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Rapid detection of new and expanding human settlements in the Limpopo province of South Africa using a spatio-temporal change detection method

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ABSTRACT

Recent development has identified the benefits of using hyper-temporal satellite time series data for land cover change detection and classification in South Africa. In particular, the monitoring of human settlement expansion in the Limpopo province is of relevance as it is the one of the most pervasive forms of land-cover change in this province which covers an area of roughly 125 000 km^2. In this paper, a spatio-temporal autocorrelation change detection (STACD) method is developed to improve the performance of a pixel based temporal Autocorrelation change detection (TACD) method previously proposed. The objective is to apply the algorithm to large areas to detect the conversion of natural vegetation to settlement which is then validated by an operator using additional data (such as high resolution imagery). Importantly, as the objective of the method is to indicate areas of potential change to operators for further analysis, a low false alarm rate is required while achieving an acceptable probability of detection. Results indicate that detection accuracies of 70% of new settlement instances are achievable at a false alarm rate of less than 1% with the STACD method, an improvement of up to 17% compared to the original TACD formulation.

1. Introduction

The most pervasive form of land-cover change in South Africa and many other developing countries around the world is human settlement expansion. In many cases, new human settlements as well as existing settlements expand informally and these expansions occur in areas that were previously covered by natural vegetation. Informal or unplanned settlements usually are formed as people move closer to employment opportunities, or in response to environmental and/or market forces. These settlements occur in various locations and often lack basic services such as electricity, running-water, water-borne sewage and refuse removal. The spatial layout is often unplanned and informally developed by the inhabitants of the settlements themselves (Palframan, 2005). Fig. 1 shows an informal settlement in the Limpopo province of South Africa which developed between the years 2003 and 2009 in an area that was initially mostly covered by natural vegetation. The development of these settlements need to be detected so that they can be mapped in detail and accommodated during planning sessions undertaken by regional and local government.

Detailed mapping of settlements are usually done by analysts digitizing features from aerial photography or high resolution satellite images at 1:10 000 scale. The feature data sets need to be updated regularly (at least every two years) to support spatial planning, especially where it concerns new settlements. Updating maps over large areas using manual photo-interpretation to scan the entire area is slow and costly. Due to constraints in cost and resources experienced by most mapping agencies, feature datasets can be up to a decade old, while only a small percentage of the area actually experienced change. Methods that can rapidly indicate areas having a high probability of change is thus very valuable to analyst as this can be used to direct their attention to high probability change areas for further evaluation using, for example, higher resolution imagery of the area. By using such a targeted approach, an increase in mapping efficiency of up to ten times has been observed compared to a complete re-extraction (Mitchell, 2012). We therefore focus on the development of automated change

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Fig. 1. Example of a new settlement development in the Limpopo province of South Africa. QuickBird image on the left shows the area being mostly covered by natural vegetation in 2003, whereas the QuickBird image on the right shows a new informal settlement in 2009 (courtesy of Google^{TM}Earth). The red polygons show the footprint of three 500 m × 500 m MODIS pixels. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

detection methods based on hyper-temporal satellite imagery to ultimately try to improve the productivity of detailed mapping efforts.

Satellite time series data has proven to be an effective data source for change detection (Verbesselt et al., 2010; Lunetta et al., 2006; de Beurs and Henerby, 2005; Kennedy et al., 2007) and in particular, time series analyses of hyper-temporal satellite data has been successfully applied for land cover change detection in South Africa specifically related to the monitoring of human settlement expansion. In Salmon et al. (2011), a Neural network based post classification change detection approach was used to detect when land cover conversion takes place from natural vegetation to settlement classes. In Kleynhans et al. (2011), MODIS time-series data was modeled as a triply modulated cosine function and an Extended Kalman filter was used to track the parameters of the model and declare change based on parameter behavior. In Grobler et al. (2013), the use of Page's cumulative sum (CUSUM) test was proposed as a method to detect new settlement. It should be noted that these aforementioned methods make limited use of spatial information and are predominantly pixel based.

An autocorrelation function (ACF) change detection method was recently demonstrated to detect the development of new human settlements in South Africa (Kleynhans et al., 2012). This method uses MODIS time-series data, which have previously been shown to be separable (distinguishable) for the natural vegetation and settlement land cover classes considered in this study (Kleynhans et al., 2010). The method uses the ACF of a MODIS time-series to provide an indication of the level of time-series stationarity (by considering the stability of the time-series mean and variance over time) which is then consequently used as a measure of land cover change.

In the original formulation of the ACF approach (Kleynhans et al., 2012), a single pixel's entire time-series for a single band (spanning eight years) was used as input. A change metric was then calculated by considering the properties of the ACF of the time-series. When the resulting change index was compared to a threshold value, a per-pixel based change alarm resulted. In this paper, the aforementioned method is extended to incorporate spatial information by not only considering the change index for a single pixel but also that of its surrounding pixels to determine whether a change should be declared. The proposed spatio-temporal ACF change detection (STACD) method uses temporal only ACF change metrics as calculated using the approach in Kleynhans et al. (2012) on a per pixel basis and compares this temporal ACF change index with that of pixels in its neighborhood to increase performance. It is important to note that the method is adapted to be able to easily incorporate multiple MODIS bands. The idea behind the spatio-temporal extension to the classic ACF change detection method is that when a single threshold is used over a large area (as was done in Kleynhans et al., 2012) there will inevitably be areas that are more non-stationary due to, for example, drought in arid areas, large scale commercial agriculture, etc. This will result in large areas showing up as change in regional maps that are not necessarily the type of anthropogenic changes that are of interest. The spatio-temporal extension to the ACF change detection method mitigates these changes by considering the change properties of the pixel neighborhood.

The objective of this paper is to develop a robust change detection method that is able to detect the formation of new informal settlements in areas that are typically covered by diverse natural vegetation. The detected changes should then be used to alert operators to areas of possible changes which could thereafter be validated, and the necessary maps updated, using high resolution imagery. Although the false alarm rate of the method can be set to any percentage depending on the requirement of the operator, in our use case the false alarm rate requirement was very low (<1%) as the area on which the change algorithm is run is large and the validation of a large number of false alarms could be very costly and time consuming.

2. Data description

2.1. MODIS data

The time series data used in this study was derived from MODIS data. The MODIS instrument data are converted systematically into terrestrial, atmospheric and oceanic products. The first seven bands (covering spectral bands in the visible, near infrared and shortwave infrared range Vermote et al., 2002) are typically used for land applications and are often referred to as the MODIS land bands. The specific land product that was used was the MCD43A4 product (Schaaf et al., 2002). This specific product have been used in various land cover change detection applications (Salmon et al., 2011; Kleynhans et al., 2011; Grobler et al., 2013) and is produced using data acquired from the MODIS sensor on-board the Aqua and Terra satellites and provides one composited sample (consisting of 16 days of acquisition) every 8 days. This product has a spatial resolution of 500 m and is BRDF-corrected. The time period that was considered is 2001/01 to 2008/01 resulting in a time-series containing 315 MODIS observations. Quality control (QC) flags where not explicitly used in the preprocessing of the time series data but it should be noted that the study area that was considered does not have prolonged time-periods of cloud cover which results in the data not containing significant missing values (typically less than 4% of samples). In the rare occurrence of missing values, cubic spline interpolation was used to infer these missing values (Atkinson, 1968).

2.2. Study area

The study area is located in northern South Africa and is mostly covered by natural vegetation which predominantly consist of grassland, savanna and shrub-land. A large number of informal