Remote Sensing of Environment 216 (2018) 472–481

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Uncertainty estimation method and Landsat 7 global validation for the Landsat surface temperature product

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ARTICLE INFO

Keywords:
Remote sensing
Earth surface monitoring
Landsat
Surface temperature
Validation
Uncertainty estimation

ABSTRACT

Surface temperature is a valuable metric for many Earth monitoring applications, which motivated the development of the Landsat Surface Temperature (LST) product. The initial LST algorithm, developed by Cook, was geographically restricted since the atmospheric inputs and truth data were limited to North America (Cook, 2014. Atmospheric Compensation for a Landsat Land Surface Temperature Product. Rochester Institute of Technology). The main objectives for this product are to produce an LST image for every available Landsat thermal image, and to also provide a per-pixel estimate of LST uncertainty. Various studies were performed in order to allow the LST algorithm to operate globally, after which a thorough global validation study was performed for Landsat 7 images. In this study, the LST algorithm was found to have an average error for all cases of −0.211 K compared to the MODIS Sea Surface Temperature (SST) product. For cases where transmission was less than 0.3 and clouds were within 1 km of the validation, the LST RMSE was 2.61 K. When transmission was at least 0.85 and clouds were more than 40 km away, the RMSE was 0.51 K. A LST uncertainty estimation method was developed that utilizes standard error propagation in combination with observed trends between LST error, transmission, and cloud proximity. When the uncertainty method was applied to the global validation dataset, 20% of the estimated LST uncertainties were less than 1 K and 63% were less than 2 K. LST uncertainty can be extended to other Landsat sensors pending small validation studies, and will be an extremely beneficial tool for users, since it allows them to select all pixels in an LST image that meet their accuracy requirements.

1. Introduction

Surface temperature is a fundamental component to the comprehension and surveillance of the Earth's surface. This metric is valuable to many fields such as weather prediction, climate change research, and agriculture. Surface temperature can be derived from remotely sensed thermal imagery, which can be obtained from several satellites that capture thermal imagery of the Earth. Landsat is a series of satellites that has been capturing thermal imagery since 1982, with a spatial resolution of 60–120 m and a temporal resolution of 16–18 days (USGS, 2013). These characteristics, in addition to its well calibrated sensors and data archive, make Landsat a very attractive choice for various scientific endeavors. A Landsat-based surface temperature product would be advantageous because the database would span the past 35 years (useful for time-studies), and the moderate spatial resolution would lend itself to smaller-scale research such as monitoring lakes or small farms.

The United States Geological Survey (USGS) has funded the Rochester Institute of Technology (RIT) to develop the atmospheric compensation component of the "Landsat Surface Temperature (LST) Product." The resulting algorithm utilizes a single-band method of deriving surface temperature, and is able to produce atmospheric compensation parameters at a per-pixel level for any Landsat thermal image (Cook, 2014; Cook et al., 2014). When coupled with knowledge of surface emissivity, per-pixel surface temperatures can be obtained. The North American Regional Reanalysis (NARR) database provided the necessary atmospheric profiles (NOMADS, 2015) needed by the radiative transfer program MODTRAN (AFRL, 2015).Surface emissivity was available through the ASTER Global Emissivity Database (Hulley et al., 2015). Cook performed validation studies using Landsat 5 imagery, where the truth data came from buoy measurements in North American waters (Cook, 2014). The results of this investigation showed that under ideal conditions (e.g. no clouds) the average error in the surface temperature algorithm was −0.262 K, which was encouragingly low.

Cook's validation efforts were limited to North America because both the reanalysis product used and the source of truth data were confined to that region. The ultimate goal was to produce a product that was well validated across the globe and demonstrated for more Landsat

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https://doi.org/10.1016/j.rse.2018.06.026
Received 16 December 2017; Received in revised form 13 June 2018; Accepted 17 June 2018

sensors. This was accomplished by switching the reanalysis product to MERRA (Modern-Era Retrospective analysis for Research and Applications), and using the MODIS' Sea Surface Temperature (SST) product as truth (Kempler, 2009). In addition, a novel method was developed for estimating the per pixel uncertainty in the surface temperature product, which will be invaluable to users of the LST product who have various accuracy requirements.

2. Background

The derivation of surface temperature from single thermal band imagery requires knowledge of radiometric theory, as well as accurate sources of atmospheric variables, surface emissivity, and truth data for validation studies. There are many radiance paths that contribute to what a sensor sees, but since Landsat's thermal bands are in the thermal regime, several radiance terms can be disregarded because they are negligible in this part of the electromagnetic spectrum. Therefore, the equation to derive surface temperature from Landsat images can be expressed as follows:

$$L_{obs} = (L_T \epsilon + (1-\epsilon)L_d)\tau + L_u \tag{1}$$

In this equation, L_{obs} is the sensor-reaching radiance, L_T is the blackbody radiance emitting from a surface with temperature T, ϵ is the emissivity of the surface, L_d is downwelled radiance, τ is atmospheric transmission, and L_u is upwelled radiance. Note that the radiance terms here are in "effective spectral radiance," which uses the spectral response function of the sensor to obtain a single value of radiance per unit wavelength. Solving for surface temperature requires a method of determining the atmospheric parameters τ, L_u, and L_d, as well as a reliable source of emissivity. Once these terms have been obtained, Planck's equation can be used to create a lookup table for converting L_T to surface temperature.

The desire of the USGS was for the Landsat-derived surface temperature product to span the entire thermal archive, which would provide a great resource for many research applications. The Landsat predating Landsat 8 all have a single thermal band, so a single band method for deriving surface temperatures was needed in order to utilize Landsat's impressive thermal archive. Split window techniques are currently not viable for Landsat 8 because of the issues with the thermal infrared sensor, where stray light enters the field of view and causes banding artifacts (Montanaro et al., 2014). In order to implement a single band method for satellite-derived surface temperature, accurate knowledge of atmospheric profiles and surface emissivity is needed. Reanalysis products such as North American Regional Reanalysis (NARR) or Modern-Era Retrospective analysis for Research and Applications (MERRA) provide various atmospheric variables in vertical columns in a spatial grid (Kempler, 2009; NOMADS, 2015). MODTRAN (MODerate resolution atmospheric TRANsmission) is a radiative transfer code that is able to perform calculations from atmospheric profile information, which makes it possible to derive transmission, upwelled radiance, and downwelled radiance.

3. Methodology

3.1. LST algorithm overview

There have been several proposed single band algorithms for deriving land and/or sea surface temperatures from satellite imagery, but few have been validated or implemented on a large scale (Sobrino et al., 2004; Sun et al., 2004). For the LST algorithm, atmospheric profiles from NARR were fed into MODTRAN simulations, which produced estimates for transmission, upwelled, and downwelled radiance in a 3D grid (see Fig. 1). Various interpolation methods combined with Digital Elevation Models (DEMs) for the Landsat images produce these atmospheric parameters on a per-pixel level. When estimating transmission, upwelled radiance, and downwelled radiance for a given point in the 3D grid, surface temperature and emissivity are varied between three simulations. This is done in a way so that Eq. (2) can be used to solve for transmission and upwelled radiance, the values of which allow Eq. (3) to solve for downwelled radiance (Laraby, 2017).

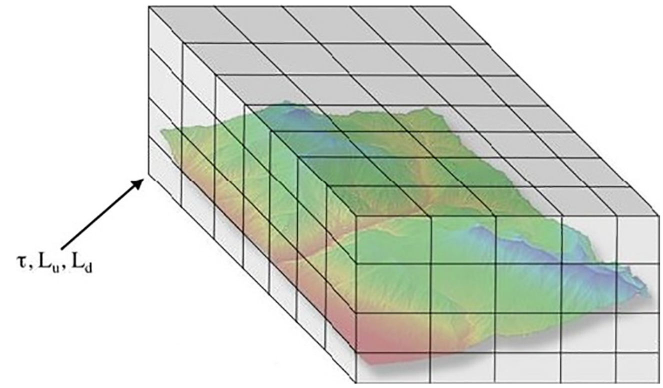

Fig. 1. Illustration of the data cube that is generated by calculating atmospheric parameters at each reanalysis point for multiple altitudes (Image from http://www.scisoft-gms.com).

$$L_{obs} = L_T\,\tau + L_u \tag{2}$$

$$L_d = \frac{\frac{L_{obs}-L_u}{\tau} - L_T\,\epsilon}{1-\epsilon} \tag{3}$$

In order to achieve the goal of producing a global LST product, a switch to a global reanalysis product known as MERRA (Modern-Era Retrospective Analysis) was made. This decision was based on a studies performed by Cook (2014) and Laraby (2017) that compared LST validation results when each of the reanalysis products were used. Approximately 400 NARR-derived and MERRA-derived LST retrievals were generated, and the two datasets were found to be statistically equivalent via a *t*-test.

Accurate and reliable truth data is crucial for validating any surface temperature retrieval algorithm. Some past-utilized sources of truth data for such algorithms include subterranean measurements (Vasquez et al., 1997), Atmospheric Radiation Measurement (ARM) observations of surface skin temperature (Sun and Pinker, 2003), field campaigns with TIR radiometers (Wan et al., 2004), and a combination of field and lab spectra measurements at two sand dune sites (Hulley and Hook, 2011). For the Landsat Surface Temperature algorithm, buoys managed by NOAA were used to provide bulk temperature measurements on a regular basis. These measurements were corrected to skin temperature using a method described by Cook et al. (2014) and compared to surface temperature retrievals (Padula and Schott, 2010; Schott et al., 2012). Unfortunately, well-maintained buoys with accurate and trustworthy bulk temperature measurements are not available across the globe. A validation study was performed, however, that showed that the MODIS (Moderate Resolution Imaging Spectrometer) Sea Surface Temperature (SST) product would be an adequate source of truth data (Laraby, 2017).

3.2. Validation

Laraby (2017) performed a study to determine if the MODIS SST product was an adequate source of ground truth compared to the buoy-derived surface temperatures that were used in past validation studies. For a total of 75 samples, the SST product was an average of 0.244 K (0.699 K standard deviation) above the buoy-derived surface temperature at the same location. For the same locations, the Landsat 7 derived LST retrievals were an average of 0.241 K below the buoy-derived temperatures (0.701 K standard deviation). These statistics were found to be satisfactory; however, the averages (though quite small) were