Enhancing the Reliability of MODIS Gross Primary Productivity (GPP) by Improving Input Data

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입력자료 개선에 의한 MODIS 총일차생산성의 신뢰도 향상

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ABSTRACT

The Moderate Resolution Imaging Spectroradiometer (MODIS) regularly provides the eight-day gross primary productivity (GPP) at 1 km resolution. In this study, we evaluated the uncertainties of MODIS GPP caused by errors associated with the Data Assimilation Office (DAO) meteorology and a biophysical variable (fraction of absorbed photosynthetically active radiation, FPAR). In order to recalculate the improved GPP estimate, we employed ground weather station data and reconstructed cloud-free FPAR. The official MODIS GPP was evaluated as +17% higher than the improved GPP. The error associated with DAO meteorology was identified as the primary and the error from the cloud-contaminated FPAR as the secondary constituent in the integrative uncertainty. Among various biome types, the highest relative error of the official MODIS GPP to the improved GPP was found in the mixed forest biome with RE of 20% and the smallest errors were shown in crop land cover at 11%. Our results indicated that the uncertainty embedded in the official MODIS GPP product was considerable, indicating that the MODIS GPP needs to be reconstructed with the improved input data of daily surface meteorology and cloud-free FPAR in order to accurately monitor vegetation productivity in Korea.

Key words : GPP, MODIS, Meteorology, FPAR, Uncertainty

I. INTRODUCTION

Vegetation growth is a consequence of atmospheric carbon sequestration into plant biomass, and its role is attracting more attention under global environmental changes including the increase of atmospheric CO₂ concentration (Nemani *et al.*, 2003). Hence, the monitoring of vegetation production has been highlighted in many ecological studies (Potter *et al.*, 1993; Churkina *et al.*, 2000; Myneni *et al.*, 2002; Nemani *et al.*, 2003; Morisette *et al.*, 2006; Friend *et al.*, 2007). In global

vegetation monitoring, landscape heterogeneity is a serious problem partly because the vegetation production is highly variable both spatially and temporally, which is hardly covered by traditional plot-based surveys (Running *et al.*, 1994). Recent development of satellite remote sensing, however, provides great opportunity for continuous monitoring of global vegetation production (Running *et al.*, 1994; Prince and Goward, 1995; Myneni *et al.*, 2002; Running *et al.*, 2004).

Global productivity can be estimated by combining remote sensing with carbon cycle processing (Heinsch

et al., 2003). The global information on an eight-day total gross primary productivity (GPP) at 1 km resolution is regularly provided by the Moderate Resolution Imaging Spectroradiometer (MODIS) through the EOS Data Gateway since December, 1999. MODIS GPP has been widely validated by using the eddy-covariance flux tower measurements across multiple biomes in continental and global scales (Heinsch *et al.*, 2006; Turner *et al.*, 2006). For a regional scale application, however, the reliability of the MODIS GPP is somewhat uncertain in terms of potential errors caused by input meteorology, a biophysical variable (i.e., fraction of absorbed photosynthetically active radiation, FPAR), and ecophysiological parameters (Kang *et al.*, 2005a; Zhao *et al.*, 2005 and 2006). The cloud effect on FPAR cannot be ignored, especially in monsoon climate regions such as the Korean Peninsula (Kang, 2005). Furthermore, a degree-by-degree spatial resolution of official input meteorology of the MODIS GPP (i.e., Data Assimilation Office, DAO, provided by NASA) is too coarse to represent the spatial meteorological variation on a regional scale. Hence, careful evaluations of the uncertain factors need be conducted prior to the regular GPP monitoring with the MODIS GPP product.

Recently, uncertainties of the MODIS GPP in Korea, caused by cloud contaminated FPAR and input meteorology, were reported that errors associated with the former and the latter were -8.5 and +25%, respectively (Kang, 2005; Kang *et al.*, 2005b). In this study, the MODIS GPP uncertainty (related with both FPAR and input meteorology) was evaluated to provide reference information on the gross estimate of the MODIS GPP uncertainty in Korea. Since reliable daily meteorological data were essential for the evaluation, we selected the ground weather stations operated by the Korea Meteorological Administration (KMA) as our study areas, and further reconstructed cloud-free FPAR time series at those weather stations from 2001 to 2003.

II. MATERIALS AND METHODS

2.1. Theoretical backgrounds on MODIS GPP algorithm

Detailed descriptions on the MODIS GPP algorithm can be found in Heinsch *et al.* (2003). The algorithm is a biophysical model describing the GPP with the incident PAR and light use efficiency controlled by daily minimum temperature ($T_{\min}$ in $^{\circ}\text{C}$) and atmospheric vapor pressure deficit (VPD in Pa) as:

$$\text{GPP} = [\epsilon] \times [\text{FPAR} \cdot \text{PAR}] \quad (1)$$

$$\epsilon = [\epsilon_{\max} \cdot f(T_{\min}) \cdot f(\text{VPD})] \quad (2)$$

$$\text{PAR} = [0.45 \times R_s] \quad (3)$$

where ϵ is the light use efficiency; $\epsilon_{\max}$ is the maximum light use efficiency specific to each biome type; and R_s is a daily incoming shortwave radiation (in $\text{MJ m}^{-2} \text{d}^{-1}$). PAR was estimated as 45% of R_s . In the official MODIS GPP, FPAR was provided by the upstream MODIS FPAR/LAI product and the DAO data were utilized for the daily meteorological variables (i.e., $T_{\min}$, VPD, and R_s). Light use efficiency was designed to increase with $T_{\min}$ but decrease with VPD (Heinsch *et al.*, 2003). As shown in the above equations, the quality of both FPAR and the meteorological variables determines the degree of uncertainty in the MODIS GPP.

Fig. 1. Locations of national weather stations used in this study. The background is a MODIS land cover map simplified to have forest, crop, and urban land cover types for graphic enhancement. A key map is an example of land cover of 5×5 pixels around the Chuncheon weather station in 2001.

2.2. Experimental design

Our study area was selected from 72 National Weather Stations operated by the KMA (Fig. 1). An area of 25 km² centered on each station was used to reconstruct the cloud-free FPAR and to recalculate the MODIS GPP. Locations of the weather stations were overlaid with 1-km resolution MODIS land cover maps (type 2, UMD classification) and then, 5-by-5 pixels (covering an area of 1,800 km²) around each station were selected.

For each pixel of a 25 km² area, meteorological conditions were assumed identical to the centered weather station but each pixel was recognized with different land covers and FPAR values. Among the 1,800 pixels, mixed forest, deciduous broadleaf forest, needleleaf forest, shrub/savanna, and crop land covers constituted 17, 1, 2, 8, and 21%, respectively. The remainder of the pixels identified as urban areas was discarded in this study, along with the shrub/savanna pixels because the land cover type is erroneous in Korean landscapes.

For each vegetation pixel, the time series of an 8-day composite MODIS FPAR from 2001 and 2003 were extracted from MODIS FPAR image and then, used to reconstruct cloud-free FPAR time series by using an interpolation method of Kang *et al.* (2005a). The method uses both land cover information and FPAR values surrounding 5×5 pixels or the FPAR values of the preceding or following week to mitigate cloud effects on FPAR by interpolation if the pixel of interest is cloud contaminated. If the pixel of interest is identified as cloud contaminated, the method searches cloud free pixels within the 5×5 pixel window with the identical biome type to calculate the interpolated FPAR of the pixel. If this spatial interpolation fails, then the method searches cloud free FPAR of the preceding and the following week for temporal interpolations of FPAR. The existence of cloud contamination was identified with quality control flags provided with the MODIS FPAR.

The DAO meteorological data were replaced with the weather station meteorological data, with which the effect of uncertainty in input meteorology on the MODIS GPP product was examined. Together with the reconstructed FPAR, the surface meteorological data were utilized to run the MODIS GPP algorithm.

In this study, four different types of MODIS GPP version were calculated with (1) the original MODIS FPAR and official DAO data (named as NON-DAO), (2) the original MODIS FPAR and the surface meteorological

data (named as NON-NWS), (3) the reconstructed FPAR and official DAO data (named as FILL-DAO), and (4) the reconstructed FPAR and the surface meteorological data (named as FILL-NWS). Although our final target was the gross evaluation of the MODIS GPP uncertainty associated with both FPAR and DAO data (i.e., NON-DAO vs. FILL-NWS), the uncertainties were tested step-by-step by correcting each input variable one-by-one. For quantifying the uncertainties, the relative error (RE, %) was calculated by assuming that the GPP of the FILL-NWS case, surface station data, and reconstructed FPAR were true, while other GPP estimates, DAO data, and original FPAR were uncertain. For example, RE of GPP estimate was evaluated as:

$$RE(\%) = \frac{[Other - GPP] - [FILL - NWS]}{[FILL - NWS]} \times 100 \quad (4)$$

In addition to the FAPR and meteorology, there are two more error sources in the MODIS GPP: one is eco-physical parameters specific to biome types and the other is the GPP algorithm itself (Eqs. 1-3). In this study, however, the additional error sources were not evaluated.

III. RESULTS AND DISCUSSION

3.1. Evaluation of DAO data and official MODIS FPAR

In comparison to the weather station data, the DAO data set underestimated T_{min} and VPD by 0.10°C and 248 Pa, respectively, and overestimated R_s by 1.0 MJ m⁻² d⁻¹ for the years from 2001 to 2003. The values of RE of VPD and R_s were -35% and +7%, respectively. The combined effect of the overestimated R_s and underestimated VPD caused higher PAR (Eq. 3) and ϵ (Eq. 2), resulting in overestimation of GPP (Eq. 1). On the other hand, the underestimated T_{min} resulted in the underestimation of GPP by decreasing ϵ . The net effect on GPP is described later in the following section.

The reconstructed FPAR by mitigating the cloud contamination effect showed more reasonable and smoother seasonal patterns than those of the original MODIS FPAR (Fig. 3). The varying degree of cloud contamination resulted in distinct seasonal variability that was more pronounced in the summer season. Consequently, the summertime RE from June to August was -15% but it was about -3% in other seasons. For the study area, the three-year mean RE resulted in a

Fig. 2. Comparisons of DAO data with ground meteorological data (NWS) from 72 weather stations: (a) average temperature (T_{avg} in $^{\circ}\text{C}$), (b) minimum temperature (T_{min} in $^{\circ}\text{C}$), (c) vapor pressure deficit (VPD in Pa), and incident solar radiation (R_s in $\text{MJ m}^{-2} \text{d}^{-1}$) from 2001 to 2003.

Fig. 3. Eight-day interval time series of the FPAR averaged for vegetation pixels only around 72 weather stations: (a) the original MODIS FPAR and (b) the reconstructed FPAR after cloud correction.

Fig. 4. Eight-day interval time series of the GPP (in $\text{gC m}^{-2} \text{d}^{-1}$) averaged for vegetation pixels only around 72 weather stations: (a) original MODIS GPP and (b) recalculated GPP after improving input data.

Table 1. Annual GPP (in $\text{gC m}^{-2} \text{y}^{-1}$) estimated from the original FPAR and DAO meteorology (NON-DAO) and filled FPAR and NWS meteorology (FILL-NWS) for each vegetation type from 2001 to 2003. (Values in parenthesis are the number of pixels of each vegetation type.)

	NON-DAO			FILL-NWS		
	2001	2002	2003	2001	2002	2003
MF (308)	1350	1378	1306	1074	1132	1153
DBF (22)	1122	1219	1117	1039	1109	1116
ENF, EBF (34)	1595	1600	1548	1281	1301	1258
Crop (373)	668	688	668	592	606	623
All	1009	1035	989	839	873	889

MX is mixed forest; DBF, deciduous broadleaf forest; ENF, evergreen needleleaf forest; EBF, evergreen broadleaf forest; Crop, crop land.

smaller magnitude (-7%) than the one (-9%) reported by Kang (2005) for the entire MODIS pixels in Korea. This is probably because most of the weather stations are located at low areas with relatively smooth topography and less cloud covers than complex terrains at high elevations.

3.2. Uncertainty of MODIS GPP

For every pixel with vegetation land cover types, seasonal patterns of the official MODIS GPP (NON-DAO) were compared with those from the recalculated GPP (FILL-NWS) by using both ground meteorological data and reconstructed PAR (Fig. 4). Dramatic reductions of GPP found in the summertime NON-DAO were smoothed in FILL-NWS, likely due to the effect of the reconstructed FPAR. The summertime

maximum GPP decreased from approximately $6 \text{ gC m}^{-2} \text{d}^{-1}$ in NON-DAO to $5 \text{ gC m}^{-2} \text{d}^{-1}$ in FILL-NWS, due to lower values of VPD and R_s at the weather stations than the DAO data.

Overall, the uncertainty of the NON-DAO was evaluated by +17% of the total RE to FILL-NWS. The RE, however, was variable with the biome types (Table 1). The highest RE was found in the evergreen forest biome (+24%) and sequentially in order of the mixed forest (20%), crop (11%), and deciduous forest (6%). Our results are compared with those from Kang *et al.* (2005b) who evaluated the RE associated with the DAO data and reported 40, 32, 17, and 16% for the evergreen, mixed, and deciduous forest and crop biome types, respectively. Overall, they reported higher RE values than those reported in this study since they cal-

Fig. 5. Biome-specific comparisons of GPP estimations with different input data: NON-DAO indicates the original MODIS GPP with original FPAR and DAO data; NON-NWS, the original FPAR but ground meteorology; FILL-DAO, reconstructed FPAR but DAO data; and FILL-NWS, the reconstructed FPAR and ground meteorology, respectively. The GPP values were averaged for each biome types from 2001 to 2003.

culated the RE based on the GPP estimates of the NON-NWS case that were lower than the FILL-NWS GPP.

One of the interesting results from our analysis is that the uncertainty of the MODIS GPP affects not only the absolute values of GPP but also the relative variation of the annual GPP for some biome types. In Table 1, the mixed (MF) and deciduous broadleaf (DBF) forests and crop biomes showed the maximum NON-DAO in 2002. However, the maximum GPPs for the biomes were found in 2003 in FILL-NWS, while the annual pattern of the evergreen forest was identical in both cases. The results indicate that the seasonality of errors contained in both the DAO and original MODIS FPAR significantly affects not only the seasonal GPP patterns (Fig. 4) but also the annual GPP variability (Table 1). Our interpretation is also supported by previous studies (Kang, 2005; Kang *et al.*, 2005b) which indicate the importance of the summertime DAO VPD and FPAR errors in MODIS GPP estimations.

The uncertainty analyses on four different GPP estimates were integrated in Fig. 5. In comparison with FILL-NWS, NON-DAO showed higher GPP by $144 \text{ gC m}^{-2} \text{ y}^{-1}$; NON-NWS, lower by $63 \text{ gC m}^{-2} \text{ y}^{-1}$; FILL-DAO, higher by $228 \text{ gC m}^{-2} \text{ y}^{-1}$ than FILL-NWS. The comparisons indicated that the errors in the meteorological data and the cloud-contaminated FPAR resulted in the respective overestimation (with RE of 26%) and underestimation (with RE of -7%) of GPP estimates with the overall GPP overestimation of 17%. The comparative patterns of relative errors were identical for every biome types. Among the biome types, however, the mixed forest biome showed the highest RE of 20, -9, and 32 % for NON-DAO, NON-NWS, and FILL-DAO, respectively. The result was contrary to the highest RE in evergreen forests reported by Kang (2005), who only considered the errors associated with FPAR and attributed his result to longer growing seasons of evergreen forests experiencing more cloudy days. Our result of the highest RE in the mixed forest, therefore, implies the more significant effect of the growing season uncertainty in DAO meteorology on the estimation of GPP.

IV. SUMMARY AND CONCLUSIONS

The MODIS GPP provides a new opportunity to monitor global vegetation productivity. Because the product is based on a simplified light use efficiency

model operated with input data of surface meteorology and FPAR, the reliability of the MODIS GPP is strongly affected by the use of reliable input data (Zhao *et al.*, 2005; Heinsch *et al.*, 2006). Though MODIS GPP currently provides periodic images of vegetation productivity, the reliability should be evaluated and the error sources of the MODIS GPP should be investigated before its practical application in land surface vegetation production in forested and/or cultivated areas. In particular, compared to the global application, the regional application of the MODIS GPP product is easier to improve by using improved meteorological variables and by applying better manipulation of cloud contamination of FPAR.

In the study area, the overall uncertainty of the official MODIS GPP was 17%, compared to the enhanced GPP estimated with ground meteorological data and cloud-free FPAR. The errors associated with DAO meteorology and cloud-contaminated FPAR affected not only the absolute values of GPP but also the relative variation of the annual GPP for some biome types. For example, mixed and deciduous forest and crop biomes showed the maximum official MODIS GPP in 2002, but the maximum GPP values were found in 2003 in the enhanced GPP.

The primary error source was associated with DAO meteorology whereas the cloud-contaminated FPAR was a secondary source for the integrated uncertainty of the official MODIS GPP. On the other hand, each biome type showed a different GPP uncertainty. The largest relative error of the official MODIS GPP was found in the mixed forest biome (RE = 20%). The mean relative error for all forest biomes was 19.6%, whereas the errors for the crop land cover was 11%.

In conclusion, our integrative analyses indicate that considerable uncertainties are embedded in the official MODIS GPP which should be corrected before its application for monitoring of vegetation productivity in Korea. It is therefore necessary to build reliable meteorological data and cloud-free FPAR, and to further investigate uncertainties associated with both biome-specific ecophysiological parameters and model algorithms.

적 요

현재 1 km 해상도의 Moderate Resolution Imaging Spectroradiometer(MODIS) 총일차생산성(GPP) 영상이 8일 간격으로 제공되고 있다. 본 연구에서 MODIS GPP 산출에 사용되는 입력기상(DAO)자료와 광합성유

효복사흡수율(FPAR) 자료의 오차를 정량화 하였고, 이들 오차가 MODIS GPP의 불확실성에 미치는 영향을 분석하였다. 입력자료의 평가를 위해 지상기상관측소의 기상자료를 사용하였고, 구름효과 등을 저감한 FPAR의 시계열을 복원하였다. 평가 결과 입력자료의 오차는 MODIS GPP에서 17% 정도 과대평가되었다. 두 오차 중에서 기상자료의 오차가 주요 원인이었으며, FPAR의 오차는 부차적인 것으로 판명되었다. 다양한 토지피복 중에서 혼효림의 MODIS GPP 오차가 약 20%로 가장 크고, 농경지는 약 11%의 오차를 보였다. 입력자료에 의한 MODIS GPP의 오차는 GPP의 계절변화뿐만 아니라 연간 GPP 변화에도 상이한 결과를 초래하였다. 따라서 MODIS GPP에 내재한 오차는 상당하다고 판단되며, 향후 GPP 모니터링에 응용하기 위해선 상기 기술한 오차 요인들을 저감한 입력자료에 의거해 MODIS GPP를 재가공할 필요가 있다.

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