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A framework for the retrieval of all-weather land surface temperature at a high spatial resolution from polar-orbiting thermal infrared and passive microwave data

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ABSTRACT

Land surface temperature (LST) is an important parameter associated with the land-atmosphere interface. Satellite remote sensing is the most effective method of measuring LST at regional and global scales. Satellite thermal infrared (TIR) measurements are widely used to retrieve LST with high accuracy and high spatial resolution but are limited to cloud-free conditions due to their inability to penetrate clouds. By contrast, satellite passive microwave (PMW) measurements are capable of penetrating clouds and providing data regardless of the cloud conditions. However, PMW measurements have limitations, such as a low spatial resolution and low temperature retrieval accuracy. Furthermore, temperature retrieval from PMW measurements yields the subsurface temperature, which differs from the LST retrieved from TIR measurements (skin temperature). This study proposes a framework for the retrieval of all-weather LST at a high spatial resolution by combining the advantages of TIR and PMW measurements. Compared to the MODIS LST product, the all-weather LST reflects the spatial variations in LST accurately. In situ LST measurements at four sites in an arid area of northwest China were used to evaluate the accuracy of the all-weather LST. The root mean square error of the LST under cloud-free conditions was approximately 2 K, whereas that of the LST under cloudy conditions varied from 3.5 K to 4.4 K. The results indicate that the all-weather LST retrieval algorithm can provide an LST dataset with reasonable accuracy and a high spatial resolution under clear and cloudy conditions.

1. Introduction

Land surface temperature (LST) is a key physical measurement in surface energy and water balance processes at regional and global scales (Coll et al., 2016; Wan and Li, 1997; Duan et al., 2014). It is widely used in various studies, including studies of climatology, hydrology, meteorology, ecology, agriculture, public health, and environmental monitoring (Anderson et al., 2008; Weng, 2009; Kustas and Anderson, 2009; Sobrino et al., 2016; Z.-L. Li et al., 2009). Compared to traditional ground-based LST measurements, satellite remote sensing provides a straightforward and consistent method of measuring LST over extended regions.

Satellite thermal infrared (TIR) measurements have been widely used to retrieve LST (skin temperature) based on different algorithms, e.g., single-channel, split-window, and multi-channel algorithms (Li et al., 2013a, 2013b). These algorithms were applied to various satellite TIR datasets, such as NOAA/AVHRR, EOS/MODIS, and NPP/VIIRS (Yu et al., 2005; Wan and Dozier, 1996; Becker and Li, 1990). Satellite-derived TIR LST has a relatively high spatial resolution (e.g., 1 km for MODIS data) and high retrieval accuracy (approximately 1–2 K). The main issue associated with satellite TIR measurements is their inability to penetrate clouds, which limits their practical applications. This is an important limitation because, on average, 60% of the land surface is covered by clouds, which alters the radiative energy exchange, reduces surface insolation and increases downward longwave radiation. Fig. 1a shows the monthly mean percentage of clear sky pixels during daytime over China in July 2009. Few TIR LST measurements are available in Southern China. Fig. 1b displays the spatially averaged percentages of clear sky pixels during the day and night over China on the 15th day of each month in 2009. As shown in Fig. 1b, the average percentages of clear sky pixels during daytime and nighttime are less than 50%.

Several methods were proposed to estimate TIR LST under cloudy conditions. These methods can be grouped into three categories: statistical methods, spatio-temporal interpolation methods, and surface energy balance-based (SEB-based) methods. Statistical methods have been proposed to fill a cloudy pixel of Aqua-MODIS LST with the corresponding Terra-MODIS LST pixel under cloud-free conditions considering the factors that control the diurnal cycle of LST, e.g., land cover,

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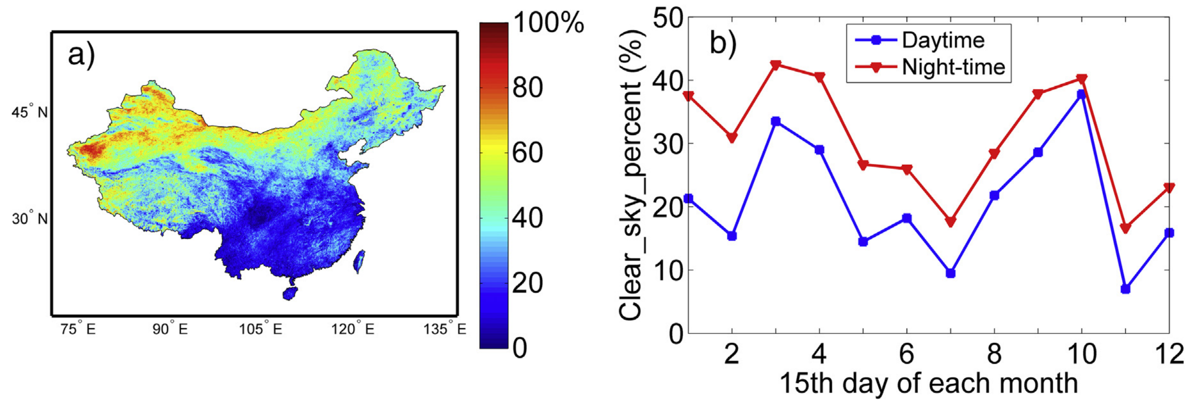

Fig. 1. (a) Monthly mean percentage of clear sky pixels during daytime over China in July 2009 and (b) Spatially averaged percentages of clear sky pixels during daytime and nighttime over China on the 15th day of each month in 2009. The two figures are generated from the MYD11A1 product.

location, elevation, and season (Coops et al., 2007; Crosson et al., 2012). This method is valid only when Terra-MODIS LST under cloud-free conditions is available. The spatio-temporal interpolation methods estimate the LST of a cloudy pixel using spatially neighboring cloud-free LST pixels with similar surface properties and/or temporally nearest cloud-free LST pixels (Neteler, 2010; Ke et al., 2013; Shuai et al., 2014; Xu and Shen, 2013; Zeng et al., 2014, Hengl et al., 2012; Metz et al., 2014). Note that an LST value filled using a statistical method or spatio-temporal interpolation method is an approximation of the theoretical cloud-free LST rather than an estimate of the actual cloudy LST. Jin (2000) and Jin and Dickinson (2000) developed SEB-based methods to estimate the LST of a cloudy pixel based on its spatially neighboring cloud-free pixels. These methods are based on the assumption that the LST difference between a cloudy pixel and its neighboring cloud-free pixels is mainly caused by their different radiation inputs and redistributions. Therefore, the LST of a cloudy pixel can be obtained based its neighboring cloud-free LSTs and an LST adjustment term depending on the surface fluxes, air temperature, and wind speed that are responsible for the difference between the pixels. Lu et al. (2011) extended the original SEB-based method to estimate MSG-SEVIRI cloudy LST using temporally neighboring pixels. The SEB-based method based on spatially or temporally neighboring pixels requires air temperature and wind speed as input data to estimate cloudy LSTs. However, these data are usually not available at a global pixel scale.

Satellite passive microwave (PMW) measurements are attractive for retrieving subsurface temperature, especially under cloudy conditions, because they are much less affected by clouds and water vapor than are TIR measurements. Nevertheless, PMW measurements have limitations. First, the spatial resolution of PMW measurements (e.g., 25 km for AMSR-E) is much lower than that of TIR measurements. Second, temperature retrieval from PMW measurements yields subsurface temperature, which is different from LST retrieval from TIR measurements (skin temperature). Nevertheless, subsurface temperatures can be converted to skin temperatures using the thermal diffusion equation (Gao et al., 2010; Moncet et al., 2011; Galantowicz et al., 2011). Third, the accuracies (approximately 5–6 K) of subsurface temperature retrieval from PMW measurements are worse than those (approximately 1–2 K) of LST retrieval from TIR measurements. A number of studies have been performed to retrieve subsurface temperature from PMW measurements. For instance, Weng and Grody (1998) proposed a physics-based subsurface temperature retrieval algorithm based on the assumption that two adjacent frequencies (19 and 22 GHz) have approximately the same surface emissivity. Aires et al. (2001) presented a method to simultaneously retrieve the subsurface temperature, cloud liquid water path, atmospheric water vapor content, and surface emissivity. Holmes et al. (2009) proposed an empirical algorithm for global subsurface temperature retrieval using the vertically polarized brightness temperature at 37 GHz.

This study aims to develop a framework for the retrieval of all-weather LST at a high spatial resolution by combining the advantages of TIR and PMW measurements. Previous studies indicated that different characteristics and limitations of TIR and PMW measurements make these two types of temperatures complimentary (Parinussa et al., 2008; Jang et al., 2014; Holmes et al., 2015; Shwetha and Kumar, 2016). Thus, the process of combining TIR and PMW measurements to generate an all-weather LST product at a high spatial resolution is promising.

2. Study area and data

2.1. Study area

In this study, China's landmass was selected as the study area. The landscape in China varies significantly across the country (Liu and Diamond, 2005). The east is characterized by extensive and densely populated alluvial plains, whereas the north is predominantly broad grasslands. The south is dominated by hills and low mountain ranges, and major mountain ranges are located to the west. Fig. 2 shows the land cover types in China.

The climate in China is mainly dominated by wet monsoons and dry seasons, which lead to significant temperature differences between winter and summer. In winter, northern winds from high-latitude areas are cold and dry, whereas in summer, southern winds from coastal areas at lower latitudes are warm and moist (Fu et al., 2008). China's climate differs from region to region due to its highly complex topography.

2.2. Satellite data

Aqua satellite was launched on May 4, 2002, and has a 1:30 am/pm equatorial crossing time. It carries six instruments (e.g., MODIS and AMSR-E) to observe the Earth's land, atmosphere, and oceans and provide high temporal frequency, spatial detail, and measurement accuracy. Both the MODIS TIR and AMSR-E PMW sensors are aboard the Aqua satellite, which provides excellent temporal collocation between MODIS TIR and AMSR-E PMW data.

Many standard MODIS data products are available to the user community. In this study, the MODIS/Aqua LST Daily L3 Global 1 km Grid product (MYD11A1, Collection 6) was used to obtain TIR LST. The MYD11A1 product was retrieved at the 1-km pixel scale using the generalized split-window algorithm (Wan and Dozier, 1996; Becker and Li, 1990).

AMSR-E measures vertically and horizontally polarized brightness temperatures at 6.925, 10.65, 18.7, 23.8, 36.5, and 89.0 GHz. The AMSR-E brightness temperature product (NSIDC-0301) in EASE-Grid projection at a 25-km resolution was used in this study. .