Dear Editor and Referees,

We would like to thank you for your helpful comments. We have done many modifications to the manuscript according to your suggestions. Please find below the point-by-point reply to the referees comments and a marked-up version of the manuscript.

We also wish to bring the Editor's attention to the fact that we would like to add Dr Tiphaine Tallec as a co-author of the paper. Indeed, her contribution was instrumental in addressing the issue of the eddy covariance measurements uncertainties that was raised by Reviewer 2.

Sincerely yours.

The authors

Anonymous Referee #1: ***"General comment: the objective is significant. The problem of land cover spatial variability and remote sensing estimation at appropriate spatial scale is a key topic. However, several problems and comments are described below and need to be addressed. In particular, I have several doubts on the spatial scales of model, remote sensing observations and eddy covariance fluxes. I think that the paper can be accepted but the following clarifications need to be addressed for properly evaluating the paper. "***

Authors: Thank you for your comments, which are pointing out that we should better highlight the issue of the spatial variability of the land cover in current land surface model. Indeed, this issue is the main motivation behind the plot scale approach described in the paper. You will find all the explanation about this approach in the following answer to your specific comments. We have done several efforts to make it clearer to the reader. Also, to simplify the comprehension, we have decided to switch the evapotranspiration unit from a monthly averaged $J.m^{-2}.d^{-1}$ to a cumulated evapotranspiration over the month in $mm.month^{-1}$. The text, figures and tables have been modified accordingly.

Anonymous Referee #1: ***"Specific comments: 1) Introduction: not really clear. You need to write more clearly the objectives and what is the new contribution of the paper."***

Authors: Efforts have been done to shorten the abstract and clarify the introduction. The objectives are now clearly defined in the new version:

> *Our study aims at evaluating the impact of introducing high-resolution information on vegetation type and LAI from Sentinel-2-like observations instead of the low resolution climatology of ECOCLIMAP-II in ISBA-SURFEX simulations. The main objective is to assess if this more accurate description of the phenological cycle, especially the agricultural practices mentioned above, translates into a better representation of the simulated evapotranspiration. We also aim at evaluating the impact on simulated drainage and runoff.*
>
> *…*
>
> *This way, we will point out the contribution on surface fluxes dynamics of using high spatial and temporal resolution vegetation forcing instead of a low resolution climatology.*

The plot scale approach, which constitutes the main novelty of the study, also appears more clearly:

> *The LSM was applied at the "plot" scale to place it under homogeneous vegetation type conditions for each computation unit (one computation unit has only one PFT). This plot-scale modeling approach allows us to take into account the spatial variability of LAI values between plots while limiting the computation time in comparison to a pixel-based approach.*

This approach is described more clearly in the dedicated part (Numerical Experiments, Sect 3.1).

Anonymous Referee #1: ***"2) The following are comments and doubts on spatial scales of remote sensing observations, model and eddy covariance fluxes. What is the height of the eddy covariance tower? What is the foot print length? Are you comparing observed fluxes with modeled fluxes at 1 km resolution? If yes, why? I noted that the foot print of the eddy covariance tower may be not homogenous: are you addressing the spatial variability of the land cover in the foot print?"***

Authors: The eddy covariance tower is 3.65m high on Lamasquère and 2.8m high on Auradé. A sentence has been added in the manuscript about it:

Each flux site is equipped with 1) eddy covariance systems to measure half-hourly sensible heat flux and evapotranspiration, installed at 2.8 and 3.65 meters above the soil at Auradé and Lamasquère sites, respectively

The tower location and data filtering insures that the footprint is totally included in the field when data are available, in accordance with the Carbo-Europe and GAG-Europe experimental protocols. Thus the vegetation in the footprint is homogeneous.
A paragraph has been added to the section 2.2.3 to explain the filtering criteria:

Half-hourly fluxes were corrected for spectral frequency loss (Moore, 1986) and corrected for air density variations (Webb et al., 1980). Flux data were filtered and flagged according to statistics and objectives criteria: data out of range, rain event, friction velocity threshold, integral turbulence characteristic, stationarity test (Papale et al., 2006; Reichstein et al., 2005) and spatial representativeness (footprint) of the fluxes. For the latter, if the calculated fetch including 90 % of the flux (Kljun et al., 2004) model for each half-hourly EC flux value (F-90) was higher than the distance between the mast and the edge of the plot in the main wind direction, fluxes were discarded. Gapfilling was finally performed depending on the duration of missing data, either following the linear regression method (duration < 1h30), or following the mean diurnal variation or look up table method (duration >1h30) according to Beziat & al. (2009).

These measured fluxes were compared to the modeled fluxes at the plot scale. This plot scale approach for the simulations is described in the answers below. It is also more accurately described in the new version of the paper.

Anonymous Referee #1: ***"3) Why are you not running ISBA at finer spatial scales? If you have remote sensing observations at 8 m resolution you can use ISBA at finer spatial scales than 1 km. The use of ISBA at finer spatial scale may help a lot to understand the effect of land cover heterogeneity on land surface fluxes. In this way, you can use properly the remote sensing observations at 8 m spatial resolution"***

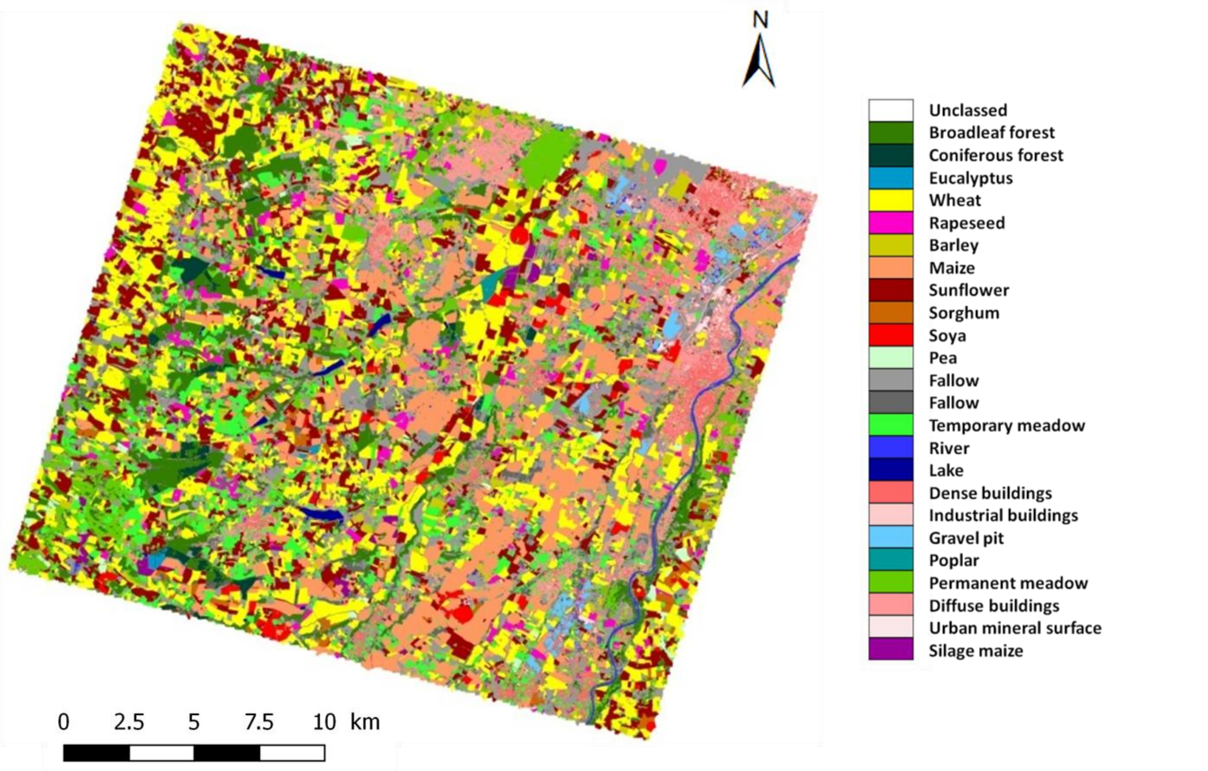
Authors: As presented in the abstract, the introduction and the section 3.1, we used a plot scale approach for both our experiments. This approach constitutes the novelty of the study. It consists in doing simulations on an irregular grid where each calculation cell is a plot, geolocalized by its centroid, defined by a polygon and associated to homogeneous vegetation (PFT). These plots are the ones determined from the Formosat-2 land cover maps (with GDAL_polygonize).
The plot scale seemed to us like a pertinent working scale for two reasons:

- It is a coherent functional landscape unit with homogeneous vegetation dynamic and thus hydro-meteorological behavior.
- It allows exploiting the high spatial resolution of Formosat-2 while limiting the calculation time compared to a pixel based approach at the resolution of Formosat. Running at 8m resolution is beyond the scope of the study and computationally intractable for such a large area.

Efforts have been done throughout the entire manuscript to make this point clearer to the reader.

Anonymous Referee #1: ***"4) Figure 4: What is the spatial scale?"***

Authors: This figure represents the study area which is a square with a 24km side. The scale has been added to the figure.



Anonymous Referee #1: ***"5) Fig. 5. What is the aggregation scale for comparing LAI values? ECOCLIMAP-II database (1 km resolution) and Formosat-2 database (8 m resolution) are providing different LAI values at the same scale."***

Authors: As described in the answer to your point 3), both our experiments were done at the field scale. The Formosat-2 LAI was calculated by averaging the pixel values in each plot. An erosion was applied to the plots, with a 16m value (twice the size of the Formosat-2 resolution) to avoid border effects and geo-location uncertainties of the remote sensing product. The method of LAI retrieval is now more accurately described in the section 2.2.1.

Each ECOCLIMAP-II grid cell is described by a composition of vegetation types (patches, Sect. 2.1). Each patch has its own LAI cycle derived from MODIS products (Faroux et al. 2013). In the reference simulation, the patches and corresponding LAI values for each field are taken from the nearest ECOCLIMAP-II regular grid cell (with a 1km resolution). Hence the comparison between the two experiments is done on each field by focusing on the same patch (i.e. the one given by the Formosat-2 land cover map).

A sentence has been added in the section 3.2 to explain this:

Each plot has a unique ISBA patch in the FORMOSAT experiment, forced by the land cover map. Thus only the corresponding patch was taken into account when comparing with the ECOCLIMAP experiment. If the corresponding patch was not present in the combination of patches given by ECOCLIMAP-II for the plot, then this plot was excluded of the results. By this way we are sure that we can compare the fluxes on specific vegetation types.

Anonymous Referee #1: ***"6) Figure 5 and 6. You need to show the comparison results for all the simulated period (2006-2010) not just one year. Are the hydrometeorological conditions the same for all the years. Typically Mediterranean regions are characterized by strong interannual variability, hence it is very interesting to evaluate it. in this way you can see the impact of the interannual variability of rainfall seasonality on LAI and fluxes."***

Authors: The figures 5 and 6 are only meant to support a discussion on the ongoing processes affected. Of course the comparison has been done over the whole period and leads to the same conclusions. A year-to-year variability is visible due to the changes in agricultural practices, which are closely related to the climatic conditions of the year. The tables 2 and 3 summarize these results by showing the correlation coefficient and the root mean square error between each experiment and in-situ measurements for both sites. It points out a systematic enhancement of the scores with amplitude depending of the year. Indeed, if the ECOCLIMAP-II LAI dynamic is closer to the measured and remotely sensed ones, the improvement is weaker and inversely. A sentence about this issue has been added in a new discussion section (Sect. 5 in the new manuscript):

The interannual variability of the results on evapotranspiration (Fig. 7) may be justified by the climatic conditions of each year. Indeed, climatic conditions influence the farmers' decisions concerning the seeding and/or harvest dates. If these dates are closer than the ones simulated by ECOCLIMAP LAI, the effect on evapotranspiration is weaker.

Anonymous Referee #1: ***"7) I'm not sure about figure 7. If you are modeling at 1 km spatial resolution, how can you simulate fluxes of specific cultivations (e.g., wheat, maize-sorghum, etc.)? in a 1 km grid cell you have more than 1 specific cultivation."***

Authors: As said in the previous answers, we have done the simulations at the field scale. In the reference simulation, each field is represented by a combination of the 12 patches available in SURFEX. ISBA simulates the fluxes on each patch separately so you can choose each of these patches when you interpret the results. To compare on a specific cultivation, you just have to choose the corresponding patch in the results of the simulation. As describe in our answer to your point 5), a sentence has been added to clarify this point.

Anonymous Referee #1: ***"8) I'm trying to understand how SURFEX using ECOCLIMAP and SURFEX using FORMOSAT (and GDAL polygonise) are modeling each land cover component. Please, add information and explanations. "***

Authors: The answers to your previous comments may have given you the answer to this one. In the reference simulation, the forcing of ECOCLIMAP-II is taken from the nearest regular grid cell for each vegetation type (patch). All these patches are simulated separately by SURFEX so you can focus on a specific patch for the results. For plots belonging to the same ECOCLIMAP-II grid cell, only parameters given by another set of forcing data than ECOLIMAP-II may change. It may be the case of the soil parameters or the meteorological forcing if they are not superposed to ECOCLIMAP-II. Also, the initialization of the soil temperature and water content may not be the same for all these plots. Indeed, our simulation grid changes every year as the land cover map changes too. Thus the plots are not exactly the same from year to year due to the polygonal segmentation with GDAL. To initialize the soil temperature and water content for each plot and each year, we use an interpolation using the inverse distance method on the 9 nearest neighboring plots in the previous year grid. To initialize the first year of simulation, we have done a simulation on the same grid but using the meteorological forcing of the year before.

Your comments let us think that our manuscript was probably not clear enough regarding the use of the crop field as a computation unit. We hope that our explanations and the modifications made to manuscript have clarified this point in particular, despite the relative complexity of the unusual way we use SURFEX-ISBA. We think that your comments helped improve the clarity of the paper. We thank you again sincerely for your evaluation of our work.

Anonymous Referee #2: ***"This paper focuses on the impact of vegetation dynamic on the simulation of evapotranspiration from a land surface model. It shows the benefits of using decametric resolution and high revisit frequency satellite imagery (FORMOSAT-2) to resolve the spatial and temporal dynamic of vegetation at the landscape scale and to drive the SURFEX/ISBA-A-gs land surface model. The authors compare***
- evapotranspiration (ET) simulated using the leaf area index (LAI) and a land cover map derived from FORMOSAT-2 satellite imagery, and
- ET simulated using vegetation variables taken from the ECOCLIMAP-II database which is the land surface parameter database used for the spatial integration of the model and provides a monthly climatology for LAI at 1 km spatial resolution.

The authors showed that the use of FORMOSAT-2 LAI improves the performances of simulated ET. The effects are more significant for summer crops than for winter crops. The issue addressed by this paper is of great interest for the land surface community. It shows the potential of new high spatial and temporal resolution satellite (SENTINEL-2) to drive land surface models using more accurate land surface characteristics. However, major revisions of the paper are needed before considering it for publication in HESS. There are a lot of confusing sentences, inaccurate definitions, some references are missing, some justifications are missing. The analysis of the results is not deep enough. A dedicated discussion section is missing. This alters the quality of the paper whilst there is enough scientific content for publication. I provide below some evidences and some suggestions for improvement. But this is not exhaustive. Substantial improvement of English and paper structure are also expected."

Authors: Thank you for your comments. Several efforts have been done to clarify the paper. The references and justifications missing have been added. We have also decided to switch the evapotranspiration unit from a monthly averaged $J.m^{-2}.d^{-1}$ to a cumulated evapotranspiration over the month in $mm.month^{-1}$ in order to simplify the comprehension. Concerning the analysis of the results, as recommended, we have added a dedicated discussion part where we interpret each interesting aspects of the results. Especially, further work has been done to include a reflection about the uncertainties of both the measurements and the remote sensing products.
Regarding the English improvement, we would like to mention that the paper was revised by American Journal Experts before the submission. The certificate can be downloaded from the Editor portal here: https://secure.aje.com/download.php?action=certificate&key=BCD9-C850-DE8C-8F39-066A&_t1490784542 . However, we did our best to further improve the English in the revised version.

Anonymous Referee #2: ***"Specific comments***

- Abstract: it is too long, too many methodological details are given"

Authors: The abstract has been shortened. Methodological details have been suppressed while the main issues and outcomes of the study have been highlighted.

Anonymous Referee #2: ***"Introduction - page 2, line 4: please clarify the idea, provide examples of agricultural practices (irrigation, crop rotation, seeding date,. . .)***

Authors: This sentence was clarified as follows:

In an agricultural river basin, farmer's practices have an impact on crop functioning. Farmers manage crop rotations, select variety, decide the seeding and harvest dates and organize irrigation supplements. In such basins, a more accurate description of crop dynamics and their effects on hydrometeorological fluxes is critical to improve the monitoring of water resources (Foley et al., 2005; Martin et al. 2016).

Anonymous Referee #2: ***"- choose between Land surface model and SVAT to use in the rest of the text"***

Authors: We decided to choose "Land Surface Model" for the entire article.

Anonymous Referee #2: ***"line 7: references are needed for SURFEX and VIC, - the meaning of SURFEX acronym needs to be given"***

Authors: Because SURFEX is not exactly a scientific model but rather a modeling platform, we decided to use ISBA in this sentence. The ISBA acronym is defined and the references are added for both VIC and ISBA:

Land surface models (LSMs), such as the Variable Infiltration Capacity (VIC, Liang & al., 1994) or Interactions between the Surface Biosphere Atmosphere (ISBA, Noilhan & Planton, 1989) models …

Anonymous Referee #2: ***"- the definition of LAI is not exact, it is defined as - "half the total developed area of green (i.e., photosynthetic active) leaves per unit ground horizontal surface area [Chen and Black, 1992]"***

Authors: Thank you for this comment. This definition and the associated reference have been added in the paper.

Anonymous Referee #2: "*page2 , line 10: LAI is not an index. It is a variable that can be simulated by the model or used as a forcing variable to drive the model - page 2, line 10: please justify, a reference is needed here. LAI is the scaling factor to compute the stomatal conductance at the canopy scale. It is not necessary the most influential parameter on the simulated evapotranspiration"*

Authors: As you wrote, the LAI is used to compute the stomatal conductance. It is not necessarily the most influential parameter on the simulated evapotranspiration. The meaning of this sentence was to say that the Leaf Area Index is the only variable representative of the vegetation dynamic to impact evapotranspiration calculation in most LSMs. As described in Noilhan & Planton (1989), the LAI is the only way the vegetation dynamic is taken into account in the evapotranspiration computation in the standard version of ISBA. The root-depth also impacts the maximum available water content to evapotranspiration but in our study, it is a fixed parameter given by ECOCLIMAP. The LAI is also the only vegetation variable to impact the evapotranspiration in VIC (Liang & al., 1994), in the Canadian Land Surface Scheme (CLASS, Verseghy & al., 1993) and the Joint UK Land Environment Simulator (JULES, Best & al., 2011). The other variables that influence the vegetative part of the evapotranspiration are either atmospheric or soil parameters.

The advantage of focusing on the LAI is also that it is a biophysical variable which is observable from space.

The sentence has thus been revised:

It is the main variable used to parameterize the effect of vegetation dynamics on evapotranspiration in most LSMs.

Anonymous Referee #2: "*Page 2, Line 12: too many references, select one or two. This remark applies for the rest of the paper.*"

Authors: We kept Verseghy & al. (1933) and Maurer & al. (2002).

Anonymous Referee #2: "*Page 2, Line 14: no needs to define a climatology - page 2, line 14: use the term climatology instead of climatological*"

Authors: The term "climatological" has been replaced by "climatology" in the entire paper.

Anonymous Referee #2: "*page 2, line 20: This holds for Europe but not for the US*"

Authors: We totally agree with this remark. Indeed, MODIS could be sufficient in North America. This is probably the reason why Sentinel-2 is an EU program. Fritz & al. (2015) have done a global map of field size which could justify this sentence.

The precision has been added:

However, for many cultivated areas and particularly in European countries (Fritz & al., 2015), field plot areas rarely exceed typical MODIS product pixel sizes (500 m, i.e., 25 hectares).

Anonymous Referee #2: *"Page 2, line 20-25: Redundancies, confusing sentences"*

Authors: This part has been revised to suppress the redundancies and try to make the idea clearer to the reader:

As a result, MODIS pixels can contain mixed LAI signatures of different crop types with different phenologies. It thus degrades the actual temporal variability of the LAI on these fields. Consequently, it is not representative of the actual hydrometeorological behavior of each land cover type (Trezza et al., 2013; Nagler et al., 2013).

Anonymous Referee #2: *"page 2 line 25-26: why ? References are needed"*

Authors: Summer and winter crops have anti-correlated phenologies. So if their LAI signatures are mixed, the resulting cycle will be a nearly constant phenology throughout the year. The variability of the LAI will be attenuated or even suppressed. A sentence has been added to explain this:

Indeed, summer and winter crops have anti-correlated phenologies so mixing these two LAI signatures leads to attenuating, or even suppressing, the LAI variability throughout the year.

However, there are no references in our knowledge that show this phenomenon.

Anonymous Referee #2: *"page 2, line 27-30: redundancies with above"*

Authors: These sentences have been reformulated to suppress the redundancies:

A potential solution to access realistic vegetation dynamic could be the use of high resolution remote sensing products. The recently launched Sentinel-2 mission generates multispectral imagery of land areas at a decametric resolution (10 m to 60 m depending on the band) over a 5-day revisit period with global coverage. Previous studies have already shown that higher resolution data can improve descriptions of vegetation and modeled water processes in agricultural landscapes for which mid-resolution imagery is unsuitable (Ferrant & al., 2014; Ferrant & al., 2016)

We found it important to show that some studies have already been carried out to evaluate the impact of the high resolution remote sensing products.

Anonymous Referee #2: ***"page 2, line 31-32: ISBA should be defined"***

Authors: The ISBA acronym is defined and referenced (Noilhan & Planton, 1989).

Anonymous Referee #2: ***"page 3, line5: ECOCLIMAP-II LAI are derived from the analysis of MODIS LAI and not SPOT/VEGETATION"***

Authors: You are perfectly right, it has been corrected.

It is a climatology derived from MODIS satellite observations collected between 1999 and 2005.

Anonymous Referee #2: ***"page 3, line 7-8: this is not clear. Provide thorough explanation on how LAI is computed in ECOCLIMAP-II"***

Authors: The ECOCLIMAP-II is produced by the mean of an unmixing algorithm applied to MODIS LAI product. For each MODIS pixel, ECOCLIMAP-II gives a combination of vegetation types (patches or PFT) with their corresponding fractions. The algorithm takes the nearest MODIS pixel with a pure vegetation type to distinguish the contribution of each patch in the mixed pixel signature. The detail of the method is given by Faroux & al. (2013). This method is briefly described in the introduction and in the presentation of the model (Sect. 2.1) within the new version of the manuscript:

Because of the low spatial resolution of MODIS, the LAI signatures of several vegetation types are often mixed in a pixel. An unmixing method is then used by Faroux et al. (2013). It uses the nearest unmixed pixels of each PFT present in the MODIS pixel considered to assess the contribution of each PFT in the LAI climatology.

Anonymous Referee #2: ***"Section 2.1 - not enough model details are given - which version of SURFEX is used ? … Is ISBA includes includes a coupled stomatal conductance-photosynthesis scheme (A-gs version)"***

Authors: We used SURFEX 7.3. ISBA is used in its standard version and not the A-gs one. The A-gs version has been tested with the AST option which includes two strategies of plant's response to water stress. It led to the same conclusions with few modifications of the monthly fluxes.
These precisions have been added to the description of the model (Sect. 2.1) :

In this study, we used the Interactions between Surface Biosphere Atmosphere (ISBA, Noilhan et Planton, 1989) nature model included in the version 7-3 of SURFEX. The ISBA model uses meteorological and physiographic data to simulate energy and water fluxes between land surfaces and the atmosphere (Fig. 1).

The version used in this study is the standard version of ISBA. It does not include a coupled stomatal conductance-photosynthesis scheme like in the A-gs version (Calvet et al., 1998).

Anonymous Referee #2: *"Which type of water transfer scheme? Energy balance ?"*

Authors: For the water transfer scheme, we used the force restore approach (Deardorff, 1977, included in ISBA by Mahfouf & Noilhan, 1996) with three soil layers (Boone & al., 1999). For the runoff calculation, we used the Variable Infiltration Capacity approach (Dumenil & Todini, 1992) to calculate a subgrid runoff even if the soil layers of the cell are not saturated. This approach has been included in ISBA by Habets & al., 1999. The energy balance scheme is a single source scheme, i.e. computing a unique surface temperature for the soil and the vegetation. It uses the concept of stomatal resistance introduced by Jarvis (1976).

These precisions have been added in the section 2.1 and the new references with it :

The water transfer in the soil is simulated on three layers with a force-restore approach presented by Deardorff (1977). This approach was integrated in ISBA by Mahfouf et Noilhan (1996). The three layers were described and calibrated by Boone et al. (1999). The surface layer volumetric water content is restored depending on the water content of both surface and root zone layer. A gravitational drainage flux is simulated when the soil water content of a layer exceeds the field capacity. In the version we used, a subgrid runoff is also calculated using the Variable Infiltration Capacity scheme first described by Dumenil and Todini (1992) and included in SURFEX by Habets et al. (1999). It allows simulating a runoff flux even when the soil is not fully saturated. A unique energy budget is simulated on the vegetation-soil layers composite by a single source scheme. A single surface temperature is used to compute the different energy fluxes. The method is detailed by Noihlan and Planton (1989).

Anonymous Referee #2: *"what about irrigation, is it simulated by the model"*

Authors: As said in the results and conclusion, the irrigation is not simulated by the model in this study. The first reason is that we do not have access to spatialized forcing of irrigation yet, neither in volume nor on the determination of irrigation area. The second reason is that without taking irrigation into account, we can isolate the effect of the LAI modification from the effect of adding irrigation. The third reason is also that there is no automatic module of irrigation for this version of ISBA yet. Currently, ISBA can simulate an automatic irrigation pattern only in the A-gs versions with interactive vegetation, i.e. with a simulated LAI. The irrigation issue is one of the main outcomes of this study and the manuscript has been modified to highlight it. This key point will be the main focus of our future work.

Anonymous Referee #2: *"the reference for the ISBA pedotrasnfer function is not correct, use Noilhan, J. and Lacarrère, P.: GCM Grid-Scale Evaporation from Mesocale Modeling, J. Climate, 8, 206–223, 1994"*

Authors: We have replaced the previous reference (Masson & al., 2013) by the one you proposed.

Anonymous Referee #2: *"page 4, line 3-5: the description of ECOCLIMAP-II is not accurate. No vegetation parameters are derived from satellite observations. Some parameters are fixed for each plant functional type. Other parameter or variables vary geographically with the type of ecosystem. This part must be properly edited.*

Authors: As described by Faroux & al. (2013), the ecosystems (or cover) are deduced from a classification based on SPOT/VEGETATION Normalized Difference Vegetation Index, crossed with already existing land cover, soil and climate maps. Each LAI profile of each vegetation type of each cover is then deduced from the MODIS LAI product as briefly described above. This is the only things that are determined by satellite observations. The other parameters come from different sources as described in Masson & al. (2003). This part has been properly modified to be more accurate.

Anonymous Referee #2: ***"Section 2.2: -page 4, line 17: "non-irrigated rotation": this is not a correct term"***

Authors: The term has been rectified:

The two main types of crops found in this area are irrigated summer crops such as maize or soy plants and rain-fed rotation crops such as wheat and sunflower plants.

Anonymous Referee #2: ***"The authors should provide a dedicated Discussion section. They should properly discuss the main outcomes of the work and discuss their limits. The issue of uncertainties need to be addressed: uncertainty in the measurements, uncertainty in the satellite imagery (registration . . .), uncertainty in the land surface model affecting the simulation of ET"***

Authors: The results and conclusion has been revised to provide a dedicated discussion part, as you suggested. We discuss the fact that the Formosat-2 LAI allows distinguishing the actual phenologic cycle and particularly the agricultural practices that modifies this cycle like seeding, harvest or crop rotations. The impact on evapotranspiration is then analyzed, showing the limits of the unmixing algorithm of ECOCLIMAP-II LAI retrieval method. It also shows the issue of the lack of irrigation in SURFEX. The uncertainties issue is also tackled as we discuss about the measurement uncertainties on LAI and LE but also about the remote sensing acquisition uncertainties. The uncertainty related to the model is hard to assess but the local comparison gave us some clue about satisfying performances on the LE simulation outside of irrigation periods. The limitations of the work are also discussed. Especially, we present the limitations introduced by the cloud coverage and the revisit frequency. Finally, the perspectives on the hydrological routing and the introduction of an irrigation process are presented.

Anonymous Referee #2: ***"English : English must be carefully edited, I provide some examples here page 2 line 4: "vegetation cover present"! "present vegetation cover" page 2 line 5 " the more accurate"! " more accurate" page 2 line 6 "to improving"! "critical to improve" page 3, line 10 "rather than"! "instead of " check in the document the use of "the" page 3, line 9: vegetation type and LAI Page 4, line 4-5: "the ISBA"! "ISBA", Shorter sentences are needed"***

Authors: We have corrected all these examples. We also shortened some sentences in the paper. We particularly paid attention to this in the sections that were edited or added.

Anonymous Referee #2: "the title is too long, some suggestions: use Earth observation instead of remote sensing products use cropland instead of cultivated area use high spatial and temporal resolution"

Authors: The title has been modified as suggested.

Anonymous Referee #2: ***"acronyms must be defined"***

Authors: We have defined all the acronyms that were not already defined.

Again, we greatly appreciate your constructive comments that helped us to improve the manuscript. We hope that we answered to all your concerns in this revision

Effects of multi-temporal high-resolution remote sensing products on simulated hydrometeorological variables in a cultivated area (southwestern France)

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Abstract. Agricultural landscapes are often ~~include~~ constituted of a patchwork of crop fields whose seasonal evolution is dependent on specific crop rotation patterns and phenologies. This temporal and spatial heterogeneity affects surface hydrometeorological processes and must be taken into account in simulations of land surface and distributed hydrological models~~as simulated by land surface and distributed hydrological models~~. The Sentinel-2 mission ~~satellite remote sensing products~~ allows for the monitoring of land cover and vegetation dynamics at unprecedented spatial resolutions and revisit frequencies (20 m and 5 days, respectively) that are fully compatible with such heterogeneous agricultural landscapes. Here, we evaluate the impact of Sentinel-2-like remote sensing data on the simulation of surface water and energy fluxes via the Interactions between the Surface Biosphere Atmosphere (ISBA) land surface model included in the EXternalized SURface (SURFEX) modelling platform~~ISBA-SURFEX land surface model~~. ~~The study area is a 24 km by 24 km agricultural zone in southwestern France. An initial reference simulation was conducted from 2006-2010 using the ECOCLIMAP-II database. This global numerical land ecosystem database was created at a 1 km resolution and includes an ecosystem classification with a consistent set of land surface parameters required for the model, such as the Leaf Area Index (LAI) and albedo measures. The LAI of ECOCLIMAP is climatologic and derived from a 2000-2005 analysis of MODIS satellite products. This low resolution induces that several vegetation covers can be mixed in a model cell. The climatic construction of LAI dynamics also suggests that there is no interannual variability in the vegetation cycle. A second simulation was performed by forcing the same model with annual land cover maps and monthly LAI values derived from a series of 105 8 m-resolution Formosat-2 images for the same period. Both simulations were conducted at the parcel scale, i.e., a computation unit covers an area of connected pixels of the same vegetation type (a crop field, forest patch, etc.). To evaluate our simulations, we used in situ measurements of evapotranspiration and latent and sensible heat flux from two eddy covariance stations in the study area.~~ The study focuses on the effect of the Leaf Area Index (LAI) spatial and temporal variability on these fluxes. We compare the use of the LAI climatology from ECOCLIMAP-II, used by default in SURFEX-ISBA, and time series of LAI derived from the high-resolution Formosat-2 satellite data (8 m). The study area is an agricultural zone in southwestern France covering 576 km² (24x24 km). An innovative plot-scale approach is used, in which each computational unit has a homogeneous vegetation type. Evaluation of the simulations quality is done by comparing model outputs with in-situ eddy covariance measurements of latent heat flux (LE). Our results show that the use of LAI derived fromFormosat-2 high-resolution remote sensingproducts significantly improves simulated evapotranspiration results with respect to ECOCLIMAP-II, especially when the a surface is covered with summer crops. The comparison with in-situ measurements shows an improvement of roughly 0.3 in the correlation coefficient and a decrease of around 30% of the Root-Mean Square Error in the simulated evapotranspiration.(the correlation coefficient with monthly measurements is increased by roughly 0.3 and the root mean square error is decreased by roughly 31%). This finding is attributable to a better description of LAI evolution processes reflected with by Formosat-2 data, which further modify soil water content and drainage levels of deep soil reservoirs. Effects on annual drainage patterns remain small but significant, i.e., an increase roughly equivalent to 4% of annual precipitation levels from with simulations using Formosat-2 data in comparison to the reference simulation values. In smaller proportions, runoff is also increased by roughly 1% of annual precipitation when using Formosat-2 data. This study illustrates the potential for the Sentinel-2 mission to better represent effects of crop management on water budgeting for large, anthropized river basins.

1 Introduction

In an agricultural a heavily anthropized river basin, farmer'sagricultural practices have an impact on crop functioning. Farmers manage crop rotations, select variety, decide the seeding and harvest dates and organize irrigation supplements..modify the type and evolution of vegetation cover present, which can profoundly alter hydrological cycles. In such basins, the more accurate description of crop dynamics and of their effects on hydrometeorologicalwater flux is critical to improveing the monitoring of water resources (Foley &et al., 2005; Martin &et al. 2016).

Land surface models (LSMs), such as the Variable Infiltration Capacity (VIC, Liang et al., 1994) or Interactions between the Surface Biosphere Atmosphere (ISBA, Noilhan and Planton, 1989)SURFEX models, are increasingly used as distributed hydrological models to study and forecast water resource evolution (e.g., Habets &et al., 2008; Tesemma &et al., 2015). In land surface models or Soil-Vegetation Atmosphere Transfer schemes (SVAT), the The Leaf Area Index (LAI), is defined as "half of the total developed area of green (i.e. photosynthetic active) leaves per unit ground horizontal surface area" (Chen and Black, 1992).which represents the evaporative surface area of vegetation, It is the main variableindex used to parameterize the effect of vegetation dynamics on evapotranspiration in most LSMs. When it is not simulated by the model, Tthe LAI is often derived or directly taken from reference tables organized by vegetation type (Verseghy & et al., 1993; Maurer & et al., 2002; Masson & al., 2003; Oleson & al., 2008; Boussetta & al., 2013; Faroux & al., 2013). The This LAI is generally computed from low- to mid-resolution long-term satellite records and provided as a climatology. from AVHRR or MODIS, but it is climatological (interannually invariant), i.e., Thus, it does not allow one to determine the impact of observed annual vegetation variability on water and energy flux on the land surface (Tang & et al., 2012; Ford & and Quiring, 2013). Studies have shown that prescribing an annual variable of remotely sensed the LAI with year-to-year variability in LSMs improves estimations of water and energy fluxes between the soil and atmosphere, ~~and~~ mainly through a more realistic evapotranspiration (Van den Hurk ~~&~~ et al., 2003; Jarlan ~~&~~ et al., 2008~~; Tang & al., 2012; Ford & Quiring, 2013~~). These studies used LAI values drawn from low- to mid-resolution satellite imagery, i.e., AVHRR (Van den Hurk ~~&~~et al., 2003) or MODIS (Tang ~~&~~et al., 2012; Ford ~~&~~and Quiring, 2013). However, for many cultivated areas and particularly in European countries (Fritz et al, 2015), field plot areas rarely exceed typical MODIS product pixel sizes (500 m, i.e., 25 hectares). As a result, MODIS pixels can contain mixed LAI signatures of different crop types with different phenologies. It thus degrades the actual temporal variability of the LAI on these fields. Consequently, it is not representative of the actual hydrometeorological behavior of each land cover type (Trezza et al., 2013; Nagler et al., 2013). ~~Trezza & al. (2013) and Nagler & al. (2013) concluded that the use of remote sensing products with a 500 m spatial resolution (in their cases, the MODIS Normalized Difference Vegetation Index) generates inaccurate evapotranspiration estimations.~~ ~~Indeed spatially averaging vegetation indexes such as the LAI also involves averaging different types of vegetation with different phenologies, degrading their actual temporal variability.~~ This ~~can be exacerbated~~ is particularly the case for regions where both summer and winter crops are cultivated, as ~~is the case for our study area~~ in southwestern France. Indeed, summer and winter crops have anti-correlated phenologies so mixing these two LAI signatures leads to attenuating, or even suppressing, the LAI variability throughout the year.

A potential solution to access realistic vegetation dynamic could be the use of high resolution remote sensing products. The recently launched Sentinel-2 mission ~~will~~ generates multispectral imagery of land areas at a decametric resolution (10 m to 60 m depending on the band) over a 5-day revisit period with global coverage. Previous studies have already shown that higher resolution data ~~These data~~ can improve the description~~s~~ of the vegetation and modeled water processes in agricultural landscapes for which mid-resolution imagery ~~has not been adapted~~ is unsuitable (Ferrant ~~&~~et al., 2014; Ferrant ~~&~~et al., 2016). ~~.~~

In this study, we used the Interactions between Surface Biosphere Atmosphere (ISBA) LSM~~ISBA land surface model~~ as part of the EXternalized SURFace (SURFEX) ~~SURFEX~~ modeling platform (Masson ~~&~~et al., 2013). ~~The~~ SURFEX was developed by the French National Center for Meteorological Research (CNRM) to represent and interface the surface processes ~~of the operational~~for atmospheric ~~models~~ and hydrological models ~~of Météo-France~~. This platform~~It~~ is also used for research purposes in the fields of climatology, meteorology and hydrology. Within SURFEX, ~~The~~ ISBA is ~~a~~ the submodel in charge of simulating variables over natural emerged areas. ~~that simulates water and energy exchange in the soil-vegetation-atmosphere continuum (outside of urban and lake areas).~~ It uses the ECOCLIMAP-II database to determine vegetation types and associated parameters (e.g., temporal LAI, fractional vegetation cover, ~~and~~ albedo) at a spatial resolution of 1 km (Masson ~~&~~et al., 2003; Faroux ~~&~~et al., 2013). Each ECOCLIMAP-II grid cell is composed of up to 12 vegetation types or plant functional types (PFTs). Each PFT's LAI forcing in ECOCLIMAP-II database has ~~The ECOCLIMAP-II LAI is climatological with~~ a temporal resolution of 10 days. It is a climatology ~~It was~~ derived from MODIS ~~and SPOT-VEGETATION~~ satellite observations collected between 1999 and 2005. ~~Up to 12 vegetation types or plant functional types (PFTs) can be included in an ECOCLIMAP-II grid cell~~. The LAI of each PFT is determined by unmixing the LAI of the ~~the grid cell~~ MODIS ~~LAI~~ grid cell using neighboring, unmixed pixels. The method, detailed in Faroux et al. (2013), consists in using the LAI of the nearest MODIS pixels with a pure PFT to unmix the effect of each PFT in the LAI signature.

Our- ~~This~~ study aims at evaluating ~~evaluates~~ the impact of introducing high-resolution information on vegetation type and ~~the~~ LAI from Sentinel-2-like observations instead of the low resolution climatology of ~~rather than~~ ECOCLIMAP-II in ISBA-SURFEX simulations. The main objective is to assess if this more accurate description of the phenological cycle, especially the agricultural practices mentioned above, translates into a better representation of the simulated evapotranspiration. We also aim at evaluating the impact on simulated drainage and runoff.

The study area is a pilot site in southwestern France (Dejoux ~~&~~et al., 2012). ~~This site~~It is considered to be representative of the cultivated area in the upper Garonne River Basin. A fraction (estimated at 13%) of crop fields in the area is irrigated, but we chose not to focus on effects of irrigation due to a lack of spatially distributed data on irrigation quantity and timing. LAI and land cover ~~values~~ maps were determined from a 5-years (2006-2010) time series of Formosat-2 satellite images, which has similar spectral and spatio-temporal characteristics as Sentinel-2. The ~~model~~ LSM was applied at the "~~field~~plot" scale to ~~identify a~~place it under homogeneous vegetation type conditions for each computation unit (one computation unit has only one PFT). This ~~field~~plot-scale modeling approach allows ~~one~~ us to ~~determine~~ take into account the spatial variability of LAI values between ~~fields~~ plots while limiting the computation time in comparison to a pixel-based approach. Our results are firstly compared to evapotranspiration in situ measurements. ~~of evapotranspiration and sensible heat flux and to a reference simulation based on ECOCLIMAP-II.~~ Then we perform a spatialized comparison between simulation's results using the MODIS based ECOCLIMAP-II LAI forcing and the FORMOSAT-2 based LAI forcing. This way, we will point out the contribution on surface fluxes dynamics of using high spatial and temporal resolution vegetation forcing instead of a low resolution climatology. Finally, we discuss the limitations of this work and challenges that must be addressed in order to upscale ~~when upscaling~~ this study to the Garonne River Basin scale using Sentinel-2 data.

2 Model and data

2.1 SURFEX-ISBA model and forcing

EXternalized SURFace (SURFEX) ~~SURFEX~~ is a modeling platform developed by the CNRM/Meteo-France ~~to~~. It simulates exchanges between land surfaces and the atmosphere (Masson ~~&~~et al., 2013). It is composed of four modules to simulate radiative budget and hydrological flux patterns for towns, lakes, oceans and natural areas. In this study, we used the Interactions between Surface Biosphere Atmosphere (ISBA, Noilhan and Planton, 1989) ~~ISBA~~ nature model included in the version 7-3 of SURFEX. ~~.~~ The ISBA model uses meteorological and physiographic data to simulate energy and water fluxes between land surfaces and the atmosphere (Fig. 1).

The version used in this study is the standard version of ISBA. It does not include a coupled stomatal conductance-photosynthesis scheme like in the A-gs version (Calvet et al., 1998). The water transfer in the soil is simulated on three layers with a force-restore approach presented by Deardorff (1977). This approach was integrated in ISBA by Mahfouf et Noilhan (1996). The three layers were described and calibrated by Boone et al. (1999). The surface layer volumetric water content is restored depending on the water content of both surface and root zone layer. A gravitational drainage flux is simulated when the soil water content of a layer exceeds the field capacity. In the version we used, a subgrid runoff is also calculated using the Variable Infiltration Capacity scheme first described by Dumenil and Todini (1992) and included in SURFEX by Habets et al. (1999). It allows simulating a runoff flux even when the soil is not fully saturated. A unique energy budget is simulated on the vegetation-soil layers composite by a single source scheme. A single surface temperature is used to compute the different energy fluxes. The method is detailed by Noihlan and Planton (1989).

The meteorological forcing is drawn from the Système d'Analyse Fournissant des Renseignements Atmosphériques à la Neige (SAFRAN, Durand et al. 1993) ~~SAFRAN~~ reanalysis data (Quintana ~~&~~et al., 2007), which provides precipitation data (in solid and liquid form), air temperature and specific humidity data at 2 meters, air pressure data, and wind and solar radiation data at hourly time intervals at an 8 km resolution. The SAFRAN data were spatially linearly interpolated to match ~~parcel~~ plot centroïds. Regarding soil parameters, by default, ~~the~~ ISBA uses the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012), which gives the percentage of clay and sand at a 30 arc-second (~1 km) resolution. Soil parameters were then computed using empirical pedotransfer functions (Noilhan and Lacarrère, 1995).~~(Masson & al., 2013).~~

The ECOCLIMAP-II database (Faroux ~~&~~et al., 2013) is used to describe vegetation cover at a 1 km resolution, thus corresponding to the resolution of the SURFEX-ISBA simulation grid. This land cover database is divided in 273 ecosystems. ~~Vegetation parameters were deduced from satellite products (MODIS, SPOT, FORMOSAT, etc.) for 273 ecosystems.~~ These ecosystems were determined by crossing a land cover classification derived from the SPOT/VEGETATION Normalized Difference Vegetation Index (NDVI) series and pre-existing land cover maps, as described by Faroux et al. (2013)~~These ecosystems were based on vegetation types, climates and soil textures~~. Twelve different functional plant types (PFT, also referred to as patches) are considered ~~in the ISBA~~ (Fig. 2) to describe these ecosystems. Each ecosystem is described by a correspondant composition ~~pixel in the SURFEX-ISBA belongs to a unique ecosystem and thus is described as a combination~~ of these twelve patches. Each grid cell in ISBA belongs to a unique ecosystem and thus is described as a combination of these patches. Vegetation parameters are thus determined for each ~~ecosystem~~ patch of this ecosystem. Some of the parameters are fixed such as root depth and minimal stomatal resistance, and some are temporally variable such as albedo and ~~the~~ LAI. In particular, the LAI follows a cycle determined from MODIS LAI analysis data for 2000 to 2005 averaged for each vegetation type of each ecosystem with a temporal resolution of 10 days~~.~~ ~~(Faroux & al., 2013).~~ Because of the low spatial resolution of MODIS, the LAI signatures of several vegetation types are often mixed in a pixel. An unmixing method is then used by Faroux et al. (2013). It uses the nearest unmixed pixels of each PFT present in the MODIS pixel considered to assess the contribution of each PFT in the LAI climatology. ISBA then uses these data to separately simulate all variables for each vegetation type present in the pixels, and then based on the fraction of each type as a weighting coefficient, it calculates global pixel fluxes.

By default, ~~The~~ ISBA ~~then uses these parameters to~~ simulate fluxes ~~at~~ on a 1 km regular grid corresponding to the ECOCLIMAP-II grid. ~~resolution.~~ But interpolation routines are included in it. It allows simulating on irregular grids, as done in this study.

~~The SURFEX separately simulates all variables for each vegetation type present in the pixels, and then based on the fraction of each type as a weighting coefficient, it calculates global pixel fluxes.~~

2.2 Data

All remote sensing and in situ data were collected as part of the Observatoire Spatial Régional (OSR) project for an agricultural area of southwestern France near Toulouse (Fig. 3, Dejoux ~~&~~et al., 2012). This area is considered to be representative of the cultivated area of the Garonne River Basin, which is characterized by a variety of land cover forms. The two main types of crops found in this area are irrigated summer crops such as maize or soy plants and ~~non-irrigated~~ rain-fed rotation crops such as wheat and sunflower plants.

2.2.1 Formosat-2 Leaf Area Index

Formosat-2 is an NSPO (Taiwan) satellite that can generate daily multispectral images of the Earth's surface at an 8 m resolution and with a swath of 24 km. It functions on a tasking mode, i.e., it does not acquire data systematically like Sentinel-2 but rather must be programmed for a target area. Its sensor detects radiation within four frequency bands of blue, green, red and near-infrared. After geometric, atmospheric and radiometric corrections were made and clouds are detected (Hagolle ~~&~~et al., 2008 and 2010), measured reflectances were entered into the neural network BV-NET, which inverts the PROSAIL radiative transfer model (Claverie, 2012). This neural network deduces a set of vegetation parameters (among them the LAI and fraction of vegetation cover (FCOVER)) for each pixel. It thus generates 8-m resolution LAI maps for each date and pixels without cloud obstruction. Finally, we had access to 105 clear images on our study area for 2006-2010. The LAI product was validated by Veloso ~~&~~et al. (2012) for the same area and time period as those used in this study with destructive measurements on the vegetation. The time series of LAI maps was then spatially averaged at the ~~field~~plot scale using the land cover map (Sect. 2.2.2 below), was interpolated between available dates and was finally temporally averaged to obtain monthly forcings of LAI for each ~~field~~ plot of the ~~domain~~study area. The spatial averaging over each plot has been done with a 16m erosion of the plots (twice the size of a Formosat-2 pixel) to avoid border effects and impact of geo-location uncertainty (Sect. 5).

2.2.2 Formosat-2 land cover maps

Annual land cover maps were generated using the previously described Formosat-2 image time series (Fig. 4, Ducrot ~~&~~et al., 2005, 2007 and 2009). Then, a supervised classification algorithm was applied to determine the vegetation type of each ~~parcel~~plot. The algorithm uses annual Normalized Difference Vegetation Index (NDVI) profiles to separate pixels into 34 classes with similar NDVI profiles. We identified 34 classes. The classification was adjusted through “Politique Agricole Commune” observations, which assign crop types for a subset of fields in images from farmers’ official declarations.

2.2.3 In situ measurements

We used in situ measurements drawn from two eddy covariance stations in the simulation domainstudy area located at Auradé (43°32’58.81” N, 01°06’22.08” E) and Lamasquère (43°50'05” N, 01°24'19” E) to evaluate the simulations. The Auradé plot is located on a hillside near Garonne river terraces. It belongs to a private cereal production farm with a wheat-sunflower-wheat-rapeseed rotation. At this site, only grain is exported, straw is stored and the plot is never irrigated. The Lamasquère plot is part of an experimental milk production farm. It is positioned along the Touch River and is characterized by a maize-winter wheat-maize-winter wheat rotation. All aboveground biomass is exported as cow feed and bedding. Maize grown in the Lamasquère plot is irrigated. In 2006, irrigation levels were measured at 147 mm between June and August.

Each flux site is equipped with 1) eddy covariance systems to measure half-hourly sensible heat flux and evapotranspiration installed at 2.8 and 3.65 meters above the soil at Auradé and Lamasquère sites, respectively; 2) meteorological sensors that to measure radiation (CNR1, Kipp & Zonen), wind speed (Windvane / prop Young), air temperature and humidity (HMP35, Vaisala); and 3) soil profile probes for water content measurements (CS616, Campbell Scientific) collected at depths of 5 cm, 10 cm, 30 cm, and 60 cm (and also 100cm at Lamasquère site). The eddy covariance (EC) system allows to monitor generates turbulent fluxes at fields scale combining synchronized measurements of 3-D wind components (Campbell, CSAT 3) and fluctuations of atmospheric of atmospheric concentrations of CO_2 and H_2O using an open path Infrared Gas Analyzer (LiCor LI-7500, IRGA). Evapotranspiration (ETR) and energy fluxes (latent heat LE and sensible heat H) are calculated and integrated over 30 minutes according to CarboEurope-IP recommendation (Aubinet et al., 1999, Béziat et al, 2009). Half-hourly fluxes were corrected for spectral frequency loss (Moore, 1986) and corrected for air density variations (Webb et al., 1980). Flux data were filtered and flagged according to statistics and objectives criteria: data out of range, rain event, friction velocity threshold, integral turbulence characteristic, stationarity test (Papale et al., 2006; Reichstein et al., 2005) and spatial representativeness (footprint) of the fluxes. For the latter, if the calculated fetch including 90 % of the flux (Kljun et al., 2004) model for each half-hourly EC flux value (*F-90*) was higher than the distance between the mast and the edge of the plot in the main wind direction, fluxes were discarded. Gapfilling was finally performed depending on the duration of missing data, either following the linear regression method (duration < 1h30), or following the mean diurnal variation or look up table method (duration >1h30) according to Beziat & al. (2009).These scalars are measured at 20 Hz and are integrated over 30 minutes to generate surface fluxes according to CarboEurope-IP flux computation procedures (Béziat et al, 2009).

The LAI was also measured for these sites using a destructive method (Claverie 2012, Ferrant et al. 2014). At both flux sites, vegetation samples were collected along two transects crossing the field over the entire growing season until harvesting roughly once a month. Ten to twenty 1.5 m-long rows were collected on each sampling day. The organs of the collected plants were separated into green and yellow leaves, stems, flowers and fruits. The Plant Area Index (PAI) was defined as half the surfaces of all green organs, and the Leaf Area Index (LAI) was defined as half the surfaces of green leaves; it was measured by means of a LiCor planimeter (LI3100, LiCor, Lincoln, NE, USA).

3 Methods

3.1 Numerical Experiments

We conducted two experiments to evaluate effects of the Formosat-2 LAI and land cover maps on ~~the SURFEX~~ ISBA simulations. The ~~simulated domain~~study area covers a 24x24 km area near Toulouse in southwestern France (Fig. 3). Simulations were carried out from 2006 to 2010. Our objective was to preserve the uniqueness of vegetation types within computation units to avoid mixing the LAI profiles of several crop types. A discretization of the ~~domain~~ area with a regular grid based on cartographic coordinates as it is done by default ~~via the SURFEX~~in ISBA would require employing a grid resolution of at least 50 m to capture the spatial heterogeneity of the landscape (230,400 grid cells). The study area was thus discretized using an original approach: rather than using a regular grid, we used the land cover map to identify connected regions of pixels sharing a common PFT (using GDAL polygonize utility with 4-pixel connectedness). This discretization does not necessarily match actual crop fields because two adjacent ~~fields~~ plots with the same PFT are merged into one ~~parcel~~plot. However, in general, a "numerical ~~parcel~~plot" corresponds to a cultivated ~~parcel~~plot. A ~~parcel~~ plot can also correspond to an ~~non-~~uncultivated area, such as a forest patch. These homogeneous ~~parcels~~ plots were determined for each year of the simulation period, as the land cover maps differ from one year to another mainly due to crop rotations. The ~~parcel~~ plot approach generates lower computation costs than the regular grid approach. The ~~domain~~ study area is composed of 12,500 to 14,500 ~~parcels~~ plots depending on the year considered, representing 84% to 91% of the total image area. The remaining surface corresponds to roads, lanes, rivers and strips of lawn between fields, which are not simulated in this study.

The first ~~simulation~~ experiment (ECOCLIMAP) is the reference simulation. It simulates fluxes based on ECOCLIMAP-II vegetation parameters, including the ~~climatological~~ LAI climatology and vegetation fraction (Sect. 2.1). ECOCLIMAP parameters are interpolated on ~~parcel~~ plot centroïds with interpolation functions included in ~~the SURFEX~~ ISBA.

The second ~~simulation~~ experiment (FORMOSAT) was carried out by prescribing the LAI using the monthly Formosat-2 LAI (Sect. 2.2.1) rather than the ECOCLIMAP-II LAI. Each ~~parcel~~ plot was also assigned a unique PFT obtained from the FORMOSAT land cover maps. We first aggregated the 34 classes of the original land cover maps to match the 12 standard PFTs of ~~the~~ SURFEX (Table 1). The other vegetation parameters were drawn from ~~the~~ ECOCLIMAP-II for the corresponding PFT.

3.2 Comparison methods

First, we did a local comparison to in-situ measurements. We extracted the outputs of both simulations from the Auradé and Lamasquère station ~~parcels~~plots. We then calculated correlation coefficient (R^2) and Root-Mean Square Error (RMSE) values between monthly ~~averages~~ cumulated ~~of the~~ measured and simulated ~~latent heat~~evapotranspiration fluxes (~~LE~~ET~~, evapotranspiration~~).

Then, we did a spatialized comparison over the entire study area. ~~w~~We analyzed differences between both simulations for the entire ~~modeling domain~~ study area by calculating correlation coefficients between the monthly simulated evapotranspiration time series for each ~~parcel~~plot. These correlation maps allow one to identify ~~parcels~~ plots where effects of using Formosat-2 data on the temporal evolution of evapotranspiration are more pronounced.

Eventually, we aggregated the simulated LAI, evapotranspiration, drainage, runoff and Soil Water Index (SWI, Eq. (1), Le Moigne 2012) values of all of the ~~parcels~~ plots based on PFT values to analyze effects of the Formosat-2 products by vegetation type. Each plot has a unique ISBA patch in the FORMOSAT experiment, forced by the land cover map. Thus only the corresponding patch was taken into account when comparing with the ECOCLIMAP experiment. If the corresponding patch was not present in the combination of patches given by ECOCLIMAP-II for the plot, then this plot was excluded of the results. By this way we are sure that we can compare the fluxes on specific vegetation types.

$$SWI = \frac{w - w_{wilt}}{w_{fc} - w_{wilt}} \quad (1)$$

where w is the volumetric soil water content, w_{wilt} is the volumetric soil water content at the wilting point and w_{fc} is the volumetric soil water content at field capacity.

4 Results

4.1 Local comparisons with in situ measurements

First, the simulated ET of both experiments has been compared to the measured ET~~Our simulated evapotranspiration comparisons between eddy covariance measurements~~ ~~of~~ on the study sites ~~in~~ Auradé and Lamasquère. It shows that using LAI derived from Formosat-2 data in the SURFEX simulation improves the correlation and RMSE of almost every year with respect to the ECOCLIMAP experiment (Tables 2 and 3). The improvement is more significant when measurement fields are covered in sunflower or maize crops, i.e., summer crops, with an improvement of the R^2 of roughly 0.3 and a decrease of around 30% of the RMSE. By contrast, the effects of Formosat-2 data are not as strong for wheat and rapeseed crops, i.e., winter crops, where the improvement on R^2 rarely exceeds 0.1, the decrease in RMSE being around 20%..

To understand why these differences appear, we compared the time series of measured and simulated LAI and evapotranspiration for both sites ~~for~~ in 2006 (Fig. 5 and 6). Silage maize was grown in Lamasquère in 2006. This crop is harvested before plant senescence.~~;~~ ~~h~~Hence, the observed cycle is shorter than a typical maize cycle. Figure 5 shows that the LAI is more realistic when using Formosat-2 data rather than the ECOCLIMAP-II MODIS climatologic LAI. The FORMOSAT LAI phenological cycle is shorter~~ and~~. It is in agreement with the LAI cycle observed in situ. LAI value increase~~s~~ due to crop growth and ~~LAI value decline~~sudden drop due to harvesting are well represented. By contrast, the ECOCLIMAP LAI is too high in the autumn and winter. ~~This shows that for this specific location and vegetation type (C4~~

~~crop type), the ECOCLIMAP-II unmixing algorithm of MODIS LAI data does not allow one to capture the actual trajectory of LAI evolution. This may be attributable to (i) the unmixing algorithm itself, (ii) the temporal averaging method used to create the climatological LAI, and (iii) small woodland areas or strips of lawn between crops fields that cannot be resolved using MODIS, although they maintain moderate LAI values during the winter.~~

This better description of the LAI based on Formosat-2 data leads to a better simulation of evapotranspiration timing (Fig. 6). In particular, the evapotranspiration peak is delayed by one month for summer crops (i.e., on Lamasquère)~~ and~~. It thus fits the measurements better. ~~(Sect. 4.2 below).~~ However, the ~~Formosat-2 data~~FORMOSAT experiment results do not match the actual amplitude of the measured evapotranspiration peak. This difference will be discussed in the discussion part (Sect. 5).~~This is most likely due to the lack of irrigation in the model given that the Lamasquère site was irrigated between June and August (147 mm). Adding the measured irrigation rates to the SAFRAN precipitation forcing improves this simulation with respect to LE measurements (not shown here).~~

By contrast, differences in evapotranspiration levels are minor for winter cheat at the Auradé site~~,~~. ~~which was covered in wheat crops in 2006.~~ LAI dynamics are similar. The main difference between observation and simulations for both experiments~~LAI evolution patterns occurring during the crop growth period are similar. The main difference between both experiments~~ occurs after the harvest period but does not lead to large differences in LE values (Sect. 4.2).

4.2 Spatial comparisons with the Formosat-2 image

We computed the correlation coefficient between the simulated evapotranspiration time series for both experiments for each ~~parcel~~plot of the study area. Figure 7 illustrates the distribution of correlation coefficients grouped by land cover type. A small correlation value denotes that the evapotranspiration time series are not in phase. Evapotranspiration patterns are not heavily modified outside of the crop fields (Fig. 7a). It~~,~~ generates~~ing~~ a correlation coefficient of almost 1 and low levels of value dispersion. From the crop areas, two populations can be identified: winter and summer crops. The temporal evolution of winter crop evapotranspiration (mostly wheat, C3) is not heavily modified (Fig. 7b). However, the effect is much more significant for summer crops (mostly maize (C4), sunflower (C3) and soy (C3) plants~~), ~~). In this case the~~generating a~~ median correlation coefficient ~~that ~~is lower than that of wheat. ~~and a considerable~~The degree of value dispersion is also considerable depending on the year (Fig. 7c and 7d).

Local comparison results suggest that the ECOCLIMAP LAI forcing does not allow for a correct representation of the evapotranspiration flux dynamics~~es~~ of summer crops over the entire ~~domain ~~study area. Indeed~~because~~ it does not capture their phenology with sufficient precision, especially in regard to the temporal extent of the cycle. ~~Replacing the C3 and C4 classes of the ECOCLIMAP (based on the plant photosynthesis mechanism) with summer and winter crops classes, even when using a climatologic LAI, may increase the precision of simulated evapotranspiration patterns for these types of crops. The identified dependence on the year may be due to agricultural practices such as sowing or harvesting dates, which are related to climatic conditions of a given year. The MODIS climatologic LAI included in ECOCLIMAP-II cannot simulate~~

~~interannual variability like Formosat-2. It is thus unable to capture effects of these practices on vegetation phenology, thus producing significant differences from the actual LAI cycle.~~

To further understand effects on hydrometeorological processes, we compared the monthly differences ~~of~~ between both experiments on LAI and evapotranspiration (~~LE~~ET) dynamics. The results were aggregated by averaging each variable of all of the C4 crop fields (maize and sorghum) for 2008 (Fig. 8a). We also compared daily Soil Water Index (SWI, Fig. 8b), drainage (DRAIN) and runoff (Fig. 8c) differences. As observed previously ~~As was done for the previous point-scale analysis~~ (Sect. 4.1), the difference in ~~LE~~ ET denotes the delay in the evapotranspiration peak with a negative difference occurring during the spring (ECOCLIMAP is higher than FORMOSAT) and with a peak occurring during the summer (Fig. 8a). It is strongly correlated with the difference in LAI~~ as well~~. The lower LAI level occurring during the spring in the FORMOSAT experiment induces a lower transpiration level because the evaporative surface~~s of each plant are~~is restricted, thus enhancing ~~their capacity for~~ stomatal resistance. As a result, the SWI in the FORMOSAT experiment remains higher than that of the ECOCLIMAP ~~simulation~~ experiment until the summer (Fig 8b). ~~A higher SWI recorded during the summer denotes that~~Then more water remains available for ~~evaporation from the soil~~evapotranspiration during summer.~~,~~ Consequently the ET~~thus rendering the LE~~ is higher during this period according to FORMOSAT experimental results. This explains why the ~~LE~~ ET difference is positive during the summer even when there is almost no difference in LAI values between the experiments. In ~~the~~ ISBA~~-SURFEX~~, drainage only occurs when the SWI is higher than 1 (Le Moigne, 2012)~~, and so~~. Hence, an increase in the SWI during the spring causes an increase in the drainage volume (Fig. 8c)~~, which~~. This increase can be significant over the year (Table 4), averaging at approximately 4% of annual precipitation and at up to 8% for sunflower and wheat crop fields. Runoff is also affected by differences in the SWI (table 5) but in smaller proportions. Indeed, the function used in both of our experiments to simulate runoff is based on the premise that even when the SWI is lower than 1, rain can saturate part of a pixel's upper soil layer, thus generating runoff in the pixel. This dripping section of a pixel increases with soil moisture. This is not the case for drainage patterns, which require a saturation of the entire soil root and sub-root layers to occur. Thus, a higher SWI, even if it remains below a value of 1, suggests that a larger part of a pixel is dripping, thus causing runoff levels to be higher in the FORMOSAT experiment (Fig 8c). ~~However, irrigation concerns continue to be the main limitation of our study given that roughly 13% of the fields in our domain are irrigated. Incorporating irrigation rules similar to those of the MAELIA platform (Therond & al., 2014) could thus affect evapotranspiration values and consequently SWI and drainage values.~~

5 Discussion

Thanks to the high spatial resolution of Formosat-2, the plot scale modeling approach could be applied at regional scale. It allows distinguishing the effects on specific vegetation types in the context of LSM studies. The revisit frequency is also sufficient to clearly monitor the phenological cycle and its critical stages at the plot scale. The local comparison between model and measurements (Sect. 4.1) clearly shows that the use of Formosat-2 (Sentinel-2 like) data allows the model to capture the seeding and harvest dates (Fig. 5) unlike with the ECOCLIMAP-II forcing. Note that the quality of the Formosat-2 acquisition is quite similar to the Sentinel-2's (Koetz et al., 2017). Especially, the geo-location uncertainty is smaller than the size of a pixel, what allows precise extraction of LAI values from plots geometry. We thus assume that it has no impact given the erosion of the polygons within our LAI retrieval method (Sect. 2.2.1). The uncertainties on radiometry are also rather small compared to the measurements' uncertainties while the Signal-Noise Ratio (SNR) is satisfying. The inner-field variability (dotted green, Fig. 5) is also clearly smaller than the measurements' uncertainties. However, some differences between the measured and remotely sensed LAI can be found. Particularly, the maximum LAI in Formosat-2 data tends to be lower than the measured one. This is due to a saturation effect of the remotely sensed LAI, pointed out by Veloso et al. (2012). But the impact on the simulated evapotranspiration amplitude is not significant. Indeed, the peak of the LAI derived from Formosat-2 on a winter wheat field (Fig. 5a) is clearly lower than the measured one but it does not induce a large difference in the evapotranspiration peak (Fig. 6a). The growth and senescence periods might also be inaccurate on some plots of the area, or even completely missing, because of the cloud obstruction. Indeed, cloud coverage is the main limitation of the use of optical remote sensing products. Even with such a high revisit frequency, a plot can remain obstructed over all the revisit dates during the phenologic cycle. Thus the model cannot take it into account. It means that for some regions of the world, like tropical regions where the cloud coverage is frequent, this method would not be appropriate.

The high-resolution LAI forcing has modified the simulated evapotranspiration, giving a more realistic temporal dynamics. However, the effect is more significant on specific crops, i.e. summer crops like maize or sunflower. Indeed, for the summer crops, the main differences between the two experiments in terms of LAI are observed during the growth and/or the senescence periods. This is less marked for the winter crops. Indeed, the temporal extent of their phenologic cycle is only slightly modified. These results are confirmed by the spatial analysis (Sect. 4.2). The impact on evapotranspiration seems to be quite similar for all summer crops fields. But the causes of this impact differ from a cultivation type to another. The case of the maize crops (Fig. 5b & 8a) shows the limits of the ECOCLIMAP-II unmixing algorithm of MODIS LAI data. In the case of C4 crops, the ECOCLIMAP-II LAI remains far too high during winter and growth and senescence periods. The resulting fluxes are thus particularly affected (Fig. 6b & 8a). It may be attributable to (i) the unmixing algorithm itself, (ii) the temporal averaging method used to create the LAI climatology, and (iii) small woodland areas or strips of lawn between crops fields that cannot be resolved using MODIS, although they maintain moderate LAI values during the winter. The case of sunflower and soya crops (Fig. 7b) is slightly different. These plants are considered as C3 crops like wheat. But the ECOCLIMAP-II phenology for C3 crops is mainly that of wheat in this region. Consequently, the sunflower is always simulated as wheat whereas their phenologies and hydrometeorological behaviors are very different. Replacing the C3 and C4 classes of ECOCLIMAP-II by a more detailed classification separating summer and winter crops could be of great interest for Land Surface modeling. Even with a MODIS LAI climatology based on the same unmixing algorithm, it could increase the precision of the simulated evapotranspiration especially for the summer crops. The interannual variability of the results on evapotranspiration (Fig. 7) may be justified by the climatic conditions of each year. Indeed, climatic conditions influence the farmers' decisions concerning the seeding and/or harvest dates. If these dates are closer than the ones simulated by ECOCLIMAP LAI, the effect on evapotranspiration is weaker.

But even if the evapotranspiration dynamic is more realistic when using Formosat-2 products, the model remains unable to simulate the actual amplitude of the measured evapotranspiration flux (Fig. 6b). This is most likely due to the fact that the model does not simulate irrigation while the Lamasquère site was irrigated between June and August 2006 (147 mm). Outside of the irrigation period, the simulated evapotranspiration when the model is forced by the Formosat-2 appears really close to the measured evapotranspiration (Fig. 6). It shows that the bias inherent to the model, outside of the lack of irrigation, is very low. Adding the measured irrigation rates to the SAFRAN precipitation forcing improves this simulation with respect to ET measurements (not shown here). Ignoring irrigation remains the main limitation of our study given that roughly 13% of the plots in our study area are irrigated. Incorporating irrigation rules similar to those of the MAELIA platform (Therond et al., 2014) could add up to the differences observed in this study and give even better results. This issue will constitute the main topic of our future work.

The spatialized comparison also shows that the soil water content, the drainage and the runoff are significantly increased (Fig. 8b & 8c) especially on summer crops. Such a difference in these fluxes could have an impact on the river discharge and groundwater recharge. Hence, further work is necessary to upscale this study at the scale of a river basin, which is the scale of the water management agencies. Sentinel-2A already images the Earth' land area at a similar radiometric spatial resolution than Formosat-2 over a 10-day revisit period. The optimal revisit period of 5 days should be achieved after the launch of Sentinel-2B. Scalable algorithms for crop type mapping and LAI retrieval are now available (Li et al., 2015; Inglada et al., 2015), allowing for the processing of large areas. While the computation costs of the hydrometeorological model at this spatial resolution may be an issue, the SURFEX modeling platform can run in a parallel mode using the Message Passing Interface protocol. These advances could allow studying the impact on the river discharge.

6~~5~~ Conclusion

Our study deals with the inter-comparison between two spatialized hydrometeorological ISBA modeling approaches in an agricultural zone in southwestern France from years 2006 to 2010. A first experiment was performed with LAI forcing from ECOCLIMAP-II database which was generated from MODIS data. It was considered as the reference simulation. Second experiment included LAI forcing from high resolution Formosat-2 (Sentinel-2 like) time series data. Both simulations were performed with plots as computing units, where plot segmentation was derived from Formosat-2 high resolution land cover maps classifications. The use of the plot scale approach allowed exploiting the high spatial resolution on coherent hydrometeorological units while limiting the calculation time compared to a pixel based approach. Thanks to the high revisit frequency of Formosat-2, we can capture the complex anthropogenic effects which affect land surface properties (e.g., seeding and harvest dates, crop rotations). The comparison between the two experiments reveals significant differences in the simulated water fluxes. Our analysis shows that summer crops LAI dynamics appear more realistic when using Formosat-2 data. Consequently, the modeled evapotranspiration also appears more realistic on this kind of crop. These results point out the limitations of both the LAI retrieval method of ECOCLIMAP-II and the lack of inter-annual variability of the vegetation in the model. As expected, however, the incorporation of satellite LAI was not sufficient to capture the amplitude of the evapotranspiration peak in the validation site where irrigation is practiced. Indeed, there is no parameterization for irrigation practices in our model while the irrigated area is known to be 13% of plots in our study area. Hence, we will now focus on the representation of the irrigation in the model. This will allow a further evaluation of the model at the catchment scale based on the observed river discharge.

The use of high spatial resolution and high revisit frequency Formosat-2 data rather than standard ECOCLIMAP-II vegetation parameters was found to improve the representation of the vegetation phenology of the SURFEX for a cultivated area characteristic of southwestern France. Local comparisons with in situ observations show that this in turn improves monthly evapotranspiration simulations. This finding is particularly true for summer crops, whereas the impact is less significant for winter crops and is even less significant outside of crop areas. From our spatial comparisons, we suggest that our local scale results are likely transposable across the whole domain.

For crop growing areas, the Formosat-2 LAI is lower than that of ECOCLIMAP-II before crops grow, and thus, the Soil Water Index (SWI) remains higher during the crop growing season. As a result, drainage and runoff levels are higher. The SWI also decreases later in the summer, making more water available for evaporation from the soil in the summer. This phenomenon generates a significant increase in evapotranspiration during the summer for summer crops when Formosat-2 products are used. Employing the ECOCLIMAP-II classification with a summer crop class may constitute a first step to ameliorating ISBA-SURFEX model realism when it is applied to agricultural areas even with a climatologic LAI.

More generally, we showed that high-resolution land cover maps and LAI time series allow one to take into account effects of the actual vegetative cycle of each parcel in an operational hydrometeorological model. These remote sensing products capture complex anthropogenic effects on land surface properties (e.g., sowing and harvest dates and fertilizer inputs). In the present study, Formosat-2 data were limited to a 24 km by 24 km area whereas water management agencies typically manage river basins at a regional scale (above 10^4 km²). Sentinel-2A already images the Earth' land area at a similar radiometric spatial resolution over a 10-day revisit period. The optimal revisit period of 5 days should be achieved in the next few months after the launch of Sentinel-2B. Our study shows that Sentinel-2 observations will soon allow us to improve the monitoring of water resources in large anthropized river basins. Scalable algorithms for crop type mapping and LAI retrieval are now available (Li & al., 2015; Inglada & al., 2015), allowing for the processing of large areas. While the computation costs of the hydrometeorological model at this spatial resolution may be an issue, the SURFEX land surface model can run in a parallel mode using the Message Passing Interface protocol. Therefore, the focus of our future studies will be to upscale this methodology to the Garonne River Basin using Landsat and SPOT-4/5 Take 5 data (Hagolle & al., 2015) to evaluate the impact of these data on river discharge and groundwater recharge at the water resource management scale.

Additional work must also be conducted to explicitly represent irrigation in the model. The approach presented in this paper enables one to better match the timing of evapotranspiration over irrigated areas. However, it fails to represent its actual amplitude, as there is no parameterization for water uptake from an aquifer or from surface water. Ongoing developments will focus on the implementation of parsimonious rule-based irrigation parameterizations in the ISBA-SURFEX (Martin & al., 2016). These developments will directly benefit from the high-resolution application of the ISBA-SURFEX presented in this paper, as irrigation rules are partly constrained by land cover type (Therond & al., 2014).

The supplements related to this article are available online at: http://tully.ups-tlse.fr/simon/surfex-configuration-files

Code and data availability

The version of SURFEX used in this study is the v7.3. The code is available here: http://www.umr-cnrm.fr/surfex//data/BROWSER/out_doc73/index.html.

For the LAI data or land cover maps, please ask to the corresponding author.

Author contribution:

J. Etchanchu formatted the data, performed the simulation, analyzed the results and wrote most of the current paper.

V. Rivalland and S. Gascoin helped at designing the experiments, processing the data and analyzing the results.

J. Cros provided the tools to process the remote sensing data.

A. Brut wrote the section 2.2.3 about the instrumentation of the two stations.

T.Tallec calculated and provided the associated uncertainties of in-situ measurement.

All the authors revised the paper.

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References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M.: Crop evapotranspiration — guidelines for computing crop water requirements, FAO Irrigation and drainage paper 56, Food and Agriculture Organization, Rome, 1998.

Aubinet, M., Grelle, A., Ibrom, A., Rannik, U., Moncrieff, J., Foken, T., Kowalski, A. S., Martin, P. H., Berbigier, P., Bernhofer, Ch., Clement, R., Elbers, J., Granier, A., Grünwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., Vesala, T.: Estimates of the Annual Net Carbon and Water Exchange of Forests: The EUROFLUX Methodology, Advances in Ecological Research, 30, 113-175, doi: 10.1016/S0065-2504(08)60018-5, 1999.

Béziat, P., Ceschia, E., Dedieu, G.: Carbon balance of a three crop succession over two cropland sites in South West France, Agr. Forest Meteorol., 149 (10), 1628–1645, doi: 10.1016/j.agrformet.2009.05.004, 2009.

Boussetta, S., Balsamo, G., Beljaars, A., Kral, T. and Jarlan, L.: Impact of a satellite-derived leaf area index monthly climatology in a global numerical weather prediction model, Int. J. Remote Sens., Special Issue, Third International Symposium on Recent Advances in Quantitative Remote Sensing, 34, 9-10, 3520-3542, doi: 10.1080/01431161.2012.716543, 2013.

Calvet, J.-C., Noilhan, J., Roujean, J.-L., Bessemoulin, P., Cabelguenne, M., Olioso, A., and Wigneron, J.-P.: An interactive vegetation SVAT model tested against data from six contrasting sites, Agric. For. Meteorol., 92, 73–95, doi: 10.1016/S0168-1923(98)00091-4, 1998.

Chen, J.M., Black, T.A.: Defining leaf area index for non-flat leaves, Plant Cell Environ., 15(4), 421-429, doi: 10.1111/j.1365-3040.1992.tb00992.x, 1992.

Claverie, M.: Estimation spatialisée de la biomasse et des besoins en eau des cultures à l'aide de données satellitales à hautes résolutions spatiale et temporelle : application aux agrosystèmes du sud-ouest de la France, Ph.D. thesis, Université Toulouse III – Paul Sabatier, 2012.

Deardorff, J. W.: A Parameterization of Ground-Surface Moisture Content for Use in Atmospheric Prediction Models, J. Appl. Meteor., 16, 1182–1185, doi : 10.1175/1520-0450(1977)016<1182:APOGSM>2.0.CO;2, 1977.

Dejoux, J.F., Dedieu, G., Hagolle, O., Ducrot, D., Menaut, J.C., Ceschia, E., Baup, F., Demarez, V., Marais-Sicre, C., Kadiri, M., &et al. : Kalideos OSR MiPy : un observatoire pour la recherche et la demonstration des applications de la télédétection à la gestion des territoires, Revue Française de Photogrammétrie et de Télédétection, Société Française de Photogrammétrie et de Télédétection, 17-30, 2012.

Ducrot, D. : Méthodes d'analyse et d'interprétation d'images de télédétection multi-sources -Extraction de caractéristiques du paysage, « Habilitation à Diriger des Recherches » thesis, INP Toulouse, 2005.

Ducrot, D., Gouaux, P. : Paysage et Télédétection dans les processus écologiques : Caractérisation des paysages par télédétection, source d'indicateurs de leur fonctionnement, JET Journées d'Ecologie Fonctionnelle, Biarritz, France, 2007.

Ducrot, D., Ceshia, E., Marais-Sicre, C.: Détection des changements de l'occupation du sol à partir d'images de télédétection multi-temporelles, « Changement de paysage » conference, Tunis, 2009.

Dumenil, H., Todoni, E.: A rainfall-runoff scheme for use in the Hamburg climate model, Adv. Theor. Hydrol., 9, 129–157, 1992.

Durand, Y., Brun, E., Mérindol, L., Guyomarc'h, G., Lesaffre, B., Martin, E.: A meteorological estimation of relevant parameters for snow models. Ann. Glaciol., 18, 65–71, doi: 10.3198/1993AoG18-1-65-71, 1993.

FAO/IIASA/ISRIC/ISS-CAS/JRC: Harmonized World Soil Database (version 1.2), FAO, Rome, Italy and IIASA, Laxenburg, Austria, 2012.

Faroux, S., Kaptué Tchuenté, A.T., Roujean, J.-L., Masson, V., Martin, E., Le Moigne, P.: ECOCLIMAP-II/Europe: a twofold database of ecosystems and surface parameters at 1km resolution based on satellite information for use in land surface, meteorological and climate models, Geoscientific Model Development, 6, 563-582, doi: 10.5194/gmd-6-563-2013, 2013.

Ferrant, S., Gascoin, S., Veloso, A., Salmon-Monviola, J., Claverie, M., Rivalland, V., Dedieu, G., Demarez, V., Ceschia, E., Probst, J.L., Durand, P., Bustillo, V.: Agro-hydrology and multi-temporal high-resolution remote sensing : toward an explicit spatial processes calibration, Hydrol. Earth Syst. Sc., 18, 5219-5237, doi: 10.5194/hess-18-5219-2014, 2014.

Ferrant, S., Bustillo, V., Burel, E. Salmon-Monviolla, J., Claverie, M., Jarosz, N., Yin, T., Rivalland, V., Dedieu, G., Demarez, V., Ceschia, E., Probst, A., Al-Bitar, A., Kerr, Y., Probst, J-L., Durand, P., Gascoin, S.: Extracting soil water holding capacity parameters of a distributed agro-hydrological model from high resolution optical satellite observation series, Remote Sensing, 8(2), 154, doi:10.3390/rs8020154, 2016.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K.: Global consequences of land use, Science, 309(5734), 570-574, doi: 10.1126/science.1111772, 2005.

Ford, T.W., Quiring, S.M.: Influence of MODIS-derived dynamic vegetation on VIC-simulated soil moisture in Oklahoma, J. Hydrometeorol., 14(6), 1910–1921, doi: 10.1175/JHM-D-13-037.1, 2013.

Fritz, S., See, L., McCallum, I., You, L., Bun, A., Moltchanova, E., Duerauer, M., Albrecht, F., Schill, C., Perger, C., Havlik, P., Mosnier, A., Thornton, P., Wood-Sichra, U., Herrero, M., Becker-Reshef, I., Justice, C., Hansen, M., Gong, P., Abdel Aziz, S., Cipriani, A., Cumani, R., Cecchi, G., Conchedda, G., Ferreira, S., Gomez, A., Haffani, M., Kayitakire, F., Malading, J., Mueller, R., Newby, T., Nonguierma, A., Olusegun, A., Ortner, S., Ram Rajak, D., Rocha, J., Schepaschenko, M., Terekhov, A., Tiangwa, A., Vancutsem, C., Vintrou, E., Wenbin, W., Van der Velde, M., Dunwoody, A., Kraxner, F., Oberstainer, M.: Mapping global cropland and field size, Glob. Change Biol., 21 (5), 1980-1992, doi: 10.1111/gcb.12838, 2015.

Habets, F., Noilhan, J., Golaz, C., Goutorbe, J.P., Lacarrère, P., Leblois, E., Ledoux, E., Martin, E., Ottlé, C., Vidal-Madjar, D.: The ISBA surface scheme in a macroscale hydrological model applied to the Hapex-Mobilhy area: Part I: Model and database, J. Hydrol., 217 (1-2), 75-96, doi: 10.1016/S0022-1694(99)00019-0, 1999.

Habets F., Boone, A., Champeaux, J.L., Etchevers, P., Franchistéguy, L., Leblois, E., Ledoux, E., Le Moigne, P., Martin, E., Morel, S., Noilhan, J., Quintana Segui, P., Rousset-Regimbeau, F., Viennot, P.: The SAFRAN-ISBA-MODCOU hydrometeorological model applied over France, J. Geophys. Res., 113, D06113 (2008) 18, doi: 10.1029/2007JD008548, 2008.

Hagolle, O., Dedieu, G., Mougenot, B., Debaeker, V.,Duchemin, B., Meygret, A.: Correction of aerosol effects on multi-temporal images acquired with constant viewing angles: application to Formoat-2 images, Remote Sens. Environ., 112, 1689-1701, doi:10.1016/j.rse.2007.08.016, 2008.

Hagolle, O., Huc, M., Pascual, D. V., Dedieu, G.: A multi-temporal method for cloud detection, applied to FORMOSAT-2, VENuS, LANDSAT and SENTINEL-2 images, Remote Sens. Environ., 114, 1747-1755, doi:10.1016/j.rse.2010.03.002, 2010.

Hagolle, O., Sylvander, S., Huc, M., Claverie, M., Clesse, D., Dechoz, C., Lonjou, V., Poulain, V.: SPOT-4 (Take 5): simulation of Sentinel-2 time series on 45 large sites, Remote Sensing, 7(9), 12242-12264, doi: 10.3390/rs70912242, 2015.

Inglada, J., Arias, M., Tardy, B., Hagolle, O., Valero, S., Morin, D., Dedieu, G., Sepulcre, G., Bontemps, S., Defourny, P., Koetz, B.: Assessment of an operational system for crop type map production using high temporal and spatial resolution satellite optical imagery, Remote Sensing, 7(9), 12356-12379, doi: 10.3390/rs70912356, 2015.

Jarlan, L., Balsamo, G., Lafont, S., Beljaars, A., Calvet, J.C., Mougin, E.: Analysis of leaf area index in the ECMWF land surface model and impact on latent heat and carbon fluxes : application to West Africa, J. Geophys. Res., 113(D24), doi: 10.1029/2007JD009370, 2008.

Kljun, N., Calanca, P., Rotach, L. W., Schmid, H. P.: A simple parameterisation for flux footprint predictions, Bound-Lay. Meteorol, 112 (3), 503-523, doi: 10.1023/B:BOUN.0000030653.71031.96, 2004.

Koetz, B., Hoersch, B., Gascon, F.: Sentinel-2 Mission Status and R&D, Landsat Science Team –Winter Meeting, Boston, 10-12 January 2017.

Le Moigne, P., Surfex scientific documentation, 2012.

Li, W., Weiss, M., Waldner, F., Defourny, P., Demarez, V., Morin, D., Hagolle, O., Baret, F.: A Generic algorithm to estimate LAI, FAPAR and FCOVER variables from SPOT4_HRVIR and Landsat sensors: evaluation of the consistency and comparison with ground measurements, Remote Sensing, 7(11), 15494-15516, doi: 10.3390/rs71115494, 2015.

Liang, X., Lettenmaier, D.P., Wood, E.F., Burges, S.J.: A simple hydrologically based model of land surface water and energy fluxes for general circulation model, J. Geophys. Res., 99 (D7), 14415-14428, doi: 10.1029/94JD00483, 1994.

Mahfouf, J.F. and Noilhan, J.: Inclusion of gravitational drainage in a land surface scheme based on the force-restore method, J. Appl. Meteorol., 35, 987–992, doi: 10.1175/1520-0450(1996)035<0987:IOGDIA>2.0.CO;2, 1996.

Martin, E., Gascoin, S., Grusson, Y., Murgue, C., Bardeau, M., Anctil, F., Ferrant, S., Lardy, R., et al.: On the use of hydrological models and satellite data to study the water budget of river basins affected by human activities: examples from the Garonne basin of France, Surv. Geophys., 37(2), 223-247, doi: 10.1007/s10712-016-9366-2, 2016

Masson, V., Champeaux, J.L., Chauvin, F., Meriguet, C., Lacaze, R.: A global database of land surface parameters at 1-km resolution in meteorological and climate models, J. Climate, 16(9), 1261-1282, doi:10.1175/1520-0442-16.9.1261, 2003.

Masson, V., Le Moigne, P., Martin, E., Faroux, S., Alias, A., Alkama, R., Belamari, S., Barbu, A., Boone, A., Bouyssel, F., Brousseau, P., Brun, E., Calvet, J.C., Carrer, D., Decharme, B., Delire, C., Donier, S., Essaouini, K., Gibelin, A.L., Giordani, H., Habets, F., Jidane, M., Kerdraon, G., Kourzeneva, E., Lafaysse, M., Lafont, S., Lebeaupin Brossier, C., Lemonsu, A., Mahfouf, J.F., Marguinaud, P., Mokhtari, M., Morin, S., Pigeon, G., Salgado, R., Seity, Y., Taillefer, F., Tanguy, G., Tulet, P., Vincendon, B., Vionnet, V., Voldoire, A.: The SURFEX v7.2 land and ocean surface platform for coupled or offline simulation of earth surface variables and fluxes, Geoscientific Model Development, 6, 929-960, doi:10.5194/gmd-6-929-2013, 2013.

Maurer, E.P., Wood, A.W., Adam, J.C., Lettenmaier, D.P.: A long term hydrologically based dataset of land surface fluxes and states for the conterminous United States, J. Climate, 15, 3237-3251, doi: 10.1175/1520-0442(2002)015<3237:ALTHBD>2.0.CO;2, 2002.

Moore, C.J.: Frequency response corrections for eddy correlation systems, Bound-Lay. Meteorol., 37 (1-2), 17-35, doi: 10.1007/BF00122754, 1986.

Nagler, P.L., Glenn, E.P., Nguyen, U., Scott, R.L., Doddy, T.: Estimating Riparian and Agricultural Actual evapotranspiration by reference evapotranspiration and MODIS Enhanced Vegetation Index, Remote Sensing, 5(8), 3849-3871, doi: 10.3390/rs5083849, 2013.

Noilhan, J., Planton, S.: A simple parameterization of land surface processes for meteorological models, Mon. Weather Rev., 117, 536-549, doi: 10.1175/1520-0493(1989)117<0536:ASPOLS>2.0.CO;2, 1989.

Noilhan, J. and Lacarrère, P.: GCM Grid-Scale Evaporation from Mesocale Modeling, J. Climate, 8, 206–223, doi: 10.1175/1520-0442(1995)008<0206:GGSEFM>2.0.CO;2, 1995.

Papale, D., Reichstein, M., Aubinet, M., Canfora, E., Bernhofer, C., Kutsch, W., Longdoz, B., Rambal, S., Valentini, R., Vesala, T., Yakir, D.: Towards a standardized processing of Net Ecosystem Exchange measured with eddy covariance technique: algorithms and uncertainty estimation, Biogeosciences, European Geosciences Union, 3 (4), 571-583, HAL id: <hal-00330317>, 2006.

~~Oleson, K.W., Niu, G.Y., Yang, Z.L., Lawrence, D.M., Thorton, P.E., Lawrence, P.J., Stöckli, R., Dickinson, R.E., Bonan, G.B., Levis, S., Dai, A., Qian, T.: Improvements to the Community Land Model and their impact on the hydrological cycle, J. Geophys. Res., 113, G01021, doi: 10.1029/2007JG000563, 2008.~~

~~Pauwels, V.R.N., Verhoest, N.E.C., De Lannoy, G.J.M., Guissard, V., Lucau, C., Defourny, P.: Optimization of a coupled hydrology-crop growth model trough the assimilation of observed soil moisture and leaf area index values using an ensemble Kalman filter, Water Resour. Res., 43, W04421, doi: 10.1029/2006WR004942, 2007.~~

Quintana-Segui, P., Le Moigne, P., Durand, Y., Martin, E., Habets, F., Baillon, M., Canellas, C., Franchisteguy, L., Morel, S.: Analysis of near-surface atmospheric variables: validation of the SAFRAN analysis over France, J. Appl. Meteorol. Clim., 47, 92-107, doi: 10.1175/2007JAMC1636.1, 2007.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov,T., Granier, A., Grunwald, T., Havrankova, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci,G., Meyers, T., Miglietta, F., Ourcival, J.-M., Pumpanen, J., Rambal, S., Rotenberg,E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., Valentini, R.: On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm, Glob. Change Biol., 11 (9), 1424-1439, doi: 10.1111/j.1365-2486.2005.001002.x, 2005.

Tang, Q., Vivoni, E.R., Muñoz-Arriola, F., Lettenmaier D.P.: Predictability of evapotranspiration patterns using remotely sensed vegetation dynamics during the North American Monsoon, J. Hydrometeorol., 13, 103–121, doi: 10.1175/JHM-D-11-032.1, 2012.

Tesemma, Z. K., Wei, Y., Peel, M. C., Western, A. W.: The effect of year-to-year variability of leaf area index on Variable Infiltration Capacity model performance and simulation of runoff, Adv. Water Resour., 83, 310-322, doi: 10.1016/j.advwatres.2015.07.002, 2015.

Therond, O., Sibertin-Blanc, C., Lardy, R., Gaudou, B., Balestrat, M., Hong, Y., Louail, T., Nguyen, V.B., Panzoli, D., Sanchez-Perez, J.M., Sauvage, S., Taillandier, P., Vavasseur, M., Mazzega, P.: Integrated modelling of social-ecological systems: The MAELIA high-resolution multi-agent platformto deal with water scarcity problems, International Environmental Modelling and Software Society (iEMSs), 7th International Congress on Environmental Modelling and Software, San Diego, CA, USA, 2014.

Trezza, R., Allen, R.G., Tasumi, M.: Estimation of actual evapotranspiration along the Middle Rio Grande of New Mexico using MODIS and Landsat imagery with the METRIC model, Remote Sensing, 5, 5397-5423, doi: 10.3390/rs5105397, 2013.

Van den Hurk, B.J.J.M., Viterbo, P., Los, S.O.: Impact of leaf area index seasonality on the annual land surface evaporation in a global circulation model, J. Geophys. Res., 108, D64191, doi: 10.1029/2002JD002846, 2003.

Veloso, A., Demarez, V., Ceschia, E.: Retrieving crops Green Area Index from high resolution multisensor remote sensing data, Proceedings of Sentinel-2 Preparatory Symposium, 2012.

Verseghy, D.L., McFarlane, N.A., Lazare, M.: CLASS – A Canadian land surface scheme for GCMS, II. Vegetation model and coupled runs, Int. J. Climatol., 13, 347-370, doi: 10.1002/joc.3370130402, 1993.

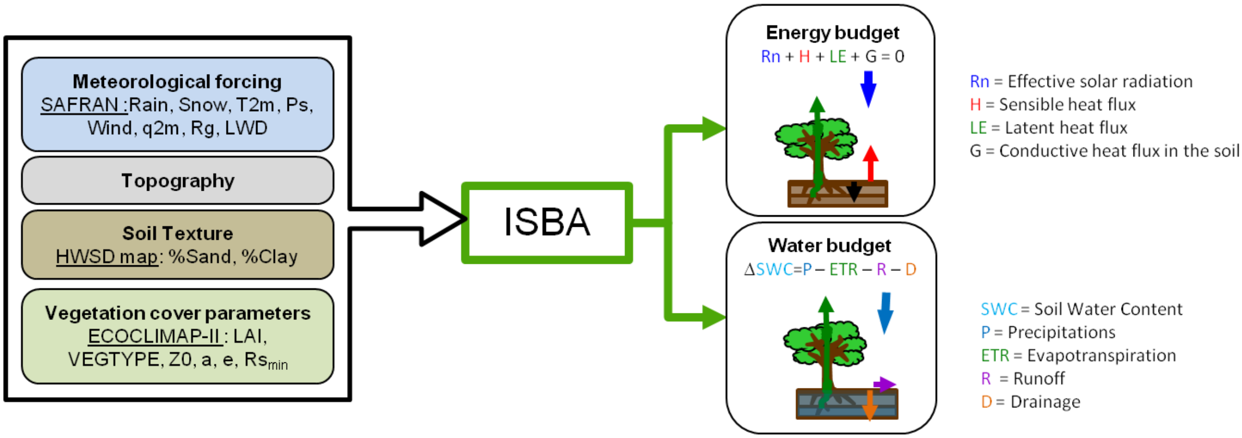


Figure 1: Schematic flowchart of ISBA inputs and outputs.

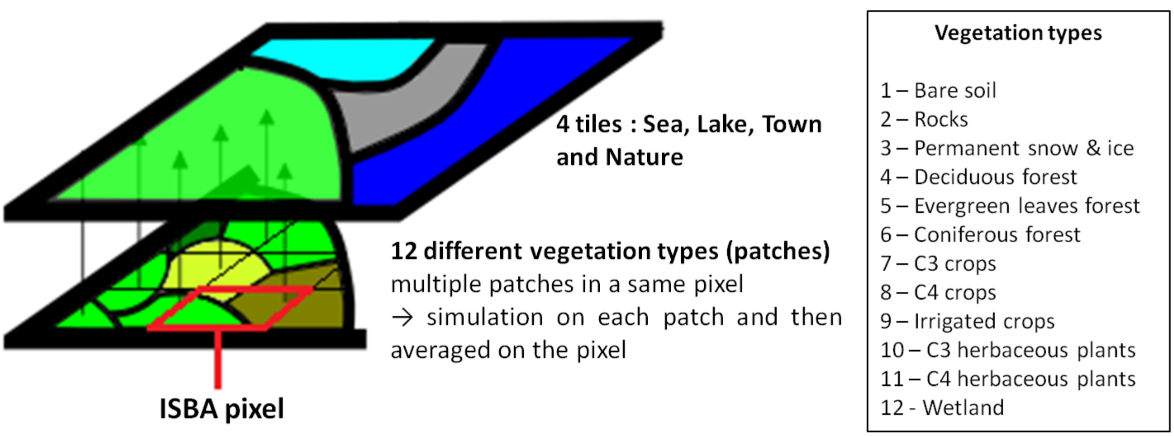


Figure 2: ISBA patch simulation principles.

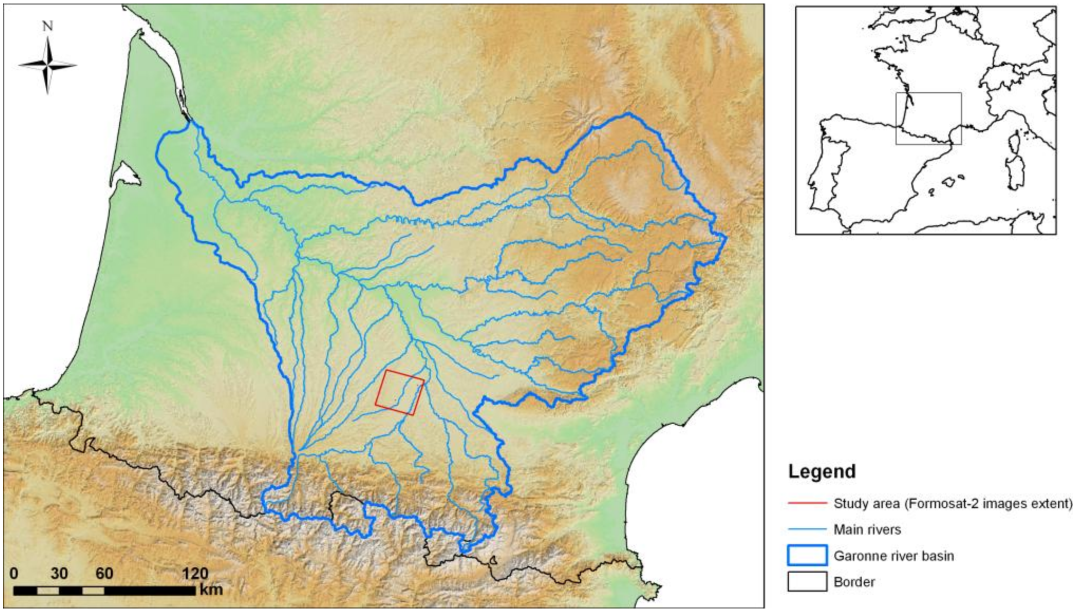


Figure 3: Study area location (red).

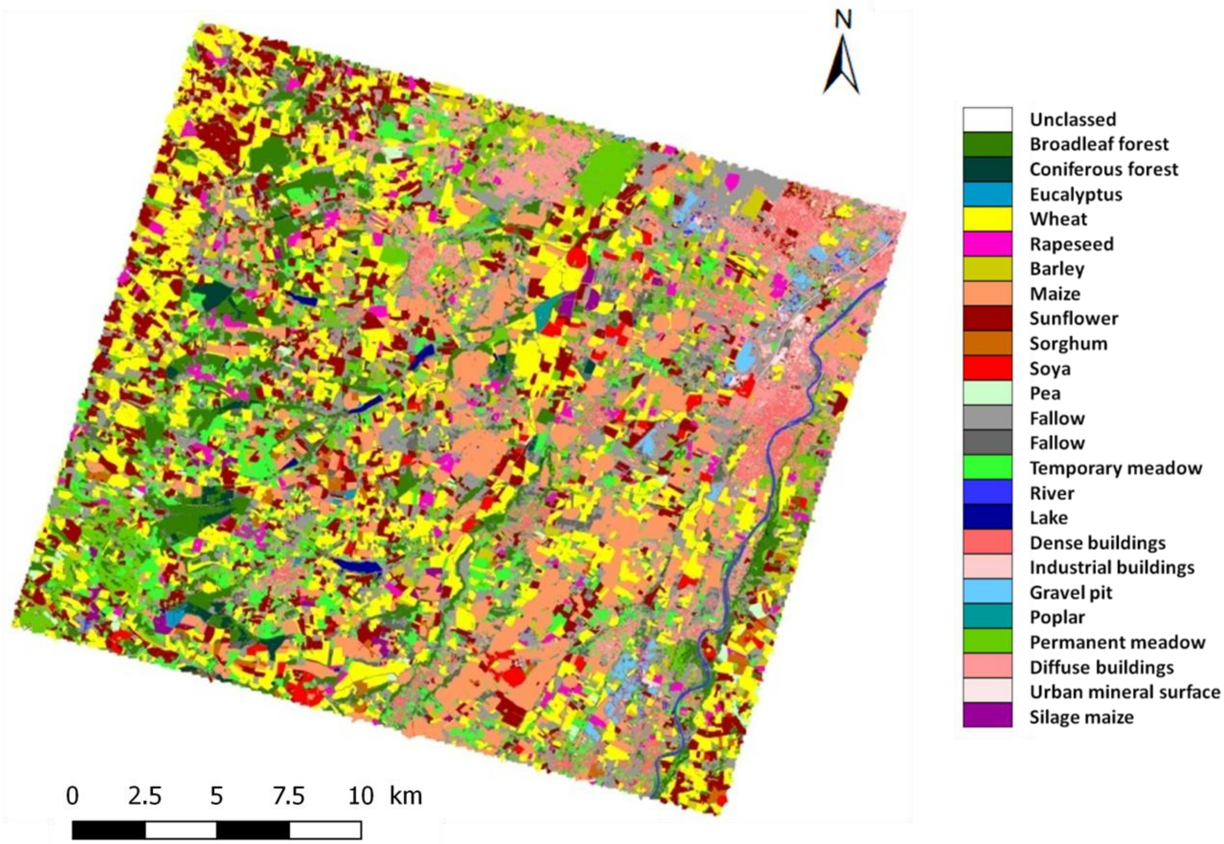


Figure 4: Land cover map for 2006.

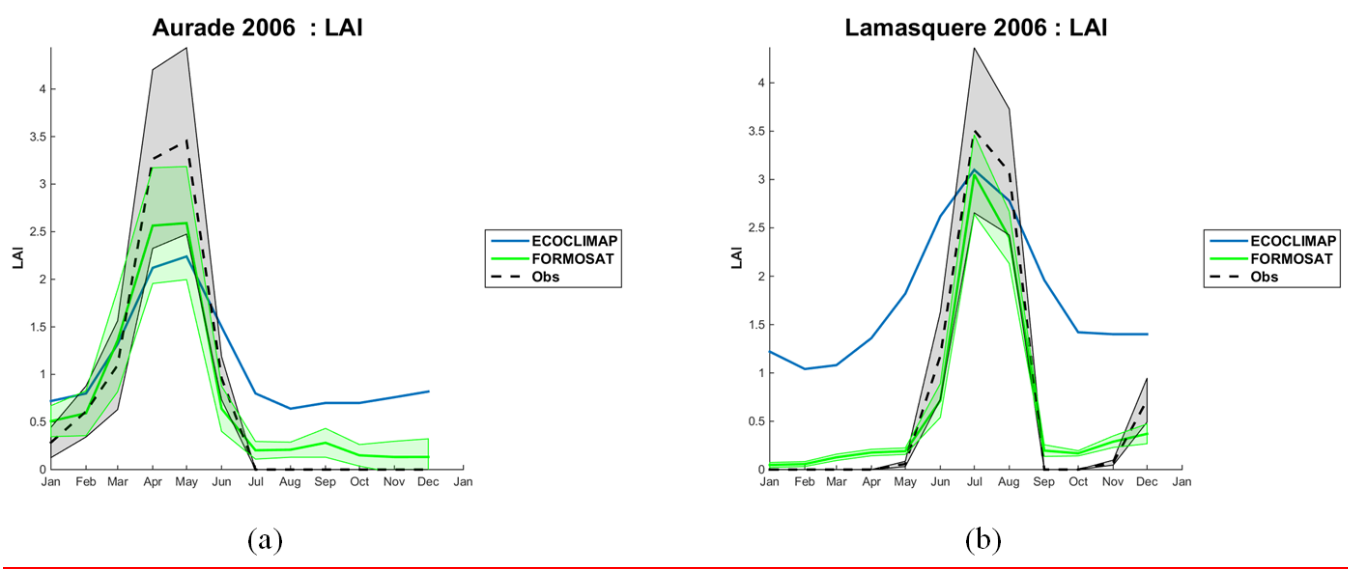


Figure 5: LAI time series for Auradé (a) and Lamasquère (b) for 2006. The filled areas represent the standard deviations for the measured (gray) and remotely sensed (green) time series.

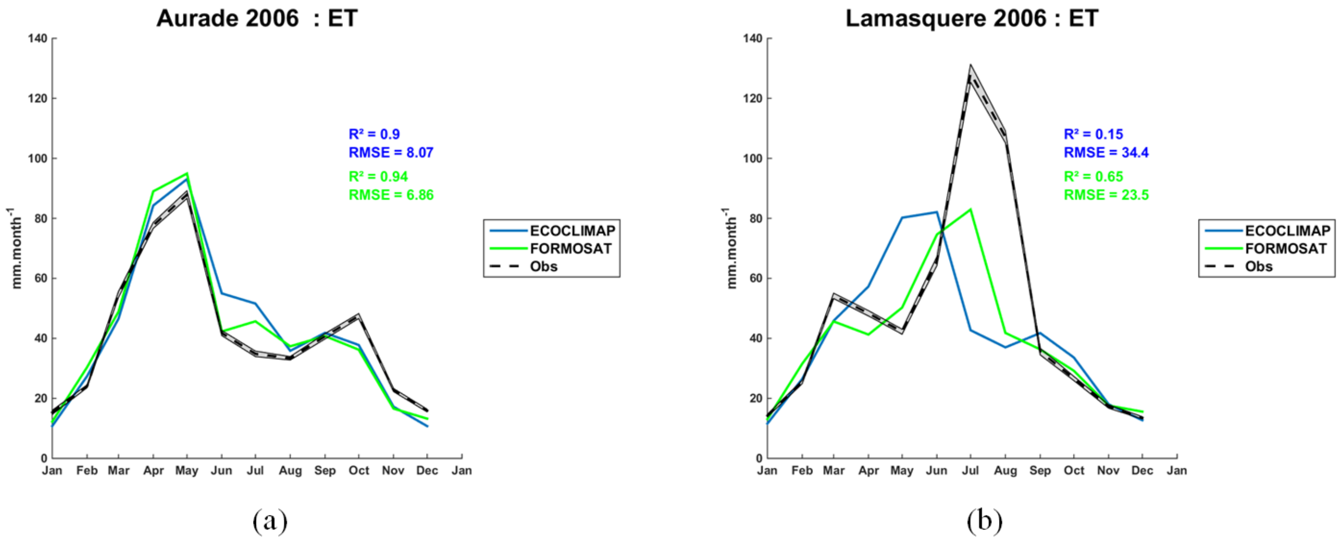


Figure 6: Evapotranspiration time series for Auradé (a) and Lamasquère (b) for 2006. The gray filled areas represent the standard deviations for the measured time series.

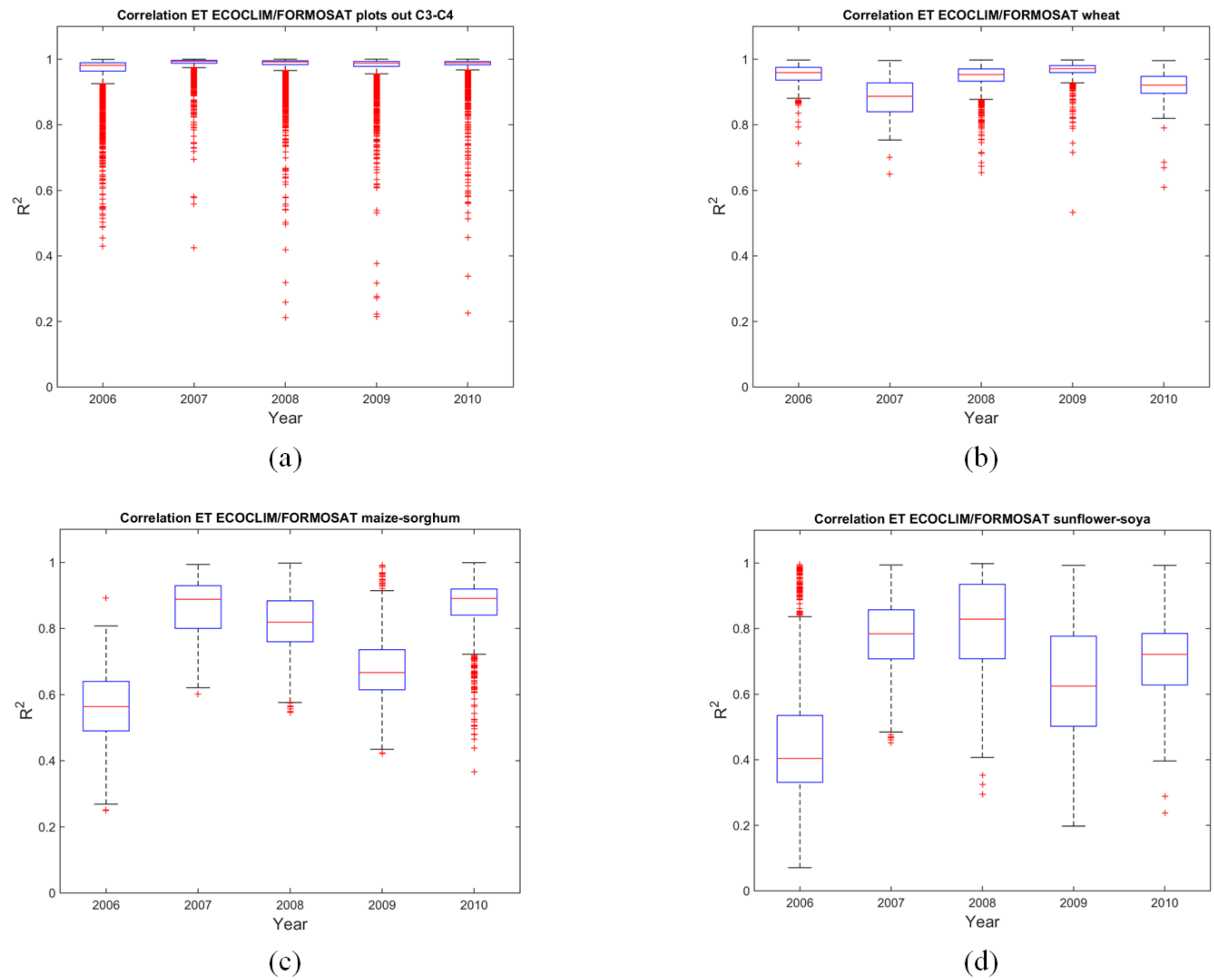
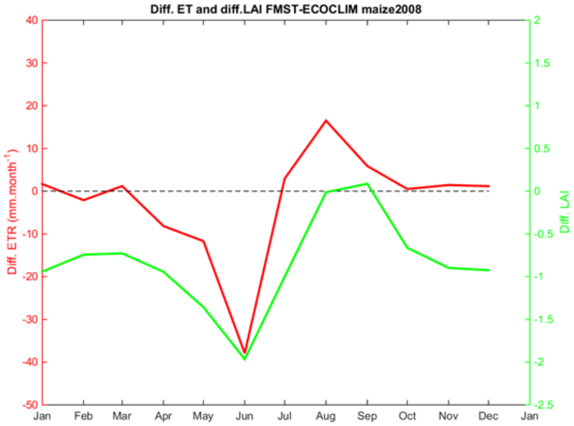
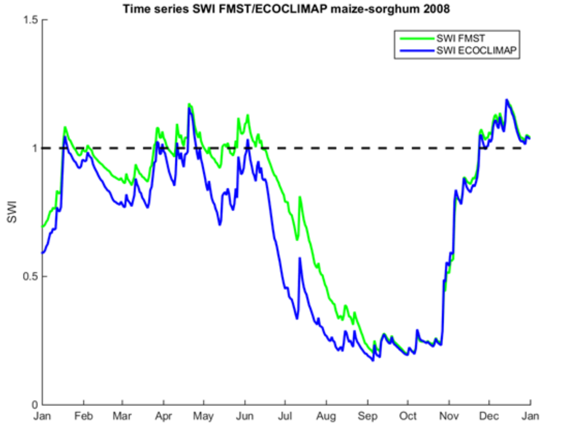


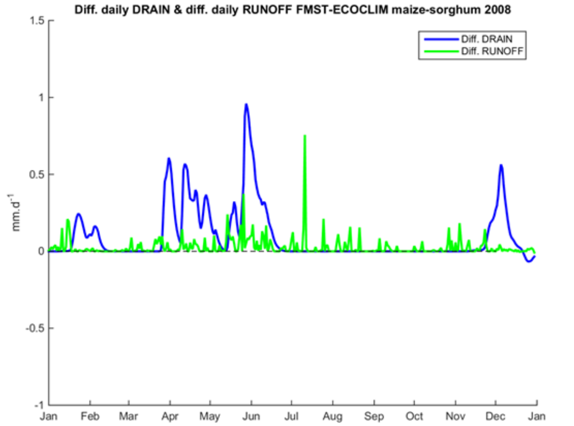
Figure 7: Correlations between the evapotranspiration time series of the two experiments on: (a) uncultivated plots; (b) wheat crops; (c) C4 crops (maize and sorghum); and (d) sunflower and soy crops. The boxplots show the medians in red. Edges of each box represent quartiles whereas whiskers represent extreme values not considered as outliers (red dots for the outliers).


Diff. ET and diff.LAI FMST-ECOCLIM maize2008
Diff. ETR (mm.month-1)
Diff. LAI
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

(a)


Time series SWI FMST/ECOCLIMAP maize-sorghum 2008
SWI FMST
SWI ECOCLIMAP
SWI
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

(b)


Diff. daily DRAIN & diff. daily RUNOFF FMST-ECOCLIM maize-sorghum 2008
Diff. DRAIN
Diff. RUNOFF
mm.d-1
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

(c)

Figure 8: (a) Differences in LAI (green) and evapotranspiration (red) between the two experiments (FORMOSAT-ECOCLIMAP) ; (b) Time series of Soil Water Index; (c) Differences in drainage (blue) and runoff (green) values; Averaged across C4 crops for 2008

Formosat-2 cover map class	SURFEX class
16. Bare soil	1. Bare soil
4. Urban area 33. Gravel pit 41. Dense buildings 42. Diffuse buildings 43. Industrial buildings 44. Urban mineral surface	2. Rocks
-	3. Permanent snow and ice
231. Mixed broadleaf forest 2311. Poplar 2312. Eucalyptus	4. Deciduous forest
-	5. Evergreen forest
232. Mixed coniferous forest	6. Coniferous forest
15. Dual crops 121. Wheat 122. Barley 123. Rapeseed 132. Sunflower 134. Soya 135. Hemp 141. Protein plants 142. Spring barley 1321. Late sunflower 1411. Pea	7. C3 crops
131. Maize 133. Sorghum 1311. Non-irrigated maize 1312. Silage maize	8. C4 crops
-	9. Irrigated crops
22. & 112. Fallow 111. Meadow 1111. Temporary meadow 1112. Permanent meadow	10. C3 herbaceous plants
-	11. C4 herbaceous plants
31. River 32. Lake	12. Wetland

Table 1: Aggregation rules of Formosat-2 cover maps by SURFEX vegetation type

Year	Crop type	R^2 ECOCLIMAP	R^2 FORMOSAT	RMSE ECOCLIMAP	RMSE FORMOSAT
2006	Wheat	0,90	0,94 =	8.07	6.86 =
2007	Sunflower	0,66	0,89 +++	20.9	12.1+++
2008	Wheat	0,79	0,89 +	31.1	19.4 +++
2009	Rapeseed	0,97	0,96 =	6.71	7.66 =
2010	Wheat	0,91	0,99 +	19.4	18.7=

Table 2: Correlation coefficient and Root-Mean Square Error of evapotranspiration for the Auradé site

Year	Crop type	R^2 ECOCLIMAP	R^2 FORMOSAT	RMSE ECOCLIMAP	RMSE FORMOSAT
2006	Maize	0,15	0,65 +++	34.4	23.5 +++
2007	Wheat	0,76	0,95 ++	21.9	14.6 ++
2008	Maize	0,0.58	0,82 +++	21.5	12.4+++
2009	Wheat	0,94	0,95 =	18.7	12.6 ++
2010	Maize	0,46	0,62 ++	27.2	22.8 ++

Table 3: Correlation coefficient and Root-Mean Square Error of evapotranspiration for the Lamasquère site

Vegetation type	2006	2007	2008	2009	2010	Interannual mean
Outside the crops	+15 (+2.9%)	+16 (+2.3%)	+41 (+5.3%)	+20 (+3.1%)	+30 (+4.7%)	+24 (+3.7%)
Wheat	-3 (-0.6%)	-1 (-0.2%)	+61 (+8.0%)	+15 (+2.3%)	+20 (+3.1%)	+18 (+2.8%)
Sunflower/soya	+5 (+0.9%)	+54 (+7.9%)	+47 (+6.1%)	+30 (+4.7%)	+48 (+7.5%)	+37 (+5.7%)
Maize/sorghum	+4 (+0.7%)	+35 (+5.2%)	+35 (+4.6%)	+18 (+2.8%)	+32 (+5.0%)	+25 (+3.8%)

Table 4: Differences between FORMOSAT and ECOCLIMAP experiments on the annual drainage level in $mm.yr^{-1}$ and the corresponding fraction of annual precipitations in % (FORMOSAT-ECOCLIMAP).

Vegetation type	2006	2007	2008	2009	2010	Interannual mean
Outside the crops	+3 (+0.6%)	+4 (+0.6%)	+7 (+0.9%)	+4 (+0.6%)	+4 (+0.7%)	**+4 (+0.6%)**
Wheat	+1 (+0.2%)	+5 (+0.7%)	+17 (+2.3%)	+7 (+1.1%)	+4 (+0.6%)	**+7 (+1%)**
Sunflower/soya	+7 (+1.4%)	+13 (+1.9%)	+10 (+1.4%)	+11 (+1.7%)	+13 (+2.0%)	**+11 (+1.7%)**
Maize/sorghum	+6 (+1.1%)	+9 (+1.3%)	+10 (+1.3%)	+9 (+1.4%)	+9 (+1.4%)	**+9 (+1.3%)**

Table 5: Differences between FORMOSAT and ECOCLIMAP experiments on annual runoff in mm.yr^{-1} and the corresponding fraction of annual precipitations in % (FORMOSAT-ECOCLIMAP).