Response to the Reviewer's comments

Simulation of Surface Fluxes in Two Distinct Environments along aTopographic Gradient in a Central Amazonian Forest using the INtegrated LAND Surface Model" by Broedel et al. (2017).

NOTE:

The authors would like to thank the reviewer for their constructive comments that have shaped the discussion and focus of our revised manuscript. Detailed point-to-point answers to the reviewer comments and sections of the revised text associated with those comments are discussed below.

Reviewers' original comments are highlighted in yellow.

Text from the revised manuscript is in bold font.

General comments:

1)Your manuscript could be improved upon significantly if you would focus your manuscript around a clear hypothesis. If your goal is to show that the small scale variability of the topographic gradient is important and a dominant control for different fluxes in your landscape you might consider building your story around that hypothesis. Compare the two models and show that the measurements and the simulations differ significantly at each site.

We understood the importance of a clear hypothesis and rewritten the text to be clearer about your hypothesis:

In order to capture the differences in land surface processes between plateaus and valleys at local scales, we hypothesize that explicit representation of soil, vegetation and hydrological processes are needed. Since valley areas are dominated by shallow water tables, vertical ecosystem fluxes and horizontal hydrological fluxes are defined by these local scale conditions which, together with other landscape elements such as soil physical and chemical properties and vegetation distributions define a very distinct environment within the *Terra Firme* forests.

2) Your abstract needs to be rewritten. It should clearly state what you have done and what the take home message is. At the moment there are a lot of minor details.

In response to the reviewer, the abstract was rewritten to:

On Amazon *Terra Firme* forest, the local landscape heterogeneity resulting from topographic variability (plateaus dissected by valleys of various dimensions) exerts significant influence in the structure and diversity of vegetation, soil pedogenesis and hydrological flows. Since valley areas are

dominated by shallow water tables, vertical ecosystem fluxes and horizontal hydrological fluxes are defined by this contrasting condition. The main objective of the present work was to determine the necessary components of the Integrated Land Surface (INLAND) model to simulate local heterogeneity effects in a central Amazon Terra Firme forest site. Results showed that the inclusion of a lumped unconfined aquifer component in the INLAND model in the valley area, in conjunction with specific soil and vegetation parameters for both the plateau and the valley, allowed the model to simulate with accuracy the differences in the seasonal water, energy and carbon partitioning between both environments. In agreement with observations, simulated latent heat flux , net ecosystem exchange of carbon and evapotranspiration were higher on the plateau area compared to the valley; while sensible heat and surface runoff fluxes were higher in the valley. These differences in behavior of surface fluxes highlights the importance of incorporating sub-grid variability for representing Amazonian ecosystems at large scale.

3) Section “f. experimental design”. While your overall manuscript is rather long this section is a little short. Make clear why you do different simulation experiments and consider an extra section where you explain 1) your model setup and 2) your model evaluation. I would recommend not mixing them.

Due to editorial restrictions about the length of manuscripts, we did not split section f “experimental design” as recommended. However, the section was reformatted to facilitate the reader understanding, leaving information relevant for the experimental design. In addition, the description of model evaluation was left in a separated paragraphed. “Experimental design” section was rewritten to:

All of the simulations reported in this study were run with the single-point off-line version of the model with the CO2 concentration set to a constant value of 400 parts per million (ppm). INLAND was forced using the observed hourly meteorological data collected at the K34 tower for 12 full years, from January 1, 2000, to December 31, 2011. For simplicity, we used the same forcing data for the spin-up period, which is a preliminary simulation to equilibrate the model parameters, such as soil temperature and soil moisture. The spin-up in our simulations was done for a period of 60 years, initialized on January 1, 1940 and was discarded in the analysis. All the simulations used a time-step of 60 minutes.

For the plateau simulations, the top-to-bottom thicknesses of the 6 soil layers in INLAND were set to 0.20, 0.30, 0.50, 1.0, 2.0 and 4.0 m, resulting in a total depth of 8 m. For the valley, the total profile depth was set to 4 m, with layer thicknesses of 0.10, 0.20, 0.30, 0.40, 1.0 and 2.0 m from the top to the bottom. The hydraulic properties of the Oxisol of the plateau areas were taken from Tomasella and Hodnett (1996), Ferreira et al. (2002) and Marques (2009), since PTFs derived using data from temperate region soils do not accurately predict the properties of tropical soils (Hodnett and Tomasella 2002). Although Oxisols have a high clay content, they have low water availability and highly saturated conductivity; these characteristics differ from temperate clay soils. In the case of the hydraulic properties for sandy soils located in valley area, we used the soil parameters recommended by Campbell and Norman (1998) and Verhoef and Egea (2014). Different soil hydraulic parameters were used for each layer of the soil profile.

We conducted two sets of simulations for each location (plateau and valley). In the first set of experiments, the vegetation was fix (or static) in the INLAND vegetation dynamics module, thus is, no change in the stand structure was allowed to occur during the simulation period. In the second set of experiments, the dynamic vegetation routine was employed to evaluate changes in vegetation cover (biomass stocks) and carbon fluxes (productivity) between the plateau and valley after 100 years of integration (from January 1, 1900 to December 31, 1999). In addition, in the case of the second set of experiments (with dynamic vegetation), two different sub-sets of simulations were conducted: a dynamic vegetation run, which initial vegetation is the current tropical forest biome, coded as dynamic vegetation 1 (DV1); and a “cold start” run that starts from bare soil and lets the

model build the vegetation cover according to climate conditions, named dynamic vegetation 2 (DV2). Plant growth, which results from the assimilation of C through photosynthesis, contributes to the formation of a canopy and is moderated by competition-related mortality. Carbon pools in live and dead biomass and in the soil are continuously updated and provide a "memory" of the state of the system over a series of years to decades (Foley et al. 2000).

The parameters of the INLAND model were fitted through a trial and error approach comparing simulations against the observational data from both the plateau and valley areas, including LE, H, Rn, NEE, soil moisture and water table level. The following ''goodness-of-fit'' statistics were used to verify the model performance (Ambrose and Roesch, 1982): bias, coefficient of determination (R2), and the Root Mean Square Error (RMSE).

4) What happens if you remove your ground water model? Is your model performance decreasing? Why do you add a conceptual groundwater model instead of switching to statured conditions with the Darcy equation? Wouldn't this be much more consistent?

In order to be more clear about the importance of the groundwater model to represent the differences between both areas, we rewritten the paragraphs in Line 243 to 253. The original sentence of the manuscript in the Line 243 to 253 was:

"The INLAND model does not explicitly represent water table dynamics. Instead, the lower boundary condition is allowed to vary from 100% free drainage to zero flux (based on an empirical coefficient ranging from 0 to 1). This means that the model can be applied to a plateau environment, although it cannot correctly simulate a valley environment where the water table remains at or very close to the soil surface for much of the year. Consequently, we incorporated into the INLAND model a lumped unconfined aquifer model developed by Yeh and Eltahir (2005 a, b), in which the water table is interactively coupled to the soil column through the soil drainage (groundwater recharge) fluxes. All processes within INLAND, except for those computing the soil moisture, were preserved with the original IBIS equations. The lumped water balance equation for an unconfined groundwater aquifer can be written as follows, according to Yeh and Eltahir (2005 a):"

And was changed to:

The INLAND model, such as most single-column land surface schemes, does not explicitly represent neither the water table dynamics nor the horizontal hydrological fluxes responsible for baseflow. In the case of the INLAND, the lower boundary condition is allowed to vary from 100% free drainage to zero flux (based on an empirical coefficient ranging from 0 to 1). This is a clear limitation in case of the valley areas, since baseflow is crucial to sustain discharge in the dry season, and it directly dependent on the time-variation of the amount of water store in the valley. Groundwater fluxes of the plateau area, on the other hand, are affected by 3-month delays due to the travel time of percolating water through a deep vadose zone of the plateaus, and consequently, groundwater responses are more gradual than in the valley areas. Consequently, we incorporated into the INLAND model a lumped unconfined aquifer model developed by Yeh and Eltahir (2005 a, b) to represent the valley area, in which the water table is interactively coupled to the soil column through the soil drainage (groundwater recharge) fluxes. The use of this methodology in INLAND for the valley area is crucial to represent the contrasting groundwater responses in both environments and, at the same time, keeping the model´s simplicity. A more physically-based representation of these processes should require a three-dimensional formulation of the Richards

equation, however at the expense of more computational cost. All processes within INLAND, except for those computing the soil moisture, were preserved with the original IBIS equations. The lumped water balance equation for an unconfined groundwater aquifer can be written as follows, according to Yeh and Eltahir (2005 a):

5) In your results and discussion you go into great detail. However for an improved readability consider moving some of the details to an appendix or consider doing a separated result and discussion section. You have nice results and discussion points it is just difficult to find them between all the model details.

The authors understand that the Results and Discussion section provides plenty of information, since the numerical experiments were exhaustive and comprehensive. Therefore, we preferred not to move our result to the appendix because it is the more important section of the paper. However, the content was reorganized in order to ensure easier and more rapid access to information in accordance with the following subsections:

a. **Representation of water table dynamics in the valley**
b. **Impact of hydrology properties parameters in the plateau**
c. **Water fluxes in the plateau and valley**
d. **Energy fluxes in the plateau and valley**
e. **Net Ecosystem Exchange in the plateau and valley**
f. **Biomass and productivity of vegetation in the plateau and valley**

6) In your conclusion you again explain in great detail that your model is capable to mimic different fluxes and states variables. You state that this confirm your initial hypothesis I would explain a little more why do you think this is true.

In accordance with the suggestion made by referee, we rewritten the conclusion section, removing unnecessary details and explain better why the initial hypothesis was confirmed and highlighting the usefulness of this work:

We have demonstrated that the inclusion of a lumped unconfined aquifer component in the INLAND model in the valley area, in conjunction with specific soil and vegetation parameters for both the plateau and the valley, allowed the model to simulate, with accuracy, the differences in seasonal energy, water and carbon partitioning of both environments, confirming our initial hypothesis.

The INLAND model captured very well the difference in the partitioning of incoming energy and carbon fluxes, mainly LE, H and NEE fluxes in both seasonal and diurnal time scales. The model also reproduced the biomass and carbon flux variability between the plateau and valley, suggesting a larger productivity of the plateau forest, in agreement with the available studies in the central and eastern Amazon. The main difference found in water balance were related to ET and R fluxes. The mean R on the plateau was significantly lower during the wet season, representing a small portion (3%) of the total precipitation over the entire period. In the valley, this percentage is much larger, representing approximately 25% of total precipitation. On the plateau, the mean ET was 14% higher than in the valley, with maximum amplitude in August, when the precipitation is lower. Considering that the study site can includes 56.9% of plateau areas and 43.1 % of valley areas (Nobre et al., 2011), and taking into account that land surface models in previous studies (for instance, Harris et al., 2004) has been parameterized based in plateau data only, based on our results we concluded that previous results might be overestimating evapotranspiration in 8 - 16 %.

The differences in the partitioning of surface fluxes for these two environments highlights the importance of incorporating sub-grid variability for representing Amazonian ecosystems at large scale, contributing to reduction the uncertainties in future climate scenarios and vegetation cover changes. Finally, since the results of this study have been validated in a Central Amazonia *Terra Firme* site, it remains to be tested INLAND´s model modifications in other Amazonian environments.

Technical comments:

1) Line 274: Where is equation 3 and 4?

The equation 3 and 4 actually is equation 1 and 2. This error has been corrected:

The groundwater model represented by Eq. (1) and Eq. (2) was interactively coupled with the soil model in INLAND such that the total length of the active unsaturated soil column varied in response to the water table depth fluctuations by keeping the number of unsaturated layers variable.

2) Line 346-347: Why do you pick the bias, R2 and the RMSE as error statistics? Why do you think these three are a good choice in your case?

We used the error statistics (bias, R2 and the RMSE) as recommended by recent modeling studies such as Shrestha et al. (2016) and Rodriguez and Tomasella (2015).

3) Line 309: Up to a grid resolution of 4 m with Darcy Richards. I know that this is common practice in the land surface community but you might want to read the papers of Lehman, Or and Vogel about the basic assumptions of the Darcy Richards equation and if they hold within a 4m large grid.

We understand the importance of basic assumptions of the Darcy Richards equation and the limitations of its use in land surface models. We are aware that the hydrologic response of the vadose zone is more dynamic close to the groundwater table and the soil surface, demanding a more detailed description of model´s layers close to the aquifer. In spite of this, simulations are enough accurate, considering the other sources of uncertainties in this type of study.

4.) Line 353: Maybe I missed that part. How do you know that your vegetation and soil parameters are optimal?

In order to be clearer about the performance evaluation, we rewritten the paragraphs about the description of error statistics, in Line 343, to:

The parameters of the INLAND model were fitted through a trial and error approach comparing simulations against the observational data from both the plateau and valley areas, including LE, H, Rn, NEE, soil moisture and water table level. The following ‘‘goodness-of-fit’’ statistics were used

to verify the model performance (Ambrose and Roesch, 1982): bias, coefficient of determination (R2), and the Root Mean Square Error (RMSE).

We also modified the word Optimal in Line 353 to:

After determined the most adequate vegetation and soil parameters set of plateau and valley forest (Table 1), and incorporating the unconfined aquifer model into INLAND to correct represent the valley area, we compared the water table depth (WTD) simulated by model with observations, from 2002 to 2006.

5) You write that your model reproduces several fluxes in the different parts of the result section reasonable well. I would consider sharing what you mean by reasonable well. Is the difference above or below the measurement uncertainty? Does it show in comparison to other models or model studies much better or similar performance?

One example is Line 476 to 480. Here you write that your model is doing well because it simulates different ET values for the plateau and the valley in good accordance with the observed data of 2006. However, your model simulates 3.7 mm day1 for the plateau and 3.2 mm day1 for the valley. Your observations are 3.0 mm day1 and 2.9 mm day1. First of all is the differences between the observations with 0.1 mm day1 above your measurement uncertainties? Is it possible to say that the two sites are different on an annual scale based on these measurements? Secondly if this is the case why do you think your model is doing well here? It overestimates the differences and the plateau observation is closer to the valley simulation.

As requested by reviewer 1 we already reformulated and clarified the expression “reasonable well” in our text, in order to better describe the performance model, including the text in the line 476 to 480.

In the Line 476 to 480, our observed data in both areas (plateau and valley) from 2006 is close each other. However, the different Leaf Area Index (LAI) in both areas (Cuartas et al., 2012; Marques-Filho et al., 2005) supports the fact of the ET fluxes in this areas shows differences. Furthermore, Hodnett et al. (1997a), based on soil moisture measurements, showed a gradual reduction of ET fluxes from plateau towards the valley bottom areas. According to Zanchi (2013), the water extraction in poorly drained valleys occurs at a shallower depth and can be reduced compared with that on plateaus. Therefore, in spite of the uncertainties of evaporation measurements, there is previous ET direct measurements and indirect information, such as vegetation structure and water balance estimations, that support the conclusion that evaporation rates in valley areas are lower than in the plateaus.

In the Line 476 to 480, we also understand the difference between simulated and observed data. The INLAND model overestimated the ET in both areas. Because this, we rewritten this paragraphs. The original sentence of the manuscript in the Line 476 to 480 was:

“The INLAND model simulated very well the difference of ET fluxes between plateau and valley, showing larger values on the plateau than that in the valley, in accordance with the observed data in 2006 (Figure 7a). The simulated annual mean ET was 3.7 mm day-1 and 3.2 mm day-1 for the plateau and the valley, respectively, values close to the observed data, from 3.0 mm day-1 in the plateau and 2.9 mm day-1 in the valley.”

And was changed to:

The INLAND model is able to predict the differences in ET between the plateau and valley, specifically, higher values of ET in the plateau compared to the valley (Figure 7a). The lumped unconfined aquifer component was essential to represent the ET in the valley because this environment is close to saturation most part of time (Figure 5a). In Central Amazonia, it is well documented that soils are related to local altitude (Chauvel et al., 1987) and that forest types are defined by topography and soil, which affects species composition, morphological structures, forest dynamics, and physiological constraints (Castilho et al. 2006). In the valley areas, dominated by poorly drained hydromorphic sandy soils, species are adapted to the conditions of episodic hypoxia as indicated by the presence of adventitious surface roots (Brito, 2010). Episodic hypoxic condition in these soils, and consequently in the root system, may induce a decrease in stomatal conductance and in the photosynthetic rate, limiting plant growth (Pezheshki 2001; Li et al., 2007).

However, in terms of magnitude of ET, INLAND simulated fluxes are higher than observations. A likely explanation for these discrepancies could be related to the lack of closure of the energy balance, a well-recognized problem of the eddy covariance method (Massman et al., 2002; Aubinet et al., 2002) that has already been reported by other studies in Amazonia (Malhi et al., 2002; Von Randow et al., 2004; Rocha et al., 2004; Wilson et al., 2002). Our analyses, for example, (not shown) revealed that on average, latent and sensible heat fluxes fell 17% short of the available energy in the plateau area, while for the valley the figure was 23%, which indicates that in both areas the energy balance did not close. In addition, a recent study of Martínez-Cob and Suvocarev (2015) showed that LE obtained with the infrared gas analyzer (IRGA-LI-COR, model LI-7500), the same instrument used in this study, is not reliable during rainy periods due to failure of the instruments caused by water drops standing over the sensors heads. Therefore, potential interference of rainfall can also be responsible for underestimation of LE in the study area, in both plateau and valley.

Finally, this is the first study that simulates local environment differences (plateau and valley) in Amazonia; therefore we cannot compared INLAND performance with other models, as suggested by the reviewer. We understand that there are various limitations in the simulations and observations, which are not unique of the INLAND model (Restrepo-Coupe et al., 2016), but given the pioneer character of this study in the area, all the reviewer comments were noted whenever possible.