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Validation of Land Surface Temperature products derived from the Visible Infrared Imaging Radiometer Suite (VIIRS) using ground-based and heritage satellite measurements

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ABSTRACT

Thermal infrared satellite observations of the Earth's surface are widely used to retrieve Land Surface Temperature (LST) and monitor LST changes around the world. Since January 2012, the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi National Polar-Orbiting Partnership (S-NPP) has provided daily observations of LST with a spatial resolution of 750 m at nadir. Comparison of the standard VIIRS LST product with the equivalent daily standard product from the Moderate Resolution Imaging Spectroradiometer (MODIS) collection-5 and with ground-based measurements over vegetated and inland water surfaces showed good agreement. Analysis indicated the accuracy and precision of the VIIRS product over these cover types was 0.2 K and 2.0 K respectively provided the analyses included appropriate compensation for any spatial heterogeneity in LST within the validation site. However, comparisons between in situ LST and the VIIRS and MODIS LST over arid and semi-arid regions indicate both satellite products significantly underestimate the LST, and the VIIRS algorithm can have large errors in the retrieved LST over areas of high atmospheric water vapor. Errors of up to 4 K were observed over semi-arid and arid areas due to incorrect characterization of emissivity, and differences of up to 15 K were observed over areas with high atmospheric water content between the VIIRS LST and matching MODIS LST.

1. Introduction

Land Surface Temperature (LST) is a key variable for surface water and energy budget calculations that can be obtained globally and operationally from satellite observations. The Visible Infrared Imaging Radiometer Suite (VIIRS) instrument was launched in October 2011 on the Suomi National Polar-Orbiting Partnership (S-NPP) satellite. VIIRS was designed to improve upon the capabilities of the Advanced Very High Resolution Radiometer (AVHRR) onboard NOAA's operational polar-orbiting satellites and provide observational overlap and continuity with both the AVHRR and the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on the NASA Terra and Aqua platforms of the NASA Earth Observing System (Justice et al., 2013).

High temporal and spatial resolution LST products known as Environmental Data Records (EDR) have been derived from VIIRS data since processing began January 18th, 2012. These products provide a new source of LST for many applications, including weather forecasting (Meng, Li, Zhan, Shi, & Liu, 2009; Zheng et al., 2012), short-term climate prediction (Reichle et al., 2009; Reichle, Kumar, Mahanama, Koster, & Liu, 2010), extreme weather monitoring (Anderson, Hain, Wardlow, Mecikalski, & Kustas, 2011), and irrigation and water resource management including agricultural drought forecasting (Anderson, Allen, Morse, & Kustas, 2012; Kerr, Lagouarde, Nerry, & Ottlé, 2004). LST is particularly useful for agricultural drought forecasting since it is very sensitive to plant water stress and a strong indicator of changes in root zone soil moisture (Anderson et al., 1997, 2012; Anderson, Norman, Diak, Kustas, & Mecikalski, 1997; Guillevic & Koster, 2002; Guillevic et al., 2002; Moran et al., 2009).

The VIIRS thermal bands measure the spectral radiance emitted by the land surface and the atmosphere. The surface-emitted radiance is

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attenuated by atmospheric constituents such as clouds, haze and absorbing gases (mainly water vapor, carbon dioxide, ozone and methane). Under clear sky conditions, the spectral radiance at the top of the atmosphere is the sum of three components: (1) the radiance emitted by the land surface and attenuated by the atmosphere, (2) the atmospheric radiance reflected by the land surface and attenuated by the atmosphere, and (3) the radiance emitted by the atmospheric constituents in the direction of the sensor. In order to retrieve LST from the thermal infrared radiance measured by VIIRS, the effect of the atmosphere must be removed and surface radiance has to be corrected for emissivity effects, which can otherwise introduce large uncertainties especially for split-window based algorithms (Jacob et al., 2008, Chap. 10; Kerr et al., 2004). Preliminary VIIRS LST EDR datasets became available publicly on October 22, 2012, and are currently being evaluated by scientists from NASA and NOAA, among others.

This study presents validation results for the VIIRS LST EDR obtained from comparisons with ground-based measurements and operational LST products from Aqua MODIS (1:30 am/pm satellite orbit). The limitations of the VIIRS LST algorithm are discussed, and guidance on methodologies and recommended good practice for validating moderate resolution satellite-based LST products is provided. Section 2 presents a short review of the different methods commonly used to validate satellite LST products and enumerates the sources of errors associated with each method. Section 3 describes the specific protocols used to evaluate the VIIRS LST EDR against ground based measurements and Aqua MODIS LST products, and discusses the challenges in retrieving the LST from satellite measurements. The different satellite products and the associated retrieval algorithms used in the study are presented in Section 3, and the in situ reference datasets are presented in Section 4. Section 5 presents the VIIRS LST validation results, while Section 6 suggests future algorithm refinements and provides general guidance on retrieving LST from remotely sensed data.

2. Satellite LST validation approaches

In order to maximize the usefulness of LST for research and studies it is necessary to know the uncertainty in the LST measurement. The VIIRS LST was designed to meet the quality specifications of operational users, such as Numerical Weather Prediction modelers. Multiple validation methods and activities are necessary to assess LST compliance with the specifications. A detailed presentation of previous satellite-based LST validation efforts is available in review studies by Li et al. (2013), Merchant et al. (2013) and Schneider, Ghent, Corlett, Prata, and Remedios (2012). Four different methods have been widely used to validate and determine the uncertainties in LST products derived from satellite measurements:

- Temperature based validation. This approach involves comparisons with ground-based measurements of LST, and has been frequently used to validate LST products retrieved from MODIS (Bosilovich, 2006; Coll et al., 2005, Coll, Galve, Sanchez, & Caselles, 2010; Guillevic et al., 2012, 2013; Hook, Vaughan, Tonooka, & Schladow, 2007; Trigo, Monteiro, Olesen, & Kabsch, 2008; Wan, 2008; Wang & Liang, 2009; Wang, Liang, & Meyers, 2008), from the Spinning Enhanced Visible and Infrared Imager onboard Meteosat Second Generation (MSG/SEVIRI) (Göttsche et al., 2013; Kabsch, Olesen, & Prata, 2008; Trigo et al., 2008), from AVHRR (Prata, 1994), from the Advance Spaceborne Thermal Emission and Reflection (ASTER) radiometer onboard Terra (Sobrino et al., 2007), from the Along Track Scanning Radiometer (ATSR) (Prata, 1994), or from VIIRS (Li et al., 2014). This approach allows the uncertainties in LST products to be determined, however, a large number of in situ measurements are needed if the validation site is spatially heterogeneous in order to characterize it correctly (Guillevic et al., 2012). Furthermore, most field radiometers collect observations at nadir angles, whereas wide field-of-view satellite scanners like VIIRS collect most observations off-nadir. These limitations provide significant uncertainty that is very difficult to eliminate. Therefore, the method is particularly suited for studies over inland water bodies which provide large spatially homogenous temperature targets and can be used to both validate and refine the retrieval algorithm (Coll, Hook, & Galve, 2009; Hook et al., 2007; Hulley, Hook, & Schneider, 2011). Unfortunately, validation over water does not assess the LST algorithm correction for surface emissivity.
- Scene-based comparisons. This approach involves comparing a new satellite LST product with a heritage LST product (Guillevic et al., 2013; Hulley & Hook, 2009a; Jacob et al., 2004; Trigo et al., 2008). The method can be particularly valuable for finding spatial disagreements between LST products for a wide range in cover types. However, this is not an absolute validation and satellite LST intercomparisons alone do not provide an independent validation measurement unless one of the satellite products has been independently validated. Different retrieval algorithms based on similar assumptions and formulations (e.g. split-window) can be highly consistent with each other but biased when compared to ground reference measurements. Also, this approach requires accounting for differences in spatial resolution, view angle and overpass time between the two different satellite datasets.
- Radiance-based validation (Coll, Wan, & Galve, 2009; Hulley & Hook, 2012; Niclòs, Galve, Valiente, Estrela, & Coll, 2011; Wan, 2014; Wan & Li, 2008). This approach requires precise estimates of channel specific surface emissivity values and atmospheric temperature, and water vapor profiles coincident with the satellite overpass. LST values are then derived by inverting a radiative transfer model. Radiance-based validation has the advantage that temperature measurements are not required at the time of the overpass. Instead emissivity measurements made at a different time can be used with model-based atmospheric information. The method is best for large-scale validation efforts on a global scale or for products with coarse spatial resolution.
- Time series comparisons (Hook et al., 2007; Merchant et al., 2013). This method is used to detect problems that can occur during the instrument's life, e.g. calibration drift (Hook et al., 2007), or unrealistic outliers due to cloud coverage (Schneider et al., 2012). However, the approach requires relatively long time series of observations over very stable targets over time. The VIIRS standard LST has only been available for 1.5 year and a longer record is required before the data lend themselves to this approach.

The four different approaches are complementary and provide different levels of information about the quality of the retrieved LST. These four methods are part of the validation plan for the ATSR LST products (Schneider et al., 2012), for example, and are usually required to achieve Stage-3 validation status as defined by the MODIS land validation protocol (http://landval.gsfc.nasa.gov).

3. Validation methodology for VIIRS LST

Under clear sky conditions, the top of atmosphere radiance measured by a spaceborne sensor ($L_{sat,\lambda}$) includes contributions from the surface emission, the atmospheric upwelling radiance ($L^{\uparrow}_{sky,\lambda}$) and atmospheric downwelling radiance ($L^{\downarrow}_{sky,\lambda}$) reflected by the Earth's surface and attenuated by the atmosphere (Eq. 1). Retrieval algorithms rely on one or more top-of-atmosphere spectral measurements to account for atmospheric effects and estimate LST.

$$L_{sat,\lambda} = \left[\varepsilon_\lambda B_\lambda(LST) + (1-\varepsilon_\lambda) L^{\downarrow}_{sky,\lambda}\right] \tau_\lambda + L^{\uparrow}_{sky,\lambda} \tag{1}$$

where ε_λ is the spectral emissivity at wavelength λ or associated with a specific (relatively narrow) domain [λ_1, λ_2] centered on wavelength λ, $B_\lambda(T)$ is the Planck function describing the radiance of a black body at temperature T, and τ_λ is the atmospheric attenuation.