Anonymous Referee #1

We first thank the reviewer for his very insightful comments, which helped us a lot to clarify and improve the paper.

General comments:

This paper compares two versions of the ORCHIDEE land surface model over the Amazon basin, focusing on the hydrological and to phenological impacts. These two versions do not differs only by the use of two different soil hydrology, as the title would have us believe, but also in the parameterization of the river routing module (page 83, line 25-27). It is therefore difficult to clearly attribute the very very slight difference between the two versions only to soil module. In addition, this paper is very long and very descriptive. This article would be clearer if the sections 3 and 4 were reduced or if only the ORCHIDEE 11LAY was used. Finally, I regret that there is no direct comparison with time-series of observed discharge. Principally for all these reasons, I propose that this article should be in major review.

Major comments:
As already mentioned, the two versions of ORCHIDEE do not differs only by the use of two different soil hydrology, but also in the parameterization of the river routing module. It is very surprising that the river routing module depends on the soil hydrology and then requires a specific tuning for the both versions. Why that ? Is it physical ? I don't think, these two module should be independents. Please clarify this fact and use the same river routing module (and the same tuning) to compare your simulation. If not, then you can change the title and the history of your paper because to focus only on soil module difference will not be justify, especially for seasonal TWS results.

There has been a misunderstanding about the parameterization of the river routing module. Both soil models are coupled with the same river routing module, with the exact same parameters. The focus of the paper, which is to compare results from the two hydrological schemes, is thus justified. Yet, because of this misunderstanding, and to answer questions from Reviewer 2, we completely rewrote Section 2.4 "River routing module". The main point is that : "*In the present study, however, to restrict the difference sources to the soil hydrology schemes alone, we used the same set of time constants with both the 2LAY and 11LAY: g = 0.24, 3.0, 25 d/m, as defined by Ngo-Duc et al. (2007).*"

This remark also leads me to wonder if this comparison between two soil modules in ORCHIDEE is not vein. It is now well know that multi-layer schemes are superior to old bucket schemes.

Despite many advantages of multilayer schemes to implement processes that depend on soil properties or soil moisture profiles (soil infiltration and surface runoff generation, root water uptake for transpiration, water table coupling, surface soil moisture assimilation), there have been very little studies on the practical difference between conceptual bucket-type models and multilayer models, when looking at the simulated water fluxes involved in the terrestrial water budget. This is the starting point of our work, and it has been made clearer in the Introduction:

"*There have been very few studies, however, to quantify the differences between conceptual bucket-type models and multilayer models, for simulated water fluxes involved in the terrestrial water budget. Confrontations to local-scale measurements have shown improved soil moisture control on ET in multilayer schemes in different domains (Mahfouf et al., 1996; De Rosnay et al., 2002; Decharme et*

al., 2011), including in the Amazon basin (Baker et al., 2008). Hagemann and Stacke (sub) also analyzed the influence of soil moisture vertical discretization on soil moisture memory and land-atmosphere coupling in the ECHAM6/JSBACH climate model. Finally, in a study coupling the ORCHIDEE (ORganizing Carbon and Hydrology in Dynamic EcosystEms, Krinner et al., 2005) LSM to the IPSL (Institut Pierre Simon Laplace) climate model, Cheruy et al. (2013) showed that the multilayer version of ORCHIDEE increased ET over Europe, in better agreement with local observations, and thus alleviated the summer warm bias of many climate models in the mid-latitudes (Boberg and Christensen, 2012; Mueller and Seneviratne, 2014).”

In addition, because this paper is very long and generally very descriptive, it looks more like a report than a scientific article with a clear message. This report is certainly very interesting for your colleagues in your laboratory, but is it the case for the entire community ? Perhaps your work would benefit to focus only on the ORCHIDEE 11LAY. This would be an effective way to shorten this work. Whatever your choice, this article would be clearer if the sections 3 and 4 were reduced.

Given the agreement between the two reviewers about the paper's length, we worked a lot to reduce it. We kept the same focus of the paper ie the comparison of 2LAY/11LAY, but we reduced the length in many places, and more particularly in the sections dealing with description of the results. The corrections are highlighted in the revised manuscript. We put also 4 tables (included a new one called Table 3) and 2 figures in the Supplementary Material section.

Another major comment is that there is no comparison between observed and simulated river discharges while daily observations exist over this basin in the HYBAM database (Guimberteau et al. 2012). For me, annual comparison is not sufficient and some skill scores, like nash criterion and/or deseasonalized root mean square error, should be used as in Guimberteau et al. (2012).

Comparison between observed and simulated river discharges already exists in the paper with the Figure 7. The time step used here is monthly. Daily outputs have not been written during the simulation process. But you are right, an objective comparison is missing. Thus, we added skill scores in the Table 3 in the Supplementary Material section.

<u>Minor comments</u>:
Page 76, Line 16-17: **Are you sure that TWS plays an important role in regulating the global climate ? TWS is it more or equally important than the ocean? Me, I am not sure. This sentence is not adequate. TWS plays a non negligible role in modulating (and not in regulating) the climate in some regions but certainly not the global climate.**

You are right, this sentence is not adequate. We removed this sentence.

Page 77, Lines 23-25: **The paper of De Rosnay et al. (2002) can be applied to ORCHIDEE, but is it universal ? Please add more references to this affirmation or delete it.**

We believe that the results obtained in one LSM can be generalized, at least partially, to other LSMs, if the methods are clear, and this is the main justification of our paper. Yet, generalization is stronger if similar studies conducted with other LSMs give similar results. To this end, we added more references dealing with comparison between multilayer schemes and old bucket schemes in the Introduction:

“As reviewed by Pitman (2003), soil hydrology parameterizations have evolved from conceptual

bucket-type models, with one or two layers, with soil moisture described in terms of available moisture between the wilting-point and the field capacity, to physically-based models solving the Richards equation for water flow in unsaturated soil, and relying on volumetric water content up to full saturation (Abramopoulos et al., 1988; Thompson and Pollard, 1995; Viterbo and Beljaars, 1995; Chen et al., 1997; Cox et al., 1999; Boone et al., 2000; De Rosnay et al., 2000; Dai et al., 2003; Decharme et al., 2011). The latter approach offers many advantages, (i) to better account for spatial variability of soil properties (Gutmann and Small, 2005; Guillod et al., 2013), (ii) to implement processes that control soil moisture profiles, such as soil water infiltration and surface runoff generation (D'Orgeval et al., 2008), root water uptake for transpiration (Feddes et al., 2001), or hydraulic coupling to a water table (Liang et al., 2003; Gulden et al., 2007; Campoy et al., 2013), and (iii) to be comparable to available satellite observations of soil moisture in the top zone (Reichle and Koster, 2005; Draper et al., 2011; De Rosnay et al., 2013). There have been very few studies, however, to quantify the differences between conceptual bucket-type models and multilayer models, for simulated water fluxes involved in the terrestrial water budget. Confrontations to local-scale measurements have shown improved soil moisture control on ET in multilayer schemes in different domains (Mahfouf et al., 1996; De Rosnay et al., 2002; Decharme et al., 2011), including in the Amazon basin (Baker et al., 2008). Hagemann and Stacke (sub) also analyzed the influence of soil moisture vertical discretization on soil moisture memory and land-atmosphere coupling in the ECHAM6/JSBACH climate model. Finally, in a study coupling the ORCHIDEE (ORganizing Carbon and Hydrology in Dynamic EcosystEms, Krinner et al., 2005) LSM to the IPSL (Institut Pierre Simon Laplace) climate model, Cheruy et al. (2013) showed that the multilayer version of ORCHIDEE increased ET over Europe, in better agreement with local observations, and thus alleviated the summer warm bias of many climate models in the mid-latitudes (Boberg and Christensen, 2012; Mueller and Seneviratne, 2014)."

Page 77-78, Lines 28-1: **According to previous remarks, this question is not addressed in this paper because the routing module is not the same according to soil module. So improve your article or delete this sentence.**

We kept this sentence because we do use the exact same routing module, with the exact same parameters, for the two soil hydrology schemes, as explained above.

Page 81, Line 26: **The fact that ORCHIDEE uses only a soil depth of 2m appears not realistic. Observations of root depth over tropical forest shows that this depth is much close to 6-8m (Canadell et al., 1996: Maximum rooting depth of vegetation types at the global scale, Oecologia, 108, 583-595). Please discuss about that in your paper. If you choose to rewrite this article in focusing only on ORCHIDEE 11 LAY, it should be interesting to test one version of your model with such soil depth. If not, please discuss about that in your paper even if it is difficult to justify that roots of tropical forest stop to only 2m depth.**

You are right, several field studies have shown that roots are occurring much deeper than 2 meters. (8, 10, 12 meters depending on the location). Canadell et al. (1996) suggested an average rooting depth of 7.3 m, based on 5 measurements with a maximum of 18 m. Moreover, several modeling studies showed that a deep soil (and deep roots) is needed in models in order to represent realistic ET and GPP during the dry season (e.g. Baker et al. 2008, Verbeeck et al. 2011). This kind of discussion already existed in the conclusion of our study (lines 2-8 page 103). We agree that taking only 2 meters for soil depth for the entire basin is not realistic. On the other hand, taking a deeper soil (eg 8 meters) for the entire amazon is not realistic as well. In the south west of the basin, in the Jarú fluxtower site, there is a much shallower soil and roots only up to 3.5 meters. Rooting depth changes spatially. The problem is that we

do not have good spatial information on soil depth over the whole Amazon basin.

We have tested the impact of different soil depths in ORCHIDEE. We attached to this report the spatial results of ET simulated in JJA, for a 2-m soil depth (upper left) and a 8-m soil depth (upper right). Differences between both are also illustrated by the two maps on the bottom. ET variation is negligible when soil depth is prescribed to 8 meters over the Amazon basin. Only small increase (+0.4mm/d) occurs in some small regions in the south. We changed the text in the conclusion to introduce more discussion dealing with soil depth uncertainties:

"*More attention should be also paid to the soil depth, which was fixed to 2 meters for the entire basin in both soil hydrology schemes, given the lack of geospatial information across the entire basin. Several field studies showed that roots can be present much deeper than 2 meters. For tropical evergreen forest, Canadell et al. (1996) estimated an average rooting depth of 7.3 m, and a maximum of 18 m, based on data from 5 sites. Deep roots observed by Nepstad et al. (1994) in northeastern Pará enable evergreen forests to maintain dry-season ET (Verbeeck et al., 2011) which feeds back on climate (Kleidon and Heimann, 2000). Several modeling studies concluded that deep soils and deep roots are needed in models, in order to represent realistic ET and GPP in Amazon forests during the dry season (e.g. Baker et al., 2008; Verbeeck et al., 2011). With the 2LAY, Verbeeck et al. (2011) showed that the soil depth had a significant effect on the seasonal cycle of water fluxes. We tested a soil depth of 8 meters in the 11LAY but found only a negligible effect owing to high soil water holding capacity in the 11LAY.*"

Table 6: **a Taylor diagram could be used instead of this table.**

Table 6 is put now in the Supplementary Material section (called Table 4) in order to reduce the length of the paper.

Anonymous Referee #2

We first thank the reviewer for his encouraging and very insightful comments, which helped us a lot to make the paper more straightforward, and of broader interest for the LSM community.

- <u>**GENERAL COMMENT**</u>

This paper evaluates the performance of two soil model formulations into a Land-Surface/Plant Phenology/River routing model of the Amazon (ORCHIDEE model). The soil models consist of a 2 layer bucket model and an 11 layer diffusive model. Model results are compared to estimates of terrestrial water storage (TWS) from GRACE mission, discharge (Q) from in situ data, evapotranspiration (ET) from a global scale dataset and leaf area index (LAI) and vegetation gross primary production (GPP). According to the authors, results from both soil models are similar. However, the 11 layer model could better represent ET, GPP, LAI, TWS and Q in southeastern sub-basins during dry season. Consequently, using the 11 layer soil model should be important to better represent hydrological processes in the drier sub-basins of the amazon, especially during dry seasons. The paper works on an important scientific question: how important is the use of multi-layer soil models if compared to simple bucket models to better represent hydrological storages and fluxes? It is always important to know how complex earth system models should be to represent important physical processes. This question is especially important for the case of the Amazon basin, where a wide range of hydrology models have been applied in the past. That's why the paper has great potential. However, some issues still need to be carefully addressed before publication. The first issue is that the 2 soil models don't seem fully comparable. It is not clear if their differences are mostly the number of layers or the several other hidden assumptions (Horton vs Dunne surface runoff, criteria for water percolation, parameters, etc...). These differences should be clearer to make it easier to extrapolate results from this paper to research outside ORCHIDEE context. Second, some of the validation datasets, as ET, are somehow uncertain. It would be necessary a better justification for the validation data. Third, the paper seems too long and descriptive, what makes it hard to read and less objective/conclusive. I present comments on these and some other issues bellow. For these reasons, I think that the paper should be published after major reviews. I hope that these comments can be useful to improve this paper/research.

- <u>**MAJOR COMMENTS**</u>

- <u>**Introduction/objectives:**</u>
The main question that the paper address is: "Does the use of an 11 layer soil diffusion scheme, rather than a simpler 2 layer scheme, improve the simulation of water storage dynamics and water fluxes?" I'd like to suggest some modifications to this question. It would be easier to extrapolate the conclusions to other research outside ORCHIDEE context if the paper compares "multi-layer soil diffusion schemes" vs "simple bucket schemes". I also think that it would be important to better clarify to which extent this question was already answered by previous research. Paragraph from lines 9 to 26 show several arguments showing the importance of accurate/multilayer soil modeling. It may be important for some things but not for others. For example, is it important for simulation ET and sensible heat fluxes? Is it important for land-atmosphere feedbacks? Discharge simulation? CO2? Total soil storage?... Which of these questions were already answered? Please make it clearer. On the other hand, you could clarify if your goal is to understand the importance of soil modeling at the Amazon basin.

You are right, thank you for these constructive remarks. We largely rewrote the introduction and added much more references to show the importance of accurate multilayer soil modeling:

"As reviewed by Pitman (2003), soil hydrology parameterizations have evolved from conceptual bucket-type models, with one or two layers, with soil moisture described in terms of available moisture between the wilting-point and the field capacity, to physically-based models solving the Richards equation for water flow in unsaturated soil, and relying on volumetric water content up to full saturation (Abramopoulos et al., 1988; Thompson and Pollard, 1995; Viterbo and Beljaars, 1995; Chen et al., 1997; Cox et al., 1999; Boone et al., 2000; De Rosnay et al., 2000; Dai et al., 2003; Decharme et al., 2011). The latter approach offers many advantages, (i) to better account for spatial variability of soil properties (Gutmann and Small, 2005; Guillod et al., 2013), (ii) to implement processes that control soil moisture profiles, such as soil water infiltration and surface runoff generation (D'Orgeval et al., 2008), root water uptake for transpiration (Feddes et al., 2001), or hydraulic coupling to a water table (Liang et al., 2003; Gulden et al., 2007; Campoy et al., 2013), and (iii) to be comparable to available satellite observations of soil moisture in the top zone (Reichle and Koster, 2005; Draper et al., 2011; De Rosnay et al., 2013). There have been very few studies, however, to quantify the differences between conceptual bucket-type models and multilayer models, for simulated water fluxes involved in the terrestrial water budget. Confrontations to local-scale measurements have shown improved soil moisture control on ET in multilayer schemes in different domains (Mahfouf et al., 1996; De Rosnay et al., 2002; Decharme et al., 2011), including in the Amazon basin (Baker et al., 2008). Hagemann and Stacke (sub) also analyzed the influence of soil moisture vertical discretization on soil moisture memory and land-atmosphere coupling in the ECHAM6/JSBACH climate model. Finally, in a study coupling the ORCHIDEE (ORganizing Carbon and Hydrology in Dynamic EcosystEms, Krinner et al., 2005) LSM to the IPSL (Institut Pierre Simon Laplace) climate model, Cheruy et al. (2013) showed that the multilayer version of ORCHIDEE increased ET over Europe, in better agreement with local observations, and thus alleviated the summer warm bias of many climate models in the mid-latitudes (Boberg and Christensen, 2012; Mueller and Seneviratne, 2014)."

Do you think that your conclusions should be extrapolated to other regions? If yes, you should clarify that the Amazon is only a case study. If not, clarify that the Amazon is the object of your study.

Our work is the very first study of comparison of the two hydrological models in ORCHIDEE. But a very recent study by Traoré et al. (under review in JGR-biogeosciences) also found over Africa that 11-layer version of the model outperforms the 2-layer version for simulating inter-annual variability of ET and soil moisture (see the following figure for ET comparison). Thus, our conclusions can be extrapolated to other regions. We have already specified it in conclusion (lines 20-23 page 102) that our study is currently extrapolated to the global scale and that we expected a signal in transition zones.
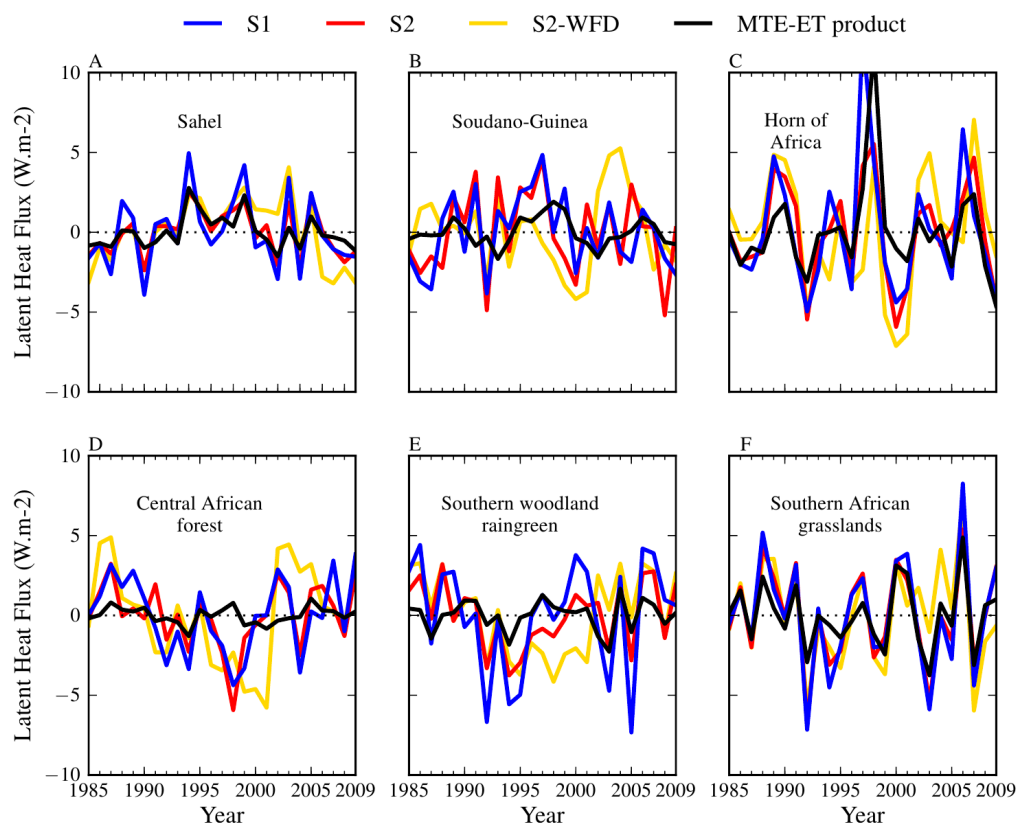
Figure 4: Comparison between interannual anomalies of ORCHIDEE evapotranspiration and MTE-ET product from fluxnet data product.

S1 corresponds to simulation with 11LAY, S2 with 2LAY and MTE-ET to the same ET product that we used for our paper (Jung et al. 2011).

- **Model description:**
I missed a more clear description about the differences between the two soil formulations. It was difficult to understand all about the model functioning by this explanation. It seems that the use of multi-layer diffusive model vs a 2 layer bucket model is not the only difference. Other differences include: 1. Dunne (2LAY) vs Horton surface runoff (11LAY). 2. Predefined runoff portioning of 5% to surface runoff and 95% to deep drainage (2LAY) vs surface runoff given by infiltration model and deep drainage given by free gravitational drainage model (11LAY) 3. Different parameters. 4. Among others... How can we know if the differences in the results are due to using 11 vs 2 soil layers or due to different parameters? Or due to different criteria for surface and deep drainage runoff? If the differences are not clear, and especially if different parameters are used, then the results get non conclusive. Some other issues: Are the parameters of both models equivalent? How the choice of the parameters could change your conclusions? Why portioning surface and deep drainage runoff into 5% and 95%?

You are perfectly right and your questions helped us a lot to achieve a useful synthesis of the differences and resemblances between the two tested soil hydrology schemes. To this end, we largely rewrote Section 2 "Model description":
- inclusion of a new Table (called Table 1) comparing the main features of the two soil hydrology schemes, cited in introduction of Section 2.2 "Soil hydrology modeling in SECHIBA", now renumbered 2.3
- thorough rewriting of the two subsections devoted to the description of 2LAY and 11LAY

- inclusion of a final subsection 2.5 "Synthetic comparison of the two soil hydrology schemes", discussing the relationships between (i) the soil hydrology schemes and their parameters, which are intimately linked, and (ii) the soil hydrology and routing schemes, especially in the case of the 2LAY, which calls for an arbitrary partitioning of total runoff into the input flows of the fast and slow routing reservoirs (also stated in the section describing the routing module). We specifically mention, at the end of subsection 2.5, that this choice "*has an impact on the relative contribution of these fast and slow reservoirs to TWS*", and this point will be further discussed in the conclusion. This is a paragraph added in section 2.5 in relation to this point:

  "*In the present case, additional differences between the simulations arise from the way total runoff is transferred to the fast and slow reservoirs of the routing scheme, supposed to receive surface runoff and drainage, respectively. The 11LAY makes a clear physical distinction between these two fluxes, contrarily to the 2LAY, which only creates total runoff when the soil reservoir is full, with no clear surface or bottom localization, as in the bucket scheme of Manabe (1969). In this case, the routing scheme has always been used with a 5-95% redistribution of total runoff to the fast and slow routing reservoirs. In this paper, we follow this choice, steming from Ngo-Duc et al. (2007), which has an impact on the relative contribution of these fast and slow reservoirs to TWS (as analyzed in Sect. 4.2).*"

You use free gravity criteria for bottom boundary conditions for the 11 LAY. Is it really how it should work in the amazon?? I guess that in some regions, vegetation may access water from shallow aquifers.

You are right, using a free gravity drainage could be a limitation to simulate hydrology over the Amazon basin, in particular in northwestern Amazonia and floodplains elsewhere. By contrast, in southeastern Amazonia, where we find the largest effect between the two soil hydrology schemes, there are deep aquifers, and free drainage seems appropriate. Campoy et al. (2013) introduced a new boundary conditions in the 11LAY of ORCHIDEE, namely impermeable bottom, and negative drainage at the soil bottom to sustain a fixed water table inside the soil column. None of these configurations was not tested in our study over the Amazon basin. Note that this question of shallow water tables sustaining ET is tightly connected to the one of soil depth, raised by reviewer 1.

- **Routing model:**
The routing model explanation needs some clarification. For example, why using manning concept to deep drainage? Manning's equation deal with channel flow and it has no relation to deep drainage flow. What do these velocities mean? Is it related to river-channel flow velocity?

The formulation of the topographic water retention index does indeed stem from an approximation of the Manning formula, proposed by Ducharne et al. (2003) for stream reservoirs only. In this framework, the effect of stream length and slope is explicit, and the one of channel roughness and cross-sectional shape is carried by a constant, called g in the routing scheme described in the present paper. This formulation has been generalized to the fast and slow reservoirs under the assumption that the tuning of the time constant compensates for the fact that the Manning formula is not designed for overland and groundwater flow modeling, and that the various parameters do not have the same values than in streams. For the stream reservoir, the time constant can be related to a stream velocity if the stream slope is known. We give an example in the paper: "*which leads to a stream velocity of around 0.5 m/s assuming a slope of 1%, both values being typical of large rivers.*"

Section 2.4 has been rewritten for the sake of clarity:

"Travel time within the reservoirs depends on a characteristic time scale, which is the product of a topographical water retention index k (in m) and a time constant g (in d.m⁻¹). The latter does not vary horizontally but distinguishes the three reservoirs, while the water retention index k characterizes the impact of topography on travel time in each sub-basin, and is assumed to be the same in the three reservoirs of a given grid cell, eventhough it derives from stream routing principles introduced by Ducharne et al. (2003). This travel time is thus assumed to be proportional to stream length in the sub-basin, and inversely proportional the square root of stream slope. This can be seen as a simplification of the Manning formula (Manning, 1895), where the time constant g compensates for the missing terms. The lengths and slopes are first computed at the 0.5°x0.5° resolution from the topographical map of Vörösmarty et al. (2000), then upscaled at the ORCHIDEE grid cell resolution, of 1°x1° in the present study (Sect. 3.1). The values of the time constants g were initially calibrated over the Senegal basin, using the 2LAY parameterization with the 5/95% partitioning of total runoff towards the fast/slow reservoirs, then generalized for all the basins of the world (Ngo-Duc et al., 2007). The stream reservoir has the lowest constant (0.24 d m⁻¹), which leads to a stream velocity of around 0.5 m.s⁻¹ assuming a slope of 1%, both values being typical of large rivers. The corresponding velocities are lower in the other two reservoirs, with a time constant g of 3.0 and 25 d m⁻¹ in the fast and slow reservoirs respectively. In former studies using the 11LAY, the time constants of these two reservoirs have been set equal to the one of the fast reservoir (g = 3.0 d m⁻¹) to balance a higher water residence time in the soil with the 11LAY (D'Orgeval, 2006; D'Orgeval et al., 2008; Gouttevin et al., 2012; Guimberteau et al., 2012a, 2013). In the present study, however, to restrict the difference sources to the soil hydrology schemes alone, we used the same set of time constants with both the 2LAY and 11LAY: g = 0.24, 3.0, 25 d m⁻¹, as defined by Ngo-Duc et al. (2007)."

Do you apply the same floodplain parameter for all grid cells? As flooding is variable in space and time in the amazon, the velocity constant of the floodplain reservoir should be variable as well. What is the impact of this simplistic assumption on the TWS results?

The residence time for the floodplain reservoir (and also for all the routing reservoir) depends on a time constant which, indeed, is constant in space, but depends also on a topographic water retention index which varies in space (see lines 16 to 21 page 83 and see page 915 in Guimberteau et al. (2012)). Thus, floodplain parameterization of ORCHIDEE enables a spatial variation of the water storage in the Amazon basin.

- **Discharge Validation:**
It would be interesting to provide an objective evaluation of model discharge time series versus observations.

Comparison between observed and simulated river discharges already exists in the paper with the Figure 7. For an objective comparison, we added skill scores in the new Table 3 in the Supplementary Material section.

- **GRACE TWS:**
GRACE Tellus released a new RL05 version. Check it there are important differences between RL04 and RL05 that could change your conclusions.

Thank you for this suggestion. We use now this new version of GRACE in the paper and all our results were updated in the text, figures or tables. The bias of the TWS amplitude between ORCHIDEE and GRACE RL05 becomes slightly higher over the Amazon basin. This is explained by the lower TWS

increase in the Madeira basin, between February and April, in RL05 product compared to RL04. However, comparison of ORCHIDEE results with the new product of GRACE did not change our conclusions which were made with the RL04 products.

- Precipitation (P):
Why didn't you use your improved data set to run the model?

You are right, we could have used HYBAM dataset but we showed that Princeton's dataset corrected by GPCC is not far from HYBAM. This is also found by Getirana et al. (submitted in Journal of Hydrometeorology) who compared several LSMs simulations on the Amazon basin according to three different corrections on Princeton's precipitation dataset: GPCC, GPCP and HYBAM. HYBAM is shown to be the best product to represent water budget over the Amazon but results with GPCC are close to that with HYBAM.

- ET:
Several other ET global datasets are available. For example, Azarderakhsh et al (2013) looked at ET from 3 different datasets over the Amazon and the estimates do not agree between each dataset. So, why did you choose Jung et al. 2010 dataset? Why it is better than the others? Please clarify it in the manuscript.

We are aware that it exists other ET products and that Jung et al. 2010 dataset may not be the best one when compared to the others. But we used Jung et al's dataset for ET because the authors provided also GPP product with the same methodology. Thus, this two products are expected to be consistent with each other. We added in the Figure 7 (now Figure 6), ET results from 3 other products to show the spread existing between the ET estimations.
We also added some modifications in the text:

  – section 3.2.2 "Evapotranspiration (ET) and Gross Primary Productivity (GPP)":

  "Here, Jung et al.'s product is chosen to evaluate ET simulated by ORCHIDEE because it also provides a consistent GPP product. Uncertainties around this ET estimate is assessed by comparison with 3 other products: GLEAM-ET (Miralles et al., 2011), NTSG-ET (Zhang et al., 2010) and PKU-ET (Zeng et al., 2014)."

  – Conclusion:

  "But ET observations uncertainties are of the same magnitude than the misfit between any of the schemes and the observations, so that a particular model scheme cannot be ruled out from these data only."

- Residual water balance:
The residual P-ET-Q over a basin equals the change in total water storage DS, including soil, ground water and rivers and floodplains. It is not clear how using shifted Q (Q*) makes that ground water and surface water storage can be neglected. Please clarify it.

You are right, P-ET-Q represents the change in total water storage DS and not only the change in soil water storage as written in the paper. Thus, we corrected in the text and in the caption of Figure 2.

- **TWS amplitude and phase assessment**:
Do you calculate the amplitude for each year and then average the results?

No, the amplitude is calculated by the mean seasonal cycle of TWS during 2003-2008 (average of monthly value during the six years then calculate amplitude, not calculate amplitude of each year then average).

If you simply use maximum and minimum values from the time series you can be more susceptible to errors due to noise in the data. You could work with percentiles, instead of maximum and minimum values. Or as you are fitting this cosine function, you could be computing the amplitude of TWS from the p coefficients.

I agree the reviewer's suggestion, the amplitude of TWS can be extracted from the p coefficient. In the new version of the manuscript, we updated the results of amplitude from the new definition as 2*p1.

- **Contributions to TWS variation:**
Some recent research (e.g. Paiva et al. 2013) show that most of TWS variability in the amazon is regulated by surface waters. I guess that your results should show more importance in the floodplain reservoir than the slow reservoir that is supposedly related to subsurface/groundwater flow. What is the reason for such difference? Is it because you are using a simplistic model that considers constant floodplain parameter in space?

Paiva et al. (2013) found that 56% of the Amazon TWS changes is governed by surface waters (corresponding to the sum of the stream, the fast and the floodplain reservoirs for ORCHIDEE), 27% by soil water and 8% for ground water (corresponding to the slow reservoir for ORCHIDEE) (we notice that one cannot find what correspond the remaining 9% !)

In our study, with the 11LAY of ORCHIDEE, we have these proportions: 35% by surface waters, 19% by the soil water and 46% by the groundwater. In ORCHIDEE, more importance is attributed to the slow reservoir in term of TWS contribution which is clearly in contradiction with the results of Paiva et al. (2013). However, uncertainties in storage contribution to TWS are large in the literature. Pokhrel et al. (2013) found that subsurface storage (soil water in the vadose zone and groundwater below the water table) contribution (71%) is far greater than surface water contribution (29%) to TWS changes. The large contribution of the groundwater to TWS variation is also found by the groundwater model of Niu et al. (2007).

Difference between our results and Paiva et al. (2013)'s cannot be attributed to the no-variation in space of the water in the floodplain reservoir of ORCHIDEE, as explained above. One of the uncertainties in ORCHIDEE could be the parameterization of the time constant g for the slow reservoir which has been calibrated over the Senegal basin and generalized for all the basins of the world. Re-parameterization of the time constants for the three routing reservoirs are being re-calibrated in ORCHIDEE.

In order to introduce a discussion dealing with surface or subsurface contribution to TWS in the Amazon basin, we modified:

  – Section 4.2.1 "Seasonal variation":

"The annual amplitude in water storage in the slow reservoir, which collects drainage, is lower with the 11LAY (46% of the total annual amplitude of TWS) than with the 2LAY (66%). Sub-surface water

contribution (sum of the fast, slow and soil reservoirs) to TWS variation simulated by the 11LAY (71%) is in agreement with Pokhrel et al. (2013)'s estimations (71%) over the Amazon basin. The physical distinction between surface runoff and drainage with the 11LAY leads to a lower drainage contribution to the total runoff over the Amazon basin (~ 69%), which is more realistic when compared to the estimations of Mortatti et al. (1997) (68.1%), than with the 2LAY (95%) (see Table 3 in Supplementary Material)."

  – Conclusion:

"By comparing the bucket model, the first property of the 11LAY leads to less drainage, which contribution to the total runoff over the Amazon basin is more realistic (69%) than the 2LAY (95%), when compared to the estimates of Mortatti et al. (1997) (68.1%). Less water is stored in the slow reservoir of the routing scheme (which represents a groundwater reservoir) with the 11LAY. We found the same contribution of subsurface water (including groundwater) to TWS over the Amazon basin (71%) than Pokhrel et al. (2013), and this result is also in line with Niu et al. (2007). However, the attribution of TWS to sub-surface versus surface water remains uncertain since other studies (Paiva et al., 2013) suggested that most of the TWS variability was regulated by surface waters."

- ET results:
I'm not sure how accurate the global ET estimates are and to which extent should we trust it. You should really compare it with other datasets. Also, if the data uncertainty is large, it is difficult to argue that 11LAY is better that 2LAY based on such small difference between model results if compared to differences to observed data and uncertainty from ET observations. Also, the vegetation model could not capture GPP and LAI dynamics. So, if the vegetation model is wrong, how can one clearly differentiate between the two soil formulations?

As said above, we added in the Figure 7 (now Figure 6), ET results from 3 other products to show the spread existing between the ET estimations.

- Conclusions:
Lines 4 to 6: This conclusion about differences in 11LAY and 2LAY is may be more related to the assumption of the 2LAY of portioning runoff as 5% surface runoff and 95% for deep drainage. This may be the cause of more water storage in the slow routing reservoir for the 2LAY. Consequently, it is difficult to say if the differences between the models are due to using 11 or 2 layers or due to all the others hidden assumptions of these models. This fact makes the study non conclusive.

In the subsection 2.5 "Synthetic comparison of the two soil hydrology schemes", we discussed the relationships between the soil hydrology and routing schemes, especially in the case of the 2LAY, which calls for an arbitrary partitioning of total runoff into the input flows of the fast and slow routing reservoirs (also stated in the section describing the routing module). In conclusion, we clearly distinguishes now the two properties of the soil models that give differences between the 2LAY and the 11LAY:

"The better simulation of the water budget and TWS with the 11LAY, in most of the sub-basins of the Amazon, owes to the combination of two of its properties: (i) the physical distinction between surface runoff and drainage and (ii) the physically-based description of soil water storage.
        By comparing the bucket model, the first property of the 11LAY leads to less drainage, which contribution to the total runoff over the Amazon basin is more realistic (69%) than the 2LAY (95%),

when compared to the estimates of Mortatti et al. (1997) (68.1%). Less water is stored in the slow reservoir of the routing scheme (which represents a groundwater reservoir) with the 11LAY. We found the same contribution of subsurface water (including groundwater) to TWS over the Amazon basin (71%) than Pokhrel et al. (2013), and this result is also in line with Niu et al. (2007). However, the attribution of TWS to sub-surface versus surface water remains uncertain since other studies (Paiva et al., 2013) suggested that most of the TWS variability was regulated by surface waters.

The second property of the 11LAY enables a higher water holding capacity by soils, resulting into a higher soil moisture level than in the 2LAY. Lower drought stress in the 11LAY scheme sustains ET, which suggests that soil moisture parameterizations are critical in LSMs over the southern part of the Amazon that has strong seasonality in precipitation and marked transition periods between wet and dry soils. Our analysis is being extended to the global scale with the objective of identifying whether differences in water budget components can be found in the transition zones identified by Koster et al. (2004a), where soil moisture is expected to influence precipitation."

- **MINOR COMMENTS:**
Section 2.1. **What is the spatial resolution of the model?**

ORCHIDEE can take different spatial resolution given the resolution of the forcing. The model takes the same spatial resolution than that of the forcing. Thus, in our study, it is 1°x1°.

Pg. 76. Line 15 The role of floodplains on the delay and attenuation of floodplains can be clearly seen in Paiva et al. [2013].

Thank you. The reference is added in the introduction:

"The seasonality of Q is further modulated by floodplains (Paiva et al., 2013)"

Pg. 77. Line 9 - 15 According to Costa et al., 2010, ET in the Amazon is driven mostly by radiation and not by soil water availability.

Indeed, Costa et al. (2010) found that ET is driven mostly by radiation in the Amazon. However, this was found only in wet equatorial sites. Costa et al's results were different in the seasonally dry southern tropical forests where ET seasonality is controlled with the surface conductance and thus with the water availability (response of the plants to water stress). We modified in the introduction:

" In the Amazon basin, a particularly important land-atmosphere feedback is precipitation recycling (Shuttleworth, 1988; Marengo, 2006), which is affected by soil moisture in the southern parts of the basin, as they experience a marked dry season, during which soil moisture availability limits ET. "

Table 5. Present the observed amplitude and error as %. Use % along the text as well.

Corrected in the text.

Figures. All the figures showing spatial results should be reviewed (4 and 6). The amazon basin domain seems to be cut close to the boundaries. For example, the northern part of Negro river basin is not shown in the figures. Is this affecting results from tables 4 and 6, for example?

We modified the Figure 4 (now Figure 1 in Supplementary Material) and Figure 6 (now Figure 5). The spatial results are now shown over all the northern South America and the Amazon basin boundaries

were added. The results are given on average over this Amazon domain. However, little difference of the domain cut with reality does not significantly affect the results.

Figure 4. It seems that large amplitude errors are concentrated along the Amazon floodplains (floodplains at Solimoes /Amazon river, Madeira River and Bolivia). These errors are compensated in other regions. Maybe it is caused by model limitations in representing floodplain storage. For example, a previous section says that the model uses a constant (in space and time) floodplain related parameter. Such assumption may be causing these large errors.

As we explained above, floodplain parameterization of ORCHIDEE enables a spatial variation of the water storage in the Amazon basin. The underestimation of the the maximal fraction of flooded areas (MFF), and thus the overestimation of the water level amplitude in the floodplain reservoir, could explain the large amplitude errors concentrated along the Amazon floodplains that we obtained in this study. This has been previously found with ORCHIDEE by Guimberteau et al. (2012). Over the main stem of the Amazon, they have shown an overestimation in water height level, even after the calibration of the time constant of the floodplain reservoir (simulation ORCH4, page 931). They attributed this error to an underestimation of the MFF used in ORCHIDEE, when compared to Hess et al. (2003), even after using a better map of MFF.

Figure 3. Please provide a figure with higher resolution.

We will contact the team from the production office of GMD journal to improve the resolution of the Figure 3.

~~Two soil hydrology formulations of ORCHIDEE (version Trunk.rev1311) tested for the Amazon basin~~Testing a conceptual and a physically-based multilayer soil hydrology schemes against observations for the Amazon basin, within the ORCHIDEE LSM (version Trunk.rev1311)

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Abstract

This study analyzes the impact of the two soil ~~model~~hydrology schemes ~~parameterizations~~ of the Land Surface Model ORCHIDEE on their estimates of Amazonian hydrology and phenology for five major sub-basins (Xingu, Tapajós, Madeira, Solimões and Negro), during the 29-year period 1980-2008. The two soil ~~models~~hydrology schemes are a simple 2-layer ~~soil~~ scheme with a bucket topped by an evaporative layer versus an 11-layer ~~soil~~ diffusion scheme. The soil ~~models~~schemes ~~were~~are coupled with a river routing module and a process model of plant physiology, phenology and carbon dynamics. The simulated water budget and vegetation functioning components ~~were~~are compared with several datasets at sub-basin scale. The use of the 11-layer soil diffusion scheme ~~did~~does not significantly change the Amazonian water budget simulation when compared to the 2-layer soil scheme (+3.1 and -3.0% in evapotranspiration and river discharge, respectively). However, the higher water holding capacity of the soil and the physically based representation of runoff and drainage in the 11-layer soil diffusion scheme~~,~~ result~~ed~~ in higher dynamics of soil water storage variation and improved simulation of the total terrestrial water storage when compared to GRACE satellite estimates. The greater soil water storage within the 11-layer soil diffusion scheme also results~~ed~~ in increased dry-season evapotranspiration ($+0.5\,\mathrm{mm\,d^{-1}}$, +17%) and improves river discharge simulation in the southeastern sub-basins such as the Xingu. Evapotranspiration over this sub-basin ~~was~~is sustained during the whole dry season with the 11-layer soil diffusion ~~model~~scheme, whereas the 2-layer soil scheme limits~~ed~~ it ~~at the end of the dry season~~after two dry months only. Lower plant ~~water~~ drought stress simulated by the 11-layer soil diffusion scheme~~,~~ leads to better simulation of the seasonal cycle of photosynthesis (GPP) when compared to a GPP data-driven model based upon eddy-covariance and satellite greenness measurements. ~~Simulated LAI was consequently higher with the 11LAY (up to +0.4) but exhibited too low a variation when compared to a satellite-based dataset. The~~A dry-season length between 4 and 7 months over the entire Amazon basin ~~was~~is found to be critical in distinguishing

differences in hydrological feedbacks between the soil and the vegetation cover simulated by the two soil ~~models~~schemes. Overall, the ~~11-~~multilayer soil diffusion scheme ~~provided~~ds little improvement in simulated hydrology on average over the wet tropical Amazonian sub-basins but a more significant improvement over the drier sub-basins. ~~However, t~~The use of ~~the 11-layer~~a multilayer soil diffusion scheme might become critical for assessments of future hydrological changes, especially in southern regions of the Amazon basin where longer dry season and more severe droughts are expected in the next century.

1 Introduction

~~Not only is the hydrological functioning of the Amazon basin complex but the river also~~The Amazon basin plays an important role within the global water cycle. Among other factors, it is responsible for 15%-20% ~~makes a large contribution to the volume of fresh~~ of the water discharged into the oceans ~~(15%-20% of the total volume,~~ (Molinier and Guyot, 1996)~~)~~. ~~The Amazon basin has therefore been the subject of many hydrological modeling studies~~The complex hydrological functioning of the basin makes it an interesting and key subject for modeling studies (e.g. Coe et al., 2007; Decharme et al., 2008; Beighley et al., 2009; Trigg et al., 2009; Fan and Miguez-Macho, 2010; Paiva et al., 2011; Guimberteau et al., 2012a; Paiva et al., 2012; Yamazaki et al., 2012). The large area of the basin (about 6 million km²) encompasses a large range of precipitation (P) regimes with different seasonalities ~~and~~that partly modulate river discharge (Q) in each sub-basin.~~, t~~The seasonality of ~~which~~Q is further modulated by floodplains (Paiva et al., 2013). Its wide extent makes of the Amazon basin a key basin to benefit from the Gravity Recovery And Climate Experiment (GRACE) satellite mission. The GRACE data have proven to give reliable estimates of the dynamics of total terrestrial water storage (TWS) in the basin (Chen et al., 2009, 2010; Xavier et al., 2010; Becker et al., 2011; Frappart et al., 2013), which helped evaluating hydrological and

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land surface models (LSMs) (Syed et al., 2005, 2008; Crowley et al., 2008; Vergnes and Decharme, 2012).

The total terrestrial water storage (TWS) (Ramilien et al., 2008) plays an important role in regulating the global climate (Famiglietti, 2004). TWS can be estimated by measuring the average amount of water in a basin. The Gravity Recovery And Climate Experiment (GRACE) satellite mission provided the first global observations of TWS, based on variation in the Earth's gravity field. TWS is directly comparable to model outputs for water balance assessment over large river basins (Schmidt et al., 2006, 2008; Syed et al., 2008; Jin and Feng, 2013). Some Land Surface Models (LSMs) have included river routing schemes that account for water storage in the river system to simulate the delay between precipitation over the basin and runoff at the river's mouth (Polcher, 2003; Alkama et al., 2010). Such schemes give better predictions of TWS (Ngo-Duc et al., 2007). GRACE observations over the Amazon basin improved the characterization of the spatio-temporal variability of the amount of water in the Amazon basin (Xavier et al., 2010; Becker et al., 2011), led to the identification of the factors responsible for differences between modeled discharge and observed river flow (Syed et al., 2005) and to the evaluation of the different contributions of the components of the annual water mass balance (Crowley et al., 2008; Frappart et al., 2013). Regional studies also investigated water storage over Amazonian sub-basins such as the Rio Negro tributary (Frappart et al., 2008, 2011). Moreover, the GRACE TWS products have also proven to be reliable for assessment of extreme events, such as Amazonian floods (Chen et al., 2010) and droughts (Chen et al., 2009; Frappart et al., 2012).

Soil moisture change makes an important contribution to change in TWS. Soil moisture variations make an important contribution to TWS variations (Entekhabi et al., 1996; Yeh et al., 2006). In turn, soil moisture variations Soil moisture also influence controls under specific conditions the partitioning of surface net radiation into sensible versus latent heat flux at the surface, and consequently the ratio of turbulent fluxes through the atmospheric boundary layer the evapotranspiration (ET) and the land-atmosphere feedbacks, which are one of the main sources of uncertainty in climate models (Koster et al.,

2004b; Douville, 2010). In the Amazon basin, a particularly important land-atmosphere feedback is precipitation recycling (Shuttleworth, 1988; Marengo, 2006), which is affected by soil moisture in the southern parts of the basin, as they experience a marked dry season, during which soil moisture availability limits ET. Seasonal and inter-annual droughts also impact the biosphere and carbon fluxes, with still disputed conclusions (e.g. Keller et al., 2004; Lewis et al., 2011; Verbeeck et al., 2011; Gatti et al., 2014). ~~The role of soil moisture in controlling evapotranspiration (ET) is important over the Amazon basin, and particularly in south Amazonia, where a high rate of water recycling is sustained (Marengo, 2006) through transpiration (Shuttleworth, 1988).~~ The Amazon basin is thus an interesting domain for evaluating soil moisture parameterizations, which are a critical component of LSMs to achieve an accurate modeling of the water, energy, and CO_2 fluxes in Earth system models. ~~Thus, soil moisture parametrization in LSMs plays a critical role in accurate modeling of the hydro-climatology and CO_2 fluxes. In addition, accurate soil moisture modeling is needed to represent the feedbacks between the land surface and the atmosphere, which are one of the main sources of uncertainty in climate models (Douville, 2010; Koster et al., 2004b).~~

As reviewed by Pitman (2003), soil hydrology parameterizations have evolved from conceptual bucket-type models, with one or two layers, with soil moisture described in terms of available moisture between the wilting-point and the field capacity, to physically-based models solving the Richards equation for water flow in unsaturated soil, and relying on volumetric water content up to full saturation ~~Multilayer schemes have been introduced in LSMs to better describe the water diffusion through the soil~~ (Abramopoulos et al., 1988; Thompson and Pollard, 1995; Viterbo and Beljaars, 1995; Chen et al., 1997; Cox et al., 1999; Boone et al., 2000; De Rosnay et al., 2000; Dai et al., 2003; Decharme et al., 2011). The latter approach offers many advantages, (i) to better account for spatial variability of soil properties (Gutmann and Small, 2005; Guillod et al., 2013), (ii) to implement processes that control soil moisture profiles, such as soil water infiltration and surface runoff generation (D'Orgeval et al., 2008), root water uptake for transpiration (Feddes et al., 2001), or hydraulic coupling to a water table (Liang

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et al., 2003; Gulden et al., 2007; Campoy et al., 2013), and (iii) to be comparable to available satellite observations of soil moisture in the top zone (Reichle and Koster, 2005; Draper et al., 2011; De Rosnay et al., 2013). There have been very few studies, however, to quantify the differences between conceptual bucket-type models and multilayer models, for simulated water fluxes involved in the terrestrial water budget. Confrontations to local-scale measurements have shown improved soil moisture control on ET in multilayer schemes in different domains~~These schemes have improved ET modeling compared to simpler representations of the soil, as shown by the results of global scale simulations and comparison with local measurements~~ (Mahfouf et al., 1996; De Rosnay et al., 2002; Decharme et al., 2011), including in the Amazon basin (Baker et al., 2008). Hagemann and Stacke (sub) also analyzed the influence of soil moisture vertical discretization on soil moisture memory and land-atmosphere coupling in the ECHAM6/JSBACH climate model.~~Moreover, the physical characteristics of the soil taken into account in these multilayer schemes result in better representation of the impact of soil hydrology on land–atmosphere exchanges (Guillod et al., 2013).~~ Finally, in a study coupling the ORCHIDEE (ORganizing Carbon and Hydrology in Dynamic EcosystEms, Krinner et al., 2005) LSM to the IPSL (Institut Pierre Simon Laplace) climate model, Cheruy et al. (2013) showed that the multilayer version of ORCHIDEE increased ET over Europe, in better agreement with local observations, and thus alleviated the summer warm bias of many climate models in the mid-latitudes (Boberg and Christensen, 2012; Mueller and Seneviratne, 2014).

Using the ORCHIDEE LSM, ~~T~~the main question ~~we~~ addressed in this study is «Does the use of a~~n 11-layer~~multilayer soil diffusion scheme, rather than a simpler ~~2-layer~~conceptual bucket-type scheme, improve the simulation of water storage dynamics and water fluxes in the Amazon?». To answer this question, we compare ~~the water budget simulated by two soil hydrology/moisture parameterizations of the LSM~~the results of two versions of ORCHIDEE fitted with these two soil hydrology schemes ~~ORCHIDEE (ORganizing Carbon and Hydrology in Dynamic EcosystEms, Krinner et al., 2005) for~~over the Amazon basin and its main sub-basins, and evaluate the performance of each ~~soil model~~version

against different ~~sets of~~ hydrological (TWS and ET) and vegetation-related (Leaf Area Index (LAI), Gross Primary Production (GPP)) ~~observations~~datasets. ~~For the first time, we compare both soil models embedded in the ORCHIDEE LSM coupled to the same river routing scheme and interactive phenology/carbon cycle module.~~

We first give a brief description of the ORCHIDEE model in Sect. 2, including its carbon cycle module (Sect. 2.2). The two soil hydrology parameterizations and their coupling with the river routing scheme are detailed in sections 2.3 and 2.4, respectively. The atmospheric forcing data and the different observations used to evaluate each version of ORCHIDEE, are described in Sect. 3. In Sect. 4, we evaluate the water budgets from the observations (Sect. 4.1.1) and the two soil hydrology ~~models~~schemes (Sect. 4.1.2) in five Amazonian sub-basins (Solimões, Madeira, Tapajós, Xingu and Negro). In each sub-basin, simulated TWS is compared to GRACE observations (Sect. 4.2). ET and Q differences between the two simulations are given in Sect. 4.3. We then focus on the Xingu sub-basin in the drier southeastern part of the Amazon basin (Sect. 4.4) where soil moisture, and therefore its computation in the model, is likely to limit ET during the dry season (Da Rocha et al., 2009a,b) and may affect in turn dry season precipitation (Koster et al., 2004a). The Xingu case study is also justified because this sub-basin is expected to experience longer dry seasons, ~~and~~ more severe droughts (Li et al., 2006, 2008) and lower minimum river discharge rates (Guimberteau et al., 2013) in the future. We test the sensitivity of the simulated ET by the two soil hydrology ~~models~~schemes to the dry season length over the Amazon basin in Sect. 4.5.

2 Model description

2.1 General Land Surface Model

ORCHIDEE is an LSM simulating energy, water fluxes, CO_2 and ecosystem carbon cycling. It is the land component of the ~~Institut Pierre Simon Laplace~~ (IPSL~~)~~ coupled climate model. In uncoupled simulations, feedbacks with the atmosphere are removed

and the model is run offline, a mode frequently used to test model performance when compared to observations, as in this study. ORCHIDEE includes two main modules:

(1). The Surface-Vegetation-Atmosphere Transfer scheme (SVAT) SECHIBA (Schématisation des Echanges Hydriques à l'Interface entre la Biosphère et l'Atmosphère, Ducoudré et al., 1993; De Rosnay and Polcher, 1998) simulates energy and water exchanges between the atmosphere and the land surface, and the resulting soil water budget. SECHIBA includes two possible configurations to represent soil hydrological processes (Sect. 2.3) whose results are evaluated in this study (Sect. 4).

(2). Phenology and carbon dynamics are simulated by the STOMATE (Saclay Toulouse Orsay Model for the Analysis of Terrestrial Ecosystems, Viovy, 1996) module (Sect. 2.2) coupled with SECHIBA. STOMATE links the fast hydrological and biophysical processes of SECHIBA with the carbon dynamics ~~(photosynthesis, allocation, biomass change and mortality, litter and soil carbon decomposition)~~. Further, STOMATE calculates plant phenology, driven by climatic and biotic factors such as leaf age. The Dynamic Global Vegetation Model (DGVM) LPJ (Lund-Postdam-Jena, Sitch et al., 2003) includes all the parameterizations of the vegetation dynamics such as tree mortality, fire, etc. For this study, this module has not been activated.

2.2 Vegetation modeling with STOMATE

In each grid cell, up to twelve Plant Functional Types (PFTs) can be represented simultaneously, in addition to bare soil. In the Amazon basin, the dominant PFT is «Tropical broad-leaved evergreen forest» (83%) compared to «C4 grassland» (7%), «C3 grassland» (5%), «Tropical broad-leaved raingreen forest» (3%) and others (2%). Their fraction is adapted from the 1 km global land cover map (International Geosphere Biosphere Programme (IGBP), Belward et al., 1999) reduced by a dominant-type method to 5 km spatial resolution with the Olson classification (Olson et al., 1983). Maximal fraction of vegetation is thus defined for each grid cell. It is modulated by the Leaf Area Index (LAI) growth, specific to each PFT represented in the model. LAI dynamics (from carbohydrate allocation) is simulated by STOMATE which deals with the allocation of assimilates, autotrophic respiration components, foliar development, mortality and litter and soil organic matter decomposition. A factor of representing drought stress

(McMurtrie et al., 1990) linearly computes the rate of Ribulose Biphosphate (RuBP) regeneration and the carboxylation rate. The drought stress and the leaf age of the vegetation directly influence the photosynthetic capacity (Farquhar et al., 1980; Collatz et al., 1992) and indirectly the stomatal conductance (Ball et al., 1987) and thus impact the transpiration.

2.3 Soil hydrology modeling with SECHIBA

SECHIBA is the physical module of ORCHIDEE and simulates water and energy fluxes between the soil and the atmosphere through the vegetation, at a 30-minute time step. Two soil hydrolog~~icaly~~y schemes (the 2-layer ~~soil~~ scheme (hereafter called « 2LAY ») and the 11-layer ~~soil diffusion~~ scheme (hereafter called « 11LAY »)) are available to simulate the soil water fluxes and storage, controlling runoff and ET fluxes. In both ~~models~~schemes, ET is the sum of evaporation of water intercepted by the canopy, transpiration (controlled by a stomatal conductance calculated by STOMATE as a function of ~~of vegetation which is related to~~ water availability in the soil column and ~~to~~ a fixed root density profile (De Rosnay and Polcher, 1998)), bare soil evaporation ~~related to water availability in the soil~~(which decreases with soil moisture in the top layer), snow sublimation and floodplains evaporation. We give here a brief description of the two soil ~~models~~hydrology schemes, which are synthetized in Table 1. ~~These models have the same 2 m soil depth and are both coupled to STOMATE and the same routing model. More details are given by Ducoudré et al. (1993) and Guimberteau et al. (2012b) for the 2-layer soil scheme, and for the 11-layer soil diffusion scheme.~~

2.3.1 ~~2-layer soil scheme~~2LAY

The 2-layer soil scheme (Ducoudré et al., 1993; Guimberteau et al., 2012b) ~~(hereafter called « 2LAY »)~~ is frequently used with the STOMATE module, and recently for the Coupled Model Intercomparison Project Phase 5 (CMIP5) IPCC (Intergovernmental Panel on Climate Change) climate scenarios. It is ~~an idealized~~a conceptual model, in

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which ~~field capacity~~maximum water storage is regarded as an available water holding capacity, between the wilting point and the field capacity, and globally set to $300\ \mathrm{kg\,m^{-2}}$ over a two-meter soil depth. The hydrological scheme ~~is represented by~~relies on two layers linked by a ~~drainage~~downward water redistribution flux, involving three empirical parameters (Ducharne et al., 1998). The top layer is subject to root extraction and bare soil evaporation, which are both limited by a resistance depending on the layer's moisture (Ducoudré et al., 1993) ~~and root extraction~~. The amount of water stored in this top layer is directly controlled by rain falling through the canopy, ~~and the top layer~~it can disappear when its water content is fully evaporated. The water content in the deep layer is only reduced ~~depends only to water extraction by~~ by root extraction for transpiration, which depends on soil moisture and the root profile. Runoff is computed as in the bucket model of Manabe (1969) and occurs only when total soil moisture reaches the maximum water storage ~~the soil bucket is saturated~~. ~~The total soil water excess gives~~In such a case, excess water is converted to runoff, which can be considered as Dunne runoff (Dunne and Black, 1970). ~~This flux is assumed to be partitioned into 95% deep drainage and 5% surface runoff.~~ In the 2LAY, ~~The~~a separate water budget is computed ~~separately~~ for each ~~Plant Functional Type (PFT)~~ tile within ~~the~~a mesh, and then averaged over the grid cell. ~~In the 2LAY, soil texture does not influence field capacity.~~

2.3.2 ~~11-layer soil diffusion scheme~~11LAY

~~The second hydrological model is the~~The 11-layer soil diffusion scheme is described in De Rosnay et al. (2000, 2002); Campoy et al. (2013)~~, hereafter called « 11LAY »~~. It has been used in the Amazon basin for streamflow evaluation (Guimberteau et al., 2012a) and for studying future annual extreme flow variation under climate change~~, for the Amazon basin~~ (Guimberteau et al., 2013). The 11LAY ~~scheme~~ simulates vertical ~~soil flow~~water flows based on a physical description ~~processes from the Fokker-Planck equation that resolves~~ of water diffusion and retention in ~~non-~~unsaturated soils, ~~conditions steming~~ from the Richards equation (Richards, 1931), which allows capillary rise. For numerical integration, ~~T~~the 2-meter soil column is divided into 11 discrete layers ~~whose~~,

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with ~~thickness increases geometrically downward with depth~~geometrically increasing thickness with depth. The relationships between volumetric water content, hydraulic conductivity, and matric potential, are described in ORCHIDEE by the Mualem-Van Genuchten model (Mualem, 1976; Van Genuchten, 1980), using parameters defined by Carsel and Parrish (1988) as a function of soil texture. The saturated hydraulic conductivity is also modified (D'Orgeval et al., 2008) to take into account two properties that have opposite effects on conductivity (Beven and Germann, 1982; Beven, 1984): 1) increased soil compactness with depth and 2) enhanced infiltration capacity due to the presence of vegetation that increases soil porosity in the root-zone.

Soil texture heterogeneity between grid cells is taken into account by ~~employing~~means of three different soil types (coarse, medium and fine textured). Their spatial distribution is diagnosed by interpolating the $1° \times 1°$ Food and Agriculture Organization texture map (FAO, 1978) by Zobler (1986) ~~at a scale of $1° \times 1°$, considering only~~upscaled to the working resolution of ORCHIDEE by only keeping the dominant ~~soil type on~~texture in each grid cell. For instance, this leads to saturated water contents between 820 $\mathrm{kg\,m^{-2}}$ (coarse and fine textures) and 860 $\mathrm{kg\,m^{-2}}$ (medium texture) in the 2-meter soil, with an average water storage capacity of 687 $\mathrm{kg\,m^{-2}}$ above the residual water content in the Amazon basin.

~~In ORCHIDEE, the five textural classes (coarse, medium-coarse, medium, medium-fine and fine) are reduced to three, with ORCHIDEE's medium class grouping the Zobler classes of medium-coarse, medium and medium-fine. At the working ORCHIDEE resolution, only the dominant texture in each grid cell is used. The relationships between hydraulic conductivity, volumetric water content and matrix potential are described in ORCHIDEE by the Mualem-Van Genuchten model (Mualem, 1976; Van Genuchten, 1980), using parameters estimated by Carsel and Parrish (1988) for the corresponding soil texture classes of the United States Department of Agriculture (USDA). The maximal soil water content in the 2-meter soil is between 820 $\mathrm{kg\,m^{-2}}$ (coarse and fine classes) and 860 $\mathrm{kg\,m^{-2}}$ (medium class) depending on soil texture. The saturated hydraulic conductivity is modified (D'Orgeval et al., 2008) to take into account two properties that~~

~~have opposite effects on conductivity (Beven and Germann, 1982; Beven, 1984): 1) increased soil compactness with depth and 2) enhanced infiltration capacity due to the presence of vegetation that increases soil porosity in the root-zone.~~ The vertically explicit modeling of soil water fluxes enables a more physically-based runoff computation than is achieved in the 2LAY (De Rosnay et al., 2002). The precipitation rate and the soil hydraulic conductivity ~~capacity of the soil to infiltrate~~ govern ~~the~~ the production of runoff ~~that can be assigned to Hortonian runoff Horton (1933). The precipitation~~ partitioning between soil infiltration and surface runoff production, ~~and soil infiltration~~ which can be regarded as Hortonian runoff (Horton, 1933). ~~is parameterized through a~~ Soil infiltration involves a time-splitting procedure ~~according to Green and Ampt (1911)~~ where the wetting front moves with time through the soil layers ~~(d'Orgeval et al., 2008)~~, according to Green and Ampt (1911), and partial reinfiltration is allowed in grid cells where the local slope is $\leq 0.5\%$ (D'Orgeval et al., 2008). The second contribution to total runoff is ~~F~~free gravitational drainage ~~occurs~~ at the bottom of the soil ~~(bottom boundary condition)~~. Finally, ~~I~~independent water budgets are computed over three groups of PFTs (grouping bare soil, trees, and grass/crops) within ~~each grid cell~~the mesh, before ~~and then~~ averag~~ed~~ing over the grid cell.

~~Vegetation modeling with STOMATE~~

~~In each grid cell, up to twelve PFTs can be represented simultaneously, in addition to bare soil. In the Amazon basin, the dominant PFT is «Tropical broad-leaved evergreen forest» (83%) compared to «C4 grassland» (7%), «C3 grassland» (5%), «Tropical broad-leaved raingreen forest» (3%) and others (2%). Their fraction is adapted from the 1 km global land cover map (International Geosphere Biosphere Programme (IGBP), Belward et al., 1999) reduced by a dominant-type method to 5 km spatial resolution with the Olson classification (Olson et al., 1983). Maximal fraction of vegetation is thus defined for each grid cell. It is modulated by the Leaf Area Index (LAI) growth, specific to each PFT represented in the model. LAI dynamics (from carbohydrate allocation) is simulated by STOMATE which deals with the allocation of assimilates, autotrophic respiration components, foliar development, mortality and soil organic matter decomposition.~~

~~The water stress of the vegetation influences only the photosynthetic capacity. A factor of representing water stress McMurtrie et al., 1990 linearly computes the rate of Ribulose Biphosphate (RuBP) regeneration and the carboxylation rate.~~

2.4 River routing module

The routing module (Polcher, 2003; Guimberteau et al., 2012a) calculates the daily continental runoff to the ocean. This scheme is based on a ~~parametrization~~parameterization of water flows on a global scale (Miller et al., 1994; Hagemann and Dumenil, 1998). ~~The~~A global map of the major watersheds (Vörösmarty et al., 2000) delineates the basin boundaries and allocates one of eight possible directions to the water flow within each grid cell. The 0.5°x0.5° resolution of the basin map is higher than the atmospheric forcing resolutions commonly used and it is therefore possible to have more than one basin in an ORCHIDEE grid cell (sub-basins). Water ~~between each sub-grid basin~~ is transfered between each sub-grid basin through three linear water reservoirs, with no direct interaction with the atmosphere (except over floodplain areas). In each sub-basin, total runoff is transformed into river discharge owing to the so-called fast and slow reservoirs, designed to respectively account for delay and attenuation of overland flow and groundwater flow at the grid cell scale. These two reservoirs are fed by surface runoff and ~~deep~~ drainage when using the 11LAY, and by an arbitrary partitioning of total runoff when using the 2LAY, with 5% feeding the fast reservoir and 95% feeding the slow reservoir (Ngo-Duc et al., 2007)~~are transformed into river discharge corresponding to fast and slow reservoirs, respectively~~. Outflow from these two reservoirs becomes streamflow at the outlet of the sub-basin, and~~Both discharges~~ feeds the stream reservoir of the next downstream sub-basin, which also receives ~~the discharge~~inflow from all upstream stream ~~sub-basins~~reservoirs.

Travel time within the reservoirs depends on ~~their different residence times~~a characteristic time scale, which is ~~. The residence time is~~ the product of a topographical water retention index k (in m) ~~water retention index and a velocity constant~~and a time constant g (in $d.m^{-1}$). The latter does not vary horizontally ~~. For each grid cell, the water retention~~

~~index is given by a 0.5°x0.5° resolution map obtained by a simplification of Manning's formula (Manning, 1895; Ducharne et al., 2003). This retention index is common to all three reservoirs in a grid cell but varies between grid cells, depending on topography. The velocity constant does not vary spatially~~ but distinguishes the three reservoirs~~. ,~~ while the water retention index k characterizes the impact of topography on travel time in each sub-basin, and is assumed to be the same in the three reservoirs of a given grid cell, eventhough it derives from stream routing principles introduced by Ducharne et al. (2003). This travel time is thus assumed to be proportional to stream length in the sub-basin, and inversely proportional the square root of stream slope. This can be seen as a simplification of the Manning formula (Manning, 1895), where the time constant g compensates for the missing terms. The lengths and slopes are first computed at the 0.5°x0.5° resolution from the topographical map of Vörösmarty et al. (2000), then upscaled at the ORCHIDEE grid cell resolution, of 1°x1° in the present study (Sect. 3.1). ~~The corresponding three values of the velocity constant have been~~The values of the time constants g were initially calibrated over the Senegal basin, ~~with~~using the 2LAY parameterization with the 5/95% partitioning of total runoff towards the fast/slow reservoirs ~~(Ngo-Duc et al., 2007) and~~, then generalized for all the basins of the world (Ngo-Duc et al., 2007). The stream reservoir has the ~~highest velocity~~lowest constant $(0.24\,\mathrm{d\,m^{-1}})$, which leads to a stream velocity of around $0.5\,\mathrm{m.s^{-1}}$ assuming a slope of 1%, both values being typical of large rivers. The corresponding velocities are lower in the other two reservoirs, with a time constant g of 3.0 and $25\,\mathrm{d\,m^{-1}}$ in the fast and slow reservoirs respectively. In former studies using the 11LAY, the time constants of these two reservoirs have been set equal to the one of the fast reservoir $(g = 3.0\,\mathrm{d\,m^{-1}})$ to balance a higher water residence time in the soil with the 11LAY (D'Orgeval, 2006; D'Orgeval et al., 2008; Gouttevin et al., 2012; Guimberteau et al., 2012a, 2013). In the present study, however, to restrict the difference sources to the soil hydrology schemes alone, we used the same set of time constants with both the 2LAY and 11LAY: $g = 0.24$, 3.0, $25\,\mathrm{d\,m^{-1}}$, as defined by Ngo-Duc et al. (2007).~~is lower in the fast reservoir $(0.33\,\mathrm{m\,d^{-1}})$ and still lower in the slow reservoir $(0.04\,\mathrm{m\,d^{-1}})$. However, when the 11LAY~~

~~parameterization was used, the velocity constant of the slow reservoir was increased to the one of the fast reservoir (D'Orgeval, 2006). The goal was to simulate consistent river discharge between both soil models despite a higher residence time of water in the soil when using 11LAY parameterization. However, in order to facilitate the detection of the effect of the soil model parameterization on the TWS, we changed the velocity constant of the slow reservoir for the 11LAY model and set it equal to the one used in the 2LAY.~~

The routing scheme also includes a floodplain/swamp parameterization (D'Orgeval et al., 2008), recently improved by Guimberteau et al. (2012a) for the Amazon basin, by means of a new floodplain/swamp map. Over the floodplain areas, the water from the upstream reservoirs is delayed in a floodplain reservoir before going into the stream reservoir. The ~~velocity~~time constant of the floodplain reservoir is the same, for both soil hydrology ~~models~~schemes, ~~is the same ($0.4\,\mathrm{m\,d^{-1}}$)~~ and equal to that found by Guimberteau et al. (2012a) who calibrated it for the Amazon basin $(2.5\,\mathrm{d\,m^{-1}})$.

2.5 Synthetic comparison of the two soil hydrology schemes

For easier comparison of their effects on the Amazon basin hydrology, the 2LAY and the 11 LAY are used here with the same 2-meter soil depth and the same root density profiles, which depend on PFTs. They are both coupled to the same soil thermal scheme (using a 7-layer discretization over 5.5 meters), the same routing module, and to the STOMATE vegetation module.

The differences between the hydrological simulations performed with these two schemes (described in Sect. 3.1, and analyzed in Sect. 4), are together due to the different description of soil water flow and storage, and to the related parameters (Table 1), since these two components are intimately linked. This is not particular to the present study, but is true of any comparison between a soil hydrology scheme that relies on available water content (between wilting point and field capacity), with conceptual parameterizations of soil water flow, and a scheme that is physically-based, and relies on volumetric water content (between residual moisture and saturation) and the Richards equation.

In the present case, additional differences between the simulations arise from the way total runoff is transferred to the fast and slow reservoirs of the routing scheme, supposed to receive surface runoff and drainage, respectively. The 11LAY makes a clear physical distinction between these two fluxes, contrarily to the 2LAY, which only creates total runoff when the soil reservoir is full, with no clear surface or bottom localization, as in the bucket scheme of Manabe (1969). In this case, the routing scheme has always been used with a 5-95% redistribution of total runoff to the fast and slow routing reservoirs. In this paper, we follow this choice, steming from Ngo-Duc et al. (2007), which has an impact on the relative contribution of these fast and slow reservoirs to TWS (as analyzed in Sect. 4.2).

3 Methods and dataset

3.1 Simulation design and forcing datasets

ORCHIDEE is forced by the Princeton Global Forcing (Sheffield et al., 2006) at a 1°×1° spatial resolution. It is based on the National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis datasets (Kistler et al., 2001). The temporal resolution is three hours and the time series cover the period 1948-2008. All the required forcing variables (Table 1see Table 1 in Supplementary Material) come directly from NCEP-NCAR, except the precipitation. The latter has been corrected using the monthly CRU (Climatic Research Unit) dataset (New et al., 2000) and statistically downscaled from 2°×2° to 1°×1° resolution using relationships developed with the Global Precipitation Climatology Project (GPCP, Huffman et al., 2001) daily product. A similar method has been used to disaggregate from daily to three hourly using the Tropical Rainfall Measuring Mission (TRMM, Huffman et al., 2007) satellite data product. For this study, the precipitation data were further corrected by the new product (Version 5) of GPCC (Global Precipitation Climatology Centre, Schneider

et al. (2014)) (1901-2009), which seems to be the better global product for hydrological applications (Decharme and Douville, 2006).

Two simulations with the 2LAY and the 11LAY ~~were~~are performed using SECHIBA coupled with STOMATE, the routing scheme and the floodplain parameterization. Each simulation ~~was~~is conducted for 34 years (1975-2008), the first 5 years of the period being discarded in order to ensure a state of hydrological equilibrium at the beginning of the analyzed time series. Thus, the 29-year period from 1980-2008 ~~was~~is analyzed for the Amazon basin and its five large sub-basins: the Madeira, Tapajós and Xingu in the south, the Solimões in the west and the Negro in the north (Fig. 1).

3.2 Evaluation datasets

Several datasets (Table 2) ~~were~~are used to evaluate the hydrology, the carbon fluxes and the phenology simulated by ORCHIDEE. This comparison aims to determine whether the 11LAY gives a better representation of Amazonian hydrology and vegetation feedback.

3.2.1 Total ~~soil~~terrestrial Water Storage (TWS)

TWS is the integrated water amount stored on and below the land surface. In this study, we use~~d~~ the ~~1°x1° monthly~~ GRACE dataset which originates from a mission mapping the Earth's gravity field, and from which monthly terrestrial water storage variations can be derived. We use the latest solution RL05~~4~~ 'ss201008DSTvSCS1401' ~~version~~ produced by the University of Texas at Austin / Center for Space Research (CSR) ~~and the GeoForschungsZentrum at Potsdam (GFZ), downloaded from the TELLUS website~~. In order to compare the TWS simulated by ORCHIDEE to GRACE data, we calculate~~d~~ from ORCHIDEE outputs the sum of soil moisture, snow-pack (negligible in Amazonia), water on the canopy and the free water stored in the four water routing reservoirs. GRACE data cover the ~~10~~12-year period April 2002-~~July~~October ~~2011~~2013 and are expressed as the difference in water depth equivalent from the 5-year average

for 2003-2007. In each grid cell, the corresponding 5-year average is removed from the 2003-2008 studied time-series of TWS output from ORCHIDEE. The GRACE data were filtered and corrections applied for bias and leakage (Swenson and Wahr, 2002, 2006). GRACE measurements are particularly accurate over the Amazon basin where TWS error is estimated to be 15 mm (i.e. about 4.2% of the TWS annual amplitude) (Wahr et al., 2004). Comparison of simulated TWS with GRACE data is only recommended over river basins having areas of 400,000 km² or larger (Swenson et al., 2003). The Amazon basin, which extends over about 6 million km², is therefore suitable. The Amazon sub-basins on which we focus also have areas greater than 400,000 km², except for the Negro sub-basin which is close to 300,000 km² in area (Table 3). Thus, the results of TWS over this latter sub-basin should be taken with caution.

3.2.2 Basin-scale water budget

Precipitation (P)

A precipitation dataset for the Amazon basin has recently been collected and harmonized by the ORE (Environmental Research Observatory) HYBAM (Geodynamical, hydrological and biogeochemical control of erosion / alteration and material transport in the Amazon basin - http://www.ore-hybam.org). Thi~~u~~s dataset is independent from ~~that~~the one produced by Sheffield et al. (2006). Daily in situ raingauge observations from the meteorological services of Amazonian countries have been interpolated at 1°x1° resolution over the basin. The correction of CRU-NCEP precipitation by the ORE HYBAM dataset contributed to significant improvements in river discharge simulation with ORCHIDEE (Guimberteau et al., 2012a).

Evapotranspiration (ET) and Gross Primary Productivity (GPP)

The increased number of in situ ET measurements and more advanced satellite remote sensing algorithms now enable ET to be mapped at a global scale. ~~These maps~~

can be used to evaluate LSM performance (e.g. Mueller et al., 2011). For this study, we use ~~monthly~~ ET estimates ~~at 0.5°x0.5° resolution~~ from Jung et al. (2010). This product, ~~(~~hereafter called « MTE-ET » (Model Tree Ensemble-EvapoTranspiration)~~)~~, was derived from an empirical up-scaling of FLUXNET eddy-covariance measurements using a machine-learning algorithm called MTE. The FLUXNET global network collects continuous in situ measurements of land-surface fluxes. Data from 253 globally distributed flux towers (4 in the Amazon basin) were processed, corrected and combined with monthly gridded global meteorological data and the remotely sensed fraction of absorbed photosynthetically active radiation (Advanced Very High Resolution Radiometer (AVHRR), Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and MEdium Resolution Imaging Spectrometer (MERIS)). The MTE-ET product has already been used for the evaluation of coupled and uncoupled LSM simulations (Mueller et al., 2011) and contributed to the creation of global long-term records of the terrestrial water budget (Pan et al., 2012).

Vegetation Gross Primary Production (GPP) quantifies the gross CO_2 flux taken up during photosynthesis. Jung et al. (2011) provided a global data-driven GPP product (hereafter called « MTE-GPP ») using a similar algorithm to that used to give ET. ~~We used GPP generated at a 0.5°x0.5° spatial resolution and a monthly temporal frequency from 1982 to 2008.~~

Here, Jung et al.'s product is chosen to evaluate ET simulated by ORCHIDEE because it also provides a consistent GPP product. Uncertainties around this ET estimate is assessed by comparison with 3 other products: GLEAM-ET (Miralles et al., 2011), NTSG-ET (Zhang et al., 2010) and PKU-ET (Zeng et al., 2014).

River discharge (Q)

River discharge data have been collected and harmonized by the ORE HYBAM project (Cochonneau et al., 2006). The same database used by Guimberteau et al. (2012a) is ~~used here, but~~ updated up to 2011. Six river gauging stations (Table 3), representative of the main sub-basins of the Amazon basin (Fig. 1), are used to evaluate river

discharge simulation by ORCHIDEE. Óbidos (OBI) is the last gauging station before the mouth of the Amazon and is thus the most representative station to assess the average simulated river flow over the whole basin. The station Fazenda Vista Alegre (FVA) measures the discharge of the Madeira sub-basin, in the southern part of the Amazon basin. The Madeira sub-basin has the largest contributing area and provides nearly 15% of the total river flow measured at Óbidos (Table 3). But the largest contribution comes from the western region, gauged at São Paulo de Olivença (SPO) on the Rio Solimões, where the average river flow is about 26% of the total flow measured at Óbidos. The Negro sub-basin at Serrinha (SER) has the lowest area, but makes a large contribution to the total discharge due to the high precipitation. The two southeastern sub-basins of the Tapajós and the Xingu rivers, gauged at Itaituba (ITA) and Altamira (ALT) respectively, flow into the Amazon downstream of the Óbidos station (Fig. 1).

For each gauging station, we have estimated an empirical basin lag time as the delay between the peaks of precipitation and river discharge due to the time required for runoff to travel to the basin outlet. This lag depends on the basin characteristics (size, soil, geology, slope, land use...). The Amazon basin hydrograph exhibits a basin lag time of about four months mainly due to the large size of the basin and the long residence time of water in the floodplains. The basin lag is lower (about one month) in the smaller sub-basins such as the Tapajós and the Negro. For the purpose of water budget estimation, we use an equivalent runoff, Q^*, as the discharge Q time-series, back-shifted using the empirical lag.

Residual water balance ($\dot{\Delta S}$)

The water balance equation gives the change in soil total water storage $\dot{\Delta S} = \frac{\Delta S}{\Delta t}$, the residual of $P - ET - Q^*$, including soil water, ground water, rivers and floodplains. It represents the amount of water that enters in the soil system during the wet season ($\dot{\Delta S} > 0$) or is released ($\dot{\Delta S} < 0$) during the dry season. The mean annual change in storage is assumed to be negligible ($\overline{\dot{\Delta S}} \simeq 0$). However, inconsistencies between the different ob-

servation datasets could lead to a non-zero annual water storage ($\overline{\dot{\Delta S}} \neq 0$). The water balance closure condition is not fulfilled over the Solimões (bias of -25%), the Xingu (-10%) and the Negro (-6%) sub-basins, probably due to the underestimated precipitation in the ORE HYBAM dataset over the western and north western sub-basins (Azarderakhsh et al., 2011; Guimberteau et al., 2012a) or to the low density of flux towers measuring ET over the Amazon basin in the MTE-ET product. For the Amazon, the Tapajós and the Madeira basins, the bias is between -5 and -2%.

3.2.3 Leaf Area Index (LAI)

A Leaf Area Index (LAI) dataset is critical for monitoring global vegetation dynamics. For this study we use Zhu et al. (2013)'s product, based on a neural network algorithm which combines the third generation Global Inventory Modeling and Mapping Studies (GIMMS) Normalized Difference Vegetation Index (NDVI3g) and best-quality Terra Moderate Resolution Imaging Spectroradiometer (MODIS) LAI for the overlapping period 2000–2009. ~~The global field of LAI was generated at 1/12 degree spatial resolution and a 15-day temporal frequency from 1982 to 2011.~~ The comparison of the LAI with 45 sets of field measurements from 29 sites representative of all major biomes indicated a reasonable agreement ($p < 0.001$; RMSE = 0.68 LAI, Zhu et al., 2013).

3.3 TWS ~~A~~amplitude and phase assessment

To give an accurate estimate of the difference in TWS change between ORCHIDEE and GRACE, we use two indicators measuring the amplitude (α in mm) and the phase (ϕ in days) of the TWS seasonal cycles. ~~The amplitude is defined as the difference between the monthly maximum and minimum values between January and December.~~ The phase is computed by a fit to the cosine function as follows:

$$Y = p_0 + p_1.\cos\left(\frac{2\pi.D}{365} - \frac{\phi_1.2\pi}{365}\right) + p_2.\cos\left(\frac{4\pi.D}{365} - \frac{\phi_2.2\pi}{365}\right) + p_3.\cos\left(\frac{8\pi.D}{365} - \frac{\phi_3.2\pi}{365}\right) \quad (1)$$

where Y is TWS (monthly average during 2003–2008), D is the day year, ϕ_1, ϕ_2 and ϕ_3 are the phases of the seasonality, and p_0, p_1, p_2 and p_3 are regressed parameters. For the phase difference, only the phase of the first harmonics (ϕ_1 in Eq. 1) is considered here. The amplitude is defined as $2p_1$.

4 Results and discussion

4.1 Water budgets for the Amazon sub-basins

4.1.1 Overview of observed water budgets

Water budgets wereare first calculated from the different sets of observations: P (ORE HYBAM), ET (MTE-ET) and Q (ORE HYBAM) (Table 4). From these «observed» basin-level water budgets, the estimated precipitation amount over the Amazon basin is $6.2\,\mathrm{mm\,d^{-1}}$. Half of this water runs off to the mouth ($3.3\,\mathrm{mm\,d^{-1}}$) and the other half evaporates ($3.2\,\mathrm{mm\,d^{-1}}$) in agreement with the estimates by Shuttleworth (1988) (based on on-site measured precipitationP and ET estimated from a model calibrated against micro-meteorological measurements) and Callede et al. (2008) (based on precipitationP and river dischargeQ observations). Monthly precipitation averaged over the Amazon basin is between $3.5\,\mathrm{mm\,d^{-1}}$ in August and $8.2\,\mathrm{mm\,d^{-1}}$ in February (Fig. 2a). This is reflected in the western Solimões sub-basin (Fig. 2e), which receives $P = 5.7\,\mathrm{mm\,d^{-1}}$ in annual precipitationaverage (Table 4). The seasonal amplitude of precipitation is larger in the Madeira sub-basin (Fig. 2d) which includes southern tropical regions subject to the seasonal displacement of the Inter-Tropical Convergence Zone (ITCZ) during the year. The JJA dry season is particularly marked in the Xingu and Tapajós sub-basins in the southeast (Fig. 2b and 2c, respectively), with dry-season precipitation close to zero. By contrast, the DJF wet-season precipitation for those sub-basins averages about $10.0\,\mathrm{mm\,d^{-1}}$. The northern tropical sub-basin of the Rio Negro (Fig. 2f) receives

high precipitation throughout the year ($8.7\,\mathrm{mm\,d^{-1}}$, ~~Table 4~~) with a maximum in May ($12.0\,\mathrm{mm\,d^{-1}}$).

In contrast to the precipitation, the seasonal cycle of ET is flat during the year over the Amazon basin and its sub-basins ~~(Fig. 2)~~. The mean annual value oscillates between $3.0\,\mathrm{mm\,d^{-1}}$ for the Solimões and $3.4\,\mathrm{mm\,d^{-1}}$ for the Xingu ~~(Table 4)~~.

Thus, change in ~~soil~~total water storage (and consequently ~~river discharge~~Q) seasonal variations are strongly modulated by the precipitation seasonality. In the southern sub-basins (Xingu, Tapajós and Madeira), ~~soil~~ water storage increases from October to April ~~(Fig. 2b to 2d)~~. The dry season occurs from May to September and is highlighted in JJA by an ET much higher (up to about $+3.0\,\mathrm{mm\,d^{-1}}$ for the southeastern sub-basins) than precipitation, which is close to zero, leading to severe low-flow. The results in ~~soil moisture~~ water storage change derived from water fluxes of several datasets should be taken with caution for the Solimões and Negro sub-basins, due to large errors in water balance closure estimated in Sect. 3.2.2 ~~(Table 4 and Fig. 2)~~.

4.1.2 Simulated water budgets

The water budgets simulated by the two soil ~~models~~hydrology schemes and their bias with the observations are given in Table 4. Annual precipitation from Sheffield's forcing data is close to the ORE HYBAM over the Amazon basin (-1.2%) and its sub-basins (between -3.2% for the Madeira and +2.4% for the Solimões). The good agreement between simulated annual river discharge at Óbidos and ORE HYBAM data (~~<5%~~$\leq$ 6%) results from a compensation between an overestimation in the south (between +~~20~~15 and +~~30~~25% for the Madeira) and an underestimation in the western sub-basin (around -15% for the Solimões), as already reported by Guimberteau et al. (2012a). In addition to the uncertainty in the forcing precipitation, the bias in river discharge may be explained by the low ET simulated by ORCHIDEE (between -13% for the Xingu and the Madeira to -20% for the Solimões ~~for~~wiyh the 11LAY) when compared to MTE-ET. However, the ET underestimation by ORCHIDEE for the Amazon basin (-15%) is within the estimated error of annual MTE-ET ($\pm13\%$) (see error bars in Fig. 1d for the

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bioclimatic zone «equatorial, fully humid» in Jung et al. (2010)). The underestimation in both ET and Q over the Solimões sub-basin suggests a disagreement between the evaluation datasets.

~~On average, the difference in simulated water budgets between the two soil models was small over the Amazon basin (about 3%)~~Over each sub-basin, the 11LAY systematically simulates a better water budget than the 2LAY. However, the differences in the results between the two soil hydrology schemes are small over the Amazon basin. ~~However, the water budget was slightly improved with the 11LAY which systematically reduced the bias for each sub-basin (Table 4). Except for the Negro sub-basin where the values of ET and thus of Q are similar for both simulations, bias in annual ET was reduced by 3 to 4% with the 11LAY, which simulated higher ET than the 2LAY. The overestimation in annual river discharge at the southern stations was consequently between 5 to 10% less when using 11LAY than when using 2LAY. Contradictory effects on the bias of ET and Q by the two models over the Solimões sub-basin, result from the error in closure of the observed water balance.~~

4.2 Total water storage change and contribution from the different reservoirs

Seasonal (Sect. 4.2.1) and interannual (Sect. 4.2.2) variations in TWS from the two soil hydrology versions of ORCHIDEE are compared to the GRACE data over the Amazon basin and its sub-basins, during the 2003-2008 period.

4.2.1 Seasonal variation

The two different soil ~~models~~hydrology schemes simulate a similar TWS seasonal cycle over the entire Amazon basin (Fig. 3a ~~and Table 5~~) with a half-monthly delay and an overestimated amplitude of about 7 and 14% ~~30 and 56 mm~~ compared to GRACE data, ~~(~~for the 2LAY and 11LAY, respectively~~)~~ (see Table 2 in Supplementary Material). This positive amplitude bias ~~was~~is predominant along the Amazonian rivers (main stem of the Amazon and the Madeira, Tapajós and Xingu, ~~Figs. 4a and 4b~~see Figures 1a

and 1b in Supplementary Material) suggesting the routing reservoir storages play~~ed~~ a prevalent role in the overestimation of the TWS seasonal amplitude. ~~TWS phase simulated by ORCHIDEE was overestimated (i.e. modeled TWS change occurred later than observed) by more than 25 days in the northern region of the Amazon basin and in the southern floodplain areas of the Madeira sub-basin (Figs. 4c and 4d). Underestimation (i.e. modeled TWS change occurred earlier than observed) by 20 days was also simulated in the Andes and in the two southern sub-basins (Tapajós and Xingu). Higher monthly correlation between observed and simulated TWS was obtained with the 11LAY over the Amazon basin (Table 6). Storage increase during the early wet season was underestimated by the two models (50 mm in January and February) and the simulated TWS maximum in May was overestimated by 30 mm (Fig. 3a).~~ The 11LAY ~~was~~is better at representing the TWS decrease, leading to better capture of the timing of the TWS minima. More strikingly, the five water storage reservoirs of the model contribute~~d~~ to TWS in a different way according which soil ~~model~~hydrology scheme ~~was~~is used. In both simulations, changes in the slow reservoir water content (in green in Fig. 3a) ~~made~~make the largest contribution to total TWS change. The annual amplitude in water storage in the slow reservoir, which collects drainage, ~~storage was~~is ~~higher~~lower with the ~~2~~11LAY (~~61~~46% of the total annual amplitude of TWS) than with the ~~11~~2LAY (~~41~~66%). Subsurface water contribution (sum of the fast, slow and soil reservoirs) to TWS variation simulated by the 11LAY (71%) is in agreement with Pokhrel et al. (2013)'s estimations (71%) over the Amazon basin. The physical distinction between surface runoff and drainage with the 11LAY leads to a lower drainage contribution to the total runoff over the Amazon basin ($\sim 69\%$), which is more realistic when compared to the estimations of Mortatti et al. (1997) (68.1%), than with the 2LAY (95%) (see Table 3 in Supplementary Material). By contrast, more water ~~was~~is stored in the soil (in blue ~~in Fig. 3a~~) with the 11LAY (~~34~~19% of the total annual amplitude of TWS compared to ~~2~~46% with the 2LAY) thanks to the higher soil water holding capacity of the 11LAY. ~~11LAY drainage depends upon the soil water diffusion computation and the higher soil water holding capacity of the 11LAY enabled more water storage in~~

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~~the soil.~~ The combination of these two effects lead~~s~~ to ~~a lower drainage contribution to the total runoff (43%) compared to the 2LAY where the total soil water excess giving runoff is partitioned arbitrarily into 95% drainage and 5% surface runoff. Thus, water in the 2LAY was primarily stored in the slow reservoir, which collects the drainage; while, because the 11LAY had more water storage in the soil reservoir, it produced~~ a ~~higher~~better ~~amplitude in the TWS seasonal cycle~~agreement with GRACE in the 11LAY simulation (see Table 4 in Supplementary Material for correlations).

According to GRACE data, the southern sub-basins (Xingu, Tapajós and Madeira) exhibit a pronounced TWS seasonal cycle (Fig. 3b to d), which is due to the high annual precipitation amplitude (see Sect. 4.1.1). This more pronounced TWS seasonal cycle in the south is well represented by ORCHIDEE ~~which exhibited high seasonal correlation with GRACE~~ ($r^2 > 0.95$) ~~(Table 6)~~. When the seasonal cycle is removed from the time-series to reveal the interannual variability (IAV), the monthly correlation in the Xingu and Tapajós sub-basins strongly decreases ~~in the Xingu and Tapajós sub-basins~~ ($0.46 < r^2 < 0.68$), suggesting that TWS IAV ~~was~~is difficult to capture (see Sect. 4.2.2). The simulated TWS amplitude is~~was~~ overestimated by between ~~45~~10 to ~~195 mm~~ 30% in the three southern sub-basins ~~(Table 5)~~, while the phase ~~was~~is well captured by both ~~models~~soil hydrology schemes (difference between -~~10~~9 to +8 days). TWS phase is overestimated (i.e. modeled TWS change occurs later than observed) in the southern floodplain areas of the Madeira sub-basin (see Figures 1c and 1d in Supplementary Material). The 11LAY systematically produce~~d~~s a better amplitude when compared to GRACE in the three sub-basins~~, due to the larger storage of water in the soil reservoir (Fig. 3b to d)~~. The amplitude ~~was~~is particularly improved in the southern part of the Tapajós and the northern part of the Xingu sub-basins ~~(Fig. 4a and 4b)~~. Phase improvement ~~was~~is obtained with the 11LAY in the southern parts of these two southeastern sub-basins ~~(Fig. 4c and 4d)~~.

The western Solimões sub-basin has the lowest TWS amplitude, which ~~was~~is well captured by ORCHIDEE - particularly by the 11LAY (Fig. 3e ~~and Table 6~~). ~~Here again, deseasonalized TWS anomalies are much lower (Table 6).~~ The simulated TWS am-

plitude is overestimated by ~~about 30~~ 6 to ~~40 mm~~ 16% when compared to GRACE data, but lower bias occurs with the 11LAY. The phase ~~was~~is well captured by both ~~models~~soil hydrology schemes ~~(Table 5)~~(bias lower than 3 days), except in the Andes where it is lagged by more than 25 days ~~(Fig. 4)~~.

The simulated TWS anomalies in the northern Negro sub-basin (Fig. 3f) exhibit ~~low~~ correlations lower than 0.80 with GRACE, ~~(Table 6)~~ with a phase delay of ~~more than~~about one month and an underestimation of the amplitude by up to 12% (11LAY)~~about 100 mm (Table 5 and Fig. 4)~~. ~~Here again, compared with the 2LAY,~~ The amplitude is better captured by the 2LAY (bias of 0.4%) compared to the 11LAY whereas the bias in phase is reduced by 7 days with the 11LAY~~the bias by 34 mm and 7 days in amplitude and phase, respectively~~. For both soil ~~models~~hydrology schemes, the beginning of the storage period ~~was~~is delayed and the depletion exhibit~~ed~~s too slow a decrease of stored water ~~(Fig. 3f)~~ relative to the GRACE data.

The slow reservoir ~~made~~makes a large contribution to the TWS seasonal cycle over the northern and western sub-basin in both schemes indicating that deep drainage ~~was~~is prevailing in these soils, in agreement with the results of Miguez-Macho and Fan (2012). The underestimated amplitude of the simulated TWS compared to GRACE over the Negro sub-basin could be explained by the negative bias in the precipitation forcing dataset. Using satellite data products, Azarderakhsh et al. (2011) estimated from the water balance equation, that precipitation over the western and northwestern regions could be underestimated by up to $3.2\,\mathrm{mm\,d^{-1}}$.

4.2.2 Interannual variation (IAV)

~~Using the d~~Deseasonalized TWS time series ~~for the period 2003-2008 reveals the IAV in modeled TWS anomaly predicted by the two soil models in comparison to~~from GRACE data, over the Amazon basin,~~. Fig. 4a shows the observed TWS averaged over the entire Amazon basin. It~~ reveals that the three first years of the period 2003-2008 are drier than the ~~2003-2008~~period average, while the last three years are wetter than average (Fig. 4a). This pattern agrees with Sheffield's precipitation anomaly variation.

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The TWS drop in GRACE during the intense drought of 2005 is due to the persistent negative monthly anomaly of precipitation during the year. The abrupt increase of rainfall anomaly at the end of 2005 ~~(−0.5 mm d^{-1} in November to +1.5 mm d^{-1} in December)~~ and the persistent high positive anomaly in precipitation in January (+1.25 mm d^{-1}) lead to a TWS positive anomaly at the beginning of 2006. The simulated TWS anomaly variation ~~over the Amazon basin~~ is closer to GRACE data with the 11LAY than with the 2LAY ~~(Table 6), particularly during the negative anomaly period from mid-2004 until the beginning of 2006 (Fig. 4a)~~. During 2005 drought, ~~T~~the too large a decrease in TWS simulated by both soil hydrology schemes ~~2005 drought is captured by ORCHIDEE but with too large a decrease in TWS at the end of the year, especially in~~is less pronounced with the 11LAY than the 2LAY (~~TWS lower than observed at the end of the year by~~ bias up to -125 mm with GRACE). ~~ORCHIDEE simulated a~~Overestimation of the ~~positive~~ wet anomaly at the beginning of 2008 is ~~overestimated by about 100 mm at the beginning of 2008, but bias was~~ lower ~~(80 mm)~~ with the 11LAY (+100 mm).

Similar patterns occur~~red~~ in the Madeira sub-basin but with less amplitude (Fig. 4d). The southeastern sub-basins (Xingu and Tapajós, Figs. 4b and 4c, respectively) exhibit~~ed~~ higher abrupt transitions in TWS than the Madeira sub-basin, during the ~~entire studied~~2003-2008 period. ~~GRACE shows high~~In the beginning of 2006, ~~increases in~~ positive TWS anoma~~l~~yies (by up to +~~2~~100 mm ~~in the beginning of 2004~~) are associated with intense precipitation events (up to +5.0 mm d^{-1}). These mainly occur~~red~~ at the beginning of 2004 and 2006 for the Xingu, and only in 2006 ~~and 2008~~ for the Tapajós. These events ~~were~~are not well captured by either soil ~~model~~hydrology scheme, except for 2004 in the Xingu, with the 11LAY. Overall, the TWS increase in 2008 ~~was~~is systematically overestimated by ORCHIDEE in the southern sub-basins.

Low IAV of TWS measured by GRACE in the Solimões sub-basin (Fig. 4e) ~~was~~is overestimated by ORCHIDEE, and particularly by the 2LAY (up to +100 mm ~~with the 2LAY~~). ~~However, 11LAY reduced the bias leading to better correlation with GRACE (Table 6). Improvement particularly occurred from mid-2006 to the end of 2007 where 11LAY bias decreased by up to 30 mm.~~

By contrast, high IAV of TWS is measured in the Negro sub-basin ~~depicted high IAV of TWS~~ (Fig. 4f). When compared to GRACE data, ORCHIDEE estimate~~d~~s captur~~ed~~e the intense dry event~~s~~ in early 2004 (TWS anomalies of ~~up to~~ -100 mm ~~in TWS)~~ ~~during the beginning of 2004 and mid-2005~~, but overestimate~~d~~ ~~them~~TWS decreases by more than 70 mm in ~~early~~ 2005 and 2007.~~-~~

Overall, the 11LAY provide~~d~~s similar TWS variation to the 2LAY but reduce~~d~~s the bias with GRACE in the Amazon sub-basins. ~~Note that the introduction of a more process-based soil hydrology model did not degrade the overall model-data agreement - an achievement that should not be overlooked.~~

4.3 Spatial patterns and seasonal variations of ET and river discharge

Both soil ~~models~~hydrology schemes simulate~~d~~ similar spatial patterns in annual ET over the basin (thus, only shown for the 11LAY in Fig. 5a), with the highest ET ($> 3.5\,\mathrm{mm\,d^{-1}}$) over the floodplains near the mouth of the Amazon, and along the Guaporé and Mamoré rivers in the southern region (see Fig. 1 for the location of the rivers). The 11LAY g~~a~~ives higher annual ET than the 2LAY in the southern regions (southern parts of the Madeira, Tapajós and Xingu sub-basins), in the Andes, near the mouth of the Amazon and in the northernmost part of the basin (between $+0.1$ and $+0.7\,\mathrm{mm\,d^{-1}}$, Fig. 5c) whereas very few regions exhibit~~ed~~ higher annual ET with the 2LAY. Simulated ET ~~was~~is strongly underestimated when compared to MTE-ET, in the foothills of the eastern Andes ($> 1.0\,\mathrm{mm\,d^{-1}}$) and, too a lesser degree, in the center of the basin (between -0.4 and $-0.7\,\mathrm{mm\,d^{-1}}$, Fig. 5e). By contrast, simulated ET ~~was~~is overestimated in floodplain areas (up to more than $1.0\,\mathrm{mm\,d^{-1}}$~~, Fig. 5e~~). However, the MTE-ET product does not take into account floodplain areas and might underestimate actual ET. The largest difference in ET between the two soil ~~models~~hydrology schemes occur~~red~~s during the end of the dry season (JAS) in the southeast of the Amazon basin (Fig. 5d). The southern part of the Xingu sub-basin exhibit~~ed~~s a dry-season ET of about $4.0\,\mathrm{mm\,d^{-1}}$ with the 11LAY (Fig. 5b), more than $1.0\,\mathrm{mm\,d^{-1}}$ higher than with the 2LAY (Fig. 5d). The 11LAY overestimate~~d~~s the ET by $0.5\,\mathrm{mm\,d^{-1}}$ in this region when compared to MTE-ET

(Fig. 5f). We will further investigate the effect of soil water storage parameterization on dry-season ET over the Xingu sub-basin in Sect. 4.4.

The dry-season ET increase simulated by the 11LAY is also apparent in the seasonal cycles of ET over the Xingu and Tapajós sub-basins in Figures 6b and 6c, respectively. In the other sub-basins, both soil ~~models~~hydrology schemes provide~~d~~ similar seasonal cycles in agreement with MTE-ET (Fig. 6d to 6f). However, a large spread in ET estimations exists in the sub-basins (except in the Solimões), when MTE-ET product is compared with GLEAM-ET, NTSG-ET and PKU-ET.

The 11LAY better simulates the river discharge than the 2LAY over the Amazon basin and all its sub-basins (Fig. 6), expect over the Solimões (see Table 3 in Supplementary Material). Improvement of river discharge with the 11LAY is related to the better partitioning of total runoff in surface runoff and drainage ~~By means of water conservation (precipitation is the same for both simulations),~~ and to the higher ET in the Xingu and Tapajós sub-basins ~~with the 11LAY results in river discharge~~leading to a better river discharge decrease~~s~~ during the recession limb ~~in the Xingu and Tapajós sub-basins~~ (Fig. 6b and c, respectively)~~, leading to better agreement with the ORE HYBAM data.~~

4.4 Dry-season evapotranspiration. Case study of the Xingu sub-basin.

~~The largest impact of the soil hydrology parameterization on ET and river discharge occurred for the Xingu and Tapajós sub-basins, in the southeastern region of the Amazon basin.~~ The Xingu sub-basin, chosen as a case study in this section, is characterized by the existence of a marked dry season with low rainfall in JJA (Fig. 7a). During this season, the land surface receives less than 5% of the annual total precipitation, with monthly precipitation that does not exceed $2.0\,\mathrm{mm\,d^{-1}}$ (yellow bands in Fig. 7a). The dry season is between two transition periods in MAM (and SON), where precipitation falls (rises) abruptly, by about $6.0\,\mathrm{mm\,d^{-1}}$. The wet season occurs in DJF and brings $P = 10.6\,\mathrm{mm\,d^{-1}}$ ~~of precipitation~~ on average.

On average, over the 2003-2008 period, the MTE-ET product shows rather flat ET variation ~~when compared to the model results~~ (Fig. 7b). Lowest MTE-ET mainly occurs

after the wet season whereas it is higher during the dry season with the maximum occurring during the transition period (SON), when precipitation and TWS anomalies increases (SON). This is consistent with GRACE observations, showing a TWS increase during the transition period onset in September, an abrupt increase during the DJF wet season and a maximum value in MAM (Fig. 7a and 7c, respectively). Both soil modelshydrology schemes simulated similar ET variation during the rainy seasons until the dry season onset (June and July, Fig. 7b). During these two months, The soil modelsthey both estimated an ET increase during these two months, in response to the radiation increase and the high water demand from the vegetation; this demand could be met from the available water previously stored in the soil during the wet season (Fig. 7c). However, after the third consecutive dry month, the ET from the 11LAY continueds to increase, while the 2LAY faileds to sustain ET which decreaseds in August and September (yellow bands in Fig. 7b). Interestingly, the largest decrease occurreds during the years which hadve the longest dry seasons with low precipitation amount before and after JJA (2004 and 2007). This sensitivity of the soil modelhydrology scheme parameterization to the dry season length will be further studied in Sect. 4.5. The simulated ET is poorly correlated with the MTE-ET dataset but the monthly correlation is higher with the 11LAY (0.49) than with the 2LAY (0.33). The low correlation can largely be attributed to the dry season ET simulation, as correlation is higher when the JJA period is removed from the time-series (0.63 and 0.47 according to the 11LAY and 2LAY, respectively). The ET increase during the dry season relative to the annual value, is much higher in the simulations (up to $+0.85\,\mathrm{mm\,d^{-1}}$) than MTE-ET estimation (up to $+0.20\,\mathrm{mm\,d^{-1}}$).

TWS simulated by both models was similar and in good agreement with GRACE variations (solid lines in Fig. 7c). However, the contribution of the soil reservoir (dashed bold lines in Fig. 7c) is found to be different. 11LAY simulated a higher amplitude compared to the 2LAY as reported in Sect. 4.2.1. In the wet season, the 2LAY produced an earlier maximal soil water storage (January) which remained constant until June, whereas 11LAY produced higher anomalies and a longer period soil water recharge

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~~(until March). After the wet season (e.g., March 2004, Fig. 9a), soil saturation was more rapidly reached with the 2LAY and water excess induced runoff which was mainly stored in the slow reservoir of the routing scheme (in green). By contrast, 11LAY had higher water storage in the soil (about 700 mm) than 2LAY (300 mm) (in blue), because of the higher water holding capacity of the soil. 11LAY simulated a larger decrease in soil water storage and its anomaly remained lower than the 2LAY during the recharge at the end of the year (yellow bands in Fig. 7c).~~ In the wet season, the 2LAY produces an early maximal soil water storage (January) which remains constant until June (Fig. 7c), whereas the 11LAY produces higher anomalies, a longer period of soil water recharge (until March) and stores more water in the soil (see Figure 2a in Supplementary Material). ~~The yellow bands on Figures 7a to 7c, show the propagation of the precipitation deficit over time through the hydrological system, leading to phase-lags in ET and TWS, already described by McNab (1989) and Entekhabi et al. (1996). The larger storage of water in the soil with 11LAY in August and September~~The latter feature ~~(e.g. 445 mm compared to 65 mm in the 2LAY model, for September 2004, Fig. 9b)~~ was used ~~for~~enables to sustain ~~ET during the dry season~~dry-season ET. By contrast, ~~T~~the almost depleted 2LAY soil reservoir (see Figure 2b in Supplementary Material for the end of the dry season) ~~(Fig. 9b)~~ fail~~ed~~s to sustain ET during the three consecutive dry months (JAS). The yellow bands on Figures 7a to 7c, show the propagation of the dry-season precipitation deficit over time through the hydrological system, leading to phase-lags in ET and TWS, already described by McNab (1989) and Entekhabi et al. (1996).

~~The STOMATE module of ORCHIDEE simulates vegetation CO_2 fluxes influenced by soil water storage.~~ During the wet season, ~~M~~monthly GPP ~~variations over the Xingu sub-basin were similar in~~simulated by both ~~models~~soil hydrology schemes, is simil~~ar~~during the wet season when compared to MTE-GPP estimates (Fig. 7d). ~~GPP was higher than the mean annual value due to low water stress during this period.~~ The 2LAY overestimate~~d~~s GPP anomalies ~~during the wet season~~ while the 11LAY capture~~d~~s the MTE-GPP variation. During the beginning of the dry season, MTE-GPP decrease ~~was~~is overestimated by ORCHIDEE. ~~Thus, b~~Both ~~models~~soil hydrology schemes simulated

a delay of 3 months in GPP minima during the dry season. Lower ~~water~~drought stress with the 11LAY ~~during the dry season (Fig. 9b)~~ lead~~s~~ to less severe decrease in GPP compared to the 2LAY ($-1\,\mathrm{gC\,m^{-2}\,d^{-1}}$ and $-4\,\mathrm{gC\,m^{-2}\,d^{-1}}$ in September compared to the mean annual value, for the 11LAY and 2LAY, respectively) and to a better agreement with MTE-GPP (yellow bands in Fig. 7d). The LAI decrease ~~was~~is consequently slightly less pronounced with the 11LAY (-0.1) when compared to the 2LAY (-0.3) during the dry season (yellow bands in Fig. 7e). However, both ~~models~~soil hydrology schemes display~~ed~~ smaller monthly anomalies of LAI than the GIMMS data. This may suggest a lack of realism in representing the interactions between hydrology and phenology in ORCHIDEE. Further site-level simulations should be performed, i.e. comparing simulated fluxes to flux tower measurements to identify the missing modeling processes in ORCHIDEE, such as leaf litterfall dynamics (De Weirdt et al., 2012). However, estimates of the LAI variation of tropical forest from remote sensing data are highly inaccurate (see Fig. 9d in Garrigues et al., 2008).

4.5 Evapotranspiration sensitivity to dry season length

The 11LAY ~~model~~scheme simulate~~d~~s more ET than the 2LAY during the dry season, over the Amazon basin. To test the sensitivity of the two soil ~~models~~hydrology schemes to dry season duration, we define~~d~~ the dry-season length (DSL) as the mean annual number of months with $P < 2.0\,\mathrm{mm\,d^{-1}}$ over the time period 1980-2008. Using an alternative definition which ~~took~~takes into account only consecutive months with $P < 2.0\,\mathrm{mm\,d^{-1}}$ ~~did~~does not change the results. Representing ET variation from the two soil ~~models~~hydrology schemes as a function of the DSL over the whole Amazon (Fig. 8a) shows that the maximum ET ~~was~~is simulated by ORCHIDEE when the dry season ~~was~~is 4 months. A ~~DSL~~DSL $\leq 4\,\mathrm{months}$ ~~of less than 4 months~~ applies to ~~70~~85% of the total grid cells over the Amazon basin. When DSL is between 4 and 7 months, ET decrease is more pronounced with the 2LAY than the 11LAY. The maximum difference between the two ~~models~~soil hydrology schemes ~~was~~is with a DSL ~~is~~of 5 months ($+0.45\,\mathrm{mm\,d^{-1}}$, Fig. 8b), which applies to only 5% of the total grid cells ~~(Fig. 8a)~~. For

longer dry seasons (~~DSL > 7 months~~ $DSL \geq 7\,\mathrm{months}$, for ~~5~~8% of the total grid ~~-~~cells), the impact of soil ~~model~~hydrology scheme ~~parameterization~~ on ET ~~was~~is negligible.

Figure 8b highlights the differences in ET components, which contribute to the total ET, and LAI differences between the two soil ~~models~~hydrology schemes when DSL increases. For short dry seasons (DSL <4 months), the 11LAY estimate~~d~~s higher bare soil evaporation ($+0.07\,\mathrm{mm\,d^{-1}}$) when compared to the 2LAY. The 11LAY water content in the very thin first layer ~~was~~is directly evaporated to satisfy the climatic demand. By contrast, the resistance to bare soil evaporation in the superficial layer of the 2LAY limit~~ed~~s the water exchange. The 11LAY transpiration ~~was~~is consequently smaller than that estimated by the 2LAY. Evaporation of water intercepted by the canopy ~~was~~is the main ET component ($+0.05\,\mathrm{mm\,d^{-1}}$) contributing to ET increase with the 11LAY when DSL takes values of less than 4 months. For a longer dry season (4 and 5 months), bare soil evaporation continue~~d~~s to increase (up to $+0.25\,\mathrm{mm\,d^{-1}}$) and lower ~~water~~drought stress with the 11LAY (as reported in Sect. 4.4) lea~~d~~s to enhanced transpiration of the same magnitude, increasing canopy leaf area (up to +0.4 of LAI~~, Fig. 8b~~). ~~For grid cells with a DSL between 6 and 10 months~~For extreme DSL ($DSL \geq 6\,\mathrm{months}$), neither of the ~~models~~soil hydrology schemes could supply ET because this period of ~~water~~drought stress is too long. Under these conditions, transpiration (and LAI) difference between the two soil ~~models~~hydrology schemes decreases. Bare soil evaporation ~~was~~is still higher with the 11LAY (around $+0.25\,\mathrm{mm\,d^{-1}}$), whereas difference in evaporation by interception loss decrease~~d~~s with decreasing LAI difference. ~~Total ET remained higher with the 11LAY until a DSL of about 10 months. However, transpiration with the 2LAY became higher when DSL was greater than 7 months. For extreme DSL (> 7 months), which applies to only a few grid cells over the domain (Fig. 8a), the soil water column was never saturated. Under these conditions, t~~The higher water holding capacity of the 11LAY compared to the 2LAY no longer ha~~d~~s any effect on ET supply. Moreover, the drainage flux, which is prescribed in the deepest soil layer of the 11LAY, decrease~~d~~s the residence time of the water in the soil column compared to the 2LAY where drainage flux does not exist. ~~Water~~Drought stress consequently

bec~~a~~omes higher in the 11LAY leading to lower transpiration (up to $-0.2\,\mathrm{mm\,d^{-1}}$) and lower LAI (up to -0.4). For $\mathrm{DSL} \geq 10\,\mathrm{months}$, the difference in bare soil evaporation between soil hydrology schemes decreases and ~~T~~total ET then bec~~a~~omes lower with the 11LAY than with the 2LAY. ~~when DSL was greater than 10 months; the difference in bare soil evaporation between soil models then decreased.~~

5 Conclusions

The ~~availability of~~ testing of two soil hydrology ~~models~~schemes in ORCHIDEE ~~created an opportunity to test~~allows to assess the~~ir~~ ~~different impacts~~effects ~~of these models~~ on the ~~estimated~~ Amazonian water budget and carbon flux dynamics, at the scale of the major tributary sub-basins ~~and, for the first time, on carbon flux dynamics~~. Over the entire basin and its sub-basins, the differences in ~~the~~ water budget components ~~between~~simulated by the two ~~soil models~~schemes ~~were~~are small. ~~The sub-basin scale study did not reveal any large annual differences between the models. Although the differences are small (around 5%), t~~The 11-layer soil diffusion scheme (11LAY) ~~did slightly~~ reduces the bias in the ~~estimates~~simulation of ET ~~(up to -4%)~~ and Q ~~(up to -10%), mainly in the southern sub-basins~~ in the sub-basins when compared with observations. But ET observations uncertainties are of the same magnitude than the misfit between any of the schemes and the observations, so that a particular model scheme cannot be ruled out from these data only. On another hand, the 11LAY improves the simulation of total water storage (TWS) anomalies.

~~The main difference between the soil models lies in the water reservoir contribution to TWS. The higher water holding capacity in 11LAY allows more water to be stored in the soil and its physically based partitioning of runoff and drainage results in better estimates of ET sustainability and TWS variations. The 2LAY parameterization leads to most of the water being stored in the slow routing reservoir, which does not interact directly with the atmosphere and thus does not allow ET to occur from stored water.~~ ~~This difference in~~Differences between the 2LAY and the 11LAY parameterizations ~~particularly~~

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~~affects ET during the dry season in the southern Xingu sub-basin.~~ are also more significant in the Xingu and Tapajos southeastern sub-basins exposed to a marked dry season, than the other sub-basins. ~~The 11LAY~~During the dry season, in the Xingu, the 11LAY ~~can~~ sustains ET ~~for~~during the three consecutive dry months~~;~~, whereas the ~~2LAY~~2-layer bucket-type scheme (2LAY) ~~limits it~~ strongly reduces ET~~when the dry season is too long~~ after two dry months only. The increase of dry-season ET (+17%) in the 11LAY compared to the 2LAY leads to a better representation of GPP and prevents a reduction of LAI during the dry season.

The better simulation of the water budget and TWS with the 11LAY, in most of the sub-basins of the Amazon, owes to the combination of two of its properties: (i) the physical distinction between surface runoff and drainage and (ii) the physically-based description of soil water storage.

By comparing the bucket model, the first property of the 11LAY leads to less drainage, which contribution to the total runoff over the Amazon basin is more realistic (69%) than the 2LAY (95%), when compared to the estimates of Mortatti et al. (1997) (68.1%). Less water is stored in the slow reservoir of the routing scheme (which represents a groundwater reservoir) with the 11LAY. We found the same contribution of subsurface water (including groundwater) to TWS over the Amazon basin (71%) than Pokhrel et al. (2013), and this result is also in line with Niu et al. (2007). However, the attribution of TWS to sub-surface versus surface water remains uncertain since other studies (Paiva et al., 2013) suggested that most of the TWS variability was regulated by surface waters.

The second property of the 11LAY enables a higher water holding capacity by soils, resulting into a higher soil moisture level than in the 2LAY. Lower drought stress in the 11LAY sustains ET, which suggests that soil moisture parameterizations are critical in LSMs over the southern part of the Amazon that has strong seasonality in precipitation and marked transition periods between wet and dry soils. Our analysis is being extended to the global scale with the objective of identifying whether differences in wa-

ter budget components can be found in the transition zones identified by Koster et al. (2004a), where soil moisture is expected to influence precipitation.

~~Lower water stress in the 11LAY gave a better representation of the decrease in carbon fluxes during the dry season, limiting the LAI variation. Overall, our study highlights the dominant effect of the dry-season length on ET, vegetation phenology and carbon dynamics over the Amazon basin. More attention should be paid to improving the representation of the soil hydrology and the relationship between water-stress and vegetation dynamics in LSMs. Developing these relationships would improve our ability to simulate feedbacks on dry-season precipitation, and thus on low river flows which could severely decrease in the future over southern Amazonia (Guimberteau et al., 2013).~~

~~Our study suggests that soil moisture plays an important role in those regions of Amazonia that have strong seasonality in precipitation, with marked transition periods. This comparative study between the two soil models of ORCHIDEE is currently being extended to a global scale with the objective of identifying whether a signal can be found in the transition zones identified by Koster et al. (2004), where soil moisture is expected to influence precipitation. From the perspective of the EU-FP7 AMAZALERT (Raising the alert about critical feedbacks between climate and long-term land-use change in the Amazon) project, the present~~ The results from this study ~~work~~ also emphasize~~s~~ the need to improve the representation of the ~~water~~ drought-stress impact on carbon fluxes and transpiration ~~and vegetation dynamics, and the potential feedbacks these may have on Amazonian hydrology~~. Additional comparisons of site-level simulations with flux tower measurements across the basin would help to identify the main processes involved in ~~water~~ drought stress and lead to better understanding of the relationships between drought, the carbon cycle and phenology. ~~The small improvement gained by using the 11-layer soil diffusion scheme on the Amazonian water budget should be further verified, particularly in areas where the forest has deep roots. We suspect that soil depth, and specifically rooting depth, should be extended to greater values than 2 meters because~~ More attention should be also paid to the soil depth,

which was fixed to 2 meters for the entire basin in both soil hydrology schemes, given the lack of geospatial information across the entire basin. Several field studies showed that roots can be present much deeper than 2 meters. For tropical evergreen forest, Canadell et al. (1996) estimated an average rooting depth of 7.3 m, and a maximum of 18 m, based on data from 5 sites. ~~the d~~Deep roots observed by Nepstad et al. (1994) in northeastern Pará enable ~~Amazonian vegetation~~evergreen forests to maintain dry-season ET (Verbeeck et al., 2011)~~; this phenomenon is likely to have a significant impact on the~~ which feeds back on climate (Kleidon and Heimann, 2000). Several modeling studies concluded that deep soils and deep roots are needed in models, in order to represent realistic ET and GPP in Amazon forests during the dry season (e.g. Baker et al., 2008; Verbeeck et al., 2011). With the 2LAY, Verbeeck et al. (2011) showed that the soil depth had a significant effect on the seasonal cycle of water fluxes. We tested a soil depth of 8 meters in the 11LAY but found only a negligible effect owing to high soil water holding capacity in the 11LAY.

Overall, this study highlights the effect of the dry-season length on ET, vegetation phenology and GPP, and their sensitivity to soil hydrology over the Amazon basin. The multilayer diffusion soil scheme is shown to be reliable to further investigate the potential feedbacks between surface hydrology and precipitation, especially in southern Amazonia where low river flows could severely decrease in the future (Guimberteau et al., 2013).

6   Code availability

The source code of the ORCHIDEE model can be obtained upon request (see http://labex.ipsl.fr/orchidee/index.php/contact). Documentation on the code including scientific and technical aspects, is available here:
https://forge.ipsl.jussieu.fr/orchidee/wiki/Documentation.

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	2LAY	11LAY
Number of soil moisture layers	2	11
Soil depth	2m	2m
Soil moisture range	Wilting point - Field capacity	Residual water content - Saturation
Max. water storage in this range (average over the Amazon basin)	300kg.m^{-2}	687kg.m^{-2}
Infiltration processes	Unlimited until saturation	Limited by hydraulic conductivity with enhancement by roots, and reinfiltration in flat areas
Surface runoff processes	Saturation-excess (Dunne)	Infiltration-excess (Horton)
Soil moisture redistribution	Downward flux between the 2 layers with 3 parameters	Following Richards equation with hydrodynamic parameters based on the Mualem-Van Genuchten model with vertical decay of saturated hydraulic conductivity
Drainage at the soil bottom	No	Gravitational drainage
Dependance on soil texture	No	Yes, for 5 parameters (residual and saturated water contents, and 3 Mualem-Van Genuchten parameters)

Table 1. Main differences and resemblances between the two soil hydrology schemes, the 2LAY and 11LAY

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Variable	Dataset	Resolution		Coverage		References
		Spatial	Temporal	Spatial	Temporal	
TWS change	GRACE	1.0°	Monthly	Global	2002-2011 2013	Bettadpur (2012)
P	ORE HYBAM	1.0°	Daily	Amazon basin	1980-2009	Guimberteau et al. (2012a)
Q	ORE HYBAM	Station	Monthly	Amazon basin (scattered)	1980-2011	Cochonneau et al. (2006)
ET	MTE-ET	0.5°	Monthly	Global	1982-2008	Jung et al. (2010)
	GLEAM-ET	0.25°	Daily	Global	1984-2007	Miralles et al. (2011)
	NTSG-ET	0.5°	Daily	Global	1983-2006	Zhang et al. (2010)
	PKU-ET	0.5°	Monthly	Global	1982-2009	Zeng et al. (2014)
GPP	MTE-GPP	0.5°	Monthly	Global	1982-2008	Jung et al. (2011)
LAI	GIMMS	(1/12)°	Half-monthly	Global	1982-2011	Zhu et al. (2013)

Table 2. List of evaluation datasets

Station		River	Lat	Lon	Qmean $(m^3 s^{-1})$	Qmean contribution at OBI (%)	Basin area (km^2)
Óbidos	OBI	Amazonas	-1.95	-55.30	179,263	100	4,680,000
Altamira	ALT	Xingu	-3.38	-52.14	7,900	-	469,100
Itaituba	ITA	Tapajós	-4.24	-56.00	11,767	-	461,100
Fazenda Vista Alegre	FVA	Madeira	-4.68	-60.03	27,705	15	1,293,600
São Paulo de Olivença	SPO	Solimões	-3.45	-68.75	46,717	26	990,781
Serrinha	SER	Negro	-0.48	-64.83	16,363	9	291,100

Table 3. List of ORE HYBAM gauging stations over the Amazon basin. Qmean is the mean annual discharge from ORE HYBAM data, averaged over the period 1980–2008.

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	Amazon (OBI)				Xingu (ALT)				Tapajós (ITA)			
	P	ET	Q	$\dot{\Delta}s$	P	ET	Q	$\dot{\Delta}s$	P	ET	Q	$\dot{\Delta}s$
2LAY	6.1	2.6	3.5	0	5.4	2.8	2.6	0	5.7	2.7	3.0	0
11LAY		2.7	3.4	0		2.9	2.5	0		2.9	2.8	0
Obs	6.2	3.2	3.3	-0.3	5.4	3.4	1.5	+0.5	5.7	3.3	2.2	+0.2
	Bias				Bias				Bias			
2LAY	-0.1 (-1.2)	-0.5 (-17)	+0.2 (+65)		0 (+0.1)	-0.6 (-17)	+1.1 (+7994)		0 (0)	-0.6 (-18)	+0.8 (+3431)	
11LAY		**-0.5 (-15)**	**+0.1 (+34)**			**-0.5 (-13)**	**+1.0 (+8369)**			**-0.4 (-15)**	**+0.6 (+279)**	

	Madeira (FVA)				Solimões (SPO)			
	P	ET	Q	$\dot{\Delta}s$	P	ET	Q	$\dot{\Delta}s$
2LAY	5.0	2.6	2.4	0	5.8	2.3	3.5	0
11LAY		2.8	2.2	0		2.4	3.4	0
Obs	5.2	3.2	1.8	+0.2	5.7	3.0	4.1	-1.4
	Bias				Bias			
2LAY	-0.2 (-3.2)	-0.5 (-17)	+0.6 (+2428)		+0.1 (+2.4)	-0.7 (-24)	**-0.6 (-14)**	
11LAY		**-0.4 (-13)**	**+0.4 (+1621)**			**-0.6 (-20)**	-0.7 (-1617)	

	Negro (SER)			
	P	ET	Q	$\dot{\Delta}s$
2LAY	8.4	2.8	5.6	0
11LAY		2.8	5.6	0
Obs	8.7	3.3	4.9	+0.5
	Bias			
2LAY	-0.3 (-3.0)	-0.5 (-15)	+0.7 (+15)	
11LAY		**-0.5 (-14)**	**+0.7 (+15)**	

Table 4. Mean annual values ($\mathrm{mm\,d^{-1}}$), and bias against the observations (in $\mathrm{mm\,d^{-1}}$ and % in brackets), of the water budget components simulated by the 2LAY and 11LAY, for each sub-basin, averaged over the period 1980-2008. The bold values indicated the smallest bias between the 2LAY and 11LAY for a given sub-basin.
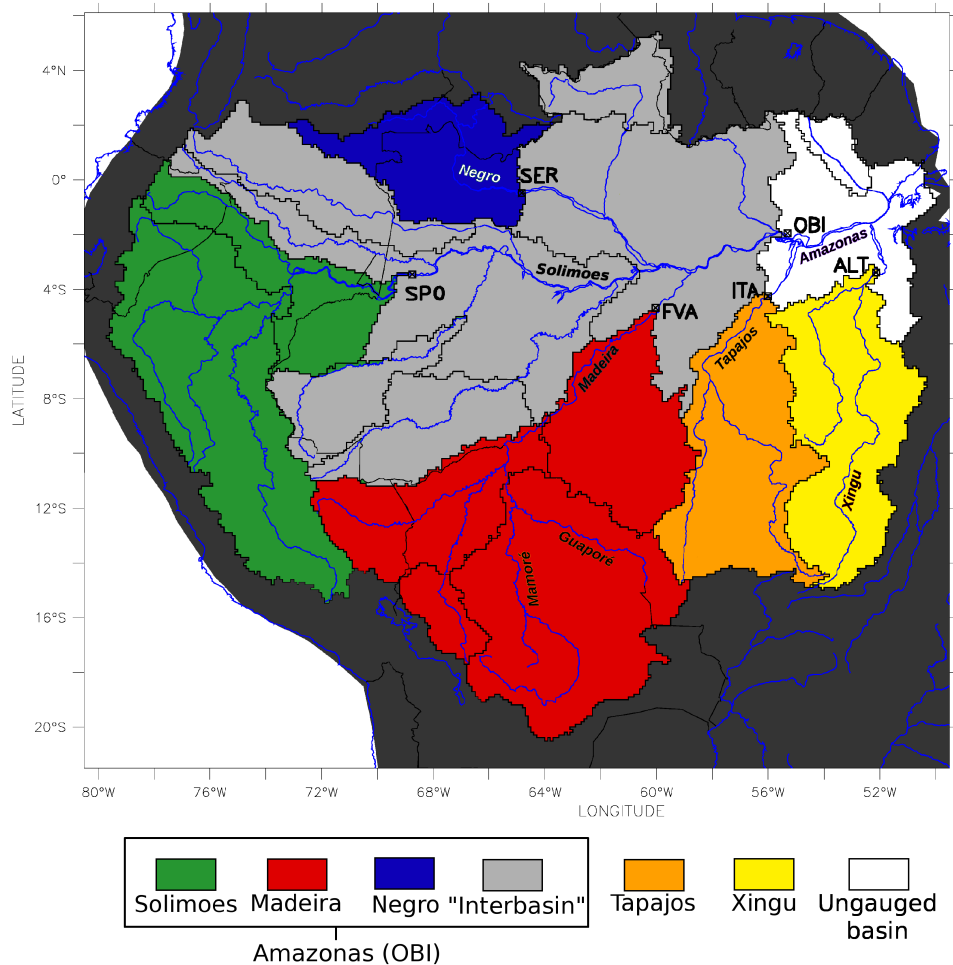
Fig. 1. Map of the Amazon sub-basins and their corresponding gauging stations. Color is used to indicate the sub-basins studied here. Modified from Guimberteau et al. (2012a).
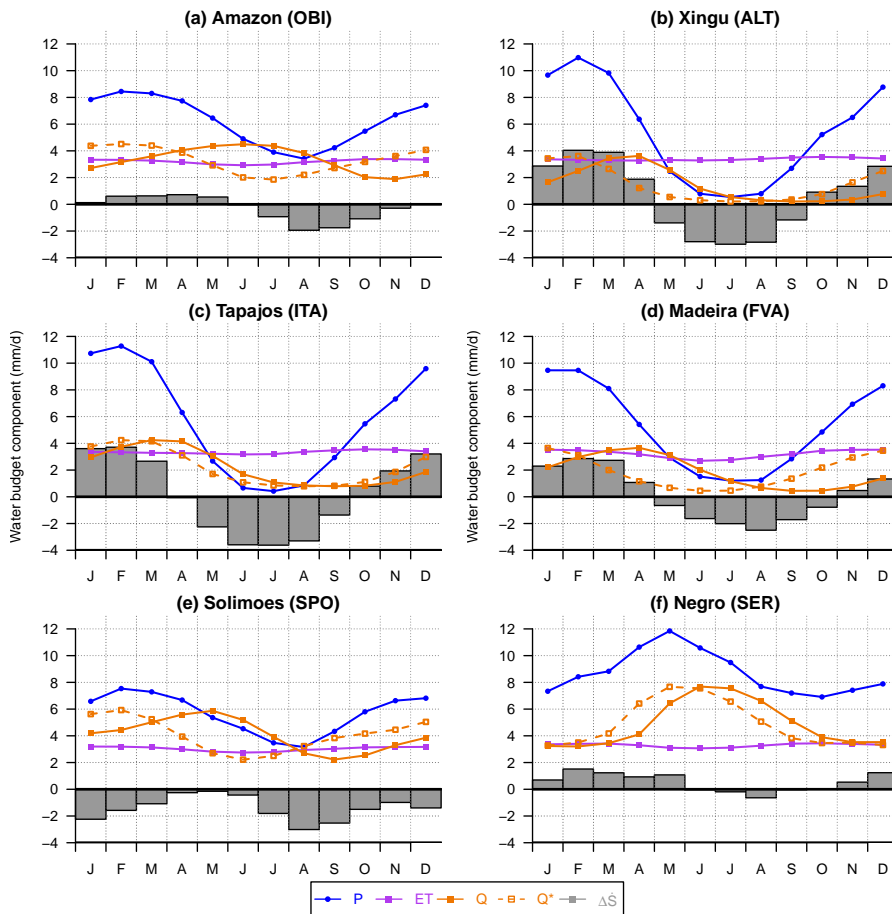
Fig. 2. Monthly mean seasonalities of the water budget components $(\mathrm{mm\,d^{-1}})$ from observations, for ~~each sub-basin~~the Amazon basin and its sub-basins, averaged over the period 1980-2008. Q^* is the equivalent runoff as the discharge Q time-series, back-shifted using the empirical lag. The change in ~~soil~~total water storage ΔS is estimated as residual of P-ET-Q*.

(a) Amazon

(b) Xingu (ALT)
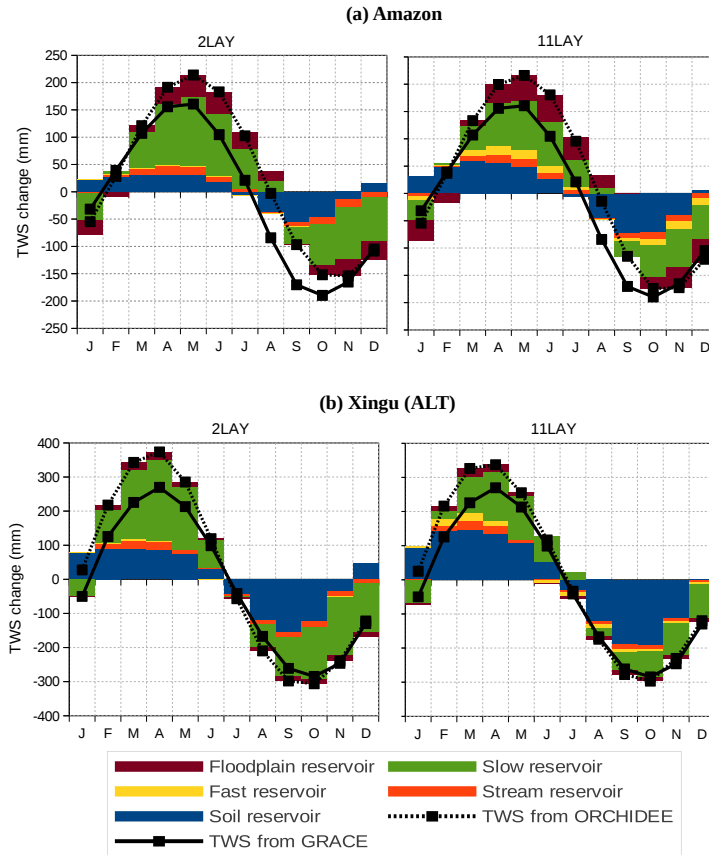
Fig. 3. Monthly mean change of the water storage components (mm) in the different water reservoirs of ORCHIDEE for simulations ~~with the~~ 2LAY (**left**) and ~~the~~ 11LAY (**right**), for ~~each sub-basin~~the Amazon basin and its sub-basins, averaged over the period 2003-2008. The thick black line represents the independent GRACE observation. The dotted black line is the sum of water storage across all the ORCHIDEE water reservoirs.
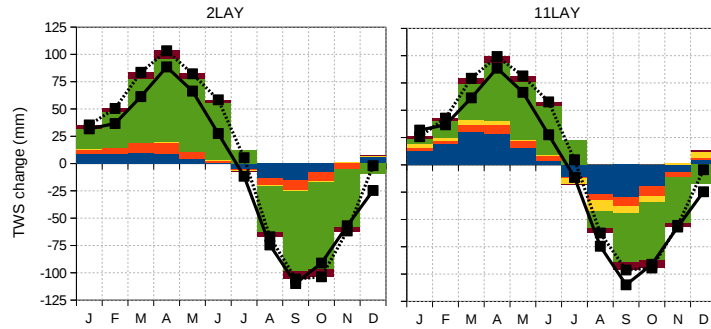
(c) Tapajos (ITA)
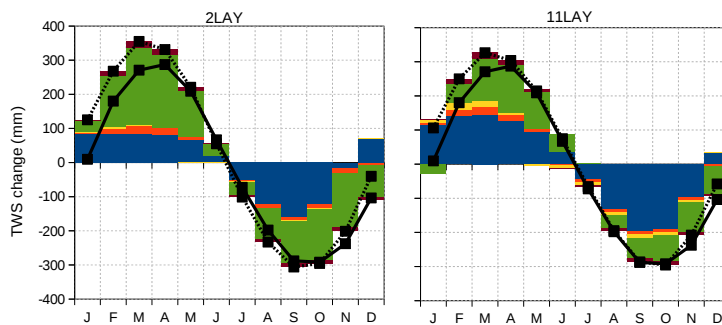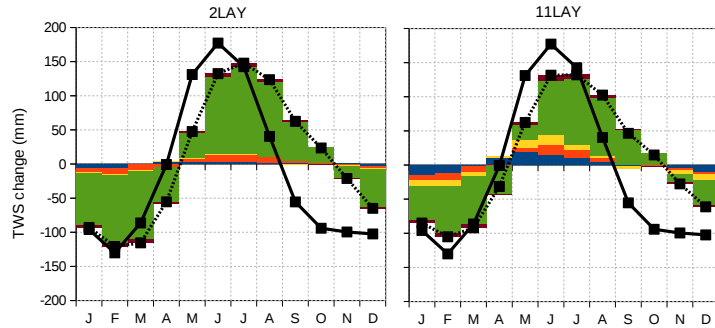
(d) Madeira (FVA)
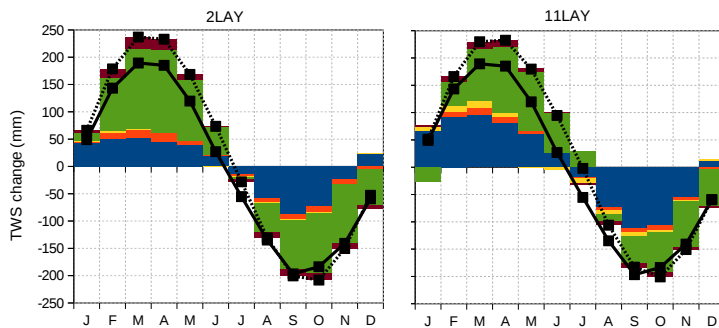
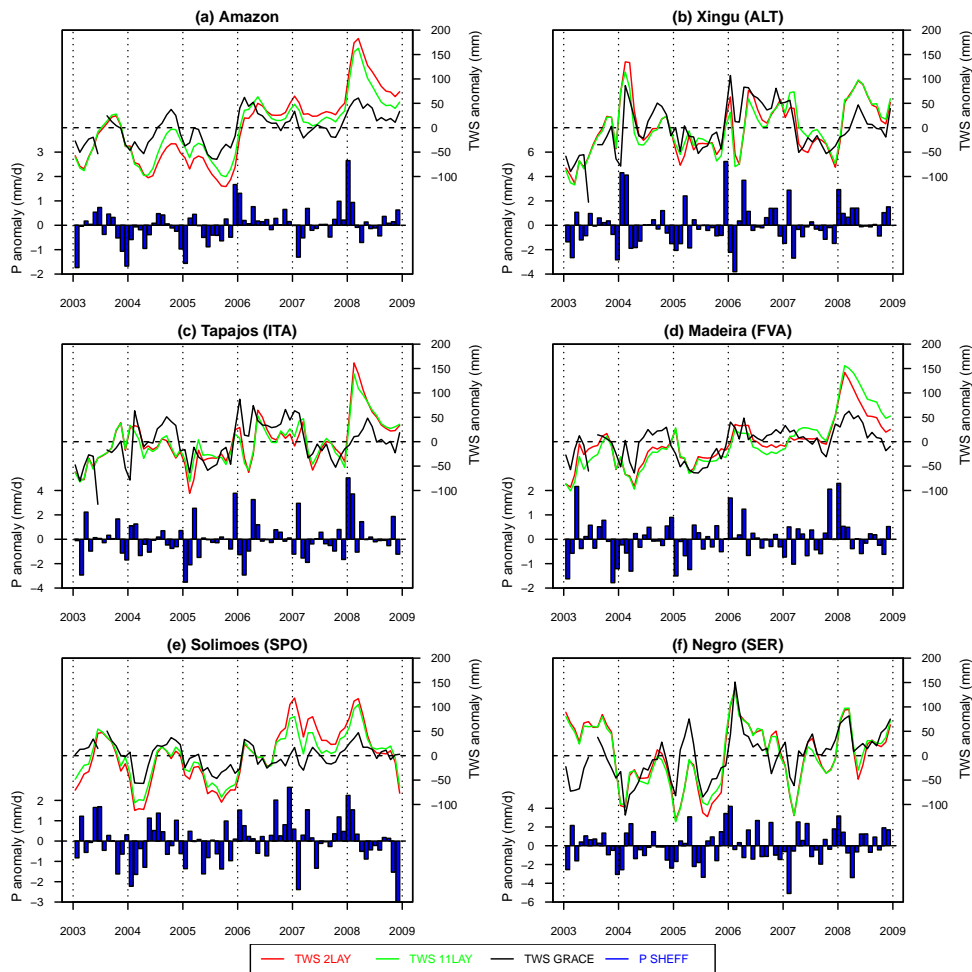**Fig. 3.** Continued

Fig. 3. Continued

Fig. 4. Interannual monthly variation of deseasonalized TWS (mm) from simulations (2LAY and 11LAY) compared to GRACE data, and Sheffield precipitation anomalies (mm d⁻¹), for ~~each sub-basin~~the Amazon basin and its sub-basins for the period 2003-2008.

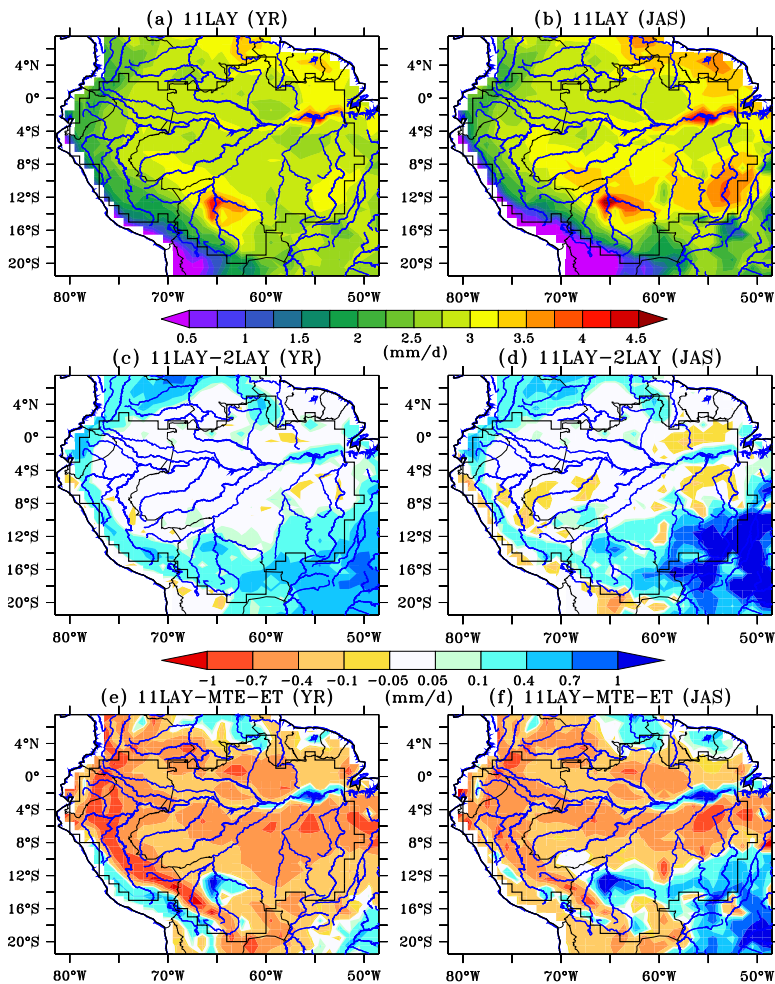**Fig. 5.** Mean ET $(\mathrm{mm\,d^{-1}})$ simulated by the 11LAY ~~over the Amazon basin~~, averaged over **(a)** the complete year and **(b)** JAS, averaged over the period 1980-2008. Differences with **(c, d)** 2LAY and **(e, f)** MTE-ET.
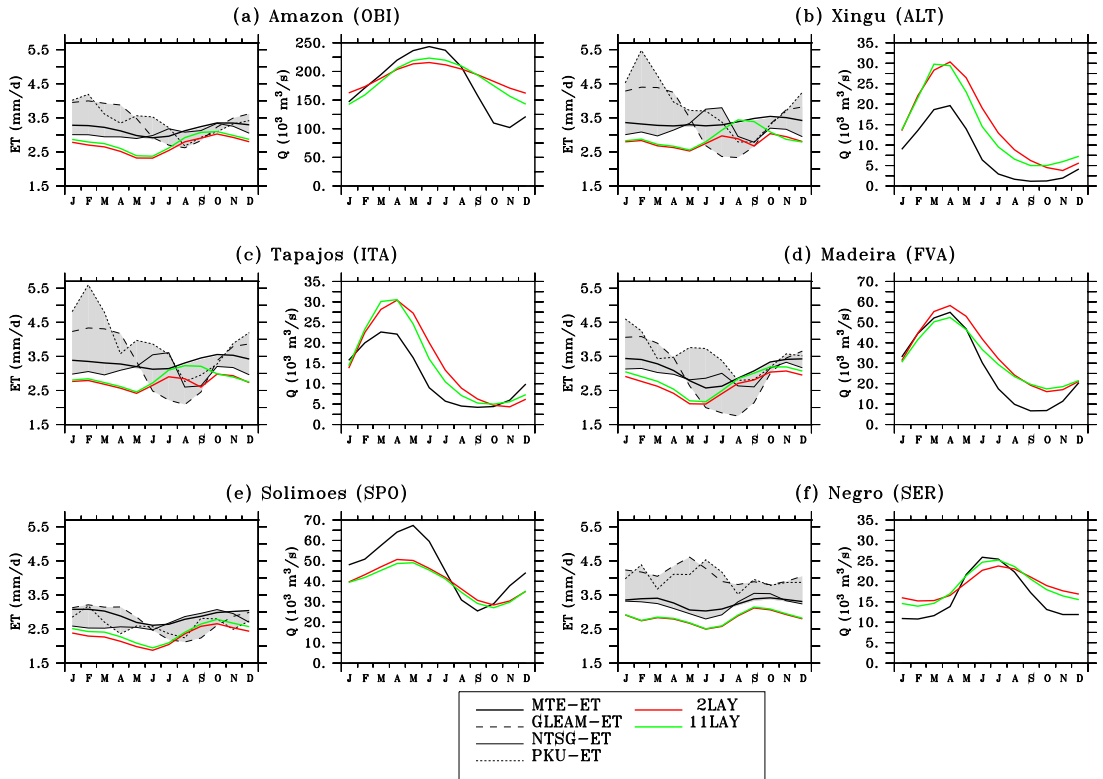
Fig. 6. Monthly mean seasonal ET averaged over the different sub-basins $(\mathrm{mm\,d^{-1}})$ and river discharge at the gauging stations $(\mathrm{m^3\,s^{-1}})$, from the 2LAY and 11LAY simulations compared to the observations, averaged over the period 1980-2008. The envelope (in gray) defines for each month the spread existing between the 4 ET products.
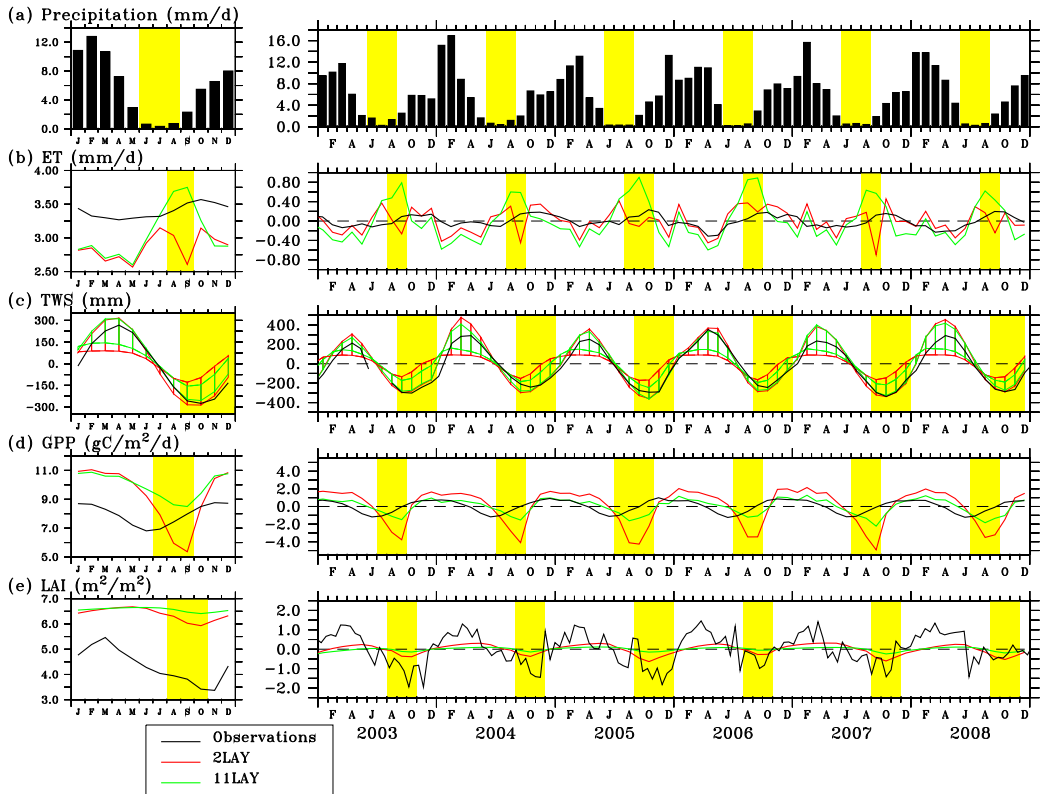
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Fig. 7. Seasonal cycle (left panels) and interannual monthly variation of anomaly (except precipitation) (right panels) in **(a)** precipitation $(\mathrm{mm\,d^{-1}})$, **(b)** ET $(\mathrm{mm\,d^{-1}})$, **(c)** TWS change (mm) **(d)** GPP $(\mathrm{gC\,m^{-2}\,d^{-1}})$ and **(e)** LAI $(\mathrm{m^2\,m^{-2}})$ averaged over the Xingu sub-basin, from simulations (2LAY and 11LAY) and observations, for the period 2003-2008. For anomaly computation, the mean value over the period considered was subtracted from each monthly value of the variable. The yellow band indicates the dry season (in (a)) and the period during which the difference in results between the 2LAY and 11LAY is high (in (b) to (e)). The shaded area (red and green in (c)) corresponds to the simulated anomaly of water stored in reservoirs other than the soil reservoir (dotted red and green lines in (c)).
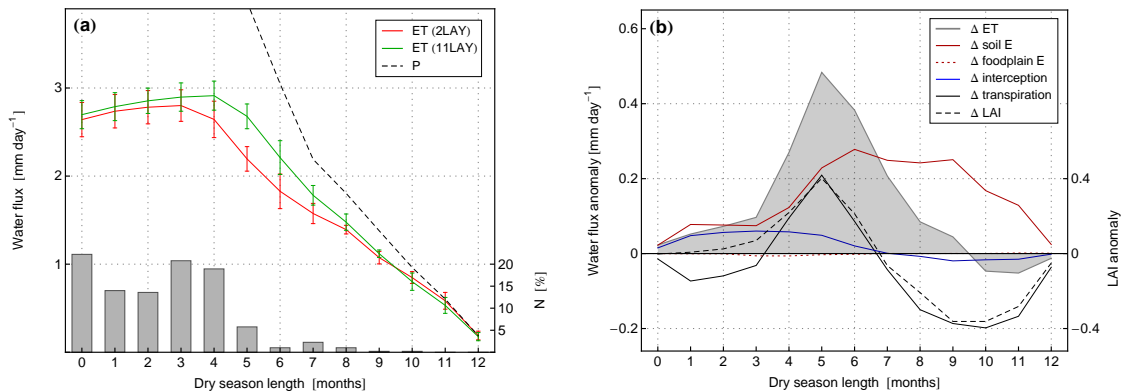
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Fig. 8. (a) Mean annual ET $(\mathrm{mm\,d^{-1}})$ from simulations (2LAY and 11LAY) and Sheffield precipitation $(\mathrm{mm\,d^{-1}})$ over the Amazon basin as function of the dry season length (DSL in months, see Sect. 4.5 for its definition). Solid lines represent the mean ET and spread (1 std) within moving bins of DSL of 1 month, according to the two simulations. The values are obtained from individual grid cells of the simulated domain. Density of grid cells (N in %) associated with each DSL value is given in the histogram. **(b)** Differences of mean annual ET $(\mathrm{mm\,d^{-1}})$, its components $(\mathrm{mm\,d^{-1}})$ and LAI $(\mathrm{m^2\,m^{-2}})$ between the 11LAY and 2LAY according to the DSL, over the Amazon basin, for the period 1980-2008.

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Supplementary material

Name	Description	Units	Sources
T_{air}	Two-meter air temperature	K	NCEP–NCAR reanalysis / CRU TS3.0
Q_{air}	Two-meter air specific humidity	$kg\,kg^{-1}$	NCEP–NCAR reanalysis
Wind	Ten-meter wind speed	$m\,s^{-1}$	NCEP–NCAR reanalysis
P_{surf}	Surface pressure	Pa	NCEP–NCAR reanalysis
SW_{down}	Surface downward short wave flux	$W\,m^{-2}$	NCEP–NCAR reanalysis / NASA Langley SRB V3.0
LW_{down}	Surface downward long wave flux	$W\,m^{-2}$	NCEP–NCAR reanalysis / NASA Langley SRB V3.0
P	Precipitation rate	$kg\,m^{-2}\,s^{-1}$	GPCC

Table 1: List of atmospheric variables in the Princeton forcing data.

	Amazon		Xingu (ALT)		Tapajós (ITA)		Madeira (FVA)		Solimões (SPO)		Negro (SER)	
	$\Delta\alpha$	$\Delta\phi$	$\Delta\alpha$	$\Delta\phi$	$\Delta\alpha$	$\Delta\phi$	$\Delta\alpha$	$\Delta\phi$	$\Delta\alpha$	$\Delta\phi$	$\Delta\alpha$	$\Delta\phi$
2LAY	+30 25	+15	+195 154	-6	+94 87	-10 9	+58 75	**+3**	+42 29	-3 +0.3	-13 2 -47	+43 31
11LAY	+56 52	**+13 12**	+152 110	-65	**+61 46**	**-65**	**+45 62**	+8	**+26 12**	-1 +2.5	**-98 -77**	**+36 24**

Table 2: Amplitude ($\Delta\alpha$ in mm) and phase ($\Delta\phi$ in days) differences of TWS between simulations (2LAY and 11LAY) and GRACE, for ~~each sub-basin~~ the Amazon basin and its sub-basins, for the period 2003-2008. The bold values correspond to the lowest bias between 2LAY or 11LAY with GRACE for a given sub-basin.

Sta.	Observed			2LAY						11LAY					
	Q_{mean}	Q_{min}	Q_{max}	Q_{mean}	Q_{min}	Q_{max}	Nash	N-RMSE	D/R_{tot}	Q_{mean}	Q_{min}	Q_{max}	Nash	N-RMSE	D/R_{tot}
OBI	179 060	66 220	260 500	190 282	135 912	253 740	0.43	22.4	0.95	185 859	111 321	262 069	**0.58**	**19.1**	0.69
				(6.2)	(105.2)	(-2.6)				**(3.8)**	**(68.1)**	**(0.6)**			
ALT	7 788	707	30 120	15 142	1 881	40 329	-0.63	118.2	0.95	14 273	3 030	46 964	**-0.33**	**107**	0.55
				(94.4)	**(165.7)**	**(33.9)**				**(83.3)**	(328)	(55.9)			
ITA	11 826	2 908	27 410	15 489	2 405	43 073	0.06	62.7	0.95	14 974	3 161	48 298	**0.23**	**56.8**	0.53
				(31.0)	(-17.3)	**(57.1)**				**(26.6)**	**(8.7)**	(76.2)			
FVA	27 873	2 914	69 530	34 520	11 576	78 081	0.70	36	0.95	32 328	13 436	75 934	**0.74**	**33.7**	0.61
				(23.8)	**(297.2)**	(12.3)				**(16.0)**	(361.1)	**(9.2)**			
SPO	46 660	15 280	81 660	40 006	20 236	68 561	**0.45**	**24.6**	0.95	38 927	19 562	66 540	0.40	25.7	0.70
				(-14.3)	(32.4)	**(-16.0)**				(-16.6)	**(28.0)**	(-18.5)			
SER	16 377	3 603	31 790	18 893	11 182	27 776	0.47	29.2	0.95	18 788	9 716	29 984	**0.65**	**23.9**	0.79
				(15.4)	(210.4)	(-12.6)				**(14.7)**	**(169.7)**	**(-5.7)**			

Table 3: Statistical results of observed and simulated discharges (Q_{mean}, Q_{min}, Q_{max} (all in $m^3.s^{-1}$), Nash coefficient and N-RMSE (%)) for the studied stations over the period 1980-2008. Values between brackets are relative differences (%) between simulation and observations. See Guimberteau et al. (2012) for more details on the computation of the indicators. The bold values correspond to the best score between 2LAY and 11LAY with observations for a given station. Values of the ratio of drainage (D in $kg.m^{-2}$) and total runoff ($R_{tot} = R_{surf} + D$, in $kg.m^{-2}$), simulated by the 2LAY and 11LAY, are also indicated for each sub-basins.

	Amazon	Xingu(ALT)	Tapajós (ITA)	Madeira (FVA)	Solimões (SPO)	Negro (SER)
2LAY	0.91 0.90 (0.85 0.76)	0.97 0.98 (0.66 0.68)	0.97 (0.55 0.46)	**0.98** (0.81 0.70)	0.84 0.86 (0.50 0.59)	0.70 0.73 (0.57 0.60)
11LAY	**0.95 (0.90 0.83)**	0.97 0.98 (0.61)	**0.98 0.97 (0.56 0.47)**	0.96 0.95 (0.77 0.64)	**0.89 0.91 (0.60 0.69)**	**0.75 0.77 (0.58 0.61)**

Table 4: Monthly correlation of TWS anomalies, between simulations (2LAY and 11LAY) and GRACE, over the Amazon basin and its sub-basins, for the period 2003-2008. Values between brackets indicate correlation of deseasonalized TWS anomalies. The bold values correspond to the highest correlation between 2LAY or 11LAY with GRACE for a given sub-basin.
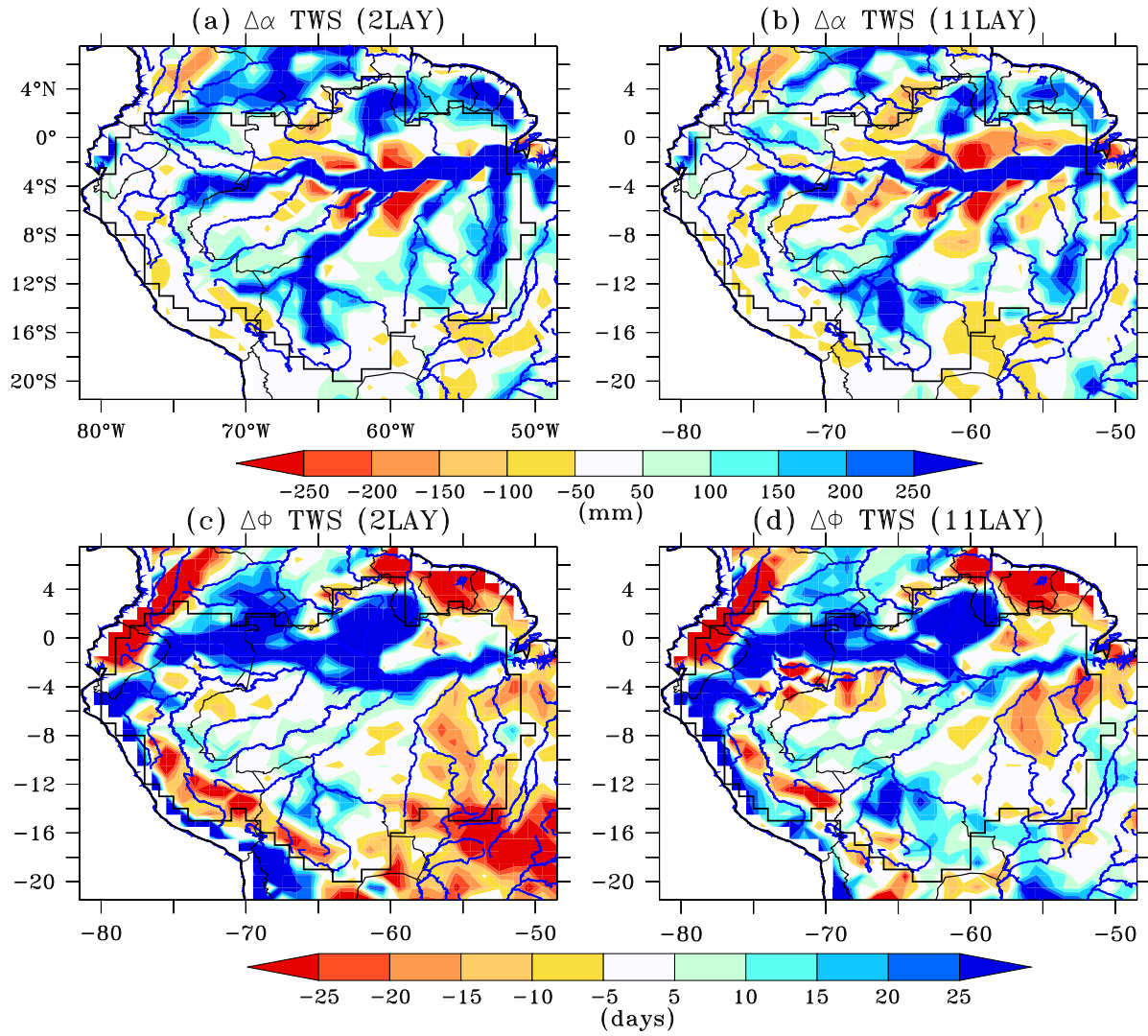
Figure 1: Differences in **(a, b)** amplitude ($\Delta\alpha$ in mm) and **(c, d)** phase ($\Delta\phi$ in days) of TWS between simulations (2LAY and 11LAY) and GRACE, averaged over the period 2003-2008.
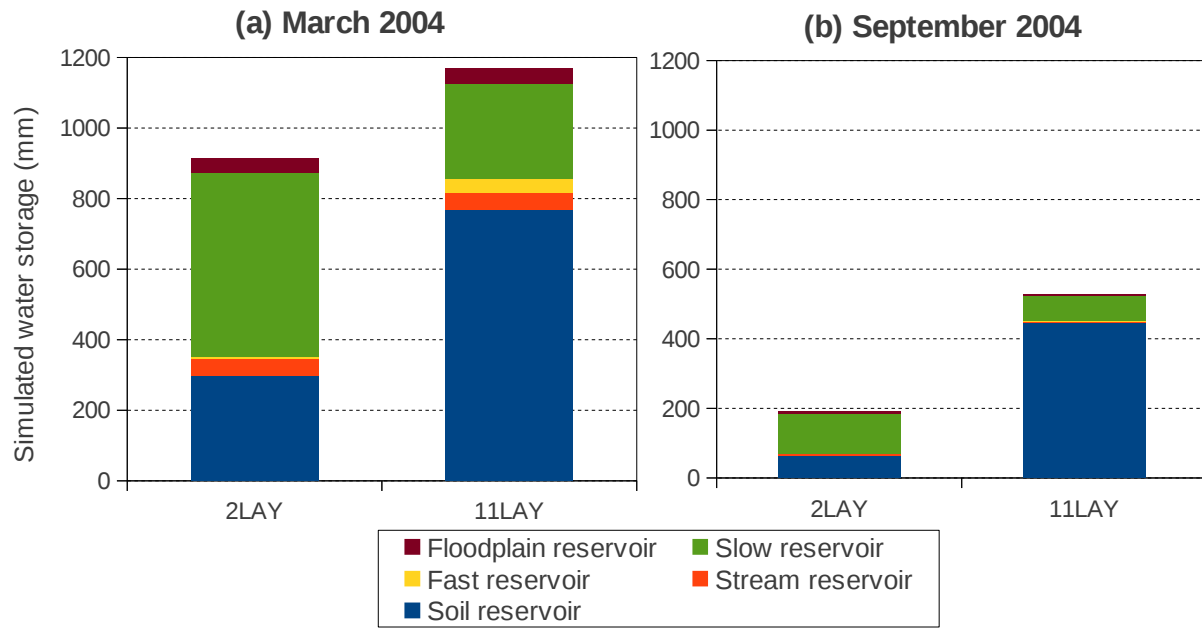
Figure 2: Monthly water storage distribution in the different reservoirs of ORCHIDEE (mm) between 2LAY and 11LAY, averaged over the Xingu sub-basin, during two contrasting months of 2004: **(a)** March (after the wet season) and **(b)** September (after the dry season).