI time series of 7 years (161 data points) and (b) location of bad-quality observation detected by the first derivative.

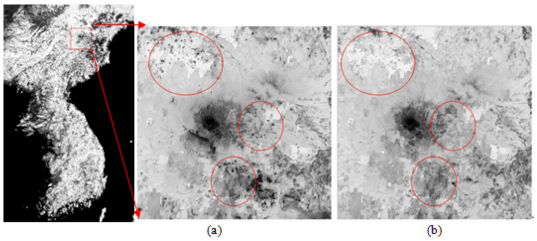

Fig. 5. Comparison of images: (a) a sample image before data reconstruction and (b) after data reconstruction by implementing the proposed method.

Now, in Fig. 6, the reconstructed time series are compared with the original ones to investigate the denoising performance. In the case of Fig 6(b), there exists great variability in the data stream. The locations detected statistically with 99.8% confidence interval limits are marked as '+'. All the data were replaced based on the statistics of the NDVIs observed at the same time of year as explained in the previous section.

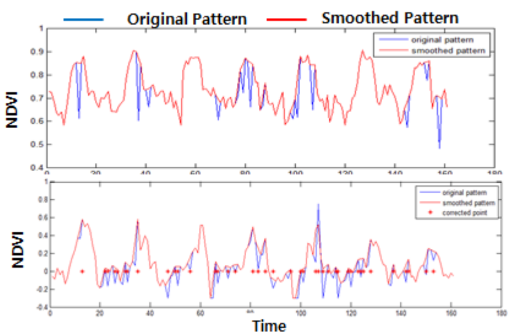

Fig. 6. Comparison of the reconstructed NDVI time series with the original one showing the locations of bad or missing observations.

3.2 Evaluation Using Harmonic Model

Qualitative time series data are required for accuracy of the NDVI analysis employed in various applications including agricultural monitoring and forecasting, land-cover characterization, and land-cover/use change detection. With this concept, a harmonic model was employed to evaluate the denoising effect on the following NDVI analysis. Harmonic analysis decomposes a time-dependent complex curve into a series of sinusoidal terms, each defined by a unique amplitude and phase angle [**18**]. Each component term accounts for some percentage of the total variance in the original time series data. Harmonic analysis has proven to be useful in analyzing seasonal and interannual variation in land surface condition observed by remotely sensed NDVI time series data such as the AVHRR and MODIS.

In Fig. 7, the denoising effect on the application of harmonic analysis is displayed. As shown in Fig. 7(a), bad-quality data streams such as the circled cases cannot be presented well by harmonic modeling. In contrast, Fig. 7(b) shows better harmonic model fitting after application of the proposed denoising method. This means that the proposed method can successfully reconstruct a good data stream for the analysis of NDVI temporal dynamics. Fig. 8 visually compares the results of harmonic model fitting on the data stream reconstructed by a wavelet-based denoising method and the proposed method in more detail. We can see that the temporal profile is represented more correctly using the harmonic model after data reconstruction by the proposed method. It is also noticed that it shows better fitting compared with wavelet-based filtering.

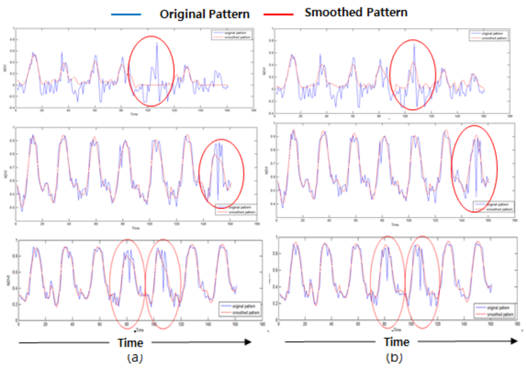

Fig. 7. Evaluation of denoising effect on NDVI analysis using a harmonic model (a) application of a harmonic model before denoising (b) after denoising by implementing the proposed method.

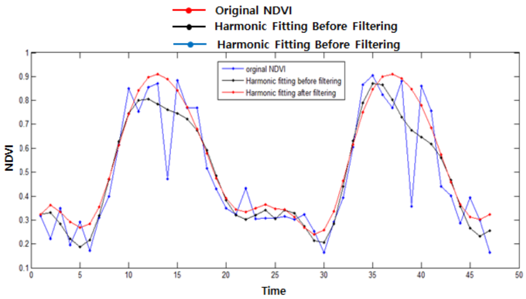

Fig. 8. Comparison of the denoising effect: blue- original data, red- harmonic model fitting after data reconstruction by the proposed method, black- harmonic model fitting after data reconstruction by a wavelet-based method.

4. Conclusions

NDVI is the most widely used vegetation index in vegetation monitoring and its related studies since it carries valuable information regarding land-surface properties. For long-term monitoring, multi-temporal NDVI data is generally analyzed in the time domain. However, the inevitable noise impedes further NDVI analysis. Therefore, noise reduction to make high-quality data streams is an important preprocessing method to increase the reliability of the NDVI research.

In this study, a noise reduction method based on the statistics of observed oscillations of the time series is proposed, where anomalous (noisy) observations are statistically identified and corrected while the rest of the data within the normal range of oscillation are preserved. It is important that as much of the original data as possible should be conserved through the noise filtering process for further NDVI analysis.

The first derivative of monotonic function successfully enables us to detect an abnormal switch from decreasing to increasing or vice versa, which implies the possibility of the existence of noise at the time of NDVI time series. In this work, instead of subjective parameters, abnormal change in the data stream such as a sudden spike or drop is identified based on the statistics of the observed oscillations calculated from the whole NDVI data set. The observed NDVI oscillations can be approximately assumed to be normally distributed when the time series data are analyzed. The degree of noise reduction depends on the criteria for outliers in the distribution of NDVI oscillations. Here, the confidence interval limit of normal distribution is employed for the detection of noisy observations. For instance, in the case of the selection of a 99.8% confidence interval for mean of the first derivatives, it means that most of the data are preserved and only 0.02% observations outside of the confidence interval are statistically corrected. The process is free from selection of an arbitrary threshold value or the experience of the analyst.

The performance of the proposed method was tested with simulated data and the multi-temporal NDVI images over 7 years. A Harmonic model widely employed in various applications of vegetation monitoring was utilized to verify the denoising effect on VI analysis. The results imply that the proposed method can be successfully employed for data reconstruction to make qualitative data streams for the study of vegetation dynamics.

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