We thank Reviewer 1 for the constructive comments. We have addressed all the comments raised by the referee in the response point by point and introduced the corresponding modifications in the manuscript. Below, we repeat the Reviewers' comments in normal font. Our replies are in bold-face and changes in the original manuscript are in italic.

Overview:

This manuscript describes the inclusion of a model for the roughness sublayer into a column model. Results are compared to observations during the CHATS experiment, during which large-scale effects on quantities of the ABL were of importance. Overall, the results of the manuscript appear to be valid and of interest to the readership of ACP. I therefore recommend publication of the manuscript pending the revisions and comments outlined below.

General Comments:

1) There seems to be a systematic problem with the fluxes as compared to the EC method, which deserves some additional discussion (see specific comments) to strengthen the overall results of the paper.

Answer: Here we quote Foken (2008) with respect to energy balance closure: "The comparison of observational data and model output remains problematic". As discussed in Foken (2008), the reasons for the energy balance non-closer are related to the large scale turbulent structures, which the measurements in the surface layer are not able to capture. Due to this reasons, some studies even suggested that the energy balance (EB) closures should not be used as a quality criteria for turbulent fluxes (Aubinet et al. 1999). Nevertheless, we still use the sensible and the latent heat here, since we would like to compare the surface fluxes calculated with and without RSL parameterization. To make it more precise, we have modified the concluding statement (P9 L4-6): "The comparison presented here confirms that our modelling system is capable of reproducing the diurnal variations in radiation and surface energy balance with sufficient accuracy". The new statement reads:

New: "The comparison presented here confirms that our modelling system is capable of reproducing the diurnal variations in radiation with sufficient accuracy. As in many other studies (see Foken 2008), the observed surface energy balance remains not closed, but with the deviations of similar magnitude as observed in other studies above high canopy.

2) Both days discussed in this manuscript have strong influence of largescale processes, which are difficult to quantify (and allow for adjusting of results to measurements). In my opinion, while this shows that the model can be used for realistic conditions, the paper would be greatly strengthened by including an ideal day with no large scale forcing.

Answer: As mentioned in the manuscript, in selecting the most appropriate days to carry out our research we define the following criteria: well-mixed boundary layer cloudless conditions, well-developed RSL (southerly winds during the entire day to maximize the effect of the footprint). In the entire period during the observations, mesoscale effects (e.g. horizontal fronts) were relevant, having a large impact on the diurnal variability of the measured quantities (Mayor 2011), similar as in our case studies (e.g. potential temperature drop of 1-2 K at around noon). These mesoscale effects have been previously studied and analyzed over the California Valley region where very active advection and topography driven flows where found (e.g. Zaremba; Carroll 1999; Bianco et al. 2011). We therefore took this opportunity to study the canopy effects on the CBL dynamics by also taking the large-scale effects into account in a systematic way.

Placed in more general context, there are several reasons why we chose the CHATS dataset as the main observational evidence to study the effects of RSL on the CBL-dynamics. High-quality measurements of the thermodynamics (and chemistry, used in our current work) is the first reason. Another reason is

related to the canopy homogeneity in combination with the observed, relatively constant- wind direction, which allows a well-developed roughness sublayer above the canopy. This is convenient for studying canopy-atmosphere interaction in an 'idealized' way, since an irregular shape and distribution of the canopy would bring additional uncertainty in the turbulence structure within and above the canopy (Raupach et al. 1996; Finnigan et al. 2009).

3) In general, some of the figures should be enhanced to improve legibility (font sizes, and line thickness).

Answer: We find this remark of the referee to improve the visualization in several figures. Thus, we increased the font size and readability in Fig. 2,3,4,5.

<u>Specific comments:</u>

4) P1 L26: The atmospheric boundary layer (ABL), as a part of the global climate, is a dynamic system that is highly dependent . . . –> The ABL may be part of the climate system, but is in my opinion not climate itself. Please rephrase.

Answer: We modified the statement as follows:

New: "The atmospheric boundary layer (ABL), as a component of the global climate system, is characterized by the turbulent exchange of energy, momentum and matter between the Earth's surface and the lower atmosphere, as well as by the influence of larger-scale atmospheric processes (Stull 1988)."

5) P2 L5: These structures are responsible for most of the momentum (70%) and turbulent kinetic energy (90 %) exchange between canopy and atmosphere Fininnigan, 2000; Finnigan et al., 2009) –> these numbers are in my opinion not generalizable, please substitute with a more general formulation (e.g. majority).

Answer: We agree with the referee's remark; since the statement belongs to the introduction, we can be more general. We used the following modification:

New: "These structures are responsible for majority of the momentum and turbulent kinetic energy exchange between canopy and atmosphere (Finnigan 2000; Finnigan et al. 2009)."

6) P2 L30: Extending these previous works, our study aimed to elucidate the ABL system for real conditions, taking the representation of the RSL into account. –> This sounds a bit clumsy

Answer: we slightly modified this statement:

New: "Here, we extend on previous studies by analyzing the impact of the RSL representation on the dynamic evolution of the ABL constrained and evaluated with available observations."

7) Introduction: since the work is about the effects of the RSL, it would be good to provide the reader with some estimate of the vertical extent of the RSL, in which MOST does not apply. This could be order of canopy heights or some scaling with respect to u*, LAI, hc.

Answer: We modify the following sentence in P2L5 to inform the reader about the vertical extent of the RSL:

New: "These structures are responsible for majority of the momentum and turbulent kinetic energy exchange between canopy and atmosphere (Finnigan, 2000; Finnigan et al., 2009). Dependent on canopy density and height, as well as atmospheric diabatic stability, the vertical extent of the RSL is estimated to reach up to 2-3 canopy heights (Dupont; Patton 2012; Shapkalijevski et al. 2016),."

8) Figure 1: please make sure that all variables are explained in the caption. I find the use of hc for canopy

height and h for MLH confusing. I assume that there is a temporal component in that Figure as the ABL grows from left to right. Please explain this as well in the caption. Also, it would be good if the text would mention before the Figure, what are the variables that are actually predicted by the model?

Answer: We modified the text in the caption of Fig. 1 to better explain the figure and introduce all the variables, including the ones calculated by the MXLCH model:

Old: "Figure 1: Schematic overview of the coupled land-vegetation-atmospheric mixed-layer model, with both including and omitting the RSL effects in the flux-profile relationships. The vertical origin of the co-ordinate system is placed at the displacement height *d*. The height of the surface layer is calculate as 10 % of the boundary-layer height (Stull 1988)."

New: "Figure 1: Schematic overview of the coupled land-vegetation-atmospheric system and its representation in the mixed-layer model. The vertical origin of the co-ordinate system is placed at the displacement height d. The height of the surface layer is estimated as 10 % of the boundary-layer height (Stull 1988). The scheme illustrates the diurnal (convective) evolution of the boundary-layer height (h) and stability dependent roughness lengths for momentum and scalars (z_{0M} and z_{0H}). Profiles of boundary-layer state variables (wind speed, |U|, potential temperature, $\langle\theta\rangle$, and specific humidity, $\langle q\rangle$), are also presented, both including and omitting the RSL effects in the flux-gradient relationships."

For the second part of the referee's comment about the predicted variables by the model, we placed a note (sentence) in the text before Fig. 1 the the model variables are explained later in this section.

9) P6 L3: please provide equation for c_d, since this is the variable affecting L_c. Also, could you provide some information about the choice of a(z) = const. How much of a difference does this make?

Answer: In our modelling framework, $c_d = \left(\frac{u_*}{|U|}\right)^2$, and is calculated at the canopy top. We included this equation in the text (P6 L3) as follows:

New: " .., while c_d is the leaf drag coefficient, calculated from the observations at the canopy top ($c_d = u_*^2/|U|^2$). "

Next to that, the assumption that *a(z)* is constant originates from Harman and Finnigan (2007), who assumed this for dense canopy. Shapkalijevski et al., (2016) showed that this assumption holds for the fully vegetated CHATS canopy. Finally, apart from this study, but related to the referee's question, Ouwersloot et al., (2016) by using high-resolution large eddy simulation over canopy under neutral conditions found that the impact of applying *a* either constant or non-constant in height *a* has small impact on the profiles of wind speed and shear within and above the canopy.

10) P7 L21: We used the observations at the highest measurement level at the tower (29 m above ground surface) to evaluate the model results away from the canopy, where the RSL effects are minimal.–> Please justify and compare to likely RSL height. 29m is probably not representative of the MLH as a whole. I understand in the absence of profiles, compromises have to be made, but they should be articulated.

Answer: 29 m is the highest measurement level. We agree with the referee that this height is still in the surface layer. However, it is the closed to the mixed-layer characteristics. A deviation will indeed still be present, but since the surface layer is approximately 50 m at its deepest and the logarithmic profiles within the surface layer result in weaker deviations (with respect to mixed-layer values) in the upper part of that layer, the observations won't show strong deviations compared to mixed-layer values. This assumption is supported by the observations of the quantities of the two upper-most levels (23m and 29m). For instance, the slope derived from the potential temperature or specific humidity at 23 and 29m is less than 1% with respect to the vertical coordinate.

The following text is added in the manuscript to better explain the assumption of selecting the 29 m as a representative mixed-layer height in this study:

(New): The level of 29 m is considered to be representative of the mixed-layer values, since it is either located within the mixed layer or in the upper part of the surface layer, where deviations compared to mixed-layer values are small. Therefore, we employ it as the most representative of the mixed-layer characteristics.

11) P8 L8: Figure 2a,b shows the observed and modelled components of the net radiation: downwelling and upwelling shortwave (SW) ´ . . . –> This may be a good time to remind the reader how fluxes are modeled, as this if important to assess the difference between EC and model.

Answer: Since the procedure of modelling the radiation and surface fluxes is already demonstrated and evaluated in a number of studies (e.g. van Heerwaarden et al. 2009; Ouwersloot et al. 2012; van Stratum et al. 2012; Vilà-Guerau de Arellano et al. 2015), here (ate the place suggested by the referee) we have placed a general explanation to inform the reader:

New: "the surface fluxes in the model are calculated from the differences between the surface and the roughness sublayer (reference height) values of the mean quantities and the transfer coefficients for momentum and scalars."

12) Figure 3 and associated text: It is well know that EC leaves fluxes unclosed. However, I have two comments based on Figure 2 and 3. (1) Please switch the axes in Figure 3 as it is commonly done; (2) In forest canopies energy and moisture storage inside the canopy can play a role on the diurnal scale. So that EB closure should also be looked at as the daily integral of fluxes (unless storage is otherwise accounted for). Also, Modeled fluxes seem to be systematically worse in the afternoon. Is there a reason for this?

Answer:

(1) We switched the axes in Fig. 3.
(2) Regarding the energy and moisture storage inside the canopy, we refer to P8 L20-27 in the manuscript, where we expressed that and how we included the storage terms in the energy balance.

Finally, instead of the referee' s statement "Modeled fluxes seem to be systematically worse in the afternoon", we conclude that modelled fluxes deviate systematically ,ore from EC fluxes in the afternoon. In spite of the difficulty in reproducing local process driven by the canopy at the surface and the large-scale effects at around noon, modelled surface fluxes were systematically worst in the early afternoon, when the effects of the large-convective (boundary-layer) eddies on the surface turbulence are expected to be larger (Zilitinkevich et al. 2006).

13) P11 L19: Both C_M and |U| are altered in opposite directions, with magnitudes that fit the observation (Fig. 6a,b), thus leading to a relatively constant u* –> This behavior is not obvious to me from the methods section, please give some information about the mechanism and also please comment on the impact of the apparent difference between observed and modeled u*.

Answer: To make the statement clearer, first we have corrected and modified it. The modified sentence is:

New: "Both C_M and |U| are altered in opposite directions when the RSL representation is introduced (Eq. 4 and 5), with magnitudes that fit the observation (Fig. 6a,b), thus leading to a relatively unchanged u_* (see Eq. 6)".

Second, we noticed a mistake in the published formulation of the friction velocity (Eq. 6):

$\boldsymbol{u_* = \sqrt{C_M(z_r)|U(z_r)|}}$,

where the wind speed modulus should be outside the "√" operator. Thus the modified and corrected formulation is:

New:

$$\boldsymbol{u_* = \sqrt{C_M(z_r)}\,|U(z_r)|.} \qquad (6)$$

The main mechanism for the similarity in u_* of the model runs with and without the roughness sublayer effects, as discussed in the manuscript on page 11 and line 08 – 14, involves canopy effects on the drag C_M and $|U|$. C_M is decreased 4 order of magnitudes, while $|U|$ is increased by 50% when RSL is included. Consequently, the resulting u_* remains relatively unchanged (Eq. 6). Physically, this can be explained by the presence of an inflection point of the mean wind speed at canopy vicinity, which leads to smaller drag and thus larger wind speed (but smaller gradients) within the RSL than postulated by the standard similarity theory.

Finally, the underestimation of the observed u_* for both numerical experiments is commented on page 11 lline 16:

"Both the MXL+RSAD and MXL+MSAD model runs, i.e., with and without the effects of the RSL included, underestimate u_* by about 30% with respect to the observed daily average (Fig. 6c and Table 2).

14) Figure 7 and associated text: Please provide some interpretation of the meaning of this findings.

Answer: On page 12 line 9 we added the following concluding sentence:

New: In summary, although the variation of the RSL scale β strongly affects the surface shear partitioning in the momentum budget, the total momentum tendency remains relatively unchanged due to compensation by the geostrophic and entrainment contribution. This means that the imposed pressure gradient force, integrated over the BL-depth is balanced by the surface friction and momentum entrainment. Since the boundary-layer depth is similar between the both runs, then pressure gradient force and momentum entrainment are altered to balance the differences in the surface shear between the runs.

15) P13 L22-25: In the absence of detailed observations of the temporal evolution at the entrainment zone, we are able to provide only first order estimates of the large scale effects relevant to our cases and discuss their impacts on the budgets of potential temperature and specific humidity (Fig. 10). –> See general comment about largescale effects. In my opinion this is a limitation of the manuscript as these conditions can be used to make things work and warrants some discussion by the authors.

Answer: We are aware of this limitation in our study. Please see the answer to general comment (2) for more explanation. Here we would like to state that although the large scale forcing strongly affects the CBL dynamics over CHATS (as mentioned several times in the manuscript), they will equally affect both numerical runs with and without RSL representation. Thus, we can conclude that the results in this study about the RSL effects on the CBL dynamics are still relevant when considering the large-scale processes. The contribution of the RSL effects on the budgets of the (thermos-)dynamic quantities, compared to the contribution by the large scale processes is much smaller however.

16) Figure 9b+10b: I find the sensitivity analysis for fluxes a bit confusing, given the fact that I don't know from the methods how these are related. If I understand the methods correctly, then the effect of beta and Lc on fluxes purely arises from changes in the displacement height. Or are there other effects at play.

Answer: Performed sensitivity analysis showed that the modeled surface fluxes are affected by the variation of RSL scales (atmospheric stability dependent β and L_c) via the changes in the displacement

height and the stability dependent roughness lengths for momentum and scalars. There are no other effects in play. This is stated on page 13 lines 4-9.

17) P15 L9-11: However, due to compensation between the drag coefficients and the differences in the mean variables at two levels within the roughness sublayer, the modelled surface momentum and heat fluxes remain relatively unchanged (< 3 %). –> A similar argument probably applies to other fluxes. A critical reviewer might raise the question, what the advantage of the RSL formulation is, if it has little effect on the MLH and on fluxes (due to compensation of terms). I suggest that the authors add a sentence or two to explain why the RSL formulation matters based on the results presented.

Answer: We have modified the last paragraph of the Conclusions section to better explain why the RSL matters based on presented results:

New: "In our modelling framework, and in general in the coupled land-atmosphere models, the representation of the surface fluxes is locked and controlled by the boundary conditions. The sensible and latent heat fluxes are bounded by the surface available energy, and the momentum flux is constrained by the pressure gradient and the entrainment of momentum, the latter dependent on the boundary-layer growth. In consequence, adding a roughness-sublayer representation in the surface scheme of the model, alters the partitioning of the surface fluxes (e.g. sensible and latent heat) through the altered roughness length and displacement height. Specifically for our case studies, the canopy's impact on convective boundary-layer dynamics is relatively minor, due to its small effect on modelled surface fluxes and the bulk boundary-layer properties well above the canopy ($z > 2h_c$). The tall canopy however strongly affects the mean gradients and transfer coefficients within the roughness sublayer. Thus, considering the roughness sublayer parameterization is important when comparing observations and large-scale model outputs of the mean quantities near and just above the canopy."

<u>Technical (not necessarily complete):</u>

18) P7 L11: specific moments / a specific moment?

Answer: we corrected as "..a specific moment.."

19) Figure 2: Please increase font size in figure

Answer: We increased the font size in Fig. 2.

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