Remote Sensing of Environment 158 (2015) 110–125

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Diurnal temperature cycle as observed by thermal infrared and microwave radiometers

T.R.H. Holmes [a,b,*], W.T. Crow [a], C. Hain [c], M.C. Anderson [a], W.P. Kustas [a]

[a] USDA-ARS, Hydrology and Remote Sensing Lab, Beltsville, MD, USA
[b] Science Systems and Applications, Greenbelt, MD, USA
[c] Earth System Interdisciplinary Center, University of Maryland, College Park, MD, USA

ARTICLE INFO

Article history:
Received 21 July 2014
Received in revised form 15 October 2014
Accepted 25 October 2014
Available online 2 December 2014

Keywords:
Land surface temperature
Diurnal temperature cycle
Thermal infrared
Passive microwave

ABSTRACT

Land surface temperature (LST) is a key input to physically-based retrieval algorithms of hydrological states and fluxes, and global measurements of LST are provided by many satellite platforms. Passive microwave (MW) observations offer an alternative to thermal infrared (TIR) LST retrieval approaches. Although MW has a lower spatial resolution, its temporal record is more complete as it is more tolerant to clouds. Moreover, merging TIR and MW LST with independent random errors should result in enhanced LST products. Despite these benefits, MW-based LST retrievals are not widely adopted for land applications except as an input to soil moisture retrieval algorithms. This research aims to facilitate expanded use of MW-based LST by formulating a model to explain the systematic differences in comparison to TIR-LST, and quantifying random errors in each datastream. To that end, we compile a 6-year MW-LST dataset over the African continent, combining observations from seven inter-calibrated low orbiting satellites equipped with suitable microwave radiometers. We compare the diurnal timing and amplitude of this dataset to TIR-LST time-series produced by LSA-SAF from the Meteosat Second Generation geostationary satellite. A third independent data source, the skin temperature as modeled by the Modern Era Reanalysis for Research and Applications (MERRA) as produced at NASA's Global Modeling and Assimilation Office, is included in a triple collocation analysis to calculate the random error in the amplitude anomaly. Results suggest that the anomaly in diurnal LST amplitude over much of the African domain can be estimated from TIR and MW with similar levels of random error for clear sky days, except over dry sandy desert areas where the MW sensing depth extends too far below the surface. The temporal sampling advantage of MW, due to higher cloud tolerance in comparison with TIR retrievals, appears to be substantial but will need to be verified by follow-on studies. Overall the results of this study present a significant step forward in reconciling the systematic differences in LST, preparing the way for a global merger of MW and TIR LST time-series.

1. Introduction

Land surface temperature (LST) is a key variable in many hydrological studies, mainly through its role in satellite retrievals of soil moisture (Owe, De Jeu, & Walker, 2001), evapotranspiration (Anderson et al., 2011), and Earth radiation budget (Gupta, 1989). Because of this widespread utility, a significant number of earth observation satellites carry a thermal infrared (TIR) radiometer to measure brightness temperature, from which LST may be retrieved. In addition, several satellites with multi-frequency passive microwave (MW) radiometers include frequency bands (e.g. 37 GHz) that can be used to estimate LST (Holmes, De Jeu, Owe, & Dolman, 2009; Prigent & Rossow, 1999). This abundance of LST information provides flexibility for supporting different modeling applications, allowing the user to choose an LST estimate best suited to the application in terms of spatial resolution and tolerance to clouds. However, little emphasis has been placed on evaluating performance of different LST products in retrievals of soil moisture or ET, although LST remains one of the main contributors to uncertainty in these retrievals, especially over short time scales (Holmes & Jackson, 2010). More generally, uncertainties associated with current LST estimates affect our ability to monitor the global hydrological cycle because it is a boundary condition fundamentally tied to the surface energy balance and the relative partitioning of available energy into sensible and latent heat flux. The goal of this research is to facilitate a merger of LST estimates acquired from both MW and TIR observations into a robust integrated LST estimate that will improve the reliability, continuity and mutual consistency of existing LST products.

The large spatial and temporal heterogeneity in terrestrial LST fields complicates efforts to inter-compare measurements acquired from retrieval techniques which vary in viewing angle, spatial resolution and/or temporal resolution (Ermida et al., 2014; Guillevic et al., 2012).

* Corresponding author at: USDA-ARS, Hydrology and Remote Sensing Lab, BARC-West, B007, 10300 Baltimore Ave., Beltsville, MD 20705, USA. Tel.: +1 301 504 7614.
E-mail address: thomas.holmes@ARS.USDA.GOV (T.R.H. Holmes).

http://dx.doi.org/10.1016/j.rse.2014.10.031
0034-4257/

Uncertainties regarding vertical sampling depth within the soil or vegetation add further complexity when estimates are derived from different sensor technologies or land surface models (LSMs) (Holmes, Jackson, Reichle, & Basara, 2012). The lack of information about differences between various LST estimates is a barrier to integrating alternative LST estimates into an enhanced combined product. This lack of knowledge extends to both the systematic characteristics of the error (i.e., that part of the difference which is constant and/or has a systematic variation with day of year or hour of day) and the magnitude of wholly random retrievals errors. Recently, a new approach was developed to systematically reconcile the structural components of the modeled and measured LST time-series acquired from various MW sensors, while reducing random error through application of a basic Kalman Filter (Holmes, Crow, Yilmaz, Jackson, & Basara, 2013). In that study the aim was to remove systematic differences in LST to allow for further random noise reduction through a Kalman filter. The approach was limited to MW LST estimates (particularly Ka-band, 37 GHz) and did not consider the integration of TIR-based LST. In this paper the main aim is to study how well daily estimates of MW and TIR-based LST agree, and if they can potentially be integrated to provide a single estimate of diurnal amplitude (A). This is because A is used as a standalone input to energy balance approaches (Anderson et al., 2011) and MW-based LST has been identified as a potential supplement to current TIR-based estimates.

The methodology of estimating LST from TIR is well-developed (Norman & Becker, 1995), and there are currently multiple off-the-shelf LST products available. Here we make use of the skin temperature product produced by the Land Surface Analysis Satellite Applications Facility (LSA SAF, see http://landsaf.meteo.pt) from TIR imagery collected with the Meteosat Second Generation (MSG) geostationary (GEO) satellite, as the 15-minute temporal resolution of this product is ideal for investigating diurnal features in LST. Because TIR-based retrieval of LST is not possible under cloudy conditions, the hypothesis is that MW observations, with greater tolerance for clouds obscuring the land surface, can be used for gap filling satellite-derived time-series. Because there is no readily available MW-based LST database equivalent to TIR based sets, Ka-band brightness temperature observations from a combination of satellites serve as a proxy for MW LST (similar to the approach in Holmes, Crow, Yilmaz et al. (2013)). A physical interpretation of the systematic differences between these MW and TIR LST will be developed by considering both radiative transfer (Mo, Choudhury, Schmugge, Wang, & Jackson, 1982) and sensing depth considerations (Holmes, Crow & Hain, 2013). A third data source with estimates of LST, independent from TIR and MW, is provided by land surface models. Specifically, we use the 'skin temperature' surface level state from the Global Modeling and Assimilation Office (GMAO) Modern Era Reanalysis for Research and Applications (MERRA, see http://gmao.gsfc.nasa.gov/research/merra).

The temperature records for this study are described in Section 2, together with the method used to summarize their DTC. Section 3 presents a radiative transfer based methodology to remove systematic differences between MW and TIR estimates of daily mean temperature and diurnal A. In Section 4 A is singled out for a detailed study of its random error. Finally, Section 5 presents a comparison of both TIR and MW LST in terms of their absolute values before and after the identified systematic differences are removed. This work will support the implementation of the global merger of MW and TIR data to create a continuous global LST product for the period 2003–2011, which may be used for remote sensing-based retrieval of soil moisture, ET and precipitation.

2. Materials

The data sets for this investigation are the same as those used in a previous study of the phase and timing of diurnal land surface temperature cycles (Holmes, Crow, & Hain, 2013): MW imagery from 7 Ka-band satellites, modeled LST from MERRA, and the Meteosat Second Generation-9 (MSG) TIR LST product. In this study, the time period of analysis is extended to six years, January 2007 to December 2012, but the domain is limited to the coverage of MSG: Europe and Africa. All data sets are binned to a common 0.25-degree resolution grid box. Hereinafter, variables derived from these three data sources are distinguished by the following superscripts, I: thermal infrared, M: passive microwave, R: reanalysis (MERRA). A brief description of the three data sets is provided below.

2.1. Thermal infrared observations

Land surface variables derived from EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites) satellites are provided by the Land Surface Analysis Satellite Applications Facility (LSA SAF, see http://landsaf.meteo.pt). Land surface temperature is retrieved from the TIR window channels at 10.8 and 12.0 μm of the Spinning Enhanced Visible and Infra Red Imager (SEVIRI). The TIR radiances are converted to LST via the Generalized Split-Window (GSW) algorithm (Wan & Dozier, 1996). The retrieval of the emissivity needed for the GSW is based on the Vegetation Cover Method (VCM; Caselles, Coll, & Valor, 1997), which relies on the use of a geometrical model to compute an effective emissivity based on the knowledge of the Fractional Vegetation Cover (FVC), also retrieved by the LSA SAF. The identification of cloudy pixels is based on the cloud mask generated by software from NWC SAF (Nowcasting and Very Short Range Forecasting Satellite Application Facility). The uncertainty of the LSA SAF LST product is estimated to be ~2 K, with values above 3 K for higher LST range (Trigo et al., 2011). It has been validated in a number of studies — the most recent of which show very high accuracy with little bias relative to in situ data (Ermida et al., 2014; Göttsche, Olesen, & Bork-Unkelbach, 2013). Some earlier studies (e.g.Kabsch, Olesen, & Prata, 2008) noted a positive bias relative to in situ measurements at higher temperatures, but this may be partially attributed to unaccounted effects of viewing and illumination angles (Ermida et al., 2014).

Because SEVIRI is located on the geostationary MSG satellite, fine temporal resolution (15 min) observations are available. LST is provided on a 3-km equal area grid. For comparison with the lower spatial resolution MW and LSM data, it was aggregated to a 0.25-degree regular grid via simple averaging of the oversampled data contained in each grid box. The regridded LST dataset (identified with the superscript I: T^I) relies on the cloud mask of the original LST provided by LSA SAF. However, if more than two-thirds of the 3-km observations are masked out for a particular location and time, then the sampled average is rejected. This threshold slightly reduces the available observations for any given location in T^I as compared to the original 3-km dataset. We further limit the coverage of the MSG-9 to the domain covered with an Earth incidence angle up to 78° to avoid artifacts at large view angles. The resulting T^I domain covers Africa, Europe and the Middle East. Note however, that for dates before July 7, 2008, LSA SAF provides data only up to a 60° incidence angle — thus limiting the available data record in the North-East quadrant of the domain.

2.2. Microwave Ka-band observations

The microwave temperature data set (identified with superscript M: T^M) is based on the combined records of seven separate low earth orbiting satellites that measure vertical polarized Ka-band (37 GHz) brightness temperature. This record includes observations from polar orbiting satellites with local observation times between 6 and 10 AM/PM: the Special Sensor Microwave and Imager (SSM/I) on several satellites from the Defense Meteorological Satellite Platform (DMSP) and the Coriolus-WindSat. Two additional satellites are crucial for capturing the diurnal temperature cycle (DTC) with a combination of multiple low orbiting satellites. One is the Advanced