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Reconstruction of the land surface temperature time series using harmonic analysis

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ABSTRACT

Satellite remote sensing is an important approach for obtaining land surface temperature (LST) over wide temporal and spatial ranges. However, the presence of clouds generates numerous missing and abnormal values that affect the application of LST data. To fill data gaps and improve data quality, the Harmonic ANalysis of Time Series (HANTS) algorithm was employed to remove cloud-affected observations and reconstruct the Moderate Resolution Imaging Spectroradiometer (MODIS) LST data taken in the year 2005 for the Yangtze River Delta region of China. Analysis of MODIS data quality indicated that the yearly proportion of high-quality LST data in this region was less than 50% with numerous missing and low-quality data points. To reconstruct 8-day LST via the removal of cloud-contaminated observations, we applied pixel-by-pixel harmonic fitting to the time series and used fitted values to replace the missing and abnormal values in the original LST data. To evaluate the reconstruction performance, a simulated dataset was generated according to the percentage of cloud coverage in each 8-day period. Satisfactory validation results indicate that the harmonic method can effectively fit the NA Values caused by cloud cover and fill data gaps in the LST data, which can significantly improve the practical value of the MODIS LST dataset.

1. Introduction

As an essential parameter in the energy exchange between land and atmosphere (Sellers et al., 1988; Sobrino et al., 2003), land surface temperature (LST) is widely used in various scientific fields, including climatology, hydrology, agriculture, ecology, public health and environmental science (Running et al., 1994; Schmugge et al., 2002; Wan et al., 2002; Sun et al., 2004; Tatem et al., 2004; Estes et al., 2009). Due to the large spatial heterogeneity in the factors that affect surface temperature (e.g., solar radiation, albedo, soil thermal properties, and vegetation cover) and the complexity of the spatio-temporal distribution of surface temperature, conventional observations at ground sites are not sufficient to accurately characterize the distribution of surface temperature over a wide area. Satellite remote sensing provides a straightforward and consistent way to observe land surface characteristics over large scales. Satellite observation has an inherent limitation that it can only obtain the instantaneous land surface temperature at the overpass time, which to some extent limits its practical applications. However, satellite based thermal remote sensing is still a valuable complement to the traditional ground-based measurement because it is the only means available to provide spatially continuous LST information at regional and global scale. The Intergovernmental Panel on Climate Change (IPCC) has pointed out the urgent need for long-term remotely sensed LST data in global warming studies (Houghton et al., 2001). In recent decades, the application of thermal infrared remote sensing data to retrieve LST has become a major research topic in remote sensing research. Many scholars have studied retrieval methods for surface temperature data and developed several classical retrieval methods such as the split-window algorithm, the mono-window algorithm, and the single-channel algorithm (Price, 1984; Becker and Li, 1990; Sobrino et al., 1991; Franca and Cracknell, 1994; Wan and Li, 1997; Qin et al., 2001a, 2001b; Jimenez-Munoz and Sobrino, 2003). These methods have been broadly applied to various satellite data such as NOAA/AVHRR (National Oceanic and Atmospheric Administration/Advanced Very High Resolution Radiometer), Landsat/TM (Thematic Mapper), EOS/MODIS (Earth Observing System/Moderate Resolution Imaging Spectroradiometer), Envisat/AATSR (Advanced Along-Track Scanning Radiometer), etc. (Sobrino et al., 2004; Wan et al., 2004; Pinheiro et al., 2006; Sòria and Sobrino, 2007; Zhong et al., 2010).

However, a key issue in satellite derived LST data is the interference of clouds. LST cannot be retrieved from remote sensing images with cloud coverage, which results in numerous missing data points. In addition, the LST values of the pixels with partial cloud coverage that are not identified by the cloud detection algorithm are not

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accurate. The incompleteness and uncertainties caused by cloud coverage greatly affect the application of remotely sensed LST data. To improve the practical value of remotely sensed LST data, techniques to effectively fill data gaps and eliminate cloud interference need to be applied. In recent years, studies have been conducted to reconstruct remotely sensed LST data. Neteler (2010) proposed a method to identify pixels with cloud contamination based on the LST histogram and reconstructed daily MODIS LST data in the central-eastern Alps according to the temperature gradient. Ke et al. (2011) reconstructed 8-day MODIS LST data taken in the year 2008 in the northeastern Qinghai–Tibet Plateau using a spatial interpolation algorithm based on the elevation–temperature relationship. Crosson et al. (2012) used LST from the Terra/MODIS (morning overpass) to fill missing LST data of the Aqua/MODIS (afternoon overpass). In general, there are few studies on the reconstruction of cloud-free remotely sensed LST data. The objective of this paper is to explore a novel method to reconstruct remotely sensed LST data. The method was tested and evaluated by using MODIS 1 km 8-day LST data for the Yangtze River Delta of China. The structure of this paper is organized as follows: the study area and dataset are introduced in Section 2; the HANTS algorithm is described in Section 3; in Section 4, the data quality of MODIS LST product is first analyzed and then the HANTS algorithm is employed to rebuild cloud-free LST data; finally, the performance of HANTS for LST reconstruction is validated and discussed.

2. Study area and dataset

2.1. Study area

This area under study covers the Yangtze River Delta in Eastern China (Fig. 1). The study area consists of southern Jiangsu Province, northern Zhejiang Province, eastern Anhui Province, and Shanghai and covers an area of approximately 147,000 km^2. This delta has a marine monsoon subtropical climate with four distinct seasons. The average annual air temperature is 15.5 °C, ranging from a mean monthly minimum temperature of 0.3 °C in January to a mean monthly maximum temperature of 32.4 °C in July. The mean annual precipitation varies from 1000 mm to 1800 mm. There are over 135 days with high cloud coverage (cloud coverage > 80%). The northern and middle regions of the delta are mostly plains, and the land cover is dominated by agriculture area. The southern region is characterized by mountains covered with forest.

2.2. Dataset

The Aqua/MODIS land surface temperature product (MYD11A2, Version 005) acquired in 2005 was collected from the Reverb website (http://reverb.echo.nasa.gov). MYD11A2 is an 8-day composite land surface temperature product at 1-km resolution, which provides LST and corresponding quality assessment information at the overpass time of approximately 1:30 pm local solar time.

AQUA/MODIS LST data products are produced as a series of several products (Wan, 2007). The first LST product (MOD11_L2) is processed by retrieving the land surface temperature at the satellite overpass time using a split-window algorithm. Then the daily product (MYD11A1) is generated by mapping the pixels in the MOD11_L2 products for a day to the Earth locations on the sinusoidal projection. The 8-day composite LST product (MYD11A2) is calculated by averaging of the clear-sky LSTs of the MYD11A1 product during the 8-day period to reduce the large number of data gaps caused by cloud coverage.

3. Methods

The HANTS algorithm (Menenti et al., 1993; Verhoef, 1996) was developed to remove cloud-contaminated values in Normalized Difference Vegetation Index (NDVI) time series. The HANTS algorithm allows greater flexibility in the frequency choices and time series length than the Fast Fourier Transform (FFT) algorithm. In addition, it is relatively easy to exclude certain points from the time series because the samples are not required to be equidistant in time. By removing the obvious outliers in the time series, the extracted harmonics are much more reliable than the straightforward FFT algorithm (Roerink et al., 2000).

The HANTS algorithm applies a least squares curve-fitting procedure based on harmonic components by considering the most important frequencies in the time profiles. The fitted curve in the

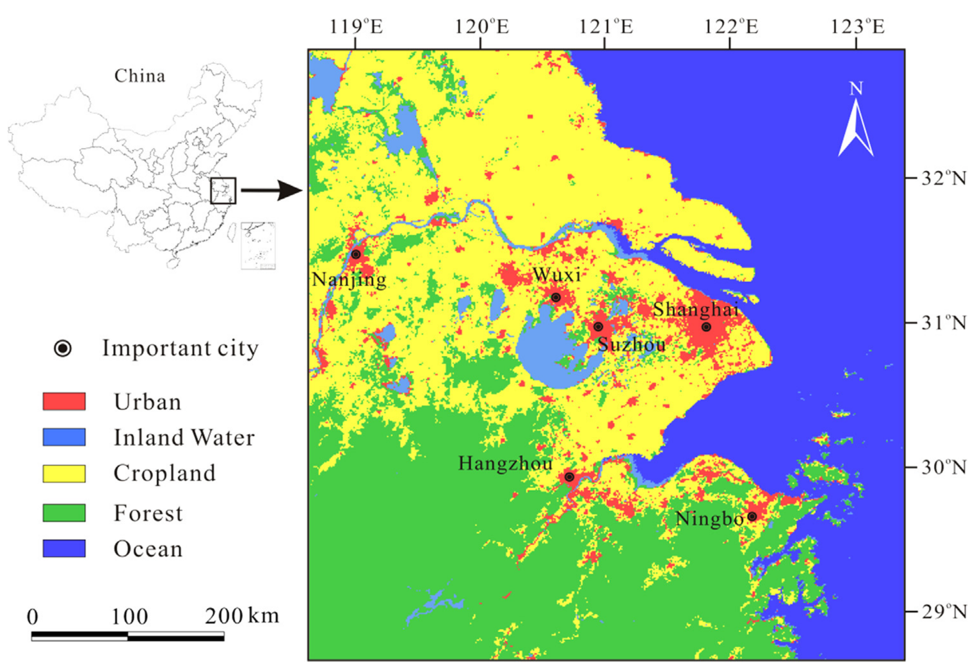

Fig. 1. Map of the study area.