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Reconstruction of Landsat time series in the presence of irregular and sparse observations: Development and assessment in north-eastern Alberta, Canada

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ABSTRACT

Time series analysis of Landsat is limited by sparse and irregular sampling of clear-sky observations due to acquisition limitations, clouds, shadows, atmosphere, and sensor artifacts. Many remote sensing applications utilizing coarse spatial resolution time series methods are not suitable for Landsat due to observation sparsity. In this research we develop an imputation based approach to constrain the harmonic modeling method of Zhu et al. (2012, 2015) and Zhu and Woodcock (2014b) to reconstruct Landsat time series at a regular temporal interval. The approach was assessed for a boreal forest region in central Canada for different sparsity conditions. The imputed Landsat estimates for a specific pixel were predicted from climate or AVHRR data. These estimates were given a small weight relative to available Landsat observations in fitting the final harmonic model essentially constraining it to a more plausible range. In addition we implemented the model in a piecewise manner to handle non-linear temporal drift related to factors such as climate change, drought, or the allometric nature of vegetation regrowth. Results show that the inclusion of imputed estimates improved model predictions in the presence of observation sparsity. Where there were less than 3 observations within ± 20 days the imputation approach performed better, with a reduction in average reflectance error of 0.001 to 2.5. Error assessment with hold out observations, comparison to MODIS time series, and example predicted images are presented.

1. Introduction

Time series analysis has been widely utilized to enhance environmental monitoring and information extraction applications from coarse resolution earth observation (EO) archives. Some common examples are land cover mapping (Borak et al., 2000; Zhan et al., 2000; Pouliot et al., 2013), change detection (Lambin, 1996; Fraser et al., 2005; Lunetta et al., 2006; Hansen et al., 2008; Pouliot et al., 2009a), seasonality (Ramsay, 1998; Zhang et al., 2003; Latifovic and Pouliot, 2007; Zhao and Fernandes, 2009), phenology (White et al., 1997, 2009; Pouliot et al., 2010) and improved cloud and cloud shadow detection (Rossow and Garder, 1993; Cihlar et al., 1999; Lyapustin et al., 2008). With coarse resolution EO data, daily or close to daily measurements of the globe are acquired and thus recognized interpolation methods can be used to generate regularly sampled time series. However, for the Landsat historical record, cloud, haze, shadow, and sensor artifacts combined with the 16 day satellite repeat visit leads to irregular and sparse clear-sky measurements. Generation of regularly sampled time series cannot be easily accomplished with standard interpolation approaches where seasonal properties that change on the order of days to weeks are desired. Thus, time series methods developed for coarse resolution sensors are not suitable for historical Landsat data without some method to provide regularly estimated values.

The degree of irregular and sparse observations varies globally due to several factors other than cloud probability and satellite revisit. Historical Landsat coverage is greatest over the US than elsewhere in the world as shown in Ju and Roy (2008) and Kovalskyy and Roy (2013) due to various trade-offs in acquisition logistics and receiving station capacity particularly with Landsat 5. A mitigating factor is that scene overlap increases towards the poles. At the equator scene overlap is approximately 7% and increases to 80% at ± 80° latitude. Thus, the greater overlap compensates for the satellite repeat visit limitations, but annual seasonal cycles are of shorter duration towards the poles and require greater sampling for adequate characterization. Considering these factors, the more problematic areas for Landsat sampling can generally be identified as regions outside the United States, at low latitudes where scene overlap is minimal, in northerly regions with rapid seasonal development, and where cloud probabilities are largest such as costal zones and mountain regions. Depending on the location, technical implementation of Landsat time series applications may be most

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efficiently achieved by an image based approach where overlap is small (i.e. low latitudes) and a pixel based approach where overlap is large (i.e. high latitudes).

Methods to circumvent the sparsity of clear sky observations in Landsat time series are starting to be developed. Pooling observations for several years for phenology assessment has been carried out in Fisher et al. (2006) and Melaas et al. (2013). Methods combining coarse resolution MODIS data with Landsat have also been developed and have shown good performance, but are limited to the temporal extent of the coarse resolution data record (Gao et al., 2006; Hilker et al., 2009; Zhu et al., 2010; Hwang et al., 2011; Emelyanova et al., 2013). In the United States, Zhu et al. (2015) have developed and tested a harmonic modeling approach with considerable success that does not depend on other sensors. The approach has evolved from an initial version intended for change and near-real time change applications (Zhu et al., 2012), has been tested for post-seasonal cloud screening with Landsat (Zhu and Woodcock, 2014a), and for land cover monitoring in Zhu and Woodcock (2014b). In their approach, time series are modeled with harmonic sine and cosine basis, linear trend, and offset terms. The fit is carried out for segments of the time series where land cover change has not been detected. For abrupt changes the time series is modeled separately before and after the change event. In their work the model fit has been determined by least squares, weighted least squares, and regularized least squares approaches to enhance stability and efficiency. Similar to this approach is the B-Fast method developed by Verbesselt et al. (2010, 2012), but a more simplified harmonic based model was required for application to Landsat in tropical forests (DeVries et al., 2015). As stated in Zhu et al. (2015) the minimum sampling requirements are twelve samples to obtain a reliable result. This requirement may be achieved in the US, but in many other regions this could dramatically reduce the applicability of the method, particularly pre-2000, before Landsat 7 was operational. Further, in other regions with shorter seasonal cycles, snow cover, drought and other factors resulting in non-linear drift could result in the model being under-fit and needs to be investigated. An effective strategy to predict regular observations from Landsat for historical analysis is needed to better understand historical land cover, land cover change and seasonality.

1.1. Objectives

The objectives of this research were twofold. The first was to improve the accuracy of the harmonic model approach of Zhu et al. (2015) for Landsat modeling in the presence of sparse and irregular clear-sky Landsat observations. The second was to evaluate the accuracy related to sparsity in a northern boreal forest region.

2. Data and methods

Due to the multifaceted nature of the research an overview of the main elements of the methodology and the assessments undertaken to evaluate performance are provided in Fig. 1. To address sparse sampling we used an imputation approach to estimate Landsat observations from climate or AVHRR data. These estimated values were used to generate a final harmonic model based prediction using a weighted approach where the imputed values were given a small weight and clear-sky Landsat observations a large weight. The purpose of the imputation was to provide crude estimates to constrain modeling, particularly in regions of sparse observations. It is important to note that a high quality imputed estimate was not strongly required to achieve reasonable results. A second key modification from Zhu et al. (2015) was implementation in a piecewise manner to account for non-linear drift in the time series related to environmental or anthropogenic factors such as climate change, insect damage, allometric nature of vegetation regrowth, or possible pollution effects. To assess performance three evaluations were undertaken: 1) leaving a Landsat observation out for validation, 2) comparison with MODIS time series, and 3) visual evaluation of predicted image outputs. The elements in the figure are discussed in detail throughout the methods section.

2.1. Landsat time series

Landsat time series for three adjacent image footprints covering the north-eastern Alberta Oil Sands region of path/row designations 041/020, 042/020, and 043/020 were acquired for the period 1985–2012. Fig. 2 shows the study area and Landsat image footprints. In total there were 1731 Landsat 5 and 7 (L1T, L1G) images downloaded and processed for this analysis. Processing into a standard projection (Lambert Conic Conformal), radiometric calibration, scene identification (cloud, cloud shadow, water, and snow), and quality control was performed using the Moderate Resolution Time Series Data Management and Analysis System developed at the Canada Centre for Remote Sensing (CCRS, Latifovic et al., 2015). This system has been benchmarked against LEDAPS (Landsat Ecosystem Disturbance Adaptive Processing System) processing code and achieves similar performance. The CCRS system was used here as it provided a means to efficiently process, quality control, manipulate and extract time series from Landsat data.

Only the red, near infrared (NIR), and shortwave (SWIR, 1.6 μm) bands were processed as these are known to contain the majority of the data variation in Landsat (Small, 2004) and reduced the overall processing requirements for this research. In addition NDVI was also processed as it is a widely used index and has a sinusoidal seasonality that is well suited to the methodology implemented here. Other indices such as the Normalized Difference Moisture Index have more complex seasonal patterns that may be more difficult to model with harmonic basis (Delbart et al., 2005).

To account for missed and sub-pixel clouds a post-seasonal cloud screening method was applied based on Normalized Difference Vegetation Index (NDVI) time series. The method used a Lowess smoother (Cleveland, 1979) with a window size of 41 days, where values falling below the fit line were replaced with fit values in the final iteration. A window size of 41 was found to provide good generalization that was robust to noise in the time series. Significant deviations were detected as z-scores at the 90% confidence level below the Lowess fit. NDVI of clouds and shadows are known to take on smaller values than vegetated surfaces making it a good index for detection of contaminated values (Holben, 1986; Cihlar et al., 1997).

2.2. Coarse resolution earth observation time series

2.2.1. AVHRR data

Time series from the Advanced Very High Resolution Radiometer (AVHRR), High Resolution Picture Transmission (HRPT) 1 km data were used as one auxiliary data source to impute missing Landsat time series values. AVHRR data were processed as described in Latifovic et al. (2005) for calibration, geolocation, cloud screening, and compositing. Sensors used included NOAA-9, 11, 16, 17 and 19. Additional cross-sensor calibration for AVHRR sensors 2 and 3 was applied as described in Latifovic and Pouliot (2013). Composites were produced at 10 day intervals from 1985 to 2012. The red, NIR, and surface temperature measurements were used in modeling.

2.2.2. MODIS data

Moderate Resolution Imaging Spectroradiometer (MODIS) time series were used as a benchmark for comparison of the predicted Landsat results for the period 2000–2012. TERRA Level 1B geolocated top of atmosphere radiance (MOD02) data were processed following the procedures described in Trichtchenko et al. (2006) for downscaling of 500 m resolution bands to 250 m, Khlopenkov and Trichtchenko (2008) for resampling of the latitude and longitude fields to the Canada Lambert Conformal Conic projection, and Luo et al. (2008) for compositing to 10 day intervals. Only the SWIR band 6 of MODIS was

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