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Mapping vegetation heights in China using slope correction ICESat data, SRTM, MODIS-derived and climate data

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ABSTRACT

Vegetation height is an important parameter for biomass assessment and vegetation classification. However, vegetation height data over large areas are difficult to obtain. The existing vegetation height data derived from the Ice, Cloud and land Elevation Satellite (ICESat) data only include laser footprints in relatively flat forest regions (<5°). Thus, a large portion of ICESat data over sloping areas has not been used. In this study, we used a new slope correction method to improve the accuracy of estimates of vegetation heights for regions where slopes fall between 5° and 15°. The new method enabled us to use more than 20% additional laser data compared with the existing vegetation height data which only uses ICESat data in relatively flat areas (slope < 5°) in China. With the vegetation height data extracted from ICESat footprints and ancillary data including Moderate Resolution Imaging Spectroradiometer (MODIS) derived data (canopy cover, reflectances and leaf area index), climate data, and topographic data, we developed a wall to wall vegetation height map of China using the Random Forest algorithm. We used the data from 416 field measurements to validate the new vegetation height product. The coefficient of determination (R^2) and RMSE of the new vegetation height product were 0.89 and 4.73 m respectively. The accuracy of the product is significantly better than that of the two existing global forest height products produced by Lefsky (2010) and Simard et al. (2011), when compared with the data from 227 field measurements in our study area. The new vegetation height data demonstrated clear distinctions among forest, shrub and grassland, which is promising for improving the classification of vegetation and above-ground forest biomass assessment in China.

1. Introduction

The height of vegetation is useful in estimating carbon storage and sequestration and distinguishing land cover types (Gong et al., 2012; Lefsky et al., 2002). Height and cover of vegetation are the main features used for vegetation classification. In the two widely used classification systems, International Geosphere-Biosphere Programme (IGBP) and Food and Agriculture Organization (FAO) Land Cover Classification Systems, height is used as the main factor to separate forest from shrub (Bontemps et al., 2011; Hansen et al., 2000). While cover is relatively easy to extract from remotely sensed data, height is harder to map at large scale. Laser data acquired by Ice, Cloud and land Elevation Satellite (ICESat) between 2003 and 2009 (its last laser failed in October 2009) is useful in this regard (Miller et al., 2011; Zwally et al., 2002).

The data acquired from the Geoscience Laser Altimeter System (GLAS) mission is still being used to accurately measure vegetation height (Fatoyinbo and Simard, 2013). The footprint diameter of the sensor on the Earth's surface is about 70 m. The spacing between spots is approximately 170 m along track and the distance between two contiguous tracks ranges from 33 km at 80° latitude to 80 km at the Equator. The inclined orbit provides coverage between 86° N and 86° S (Schutz et al., 2005; Wang et al., 2011a). During ICESat's 7-year mission, laser altimeter data were collected over 20 different 3-month periods. These data have been used in the field of snow/ice mass balance assessment (Sørensen et al., 2011; Zwally et al., 2011), forest above-ground biomass calculation and leaf area index extraction (Nelson et al., 2009; Saatchi et al., 2011; Tang et al., 2014), lake water level change detection

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(Wang et al., 2013; Zhang et al., 2011) and urban height assessment (Gong et al., 2011).

Different forest height products with 500 and 1000 m resolution have been derived from GLAS for biomass calculation, climate modeling and ecological modeling (Bolton et al., 2013). Lefsky (2010) extrapolated height data from GLAS to global forest areas by using segmented spectral data from the Moderate Resolution Imaging Spectrometer (MODIS), and the root mean square error (RMSE) of this data is 5.9 m. Simard et al. (2011) used climatic, topographic, and other globally available ancillary variables such as forest type and tree cover to model global canopy height and obtained an RMSE of 6.1 m. Los et al. (2012) calculated vegetation height from the GLAS waveform decomposition product and improved ground surface determination by applying further calibration on desert sites and obtained an RMSE of this product of 6 m.

While the above increased the availability of height information of global vegetation, there are two main issues in these products when using them in land cover classification. First, not all vegetation types were included in these global vegetation height products. The global forest height products produced by Lefsky (2010) and Simard et al. (2011) only focused on forest canopy height while other vegetation types like shrub were not included. Secondly, vegetation height extraction in rugged terrain is still a challenge when using ICESat/GLAS data (Xing et al., 2010). GLAS waveforms broaden over sloped terrain and lead to biases in canopy height prediction over areas of high terrain relief (Chen, 2010; Pang et al., 2011). Lefsky et al. (2007) applied a terrain correction that utilized information within the GLAS waveforms to adjust the extent of the waveform. Alternatively, Simard et al. (2011) produced a slope map using 90 m resolution Shuttle Radar Topography Mission (SRTM) data between 60°S and 60°N to estimate and correct the slope bias. Most notably, Simard et al. (2011) removed all waveforms from their analysis for areas with >5° slopes or when slope correction was >25% of the GLAS-derived canopy height. Los et al. (2012) also used SRTM to calculate the slope and filtered the data when slopes exceeded 10°. In China, >40% of GLAS footprints are located in rugged areas exceeding 5° slope. More GLAS data can be used to improve coverage rate if new slope correction methods can be found to extract vegetation heights in rugged areas. Wang et al. (2014) improved GLAS waveform decomposition and the start point of the waveform signal determination by decreasing noise with a Savitzky-Golay filter and fitting waveforms by comparing them with 3-D model simulations. The method has been demonstrated to be capable of improving the accuracy of vegetation height extraction in rugged areas, especially for slopes from 5° to 15° (Wang et al., 2014). This method is not an empirical method and is not site specific, and it is suitable for estimating vegetation height at regional or global scale.

The primary objective of this study is to combine the new slope correction method with remotely sensed and climate environment data to map a wall to wall vegetation height data in China and improve the accuracy of estimated vegetation heights, especially for rugged areas. Another objective is to assess the capability of the derived vegetation height product to differentiate vegetation types.

2. Data

In order to extrapolate the vegetation height from GLAS footprints to a wall to wall vegetation height, gridded climate data (temperature and precipitation), topography data, canopy cover data, nadir BRDF-Adjusted reflectance and leaf area index data from MODIS were used to extrapolate vegetation height in an area without GLAS footprints.

2.1. Climate data

Climate data are widely used to reproduce the known patterns of vegetation distribution (Klein et al., 2015; Shi et al., 2013). Generally, average temperature, average precipitation and seasonal fluctuation control the growth of vegetation. We obtained near-surface air temperature, precipitation, and seasonal fluctuation from Worldclim (Hijmans et al., 2005). This dataset has a spatial resolution of 1 km and covers the period between 1950 and 2000.

2.2. Remotely sensed data

2.2.1. ICESat/GLAS data

ICESat/GLAS transmitted and received waveform data (GLA01) from release 33 and waveform parameterization data (GLA05) from 2003 and 2008 were used in this study (Zwally, 2011a,b). The distribution of GLAS footprints in China is shown in Fig. 1.

2.2.2. SRTM data

The Shuttle Radar Topography Mission (SRTM) digital elevation dataset was originally produced to provide consistent, high quality elevation data (Farr et al., 2007). Elevations, slopes, and aspects are important bio-geographical parameters, which control vegetation distribution and growth (Day and Monk, 1974). Elevations, slopes, aspects and the Compound Topographic Index (CTI) (Moore et al., 1991) were extracted from the void-filled 90 m resolution SRTM data (Reuter et al., 2007) as input variables for subsequent modeling. SRTM was also used to calculate slopes of areas covered by all ICESat/GLAS footprints.

2.2.3. Canopy cover data

MODIS is a key instrument aboard the Terra satellite, and can acquire data in 36 spectral bands with three different spatial resolutions (250 m for bands 1–2, 500 m for bands 3–7, and 1000 m for bands 8–36) (Justice et al., 1998). The 250 m resolution Vegetation Continuous Fields (VCF) product of MODIS acquired in 2005 was obtained from the Land Processes Distributed Active Archive Center (Hansen et al., 2003). Pixels with cloud cover were excluded according to the data quality index provided in the MODIS file (value >2). If VCF pixels of good quality were not available for 2005, VCF pixels in 2004 or 2006 were used instead.

2.2.4. MODIS NBAR data

The Nadir BRDF-Adjusted (Bidirectional reflectance distribution function) reflectances (NBAR) can partly represent the structural diversity of a forest canopy. This feature has been demonstrated to be useful for canopy height retrieval (Wang et al., 2011b). MCD43A4 products with 500 m resolution were acquired in 2005 and most of them belonged to the vegetation growing season.

2.2.5. MODIS LAI data

Leaf area index (LAI) reflects vegetation vitality and has a good correlation with vegetation structure. A new LAI product generated by time-series MODIS surface reflectance was used in this work (Xiao et al., 2014). LAI products with 1 km resolution in the growing season of 2005 were used.

2.3. Field measurement data

Field measurement data collected between 2003 and 2008 were selected, because the GLAS data was obtained at this time. Fig. 2 shows the distribution of all of the 416 forest sampling plots. 367 of these were collected from published papers in peer-reviewed Chinese journals, and the recorded information of the sampling plots includes geographic coordinates, forest type, stand volume, mean tree height and diameter at breast height (Zhang