Implementing Multi-scale AGricultural Indicators Exploiting Sentinels

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ACRONYMS

ASCAT (Advanced Scatterometer)

AST (ISBA model option with net assimilation of CO_2, enhanced soil water stress representation, but without vegetation evolution)

CDF (Cumulative Distribution Function)

CGMS (Crop Growth Monitoring System)

EKF (Extended Kalman filter)

ET (evapo-transpiration)

GEOV1 (Version 1 of LAI, FAPAR, FCover products)

ISBA-A-gs (Interactions between Soil, Biosphere, and Atmosphere, CO_2 responsive)

JRC (Joint Research Center)

LAI (Leaf Area Index)

LDAS (Land Data Assimilation System)

LDAS1 (assimilation of LAI only)

LDAS2 (assimilation of both LAI and SSM)

LSM (Land Surface Model)

MARS (Monitoring Agricultural ResourceS)

MODCOU (MODélisation COUplée nappe surface)

NIT (ISBA model option with net assimilation of CO_2, enhanced soil water stress representation, and vegetation evolution, including nitrogen dilution)

NWP (Numerical Weather Prediction)

RMSE (Root Mean Square Error)

SAFRAN (Système d'Analyse Fournissant des Renseignements Atmosphériques à la Neige)

SIM (SAFRAN-ISBA-MODCOU)

SSM (Surface soil moisture)

SURFEX (Externalized surface)

VEGETATION (The medium resolution sensor onboard SPOT4 and SPOT5)

WOFOST (WOrld FOod STudies)

1 BACKGROUND OF THE DOCUMENT

1.1 EXECUTIVE SUMMARY

The main objectives of IMAGINES are to (i) improve the retrieval of basic biophysical variables, mainly LAI, FAPAR and the surface albedo, identified as Terrestrial Essential Climate Variables, by merging the information coming from different sensors (PROBA-V and Landsat-8) in view to prepare the use of Sentinel missions data; (ii) develop qualified software able to process multi-sensor data at the global scale on a fully automatic basis; (iii) explore new paths to complement and contribute to the existing or future agricultural services by providing new data streams relying upon an original method to assess the above-ground biomass, based on the assimilation of satellite products in a Land Data Assimilation System (LDAS) to monitor the crop/fodder biomass production together with the carbon and water fluxes; (iv) demonstrate the added value of this contribution for a community of users acting at global, European, national, and regional scales.

The land data assimilation system (LDAS) developed in the SURFEX modeling platform permits the joint assimilation of remotely sensed Surface Soil Moisture (SSM) derived from ASCAT backscatter data and the GEOV1 satellite-based LAI into the ISBA-A-gs land surface model. The ASCAT data are bias corrected with respect to the model climatology by using a seasonal-based CDF (Cumulative Distribution Function) matching technique. A multivariate multi-scale LDAS based on the Extended Kalman Filter (EKF) technique is used for monitoring soil moisture, vegetation, and terrestrial surface carbon and energy fluxes across the France domain at a spatial resolution of 8 km. Each model grid box is divided in a number of land covers, each having its own set of prognostic variables. The filter algorithm is designed to provide a distinct analysis for each land cover while using one observation per grid box. The updated values are aggregated by computing a weighted average. In the framework of ImagineS, two vegetation types are considered: straw cereals and grasslands.

The added value of the assimilation of satellite products on vegetation biomass simulations is evaluated over France using reference agricultural yearly statistics of fodder production and straw cereal yields. The assimilation of LAI triggers a dramatic improvement of the correlation between the simulated biomass and the observations.

Hydro-validation is performed coupling SURFEX to the MODCOU hydrological model. LAI is found to have a marked impact on the river discharge scores. The assimilation of soil moisture observations tends to artificially increase the river discharge at wintertime and springtime, indicating that the threshold-driven drainage approach used in the SURFEX model version currently used in the LDAS is probably too simple to integrate SSM observations for hydrologic applications.

1.2 Scope and Objectives

In situ agricultural and hydrological observations over France are used to validate the LDAS-France chain operated by Meteo-France. In addition, simulations from the WOFOST crop model are used as a benchmark.

1.3 Content of the Document

The Chapter 2 presents the validation framework of the LDAS for agriculture and hydrology. Conclusions and prospects are presented in Chapter 3.

1.4 Related Documents

1.4.1 Inputs

Overview of former deliverables acting as inputs to this document.

Document ID	Descriptor
ImagineS_RP1.1	Users Requirements Document
ImagineS_RP1.2	Service Specifications Document
ImagineS_RP3.1	LDAS ATBD

1.4.2 Output

Overview of other deliverables for which this document is an input:

Document ID	Descriptor
ImagineS_RP6.3	Product User Manual of LDAS output products

2 VALIDATION FRAMEWORK

2.1 INTRODUCTION

The possibility of improving the performance of land surface models (LSMs) using remotely sensed observations is a field of active research. The mechanism of integrating observations, in a statistically optimal way, into a numerical model is called "data assimilation". The latter permits improving the representation of the dynamical behavior of a bio-geophysical system. Land data assimilation systems (LDAS) are needed to integrate satellite data providing information about land state variables such as the surface soil moisture (SSM) and leaf area index (LAI) into LSMs.

Soil moisture is a key factor controlling both the water and energy cycles (through its impact on the fluxes partitioning at the surface). In addition, it is linked to the carbon cycle through the coupling between plant transpiration and photosynthesis. A number of studies have discussed the importance of soil moisture in the description of the carbon cycle whose connexions with the hydrological cycle are largely unknown (van der Molen et al., 2011). Assimilating remotely sensed SSM data into a LSM has proved, in a large number of papers, to be effective in estimating deeper soil moisture in various contexts, such as hydrology (Houser et al., 1998; Reichle et al., 2002; Draper et al., 2011), numerical weather prediction (NWP) (Mahfouf, 2010; Dharssi et al., 2011; de Rosnay et al., 2013) and agricultural studies (Bolten and Crow, 2012).

Also, LAI impacts the exchanges of water vapor and CO_2 between the vegetation canopy and the atmosphere. A number of studies (Jarlan et al., 2008, Gu et al., 2006, Demarty et al., 2007) have shown the potential of assimilating LAI observations to correct vegetation model states.

Barbu et al. (2014) have shown that the LDAS is able to: (1) simultaneously ingest EO satellite data providing mixed signals at a grid-scale into the mosaic structure of the ISBA-A-gs LSM (Calvet et al. 1998) within SURFEX (Masson et al. 2013); (2) propagate information from the surface into the root-zone soil layer; (3) consistently impact the water and carbon fluxes; (4) improve the short-term vegetation response to drought conditions.

The scientific validation of the products aims to assess the reliability (spatial and temporal) of the products, determine accuracy and precision of the products, identify problematic areas and possible cause of errors, analyze the compliance regarding users requirements, and provide recommendations on the usability of the products. It has been shown that the above-ground biomass simulated by ISBA-A-gs over croplands and grasslands relates to agricultural yields (Calvet et al. 2012), especially for grasslands; this finding indicates that the model could be used to produce new drought indicators useful for agriculture yield monitoring and this will be investigated over France. ISBA-A-gs forms the basis of a Land Data Assimilation System (LDAS), able to ingest satellite-derived products (LAI, surface soil moisture) at a spatial resolution of 8km over France.

The LDAS France validation focuses on 1) above –ground biomass and LAI (agriculture) and 2) river discharges (hydrology).

2.2 AGRICULTURE

Biomass and leaf area index are directly affected by the LDAS systems and were therefore selected for validation. Agricultural observations were used for validation over France, for straw cereals. A comparison with crop model-based results was also performed. The comparison is performed for the 45 straw cereal locations in France proposed by Calvet et al. (2012).

2.2.1 WOFOST

WOFOST is a crop growth model that allows estimating quantitatively yields, developed by the Department of Theoretical Production Ecology (Wageningen Agricultural University, The Netherlands) and the Center for Agrobiological Research and Soil Fertility (Wageningen, The Netherlands). This model is implemented currently within the MARS Crop Growth Monitoring System (CGMS), allowing the estimation of biophysical variables related with crop yields such as potential biomass production, crop development stage, etc...

WOFOST raw simulations were provided by JRC. They are done at soil unit level and multiple times for each of the soil types within a soil polygon. Then, they are aggregated according to the provided information about the coverage of the soil types within the soil unit polygon intersected by the grid of 25 by 25 km. The WOFOST grid points corresponding to 45 straw cereal locations in France were used for this validation. Data for soft wheat (winter wheat) were extracted from 2007 to 2011 in 10 daily steps for: 1) water limited above-ground biomass (kg/m2) and 2) water limited LAI (m2/m2).

The WOFOST data were compared with the ISBA-A-gs outputs for straw cereals before (open loop) and after data assimilation, as well as with the in situ Agreste data (see below). WOFOST vs. ISBA simulations results are illustrated in Figure 1 for water limited above-ground biomass. WOFOST correlates better with the raw ISBA-A-gs model outputs than with the ISBA-A-gs simulations after integrating satellite observations. The correlation coefficient values are *R* = 0.45 and *R* = 0.25, respectively. This does not mean that the assimilation degrades the ISBA-A-gs model, as the raw WOFOST simulations used here cannot be considered as a reference. In situ agricultural yield observations are needed.

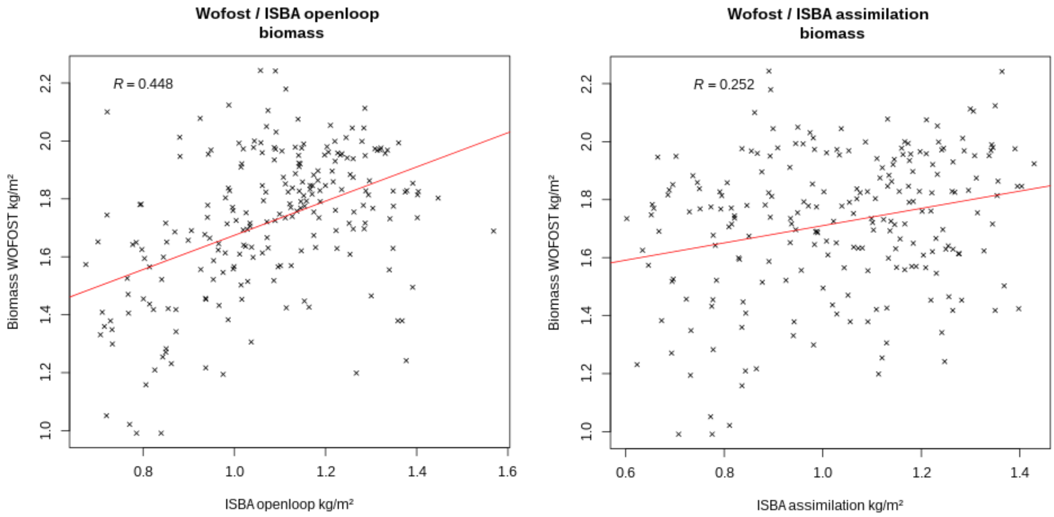

Figure 1: Water limited above-ground biomass (kg/m2) of straw cereals provided by WOFOST vs ISBA open loop (left)/ ISBA assimilation (right), for the pooled dataset (225 points corresponding to 45 locations during 5 years).

2.2.2 Agreste

Agreste is an annually updated set of agricultural data over France (Agreste, 2014). An inventory of the land use in agriculture and of the crop, forage and livestock production is made on a yearly basis. The data are provided for department administrative units. For crops, annual grain yields are supplied. The Agreste data set is used over the 2007–2011 period to examine the inter-annual variability of winter/spring cereal crop grain yields in 45 administrative units ("départements"). Each crop considered alone covers a significant fraction of each of 45 départements.

Several results are illustrated in Figure 2 for biomass and in Figure 3 for LAI. A significant improvement is shown after assimilating satellite observations for both variables. The assimilation triggers a much better performance in terms of correlation with Agreste data for both variables. While the raw ISBA-A-gs simulations are virtually uncorrelated with Agreste (left graph), the analyzed above-ground biomass and LAI correlate well with Agreste: *R* = 0.57 and *R* = 0.56, respectively (middle graphs), against *R* = 0.38 and *R* = 0.14 for raw WOFOST simulations (right graphs).

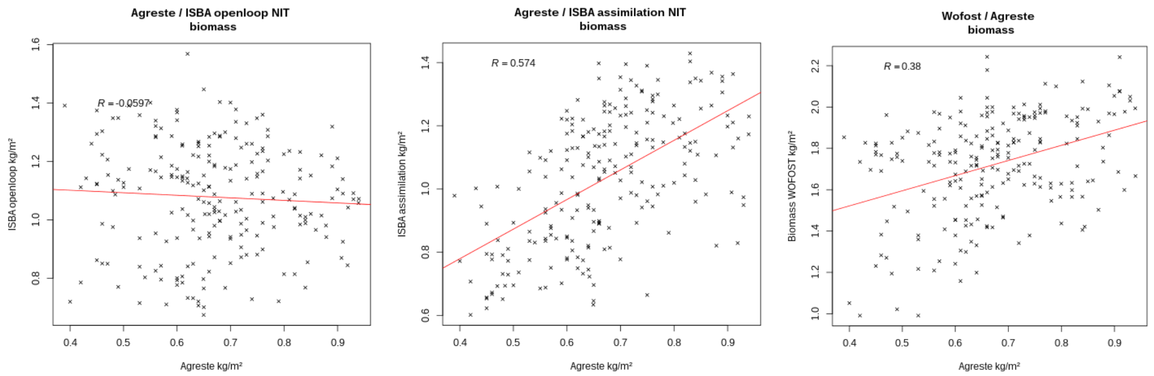

Figure 2: Simulated water limited above-ground biomass (kg/m2) of straw cereals vs. observed (Agreste) yield, over 45 administrative units in France for a 5-year period from 2007 to 2011, representing 225 observations. From left to right: ISBA model, LDAS-France (ISBA analysis), WOFOST (correlation coefficient values of -0.06, 0.57, and 0.38, respectively).

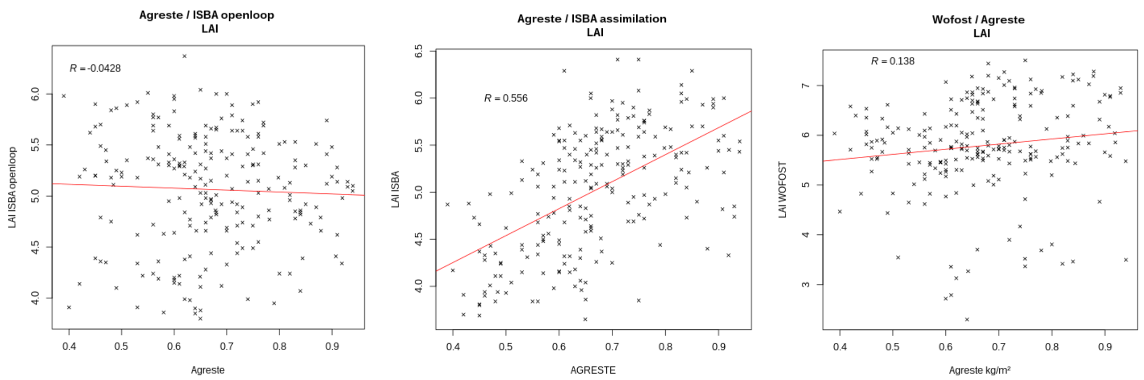

Figure 3: Simulated water limited LAI (m2/m2) of straw cereals vs. observed (Agreste) yield, over 45 administrative units in France for a 5-year period from 2007 to 2011, representing 225 observations. From left to right: ISBA model, LDAS-France (ISBA analysis), WOFOST (correlation coefficient values of -0.04, 0.56, and 0.14, respectively).

2.3 HYDRO-VALIDATION

Soil moisture is another important variable directly impacted by the assimilation of satellite products. The scarcity of in situ soil moisture data limits the possibility of an independent validation of the assimilation results. Direct observations of drainage, runoff and evapo-transpiration (ET) are not available at a large scale. On the other hand, data from a dense river discharge network over France are available. Therefore, the river discharge was chosen as the second main focus of the present validation methodology.

For this purpose, a hydrological model was coupled with ISBA-A-gs using the SAFRAN-ISBA-MODCOU (SIM) system. The MODCOU hydrological model (Habets et al. 2008) computes the spatial and temporal evolution of the piezometric level of multilayer aquifers, as well as the exchanges between aquifers and rivers, before routing the surface water through the river network. In the SIM-France system river flows are calculated every 3 hours, while the evolution of the aquifers is computed daily.

Two configurations of the ISBA LSM have been used in coupling with MODCOU:

- AST: ISBA-A-gs without dynamic evolution of LAI. The annual cycle of LAI is provided by ECOCLIMAP-II (Faroux et al. 2013) as a fixed satellite-derived climatology.
- NIT: ISBA-A-gs simulates daily LAI values.

The ISBA-A-gs NIT version is used in the data assimilation scheme, and the obtained analysis is coupled with MODCOU. Two simulations referred as to LDAS are provided:

- LDAS1: data assimilation of one variable (satellite LAI data only),
- LDAS2: data assimilation of two variables (both satellite-derived LAI and SSM).

It must be noted that the only difference between AST, NIT, and LDAS1 simulations is the representation of LAI. The drainage and runoff fluxes generated for each experiment (NIT, AST, LDAS1 and LDAS2) were routed through the surface river network using the MODCOU model.

Comparisons with observed river flow data were performed on a daily and monthly basis at the river gauges located closest to the outlet of the four largest rivers of France (Loire, Seine, Garonne and Rhone). Various statistical scores (squared correlation coefficient, simulated/observed discharge ratio, root mean square error (RMSE), efficiency (Nash score)) are shown in Table1.

Table 1 - Scores obtained for 4 stations located closest to the outlet of the four largest French rivers from August 2007 to July 2012. The Efficiency, Ratio, R^2 and RMSE (in m^3d^{-1}) scores are based on daily values. The best score values at a given river basin are in bold.

Station	Efficiency			Ratio			R^2			RMSE		
	NIT	LDAS2	LDAS1	NIT	LDAS2	LDAS1	NIT	LDAS2	LDAS1	NIT	LDAS2	LDAS1
Loire	0.22	-0.08	**0.29**	1.32	1.38	**1.29**	0.93	0.92	0.93	447.0	524.5	**425.1**
Rhône	0.53	0.54	**0.54**	1.01	0.99	**1.00**	0.84	0.83	0.84	583.7	580.4	**576.8**
Garonne	0.73	0.71	**0.74**	1.08	1.09	**1.07**	0.92	0.91	0.92	141.6	148.6	**140.2**
Seine	**0.58**	0.30	0.56	**1.23**	1.34	1.24	0.94	0.93	0.94	**120.3**	155.1	122.1

The assimilation of LAI only (LDAS1) tends to improve the overall scores for the Loire, Rhône and Garonne rivers, and slightly degrades the scores for the Seine river. The assimilation of both LAI and SSM (LDAS2) has, overall, a detrimental impact on the scores for Loire, Seine and Garonne, and an almost neutral impact on the scores provided for the Rhone river.

Figure 4 shows the cumulated distribution function (CDF) of the Nash scores for all the simulations over the France domain. The AST version shows a better overall performance compared to the NIT version of the LSM. In order to investigate the differences between the two model versions the time series of monthly averaged LAI and ET are presented in Figure 5. The AST climatologic LAI overestimates the GEOV1 data during the whole year, except for May and June, while the NIT version underestimates the observations from June to December. Lower LAI values provided by NIT lead to lower ET values, especially in winter. Therefore a larger amount of water is still present in the soil and drained out.

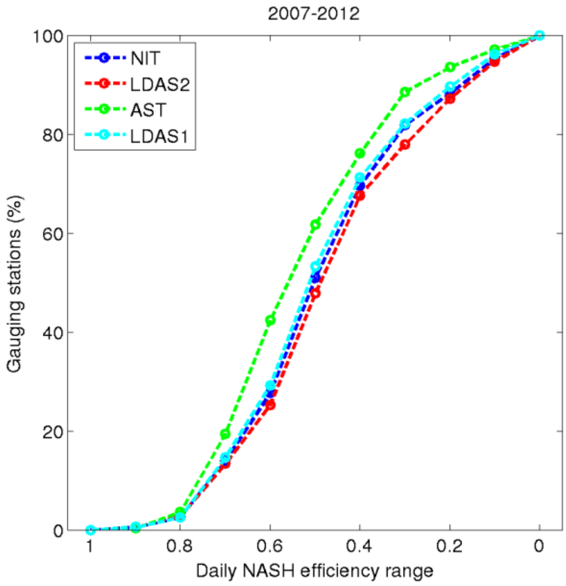

Figure 4: CDF of the daily NASH efficiency score for all four simulations over France from August 2007 to July 2012.

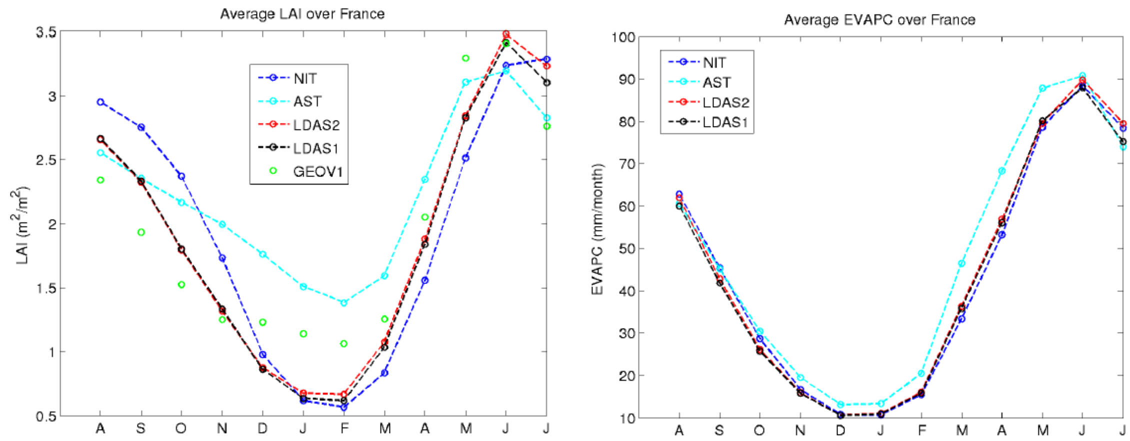

Figure 5: Monthly LAI (m2/m2) (left) and evapo-transpiration fluxes (mm/month) from August to July averaged over 2007 to 2012 over France. The GEOV1 LAI data is represented by green circles.

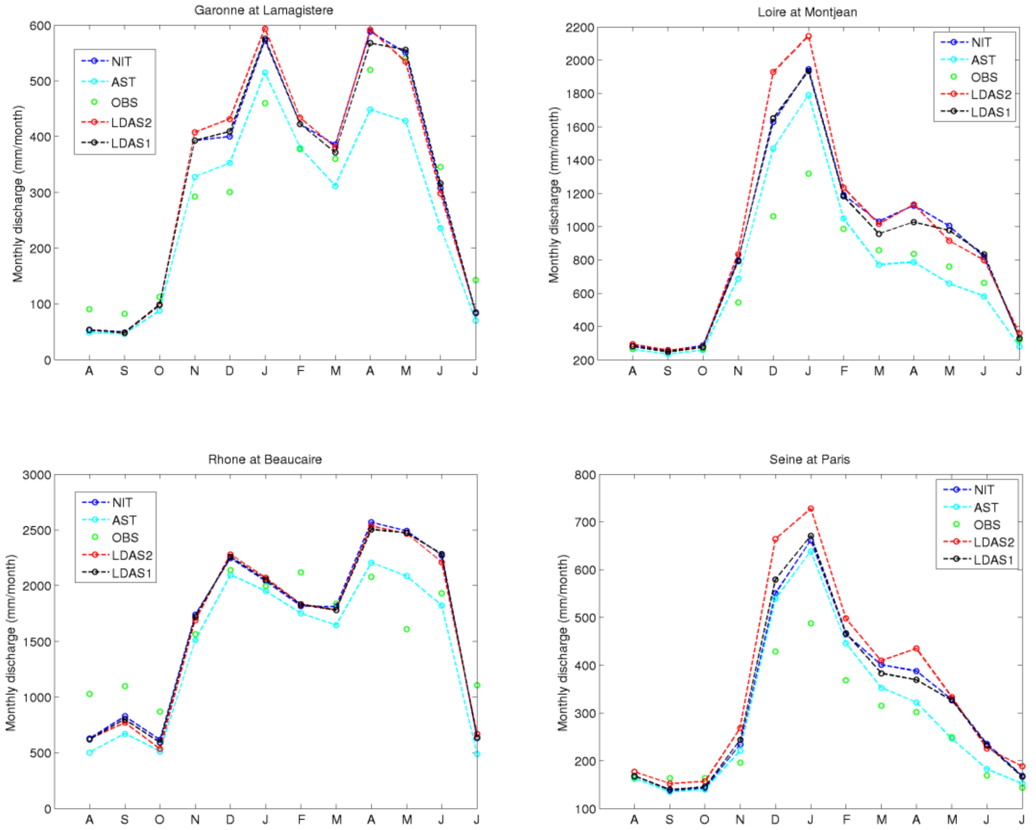

Figure 6: Average monthly river flows from Aug 2007 to July 2012 at the river gauges located closest to the outlet of the four largest rivers: Garonne, Loire, Rhone and Seine.

Figure 6 presents the monthly river flows at the river gauges located closest to the outlet of the four largest rivers as resulting from all simulations together with the gauging data. The Garonne at Lamagistere has the smallest upstream area (50,430 km^2), and logically has the lowest average discharge, but it has higher flood peaks than the Seine basin at Paris (which has an upstream area of 65,686 km^2). This is due to the fact that the Garonne encompasses part of the Pyrenees and Massif Central mountains, where heavy orographically enhanced precipitation can occur, while the Seine basin overlays a widespread aquifer, which tends to reduce the winter flood peaks and to sustain the summer low flow. The Loire at Montjean sur Loire, which has the largest upstream area (110,356 km^2) has an average discharge lower than that of the Rhone at Beaucaire, which has a smaller contributive area (96,412 km^2). This results because the Rhone basin encompasses part of several mountain ranges, notably the

Alps. For the Garonne and Loire rivers, the recession of the flood peaks are too fast in the model compared to the gauging data.

There are systematic differences between the flood peaks simulated by both ISBA-A-gs model versions (NIT and AST) and the observations. Comparisons between the two model versions and the data reveal a better agreement in terms of amplitude and in terms of inter-annual variability between the AST version and the gauging observations. Assimilation of LAI only (LDAS1) helps the NIT model to increase the LAI values during the growing phase of the vegetation (March-May) and then increases the evapo-transpiration fluxes. This changes the water balance and decreases the drainage. As a consequence the assimilation of LAI improves the simulated discharges which are closer to the observations. In contrast, the joint assimilation of LAI and soil moisture has a detrimental effect on the water balance in autumn and winter. In November and December, the assimilation of ASCAT data provides positive soil moisture increments in the root-zone reservoir that causes a supply of water to be drained out (Barbu et al., 2014). Generally, in winter, the assimilation tends to add water in the soil. The latter is already close to the field capacity when the drainage mechanism is active. The increased drainage fluxes by assimilation together with the fact that the surface scheme ISBA has an excessive drainage rate indicate that the assimilation leads to an increase of river discharge bias. These results are illustrated in Figure 7 over the Loire basin. Similar results are obtained for the other basins.

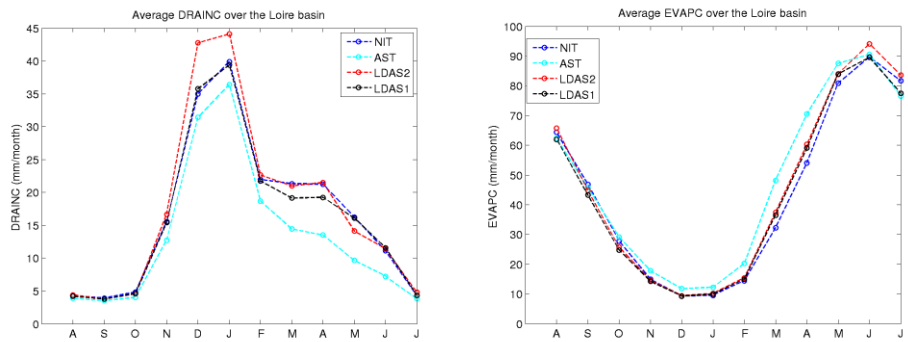

Figure 7: Monthly drainage (left) and evapo-transpiration (right) fluxes averaged over the Loire basin. The units are in mm/month.

2.4 LIMITATIONS OF THE METHOD

The assimilation results depend to a large extent upon the quality of the data to be assimilated. The remotely sensed SSM data exhibit a number of non-realistic low values associated with large uncertainties over densely vegetated areas. This may be detrimental to the analysis by causing a too large soil moisture depletion. A single, thick root-zone soil layer represents the soil hydrology in the model version. Such description may not be realistic. The propagation of surface soil moisture information within deeper layers may be affected by the lack of vertical resolution of the model. Increasing the number of soil layers will allow an explicit representation of a vertical distribution of the root profile in the soil and, subsequently, a more realistic vegetation response to water stress. In that respect, a multi-layer version of the soil hydrology is expected to improve the overall performance of the system.

Finally, the MODCOU model version used in this study does not include a representation of the reservoirs. This may explain why the overestimated wintertime and springtime LAI values of the AST simulations give the best results. This error tends to compensate for the lack of a representation of the reservoirs and better river discharge values are obtained for the wrong reason.

3 CONCLUSIONS AND PROSPECTS

The ISBA-A-gs LSM provides a detailed computation of the surface fluxes of energy, water and carbon at the sub-grid (patch) level and allows aggregating the information from different ecosystem types. Following this approach, a land data assimilation system was designed to produce the updated variables for each land cover by using one grid-scale observation. A validation methodology was implemented and focused on 1) above-ground biomass and LAI and 2) river discharges. The LDAS performance for straw cereals was tested against the Agreste agricultural data and simulations from the WOFOST crop model. It was shown that a significant improvement is obtained by using the LDAS chain. Next, the validation focus is on the river discharges. While the assimilation of ASCAT SSM data is more problematic for the water balance showing an overestimation of drainage fluxes in winter, the assimilation of LAI only has generally a positive impact on the evapo-transpirations fluxes which leads to improvements in terms of river discharges.

In the framework of IMAGINES and related European and national projects, the following SURFEX LDAS developments are planned in the next years: evaluate the use of (1) new satellite products (FAPAR, surface albedo, land surface temperature), (2) alternative data assimilation techniques (e.g. EnKF), (3) new capabilities of the SURFEX modeling platform (e.g. multilayer soil model), and (4) extend the existing LDAS-France to the global scale (over the Euro-Mediterranean area in a first stage).

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