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Assimilation of global MODIS leaf area index retrievals within a terrestrial biosphere model

J. Demarty,¹ F. Chevallier,¹ A. D. Friend,¹ N. Viovy,¹ Shilong Piao,¹ and P. Ciais¹

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[1] We investigate the capability of global leaf area index (LAI) retrievals from the Moderate Resolution Imaging Spectroradiometer (MODIS) to be assimilated within a process-oriented biosphere model in order to constrain the distribution of carbon fluxes. This is achieved by implementing a sequential data assimilation procedure within a Dynamic Global Vegetation Model. Assimilating two years (2000–2001) of satellite LAI retrievals advances the onset and the end of the growing season at high northern latitudes, by 20 and 40 days respectively. This reduces the growing season length and leads to lower estimates of global annual gross primary productivity (GPP) and net primary productivity (NPP), respectively by 5 and 3% with large variations from one vegetation biome to another. In situ measurements of monthly GPP from eddy flux towers provide an independent check on the performance of the assimilation procedure, resulting in an improvement of 25% in terms of root mean square error between modelled and observed GPP over the model grid points where the flux towers are located. **Citation:** Demarty, J., F. Chevallier, A. D. Friend, N. Viovy, S. Piao, and P. Ciais (2007), Assimilation of global MODIS leaf area index retrievals within a terrestrial biosphere model, *Geophys. Res. Lett.*, *34*, L15402, doi:10.1029/2007GL030014.

1. Introduction

[2] Various models have been developed in order to quantify the spatial and temporal variation in CO₂ exchanges between the land surface and the atmosphere. Model inter-comparisons show large spatial and temporal differences in primary productivity [Cramer *et al.*, 1999] and net carbon exchange [McGuire *et al.*, 2001]. These uncertainties hinder our understanding of the current carbon cycle. It is commonly recognized that combined process-based and data-driven models must be developed in order to improve the estimates of terrestrial carbon fluxes [Raupach *et al.*, 2005]. To this end, satellite remotely sensed fields are particularly well suited to characterize land cover changes and biophysical activity of terrestrial ecosystems [Nemani *et al.*, 2003]. They are thus commonly used to evaluate model results [Ciais *et al.*, 2005; Tian *et al.*, 2004], to drive models [Hazarika *et al.*, 2005; Liu *et al.*, 1997] and to optimize their parameters [Rayner *et al.*, 2005; Kaminski *et al.*, 2002].

[3] In this paper, we investigate the capability of global MODIS Leaf Area Index (LAI) retrievals to be assimilated

within the ORCHIDEE Dynamic Global Vegetation Model (DGVM) [Krinner *et al.*, 2005]. LAI is a key biophysical variable in terrestrial carbon models because of its close relationship with vegetation structure and its impact on the exchanges of CO₂, water vapour and energy by vegetation canopies [Myneni *et al.*, 2002]. Our objective is to analyse the impact of the assimilation of satellite-derived LAI datasets on modelled phenology and carbon fluxes. A sequential data assimilation procedure is used to constrain the modelled LAI over each grid point using the satellite derived value, within its error. The resulting carbon fluxes are compared with monthly GPP measurements made at the local scale at 40 flux tower sites in order to provide an independent test of the assimilation system.

2. Model and Data

[4] The ORCHIDEE DGVM simulates carbon cycling on time scales ranging from hours to centuries [Krinner *et al.*, 2005; Ciais *et al.*, 2005]. The carbon balance of each ecosystem is determined by photosynthesis, respiration and disturbances (harvest, fires). The seasonal onset and senescence of vegetation activity are calculated prognostically from climate for 12 plant functional types (PFTs) [Botta *et al.*, 2000]. The global distribution of the different PFTs is prescribed from appropriate land cover datasets [see Krinner *et al.*, 2005, and references therein]. The model accounts for the coexistence of several different PFTs within each surface grid point, which share the same soil water reserves. ORCHIDEE was forced by six-hourly meteorological re-analyses of the European Centre for Medium-Range Weather Forecasts at ~125-km spatial resolution over the period 1982–2001 [Uppala *et al.*, 2005]. The plant and soil carbon reservoirs were initialized by running the model to equilibrium for 1982. We chose the period 2000–2001 for assimilating Collection 4 MODIS-LAI product provided by Boston University [Yang *et al.*, 2006; ftp://crsa.bu.edu/rmyneni/myneniprducts/]. These products are provided at a 1-km spatial resolution, and derived from surface reflectance observations using a 6-biome vegetation map and the inversion of a radiative transfer model (RTM). Empirical relations between surface reflectances and LAI were used in the case when the inverted RTM inversion procedure failed. Use of this back-up or RTM retrievals is indicated by a quality flag (MODIS-QA).

[5] A dataset of monthly GPP measurements from eddy covariance flux towers [Falge *et al.*, 2005] is used to provide an independent check on the performance of the assimilation procedure. These measurements were obtained over 40 European and Northern American flux tower sites (33 forests, 4 grasslands and 3 crops) within the FLUXNET global eddy covariance network [Baldocchi *et al.*, 2001].

¹Laboratoire des Sciences du Climat et de l'Environnement, CNRS, CEA, UVSQ, Gif-sur-Yvette, France.

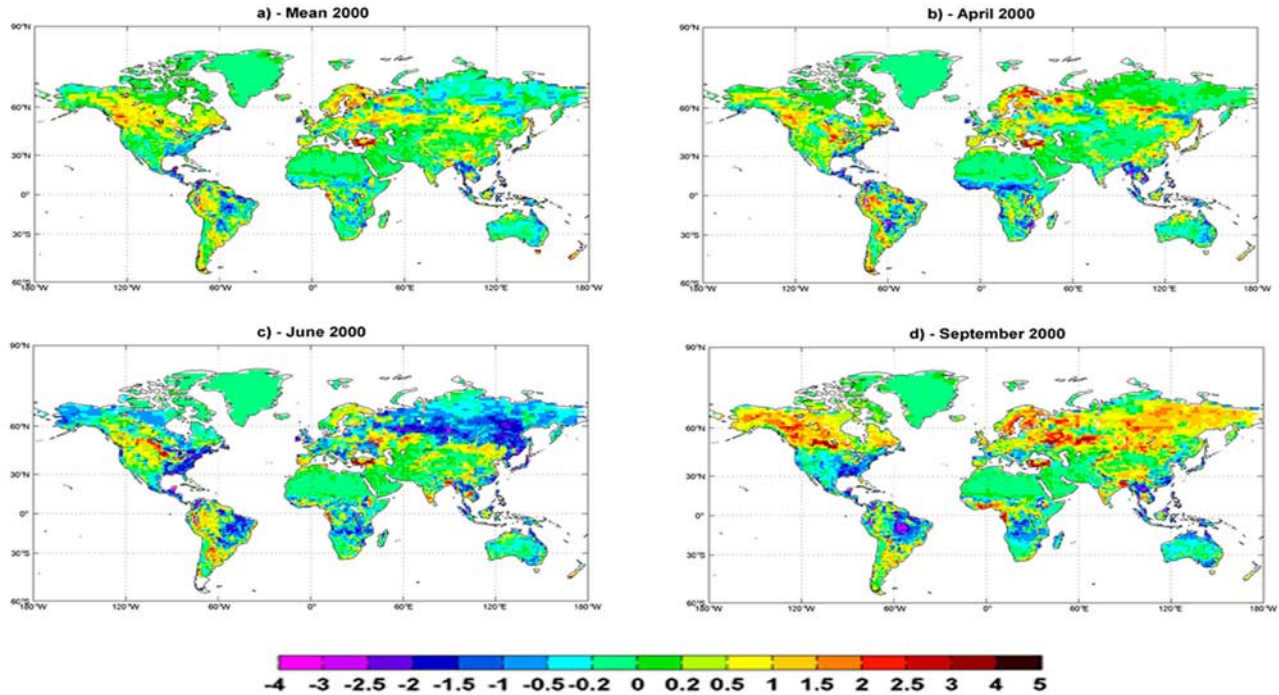


Figure 1. LAI differences between ORCHIDEE and MODIS for 2000: (a) annual mean, (b) April, (c) June, and (d) September.

GPP were estimated by difference between night-time and daytime daily gap-filled net ecosystem exchange (NEE).

3. Data Assimilation Procedure

[6] A sequential data assimilation procedure has been implemented within the ORCHIDEE DGVM. Every 10 days, the LAI is restored to the MODIS observation, if this observation is of good enough quality. In-between two consecutive restoring dates, the model is let free to calculate the dynamic evolution of LAI. The corrected LAI (LAI_c) used in the restoring procedure is estimated from the model first guess (LAI_{fg}), the MODIS data (LAI_{rs}) and the MODIS-QA (q) quality information through the relation:

$$LAI_c = q \cdot LAI_{rs} + (1 - q) \cdot LAI_{fg} \quad (1)$$

[7] Equation (1) implicitly assumes that the satellite-retrieval error is negligible compared to the model error when the observation quality is high (i.e. q close to one). Conversely, MODIS-LAI of poor quality (q close to zero) are given a small weight in the assimilation procedure.

[8] The assimilation procedure also affects LAI between two consecutive-in-time MODIS-LAI retrievals by adding the latest assimilation increment (i.e. $LAI_c - LAI_{fg}$) to the subsequent model LAIs. In the free run of the ORCHIDEE model, LAI is diagnosed daily from the modelled leaf biomass variable, which is in turn affected by LAI through photosynthesis. Our incremental data assimilation strategy insures that the information from the retrievals is propagated into all the carbon pools consistently from one time step to another, without violating the mass conservation of carbon.

This implies that the impacts of the assimilation can be analyzed through the resulting gross primary productivity (GPP), plant respiration, net primary productivity (NPP) and net ecosystem exchange (NEE).

[9] The sequential assimilation procedure was applied globally separating each PFT, using MODIS-LAI retrievals every ten days. Monthly MODIS-LAI were aggregated to the spatial resolution of the ORCHIDEE model, by taking the spatial average of all 1-km pixels for each PFT. A spatially averaged MODIS-QA was then defined for each ORCHIDEE grid point and for each PFT by the fraction of individual 1-km vegetation pixels where the primary RTM was used in the retrieval procedure. Preliminary tests indicated that the 10-day temporal interpolation of monthly MODIS-LAI provides a good compromise between result stability and data volume.

4. Comparisons of the Simulated ORCHIDEE and Satellite-Derived MODIS-LAI

[10] Figure 1 shows the annual and monthly differences between satellite-derived and modelled LAI for April, June and September 2000 (similar spatial patterns were also found for 2001). The magnitude of the regional differences in LAI is about $1-2 \text{ m}^2 \cdot \text{m}^{-2}$, with a maximum value of $3.5 \text{ m}^2 \cdot \text{m}^{-2}$ over Turkey. The model underestimates the MODIS-LAI over Siberia, Australia, Southern Africa, and eastern South America, where natural grasslands are dominant. In contrast, ORCHIDEE predicts systematically higher LAI than MODIS retrievals over boreal conifer forests and over equatorial forests in the Western Amazon and Western Africa. We attribute these differences to three main causes. First, there are some limitations in the LAI simulation by ORCHIDEE, for example the lack of treat-

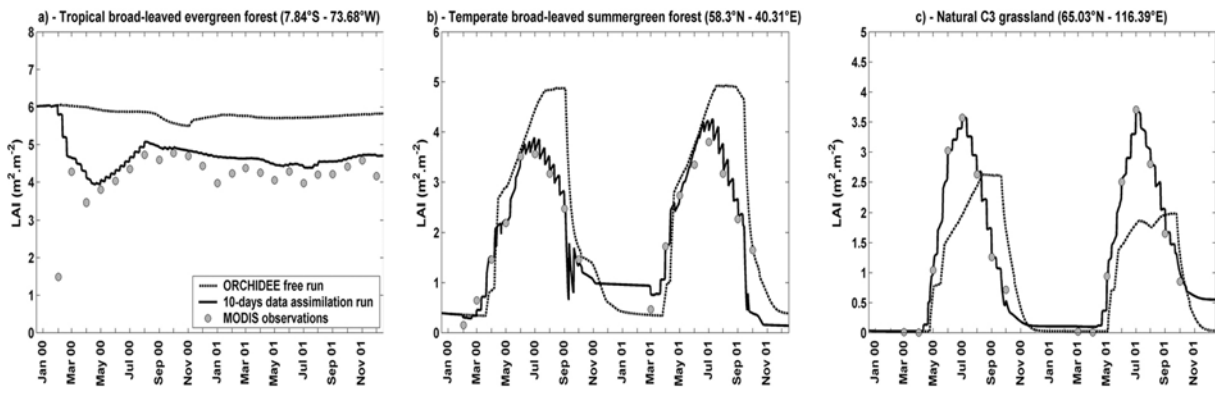


Figure 2. Examples of sequential assimilation of MODIS-LAI within the ORCHIDEE model for 3 different vegetation types. The ORCHIDEE free run (dashed line), the ORCHIDEE 10-day sequential assimilation run (dark line), and MODIS-LAI (grey circles) are indicated.

ment of canopy structure or tree clumping and errors in the phenology of cultivated ecosystems. Moreover, ORCHIDEE does not account for nitrogen limitations and irrigation impacting the seasonal development of LAI. Secondly, there are inconsistencies in the land cover between MODIS and ORCHIDEE. Lastly, there are uncertainties in the retrieval of MODIS-LAI due to atmospheric corrections, sensor calibration, and limited information content of the MODIS surface reflectances. This is especially true for equatorial regions with high cloudiness and LAI values.

[11] Figure 1 also shows a lag between the modelled and the satellite-derived LAI over many regions of the Northern Hemisphere (also noticed by *Krinner et al.* [2005]). The simulated LAI is underestimated during May–June (Figure 1c) and highly overestimated during September–October (Figure 1d), with differences in the range 0.5–3.0 m².m⁻². These differences are very significant over boreal forests and natural C3 grasslands of the high latitudes, where the presence of snow affects satellite

retrievals [*Tian et al.*, 2004], and more relative over European temperate forests.

5. Assimilation of Satellite LAI Data Within the ORCHIDEE Model

[12] Figure 2 shows examples of assimilated LAI values for a tropical broad-leaved forest in western Amazon, a temperate deciduous forest in Europe, and a natural C3 grassland in central Asia. By construction, the assimilated LAI values lie in-between the MODIS ones and the free model run. ORCHIDEE and MODIS show contrasted LAI temporal dynamics. For the tropical forest, there is a systematic model overestimation. As the MODIS-QA has been equal to zero, no assimilation has been performed before February 2000. The impact of the interpolation of the MODIS datasets in the assimilation procedure can be observed between February and March. For the European temperate forest and the C3 grassland, the modelled senes-

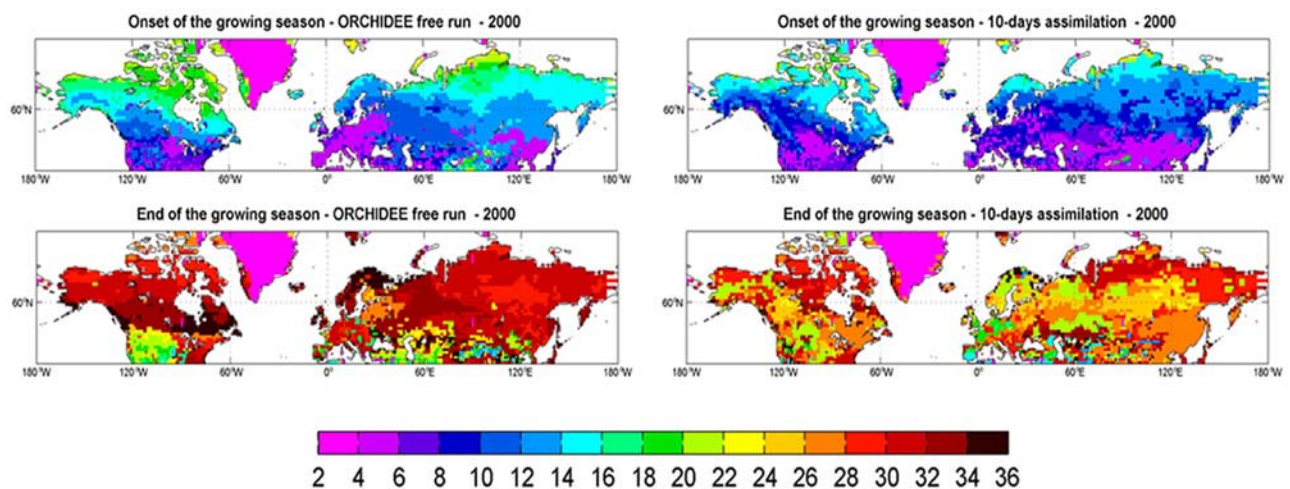


Figure 3. Impact of the MODIS-LAI assimilation on the phenology of the Northern Hemisphere. Comparisons between (left) the ORCHIDEE free run and (right) 10-day sequential data assimilation run are discussed both in terms (top) of the onset of the growing season and (bottom) of the end of the growing season.

Table 1. Impact of the Assimilation on the Main Terrestrial Carbon Fluxes During the Period 2000–2001^a

| Modelled Carbon Fluxes for the Period 2000–2001 | Mean Annual, PgC.y ⁻¹ | | RMSE With Monthly Observations, gC.m ⁻² .month ⁻¹ | | |
|--|-------------------------------------|--------|---|----------|--------|
| | Free Run | Assim. | Number | Free Run | Assim. |
| GPP | 135.8 | 128.7 | 40 | 90.9 | 68.2 |
| | <i>Quarter</i> | | | | |
| DJF | 24.4 | 23.1 | 40 | 37.0 | 26.2 |
| MAM | 32.5 | 32.5 | 40 | 129.3 | 86.0 |
| JJA | 48.2 | 46.1 | 40 | 112.0 | 94.3 |
| SON | 30.7 | 27.1 | 40 | 50.8 | 39.9 |
| | <i>Vegetation types</i> | | | | |
| Trop. broad-leaved evergreen forest | 22.7 | 19.4 | - | - | - |
| Trop. broad-leaved raingreen forest | 8.2 | 8.1 | - | - | - |
| Evergreen needleleaf forest | 10.5 | 8.0 | 14 | 54.4 | 44.2 |
| Evergreen broad-leaved forest | 2.5 | 2.2 | 3 | 72.5 | 72.7 |
| Deciduous broad-leaved forest | 8.0 | 6.5 | 8 | 119.1 | 84.3 |
| Mixed forest | - | - | 8 | 81.9 | 67.6 |
| Boreal needleleaf summergreen | 0.9 | 1.0 | - | - | - |
| Natural C3 grassland | 25.6 | 32.9 | 4 | 69.5 | 66.3 |
| Natural C4 grassland | 38.0 | 34.8 | - | - | - |
| Agricultural C3 | 12.4 | 10.4 | 3 | 152.3 | 93.3 |
| Agricultural C4 | 7.2 | 5.3 | - | - | - |
| NPP | 65.8 | 63.4 | - | - | - |
| NEE | -1.2 | 0.3 | - | - | - |

^aThe assimilation run provides lower estimates of annual GPP (5.2%) and NPP (3.4%) and higher estimates of NEE (125%). Comparison of monthly GPP with data from 40 FLUXNET sites shows the benefit of the assimilation over seasons and for most of the vegetation types.

cence occurs too late by about 40 days, even though the simulated LAI could be either too high or either too low in summer. The data assimilation procedure locally improves the fit to the MODIS-LAI data in the three cases. Variability in the assimilated LAI curve reveals small expected instabilities of the assimilation system.

[13] The assimilation of the MODIS-LAI retrievals into ORCHIDEE modifies the vegetation phenology over the Northern Hemisphere (Figure 3). We have defined the onset and the end of the growing season by the 10-day period of

the year where LAI begins to increase, and the 10-day period of the year when the inflexion of the LAI decrease occurs, respectively. As shown in Figure 2, the assimilation procedure corrects the model towards earlier onset dates (10–20 days) and earlier end-of-growing-season dates (40 days), especially at high latitudes (>50°). Over the mid latitudes and mountain regions, however, no trend is clearly observed and the assimilation leads to spatially more heterogeneous results than the ORCHIDEE free run.

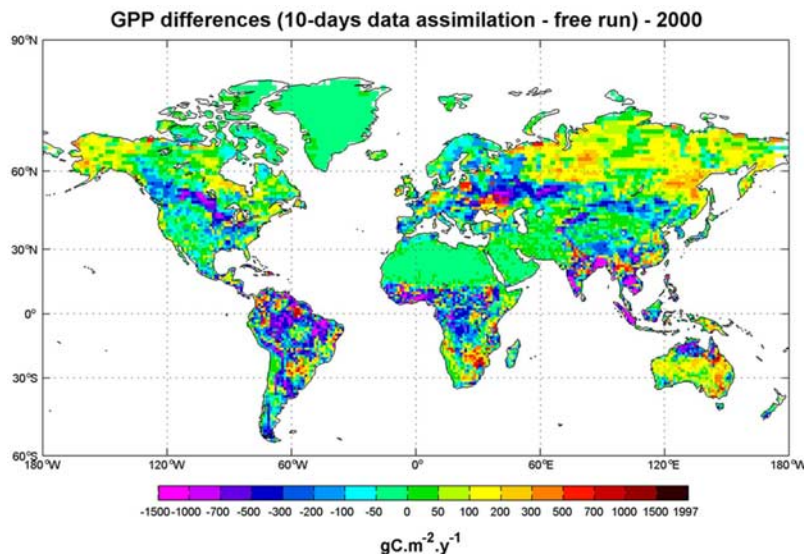


Figure 4. Impact of the MODIS on the simulated annual Gross Primary Productivity (GPP, gC.m⁻².y⁻¹) in terms of differences between the 10-day interpolated data assimilation run and the ORCHIDEE free run for 2000.

[14] The assimilation of LAI impacts the modelled carbon fluxes (Table 1 and Figure 4). The global mean GPP decreases by 7.1 PgCy^{-1} (5.2%) after assimilation. As expected, the GPP correction has a spatial pattern similar to the LAI correction. In particular, GPP decreases after assimilation over extra-equatorial regions, European Russia, southern Siberia, and mid-western North America. In contrast, GPP increases after assimilation over deciduous conifer forests (Larch) (10%) and natural C3 grasslands (28.5%) in boreal regions, as well as in South Africa and Australia where the satellite-derived LAI values are generally higher than simulated ones. Due to lower MODIS-QA, no change in GPP is inferred over Turkey even though the differences in LAI between ORCHIDEE and MODIS were the highest in that region.

[15] We have validated the assimilated monthly GPP against in situ data at 40 eddy flux tower sites globally distributed (Table 1). The RMSE between assimilated and observed annual and seasonal GPP shows that the data-assimilation improves the model (overall by 25%) for each season, and for most vegetation types. The largest improvements take place during the spring (39%) and over agricultural site (39%), temperate forests (29%) and boreal forests (19%). The assimilation delivered no improvement over the two Mediterranean forest flux tower sites, because ORCHIDEE was not constrained there by satellite retrievals (small values of the MODIS-QA).

[16] Tailing off with a reduced GPP after assimilation, the modelled NPP also decreased globally by 2.4 PgC.y^{-1} (3.5%). The NPP reduction was less than the one of GPP, given a coincident decrease of 4.7 PgC.y^{-1} in autotrophic respiration (a flux proportional to newly formed biomass). The global NPP/GPP ratio of 0.49 remained unchanged after assimilation. Regarding NEE, a global annual carbon source of 0.3 PgC.y^{-1} is determined after assimilation for the average 2000–2001. This result should be considered with caution because a 2-year assimilation window is obviously too short for the soil carbon pools to adjust to the corrected productivity inputs. Furthermore, the two years show some interannual NEE variability, with a sink of carbon (-1.1 PgC.y^{-1}) in 2000 and a net source of carbon (0.5 PgC.y^{-1}) in 2001.

6. Discussion and Conclusions

[17] We have shown that the assimilation of satellite LAI retrievals has a significant impact on the seasonal development of vegetation and on monthly and annual carbon fluxes. The assimilated global mean GPP and NPP are in agreement with satellite-based estimations derived from MODIS using simple leaf conversion efficiency relationships [Zhao *et al.*, 2005], and with Hazarika *et al.* [2005] who directly forced their ecosystem model by MODIS-LAI data. Interestingly, a better match to the point wise eddy flux tower in situ GPP measurements was found when assimilating MODIS-LAI, despite errors in LAI retrievals, unknown biases in the ORCHIDEE simulation of carbon fluxes from LAI, and the huge scale gap between a model grid point (10^4 km^2) and a flux tower (1 km^2). Such a good performance of the LAI assimilation is encouraging for future studies where flux towers and remote sensing data could be jointly used [Friend *et al.*, 2006].

[18] Our results indicate that the MODIS-LAI data contain enough useful information for correcting some deficiencies in a global DGVM, such as too high LAI values or a too long growing season over boreal forests. Yet, the use of satellite products could be substantially enhanced if we had quantitative information on the data uncertainties. Here, we hypothesized that all uncertainties associated with the MODIS-LAI data were contained in the quality flags MODIS-QA, an assumption which proved efficient for reducing the weight of unreliable satellite products, especially over tropical forests. However, the MODIS-QA remains a qualitative measure of uncertainty, and does not quantitatively account for each source of error in the LAI retrieval procedure (sensor calibration, atmospheric corrections, land cover mapping radiative transfer forward and inverse modelling). Recent exercises of validation of the MODIS datasets will be useful to assess uncertainties [Yang *et al.*, 2006]. It will also be important to quantify uncertainties in the model, in order to choose an appropriate balance between the satellite-derived information and the model information content in the data assimilation system [Chevallier *et al.*, 2006].

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F. Chevallier, P. Ciais, J. Demarty, A. D. Friend, S. Piao, and N. Viovy, Laboratoire des Sciences du Climat et de l'Environnement, CNRS, CEA, UVSQ, Orme des Merisiers, F-91191 Gif-sur-Yvette, France. (jerome.demarty@cea.fr)