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An empirical comparison of interpolation methods for MODIS 8-day land surface temperature composites across the conterminous Unites States

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ABSTRACT

Eight-day composite land surface temperature (LST) images from the Moderate Resolution Imaging Specroradiometer (MODIS) sensor are extensively utilized due to their limited number of invalid pixels and smaller file size, in comparison to daily products. Remaining invalid values (the majority caused by cloud coverage), however, still pose a challenge to researchers requiring continuous datasets. Although a number of interpolation methods have been employed, validation has been limited to provide comprehensive guidance. The goal of this analysis was to compare the performance of all methods previously used for 8-day MODIS LST images under a range of cloud cover conditions and in different seasons. These included two temporal interpolation methods: Linear Temporal and Harmonic Analysis of Time Series (HANTS); two spatial methods: Spline and Adaptive Window; and two spatiotemporal methods: Gradient and Weiss. The impact of topographic, land cover, and climatic factors on interpolation performance was also assessed. Methods were implemented on high quality test images with simulated cloud cover sampled from 101 by 101 pixel sites (1-km pixels) across the conterminous United States.

These results provide strong evidence that spatial and spatiotemporal methods have a greater predictive capability than temporal methods, regardless of the time of day or season. This is true even under extremely high cloud cover (> 80%). The Spline method performed best at low cloud cover (< 30%) with median absolute errors (MAEs) ranging from 0.2 °C to 0.6 °C. The Weiss method generally performed best at greater cloud cover, with MAEs ranging from 0.3 °C to 1.2 °C. The regression analysis revealed spatial methods tend to perform worse in areas with steeper topographic slopes, temporal methods perform better in warmer climates, and spatiotemporal methods are influenced by both of these factors, to a lesser extent. Assessed covariates, however, explained a low portion of the overall variation in MAEs and did not appear to cause deviations from major interpolation trends at sites with extreme values. While it would be most effective to use the Weiss method for images with medium to high cloud cover, Spline could be applied under all circumstances for simplicity, considering that (i) images with < 30% cloud cover represent the vast majority of 8-day LST images requiring interpolation, and (ii) Spline functions are readily available and easy to implement through several software packages. Applying a similar framework to interpolation methods for daily LST products would build on these findings and provide additional information to future researchers.

1. Introduction

Land surface temperature (LST) is the radiative skin temperature of the land surface, measured through emitted thermal infrared radiation in the diction of a given remote sensor. LST has been widely utilized across various scientific disciplines for a variety of purposes, including climatology, hydrology, metrology, land cover/land use change analysis, urban heat island monitoring, and ecosystem health assessment (Ren et al., 2011; Huang et al., 2013; Xu et al., 2013; Fan et al., 2014; Metz et al., 2014; Van Nguyen et al., 2015; Ma et al., 2017) and is a key parameter in the physics of land surface processes on regional and global scales (Liang, 2001; Yu et al., 2014).

Traditionally, LST has been recorded by radiometers at weather stations, resulting in in-situ point data. Over the past several decades, however, global LST datasets have become available via satellite remote sensing. These earth observation missions include the Moderate Resolution Imaging Spectrometer (MODIS), the Advanced Very High Resolution Radiometer (AVHRR), and Advanced Along Track Scanning

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Radiometer (AATSR) (Alfieri et al., 2013). If a researcher is interested in a large study area, satellite-derived LST is superior to readings from meteorological stations, especially in remote areas (Zeng et al., 2015). Although geostatistical methods are available for interpolation of ground observations, these can produce results with significant error due to invalid assumptions with regards to spatial averaging and the exclusion of topographic factors (Xu et al., 2013; Alfieri et al., 2013; Zhang et al., 2013; Zeng et al., 2015).

Due to its superior spatial and temporal resolution, MODIS has become the dominant satellite-based sensor for LST data (Ren et al., 2008; Zeng et al., 2016). The constellation consists of two identical sensors; one onboard the Terra satellite and another onboard the Aqua satellite. MODIS sensors estimate LST from thermal infrared bands using a split window algorithm (Li et al., 2012; Xu et al., 2013; Alfieri et al., 2013; Zeng et al., 2015). The Terra and Aqua combined sensors record the LST at each location up to 4 times a day at an approximately 1-km resolution (0.93-km); 1–2 times for the daytime temperature and 1–2 times for the nighttime temperature (Wan, 2008).

Daily MODIS LST images frequently contain invalid pixels as a result of cloud contamination (Yu et al., 2014; Metz et al., 2014). For cloudy regions, in particular, it is virtually impossible to accurately reconstruct a continuous time-series dataset (Van Nguyen et al., 2015). To overcome this issue, 8-day LST composites are available, which are derived from averaging all clear sky observations for a given pixel over an 8-day period. The high portion of missing pixels in daily LST images often makes it impractical for mapping purposes. Therefore, 8-day images are in many cases simpler to utilize and preferred (Hengl et al., 2012; Linghong et al., 2012). The use of 8-day images is also advantageous since it reduces storage space requirements and computation time. However, even these images can contain a large portion of invalid pixels. As there are numerous applications that require spatially and temporally continuous LST datasets (Qingbai and Yongzhi, 2004; Tomlinson et al., 2011; Linghong et al., 2012), several interpolation methods have been employed to fill gaps in composite images.

While a number of novel interpolation methods have been proposed for daily MODIS LST images (Neteler, 2010; Metz et al., 2014, Fan et al., 2014; Yu et al., 2015; Zeng et al., 2015; Shwetha and Kumar, 2016), our work focused on methods that have been used for 8-day composite images due to their wide applicability and easier utilization, as discussed above. Invalid values for 8-day LST composites have been interpolated over a variety of study areas, varying in both spatial and temporal extents (Refer to Table S.1 for more details). According to Metz et al. (2014), the interpolation of MODIS products can be categorized into three groups: spatial-based, temporal-based, and spatio-temporal-based. For temporal methods, invalid values are estimated on a pixel-by-pixel basis and do not consider values of geographically neighboring pixels. Spatial methods only consider the values of neighboring pixels and do not include values from different periods of time. Spatiotemporal methods consider pixels neighboring in both the temporal and spatial domain.

In terms of temporal interpolations, the Linear Temporal approach was utilized by Klingseisen (2010) and Zhang et al. (2015). For each missing pixel, the rate of change in LST between the closest proceeding and following 8-day periods with data are determined and used to construct a linear equation. Based on the temporal distance between the period in question and the LST of the closest proceeding period with data, the linear equation can be applied to fill the missing value. A more sophisticated temporal approach is Harmonic Analysis of Time Series (HANTS). This technique was originally developed for smoothing and gap-filling normalized difference vegetation index (NDVI) images, but has been used to interpolate invalid data in both daily (Maffei et al., 2012; Alfieri et al., 2013) and 8-day MODIS LST images (Xu and Shen, 2013; Xu et al., 2013; Van Nguyen et al., 2015). The algorithm uses a least squares curve fitting procedure based on harmonic components. For each harmonic, the amplitude and phase of the cosine function is determined during an iterative fitting procedure (Roerink et al., 2000).

In spatial interpolations, Linghong et al. (2012) proposed a novel method that relies on the assumption that LST is correlated with elevation. For each image, a moving window is used to interpolate invalid pixels based on the linear relationship with elevation. When a certain portion of cells within a window are valid, ordinary least squares (OLS) regression is performed, in which LST is modeled as a linear function of elevation. The LST is then interpolated based on the elevation of the center cell and the derived function. It is referred to as Adaptive Window, because this process continues after each pass until all pixels within an image are interpolated. This method was later applied by Zhang et al. (2013). Another spatial method for MODIS 8-day LST images is Spline interpolation. Three dimensional surface splines are used to interpolate a Z value (LST) for a given X and Y coordinate point. Both Hengl et al. (2012) and Kilibarda et al. (2014) used the *Close Gaps* function, available in System for Automated Geoscientific Analysis (SAGA) open source software (via the grid_tools module) for interpolation.

A simple Gradient spatiotemporal method for 8-day MODIS LST was first implemented by Hassan et al. (2007a, 2007b). This technique is based on temperature differences between the LST of pixels and average LST of images. For each 8-day image, the difference between the average LST (ie. average of all valid pixels) and each valid pixel is calculated. The average difference, or gradient, is then calculated on a pixel-by-pixel basis over a period of time. Missing values are filled by adding the average gradient of a pixel to the average LST of an 8-day image. Later studies used this approach to improve the quantification of growing degree days and surface wetness indices (Hassan et al. (2007a, 2007b) (2); Akther and Hassan, 2011; Rahman, 2011; Rahaman and Hassan, 2017)

Finally, a novel spatiotemporal approach was proposed by Weiss et al. (2014). Gaps are first filled by identifying proceeding and following calendar dates with a usable value for the gap pixel and searching outward for spatially neighboring pixels with valid values in both images. If the maximum search radius is reached without a pixel threshold being met, the search continues into calendar dates of proceeding and following years. Once the threshold is met, gap pixels are filled based on their LST from a given calendar date and the ratio of LST between images for neighboring pixels (inversely weighted by time-space distance). If all years are exhausted without the threshold being met, remaining pixels are filled using their average LST (computed across all years) and the ratio between the LST and multiyear average of valid spatially adjacent pixels within an iterative, multidirectional window. This technique, henceforth referred to as Weiss, has been extensively employed for epidemiology studies in various geographic regions (Pigott et al., 2015; Messina et al., 2015; Weiss et al., 2015; Mylne et al., 2015; Kraemer et al., 2015; Nsoesie et al., 2016; Golding et al., 2017; Longbottom et al., 2017).

The main limitation of studies that interpolated 8-day MODIS LST images is that assessment did not contrast an extensive number of methods and sites. There remains a need to compare the performance of methods across a variety conditions and using a common framework to assess interpolation accuracy across seasons, time of day, and site conditions. This study aimed to address this problem by empirically comparing six methods previously employed for interpolating invalid data in 8-day MODIS LST images (Linear Temporal, HANTS, Adaptive Window, Spline, Gradient, and Weiss). To the best of our knowledge, these constitute all methods that have been applied to 8-day MODIS LST. Our objectives were twofold: (1) determine which method is the best predictor of invalid 8-day LST pixels in daytime and nighttime images under a range of cloud cover and seasonality conditions and (2) assess how topographic, climatic, and land cover conditions impact their predictive power. The overarching goal was to provide an actionable guidance for scientists and practitioners with respect to the creation and usage of such datasets.