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An urban trees parameterization for modelling microclimatic variables and thermal comfort conditions at street level with the Town Energy Balance model (TEB-SURFEX v8.0)
by Emilie Redon et al.

Response to reviewers' comments

General response to all

In response to the reviewers' comments, some important changes have been made to the new version of the manuscript:

1. Only the TREE-BARE configuration (courtyard with trees and bare soil) was presented in the previous version. To address the issue of taking into account both tree and herbaceous vegetation in TEB-Tree, we also simulated the TREE-GRASS configuration (courtyard with trees and lawn) for which we also had data. The manuscript now presents the evaluations (figs) for the TREE-GRASS case + the scores for both TREE-GRASS and TREE-BARE cases.
2. The section 6.4 on the new formulation of the mixing length raised many questions. It is true that we do not currently have adequate data to precisely evaluate this formulation and the potential benefit of the modification. Therefore, we preferred to delete this section since the formulation of mixing length remains unchanged in TEB-Tree compared to TEB-Ref.
3. The Section about the UTCI simulation has been modified to improve its clarity and relevance. The first part compares the UTCIs simulated by TEB-Ref and TEB-Tree to discuss the role of parameterization. A second part compares the different courtyard layouts and the impact on comfort conditions by putting these results in perspective with the works of Shashua-Bar et al (2011, Fig.2).
4. Finally, an error was found in the initialization of the material properties (wall albedo). Simulations were redone and figs and scores updated.

Response to Referee #1

Specific comments:

1) Section 2.2: the authors refer to Redon et al. (2017) for the radiative effects of urban trees. However, no ground vegetation is considered in Redon et al. (2017), so how do the trees modify net radiation for underlying ground vegetation (e.g., Fig. 1).

>> It is true that the comparisons TEB vs SOLENE carried out by Redon et al (2017) were based on simulations of vegetated canyons incorporating only tree vegetation. In this case, the ground surfaces were road. Nonetheless, the code has been developed to be able to include within the canyon a fraction of ground pervious covers that is defined as a combination of bare soil and herbaceous vegetation. This is explained is Redon et al. (2017), for instance, in Fig.1, in the descriptive parameters presented in Table 1, or the text in Section 3.3. In this paper, Eq. 14 expresses the solar radiation absorbed by the ground surface (same expression for road or natural covers) including the effect of trees.

The authors should present the surface temperature of ground vegetation at some time to illustrate the impact of trees. Please provide more information.

>> As explained in the article (Section 3.1), the model is based on the "bigleaf" approach for the SEB calculation. This implies that all natural covers (tree vegetation, herbaceous vegetation, and natural soils) are combined in a composite natural compartment. Then, the model resolves for this compartment a single SEB, as well as a single temperature evolution equation. This temperature is an average or composite temperature of the natural covers. Therefore, the temperature of the vegetation located on the ground under the trees cannot be analyzed separately.
As a complement, we present in Fig 3f both Tnat (composite temperature of natural covers) and Tt (tree temperature) and discuss the differences in Section 6.3.3.

2) Section 4.1: Equation (10) accounts for the drag force of urban canyon in both horizontal and vertical directions. If I understand correctly, as shown in Fig.1, TEB model assumes a very long canyon as compared to the building width, which leads to large variations of vertical drags when wind directions change. Is the frontal index of buildings/trees considered in the model? Please elaborate.

>> The wind profile is set in TEB as a mean horizontal wind profile that does not take into account the specific orientation of the streets. The drag coefficient associated with buildings is constant (and applied consistently to the vertical for wind speed calculation). The same is true for vegetation, except that this coefficient is weighted vertically, depending on the leaf density profile.
The term of frontal area density is used in TEB to calculate the mixing length, according to the formulations proposed by Santiago and Martilli (2010). This term is calculated as a mean frontal area density simply derived from the geometric properties defined in TEB (wall surface density) but without any link to wind direction. All this is described by Lemonsu et al (2012).
We clarified in the text:
"The vertical transport of heat, humidity and momentum within and above the canyon is calculated by applying the turbulence scheme of Cuxart et al. (2000). This scheme is based on an equation for the turbulent kinetic energy, and is closed with a mixing length. This is parameterized in TEB on the basis of the work of (Santiago et al. 2010) according to the height of buildings, the mean frontal area density, and the displacement height, i.e. parameters depending on the geometry of the canyon (see Eq. 10-12 in Lemonsu et al. 2012)."

3) Section 4.2: How is the transpiration rate of trees calculated?

>> As explained in Lemonsu et al. (2012) in Appendix B, ISBA calculates the latent heat flux as a combination of evaporation/transpiration terms produced by the natural covers: evapotranspiration from vegetation ($\mathbf{QEnat_v}$), evaporation from the ground ($\mathbf{QEnat_g}$) and from the ground with freezing ($\mathbf{QEnat_{gi}}$), and vaporisation from snow ($\mathbf{QEnat_s}$): $\mathbf{QEnat = QEnat_v + QEnat_g + QEnat_{gi} + QEnat_s}$

More specifically, the transpiration is calculated as: $\mathbf{QEnat_v = ACnat\ f_v\ L_v\ (1 - v_{sn})\ Hv\ (qsat - qa)}$

with **ACnat** aerodynamic conductance for heat transfer

f_v fraction of vegetation

v_{sn} fraction of vegetation covered by snow

qsat humidity at saturation

qa air humidity above the top of the canopy

Hv Halstead coefficient (i.e., the relative humidity of vegetation canopy as defined by Noilhan and Planton, 1989)

L_v vaporisation heat coefficient

>> Conforming to the "bigleaf" approach, the transpiration is calculated for the vegetation of the complete natural cover compartment. The vegetation can include only trees (as for experiment TREE-BARE), or combine trees and grass (as for experiment TREE-GRASS). In this last case, the transpiration is not calculated separately for trees and grass but for a composite vegetation.

It seems that Equation 8 is missing in the paper.

>> The label (8) that appears on page 5 is due to a layout problem. There is no missing equation here. The equations of turbulent latent heat fluxes are not presented because they are identical to those of sensitive heat fluxes (as inidcated in the text).
However, there was a typo: *"Q_{Et} and Q_{Et}"* instead of *"Q_{Eg} and Q_{Et}"* which we have corrected.

I love the consideration of leaf area density as a vertical profile to advance the ET modeling of trees. But why would the authors use a constant LAD then? At least some results with vertically varied LAD should be presented, especially in terms of the transpiration rate.

>> We use a constant LAD profile because we assume that trees are rectangular or cylindral in shape, which is quite realistic for pruned street trees. The model has the possibility to specify other crown shapes (conical or round shapes) but we do not have suitable observations to really evaluate the consideration of these different shapes. Considering the simplifying assumptions applied in the parameterizations for radiative, energetic, or aeraulic calculations, it seemed to us superfluous to go in this level of detail. We consider that remaining a homogeneous shape in the vertical is sufficient for now.

4) Section 5.2: The attenuation coefficients are sensitive to the locations of the trees and pedestrian. What are the locations of trees and pedestrian in this case? Also the authors separate trunks from the crown. Should the radiation from trunks be considered in this case?

>> This point refers to the attenuation coefficients of radiation by the trees foliage. This is an aspect that is discussed in more detail in Redon et al (2017), which focuses on radiative calculations, but little in this paper, which does not have this as its primary objective.
Again, it should be kept in mind that the model represents in a simplified and parameterized way the tree vegetation and its effects on radiative exchanges within the canyon:

1. Trunks are not taken into account as for of this kind of models. Only foliage layer is considered.
2. Trees are defined as a coverage fraction in the canyon, with an associated height and thickness for the foliage layer. But the actual positioning of the trees is not considered. For example, the model is not able to explicitly represent two separate rows of trees. This is well described in the article by Redon et al (2017).
3. For UTCI calculation, the model does not simulate the spatial variability of comfort conditions in the street. It simply calculates an "average" UTCI for an individual in the canyon by taking into account the radiative exchanges calculated on the basis of mean form factors.

I would like to comment more, especially when you have non-cylinder shape of crowns the mixing length below the trees may also be modified. But at this moment without sufficient details of the parameterization it is hard to assess the results.

Editorial comments: Abstract: ISBA model should be spell out at its first mention

>> This was corrected in the abstract for ISBA and TEB acronyms.

Response to Referee #2

Overall:

The present paper details an update to the TEB urban canopy model. It demonstrates that the updates made improve comparisons against observations made in an arid climate. It further demonstrates that in warm climates, trees may degrade thermal comfort at night.

The authors are encouraged to compare their updated model not only to their original model, but also contextualize their modelling approach relative to other urban canopy tree models, e.g. in a Discussion section. How does the current work differ, and what are its advantages and disadvantages? In particular, it is not clear how the current approach offers conceptual and/or operational advantages over other approaches cited (lines 2.28-29), even though it is shown that the current approach is better than the previous one with ground vegetation only. Potential error introduced by combining tree and ground vegetation energy balances is not assessed.

>> It seems to us very difficult to know how to compare objectively our results and approach to other models. Within the framework of radiative exchanges, we were able to compare TEB to a high-resolution architectural model. We constrained the modelling framework and certain parameters to focus on comparing the fluxes received, reflected and absorbed. For turbulent exchanges, thsi exercise is even more complex. In the conclusion, we highlight the limitations and issues related to the use of the bigleaf approach. We also mention the eventual need to move towards a multi-budget modelling for energy exchanges.

In general, some more discussion of the results presented in the figures, especially Fig.3, would be helpful in illustrating TEB-tree's usefulness and novelty. For example, there are some variables for which the difference between observations and model output is still appreciable and may require elucidation. Other model outputs do not appear to be realistic (e.g., daytime UTCI in the sun is not reduced with TEB-Tree, which should include impacts of tree shade).

>> We realize that the interpretation of the UTCIs presented in Fig. 6 is probably difficult for the reader to understand and that I need to clarify some points:

- The model independently calculates two UTCIs in the outdoor space i.e. the UTCI in the shade and the UTCI in the sun (but without taking into account the shading fractions in the street which can be more or less important depending on the configuration and layout of the canyon). This is why in the comparisons presented, there are relatively few differences on daytime UTCIs between the two model versions. The UTCI calculated in the sun does not take into account the shading effect of trees.
- To present a more understandable and realistic UTCI, I propose to calculate an "average" UTCI based on the UTCI in the sun and the UTCI in the shade, and weighted according to the canyon fractions in the sun and in the shade. Since the model does not explicitly represent the spatial location of the elements in the canyon (but simply coverage fractions), these shade/sun fractions are calculated simply as the ratio between the direct solar radiation received by the ground surface and the direct incident solar radiation at the top of the canyon.
- Based on this average UTCI, we can see more clearly the differences between the two versions of the model and the effect of tree shading on the UTCI during the day simulated by TEB-Tree. Figure 6 has therefore been updated and the discussion part of these results has been modified accordingly.

Finally, this paper would benefit from editing for grammar and language.

Specific comments:

- 2.8: Is scattering accounted for?

>> This paragraph aims to describe how tree vegetation alters radiative exchanges in the canyon. We added a sentence: *"The scattering modulates the properties of reflected and transmitted radiation."*

- The introduction provides an acceptable overview and motivation. The distinction between models that resolve vegetation and “urban canopy models” is not made fully clear – in both cases the scale of vegetation elements is smaller than the model grid.

>> In the introduction, we have separated the presentation of CFD or radiative transfer models for which the shafts can be described as an assembly of voxels. Then, in a second step, we presented urban canopy models that rather adopt parametric approaches. This seemed to us enough detailed to introduce the scientific and objective questions of the present study.

- 4.1: How would representing the sides of the crown help?

Trees are seen as a flat horizontal surface (with an associated coverage fraction within the canyon) for calculating the interception of incoming solar radiation. But depending on position and thickness of the tree crowns, as well as inclination of the sun's rays, the edges of the crowns can intercept a part of this radiation. This effect is not taken into account in TEB, which leads to an underestimation of the incoming solar radiation interception (more or less important depending of canyon configuration and vegetation layouts). This limitation was underlined by Redon et al. 2017: *"... due to the expression of direct solar radiation intercepted by high vegetation at the top of the crown, which is treated as a horizontal surface in TEB (Eq. 1), the fluxes reaching the trees in TEB are globally underestimated compared to the SOLENE fluxes that include contributions on the vertical faces of the crown envelope "*

We modified and completed the text to clarified this point (Section 2.2):
"Due to the simplified representation of trees geometry, a general defect is the underestimatation of the incoming solar radiation interception by the tree-foliage stratum. That is explained by the fact that TEB does not represent the sides of tree crowns, that can receive in reality a part of incoming radiation according to their position and inclination of the sun's rays."

- 4.28: How are these parameters defined?

>> ISBA requires some parameters related to soil and vegetation i.e. Soil albedo, Vegetation and soil albedo, Vegetation and soil emissivity, Vegetation fraction, Stomatal resistance, Dynamical roughness length, Heat capacity of vegetation and of soil. In the standard approach where specific in situ data are not available and land covers are defined from the ECOCLIMAP database, default parameters are assigned according to vegetation types (ex. for trees, distinction is done between deciduous, evergreen trees, needleleaf evergreen trees, and for different boreal, temperate, tropical climate conditions).
For the evaluation exercise, these parameters were defined according to the local information available for the experimental site. We completed Section 3.1:
"This compartment consists of fractions of bare soil, low vegetation, and high vegetation (and possibly snow). It is characterized by mean properties calculated from thermo-radiative (albedo, emissivity, heat capacity), aerodynamic (roughness length), and physiological (stomatal resistance for plants) parameters that are prescribed independently for the different types that compose it."

- Eq. 4 & 5: These fluxes appear to be defined per plan area fraction. How is leaf area taken into consideration? A particular coverage of trees can have higher or lower leaf area.

>> The leaf area index is used to calculate the attenuation coefficient of radiation through the foliage layer (see Eq. 3, Redon et al. 2017). This has consequently an impact on the amount of radiation that passes through the tree canopy and reaches the natural ground-based surfaces (the term S_g^t). But in the expression of the fluxes weighting, we rely only on the horizontal coverage fractions.

- Eqs. 6 & 7: It is not clear that this approach can be expected to give accurate results, as we have no reason to expect that QH and QE scale linearly with vegetation fraction at different levels. Stomatal resistances are likely to differ strongly between trees and ground-based vegetation, as are aerodynamic resistances (trees are likely to be exposed to higher winds). As well, how is storage heat flux treated here, given that soil will store a lot more heat than trees?

>> You are absolutely right, it's a very strong assumption of parameterization. For now, we have preferred to keep the approach very simple rather than disaggregate the fluxes according to assumptions that are difficult to make. To go further, it would be necessary to drop the "bigleaf" approach and move towards a multi-energy budget calculation. Appropriate experimental data should also be available to assess the contribution of such an approach.
Concerning heat storage, the disaggregated fluxes between ground-based surfaces and trees are not diagnosed, simply because this is not necessary: this term does not come into play in the TEB-SBL parameterization.

- 5.26: Where is equation 8?

>> The label (8) that appears on page 5 is due to a layout problem. There is no missing equation here. The equations of turbulent latent heat fluxes are not presented because they are identical to those of sensitive heat fluxes (as inidcated in the text).
However, there was a typo: *"Q_{Et} and Q_{Et}"* instead of *"Q_{Eg} and Q_{Et}"* which we have corrected.

- 5.27: Probably QEg and QEt is meant.

>> Exactly, there was a typo: *"Q_{Et} and Q_{Et}"* instead of *"Q_{Eg} and Q_{Et}"* which we have corrected.

- 6.10: Which pressure gradient?

>> The pressure-gradient force is the force that results from a difference in atmospheric pressure and that comes into play in the geostrophic wind equation. This term is provided at the highest level of the TEB-SBL vertical grid by the atmospheric model when SURFEX is run in coupled mode, or assumed to be null in stand-alone configuration. This is already described and explained in the reference paper presenting the SBL parameterization (Masson and Seity 2007).

- 6.20-23: Eqs. 11-14 do not allow for the vertical transport of any of the quantities therein. Discussion of how vertical transport is treated should be included in these equations or better, in Eq. 9.

>> The vertical transport within and above the canyon is parameterised using the turbulent scheme of Cuxart et al. (2000) based on an equation for the turbulent kinetic energy, and it is closed with a mixing length. We clarified this pont in Section 4.1
"The vertical transport of heat, humidity and momentum within and above the canyon is then calculated by applying the turbulence scheme of Cuxart et al. (2000). This scheme is based on an equation for the turbulent kinetic energy, and is closed with a mixing length. This is parameterized in TEB on the basis of the work of Santiago and Martilli (2010) according to the height of buildings, the mean frontal area density, and the displacement height, i.e. parameters depending on the geometry of the canyon (see Eq. 10-12 in Lemonsu et al., 2012)."

- Eq. 11: What is the last term? The square of the friction velocity. How is the friction velocity defined in the urban canopy?

>> There was an error in the formulation. The friction velocity is decomposed according to the vertical levels of the SBL parameterization. So we replace u* by u*(k). We use u* at the ground for contribution of roads and u* at the top of buildings for contribution of roofs.

- Eq. 15: It appears that LAD is assumed vertically uniform, and therefore turbulent fluxes from trees are assumed to be uniform with height in the tree canopy?

>> As explained in Section 4.2, the turbulent fluxes of trees are distributed vertically according to LAD profile, i.e. homogeneously from the bottom to the top of trees, since LAD profile is assumed to be homogeneous for rectangular crowns.

- 7.15: In Fig. 1 tree crowns are illustrated as uniform layers, not cylinders.

>> The TEB model represents the canyon in a 2D plane with the assumption that this canyon has an infinite length (with the same shape and configuration). For canyons with trees, this implies that the crowns of the trees touch each other (without spacing between trees in the longitudinal direction of the canyon), creating a continuous layer of foliage.
We used the term of "cylinder" to characterize the tree crown shape. That was a way to refer to a standard type of pruned trees and to distinguish it from other shapes that may exist (ovoid or triangular), for which LAD profiles are different. But the term is indeed not well suited to the model.
For clarity, we changed cylindric by rectangular: *"For now, tree crowns are described rectangular in shape so that ..."*

- 9.11: "only reflected upward" – shortwave is not emitted by trees.

>> Yes you are right, it is corrected.

- 9.12: Why is this re-emitted radiation only upward?

>> It is assumed that it is mainly the top of the tree crowns that intercepts the incident solar radiation, so that this radiation is re-emitted upward. This formulation is the result of the work of Redon et al (2017) for the parameterization of radiative exchanges.

- 9.10-12: Is it possible to estimate the potential error from this assumption? How much could it affect the Tmrt?

>> This formulation proposed by Redon et al (2017) was applied in the comparison exercise to the high-resolution SOLENE model. It has been evaluated indirectly by evaluation multi-reflections within the canyon and solar radiation absorbed by the different elements of the canyon.

- 10.2: Citation not in reference list.

>> We now refer to Shashuabar et al. 2009.

- Section 6.2: For air temperature and humidity surely this canyon is the wrong scale (too small) to evaluate TEB-Tree? Advective effects are likely to be large?

>> It is indeed possible that there may be advection effects on the experimental site. This seems to be the case based on humidity measurements. This does represent a certain limitation for comparison to the model in forced mode on a grid point. Additional work is currently being carried out with a 3D numerical modelling configuration by coupling the surface scheme to a complete atmospheric model.

- 10.22-30: This paragraph is difficult to understand.

>> We modified the text to clarify: *"In the TEB-Ref standard approach, land cover fractions are calculated according to a single surface area without overlapping (as seen from the sky or by satellite). The sum of cover fractions is equal to 1. The tree cover has priority over what is below and is hidden, that is the case here since the tree-foliage layer covers 70 % of the canyon. In the TREE-BARE experiment, all bare ground and part of pavement are therefore hidden by trees, which modifies the real fractions (Table 1). In the TTREE-GRASS experiment, trees largely but not totally mask grass since the grass cover fraction is slightly greater than that of trees (Table 1). The TEB-Tree version describes more realistically the arrangement of elements by dissociating the tree-foliage stratum from ground-based natural covers. As a consequence, for both experiments, the cover fractions prescribed for TEB are the real ones (Table 1) and their sum is greater than 1."*

- Fig. 1 & Fig. 2: The text appears to indicate that trees do not have sides in this model, but this diagram suggests the opposite.

>> Indeed, the model does not treat the sides of the foliage layer. Nevertheless, it considers a base and a top for the foliage layer, as well as a coverage fraction in the canyon. The graphical representation

proposed in Figs. 1 and 2 therefore seemed to us to be the most explicit way of representing the model concept.

- Fig. 3 d & f: Some of the model-measurement surface temperature differences are very large (>10 K). What is the model missing in these cases? The modelled increase in east wall temperatures in the morning is not reproduced in observations.

>> Surface temperature simulations have been significantly improved by modifying the wall albedo whose prescribed value had been underestimated compared to the information from the experimental site. The albedo is now set at 0.6, which is high but corresponds to actual data provided by the team that made the measurements.
However, there is still a bias on the simulation of eastern wall temperature in the morning. I would say that this difference may be related to the specific arrangement of the trees in the canyon and the positioning of the sensor (which seems to be in the shade for a few hours). This effect is not found for the temperature of the west wall at the end of the day, which is correctly simulated by the model.
Figures and scores have be updated according to the new simulations. Additional comments have been included with regard to overestimation:
"Nonethless despite the improvement, TEB-Tree still overestimates the surface temperature especially for eastern wall in the morning. This suggests the attenuation effect by tree foliage remains underestimated by the model in this case. The deviation from the measurement can also be explained by a difference between the compared quantities. The thermometer samples a specific area of the wall, while the model calculates an average temperature for the entire wall."

- 11.20: ". . . by trees that are so tall than buildings". Do you mean trees that are as tall as buildings? Or that are taller than buildings? Can trees that are taller than buildings be implemented in this model?

>> It is a drafting error that we corrected: *". . . by trees that are **as** tall than buildings"*
Trees cannot be higher than buildings, this would require modifying radiative calculations. This point is already discussed in Redon et al (2017): *"In the current version of TEB (official SURFEX v8.0), urban trees are assumed to be less tall than surrounding buildings and systematically confined inside the canyon so that they cannot provide shade for roofs. This hypothesis is in accordance with common urban planning specifications for street tree management in Europe (in French, Municipality of Toulouse, 2008; City of Westminster, 2009; Barcelona City Council, 2011)."*

- 11.28: Tree temperature = air temperature ?? It seemed earlier that an energy balance is solved for leaves/trees, which means a surface temperature is calculated?

>> Conforming to the "bigleaf approach", natural covers (tree and bare soil for TREE-BARE and tree and grass for TREE-GRASS) are combined in a composite natural compartment. Then, the model resolves for this compartment a single SEB, as well as a single temperature evolution equation. This temperature is an average or composite temperature of the natural covers, **but not the temperature of leaves**.
Radiative calculations require to know the leaves temperature. We consequently do the assumption that leaves are in equilibrium with ambiant air and their temperature is equal to the air temperature.

- 12.13: Some justification into the selection of the mixing length would be useful. 10 cm as a mixing length seems somewhat low. Maybe scale the mixing length as LAD?

>> This issue related to of the formulation of the mixing length is interesting. However, since we do not have measurements adapted to a specific evaluation, we felt that this section did not provide useful information. We propose to delete this section, since for the time being the formulation of the mixture length remains unchanged compared to that presented by Lemonsu et al (2012).

- Eq. 25: What about the presence of buildings and their effects on mixing length? Is this already included here?

>> Indeed, the height of the buildings and the average frontal are density are used in the calculation of the mixing length (see previous comment about vertical transport)

- Fig.5: Would perhaps benefit from increased vertical resolution.

>> This issue is no more discuss in the manuscript. But we do not think increasing the vertical resolution could really improve the modelling considering the model hypotheses.

- Section 6.4: Which version, with or without the length scale modification, do the authors think is best and consider to be "TEB-Tree"?

>> The formulation of the mixture length remains unchanged compared to that presented by Lemonsu et al (2012).

- Fig. 6: Surely TEB-Tree, by virtue of accounting for shade from trees, should strongly reduce UTCI during daytime in the sun relative to TEB-Ref, which does not account for tree shade?

>> See previous comment about UTCI (General response to all (3) and response to your general comments)

- 13.22: "at night radiation conditions are the same." What about longwave radiation? Surely that differs when near a wall at night? Do you mean to say that at night there is no shortwave radiation?

>> If this is the case, it is because conceptually the calculation of the UTCI for the "sun" case and for the "shade" case is the same except for taking into account the contribution of direct solar radiation (as explained in Section 5). For other sources of radiation received by the individual, there is no difference. Nevertheless, as this part was difficult to understand, we reworked the presentation of the results and the explanation (see general comment/response to all).

- 13.30: "It remains 5 C (warmer?) than in TEB-Ref simulations"

>> The section was reworked for clarification (see general comment/response to all).

- Section 6.5: Regarding the degradation of UTCI at night due to trees – are there measurements of this effect (or of increased longwave from urban tree cover) that you can reference, for example, to indicate that your results are in line with observations?

>> No UTCI measurements were available at the experimental site for comparison. Nevertheless, we completed and improved this section of the article (see response to all) and put our results on UTCI in perspective with those published by Shashua-Bar et al (2011) who calculated indexes of thermal stress from insitu measurements.

An urban trees parameterization for modelling microclimatic variables and thermal comfort conditions at street level with the Town Energy Balance model (TEB-SURFEX v8.0)

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Abstract. The ~~TEB~~ Town Energy Balnce (TEB) urban climate model has recently been improved to more realistically address the radiative effects of trees within the urban canopy. These processes necessarily have an impact on the energy balance that needs to be taken into account. This is why a new method for calculating the turbulent fluxes for sensible and latent heat has been implemented. This method remains consistent with the "bigleaf" approach of the ~~ISBA~~ Interaction Soil-Biosphere-Atmosphere (ISBA) model which deals with energy exchanges between vegetation and atmosphere within TEB. Nonetheless, the turbulent fluxes can now be dissociated between ground-based natural covers and tree stratum above (knowing the vertical leaf density profile), which can modify the vertical profile in air temperature and humidity in the urban canopy. In addition, the aeraulic effect of trees is added, parameterized as a drag term and an energy dissipation term in the evolution equations of momentum and of turbulent kinetic energy, respectively. This set of modifications relating to the explicit representation of tree stratum in TEB is evaluated on an experimental case study. The model results are compared to micrometeorological and surface temperature measurements collected in a semi-open courtyard with trees and bordered by buildings. The new parameterizations improve the modelling of surface temperatures of walls and pavements thanks to taking into account radiation absorption by trees, and of air temperature. The wind speed is strongly slowed down by trees that is also much more realistic. The universal thermal climate index diagnosed in TEB from inside-canyon environmental variables is highly dependent and sensitive to these variations in wind speed and radiation. This demonstrates the importance of properly modelling interactions between buildings and trees in urban environments, especially for climate-sensitive design issues.

1 Introduction

The urban climate commonly refers to the modification of local climate by the urban environment. It results from the establishment of radiative, energetic, dynamic, hydrological surface processes that are pecular to urban covers properties (Oke et al., 2017). This urban climate may however present important spatial variabilities within the city. The street-level meteorological variables, i.e. air temperature, humidity, wind, are modified in by the local environment depending the morphology and arrangement of buildings, the surface properties and more generally the land covers composition (Houet and Pigeon, 2011; Fenner et al., 2014; Ndetto and Matzarakis, 2014; Alexander and Mills, 2014).

The presence of vegetation, and especially urban trees, is one element of modification of local microclimate (Bernatzky, 1982; Oke, 1989; Shashua-Bar and Hoffman, 2000; Potchter et al., 2006; Shashua-Bar et al., 2011). The trees functioning is governed by own physiological processes together with local environmental conditions. When located in a street canyon, the trees come in interaction with the surrounding urban elements. The radiative exchanges are modified as well as energy fluxes and local air flows. The incoming radiation is intercepted by the tree foliage depending on its localization and coverage in the street (Souch, 1993; Armson et al., 2012; Berry et al., 2013). It is for one part reflected upward according to reflective properties of leaves, whereas the other part is partially transmitted through the foliage or absorbed by it. The scattering modulates the properties of reflected and transmitted radiation. The multiple reflections of short- and long-wave radiation between all components of the canyon are also disrupted by the presence of trees that are furthermore an additional source of infrared emissions. A part of energy absorbed by trees is used in the transpiration process associated to photosynthesis (Peters et al., 2011; Qiu et al., 2013). This is a water exchange from aerial parts of plants to the atmosphere through stomata. The transpiration rate is related to the stomata opening level which is regulated according to environmental conditions of sunlight, temperature, humidity and wind, but also to soil water availability (Konarska et al., 2016; Litvak and Pataki, 2016). As a consequence, the energy exchanges that are mostly dominated by heat transfers through conduction and convection in built-up environments can be significantly modified with the vegetation effects (Grimmond et al., 1996; Offerle et al., 2006; Best and Grimmond, 2016). Finally, the trees are physical obstacles to the flow within the street (Heisler, 1990; Giometto et al., 2017; Martini et al., 2017). They lead to a drag effect on the mean flow and modify local turbulent exchanges which can have an impact on ventilation as well as on particles dispersion (Buccolieri et al., 2011; Abhijith et al., 2017).

Some of urban climate models are capable to simulate the presence of certain vegetated elements in the urban environment. They are not represented with the same level of accuracy, nor the same physical processes. The high spatial resolution softwares or models that are based on near-reality numerical mock-ups of the environment integrate trees as fully elements composing the scene simulated as porous media (Bruse and Fleer, 1998; Salim et al., 2015). They are obstacles on the same level as buildings, and can consequently be involved in dynamical processes in CFD modelling. They are resolved explicitly in some radiative transfer models such as SOLENE (Miguet and Groleau, 2007) or DART (Gastellu-Etchegorry et al., 1996). They are here described as turbid objects that intercept, transmit, absorb, and emit radiation, in complex interaction between all surrounding objects of the scene.

Some of urban canopy models coupled or implemented in meso-scale atmospheric models now include a representation of urban vegetation and even of trees. This is done through a simplified approach for which trees effects are parameterized (Lee and Park, 2008; Krayenhoff et al., 2014, 2015; Ryu et al., 2016; Redon et al., 2017). Despite a simplified description of the urban environment, the main physical processes can be taken into account, i.e. radiation interactions between a mean tree foliage layer within the canyon and surrounding urban facets, the modification of wind profile within the canyon by drag effect of this foliage layer, or the transpiration of trees. These models offer the interest to be able to apply over the whole city and to operate in complete three-dimensional atmospheric simulations where two-ways interactions between complex surfaces and atmosphere are resolved. They have then the capability to simulate a certain level of microclimate variability between neighbourhoods (de Munck et al., 2018) especially according to the presence of vegetation and trees, and the potential influences or interferences between local microclimates by horizontal advection.

2 Representation of natural covers in TEB

2.1 Previous developments and general approach

The Town Energy Balance (TEB) urban canopy model is one of the first model from this generation to have included urban vegetation in local-scale interaction with the built-up elements. It has been progressively made more complex by integrating new types of nature elements and new associated processes. The first step was the inclusion of ground-based vegetation within the canyon by implementing the Interaction Soil-Biosphere-Atmosphere (ISBA, Noilhan and Planton, 1989) model within TEB (Lemonsu et al., 2012). ISBA is a surface-vegetation-atmosphere transfer (SVAT) model. ~~Through this coupling , it makes~~ This coupling makes it possible to simulate the physiological behaviour of plants subject to radiative effects of urban geometry and to microclimate conditions of the urban environment. Reversely, the microclimate within the canyon can be impacted by the ~~evapotranspiration from~~ modification of surface energy exchanges due to the presence of vegetation at the ground, especially by its evapotranspiration. A module of extensive green roofs was also developed (de Munck et al., 2013) still using the ISBA model to simulate the hydrological and energetic functioning of the green roofs, as well as the energy exchanges with atmosphere and the thermal coupling with the buildings on which they are installed.

2.2 Radiative effects of urban trees

Finally the most recent developments regard trees. Redon et al. (2017) proposed a new parameterization for modelling the radiative effects of trees by including a tree-foliage stratum within the urban canyon which can partially cover ground-based surfaces. The positioning and geometry of individual trees are not described explicitly but rather approached as (1) an horizontal coverage fraction ~~in~~ within the canyon, (2) a vertical thickness by defining a mean height of trees and a mean height of trunks, and (3) a mean leaf density profile (see description in Figure 1). The trees foliage can intercept a part of incoming radiation depending on canyon geometry, that is either reflected upward, or transmitted through the foliage, or absorbed by the foliage. In addition, the foliage layer takes part of radiation inter-reflections within the canyon between the different components (trees, walls, road, ground-based natural covers) and contributes to infrared emissions. Separated calculations are done for direct and diffuse components of shortwave radiation, and for long-wave radiation. The direct shortwave radiation is assumed directional whereas the diffuse shortwave radiation, the longwave radiation, and any radiation after reflection are assumed to be isotropic. The radiation interactions between all components of the canyon are consequently managed using form factors calculated between all of them.

These developments were evaluated by comparison with solar enlightenment modelling performed by a high-resolution architectural software, for a large set of simple-geometry urban canyons, with various aspect ratios and various trees arrangements within (Redon et al., 2017). A Due to the simplified representation of trees geometry, a general defect is the underestimation of fluxes intercepted underestimatation of the incoming solar radiation interception by the tree-foliage stratumthat . That is explained by the fact that TEB does not represent the sides of crowntree crowns, that can receive in reality a part of incoming radiation according to their position and inclination of the sun's rays. The simplified approach is also a limitation for describing some vegetation arrangements such as multiple lanes of trees. Nonetheless, the results are quite acceptable and confirm this new version make possible to better simulate the radiative interactions in canyons with trees.

In coherence with this explicit separation of vegetation strata, there was then a need to adapt the calculation of the turbulent fluxes related to low and high vegetation as well as to include the drag effect of trees on wind profile in the canyon. These new developments and their evaluation by comparison to microclimatic measurements are presented and discussed here. There are complemented by an updated calculation of the universal thermal comfort index (UTCI) by including the effect of trees.

3 Surface energy balance of the canyon components in TEB

3.1 Descripion of natural covers with the "bigleaf approach"

The TEB model resolves the radiative budget for each component of the urban canyon. In the case of a treeless canyon, it accounts for obstruction effects due to buildings in calculation of incoming short- and long-wave radiation interception by roads, walls, and natural ground-based surfaces, as described in details in Masson (2000) and Lemonsu et al. (2012). The new version of Redon et al. (2017) now includes the additional interactions with the tree-foliage stratum. From the resolution of radiation budget, the energy quantity absorbed in short- (S^*) and long-wave (L^*) radiation by each component or net radiation (Q^*) is determined:

$$Q^* = S^* + L^* \tag{1}$$

This net energy source is redistributed as turbulent sensible (Q_H) and latent (Q_E) heat fluxes between each considered component and local atmosphere, and as a storage heat flux by conduction (Q_G) through the component itself (i.e. through the artificial-materials layers that compose the roof, the road or the walls, or in the ground for the natural covers).

For the built-up facets of urban canyon (road, wall, roof), the surface energy balance (SEB) calculations remain unchanged in the TEB model, but with Q^* potentially modified in case of canyons with trees. Since the works of Lemonsu et al. (2012), the turbulent processes for natural parts of the urban canyon (natural soils and ground-based vegetation) are resolved in TEB through the integration of the ISBA model that is here constrained by radiative and microclimatic conditions related to the urban environment. The ISBA model is based on that is called "the bigleaf approach" in which the natural covers are managed as a unique composite compartment. This compartment consists in of fractions of bare soil, low vegetation, and high vegetation (and possibly snow)according to which mean radiative, aerodynamic, and physiologic parameters are defined. It is characterized by mean properties calculated from thermo-radiative (albedo, emissivity, heat capacity), aerodynamic (roughness length), and physiological (stomatal resistance for plants) parameters that are prescribed independently for the different types that compose it. A single temperature (T_{nat}) is associated to itthe compartment, and a single SEB is resolved:

$$Q^*_{nat} = Q_{H_{nat}} + Q_{E_{nat}} + Q_{G_{nat}} \tag{2}$$

This net radiation depends on the radiation budget which is expressed as following:

$$Q^*_{nat} = S^*_{nat} + L^*_{nat} = (1-\alpha_{nat})S^{\downarrow}_{nat} + \epsilon_{nat}(L^{\downarrow}_{nat} - \sigma T^4_{nat}) \tag{3}$$

The incoming short- and long-wave radiation intercepted by natural covers compartment ($S^{\downarrow}_{nat}$ and $L^{\downarrow}_{nat}$) are calculated for a reference level at the ground within the urban canyon. The composite albedo (α_{nat}) is calculated as an average of bare soil and vegetation albedo (which are themselves average albedos of snow-covered and snow-free surfaces). Same is done for the emissivity (ϵ_{nat}).

3.2 Modification of surface energy balance due to implementation of trees

The implementation of a tree canopy in TEB like a supplementary foliage stratum makes it possible to separate the incoming radiation received by natural covers as a part received by ground-based natural surfaces ($S^{\downarrow}_g$ and $L^{\downarrow}_g$) and a part received by trees ($S^{\downarrow}_t$ and $L^{\downarrow}_t$), and also to compute the net radiation for both of them (S^*_t and L^*_t). For purpose of simplicity, the bigleaf concept used in ISBA for the SEB calculation and the resolution of the surface-layer temperature evolution equation is here remained. This requires to calculate aggregated radiation fluxes intercepted by the compartment of natural covers which is must be provided to ISBA. Considering that the foliage stratum partially overlaps the ground-based surfaces, these fluxes are aggregated according to a single the cumulative fraction of natural covers, and weighted to insure energy conservation as followingaccounting for the distribution between covers at the ground and trees:

$$S^{\downarrow}_{nat} = \frac{\delta_g S^{\downarrow}_g + \delta_t S^{\downarrow}_t}{\delta_g + \delta_t} \tag{4}$$

$$L^{\downarrow}_{nat} = \frac{\delta_g L^{\downarrow}_g + \delta_t L^{\downarrow}_t}{\delta_g + \delta_t} \tag{5}$$

Here, δ_g is the ground-based surface fraction of the canyon covered by gardens (i.e. bare soil and low vegetation) and δ_t is the overlapping fraction of tree stratum. Note that these fractions are not dependant one from the other, so that their sum can be greater than 1 (Figure 1). Both $Q_{H_{nat}}$ and $Q_{E_{nat}}$ fluxes calculated by ISBA for the composite compartment are then desaggregated simply redistributed in two contributions from ground-based natural covers (Q_{H_g} and Q_{E_g}) and from trees (Q_{H_t} and Q_{E_t}) , based on ponderation coefficients related to the cover fractionsto insure the energy conservation:

$$Q_{H_g} = \frac{\delta_g}{\delta_g + \delta_t} \; Q_{H_t} = Q_{H_{nat}} \tag{6}$$

$$Q_{H_t E_g} = \frac{\delta_t}{\delta_g + \delta_t} \; Q_{H_{nat} E_t} = Q_{E_{nat}} \tag{7}$$

Same equations are applied for Q_{E_t} and Q_{E_t}.

4 Inclusion of trees in the surface boundary layer parameterization of TEB

4.1 Principle of the surface boundary layer parameterization

The TEB-SBL (SBL referred to as surface boundary layer) parameterization has been implemented in TEB in order to improve the meteorological variable prediction within the urban canyon (Hamdi and Masson, 2008; Masson and Seity, 2009; Lemonsu et al., 2012). TEB-SBL resolves the surface boundary layer for an air volume in the canyon from a system of evolution equations for air temperature (T), specific humidity (q), wind speed (U), and turbulent kinetic energy (E). For taking into account the effects of canyon on the local atmospheric characteristics evolution, an additional forcing term is included in each of these equations, according to the approach proposed by Yamada (1982) for the drag forces related to the vegetation canopies. The equations have the same general expression, with V the considered variable and F_V the general forcing term including advection, Coriolis force, and pressure gradient:

$$\frac{\partial V}{\partial t} = F_V + \left.\frac{\partial V}{\partial t}\right|_{can} \tag{8}$$

The last term to the right is the forcing term due to the canyon. It translates a drag force for the wind, a heating/cooling effect for air temperature, a humidification/dryness effect for air humidity, and a dissipation/production effect for turbulent kinetic energy. According to Martilli et al. (2002), these additional contributions are associated to horizontal and vertical surfaces of the canyon:

$$\left.\frac{\partial V}{\partial t}\right|_{can} = \left.\frac{\partial V}{\partial t}\right|_{can}^{H} + \left.\frac{\partial V}{\partial t}\right|_{can}^{V} \tag{9}$$

For these terms, the equations are resolved according to a vertical discretisation of the air volume from the ground to a reference atmospheric level located above the top of buildings (Figure 1). As described by Lemonsu et al. (2012), the equation system of the TEB-SBL parameterization is expressed as following for each k vertical layer :

$$\left.\frac{\partial U(k)}{\partial t}\right|_{can} = -C_{d_{bld}}\,U(k)^2\,\frac{S_{V_w}(k)}{V_{air}} - u_*^2(k)\left(\frac{S_{H_R}(k)}{V_{air}} + \frac{S_{H_r}(k)}{V_{air}}\right) \tag{10}$$

$$\left.\frac{\partial E(k)}{\partial t}\right|_{can} = C_{d_{bld}}\,U(k)^3\,\frac{S_{V_w}(k)}{V_{air}} \tag{11}$$

$$\left.\frac{\partial T(k)}{\partial t}\right|_{can} = \frac{Q_{H_R}}{\rho C_p}\cdot\frac{S_{H_R}(k)}{V_{air}} + \frac{Q_{H_r}}{\rho C_p}\cdot\frac{S_{H_r}(k)}{V_{air}} + \frac{Q_{H_{nat}}}{\rho C_p}\cdot\frac{S_{H_{nat}}(k)}{V_{air}} + \frac{Q_{H_w}}{\rho C_p}\cdot\frac{S_{V_w}(k)}{V_{air}} \tag{12}$$

$$\left.\frac{\partial q(k)}{\partial t}\right|_{can} = \frac{Q_{E_R}}{\rho \mathcal{L}_v}\cdot\frac{S_{H_R}(k)}{V_{air}} + \frac{Q_{E_r}}{\rho \mathcal{L}_v}\cdot\frac{S_{H_r}(k)}{V_{air}} + \frac{Q_{E_{nat}}}{\rho \mathcal{L}_v}\cdot\frac{S_{H_{nat}}(k)}{V_{air}} \tag{13}$$

where $C_{d_{bld}}$ is the drag coefficient for buildings, u_* the friction velocity at level k, V_{air} the air volume of the SBL-scheme layer where exchanges take place, ρ is the air density, and $\mathcal{L}_v$ is the latent heat for vaporization. The sensible heat fluxes of vertical surfaces (Q_{H_w} for walls) contribute to air temperature evolution at layer k relatively to the fraction of the total wall surface in contact with the considered air layer ($S_{V_w}(k)$). The sensible heat fluxes of horizontal surfaces combine Q_{H_R}, Q_{H_r}, and $Q_{H_{nat}}$ for roofs, road, and natural covers, respectively. The roofs only contribute to air temperature for vertical level above building top (with surface S_{H_R}). The contributions of road and of natural covers are here included at the ground-level so that they affect only the first layer of TEB-SBL (with respective surfaces $S_{H_r}(k)$ and $S_{H_{nat}}(k)$). The same types of contributions are parameterized for humidity but in the form of latent heat fluxes.

The vertical transport of heat, humidity and momentum within and above the canyon is calculated by applying the turbulence scheme of Cuxart et al. (2000). This scheme is based on an equation for the turbulent kinetic energy, and is closed with a mixing length. This is parameterized in TEB on the basis of the work of Santiago and Martilli (2010) according to the height of buildings, the mean frontal area density, and the displacement height, i.e. parameters depending on the geometry of the canyon (see Eq. 10-12 in Lemonsu et al., 2012).

4.2 Distribution of heat and humidity fluxes from natural covers

The implementation of trees in TEB requires to modify the ensemble of equations in order to take into account the vertical redistribution of turbulent fluxes and the drag effect of the foliage layer.

4.3 ~~Distribution of heat and humidity fluxes from natural covers~~

The turbulent fluxes of trees (Q_{H_t} and Q_{E_t}) coming from the desaggregation of ISBA fluxes calculated with the bigleaf concept (see Eq ~~??~~6 and 7) are assumed to be produced not at ground-level but at height of the foliage layer within the canyon. These fluxes have therefore to be vertically distributed in the TEB-SBL equations that is here parameterized according to a function of the foliage density contained in each k layer:

$$Q_{H_t}(k) \quad = \quad \int\limits_k LAD(z)dz \; Q_{H_t} = \left(\frac{d_t(k)}{h_t - h_{tk}}\right) \; LAI \; Q_{H_t} \tag{14}$$

$$Q_{E_t}(k) \quad = \quad \int\limits_k LAD(z)dz \; Q_{E_t} = \left(\frac{d_t(k)}{h_t - h_{tk}}\right) \; LAI \; Q_{E_t} \tag{15}$$

with $d_t(k)$ is the foliage-layer thickness in the k layer. The leaf area index (LAI in m^2 m^{-2}) is prescribed as input data. The leaf area density (LAD in m^2 m^{-3}) is the vertical profile of LAI which depends on the total thickness of the foliage layer and the form of tree crowns. For now, tree crowns are described ~~as cylinders~~ rectangular in shape so that LAD is constant over the thickness of tree-foliage layer i.e. between h_{tk} and h_t that are the height of trunks and of trees, respectively.

These turbulent fluxes are now included in the evolution equations of temperature ~~and humidity~~ (Eq 12) and humidity (Eq 13) profiles of TEB-SBL, in addition to ground-based contributions coming from natural soils and low-level vegetation:

$$\left.\frac{\partial T(k)}{\partial t}\right|_{can} \quad = \quad \frac{Q_{H_R}}{\rho C_p}\frac{S_{H_R}(k)}{V_{air}} + \frac{Q_{H_r}}{\rho C_p}\frac{S_{H_r}(k)}{V_{air}} + \frac{Q_{H_g}}{\rho C_p}\frac{S_{H_g}(k)}{V_{air}} + \frac{Q_{H_w}}{\rho C_p}\frac{S_{V_w}(k)}{V_{air}} + \frac{Q_{H_t}(k)}{\rho C_p}\frac{V_{grid}}{V_{air}}\delta_t \tag{16}$$

$$\left.\frac{\partial q(k)}{\partial t}\right|_{can} = \frac{Q_{E_R}}{\rho \mathcal{L}_v}\frac{S_{H_R}(k)}{V_{air}} + \frac{Q_{E_r}}{\rho \mathcal{L}_v}\frac{S_{H_r}(k)}{V_{air}} + \frac{Q_{E_g}}{\rho \mathcal{L}_v}\frac{S_{H_g}(k)}{V_{air}} + \frac{Q_{E_t}(k)}{\rho \mathcal{L}_v}\frac{V_{grid}}{V_{air}}\delta_t \tag{17}$$

with δ_t the overlapping fraction of trees in the canyon, and V_{grid} the total air volume.

4.3 Aerodynamic effect of trees

The presence of trees also modifies the air flow within the canyon. For account to this, a supplementary drag term is now included in the evolution equations of momentum (Eq 10) and turbulent kinetic energy (Eq 11):

$$\left.\frac{\partial U(k)}{\partial t}\right|_{can} = -C_{d_{bld}}U(k)^2\frac{S_{V_w}(k)}{V_{air}} - u_*^2(k)\left(\frac{S_{H_R}(k)}{V_{air}} + \frac{S_{H_r}(k)}{V_{air}}\right) - C_{d_t}U(k)^2 LAD(k)\delta_t \tag{18}$$

$$\left.\frac{\partial E}{\partial t}\right|_{can} = C_{d_{bld}}U(k)^3\frac{S_{V_w}(k)}{V_{air}} + C_{d_t}U(k)^3 LAD(k)\delta_t \tag{19}$$

Numerous studies found in literature (Cassiani et al., 2008; Dupont and Brunet, 2008; Aumond et al., 2013; Krayenhoff et al., 2015) propose an optimized value of the drag coefficient of trees (C_{d_t}). Until the works of Katul et al. (1998), this coefficient is usually defined as a constant $C_{d_t} = 0.20$.

5 Parameterization of universal thermal climate index

5.1 General principle

The UTCI calculation according to the polynomial regression equation proposed by Bröde et al. (2012) (not detailed here) requires four meteorological parameters: air temperature at 2 m above the ground, the water vapor pressure at the same level, the wind speed at 10 m above the ground, and the mean radiant temperature (T_{mrt}). This equation has been implemented in TEB (Kwok et al., 2019, supplementary materials) for calculating three UTCIs that are associated with a person (1) in the street exposed to the sun, (2) in the street in the shadow, and (3) in the building.

For outdoor conditions in case of a person in the sun, T_{mrt} is calculated by accounting for the ensemble of radiation sources received by the person, i.e. the direct and diffuse incoming short-wave radiation ($S^{\downarrow}$ and $S^{\Downarrow}$), the short-wave radiation after reflection on the walls, the road, and the ground-based natural covers in the canyon (S_w^r, S_r^r, S_g^r), the incoming atmospheric long-wave radiation ($L^{\downarrow}$), and the infrared emissions from surrounding canyon surfaces ($L_w^{\uparrow}$, $L_r^{\uparrow}$, $L_g^{\uparrow}$ for walls, roads, and ground-based natural covers).

The direct short-wave radiation assumed to be unidirectional is weighted by a factor of projected area relative to the person (f_p) which depends on sun elevation (γ in $^{\circ}$) according to the formulation of Fanger (1970):

$$f_p = 0.308\, cos\left\{\gamma\left(1 - \frac{\gamma^2}{48402}\right)\right\} \tag{20}$$

The other fluxes that are considered to be isotropic in TEB radiative calculations are weighted by the form factors calculated for the person (b index is used for $body$) in relation to the surrounding elements that contribute to radiation, i.e. Ψ_{bs}, Ψ_{br}, Ψ_{bw} for the sky, the road, and the walls, respectively (ground-based natural covers have the same form factor than road). Finally, the mean radiant temperature for the person in the sun is expressed according to the expression:

$$T_{mrt} = \sqrt[4]{\frac{a_b}{\sigma\epsilon_b}\left(\frac{f_p}{sin(\gamma)}S^{\downarrow} + \Psi_{bs}S^{\Downarrow} + \Psi_{bw}S_w^r + \delta_r\psi_{br}S_r^r + \delta_g\psi_{br}S_g^r + \Psi_{bs}L^{\downarrow} + \psi_{bw}L_w^{\uparrow} + \delta_r\psi_{br}L_r^{\uparrow} + \delta_g\psi_{br}L_g^{\uparrow}\right)} \quad (21)$$

In this expression, the human body is characterized by a prescribed solar absorption coefficient ($a_b = 0.70$) and a prescribed emissivity ($\epsilon_b = 0.97$). In case the person is in the shadow, the term relative to direct short-wave radiation contribution is not taken into account, so that the expression becomes:

$$T_{mrt} = \sqrt[4]{\frac{a_b}{\sigma\epsilon_b}\left(\Psi_{bs}S^{\Downarrow} + \Psi_{bw}S_w^r + \delta_r\psi_{br}S_r^r + \delta_g\psi_{br}S_g^r + \Psi_{bs}L^{\downarrow} + \psi_{bw}L_w^{\uparrow} + \delta_r\psi_{br}L_r^{\uparrow} + \delta_g\psi_{br}L_g^{\uparrow}\right)} \quad (22)$$

5.2 Inclusion of tree effects

The new parameterization for trees in the TEB model requires to adapt the radiative contributions in the UTCI calculations for outdoor conditions. First, the initial contributions in diffuse short-wave radiation and infrared radiation (detailed in Eq 21) are corrected for the sky and the walls from the radiation attenuation effect through the tree foliage. These attenuation coefficients are those already presented in Redon et al. (2017) that are dependent on the leaf area density profile; they are referred to as τ_{sr} for attenuation between sky and road and τ_{wr} for attenuation between wall and road (see Eq B1-B4 in Redon et al., 2017).

In addition, the tree foliage contributes himself to the total infrared flux received by the person, due to is own infrared emission (function of its temperature and its emissivity) and to the reemission of infrared radiation that it receives from ground and walls. One can note that Redon et al. (2017) made the hypothesis that the short-wave radiation received by tree foliage is only reemitted upward. As a result, no contribution in diffuse short-wave radiation from trees is involved in the mean radiant temperature calculation. The final expression for a person in the sun is as following:

$$T_{mrt} = \sqrt[4]{\frac{a_b}{\sigma\epsilon_b}\left(\frac{f_p}{sin(\gamma)}S^{\downarrow} + \tau_{sr}\Psi_{bs}S^{\Downarrow} + \tau_{wr}\Psi_{bw}S_w^r + \delta_r\psi_{br}S_r^r + \delta_g\psi_{br}S_g^r + \tau_{sr}\Psi_{bs}L^{\downarrow} + \tau_{wr}\psi_{bw}L_w^{\uparrow} + \delta_r\psi_{br}L_r^{\uparrow} + \delta_g\psi_{br}L_g^{\uparrow} + \psi_{bt}L_t^{\uparrow}\right)} \quad (23)$$

The infrared emission contribution due to the the tree foliage is expressed as:

$$L_t^{\uparrow} = (1-\tau_{sr})\left\{\sigma\epsilon_t T_t^4 + (1-\epsilon_t)\Psi_{tr}(\delta_r L_r^{\uparrow} + \delta_g L_g^{\uparrow}) + (1-\epsilon_t)(1-\Psi_{tr})L_w^{\uparrow}\right\} \quad (24)$$

with ϵ_t and T_t the emissivity and temperature of the tree foliage, respectively, and Ψ_{tr} the form factor for tree regarding emission coming from the road and ground-based natural covers.

6 Evaluation of vegetated-canyon microclimate modelling under semi-arid conditions

An evaluation exercise of the TEB performances in simulating microclimatic conditions of an urban canyon with trees is performed for a real study case, i.e. the experimental campaign presented by Shashua-Bar et al. (2009). The TEB model here applied includes the ensemble of developments relative to urban trees: (1) the radiative processes detailed by Redon et al. (2017) and already evaluated by comparison with a reference model, (2) the energy exchanges between trees and air volume within the canyon, and (3) the aerodynamic effect of trees on local airflow. This version is referred to as TEB-Tree and is compared to the reference version of the model TEB-Ref (Lemonsu et al., 2012) which already integrated natural covers within the canyon but like a ground-based located compartment.

6.1 Study area and experimental data

The experimental data have been collected on campus of Sde-Boqer in the semi-desert region of Negev of southern Israel (30.85°N, 34.78°E, 475 m of altitude) during summer 2007 (Shashua-Bar et al., 2009). Two semi-adjacent courtyards with comparable characteristics in terms of geometry and materials have been set-up according to six landscape arrangments incorporating various combinations of bare soil, lawn, and trees. The present study case concentrates exclusively on the arrangement with bare soil and cases here studied are the courtyard arranged with trees and bare ground, and the one arranged with trees and grass, respectively referred to as TREE-BARE and TREE-GRASS according to Shashua-Bar et al. (2011). The trees . In this case the trees are a *Prosopis juliflora* and a *Tipuana tipu*, that are common species for the region and are known to be water-consumption saving (Kremmer et Galon, 1996)(Shashua-Bar et al., 2009). A drip irrigation was installed for each tree around the trunk. The lawn is *Durban grass* watered separately by sprinklers once in the morning.

The courtyard was courtyards were equipped with sensors recording (1) air temperature, relative humidity, vapour pressure and wind speed at 1.5 m above the ground, (2) radiation fluxes (incoming and outgoing radiation, and net radiation) at the roof top, (3) surface temperatures of eastern, western, and southfacing walls, pavement, soil and tree foliage, and as well as soil and pavement for TREE-BARE and grass for TREE-GRASS, and (4) transpiration from the trees (using the sap flow method)for both cases and evaporation from the grass with mini-lysimeters for TREE-GRASS. A meteorological station located 400 m northwest of the site in an open desert area recorded for the same period air temperature and humidity at 1.5 m above the ground, wind speed and direction at 10 m, as well as soil temperature.

6.2 Numerical configuration and experiments

The simulations are performed by running TEB on a single grid point to which are attributed the descriptive parameters of the experimented courtyard considering its configuration is courtyards considering their configuration are close to the concept of urban canyon applied in TEB. The TEB model input parameters are prescribed according to the detailed description of the site proposed by Shashua-Bar et al. (2009). The semi-enclosed courtyard is are oriented with an angle of 12 $^{\circ}$ from the north (clockwise). Its Their width is 5.5 m and it is thery are bordered by two rows of three-meters tall buildings with flat roofs. These buildings are made of light concrete, as well as the pavement made of thin layers of light concrete laying on the ground. All impervious covers are light color with high albedo of 0.35 0.60 for walls and 0.40 for roofs and pavement. All thermal and radiative properties are listed in Table 1 in Lemonsu et al. (2012). The For TREE-BARE, the ground inside of the courtyard consist consists in 70 % of pavement and 30 % of bare soil. The tree crowns present a overlapping rate of 70 % of ground-based surfaces. For TREE-GRASS, the tree coverage rate is unchanged, while 20 % of the ground is covered by pavement ad 80 % by grass.

The TEB input parameters derived from these real data differ depending on the version TEB-Ref or TEB-Tree that is used (see the description of configurations in Figure 2 and Table 1). ~~The~~ In the TEB-Ref ~~version treats the ensemble of natural elements like a composite cover . If there is trees, the spatial coverage of crowns is considered as a ground-based surface which can consequently mask other elements. This~~ standard approach, land cover fractions are calculated according to a single surface area without overlapping (as seen from the sky or by satellite). The sum of cover fractions is equal to 1. The tree cover has priority over the surfaces that are hidden because located below, which is the case here since the ~~tree foliage~~ tree-foliage layer covers 70 % of the canyon. ~~So that in this configuration, the canyon in the TEB approach is described as being composed of 30 % of pavement and 70 % of nature. This fraction of nature is exclusively high vegetation in this case, whereas the fractions of low vegetation and of bare soil are 0. The~~ In the TREE-BARE experiment, all bare ground and part of pavement are therefore hidden by trees, which modifies the real fractions (Table 1). In the TREE-GRASS experiment, trees largely but not totally mask grass since the grass cover fraction is slightly greater than that of trees (Table 1). In comparison, the TEB-Tree version describes more realistically the arrangement of elements by dissociating the tree-foliage stratum from ground-based natural covers. As a consequence~~in this case, the ground-based surfaces are the same than the real ones~~ , for both experiments, the cover fractions prescribed for TEB are the real ones (Table 1) and their sum is greater than 1. As for morphological parameters, they remain the same in the two experiments i.e. ~~70 % of pavement and 30 % of nature, this latter is exclusivement bare soil. In addition, the tree-foliage overlapping fraction is 70 % of the canyon.~~ a wall-plan area ratio of 0.71 and an aspect ratio of 0.55.

The meteorological forcing data that must be provided to TEB, i.e. air temperature, humidity, wind speed, incoming short- and long-wave radiation, and atmospheric pressure above the top of the canyon, are coming from in situ measurements collected above the roof and from data recorded by the reference meteorological station. The method is described in details in Lemonsu et al. (2012).

6.3 Results of evaluation

~~The~~

6.3.1 Microclimatic variables

The results obtained for the TREE-GRASS experiment are presented in detail here by comparing the modelled and measured diurnal cycles of the various parameters documented. They are complemented by the scores obtained for the TREE-BARE experiment. The comparison of microclimatic conditions and surface temperatures observed and simulated within the canyon indicates an improvement of simulation results with the new TEB-Tree version in comparison with TEB-Ref (Figure 3). For air temperature, the improvement brought by TEB-Tree is noted for daytime hours: the simulated diurnal cycle is in better agreement with the observed one. In comparison, the TEB-Ref case indicates a too early warming in the morning. The statistical scores for the whole diurnal cycle (compiled in Table 2) are slightly better with a mean absolute error (MAE) and a root-mean square error (RMSE) of ~~0.69 and 0.89~~ 0.67 and 0.83 $^\circ$C, respectively, instead ~~0.73 and 0.93~~ 0.74 and 0.90 $^\circ$C for TEB-Ref. ~~Inversely, a more important underestimation of air humidity by~~ For the TREE-BARE experiment, the improvement brought by TEB-Tree ~~than TEB-Ref is notedduring the day~~on air temperature modelling is confirmed by the statistical scores but remains quite low (Table 2). The simulation of the specific humidity is very slightly improved in the TREE-GRASS experiment, but both versions of the model give the same results for the TREE-BARE configuration. In the two experiments whatever the model version, an overall underestimation of humidity is noted, whereas an increase ~~of humidity~~ during daytime could reasonably be expected in the new version considering the latent heat flux from natural covers is now vertically distributed in TEB-Tree. The reason of this bias is discussed in the analysis of vertical profiles presented in Section **??**. A clear impact of the new parameterization is observed on wind. By considering the drag effect of tree foliage stratum in equations of TEB-SBL, the air flow is ~~significantly~~ decelerated. The wind speed simulated in TEB-Tree is significantly lower than in ~~TEB-REF~~TEB-Ref, that is more conform to measurements. MAE et RMSE are reduced from ~~0.97 and 1.10~~ 1.05 and 1.12 m s^{-1}, respectively, to ~~0.47 and 0.53~~ 0.37 and 0.41 m s^{-1} for TREE-GRASS, and from 1.02 and 1.14 m s^{-1}, respectively, to 0.57 and 0.64 m s^{-1} for TREE-BARE. Nonetheless, an overestimation of wind persists during the day. ~~The surface temperatures, that is for walls or pavement,~~

6.3.2 Surface temperatures

The wall surface temperatures simulated in TREE-GRASS are significantly improved by taking into account the radiative effects of tree foliage (Figure 3). The incoming radiation received by the canyon facets is reduced due to interception and attenuation by trees that are ~~so~~ as tall than buildings. As a result, the surface temperature maxima are lower in TEB-Tree than in TEB-Ref by ~~almost 10~~4-5 $^\circ$C for eastern ~~wall and pavement, a little bit less for western wall~~and western walls. Inversely at night, the tree foliage limits the cooling by trapping of infrared emission so that the surface temperatures are higher in TEB-Tree than TEB-Ref. ~~The comparison to measurements confirms that all these modifications lead to an improvementin simulation of surface temperatures.~~ Nonethless despite the improvement, TEB-Tree still overestimates the surface ~~temperatures at daytime, and underestimates them at nighttime, compared to observations, suggesting the~~ temperature especially for the eastern wall in the morning. This suggests the attenuation effect by tree foliage remains underestimated by the model in this case. ~~Finally, the tree foliage temperature and the evapotranspiration of trees are analyzed (Figure 4). For TEB-Tree, the hypothesis is done that the tree foliage temperature is in equilibrium with air temperature. The comparison to measurements shows that in the present case, the foliage is a bit warmer than ambiant air by around 2 $^\circ$C during the day. The tree transpiration flux is correctly simulated by the model. Especially,~~ The deviation from the measurement can also be explained by a difference between the compared quantities. The thermometer samples a specific area of the wall, while the model calculates an average temperature for the entire wall. The same improvement is noted in TREE-BARE, as well as for pavement temperature that was also measured during the ~~daily maximum is more realistic in TEB-Tree than TEB-Ref. The transpiration is indeed overestimated by TEB-Ref during daytime hours probably due to the too strong wind. The new parameterization makes possible to significantly~~

reduce this bias experiment (Table 2). Nonetheless, a default persists in the morning. According to the measurements conducted with the sap-flow method, the transpiration process starts very early (about 5 am) whereas it is delayed in the simulations by almost two hours. The origin of this bais is not clearly identified: it could be explained by the parameterization of transpiration itself but the sensitivity tests done did not make possible to fix the problem. The sap-flow measurements highlight that the transpiration flux starts before sunrise which the model is not able to simulate (as long as net radiation is zero).

6.4 Impact of mixing length on atmospheric vertical profiles

6.3.1 Trees-related variables

The mixing length (L) is parameterized in TEB on the basis of the work of Santiago and Martilli (2010) according to the height of buildings, the frontal area density, and the displacement height, i.e. parameters depending on the geometry of the canyon (see Eq. 10-12 in Lemonsu et al., 2012). However, the formulation depends on the vertical level considered within or above the urban canopy layer. In the lower half of the canyon, the mixing length (which characterizes the size of turbulent eddies) is constrained by the distance to the ground. Nevertheless, trees can be expected to influence the size of eddies in the canyon. Therefore, a formulation which takes into account the presence of trees in a simple way is tested here in order to assess the impact on microclimatic variables in the canyon. It is simply assumed that (1) within the foliage layer, the mixing length is arbitrarily fixed to 10 cm; and (2) below the trees, the mixing length (L_t) is constrained by the minimum distance between the ground distance and the distance to the base of the tree-foliage layer. A mean mixing length (L_{can}) is then calculated as the average of the two mixing lengths for the treeless part of the canyon (L) and the part with trees (L_t) according to the tree cover fraction:

$$L_{can}(z) = (1-\delta_t)\ L(z) + \delta_t L_t(z) = (1-\delta_t)\ L(z) + \delta_t\ min\{z, h_{tk} - z\}$$

Figure ?? compares the vertical profiles of air temperature, specific humidity, and wind speed simulated in the canyon at 3 am and 3 pm by TEB-Ref , and TEB-Tree , and TEB-Tree(L$_t$) which considers the new mixing length parameterization depending on trees. Day and night, TEB-Ref simulates a quite progressive decrease in wind speed when approaching the ground, due to the drag effect of walls over the entire height of canyon. For TEB-Tree, the additional drag effect of trees leads to a strong inflection on wind speed between both calculate a composite temperature of natural covers (T_{nat}) which is compared here to the 3rd and 4th vertical levels of TEB-SBL i.e. where the foliage layer is located. This inflection is still reinforced with measured foliage temperature (Figure 3f). The foliage presents a much lower diurnal temperature amplitude than that of T_{nat} which is expected since T_{nat} includes a contribution of bare soil or grass depending on the experiment. The evolution of foliage temperature is much better captured by the tree temperature (T_t) diagnosed by TEB-Tree (L$_t$) so that the vertical profile is shifted towards slightly lower wind speeds within the canyon that result in better statistical scores compared to observations: MAE and RMSE of 0.28 and 0.32 m s^{-1}, respectively, instead 0.47 and 0.53 m s^{-1} for TEB-Tree (Table 2). During the day, TEB-Ref simulates a specific humidity profile that increases sharply as it approaches the ground. In this version, all vegetation is simulated on the ground and covers the bare soil and a part of pavement. Therefore, the evaporation term (through the under the simple assumption that the foliage temperature is in equilibrium with the ambient temperature. The comparison between air temperature and foliage measurements confirms that this approximation is quite realistic. Finally, the measured evapotranspiration (combining tree transpiration and grass evaporation) is converted in latent heat flux) is strong and is injected into TEB-SBL at the first vertical level, which explains the shape of the simulated profile. The TEB-Tree humidity profile is more homogeneous because the moisture supply comes from ground for part, but also from the trees in (Q_E) and compared to model outputs (Figure 4). Until noon, Q_E simulated by TEB-Ref is in good agreement with the observations. But Q_E decreases rapidly to zero in the afternoon, while the measured flux remains positive. TEB-Tree simulates a much higher Q_E during the day that persists up to 6 pm. Even if the day cycle is poorly reproduced in both cases, the levels above. But the air specific humidity remains overall lower than in TEB-Ref because the real cover fraction of vegetation is lower. daily water quantity evaporated is more realistic with TEB-Tree (L_t) reduces turbulent mixing below the trees which tends to trap moisture longer in the lower layers. This partially correct the biases of TEB-Tree by improving significantly the scores (see Table 2). Finally for temperature, TEB-Ref simulates a progressive decrease in temperature in the canyon because the configuration with an aspect ratio of 0.55 does not result in much radiative trapping. On contrary, the foliage layer of TEB-Tree blocks infrared emissions from walls and floors within the canyon while being itself a significant source of infrared emissions at night. This explains why the temperature is significantly higher than in than with TEB-Ref. During the day, , since bias is less than 1 % instead -42 % for TEB-Refsimulates an homogeneous profile in the canyon because the heat contributions (in the form of sensible heat flux) come from both ground-based surfaces and walls. TEB-Tree shows a very substantial decrease in temperature because the trees strongly reduce the radiation received by the ground and the walls. As a result, surface temperatures are lower (as noted in Figure 3) and sensible heat fluxes are reduced. By reducing turbulent mixing, TEB-Tree(L_t) does not evacuate heat outside the canyon and gives a very different profile from TEB-Tree with much warmer air temperatures in the canyon.

6.4 Modelling of thermal comfort

An interest of this new parameterization for trees in urban canyons is to better predict outdoor thermal comfort conditions. The air temperature is not so different between the two experiments TEB-Ref and TEB-Tree. The modifications in radiation exchanges, energy fluxes, and ventilation induced by the presence of trees may have nonetheless a significant impact on heat perception by people. This is here quantified through the UTCI diagnosis whose formulation has been adapted in TEB-tree TEB-Tree in order to include the radiation effects due to tree-foliage stratum as detailed in Section 5.2. Even if no observation of thermal comfort is available for an objective evaluationAlthough we do not have any UTCI measurements for direct comparison, it is however interesting to compared the UTCI simulated according to both versions TEB-Ref and TEB-Tree. These results are presented In Figure 5 for the situation for which people are in the sun (left) or in the shade (right). For indicative purpose, the air temperature simulated in the canyon is also presented. The UTCI for cases interesting to study how the two versions of TEB compare. In addition, the model results can be put in perspective with the study of Shashua-Bar et al. (2011) who investigated the influence of trees and grass on outdoor thermal comfort from the same experimental data.

6.4.1 Sensitivity of UTCI to the new TEB-Tree parameterization

The model calculates two separate UTCIs i.e. in the sun and in the ~~shade only differ for daytime hours because at night radiation conditions are the same. For TEB-Ref, the UTCI is greater than air temperature between 6 am and 3 pm for the case in the sun, and then becomes largely lower than air temperature by 6-7 $^{\circ}$C during the evening and night. This high daily amplitude is mainly driven by the radiative exchanges. The UTCI calculated in~~ shadow. For the ~~shade is significantly lower than that in the sun during daytime: people are more preserved from heat due to shadow effects. It remains in this case always below air temperature. Using TEB-Tree,~~ analysis of the results, they are averaged in a single UTCI according to the proportion of shade and sunlight in the courtyard. Since the model does not explicitly represent the spatial location of the elements in the canyon but simply coverage fractions, these shade/sun fractions are calculated simply as the ratio between the direct solar radiation received by the ~~UTCI is quite different. During the day , it is slightly greater than for~~ ground surface and the direct incident solar radiation at the top of the canyon. TEB-Ref ~~because the wind speed is weaker due to the drag effect of trees. But the main difference is noticed during the night (and in a lesser extend,~~ and TEB-Tree are compared in Figure 5 (left) for the TREE-GRASS configuration. Taking into account the foliage layer, TEB-Tree creates much more shade in the ~~morning and in~~ courtyard than TEB-Ref which only represents the shade of buildings. Therefore, the ~~evening): the~~ UTCI simulated by TEB-Tree is lower during the day than that of TEB-Ref. This difference is 1.8 $^{\circ}$C on average for the daytime hours and reaches 3 $^{\circ}$C at maximum at 2 p.m. For the present study case, it can be seen that the orders of magnitude of the differences in UTCI obtained by comparing the two versions TEB-Ref and TEB-Tree are very significant in terms of predicting heat stress. The TEB-Ref version simulates high heat stress conditions in the middle of the day while TEB-Tree simulates UTCIs do not exceeding moderate heat stress conditions. Inversely during the night, the infrared radiation downward emitted by the tree-foliage stratum ~~–~~ in TEB-Tree (and potentially received by a person in the street ~~–~~) significantly limits the decrease in nocturnal UTCI. ~~It remains 5~~The UTCI remains on average 1.2 $^{\circ}$C higher than in TEB-Ref simulations. This result is important to be emphasized which highlights that street trees may degrade thermal comfort conditions at night by trapping radiation and amplifying downward infrared emissions inside the canyon while reducing ventilation.

6.4.2 Comparison of comfort conditions depending on courtyard layouts

Shashua-Bar et al. (2011, see Figure 2) compared thermal conditions of the different courtyard layouts based on an index of thermal stress (expressed in W). This index was normalized to smooth the influence of variations in weather conditions from one measurement day to the next. To get closer to these works, UTCIs simulated by TEB-Ref and TEB-Tree for the two configurations TREE-BARE and TREE-GRASS, but also for cases EXPOSED-BARE and EXPOSED-GRASS previously studied by Lemonsu et al. (2012) are compared. These two latter configurations are equivalent to TREE-BARE and TREE-GRASS, respectively, in terms of ground properties but without trees. Identical weather conditions are applied for all courtyard layouts, using those of the TREE-GRASS experiment (Figure 5, right).

It can be seen that the case most exposed to heat stress during the day is the EXPOSED-BARE layout. Thanks to the evapotranspiration of lawn, the EXPOSED-GRASS layout allows local cooling and slightly reduces the UTCI. The two configurations with trees are the most effective during the day: TREE-BARE improves comfort conditions mainly by increasing shade, while TREE-GRASS combines the benefits of shading and near-surface evapotranspiration. For the studied weather situation, only TREE-GRASS makes it possible to insure moderate heat stress conditions within the courtyard. At night, the treeless configurations allow a more significant lowering of UTCI than those with trees. As already mentioned previously, trees contribute to infrared radiation trapping and are themselves an additional source of radiation. On the other hand, their aerodynamic effect significantly reduces wind speed within the courtyard, which also contributes to limit the decrease in UTCI. These results are in agreement with those of Shashua-Bar et al. (2011, see Figure 2). It is difficult to conclude on the realism of the orders of magnitude for the simulated UTCIs, since indices are not the same in the two studies and the method for comparison or normalization is also different. Nonetheless, whether for the day or night period, the same ranking between configurations in terms of impact on thermal comfort conditions is found. These results are not achievable with the TEB-Ref version, which simulates very similar comfort conditions regardless of the courtyard configuration (not shown).

7 Conclusions

The TEB model has evolved considerably in recent years, particularly with the objective of improving the representation of vegetation in urban areas. After the implementation of ground-based low vegetation inside the canyon, and of green roofs on buildings, an explicit representation of the tree-foliage layer was implemented. A detailed parameterization of associated radiative processes was developed and tested by Redon et al. (2017) with very encouraging results. The whole issue in this study was to treat the energy exchanges of vegetation by taking into account the dissociation of vegetation strata, and to include the drag effect of trees on wind speed in the canyon.

The strategy is rather simple by maintaining the bigleaf approach for using the ISBA SVAT model i.e. by calculating a single energy balance for natural covers, treated as a composite compartment. Nevertheless, the incident radiative fluxes provided to ISBA are calculated as a weighted average of those received by the natural ground surfaces and those received by the trees according to the coverage fractions. The energy fluxes calculated by ISBA are then redistributed according to the same principle between ground surfaces and trees, then injected into the SBL parameterization of TEB for the calculation of the air temperature and humidity vertical profiles of the air in the canyon. Besides, a drag term of trees depending on the horizontal coverage fraction and the leaf density profile of trees is included in evolution equations of momentum and TKE. It is in addition to the drag term already configured for buildings.

An evaluation exercise conducted in comparison to field measurements shows that thanks to these new developments, the model better simulates surface temperatures and air temperature in the canyon. The main ~~improvement concerns the wind,~~ improvements concern (1) the wall and ground surface temperatures that are much less overestimated than with the initial parameterization due to tree shading; and (2) the wind which is now slowed down by the presence of trees as observed. ~~Some~~

~~tests were also dedicated to the formulation of a new mixing length. They showed a significant sensitivity in~~ There is no very significant effect on air temperature and humidity ~~vertical profiles modelling to these parameterization choices. However, more complete evaluations are required to set the parameterization in a more robust and objective way. Also in~~ and it is difficult to conclude on the quality of the turbulent fluxes parameterization. In the future, it could be necessary to move towards a Multi-Energy Budget (MEB) approach (Boone et al., 2017) to solve the energy balance separately from ground surfaces and trees. The bigleaf approach reveals limitations, and raises conceptual questions about the choice of forcing level for energy fluxes calculations or the representativeness of a single temperature attributed to the composite layer of natural covers.

Finally, the UTCI diagnosis was reformulated by taking into account the presence of trees. This essentially consisted of adding infrared emissions from trees to the mean radiant temperature calculation. The other modifications presented here and in Redon et al. (2017) have also an influence on the UTCI because they modify radiative exchanges, and micrometeorological variables in the canyon, particularly wind. ~~Although it was not possible here to evaluate the simulated UTCI due to lack of observation, it is very interesting to note that the~~ The results obtained by comparing different courtyard layouts with and without trees are in accordance with those of Shashua-Bar et al. (2011). The presence of trees ~~degrades the~~ improves thermal comfort conditions during the ~~night. Additional evaluations were~~ day because of shadow effecs but degrades them during the night. Only the TEB-Tree version is able to correctly simulate these effects that was confirmed by an additional evaluations conducted for another study site ~~(de Munck et al., 2018) and confirmed this effect~~in France (de Munck et al., 2018). This underlines the relevance of explicitly taking trees into account in urban climate models in order to more realistically model urban design strategies and impacts on comfort.

Code availability. The TEB code is available in open source via the surface modeling platform SURFEX, downloadable at http://www.umr-cnrm.fr/surfex/. This Open-SURFEX will be updated at relatively low frequency (every 3 to 6 months) and developments presented here are not yet included in the last version. If you need more frequent updates, or if you need what is not in Open-SURFEX (DrHOOK, FA/LFI formats, GAUSSIAN grid), we invite you to follow the procedure to open a GIT account and to access real-time modifications of the code (see instructions in the previous link).

Data availability. The model outputs are available upon request from the corresponding author. The experimental data that are used for the evaluation stage were provided by Prof. Evyatar Erell from Ben-Gurion University of the Negev. To access this data, it is necessary to contact directly Prof. E. Erell.

Author contributions. All three co-authors have contributed to the development and improvement of the TEB's code in SURFEX V8.0. Besides, E. Redon and A. Lemonsu performed the evaluation step by performing the simulation and comparing the model results with the experimental data.

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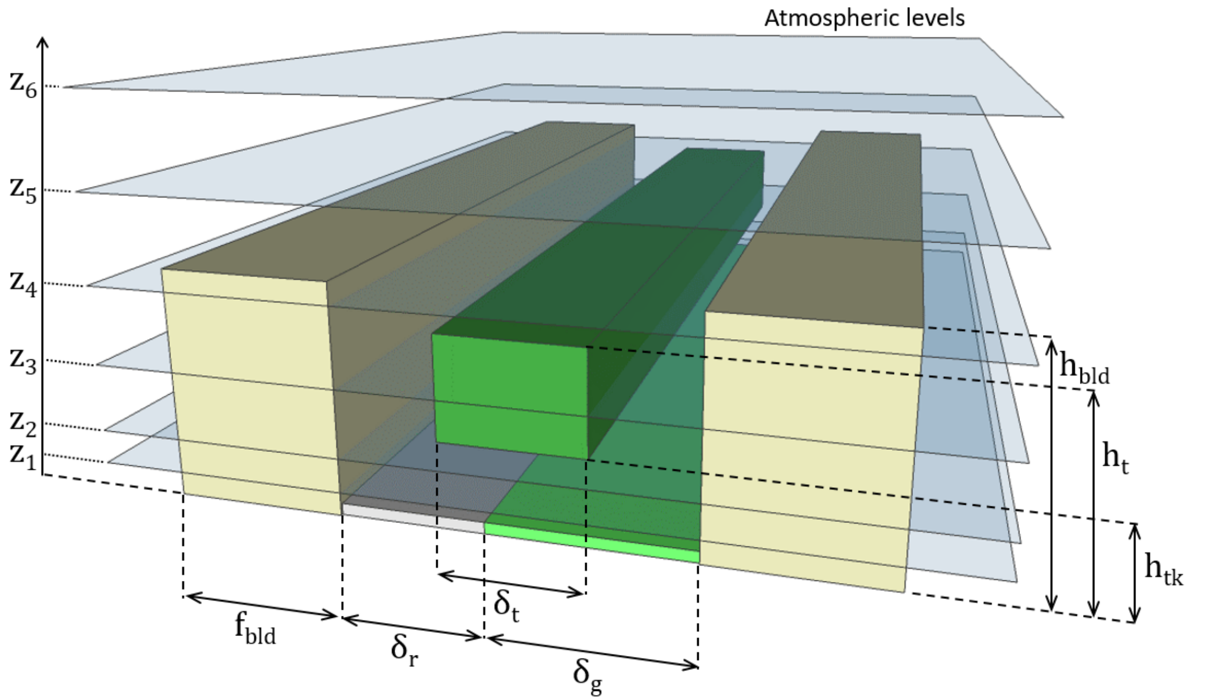

Figure 1. Schematic representation of the TEB's urban canyon integrating a part of ground-based natural covers and an explicit tree-foliage layer, and of the atmospheric vertical levels of the SBL scheme coupled to TEB to compute vertical profiles of micrometeorological variables inside and above the canyon.

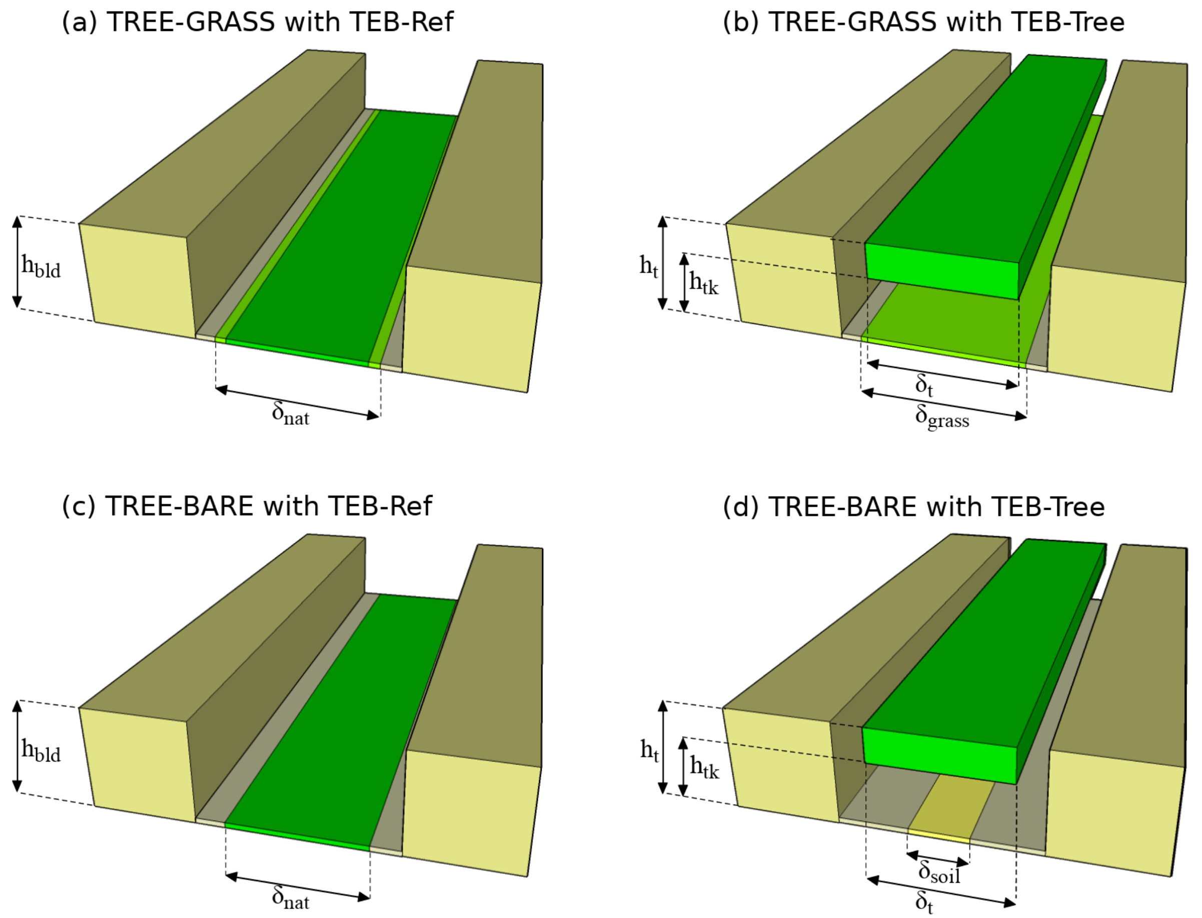

Figure 2. Comparison of ~~the two~~ urban canyon ~~configurations~~ characteristics prescribed ~~to represent the experimental site of Sde-Boqer according to the~~ by TEB-Ref (~~a~~left) and TEB-Tree (~~b~~right) versions for the experiments TREE-GRASS (top) and TREE-BARE (bottom).

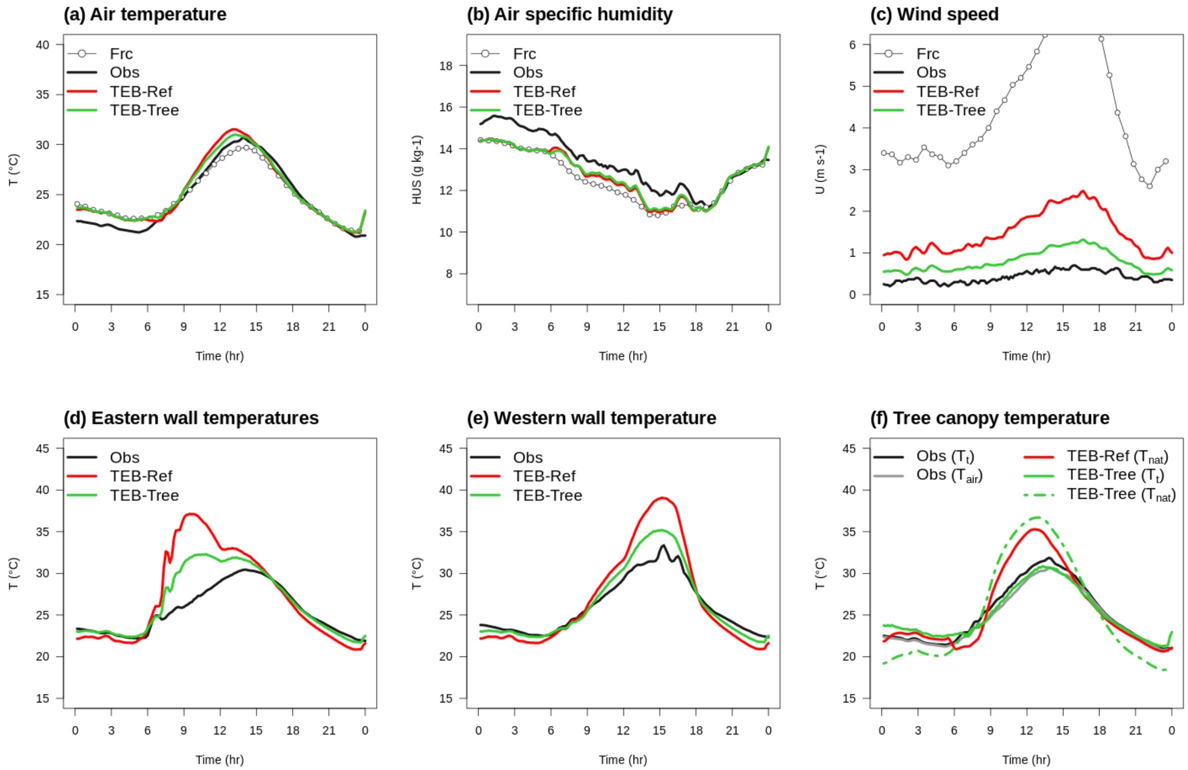

Figure 3. Comparison of the TEB-Ref and TEB-Tree results (red and green lines, respectively) with meteorological variables (top panel) and surface temperatures of urban facets and trees (bottom panel) measured within the courtyard (black line). For air temperature, specific humidity and wind speed, the gray line with symbols indicates the forcing data above the buildings.

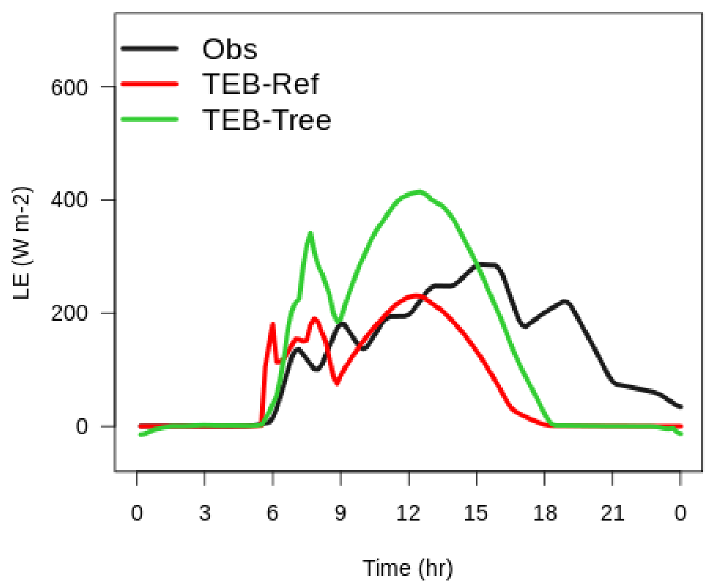

Figure 4. Comparison of the TEB-Ref and TEB-Tree results (red and green lines, respectively) with ~~foliage temperature and~~ the latent heat flux deduced from measurements of tree transpiration ~~flux measured for trees located within the courtyard~~ and grass evaporation (black line).

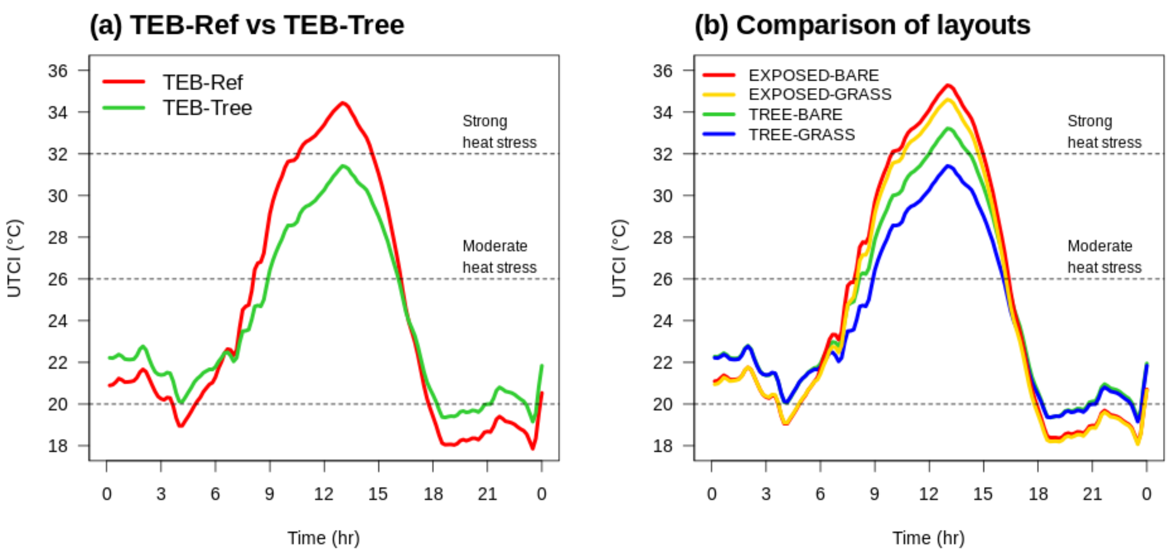

Figure 5. (a) Comparison of vertical profiles in air temperature, specific humidity, and wind speed UTCI simulated within in the courtyard according with by TEB-Ref (red line) , and TEB-Tree (green line) , and TEB-Tree including a new parameterization for mixing length TREE-GRASS configuration; and (dashed green lineb) . The location Comparison of tree-foliage layer is represented UTCIs simulated by the hatched strip, and the measurement level by the dashed black lineTEB-Tree for four different courtyard layouts.

Comparison of UTCI in the sun (a) and in the shade (b) simulated by TEB-Ref (red line) and TEB-Tree (green line). The black line is the air temperature measured within the courtyard.

Table 1. TEB's input parameters according to the two configurations prescribed to represent the experimental site of Sde-Boqer according to the TEB-Ref and TEB-Tree versions (in accordance with Figure 2).

		TREE-BARE		TREE-GRASS	
		TEB-Ref	*TEB-Tree*	*TEB-Ref*	*TEB-Tree*
Building fraction	(-)	~~0.35~~ 0.350	~~0.35~~ 0.350	0.350	0.350
Pavement fraction	(-)	~~0.20~~ 0.195	~~0.45~~ 0.450	0.130	0.130
Ground-based nature fraction	(-)	~~0.45~~ 0.455	~~0.20~~ 0.200	0.520	0.520
- High vegetation	(-)	~~1.00~~ 1.000	~~0.00~~ -	0.875	-
- Low vegetation fraction	(-)	~~0.00~~ 0.000	~~0.00~~ 0.000	0.125	1.000
- Bare soil fraction	(-)	~~0.00~~ 0.000	~~1.00~~ 1.000	0.000	0.000
Tree overlapping fraction / canyon	(-)	~~0.00~~ -	~~0.70~~ 0.700	-	0.700
Building height	(m)	3.0	3.0	3.0	3.0
Aerodynamic roughness length	(m)	0.3	0.3	0.3	0.3
Wall-plan area ratio	(-)	0.71	0.71	0.71	0.71
Canyon aspect ratio	(-)	0.55	0.55	0.55	0.55

Table 2. Mean absolute error (Model-Obs) and root-mean square error in temperature, humidity, and wind speed at 1.5 m agl, in surface temperature of walls and tree foliage, and in evaporation. The scores are calculated for TEB-Ref , and TEB-Tree, and TEB-Tree including a new parameterization for mixing lengththe two courtyard configurations TREE-GRASS and TREE-BARE.

			TEB-Ref		*TEB-Tree*	
			MAE	RMSE	MAE	RMSE
TREE-GRASS	$T_{1.5m}$	(°C)	0.80 0.74	0.96 0.90	0.69 0.67	0.89 0.80 1.01 0.83
	$q_{1.5m}$	(g kg^{-1})	0.29 0.64	0.41 0.74	0.45 0.61	0.60 0.39 0.51 0.71
	$U_{1.5m}$	(m s^{-1})	0.98 1.05	1.11 1.12	0.47 0.37	0.53 0.41
	0.28 $T_{Swall(East)}$	0.32 (°C)	2.52	4.02	1.21	2.04
	$T_{Swall(East)}$ $T_{Swall(West)}$	(°C)	4.65 2.03	7.08 2.82	2.32 0.90	3.26 1.28
	T_{Tree}	2.62 (°C)	3.68 1.32	1.84	0.71	0.85
	$T_{Swall(West)}$ LE_{Tree}	(°C)	3.78 71.60	4.96 102.88	1.91 83.38	2.27 108.10
TREE-BARE	$T_{1.5m}$	2.23 (°C)	2.68 0.77	0.99	0.75	0.94
	$T_{Spavement}$ $q_{1.5m}$	(g kg^{-1})	8.10 0.64	9.97 0.86	4.14 0.65	4.96 0.86
	$U_{1.5m}$	4.47 (m s^{-1})	5.42 1.02	1.14	0.57	0.64
	T_{Tree} $T_{Swall(East)}$	(°C)	1.45 3.01	1.87 4.21	1.52 1.30	2.01 2.08
	1.36 $T_{Swall(West)}$	1.81 (°C)	2.68	3.23	1.02	1.46
	$T_{Spavement}$	(°C)	5.25	7.34	2.54	3.88
	LE_{Tree} T_{Tree}	(°C)	86.47 1.61	110.89 2.26	59.37 1.14	83.89 1.57
	77.74 LE_{Tree}	99.79 (°C)	12.76	15.49	16.92	21.60