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Retrieval of leaf area index using temporal, spectral, and angular information from multiple satellite data

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ABSTRACT

The leaf area index (LAI) is one of the most critical structural parameters of the vegetation canopy in regional and global biogeochemical, ecological, and meteorological applications. Data gaps and spatial and temporal inconsistencies exist in most of the existing global LAI products derived from single-satellite data because of their limited information content. Furthermore, the accuracy of current LAI products may not meet the requirements of certain applications. Therefore, LAI retrieval from multiple satellite data is becoming popular. An existing LAI inversion scheme using the ensemble Kalman filter (EnKF) technique is further extended in this study to integrate temporal, spectral, and angular information from Moderate Resolution Imaging Spectroradiometer (MODIS), SPOT/VEGETATION, and Multi-angle Imaging Spectroradiometer (MISR) data. The recursive update of LAI climatology with the retrieved LAI and the coupling of a canopy radiative-transfer model and a dynamic process model using the EnKF technique can fill in missing data and produce a consistent accurate time-series LAI product. During each iteration, we defined a 5 ∗ 1 sliding window and compared the RMSEs in the selected window to determine the minimum. Validation results at six sites demonstrate that the combination of temporal information from multiple sensors, spectral information provided by red and near-infrared (NIR) bands, and angular information from MISR bidirectional reflectance factor (BRF) data can provide a more accurate estimate of LAI than previously available.

1. Introduction

The booming development of land-surface ecosystems modeling and environmental monitoring techniques has resulted in an urgent demand for high-quality, long-term consistent biophysical parameters. Leaf area index (LAI), defined as one half of the total leaf surface area per unit horizontal ground surface area (Chen & Black, 1992) , measures the amount of leaf material in an ecosystem, which imposes important controls on photosynthesis, respiration, rain interception, and other processes (GTOS, 2007). Consequently, LAI is a key variable that couples vegetation to the modeling of ecosystem productivity (Running et al., 1999; Zhang, Anderson, Tan, Huang, & Myneni, 2005), energy, and mass exchange between the land surface and the atmosphere (Bonan, 1995; Dickinson, 1995; Nouvellon et al., 2000; Sellers et al., 1997). Currently, two approaches are widely used to retrieve LAI from satellite data (Liang, 2007). The first uses empirical or semi-empirical statistical relationships between LAI and spectral vegetation indices (Baret & Guyot, 1991; Liang, 2004; Myneni, Hall, Sellers, & Marshak, 1995; Wang, Huang, Tang, & Wang, 2007). Vegetation indices are designed as a combination of surface reflectance to maximize information about canopy characteristics and minimize interference factors from the atmosphere and soil. The second approach is the inversion of a radiative-transfer model that simulates surface reflectance from canopy structure parameters (e.g., LAI), soil, leaf optical properties, and view-illumination geometry (Myneni, Nemani, & Running, 1997; Xiao, Liang, Wang, Song, & Wu, 2009). Moreover, simulated lookup tables (LUTs) (Knyazikhin, Martonchik, Myneni, Diner, & Running, 1998; Shabanov et al., 2005) and trained neural networks (NNs) (Bacour, Baret, Béal, Weiss, & Pavageau, 2006; Fang & Liang, 2003a; Walthalla et al., 2004) are commonly used to simplify the process of deriving radiative-transfer models and to improve the efficiency of inversion.

Several LAI products have been derived from various sets of satellite observation data using the above three approaches over regional to global domains. NOAA/AVHRR is the early moderate resolution sensor used to produce global LAI values at 0.25° spatial sampling and a monthly time cycle (Buermann, Dong, Zeng, Myneni, & Dickinson, 2001; Los et al., 2000; Myneni et al., 1997; Sellers et al., 1996) and ECOCLIMAP LAI (Masson, Champeaux, Chauvin, Meriguer, & Lacaze, 2003) at

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1/120° spatial sampling and the same time cycle as AVHRR LAI.CYCLOPES (Baret et al., 2007). GLOBCARBON (Deng, Chen, Plummer, Chen, & Pisek, 2006) and a CCRS regional product (Fernandes, Butson, Leblanc, & Latifovic, 2003) have been derived from SPOT/VEGETATION since 1998. Their spatial resolutions are 1/112°, 1/11.2°, and 1 km respectively; the temporal resolution of CYCLOPES and CCRS is 10 days, while that of GLOBCARBON is one month. A widely used eight-day synthesized LAI product has been generated from Terra-Aqua/MODIS at 1 km spatial resolution since 2000 (Knyazikhin et al., 1998; Yang et al., 2006). The Langley Atmospheric Sciences Data Center (ASDC) has been routinely processing a LAI product from MISR data since October 2002 (Diner et al., 1999). Recently, a Global Land Surface Satellite (GLASS) LAI product with 5/1 km spatial resolution and an eight-day temporal sampling period was generated from time-series AVHRR/MODIS reflectance data using general regression neural networks (Xiao et al., 2013). Other global LAI data sets produced from ADEOS/POLDER (Roujean & Lacaze, 2002), ENVISAT/MERIS (Bacour et al., 2006), and MSG/SEVIRI (García-Haro, Coca, & Miralles, 2008) are restricted by time period or spatial coverage.

Validation campaigns aimed at improving the understanding of these satellite LAI products for users and developers are ongoing. Current research has revealed that the uncertainties of typical LAI products such as MODIS, CYCLOPES (Fang, Wei, & Liang, 2012), MISR (Hu et al., 2007), GLOBCARBON, and ECOCLIMAP (Garrigues, Lacaze, et al., 2008) are still unable to meet the target accuracy of ± 0.5 according to the Global Climate Observation System (GCOS) requirement (GCOS, 2006). Furthermore, LAI data gaps and inconsistencies existing in these products may also restrict their application (Wang, 2012; Xiao, 2012).

Most of the LAI products mentioned above are generated from single-satellite observation data; the limited amount of information in the retrieval process accounts for the appearance of data gaps and inconsistencies, especially under poor observation conditions. Several attempts have been made to improve the quality of LAI data. One way is to develop complex algorithms based on physical principles and integrating various sources of prior information. Combal et al. (2002) used prior information to solve the ill-posed inverse problem of canopy biophysical variable retrieval. Koetz, Baret, Poilvé, and Hill (2005) used coupled canopy structure dynamic and radiative-transfer models to estimate biophysical canopy characteristics. Another approach is to integrate remotely sensed information from multiple satellite data sets into the retrieval process. Gonsamo and Chen (2014) incorporated background, topography, and foliage clumping information to improve the University of Toronto (UofT) LAI algorithm. Ganguly et al. (2008) developed a multi-sensor retrieval algorithm to derive LAI and FAPAR products from the Advanced Very High Resolution Radiometer (AVHRR), which demonstrated the effectiveness of more measured information (spectral and/or angular variation). Gray and Song (2012) developed a novel approach for mapping effective LAI using spectral information from Landsat, spatial information from IKONOS, and temporal information from MODIS.

Xiao, Liang, Wang, and Jiang (2011) developed coupled dynamic and radiative-transfer models to estimate real-time LAI from MODIS time-series data. This approach is able to fill in gaps and to provide better accuracy. However, it is based on MODIS data alone. In this study, this method has been further extended to integrate multiple satellite data with various sets of temporal, spectral, and angular information to improve accuracy, fill in gaps, and eliminate inconsistencies. Moreover, the practice of using the retrieved LAI as prior information to update the dynamic model was demonstrated to be beneficial to the further development of inversion. The following sections present the detailed methodology, validation results, discussion, and conclusions.

2. Methodology

The basic procedure of the extended method is briefly illustrated in Fig. 1. The combination of time-series MODIS, CYCLOPES, and MISR LAI data can minimize gaps and produce better LAI climatology because of the different observation cycles of multiple sensors. The LAI climatology works in the background using the assimilation method and the initial values to construct the dynamic model. High-quality, cloud-free land-surface reflectance data extracted from MODIS, SPOT/VEGETATION, and MISR are used to update the predictions of the dynamic model recursively with the help of the EnKF technique and the radiative-transfer model. The updated LAI is then used to improve the predictions of the dynamic model.

In the extended approach, an iterative method is proposed to improve retrieval accuracy. Retrieved LAI values are used to substitute for LAI climatology to provide better estimates for the dynamic model and the radiative-transfer model. The root mean square error (RMSE) between the retrieved LAI values and LAI climatology is used to measure the improvement in the retrieval process and determine exit criteria for the iterations. A decreasing RMSE with further iterations means that the LAI climatology is approaching the retrieved LAI values. In other words, the performance of the iterative procedure is declining, and therefore the procedure is terminated. In addition, this research has developed three progressive tests to assess the performance of temporal, spectral, and angular information in the retrieval process and to find out the best way to combine them. Data sets (including field measurements and remote sensing data) and critical components of this method are described in detail below.

2.1. Field measurement of LAI

Various validation studies have involved taking detailed field measurements of LAI using direct methods (e.g., destructive sampling) and indirect methods (e.g., LAI-2000, AccuPAR, Digital Hemispherical Photographs, etc.) (Garrigues, Shabanov, et al., 2008; Jonckheere et al., 2004; Weiss, Baret, Smith, Jonckheere, & Coppin, 2004). In the present study, LAI measurements for six sites were selected from existing research networks, including FluxNet (WWW1), AmeriFlux (WWW2), Bigfoot (Cohen & Justice, 1999), and VALERI (WWW3) (Baret et al., 2005), based on the principles of enough observations during the survey period and typical land-surface biomes. The biomes of the selected validation sites can be categorized into cropland, grassland, and forest. Basic information on the validation sites is listed in Table 1.

The Bondville site is an agricultural site in the Midwestern United States near Champaign, Illinois. The field was continuous no-till with alternating years of soybean and maize crops (Kuusk, 2001). The Rosemount-G19 AmeriFlux site is located within an exclusively agricultural landscape, and the type of agriculture is common among the upper Midwestern states of the United States. The Mead Irrigated site is located in Nebraska, United States, and the biome of this validation site is maize. Hainich contains the largest coherent area of deciduous trees in Germany. The dominant trees are beech, mixed with ash, maple, tilia cordata, hornbeam, and chequer tree. The Dahra North and Tessekre North sites are located close together in Africa and are both covered with sparse grass savanna. The field LAI measurements for these two sites were relatively lower than the others listed in Table 1 and were used to test the applicability of the proposed method, especially under conditions where background noise is obvious and the vegetation distribution is sparse.

The measurement method for the above validation sites was indirect except for Mead Irrigated and Bondville. The result of destructive sampling is true LAI, while the results of indirect methods (e.g., LAI-2000 and AccuPAR) are known as effective LAI because of the assumption of uniformly distributed leaves and ignorance of foliage clumping. To eliminate the effect of foliage clumping due to the indirect measurement methods described above, effective LAI measurements must be converted to true LAI. VALERI (WWW3) provides numerous measurements of effective LAI and the corresponding true LAI, enabling linear regression models based on specific biomes (e.g., cropland, grassland, and forest) to be built to perform conversion from effective LAI to true LAI