Reviewer 1

We thank reviewer 1 for the detailed and thorough comments. Our replies to the comments are inserted below in blue colour.

Dear authors,

after reading your paper, I had generally good impressions, but I also found the methods section confusing.

The overall structure of the paper is fine. I really like the choice of experiments for the model evaluation, and it provides a clear overview of the strengths and limitations of the model. I do think this model has potential to help advance our understanding of climate-land surface-human activity interactions (high scientific significance), and therefore think that this work has good scientific value.

However, I would recommend a thorough revision/restructuring of the methods section before publishing. I found it quite confusing to work out how exactly the model calculates certain things on a first reading, and a second reading (with pen and paper) still left things unclear. Because of this I couldn't rate the presentation and the reproducibility high. I clicked "major revisions", but the focus is mainly on the explanation of the methods rather than the science. I am of course willing to review the revised manuscript.

We thank the Reviewer for the generally positive review. We are also very grateful for the thorough analysis of our methods, which led to a great improvement of the presentation of the model description.

One important part to emphasize is the role of the FMS coupler. FMS standardizes the interfaces between various model components and handles the fluxes between them. Hence, FMS has several tasks of a LSM, including the calculation of aerodynamic resistance, drag, and air stability calculation by taking into account information from the land model and the atmosphere. In our coupling approach we just provide the same variables to FMS as Lad, which are roughness length, albedo, humidity and surface/canopy temperature. The coupler then calculates the fluxes to the atmosphere, e.g. q_flux, and makes this information available for the land model in the next time step. Since our coupling approach is limited to the interface between LPJmL and FMS, it is beyond the scope of this paper to explain in detail the processes within FMS and the atmosphere. To avoid misunderstandings, we also changed the name of the blue box of Fig. 2 in the paper to FMS coupler. The variables stated there are all calculated in the coupler, using input from the atmosphere model. To clarify and explain better the role of the coupler, we added to section 2.3.

"In this Section we describe our coupling approach at the interface between the land model (LPJmL) and the FMS coupler. FMS calculates the fluxes between the different model components and provides this information to the sub-components. The tasks of the coupler also include the calculation of air stability and surface drag, hence it has some functionality of a land surface model. Because it is beyond the scope of this paper to explain the processes within FMS in detail, we refer to Milly and Shmakin, 2002 and Anderson et al., 2004 for further details."

In the following we answer the comments and questions of the Reviewer in detail:

It is stated in line 139 that the variables that are exchanged on the "fast" time step are: canopy humidity, soil temperature, canopy temperature, roughness length and albedo. Some first questions that come to mind:

- Does canopy temperature refer to bulk surface temperature?

The reviewer is right, that by using an energy balance equation we are calculating a surface temperature. Since we do not have a height dependent scheme in our canopy, this surface temperature is used for the calculation of the canopy evapotranspiration and humidity. Hence, we effectively use the calculated surface temperature as the temperature of the canopy layer, similar to the parameterization in LaD. We added this information to 2.3.2 to express this more clearly:

"Since our approach does not account for a height dependent canopy temperature, we used here the surface temperature as an approximation for the canopy temperature, which is then used to calculate canopy humidity and evapotranspiration. Hence, surface temperature and canopy temperature are assumed to be the same, following the approach in the LaD model (Milly et al. 2002)."

- Do all the tiles in a gridcell have the same "canopy" temperature (even the bare soil fraction?)

In LPJmL, each grid cell contains several so-called stands, one for natural vegetation, and one for each crop type (CFT) and for managed grassland. The natural vegetation is subdivided into plant functional types (PFTs). The surface/canopy temperature is calculated separately for each stand, and then averaged over all stands before it is used for humidity calculations and passed to the coupler. We added an explanation of the stand structure of LPJmL to the LPJmL model description in 2.2 (see our response to your last question), and added the following sentence to 2.3.2:

"While the temperature is calculated individually for each stand, a weighted average over all stands within one gridcell is used in the humidity calculation and passed to the coupler."

- What is soil temperature and why does the atmosphere need it?

In our implementation, the surface/canopy temperature interacts with the atmosphere. However, for simulating permafrost, soil hydrological processes and soil heat transfer, soil temperature is computed within LPJmL5. Therefore, soil temperature is the temperature in the various soil layers in LPJmL5 (i.e. 6 layers in the current version). It is not needed by the coupler or the atmosphere, just internally used by LPJmL. Since the climate input from the coupler and the whole temperature routine operates on the fast time-step, the soil temperature is also calculated hourly. For the other daily calculations in LPJmL5 a daily mean is applied. The soil temperature uses the air temperature as an input, which is highly dependent on the new canopy temperature. We also added the description of the time step for both temperature calculations (fast time step). To clarify, we added in Section 2.3.2:

"The soil temperature is still important for internal processes in LPJmL5 such as permafrost but not needed in the coupler to calculate fluxes from the land to the atmosphere. The calculation of heat transfer in the soil layers uses the heat-convection scheme as in stand-alone LPJmL5 (Schaphoff et al. 2018a) by taking into account the air temperature, which highly depends on the canopy temperature. Both temperature calculations, for the surface/canopy temperature and for the soil temperature, operate on the fast time step."

- How does the atmosphere use roughness length to calculate the turbulent fluxes? Does it assume neutral stability conditions?

The aim of our paper is to describe the interface between the land component (LPJmL5 in our case) and FMS coupler. With respect to the roughness length, we have not modified any other parts in the coupler nor the atmosphere. Therefore, any handling of roughness length and assumptions referring to stability conditions in the atmosphere remain the same. LPJmL5 provides roughness length, which depends on the FPC of the PFT composition as well as CFT assemblage present in any grid cell. The coupler uses this and additional information from the land model and the atmosphere to calculate (and exchanges with the land component) aerodynamic resistance and surface drag, which depend on the roughness length, the height, where potential temperature is defined, and on the Monin-Obukhov length. In the coupled setup of the CM2Mc model, the atmosphere is not set to neutral stability but dynamically computes stability for each grid cell and throughout the sub-daily cycle. More information is available in Milly et al. 2002 and Anderson et al. 2004. We added a better explanation about the calculations in the coupler to 2.3 (see our response to first general remark) and added a sentence on the purpose of the roughness length to 2.3.3:

"The coupler uses the roughness length to calculate aerodynamic resistance and surface drag and provides these variables to the different submodels of the ESM."

EVAPOTRANSPIRATION AND CANOPY HUMIDITY CALCULATION

The aim of this calculation is, given q_flux and e_a, from the previous time step, calculate updated q_ca, which will be used by the atmosphere (along with roughness length) to calculate an updated q_flux and e_a, and so on.

Yes, this is one important aim, but please note that the calculation of q_flux is performed within the FMS coupler. Both the land model and the atmosphere provide their boundary humidity conditions. The coupler then calculates the moisture flux between atmosphere and land, q_flux, and provides it to the land model as well as to the atmosphere. Other aims of this calculation are to provide essential variables for calculations done in LPJmL such as evapotranspiration for plants or for calculating the energy balance.

Since the atmosphere provides q_flux, this means it must be assuming neutral stability conditions or using some parametrized stability functions (e.g. Louis 1979) to avoid the need for the LSM to iteratively calculate q_flux. How does this happen?

q_flux is provided and calculated by the FMS coupler by taking into account the humidity from the land model and from the lowest layer of the atmosphere. Hence, the coupler provides some necessary LSM functionality. We take q_flux to compute delta_q_ca (equation 9) to couple ET, as simulated by LPJmL5, and relate it to the canopy/surface temperature.

As explained above, the atmosphere does not assume neutral stability. However, the explanation of how exactly the coupler interacts with the atmosphere is beyond the scope of this paper. Since we did not modify any of those functions, we focus on the interaction between land and coupler in our paper. We added a better description of the processes within the coupler to Section 2.3 (see response to first general remark). For further information on the interaction between coupler and atmosphere we refer to the respective publications and model documentations which we also cite in the paper (Milly et al. 2002, Anderson et al. 2004, Galbraith et al. 2011).

The algorithm proceeds as follows

1. - Calculation of potential evapotranspiration. According to Eq. 1, you are using a daily value of ET0. Why is this? Are you calculating this quantity on a daily or a subdaily basis?

The implementation of ET0 is subdaily. While the subdaily time step is currently set to one hour, it is however flexible and hence, we stated here the more general daily form of the Penman Monteith equation. For the implementation the resulting evapotranspiration is then divided by the number of timesteps per day, which is however not necessary in the model description, in our opinion. We added the information in the text in 2.3.2 and in a new overview figure (see below), that ET0 is calculated on a subdaily basis:

“ET_0 is presented here in the general daily form, but applied to the model on the subdaily timescale, therefore divided by the number of time steps per day (in the current version 24).”

2. - Potential canopy conductance from assimilation using Medlyn's model. Is assimilation daily or subdaily? Assimilation, like stomatal conductance, varies greatly during the diurnal cycle.

This step is unfortunately calculated daily, because it is a core calculation in LPJmL5 in relation to the photosynthesis routine. By changing this to a new subdaily parameterization, large parts of LPJmL would have to be adapted as well and the results would deviate largely from the original model. Since we wanted to keep the basic functions of LPJmL5, e.g. photosynthesis, as close as possible to the stand alone version, we decided to use daily values in this step. The actual water-stressed canopy conductance is, however, calculated subdaily using the Penman-Monteith formula (Eq. 1 in the manuscript). We added to Section 2.3.2:

"While the new potential evapotranspiration is calculated in the subdaily time step, the non-water-stressed canopy conductance is calculated in a daily time step, due to the daily calculation of the photosynthesis in LPJmL5."

3. - Supply/demand approach to calculate TRANSPIRATION, from which an stressed canopy conductance is derived using Penmann-Monteith again. -> OK.

I am guessing all these steps occur at a subdaily timestep but this is not clear from the text, especially because of the daily potential evapotranspiration (Eq. 1).

Almost all steps are subdaily, only potential canopy conductance is computed daily (see response to point 2, above). The variables g_i and g_e are also calculated daily, but they are based on a simple approach and do not have any subdaily input variables. We added an explanation about the length of the corresponding time step in Section 2.3.2 (see above) and information about the time step for each step of the calculations to the text and added a new overview figure for the humidity calculation (see new overview figure below). By this, we hope to have clarified at which time step those variables are calculated.

4. - Calculation of parametrized soil evaporation conductance -> OK

5. - Calculation of parametrized interception conductance -> What is Pr in Eq. (5)? Why are you using equilibrium evapotranspiration (Eq) in this formula, rather than the new Penmann-Monteith based ET0?

We thank the reviewer for noting an error in the formula. Indeed, we used ET0 instead of E_q in the model and corrected Eq. 5 in the paper accordingly. Pr denotes the precipitation, whose variable declaration was added in 2.3.2. Equation 5 now reads:

$$g_i = \mathrm{GI}_{\mathrm{MAX}} \cdot i \cdot Pr / ET_0 \cdot f_v$$

Now we get to the updating of Dq_ca (I use D for the Delta symbol).

6. - Where does Eq. (9) come from? If there is a reference for this equation, you should mention the principle from which it is derived and give the reference (e.g., q_ca is calculated from water conservation as in Author et al. (year).). If you have derived this equation yourself, I would like to see it derived in the paper too, maybe in an appendix if you don't want to put it in the main text. Apart from the derivation, a clear explanation of where or how each of the terms is calculated would be welcome (for example, the evaporation-humidity gradient).

We thank the reviewer for identifying this gap in the model description. In fact, the derivation of Eq. (9) is not straightforward since it was not documented explicitly in the original LaD paper. Using earlier publications (Milly et al., 1991) we have now derived Eq. (9) with the following steps:

Assuming equilibrium conditions the flux entering the canopy layer from soil and vegetation through evapotranspiration ET or E_{in} equals the flux leaving the canopy layer into the atmosphere q_{flux} or E_{out}.

$$E_{in}(t) = E_{out}(t) \tag{C1}$$

The water fluxes for the next time step t+1 yield:

$$E_{in}(t) + \frac{dE_{in}}{dt} = E_{out}(t) + \frac{dE_{out}}{dt}, \tag{C2}$$

using

$$E(t+1) = E(t) + \frac{dE}{dt}. \tag{C3}$$

Using (Milly and Shmakin, 2002) and Eq. 7 from this paper yields for E:

$$E = \frac{\rho}{r_a}[q_s - q_a] = g_c[q_s - q_a], \tag{C4}$$

where ρ is the air density, r_a the aerodynamic resistance, g_c the canopy conductance, q_s the saturation humidity and q_a the actual humidity. The derivation of Eq. C4 can be used for $\frac{dE_{in}}{dt}$. Eq. C2 then yields:

$$\frac{dE_{out}}{dt} = E_{in} - E_{out} + g_c \frac{d[q_s - q_a]}{dt} \tag{C5}$$

Rearranging this equation yields:

$$\frac{dE_{out}}{dt} + \frac{dq_a}{dt} \cdot g_c = E_{in} - E_{out} + \frac{dq_s}{dt} \cdot g_c \tag{C6}$$

Expanding $\frac{dE_{out}}{dt}$ with q_a yields:

$$\frac{dq_a}{dt} \cdot \frac{dE_{out}}{dq_a} + \frac{dq_a}{dt} \cdot g_c = E_{in} - E_{out} + \frac{dq_s}{dt} \cdot g_c \tag{C7}$$

Rearranging Eq. C7 yields:

$$\frac{dq_a}{dt} = \frac{E_{in} - E_{out} + \frac{dq_s}{dt} \cdot g_c}{\frac{dE_{out}}{dq_a} + \frac{dq_a}{dt} \cdot g_c} \tag{C8}$$

Expanding $\frac{dq_s}{dt}$ with dT for the temperature change yields:

$$\frac{dq_a}{dt} = \frac{E_{in} - E_{out} + \frac{dq_s}{dT} \cdot \frac{dT}{dt} \cdot g_c}{\frac{dE_{out}}{dq_a} + g_c}, \tag{C9}$$

which is the final form for the change of actual humidity over a timestep. By using Δq_{ca} for $\frac{dq_a}{dt}$, ET for E_{in}, q_{flux} for E_{out} and $\frac{de}{dq}$ for $\frac{dE_{out}}{dq_a}$ the final form yields:

$$\Delta q_{\text{ca}} = \frac{ET - q_{\text{flux}} + \frac{dq_s}{dT} \cdot g_c \cdot \frac{dT}{dt}}{\frac{de}{dq} + \cdot g_c}. \tag{C10}$$

We added this derivation to the Appendix C. The gradients in the equation over time are the differences over one time step, while the gradient of q_sat over temperature is the slope of the water vapor pressure curve in relation to temperature.

7. - ET in Eq. (9) is the total evapotranspiration, coming from all the gridcell tiles, i.e., using the g_c, g_i and g_e calculated above. How do you arrive to ET from gc? I guess you use Penmann-Monteith again, but this is not specified in the text.

Yes, we used the Penman-Monteith equation as in (1), now applying the water-stressed canopy conductance gc. We thank the Reviewer for noting this and added the missing information to the explanation of this step of the methods in 2.3.2:

"...and ET the final evapotranspiration, consisting of transpiration, evaporation, interception and sublimation from surface or vegetation into the canopy layer. For the calculation of ET we used the Penman-Monteith equation (Eq. 1), now applying the total water-stressed canopy conductance g_c (Eq. 7)."

SURFACE ENERGY BALANCE

- Line 245: K and L: incoming, outgoing or net? If it is incoming it cannot be net. Same for outgoing. Net means incoming minus outgoing. Also, if one is incoming and the other one outgoing, shouldn't they contribute in opposite ways, and thus have different signs? I suspect K+L is just net radiation. In the reference you give for this equation (Milly and Schmakin 2002) the radiation balance in that paper looks different. Maybe you could simply use Rn in Eq. (10), and mention that net radiation is calculated as in Milly and Schmakin (2002)? Also, how do these two relate to the net radiation, Rg, used in Eq. (1)?

We use the net incoming shortwave radiation. This means, compared to the incoming radiation at the top of the atmosphere, the radiation which reaches the surface after part of the radiation is absorbed by the atmosphere or reflected by clouds or surface. The FMS coupler provides shortwave downward radiation, reaching the canopy. Using the surface albedo from LPJmL5 we then calculate the net shortwave radiation. The net outgoing long-wave radiation also takes into account incoming long-wave radiation through the greenhouse gas effect. Hence, these are not net total radiative fluxes, but the net of incoming and outgoing fluxes. We agree with the Reviewer, that it is easier to use just the total net radiation at the surface, as it has been used in equation 15 in Milly and Schmakin, 2002. It is also true that we already used the net radiation R_n in Eq. (1) and use the same variable now in the revised manuscript also for Eq. 10:

$$\Delta T = \frac{R_n - m \cdot LE_f + ET \cdot LE_v - Q_{sn} - H}{C_s \cdot \Delta_t},$$

- Line 248: In this implementation, the boundary temperature to the soil layers and the canopy temperature are the same as in LaD (Anderson et al., 2004). -> Is there a comma missing here? Are the boundary temperature between the soil layers and the canopy temperature the same, as in LaD? Or are they the same as in LaD? So I guess what this means is that the soil temperature calculation is now driven by the bulk surface temperature rather than the air temperature. Do tiles in LPJmL have separate soil columns or do they all share the same soil column?

We thank the Reviewer for noting this. There is indeed a comma missing. In the revised manuscript we deleted this sentence but added the following information to 2.3.2 (as stated above):

"Since our approach does not account for a height dependent canopy temperature, we used here the surface temperature as an approximation for the canopy temperature, which is needed for the calculation of canopy humidity and evapotranspiration. Hence, surface temperature and canopy temperature are assumed the same, following the approach in the LaD model (Milly et al. 2002)."

The soil temperature calculation is still depending on the air temperature, provided by the coupler, which is of course very similar to the surface/canopy temperature. As explained above, the surface temperature and the canopy temperature are assumed the same in our implementation, which could be improved in further development of the model. All stands in LPJmL have their own surface temperature, which is later averaged before provided to the coupler. As stated above we added an explanation for this to 2.3.2:

"While the temperature is calculated individually for each stand, a weighted average over all stands within one gridcell is used for the coupler and the calculation of the humidity."

- Again, reading the LaD reference, it is clear that they do calculate fluxes taking into account air stability, while it is not clear how you do this in your model. It is normally the job of the LSM to calculate the turbulent fluxes. I guess this is now done in some sort of surface layer in the atmosphere model. But it should be clear why you can replace Lad with LPJmL and avoid the stability calculation.

As discussed in the beginning of this response letter, the calculation of the fluxes between land and atmosphere, as well as air stability are done in the FMS coupler. By replacing LaD we just have to provide the necessary variables (roughness, humidity, temperature and albedo) and do not change the handling of the fluxes within the coupler. Hence, it is not necessary to calculate the stability calculations in LPJmL. For more details, see our response at the beginning of the response letter to your general remark.

I want to reiterate that I find the scientify quality of the paper good. However, I think all the points above should be addressed in order to make it clearer to the reader how the model works, especially since this is a model description paper. This would substantially improve clarity and reproducibility. Special attention should be given to:

- The air stability question.

That is handled by the coupler in cooperation with the atmosphere component, see remark about our text improvement above.

- Derivation of Eq. (9).

- The confusing daily/subdaily issue in Eq. (1). If ET0 is subdaily, the equation needs a correction. If it is daily, it needs justification, given that it is used to calculate g_c, which varies diurnally.

Again, we are very grateful for the positive evaluation of the scientific quality and for the thorough evaluation of the model description and for noting a few inconsistencies. We hope to have now clarified the issues with our explanation in our responses above and our modifications in the manuscript text.

Some further suggestions to improve the exposition, apart from addressing the above points:

- Figure 2 is a bit cluttered. Maybe you could add a similar figure besides it where you explain the logic of the evapotranspiration scheme.

This is a very good idea. The new version of the manuscript now includes a flowchart for the logic of the evapotranspiration/humidity scheme.

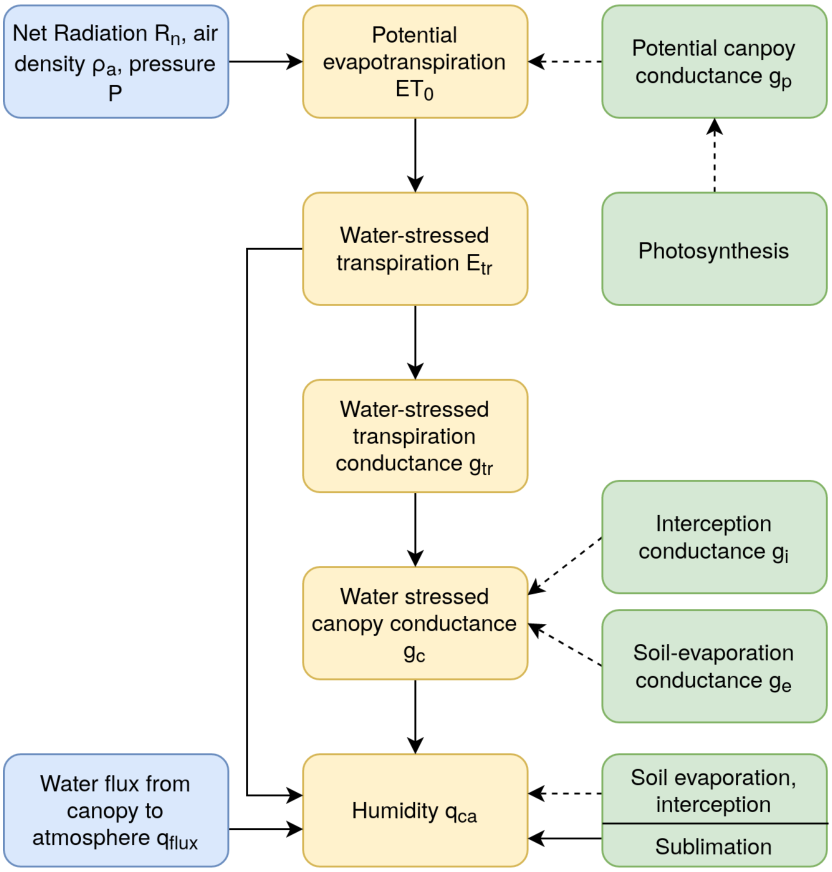

Fig. 1: Schematic overview of the most important processes to determine the canopy humidity. The yellow color denotes newly implemented processes in the new canopy layer in LPJmL5, green internal LPJmL5 calculations and blue denotes input, provided by the FMS coupler. Daily processes are indicated by a dotted line, processes operating on the sub-daily time step by a solid line.

- A table of symbols would be very helpful. You could list the symbol, the units, whether it is an input to the LSM or an output to the atmosphere and the time step at which it is calculated/exchanged.

We added the table for the variables and parameters to the Appendix A of the revised manuscript. Further information about time steps and input/output to the coupler/atmosphere can be found in the schematic figures, including the new one from the remark above.

There are also a few minor points:

- Line 435: "Simulated AGB shows overall a good pattern, with largest values in the tropics, decreasing biomass in the subtropics and a local maximum in the temperate and boreal zone (Fig. 7b)." I think this is more easily seen in Fig. 7d than in Fig. 7b.

We thank the Reviewer for noting this and changed it to Fig. 7d.

- The DOI for Shapoff et al 2018a is wrong (it takes you to the second part of the paper instead of the first one) (https://doi.org/10.5194/gmd-11-1343-2018)

We thank the Reviewer for noting this and changed the DOI to the first paper, Schaphoff et al. 2018a.

- The lines in plot 7d can be confusing for a colorblind person. I would suggest changing either the green or the red one, and also making the lines a bit thicker.

Sorry for not thinking of colour blindness in the first place. We thank the Reviewer for the suggestion and changed the green line to a black one and slightly increased line thickness.

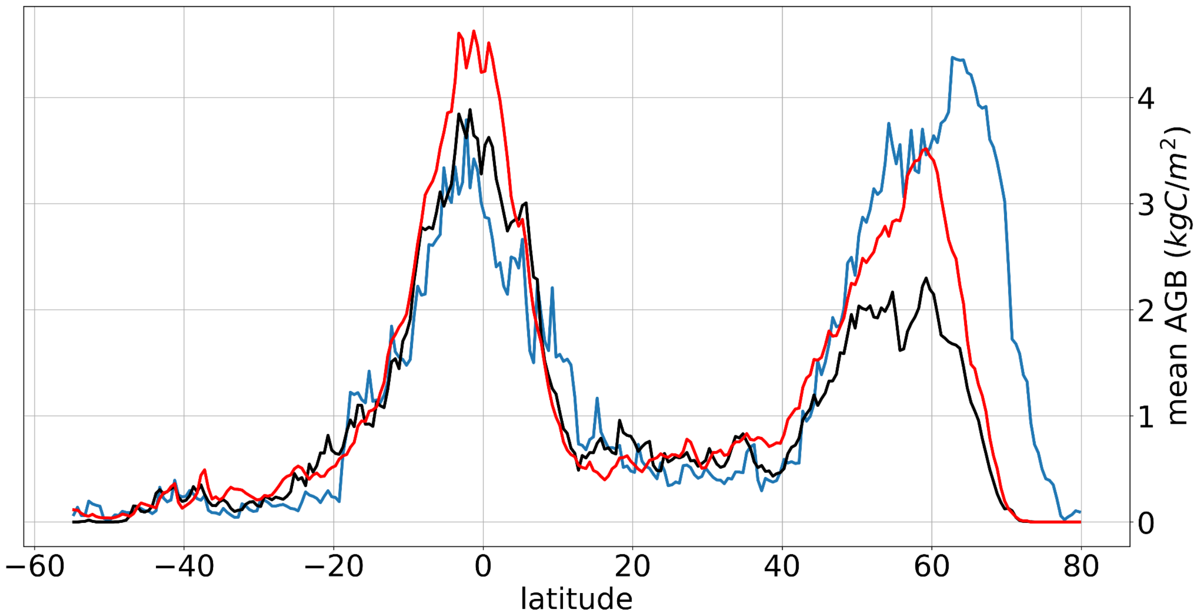

Fig 2.: Latitudinal sum of above-ground biomass from CM2Mc-LPJmL

I have another minor comment/suggestion that I think would make things clearer. It would be helpful to have a short description of how LPJmL represents land in section 2.2. Two or three lines would suffice. Something like this paragraph from section 2 of von Bloh et al. (2018):

"In the LPJmL model vegetation is represented by different plant functional types (PFTs) that can establish concurrently within a cell. These established PFTs share the same soilstand and compete for light, water, and nitrogen resources,while crop functional types (CFTs) are established exclusively at sowing on their own soil stand."

This would answer several questions that can come to mind while reading your manuscript without having to go to the more complete descriptions.

We thank the Reviewer for this useful suggestion. We hope our earlier answers were clear about the individual calculation of temperature in the stands within one cell. Following the suggestion of the Reviewer we added a sentence to the model overview of LPJmL in section 2.2. :

"LPJmL5 simulates global vegetation distribution as the fractional coverage (foliage projective cover or FPC) of plant functional types (PFTs, Appendix B) which changes depending on climate constraints and plant performance (establishment, growth, mortality). Plants establish according to their bioclimatic limits (adaptation to local climate) and survive depending on their productivity and growth, their sensitivity to heat damage, light and water limitation as well as fire-related mortality. The interaction of these processes describes the simulated vegetation dynamics in natural vegetation. The model also simulates land use, i.e. the sowing,growth and harvest of 14 crop functional types and managed grassland (Rolinski et al., 2018). The proportion of potential natural vegetation and land-use within one grid cell is determined by the prescribed land-use input. Each type of land cover, i.e. natural vegetation, managed grassland or crops, have their own respective stand. While receiving the same climate information, soil and water properties as well as carbon-related processes are simulated separately. "