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Comparison of carbon assimilation estimates over tropical forest types in India based on different satellite and climate data products

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ABSTRACT

Carbon assimilation defined as the overall rate of fixation of carbon through the process of photosynthesis is central to the climate change research. The present study compares the two well-known algorithms in satellite based carbon assimilation estimation, the Vegetation Photosynthesis Model (VPM) and the MOD 17A2 GPP Model, over the tropical forest types in India for a period of two years (September, 2006–August, 2008). The results indicate that the evergreen forest assimilate carbon at a higher rate while the rate is lower for montane grasslands. The comparison between the model results shows that there are large differences between these estimates, and that the spatial resolution of the input datasets plays a larger role than the algorithms of the models. The comparison exercise will be helpful for the refinement and development of the existing and future GPP models by incorporating the empirical environmental conditions.

1. Introduction

Tropical forests contain ∼25% of the carbon in the terrestrial biosphere (Bonan, 2008), account for ∼33% of terrestrial net primary production (NPP) (Sabine et al., 2004), and can sequester large amounts of carbon annually (approximately 4 MgC/ha/year) (Luyssaert et al., 2007). These spatio-temporal estimates that utilize climate constrained light-use and production efficiency equations, as demonstrated by products such as MODIS MOD17 (Running et al., 2004; Heinsch et al., 2006), CASA (Potter et al., 1993; Lobell et al., 2002), and GLO-PEM (Prince and Goward, 1995; Goetz et al., 1999), are subject to errors and uncertainties arising from state variables (for example, land cover and plant biomass), interpolated meteorology, model logic, and model parameters. Quantifying model errors and uncertainties allows carbon flux estimates to be reported with known levels of confidence (Heinsch et al., 2006; Zaehle et al., 2005; Kyriakidis and Dungan, 2001), and identifying and minimizing these inaccuracies will improve model predictions.

In particular, NASA land products MOD17A2/A3, which provide 8-day estimates of gross primary production (GPP) and annual estimates of net primary production (NPP) (Running et al., 2004) are among the primary sources of information on carbon exchange at the global scale. However, several recent studies have highlighted limitations of these models (Heinsch et al., 2006; Turner et al., 2005; Yuan et al., 2007; Wu et al., 2010). The most serious limitation arises from the uncertainties of coarse resolution DAO (Data Assimilation Office; now replaced by the Global Modeling and Assimilation Office) meteorological reanalysis data used in MOD17 (Heinsch et al., 2006; Zhao et al., 2006). MOD17 also depends on estimates of light use efficiency (LUE) obtained from lookup tables based on vegetation type, which may contain errors either in the original estimate of LUE for a particular vegetation type or in the assignment of vegetation type to a pixel. Although it may be possible to correct problems with the MOD17 by improving the accuracy of the meteorological and other data inputs, it is also worthwhile to explore alternative methods for estimation of global GPP.

The Vegetation Photosynthesis Model (VPM) proposed by Xiao et al. (2004a,b) assumes that the leaf and forest canopies are composed of photosynthetically active vegetation (PAV, mostly chloroplast) and non-photosynthetic vegetation (NPV, mostly senescent foliage, branches and stems). The Fraction of Photosynthetically Active Radiation (FPAR) absorbed by photosynthetically active parts of the vegetation is represented by the Enhanced Vegetation Index (EVI) (Huete et al., 1997, 2002) in the model. The model also utilizes the Land Surface Water Index (LSWI) (Xiao et al., 2002) to capture the effects of water stress and leaf phenology, especially for vegetation that becomes dormant in summer. VPM has been validated in different vegetation types such as temperate evergreen

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needleleaf forest (Xiao et al., 2004a), deciduous broadleaf forest (Xiao et al., 2004b; Wu et al., 2010), tropical moist evergreen forest (Xiao et al., 2005), alpine ecosystems (Li et al., 2007), wheat and maize cropping systems (Yan et al., 2009) and a number of other biomes (Mahadevan et al., 2008).

India has a geographical area of 328 Million hectares (Mha), of which 51 Mha is tropical forest (FSI, 2003). India is presently a non-Annex I country in the Kyoto Protocol of the UNFCCC and is exempted from binding Green House Gas (GHG) emission targets, but as it makes the transition to a developed economy, its status could be revised (Joseph et al., 2010). A few efforts have been made to estimate the primary productivity at country level using process models such as C-Fix (Chhabra and Dadhwal, 2004), PEM (Hooda et al., 2003) and CASA (Nayak et al., 2010). Similarly, at the ground level the efforts are being implemented to establish a network of flux towers called INDOFLUX (Sundareshwar et al., 2007). The challenge is how much spatial coverage flux towers can provide and how the measurements can be interpolated under diverse climatic, topographic and biotic gradients. Therefore, as a surrogate, it is essential to explore remote sensing based methodologies for rapid estimation of carbon flux which helps in the trade-off analysis in carbon budget and policy formulations for climate change mitigations.

The present study compares two carbon assimilation algorithms; the VPM and the MOD17A2 GPP model over tropical forest types in India. The research questions addressed in the study are (i) Is there any significant variation in the estimates of VPM and MOD17A2 GPP? (ii) How do global level data products such as MOD17A2 GPP work at the local scale? (iii) Is there any difference in the MOD17A2 GPP estimate when the ground measured data replaces the DAO global data? (iv) If yes, is it due to the algorithm difference or due to the changes in the resolution of the input datasets?

2. Materials and methods

2.1. Study area

Anamalai region located in the southern Western Ghats (Fig. 1) is one of the active zones of speciation and localized centres of endemism (Blasco, 1970; Nair and Daniel, 1986), and thereby known as one of the 25 micro centres of diversity in the Indian Subcontinent (Nayar, 1996). The overall terrain is hilly with altitudes ranging from 220 m at the foothills in the north-east to 2550 m (in the Grass Hills area) in the south-west. The annual rainfall varies from 500 mm in the rain shadow eastern slopes to 5000 mm in the west. Mean daily temperature varies from <5 °C in the winter at elevations above 2000 m to nearly 40 °C in the eastern plain in the summer. Eco-climatically, the area could be considered as a miniature of the Western Ghats Biodiversity Hotspot, and harbours all major forest types found in the Western Ghats (Joseph et al., 2009).

2.2. Data used

- *MODIS daily surface reflectance images* – MODIS Surface Reflectance and radiance product (MOD02HKM) is a seven-band image computed from the MODIS Level 1A scans of raw radiance of bands 1 (620–670 nm), 2 (841–876 nm), 3 (459–479 nm), 4 (545–565 nm), 5 (1230–1250 nm), 6 (1628–1652 nm), and 7 (2105–2155 nm). Channels 1 and 2 have 250 m resolution originally, but are aggregated to 500 m in this product, and channels 3 through 7 have 500 m original resolution. Thus the entire channel data set is co-registered to the same spatial scale in the 500 m product.
- *IRS P6 LISS III image* – IRS P6 LISS III image (Indian Remote Sensing satellite) has a spatial resolution of 24 m, and four bands (0.52–0.59, 0.62–0.68, 0.77–0.86 and 1.55–1.70 μm).
- *Meteorological Data* – These comprise total shortwave radiation, atmospheric temperature, precipitation and relative humidity measured at four weather stations scattered across the landscape.
- *MODIS 15 A2 LAI and FPAR Product* – The MOD15 A2 Leaf Area Index and Fraction of Photosynthetically Active Radiation absorbed by vegetation are 8 days composite provided at 1 km spatial resolution. The data are provided as a level-4 composited product in Sinusoidal projection.
- *MODIS 17 A2 GPP Product* – MODIS Terra Gross Primary Productivity 8-day Global 1 km SIN Grid V005 (MOD17A2) is a cumulative composite of gross primary productivity (GPP) values. Detailed description about the algorithm and composition of the product could be found in Heinsch et al. (2003) and Running et al. (2004).

2.3. Modeling framework

2.3.1. Vegetation photosynthesis model

The VPM was built upon the conceptual partitioning of chlorophyll ($FPAR_{PAV}$) and non-photosynthetically active vegetation (NPV) within the canopy.

$$GPP = \varepsilon_g \cdot FPAR_{PAV} \cdot PAR \tag{1}$$

where $FPAR_{PAV}$ is the fraction of photosynthetically active radiation (PAR) absorbed by leaf chlorophyll in the canopy, PAR is the incoming photosynthetically active radiation, and ε_g is the light use efficiency.

The value of ε_g was initially considered as relatively constant but substantial differences have been found that depend on ecosystem type, age, species composition, fertility and stresses (Ruimy et al., 1995; Lagergren et al., 2005), ε_g is therefore a crucial parameter to estimate. In the VPM, ε_g is determined as:

$$\varepsilon_g = (\varepsilon_0 \cdot Tscalar \cdot Wscalar \cdot Pscalar) \tag{2}$$

where ε_0 is the maximum light use efficiency, and *Tscalar*, *Wscalar* and *Pscalar* are the down-regulation scalars for the effects of temperature, water and leaf phenology, respectively.

The values of ε_0 were taken from Biome-BGC model (White et al., 2000; Thornton et al., 2002) after an extensive literature survey. Temperature control on the photosynthetic process is represented as *Tscalar* and is calculated using the equation developed for the Terrestrial Ecosystem Model (Raich et al., 1991).

$$Tscalar = \frac{(T - T_{min})(T - T_{max})}{[(T - T_{min})(T - T_{max})] - (T - T_{opt})^2} \tag{3}$$

where T_{min}, T_{max} and T_{opt} are minimum, maximum and optimal temperature for photosynthetic activities. After careful examination of literature, the values of minimum, maximum and optimum temperature were taken as 5 °C, 40 °C and 28 °C, respectively, for the present study (Tian et al., 1998; Ishida et al., 1999; Pons and Welschen, 2003; Xiao et al., 2005).

The effect of water on plant photosynthesis (*Wscalar*) has been estimated as a function of soil moisture and/or water vapour pressure deficit (VPD) (Running et al., 2000). In the VPM, an alternative and simple approach that uses a satellite-derived water index (LSWI) to estimate the seasonal dynamics of *Wscalar* is used,

$$Wscalar = \frac{1 + LSWI}{1 + LSWI_{max}} \tag{4}$$

where $LSWI_{max}$ is the maximum LSWI value within the photosynthetically active period. LSWI is calculated as the normalized