Reply to reviewer's comments

Typographical convention:

Black -> reviewer's comment

Blue -> author's comment

Red -> modification to the manuscript

Underlined -> text added to the original version

~~Strikethrough~~ -> text removed from the original version

The line numbers refer to the original version of the manuscript.

Reviewer 2 (RC2)

This paper describes and evaluates COSMO-BEP-Tree v1.0: a coupled urban climate model with explicit representation of street trees. The authors assess the model during a heatwave event with observations from flux towers, surface stations and satellites. The authors have presented a very strong study which is thorough and convincing. The issue of integrating the effects of street trees in urban meteorological models is important because increasing tree cover is "go-to" response of urban planners who wish to reduce urban heat impacts. As the manuscript shows, interacting processes are complex and outcomes not always obvious. The evaluation is clear and thorough, and the technical achievements will be beneficial for future urban studies.

The lack of open availability of the source code is disappointing for a study presented in GMD. The process for accessing code outlined in the study is not timely, and includes mailing physical documents and/or negotiation. I have therefore not reviewed the code. The authors should reconsider publishing the code openly on a persistent public archive. Detailed comments follow.

We are happy that the reviewer appreciated the paper.

We regret that the source code was not easily accessible. Unfortunately, we have to conform to the CLM-Community licence agreement that only allows sharing the code with registered members. As such, we cannot publish the code on a public archive and we don't have control on the registration process.

However, we agree with the reviewer that the registration procedure must be simplified and made timely. We will make this point to the CLM-community.

Pg 2 ln 12: "Tree transpiration reduces the surface temperature of the foliage by converting part of the solar radiation to latent heat" not only solar radiation.

We thank the reviewer for pointing out the inaccurate description of the energy exchanged during transpiration.

We edited the sentence as follows:

Pg 2 ln 12: "~~In terms of heat interactions,~~ Through tree transpiration~~ the~~, leaf surface temperature is reduced~~s~~ resulting in the extraction of sensible heat from the air ~~of the foliage by converting the solar radiation to latent heat~~ (Green, 1993)."

Pg 2 ln 15: "Modelling studies on the cooling potential of street trees have almost exclusively been performed at the scale of individual street canyons to single neighbourhood...Only very few studies investigate the city-wide impact of street trees, mainly due to the limited availability of models able to represent street trees at the scale of the city..." It would be useful here to acknowledge the various mesoscale urban meteorological models which have incorporated vegetation as low-height gardens within the street canyons (e.g. Thatcher and Hurley, 2012; Lemonsu et al, 2012; Wang et al 2013). Although not "street-trees" (as they do not provide shading on walls or reduce canyon sky view), they do shade the ground and interact directly with canyon radiation/turbulent fluxes and momentum budgets, alter the Bowen ratio and reduce canyon surface temperatures. This will also give an opportunity to be clearer about the authors definition of "street trees" when the concept is introduced, as readers may assume models within-canyon low vegetation, or even external vegetation tiles, are doing the same thing. The statement "very few studies investigate the city-wide impact of street trees" could then be more carefully stated, as there have been many studies at city or larger scales which have assessed the impact of urban vegetation, but most have used schemes with low vegetation or used a tiled approach, and hence missed important shading and sky view effect which is the strength of the current study.

* Thatcher M and Hurley P 2012 Simulating Australian urban climate in a mesoscale atmospheric numerical model Boundary-Layer Meteorol 142 149–75
* Lemonsu A, Masson V, Shashua-Bar L, Erell E and Pearlmutter D 2012 Inclusion of vegetation in the Town Energy Balance model for modelling urban green areas Geosci. Model Dev. 5 1377–93
* Wang Z-H, Bou-Zeid E and Smith J A 2013 A coupled energy transport and hydro-logical model for urban canopies evaluated using a wireless sensor network Quarterly Journal of the Royal Meteorological Society 139 1643–57

We thank the reviewer for these excellent suggestions. We re-worded the section in order to acknowledge studies using the tile approach and those explicitly representing low vegetation.

Pg 2 ln 15: "~~Modelling studies on the cooling potential of street trees have almost exclusively been performed at the scale of individual street canyons to a single neighbourhood (e.g. Gromke et al., 2015; Ng et al., 2012). Only very few studies investigated the city-wide impact of street trees, mainly due to the limited availability of models able to represent street trees at the scale of the city or at even larger scales. In fact, the vast majority of meso-scale urban climate models only represent~~ trees ~~vegetation outside the street canyon, neglecting important effects such as the shading effect of trees on the canyon's surfaces.~~"

Pg 2 ln 15: "The climatic impact of urban vegetation has been investigated in numerous previous studies from the scale of the single street canyon to that of the entire urban region (e.g. Gromke et al., 2015; Ng et al., 2012; De Munck et al., 2018). However, studies on entire urban regions primarily focused on low vegetation, representing low height gardens and green roofs (e.g. Wang et al., 2013; De Munck et al., 2018). Street trees, instead, have generally only been represented in a separate natural tile (e.g. Schubert and Grossman-Clarke, 2013; Li and Norford, 2016). This approach precluded considering any interactions between trees and urban surfaces in a street canyon, such as shading and sheltering effects (Krayenhoff et al. 2014, 2015). Other studies employed somewhat more sophisticated methods but still neglect some of the critical interactions between trees, canyon surface and airflow (e.g. Thatcher and Hurley, 2012)."

New references:

Schubert, Sebastian, and Susanne Grossman-Clarke. "The Influence of green areas and roof albedos on air temperatures during Extreme Heat Events in Berlin, Germany." Meteorologische Zeitschrift 22.2 (2013): 131-143. https://doi.org/10.1127/0941-2948/2013/0393

De Munck, C., et al. "Evaluating the impacts of greening scenarios on thermal comfort and energy and water consumptions for adapting Paris city to climate change." Urban Climate 23 (2018): 260-286. https://doi.org/10.1016/j.uclim.2017.01.003

Li, Xian-Xiang, and Leslie K. Norford. "Evaluation of cool roof and vegetations in mitigating urban heat island in a tropical city, Singapore." Urban Climate 16 (2016): 59-74. https://doi.org/10.1016/j.uclim.2015.12.002

Krayenhoff, E. S., et al. "A multi-layer radiation model for urban neighbourhoods with trees." Boundary-layer meteorology 151.1 (2014): 139-178. https://doi.org/10.1007/s10546-013-9883-1

Krayenhoff, E. S., et al. "Parametrization of drag and turbulence for urban neighbourhoods with trees." Boundary-layer meteorology 156.2 (2015): 157-189. https://doi.org/10.1007/s10546-015-0028-6

Thatcher, Marcus, and Peter Hurley. "Simulating Australian urban climate in a mesoscale atmospheric numerical model." Boundary-layer meteorology 142.1 (2012): 149-175. https://doi.org/10.1007/s10546-011-9663-8

pg 6 ln 4: Why are the intensity terms (ΔV_i and r_i) dimensionless? Shouldn't they have units?

We apologize that the units were missing. Both terms indeed have units of [W m^{-2}].
The sentence will be changed as follows:

pg 6 ln 4: "where ΔV_i is the reduction in intensity of ray i due to the tree foliage [W m^{-2}], r_i is the initial intensity of the ray i [W m^{-2}], … "

pg 8 ln 13 "street trees do not interact with soil moisture content as represented by COSMOS's land surface scheme" More explanation as to why this was the case –technical constraints? Or was it assumed that all soil is constantly irrigated in urban areas? You may wish to mention the drawback of this assumption (i.e. over estimating latent heat) at this time. Otherwise, do the underlying LSM soil and urban scheme exchange any fluxes? How? Figure 1 could be used here to better explain how fluxes of the urban scheme are coupled to the atmosphere and LSM.

This point was also raised by the other reviewer. We added further discussion on the lack of interaction with soil moisture.

Further motivation is provided in the section "Methodology"

pg8 ln 12: "Although moisture exchange between street trees and the atmosphere is implemented, street trees do not interact with soil moisture content as represented by COSMO's land surface scheme. In other words, a mechanistic interaction between soil moisture and the transpiration of street trees is not included, assuming that the transpiration is never limited by soil water availability. A careful representation of soil moisture in the urban tile would have required a new urban hydrology scheme, which was beyond the scope of the study. The missing interaction with soil moisture may reduce the model ability to represent variations in transpiration during periods with large changes in soil moisture (Konarska et al., 2016; Asawa et al., 2017). Nevertheless, street trees are less sensitive to variations in soil moisture than short vegetation, thanks to their deeper root system (Chen et al., 2011; Asawa et al., 2017)."

References:

Chen, Lixin, et al. "Biophysical control of whole tree transpiration under an urban environment in Northern China." *Journal of Hydrology* 402.3-4 (2011): 388-400. https://doi.org/10.1016/j.jhydrol.2011.03.034

Asawa, Takashi, Tomoki Kiyono, and Akira Hoyano. "Continuous measurement of whole-tree water balance for studying urban tree transpiration." *Hydrological Processes* 31.17 (2017): 3056-3068. https://doi.org/10.1002/hyp.11244

Konarska, Janina, et al. "Transpiration of urban trees and its cooling effect in a high latitude city." International journal of biometeorology 60.1 (2016): 159-172. https://doi.org/10.1007/s00484-015-1014-x

pg 10 ln 6: For the last terms of eq 13, why is Ts associated with fnat, and Tg be with furb? I don't understand whether this temperature averaging approach is valid. I can see the equation is taken from Schubert (2013), but it is not explained there either. For example, take the extreme position where fnat=0, furb=1, then the equation simplifies to: T2m = Ts + r (T1 – Tg) Why is Tg part of the T2m temperature if there is no fnat? Also, how is the urban surface temperature here defined? Does it, for example, include the roof facets? I was pleased to see the clear definition of surface temperature for the evaluation of the satellite observations (pg 17) which was based on the facets that the satellite sees (roofs streets and natural surfaces rather than walls). But it's not clear that definition is appropriate for 2m temperature out of sight of roofs, and within sight of walls. If the same satellite-based definition is used for the T2m calculation, authors should note that's likely to lead to underestimation of the cooling benefit of street trees for temperatures within the canyon.

We apologize that the terms were mixed up in the second part of the equation. f_{nat} should always go with T_g and f_{urb} with T_s . Additionally, the definition of T_s was not consistent with its use later in the manuscript (where it is referred to as T_{str}).

We corrected the formula and the following explanation.

P10, L6 "T_{2m} = (f_{nat} T_g + f_{urb} ~~T_s~~ T_{str}) + r (T_1 − (f_{nat} ~~T_s~~ T_g + f_{urb} ~~T_g~~ T_{str})),

where T_g is the surface temperature of the natural tile, T_{str} is the street surface temperature ~~of the urban tile~~, … "

pg 11 ln 3: It would be useful to include information here about the average fraction of green cover in Basel, for easy comparison with other urban studies.

We thank the reviewer for the suggestion. However, we think that the average fraction of green cover (as normally defined in urban climate studies) is not the best measure, since it includes all urban vegetation (e.g. parks), not only street trees, which is the focus of the present study. Instead, we calculated the average canopy cover from street trees only.

Additionally, we included an additional figure that shows the variability of the canopy cover from street trees in the different districts (Figure R1). The figure is added to the Supplement.

pg 11 ln 5: "The average canopy cover from street trees is about 20% when considering the entire urban area, but it varies from 6 to 31% in the different districts (see Supplement)."

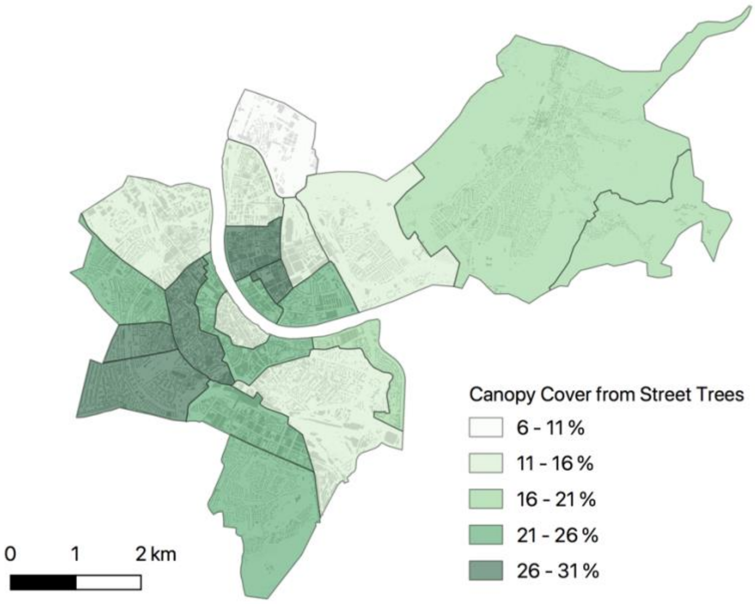

Figure R1 - Canopy cover from street trees in the administrative districts of Basel-Stadt. The building geometries are shown in the background.

p 11 ln 23: There is discussion of atmospheric initial conditions and on soil properties but it is not clear how soil moisture was initialised. Soil moisture has significant impact on the intensity of heatwaves (e.g. see Wang et al 2019), and soil moisture has memory much longer than the 5-day spin up, so this variable needs to be carefully initialised.

* Wang P, Zhang Q, Yang Y and Tang J 2019 The Sensitivity to Initial Soil Moisture for Three Severe Cases of Heat Waves Over Eastern China Front. Environ. Sci. 7

Soil moisture is indeed a critical quantity in these simulations. Soil moisture (in the non-urban tiles) is computed prognostically for 7 soil layers by the land-surface module TERRA of the COSMO model. Initial soil conditions for our simulations were taken from the operational COSMO-2 analyses of MeteoSwiss. Since the COSMO-2 model (covering the Alpine domain) is nested into the COSMO-7 model (covering Europe), which itself is nested into ECWMF's IFS model, the initial soil moisture field ultimately goes back to the soil moisture analyses of ECMWF's operational IFS model.

We edited the sentence regarding initial and boundary conditions by specifically mentioning that they include soil moisture.

P 11 ln 21: "Soil moisture, a key variable for accurate representation of heatwaves (Wang et al., 2019), is also initialised with the COSMO-2 analyses, which trace back to the soil moisture analyses of ECMWF's operational IFS model (De Rosnay et al, 2013)."

New references:

Wang, Pinya, et al. "The sensitivity to initial soil moisture for three severe cases of heat waves over Eastern China." Frontiers in Environmental Science 7 (2019): 18. https://doi.org/10.3389/fenvs.2019.00018

De Rosnay, Patricia, et al. "A simplified Extended Kalman Filter for the global operational soil moisture analysis at ECMWF." Quarterly Journal of the Royal Meteorological Society 139.674 (2013): 1199-1213. https://doi.org/10.1002/qj.2023

pg 13 Table 1, please provide explanation for name acronyms here for easier reference.

We extended Table 1 in order to ease the reference.

Name	L_{De}	g_s	Description
STD	Std	Std	Current conditions
LA0	0	Std	No street trees
LA+	+50%	Std	Increased leaf area density
LA-	-50%	Std	Decreased leaf area density
SC+	Std	+50%	Increased stomatal conductance
SC-	Std	-50%	Decreased stomatal conductance

pg 18 ln 4. I didn't find the attribution of the night-time overestimation of air temperature to the inability of COSMO to represent nocturnal stable boundary layer conditions convincing. If it were an issue with COSMO failing to represent a stable boundary layer, then it should occur in the non-urban site (BLER) night-time cooling rate. However, the supplementary Figure 1 indicates the rate of cooling matches observations well (al-though with a positive bias throughout), which to me indicates the evolution of stability conditions are probably reasonable at the rural site. It therefore seems the overestimation of night-time urban air temperatures could just as easily be from issues within the urban scheme configuration rather than the atmospheric model or stability issues. The supplementary Figure 2 indicates the bulk albedo may be low, and the material properties of facets listed in Table 2 store a lot of heat. I understand those values are based on previous studies, but those values were derived through optimising WRF SLUCM and so are not necessarily realistic urban parameters, but could simply be accounting for deficiencies in that model. Therefore, the parameters won't necessarily be appropriate for BEP-TREE at Basel. I'm not asking for the simulations to be redone, but the authors shouldn't be so quick to simply attribute night-time errors to the atmospheric model when urban parameters may be the issue (low albedo, high heat storage).

We thank the reviewer for pointing out this important aspect.

By re-examining the figures, we agree with the reviewer that the attribution of the night-time overestimation of air temperature at the BKLI tower site (urban site) cannot be explained by the model inability to representing the stable boundary layer.

We agree that the bias may be due to the choice of material properties, especially the too low albedo (as substantiated by the radiation fluxes – Supplement, Figure 2).
However, we remark that some aspects are still inconsistent with the observations, such as the fact that a clear bias was not present at the 2-m stations.

In view of these arguments, we edited the paragraph as follows:

pg 18 ln 1: "The model simulates the evolution of air temperature very well during the evaluation period (Figure 5a) although a slight overestimation with a MBE of 0.51 K and a systematic RMSE of 0.51 K was found. The overestimation occurs mostly during night-time and it seems to be related to an underestimation of the bulk albedo (Supplement) which can be traced back to the choice of material properties (Table 2). A too low albedo may have produced an excess in heat storage with consequently larger sensible heat release at night. Nevertheless, a night-time overestimation of temperature was not found at the near-surface sites, indicating that more analyses are needed to better understand eventual issues with the choice of material properties."~~, an issue that was observed also in other urban climate studies with COSMO (Schubert and Grossman-Clarke, 2014; Wouters et al., 2016) and other models (e.g. Lee et al., 2011). The night-time overestimation of air temperature is attributed to the inability of COSMO to represent very stable boundary layer conditions (Cerenzia, 2017).~~"

Additionally, we added a line about this issue in the "Future Work" section.

Pg 27 ln 16: "Even if generally comparable with other models, the performance of COSMO-BEP-Tree still has room for improvements. The model evaluation against urban flux tower measurements revealed a systematic underestimation of specific humidity (q). The source of this bias needs to be better investigated by, for instance, (a) analysing the soil moisture content and (b) evaluating q at the model boundaries provided by another model. The model evaluation reveals an overestimation of night-time air temperature above the urban canopy layer, which can be due to the use of default values of material properties. …"

pg 20 ln 27 "are" -> area

Thank you for pointing out the typo.

pg 20 ln 27: "… and leaf area index from street trees …"

pg 26 "Future Work" It was noted earlier that BEP-TREE does not interact with LSM soil moisture - this is a major limitation which should be discussed here.

We extended the section "Future Work" accordingly.

pg26, ln 18: "In order to improve the representation of the transpiration from street trees and therefore the modelling of the associated latent heat fluxes, a mechanistic stomata model (e.g. Damour et al. (2010)) will have to be implemented. Furthermore, to properly represent soil water scarcity during extended drought periods, an urban hydrology model would have to be implemented (e.g. Järvi 2011, Yang 2015, Stavropulos-Laffaille 2018)."

References:

Järvi, Leena, C. S. B. Grimmond, and Andreas Christen. "The surface urban energy and water balance scheme (SUEWS): Evaluation in Los Angeles and Vancouver." *Journal of hydrology* 411.3-4 (2011): 219-237. https://doi.org/10.1016/j.jhydrol.2011.10.001

Yang, Jiachuan, et al. "Enhancing hydrologic modelling in the coupled weather research and forecasting–urban modelling system." *Boundary-Layer Meteorology* 155.1 (2015): 87-109. https://doi.org/10.1007/s10546-014-9991-6

Stavropulos-Laffaille, Xenia, et al. "Improvements to the hydrological processes of the Town Energy Balance model (TEB-Veg, SURFEX v7. 3) for urban modelling and impact assessment." Geoscientific Model Development 11.10 (2018): 4175-4194. https://doi.org/10.5194/gmd-11-4175-2018

pg 27 ln 21 "attributed to the inability of the model to reproduce a very stable atmospheric conditions" again, if this argument is used it should be better supported with information from the current study. For example, was the minimum value of turbulent diffusion coefficients (K_i,min) set at 1 m2/s (per Buzzi 2011) in the current experiments? What were the stability conditions at the rural site? Did an inversion form? Why is the rate of cooling at night at the rural site seemingly correct if a stability is incorrectly simulated? Do the observed wind speeds support the conclusion that very stable atmospheric conditions should have formed on those nights? Is there other observational support for the stability or non-stability of rural sites in the area (non-urbanflux towers, boundary layer measurements etc)?

We thank the reviewer for pointing out this aspect.

We included an additional figure (Figure R2, added to the Supplement) that supports our argument regarding the formation of stable boundary layer conditions. By comparing the air temperatures at the rural reference site BLER (2 m a.g.) and at neighbouring St. Chrischona Tower (STCT, 230 m above ground, 3.4 km away from BLER), we can see that stable boundary layer conditions (characterised by a strong temperature inversion) were present during several nights.

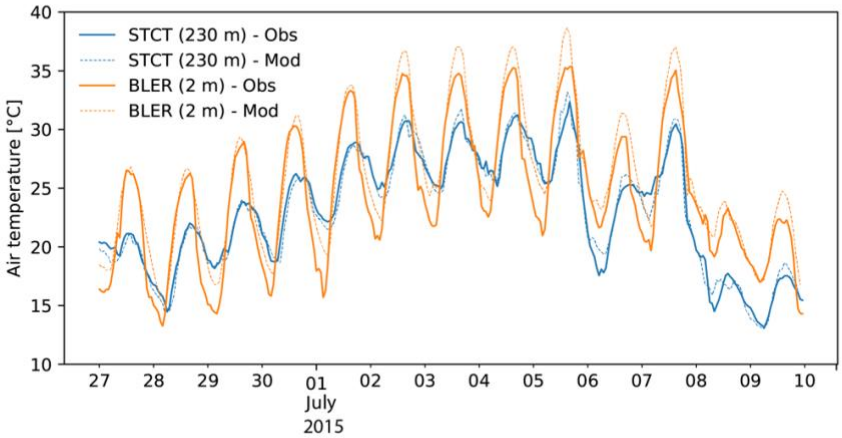

Figure R2 - Air temperature evolution at the sites of St. Chrischona (STCT, 230 m a.g., lat=47.571767, lon=7.687094) and BLER (2 m a.g.). Solid and dashed lines indicate observations (Obs) and model simulation (Mod), respectively.

Additionally, we can further see that the night-time air temperature at the rural site of BLER is overestimated, especially during nights with stable boundary layer conditions. By contrast, the model compares very well against the observation at the tower.

However, we agree with the reviewer that a misrepresentation of the stable boundary layer conditions in COSMO cannot fully explain the bias. This is especially clear in the central part of the period, where a positive bias is present throughout the day.

We further examined the data and found a large underestimation of albedo at the rural site (see Figure R3 below, added to the Supplement). For completeness, we included a new figure (in the Supplement) with all the components of the radiation balance at the rural site BLER.

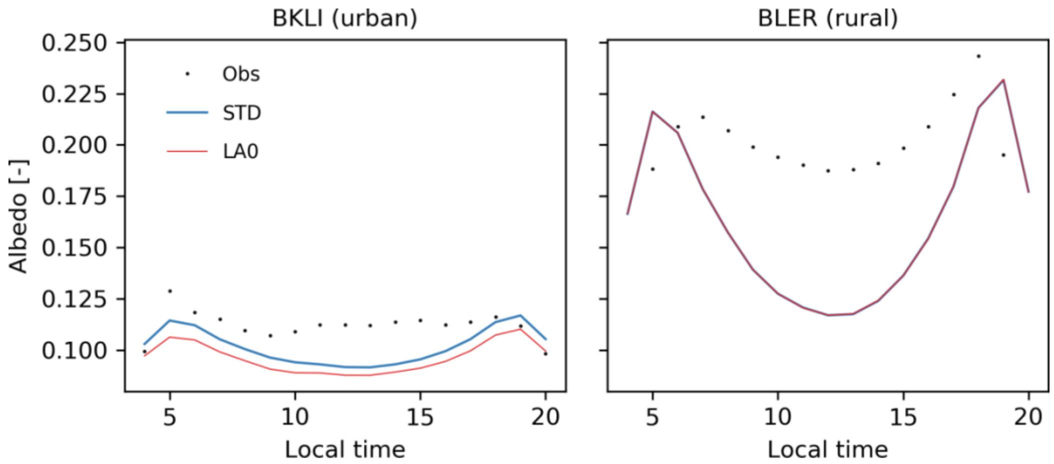

Figure R3 - Average diurnal profile of observed (Obs) and modelled (STD, LA0) albedo. Albedo is calculated as the ratio between upward and downward short-wave radiation. The site BKLI is charachterized by an urban fraction (f_{urb}) of 0.79.

This large underestimation has been already found in another urban study with COSMO-CLM (Schubert et al., 2014) and it is attributed to a misrepresentation of albedo in the land-surface model of COSMO-CLM.

By default in COSMO-CLM, albedo values are determined as a function of soil type, soil moisture and plant fraction. However, there is no distinction between vegetation type and a constant background albedo value for vegetation of 0.15 is applied (Tölle et al., 2018).

For the configurations at the BLER site, the model estimates a daily average value of about 0.15. This value is somewhat smaller then what expected for the land cover at the site, where agricultural fields with crops are present (albedo = 0.18-0.25, Oke et al., 2018). It is not clear, however, whether this bias is a specific problem at the BLER site or a more general issue over the rural areas that surround the city.

Based on this analysis, we recommend that future studies consider the use of more advance method for albedo estimation, as developed and tested in recent studies with COSMO-CLM (e.g. Tölle et al., 2018).

In conclusion, we think that both aspects (inability to represent very stable boundary layer conditions by COSMO and underestimation of albedo) may play a role in determining the air temperature bias at the rural reference site BLER.

We reconsidered our analysis and made changes to the manuscript as follows:

pg 20 ln 23 "This is probably determined by the combined effect of underestimation in surface albedo and misrepresentation of atmospheric stability (Supplement). A similar underestimation of albedo at rural sites has been already found by Schubert and Grossman-Clarke (2014). The underestimation is attributed to the default albedo scheme of COSMO-CLM, which fails to represent different vegetation types. It is unclear, however, whether this bias is due to specific conditions at the BLER site (grassland) or due to a general misrepresentation in the land-surface model of COSMO-

CLM. The misrepresentation of stable boundary layer conditions is a well-known issue of COSMO (Buzzi et al., 2011; Cerenzia, 2017) and has already been reported in previous studies (Schubert and Grossman-Clarke, 2014; Mussetti et al., 2019)."

pg 27, ln 19-23 "The model evaluation at 2-m reveals an overestimation of the air temperature at the rural sites especially at night. Beside previous studies where this bias was attributed only to the misrepresentation of stable boundary layer conditions (Mussetti et al., 2019), the present study provides new evidences that point out to an underestimation of albedo over rural areas. Future studies need to address this issue that partially limits the model ability to represent the urban heat island effect. Potential solutions include the use of more advanced representations of albedo, already available as options in COSMO-CLM, with explicit consideration of vegetation type or satellite-based albedo values (Tölle et al., 2018). ~~This issue has been already found in other studies (e.g. Schubert and Grossman-Clarke, 2014) and is attributed to the inability of the model to reproduce very stable atmospheric conditions (Buzzi et al., 2011).~~ In respect to the representation of stable boundary layer conditions, more recent versions of the COSMO model (from version 5.4a onward) promise a better performance thanks to a revised turbulence scheme."

References:

Schubert, Sebastian, and S. Grossman-Clarke. "Evaluation of the coupled COSMO-CLM/DCEP model with observations from BUBBLE." Quarterly Journal of the Royal Meteorological Society 140.685 (2014): 2465-2483. https://doi.org/10.1002/qj.2311

Tölle MH, Breil M, Radtke K and Panitz H-J (2018) Sensitivity of European Temperature to Albedo Parameterization in the Regional Climate Model COSMO-CLM Linked to Extreme Land Use Changes. Front. Environ. Sci. 6:123. https://doi.org/10.3389/fenvs.2018.00123

Finally, I found myself referring to the rural figure often throughout the manuscript, it may be better placed in the main body near figure 6.

We added the daily evolution of T_{2m} at the rural reference site BLER to Figure 6.

pg 21, caption Figure 6: "Figure 6. Comparison between period averaged daily profiles of observed (Obs) and model-simulated 2-m air temperature at the sites BFEL, BSJO, SLFR, ~~and~~ BBIN and BLER during the selected period (discarding the first 5 days as spin-up). Black dots indicate the observations. Blue lines and red lines indicate the results from the STD and LA0 model runs, respectively. The range of variability within the selected period is shown as shaded area for Obs (grey) and STD (light blue)."

pg 28 ln 16 "additionally explained by an underestimation of the night-time temperature" I believe the night-time temperature is overestimated at the BKLI site.

We thank the reviewer for pointing out the typo.

pg 28 ln 16: “At the most urban site, it is additionally explained by an overunderestimation of the night-time temperature.”