The Vertical City Weather Generator (VCWG v1.3.0)

Response to Reviewers Moradi et al.

November 8, 2020

Dear Dr. Wolfgang Kurtz:

Thank you for your comments and those of the reviewers. We have implemented all of your suggestions. In brief, we have separated the exploration analysis from the validation analysis based on the reviewers' requests. The detailed exploration analysis (sensitivity analysis) is now provided as supplementary material. Only a section less than one page in the main manuscript summarizes the findings of the exploration analyses. For the validation, we have extended the analysis period to 8 months from December 2001 to July 2002 corresponding to the BUBBLE campaign. This extended time duration was the maximum time duration for which both rural and urban weather measurement data could be accessed. We have fully specified roughness lengths for momentum, temperature, and specific humidity as well as zero displacement height as part of the Monin-Obukhov Similarity Theory (MOST) model in the rural area. We have performed one extra exploration run of the model to investigate the effect of the location of the building waste heat release on UHI. The introduction is shortened by removing redundant material and absorbing the sections on objectives and structure of the paper together.

Overall, we are very convinced that these improvements should satisfy the reviewers' requests. We hope this version will by satisfactory and aligned with the journal's high standards. Please do not hesitate to provide more feedback.

Regards,

Amir A. Aliabadi

1 Topical Editor Decision: Dr. Wolfgang Kurtz

Dear authors, thank you for your revised manuscript which was again evaluated by two referees (one former and one new, as referee #1 was not available anymore). According to the reviewer comments, several further clarifications are needed to improve the manuscript. Both referees also point out that the sensitivity analysis in section 3.2 should be shortened to some extent. Referee #3 instead suggests to put more weight on the validation experiments e.g. by prolonging the length of the validation period.

Response: Thank you. We have moved the entire section on sensitivity analysis (exploration analysis) into supplementary material. In the main manuscript we summarize the results of this analysis in one short section. We have also extended the model evaluation analysis by comparing the model results to experiments over prolonged periods. For Basel (BUBBLE) the comparison extends to 8 months, for which urban and rural observations are available. In the exploration, we analyze maximum and minimum daily UHI for Vancouver and compare with observations for one full year.

Please accommodate the reviewer comments in a further revision of your manuscript. In addition, please also comment on the reasons for changes in figures 5+7 (from previous response letter section 1.1 items 2+3).

Response: Thank you. This must refer to figures 3, 4, and 5, in the last version of the manuscript. At that time we decided to show diurnal variability in bias and root mean square error, averaged over the same diurnal hour in the dataset, for predictions of potential temperature, wind speed, and specific humidity at various heights. We also decided to show scatter in the data by plotting all the individual modeled versus observed values to the right of each diurnal plot. We have now again changed the data presentation for improved clarity. Now we are showing all scatter plots separately for all model versus observation values. In addition we are showing diurnal variation in potential temperature and specific humidity at different heights, by presenting average values for the same diurnal hour in selected months. Due to day-to-day variation of wind speed, average values for the same diurnal hour in selected months are not shown.

2 Reviewer 3

2.1 Comments

1. GENERAL: The discussion of parameter sensitivity is too long. It is more important, for a paper introducing a new model, to solidly establish the validity of said model under strictly controlled conditions (and the choice of the BUBBLE database is excellent in that regard), than to test in excessive length its sensitivity to input parameters. If I was involved in the initial review round, I would have suggested that the sensitivity study should be moved to a separate paper.

Response: Thank you. We have moved the entire section on sensitivity analysis (exploration analysis) into supplementary material. In the main manuscript we summarize the results of this analysis in one short section. We have also extended the model evaluation analysis by comparing the model results to experiments over prolonged periods. For Basel (BUBBLE) the comparison

extends to 8 months, for which urban and rural observations are available.

2. In any case, I propose to reduce/compress these expansive discussions and the associated figures by restricting the sensitivity analysis to Basel (same city that you used for validation), adding waste heat fraction to the analysis, and foregoing other cities/climates. This is consistent with my strong recommendation - also mentioned in the previous review round - to run the validation for a full year instead of two weeks. See one of my comments below.

Response: Thank you. The sensitivity analysis to model input parameters has entirely moved to supplementary material. The analysis for waste heat fraction released at street level (versus roof level) is also discussed in the supplementary material. In the main manuscript, the validation for Basel (BUBBLE) is extended to 8 months, for which urban and rural observations are available.

3. Eqn. 3: How do you calculate the Monin-Obukhov length L if the sensible heat flux is not available? Basel was an exception in that this value could be derived from deep soil temperature (Eqn. 7), but how would one proceed if this measurement is not available as is likely to be the case for the quasi-totality of rural weather stations.

Response: Thank you. As detailed in Eqns. 7 and A3 of the manuscript, the surface energy balance equation and parameterization of [Louis, 1979] are used in the rural area to obtain the sensible heat flux. The soil heat flux is determined by solving transient conduction Eqns. A4 and A5. This approach requires the deep soil temperature, which is usually available in most EPW files used to force VCWG in the rural area.

4. P914: 'Friction velocity can be determined by numerically integrating Eq. 4 from the elevation of the rural aerodynamic roughness length z_{0rur} [m] to 10 m in an iterative process'. Do you assume that the zero displacement height is zero?

Response: Thank you. This option is provided in the VCWG which allows the user to input the zero displacement height. The following statement has been added to the manuscript

Friction velocity can be determined by integrating Eq. 4, iteratively, from the elevation of the rural aerodynamic roughness length z_{0rur} [m] to $z - d_{rur}$ [m], where z = 10 m is the reference height for wind measurement and d_{rur} [m] is the zero displacement height. The aerodynamic roughness length and zero displacement height have been rigorously studied and parameterized in the literature as functions of obstacle height h_{rur} [m] and the type of rural area [Raupach et al., 1991, Hanna and Britter, 2002]. VCWG permits this specification, but the approximate values used in this study are $z_{0rur} = 0.1h_{rur}$ and $d_{rur} = 0.5h_{rur}$. This method provides a friction velocity that is corrected for thermal stability effects.

5. P9L16: 'The potential temperature profiles are also obtained by integration of Eq. 1'. I guess you start the integration from z0H. What is the value of z0H? Do you assume that it is the same as z0 (aerodynamic)? If yes, why? Same question arises for z0Q, although setting z0Q=z0H would be a more acceptable assumption than setting z0H=z0.

Response: Thank you. This option is provided in the VCWG which allows the user to input the roughness lengths for temperature and specific humidity. The roughness lengths for temperature

and specific humidity are now carefully specified. The following statements have been added to the manuscript

The potential temperature profiles are also obtained by integration of Eq. 1 [Paulson, 1970] from rural roughness length for temperature $z_{\overline{\Theta},rur}$ [m] to $z - d_{rur}$ [m], where z [m] is the desired elevation above ground (here the top of the domain). A typical value of $z_{\overline{\Theta},rur} = 0.1z_{0rur}$ [m] is often used [Brutsaert, 1982, Garratt, 1994, Järvi et al., 2011, Meili et al., 2020].

This expression [for specific humidity] should be integrated from rural roughness length for specific humidity $z_{\overline{Q},rur}$ [m] to $z - d_{rur}$ [m], where z [m] is the desired elevation above ground (here the top of the domain). It is often assumed that $z_{\overline{Q},rur} = z_{\overline{\Theta},rur}$ [m] [Brutsaert, 1982, Järvi et al., 2011, Meili et al., 2020].

6. P9L17: 'Given the similarity of heat and mass transfer'. Do you mean, 'given the similarity of sensible and latent heat transfer'?

Response: Thank you. Yes, and we corrected it in the manuscript.

7. P12L23: I agree that in Basel, air-conditioning is either non-existent or rejects waste heat at roof-level. But what value of waste heat fraction have you assumed for other cities? In your response to reviewers, you mention that the waste heat rejection has a significant impact on UHI (+1 K), yet you choose not to do a sensitivity analysis on it. Why?

Response: Thank you. For all climate zones and other cities, we have assumed $F_{st} = 0$, i.e. all waste heat from buildings are rejected at roof level. We have specified this in the manuscript. This must be the case for most modern neighborhoods and retrofitted buildings. In addition, we have performed an extra sensitivity study in the supplementary material to investigate the effect of the location of releasing waste heat on UHI. Figure below shows the effect of the location of waste heat release on diurnal variation of mean and standard deviation (band) of UHI [K] over a two-week period, when all waste heat is released at the street level ($F_{st} = 1$), half of waste heat is released at street level and the other half of waste heat is released at roof level ($F_{st} = 0.5$), and all waste heat is released at roof level ($F_{st} = 1$). According to this analysis, on average, the UHI value for the case with $F_{st} = 1$, is higher by 1 K than the case with $F_{st} = 0$. Depending on the urban configuration and amount of urban vegetation the location of waste heat release could affect UHI by even higher magnitudes.

8. Eqn. 17: I note that although your urban canopy model is multi-layer, the building energy model seems to be single-zone. To be consistent with the UCM, it would have been preferable to assume a multi-zone BEM (the height of each building zone corresponding to the outdoor UCM layering), especially in view of the varying insolation according to height. Please briefly discuss this choice in the manuscript.

Response: Thank you. We acknowledge this limitation of VCWG. In fact the building energy model, radiation model, and the urban vertical diffusion model, all assume that wall temperature is uniform with height. So even if air temperature is assumed to vary with height (given by the urban vertical diffusion model), there are limitations in accurately parameterizing convective heat transfers with the wall. We believe future work can address this issue by upgrading the



Figure S.1: Effect of the location of waste heat release on UHI [K]; diurnal variation of mean and standard deviation (band) are shown using data obtained over a two-week period; nighttime is shown with shaded regions; times in Local Standard Time (LST); blue: all waste heat released at street level ($F_{st} = 1$); red: half of waste heat released at street level ($F_{st} = 0.5$); green: all waste heat released at roof level ($F_{st} = 0$).

building energy model, radiation model, and urban vertical diffusion model to account for change of variables with height toward a multi-zone building energy model. The following statements are provided in the manuscript to outline the single-zone feature of the building energy model and to provide recommendation for future work

The building energy model is a single-zone model with respect to both the indoor and outdoor (urban canopy) environments. That is, only a single temperature is assumed for indoor air, and only a single potential temperature is assumed for outdoor air by integrating the potential temperature profile from the street to roof levels. Further, all wall temperatures are assumed to be uniform with height.

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Also the building energy model in VCWG is a single-zone model, assuming a uniform temperature with height in both indoor and outdoor environments. This limitation can be overcome by improving the radiation model, urban vertical diffusion model, and the building energy model so that wall and indoor temperatures can vary with height, allowing the development of a multi-zone building energy model.

9. P15L26: the baseline values of $\lambda_p = 0.54$ and $\lambda_f = 0.37$ that you report for Basel, are not consistent with the values of 'horizontal building density' and 'vertical-to-horizontal urban area ratio' reported by Bueno (2012) for the same city (resp. 0.4 and 0.8). Please clarify.

Response: Thank you. Please note that values of 0.4 and 0.8 in [Bueno et al., 2012] belong to table 7 in that study. In that table, the authors report results of sensitivity analysis, so the values used are not representative of the building morphometric parameters in Basel. Also note that [Bueno et al., 2012] define the vertical-to-horizontal urban area ratio differently (Please see [Bueno Unzeta, 2010] for details).

For VCWG, the input morphometric variables are street width (w = 18.2 m), building width to

street width ratio (b/w = 1.1 m), and average building height $(H_{avg} = 14.6 \text{ m})$. Using these variables provide $\lambda_p = b/(b+w) = 0.52$ and $\lambda_f = H_{avg}/(b+w) = 0.38$. These values are very close to what was reported by [Christen and Vogt, 2004] to describe the morphometric variables in Basel ($\lambda_p = 0.54$ and $\lambda_f = 0.37$).

10. P17L20: I am not convinced by your response to my review comments stating that you retain the 2-week validation period in order to avoid a more lengthy manuscript. First of all, since you are now using the BUBBLE data, the size of the manuscript will be reduced, perhaps by a few pages. Secondly, reporting, BIAS/RMSE/R2 for one year instead of 2 weeks does not require more space and the figures can also be easily adapted to be brief. My point is that it is important to assess the dynamic behaviour of the model for a full year, especially since the main goal of this paper is to establish the validity of a completely new model. If you do not have a full year of rural Basel weather data corresponding to the urban weather data, why not use rural data from a standard weather station operated by the national meteorological organization. Of course that raises the question of how to determine the surface heat flux. But this question must be addressed anyway in your next version of the manuscript, since making the algorithm reliant on the exceptional availability of said data in the BUBBLE dataset is not an acceptable solution.

Response: Thank you. We have fully addressed this issue. Now we extend the validation against the BUBBLE observations for 8 months, for which both rural and urban observations are available. Also note that calculation of the rural surface heat flux is possible using an energy balance model discussed in response to comment 3 above.

11. P18: Are all the values in the table taken from already cited papers or are some of them estimated by you-in which case some additional explanation would be in order. For example: z0, beta (is it really constant), etc.

Response: Thank you. We have now listed the source citation in the table for any of the variables used. For Bowen ratio, the average value was used for each month of observations. There may be diurnal variation of the the Bowen ratio, but this simplified parameterization is fit for purpose.

12. Fig. 6: Any specific comment about the model/observation discrepancy late at night?

Response: Thank you. We have addressed this issue in the new version of the manuscript.

13. Table 2: I cannot read the adjusted values.

Response: Thank you. The formatting of all tables were checked to ensure their values can be read conveniently.

3 Reviewer 4

The reviewed manuscript is a revised version of a manuscript describing the improvement of the 'Urban Weather Generator' into the 'Vertical City Weather Generator'. Such weather generators occupy a niche to simulate the meteorological conditions in the urban roughness sublayer with very low computational cost compared to an urban canopy model coupled to a meso-scale atmospheric model or an obstacle resolving model. Given the availability of meteorological observations in the

vicinity of the city, the weather generator can simulate the meteorological conditions in the urban environment with very low computational effort and provide input data for building energy models representative for the urban environment. Considering the previous comments of the reviewers, the manuscript has been considerably improved, but there is still room for more improvement.

Response: Thank you. We further improved the manuscript by addressing all reviewer comments.

3.1 Comments

3.1.1 Major remarks

1. At the end of Section 1.1, the urban canopy models are discussed and it is mentioned that there is 'no connection to rural meteorological conditions'. This is a problematic statement, since the objective the UCM is to solve the urban energy balance at a given point as a function of the meteorological forcing data. Thus it is trivial that they do not consider the connection to the adjacent rural area. But if the UCM is coupled to a meso-scale atmospheric model, this connection is very well taken into account by the modelling of the process of advection between rural and urban area, and even a potential urban breeze. On the contrary, the difficulty in accurately representing advection or an urban breeze seems rather to be a weakness of the Weather Generator than of the UCM coupled to a meso-scale atmospheric model.

Response: Thank you. We removed the statement about 'no connection to rural meteorological conditions'. Instead we emphasized the need for independent models that can predict the urban climate without the need for meso-scale modeling. We agree that one of the limitations of VCWG is lack of ability to incorporate advection from the rural area. This will be acknowledged as a model limitation below.

2. Section 1.2 contains many details on the functioning of the VCWG. It could be shortened considerably by introducing just the main ideas.

Response: Thank you. We shortened this section somewhat by removing the second paragraph. However, a previous reviewer asked for details of how VCWG is original and novel with respect to other models. Therefore, we had to enumerate all novel aspects.

3. Section 1.3 is also too detailed. It could become just a very short paragraph at the end of Section 1.2.

Response: Thank you. We shortened this section and absorbed it to the previous section (Objectives).

4. In the description of the VCWG, the rural and the urban models are described, but how do they interact? The advection of cooler air from the rural areas to the urban areas with the mean wind speed and a potential urban breeze is a very important process for the UHI. Is this considered and how? More details on the urban-rural interaction and the underlying assumptions of the model are required.

Response: Thank you. We agree and acknowledge the limitation of the model, which does not consider the advection from the rural area. The model assumes that the rural site is upwind of the

urban site, and the top of the domain is above the urban boundary layer. This enables the urban model to be forced from the top with potential temperature and specific humidity. The following statements have been added

It must be acknowledged that the model does not consider the horizontal advection from the rural area. The model assumes that the rural site is upwind of the urban site, and the top of the domain is above the urban boundary layer.

...

In addition, the horizontal advection from the rural area can be considered and parameterized in future work.

5. The entire Section 3.2 (model exploration) could be removed since it is not very rigorous. This would make the entire paper much shorter and a subsequent study could be made with a more detailed exploration of parameters.

Response: Thank you. We agree, and we have moved the entire exploration section to supplementary material. We have only provided one short section in the manuscript, where we briefly discuss the results of the exploration. Note that many previous reviewers asked for different exploration runs, so we had to keep this in the supplementary material. We also added a new exploration regarding location of building waste heat rejection. Please see comment 7 from reviewer 3 above.

3.1.2 Minor remarks

6. At many occasions, the word 'run' is used for 'simulation'. In my opinion, this is a bit too technical

Response: Thank you. We eliminated any reference to 'run' and used 'simulation' instead.

7. You might consider replacing 'elevation' by height above ground level (a.g.l.).

Response: Thank you. We replaced 'elevation' by a.g.l. throughout.

8. The degree symbol "' should be directly after the value, without space.

Response: Thank you. We followed this recommendation throughout.

9. I dont understand why 'Winter' and 'Summer' are written with capital letters.

Response: Thank you. Capitalization was removed.

10. The formulation 'not reported here for brevity' is used way too often, which makes the article tiring to read. It could actually just be omitted at most instances.

Response: Thank you. We omitted those statements.

11. Page 4, L28 'The VCWG is designed to cycle through...'. I do not understand what this means. It sounds as if a series of arbitrarily chosen meteorological conditions would be tested one

after the other. Please rewrite this to be more clear.

Response: Thank you. This statement is now removed.

12. Page 6, L8, what is 'building energy system'?

Response: Thank you. When referring to waste heat rejection, relevant components of the building energy system refer to, for example, condensers and exhaust stacks. This has been clarified in the manuscript.

13. Page 7, L10: 'Energy Plus'

Response: Thank you. We have checked the spelling throughout. EnergyPlusTM is a trade mark and written as one word.

14. Page 10, L28: why are you using the formulation 'temperature (energy)' here and at other instances? Although the equation for temperature comes from energy conservation, it is not usual to have such a double writing.

Response: Thank you. We have now only used 'temperature'.

15. Page 11, L14: layout problems.

Response: Thank you. Formatting was checked.

16. Page 12, L20: There could also be a waste flux at the wall levels, e.g. for wall split type air conditioners.

Response: Thank you. We acknowledge that this is a limitation of the VCWG model. This option was not considered to simplify the model and input parameters required to operate the model. In future developments, this option can be considered.

17. Page 12, L22-24: these details about BUBBLE should not be in the general model description section.

Response: Thank you. We have checked the numbering of sections and subsection. The numbering is 2. Methodology, 2.1 Vertical City Weather Generator (VCWG), and 2.2 Experimental Field Campaigns. So the description for experimental field campaign is not under the model description section. It is under the methodology section.

18. Page 13, L1-12. There are many repetitions in this part of the text, which might be reduced by reorganisation.

Response: Thank you. We have removed many repetitions of the text by reorganizing and removing the unnecessary statements.

19. Page 13, L25: 'in Bueno'?

Response: Thank you. We have checked this.

20. Page 14, L9: 'Trees cannot be higher than the buildings'.

Response: Thank you. We have corrected this.

21. Page 15, L19: 'in a typical'?

Response: Thank you. We have checked this.

22. Page 17, L16 delete 'now'.

Response: Thank you. We deleted 'now'.

23. Page 18: Average building height, Width of street canyon, Rural Bowen ratio

Response: Thank you. We have checked this.

24. Page 23, L22: Usually the drag force is proportional to λ_f , and not λ_p . Only the drag due to the friction on the roofs depends directly on λ_p , but it should be small compared to the drag force due to the vertical walls.

Response: Thank you. We agree. The following statement has been added to the supplementary material.

Note that skin drag is mostly related to roof level drag, which is less in magnitude compared to form drag caused by the building walls. This hypothesis can be confirmed using this exploration study. When λ_p is changed, it is noticed that wind speed profiles respond to a lesser extent compared to when λ_f is changed.

25. Page 27: layout problems in Table 2.

Response: Thank you. The layout of this table has been checked.

26. Page 27, L15: 'Radiation configuration' sounds as if different options of the radiation model would be tested. But this seems not to be the case. The radiation model is the same, but the input data like the orientation of the street canyon are changed.

Response: Thank you. We agree. When conducting sensitivity test on the radiation model, we only changed morphometric variables and the direction of the street canyon axis.

27. Page 27, L17: 'to investigate'

Response: Thank you. This has been corrected.

28. Page 29, L4: 'This is expected'.

Response: Thank you. This has been checked.

29. Page 29, L9: 'loose'.

Response: Thank you. This has been corrected.

30. Page 32, L4-5. I don't understand this way of reporting the results. If it is BIAS, RMSE and R^2 for minimum and maximum UHI, why are there only 3 numbers reported?

Response: Thank you. We have now reported BIAS, RMSE and \mathbb{R}^2 in section 3.2 of the main manuscript. For the Vancouver comparison, we are combining daily maximum and minimum UHI all together, and then reporting 3 values of BIAS, RMSE, and \mathbb{R}^2 , instead of 6.

31. Figure 14: would it be possible to display the same figure for the observed values (e.g. in a two panel figure)?

Response: Thank you. For Vancouver, only daily minimum and maximum UHI observations are available, which are plotted separately on the same figure as VCWG predictions. For BUBBLE, however, diurnal plots of mean and standard deviation for UHI are plotted for both observations and the model results. This is shown in Figure 8 of the main manuscript.

32. Page 33, L7: The phrase 'Appropriate input parameters are used' is not very specific.

Response: Thank you. We removed this statement.

33. Section 3.2.6. Given the strong daily cycle of the UHI it does not seem very appropriate to compare diurnally-averaged UHI values.

Response: Thank you. We agree that there could be a strong daily cycle of the UHI. But, diurnal variation of UHI is not measured, simulated, or reported for all cities. Please also note that the papers that are cited in this section mostly reported diurnally- or monthly-averaged UHI, which are used to evaluate VCWG's performance for different climate zones.

34. Page 33, L12: 'predicts'.

Response: Thank you. This has been checked.

35. Page 35, L4: 'shows'.

Response: Thank you. This has been checked.

36. Page 36, L30: This 'BIAS +- RMSE' way of reporting the results is a bit misleading since it looks as if some kind of statistical uncertainty of the bias would be reported, although it is a different metric (the RMSE) that is reported.

Response: Thank you. We now report BIAS, RMSE, and R^2 as a, b, and c, without using \pm .

37. Page 36, L31: and what about the RMSE?

Response: Thank you. We now report BIAS, RMSE, and \mathbb{R}^2 when available.

38. Page 37, L7: 'wind speed'.

Response: Thank you. This has been checked.

39. Page 37, L17: 'reveals'.

Response: Thank you. This has been corrected.

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The Vertical City Weather Generator (VCWG v1.2.3.0)

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Abstract. The Vertical City Weather Generator (VCWG) is a computationally efficient urban microclimate micro-climate model developed to predict temporal and vertical variation of potential temperature, wind speed, specific humidity, and turbulence kinetic energy. It is composed of various sub-models: a rural model, an urban vertical diffusion model, a radiation model, and a building energy model. Forced with weather data in from a nearby rural site, the rural model is used to solve

- 5 for the vertical profiles of potential temperature, specific humidity, and friction velocity at 10 m elevation.above ground level (a.g.l.). The rural model also calculates a horizontal pressure gradient. The rural model outputs are applied on to a vertical diffusion urban microclimate micro-climate model that solves vertical transport equations for energy (temperature)temperature, momentum, specific humidity, and turbulence kinetic energy. The urban vertical diffusion model is also coupled to the radiation and building energy models using two-way interaction. The aerodynamic and thermal effects of urban elements and
- 10 vegetation, surface vegetation, and trees are considered. The predictions of the VCWG model are compared to observations of the Basel UrBan Boundary Layer Experiment (BUBBLE) microelimate-micro-climate field campaign for two weeks starting 21 June eight months from December 2001 to July 2002. The model evaluation indicates that the VCWG predicts vertical profiles of meteorological variables in reasonable agreement with the field measurements. The average BIASand RMSE, RMSE, and R² for potential temperature are 0.25 K, 1.41 K, and 0.82, respectively. The average BIAS, RMSE, and R² for wind
- 15 speed , temperature, and are 0.67 ms⁻¹, 1.06 ms⁻¹, and 0.41, respectively. The average BIAS, RMSE, and R² for specific humidity are -0.20±0.50, +0.11±1.73, and +0.0011±0.0016 0.00057 kgkg⁻¹, 0.0010 kgkg⁻¹, and 0.85, respectively. VCWG-predicted mean and standard deviation In addition, the average BIAS, RMSE, and R² for Urban Heat Island (UHI) are +1.59 and 1.460.36 K, respectively, in reasonable agreement with observations reporting a mean and standard deviation for of +1.72-1.2 K, and 0.91-0.35, respectively. Based on the evaluation, the model performance is comparable to the performance
- 20 of similar models. The performance of the model is further explored to investigate the effects of urban configurations such as plan and frontal area densities, varying levels of vegetation, building energy configuration, radiation configuration, seasonal variations, and different climate zones on the model predictions. The results obtained from the explorations are reasonably con-

sistent with previous studies in the literature, justifying the reliability and computational efficiency of VCWG for operational urban development projects.

1 Introduction

Urban areas interact with the atmosphere through various exchange processes of heat, momentum, and mass, which substantially impact the human comfort, air quality, and energy consumption. Such complex interactions are observable from the Urban Canopy Layer (UCL) to a few hundred meters within the Atmospheric Boundary Layer (ABL) (Britter and Hanna, 2003). Modeling enables a deeper understanding of interactions between urban areas and the atmosphere and can possibly offer solutions toward mitigating adverse effects of urban development on the climate. A brief review of modeling efforts is essential toward more accurate model development for the understanding of urban areas-atmosphere interactions.

- 10 Mesoscale-Meso-scale models incorporating the urban climate were initially aimed to resolve weather features with grid resolutions of at best a few hundred meters horizontally and a few meters vertically, without the functionality to resolve microscale-micro-scale three-dimensional flows or to account for atmospheric interactions with specific urban elements such as roads, roofs, and walls (Bornstein, 1975). These models usually consider the effect of built-up areas by introducing an urban aerodynamic roughness length (Grimmond and Oke, 1999) or adding source or sink terms in the momentum (drage.g.
- 15 drag term) and temperature (e.g. anthropogenic heat term) and energy (anthropogenic heat) equations (Dupont et al., 2004). Therefore, if higher grid resolutions less than ten meters (horizontal and vertical) are desired (Moeng et al., 2007; Wang et al., 2009; Talbot et al., 2012), microscale micro-scale climate models should be deployed. Some efforts also have begun to develop multiseale have also begun by investigators to develop multi-scale climate models by coupling mesoscale and microscale meso-scale and micro-scale models (Chen et al., 2011; Kochanski et al., 2015; Mauree et al., 2018). Numerous studies have
- 20 used Computational Fluid Dynamics (CFD) to investigate the urban microclimate micro-climate taking into account interactions between the atmosphere and the urban elements with full three-dimensional flow analysis (Saneinejad et al., 2012; Blocken, 2015; Nazarian and Kleissl, 2016; Aliabadi et al., 2017; Nazarian et al., 2018). Despite accurate predictions, CFD models are not computationally efficient, particularly for weather forecasting at larger scales and for a long period of time, and they usually do not represent many processes in the real atmosphere such as clouds and precipitation. As an alternative, Urban
- 25 Canopy Models (UCMs) require understanding of the interactions between the atmosphere and urban elements to parameterize various exchange processes of radiation, momentum, heat, and moisture within and just above the canopy, based on experimental data(Masson, 2000; Kusaka et al., 2001; Chin et al., 2005; Aliabadi et al., 2019), physical processes from theoretical considerations, three-dimensional simulations, or simplified urban configurations (Martilli et al., 2002; Krayenhoff et al., 2014, 2015; Nazarian and Kleissl, 2016; Aliabadi et al., 2005; Krayenhoff et al., 2014, 2015; Nazarian and Kleissl, 2016; Aliabadi et al., 2005; Krayenhoff et al., 2014, 2015; Nazarian and Kleissl, 2016; Aliabadi et al., 2005; Krayenhoff et al., 2014, 2015; Nazarian and Kleissl, 2016; Aliabadi et al., 2000; Kusaka et al., 2001; Martilli et al., 2002; Chin et al., 2005; Krayenhoff et al., 2014, 2015; Nazarian and Kleissl, 2016; Aliabadi et al., 2000; Kusaka et al., 2001; Martilli et al., 2002; Chin et al., 2005; Krayenhoff et al., 2014, 2015; Nazarian and Kleissl, 2016; Aliabadi et al., 2000; Kusaka et al., 2001; Martilli et al., 2002; Chin et al., 2005; Krayenhoff et al., 2014, 2015; Nazarian and Kleissl, 2016; Aliabadi et al., 2000; Kusaka et al., 2001; Martilli et al., 2002; Chin et al., 2005; Krayenhoff et al., 2014, 2015; Nazarian and Kleissl, 2016; Aliabadi et al., 2000; Kusaka et al., 2001; Martilli et al., 2002; Chin et al., 2005; Krayenhoff et al., 2014, 2015; Nazarian and Kleissl, 2016; Aliabadi et al., 2000; Kusaka et al., 2001; Martilli et al., 2002; Chin et al., 2005; Krayenhoff et al., 2014, 2015; Nazarian and Kleissl, 2016; Aliabadi et al., 2005; Krayenhoff et al., 2014, 2015; Krayenhoff et al., 2014, 2015; Krayenhoff et al., 2014; Krayenho
- 30 . These urban canopy models are more computationally efficient than CFD models. They are designed to provide more details on heat storage and radiation exchange, while they employ less detailed flow calculations.

Urban microclimate micro-climate models must account for a few unique features of the urban environment. Urban obstacles such as trees and buildings contribute substantially to the changing of flow and turbulence patterns in cities (Kastner-Klein

et al., 2004). Difficulties arise when the spatially inhomogeneous urban areas create highly three-dimensional wind patterns that result in the difficulty of parameterizations (Roth, 2000; Resler et al., 2017). For example, the surfaces of urban obstacles exert form and skin drag and consequently alter flow direction and produce eddies at different spatiotemporal spatio-temporal scales. This can lead to the formation of shear layers at roof level with variable oscillation frequencies (Tseng et al., 2006;

- Masson et al., 2008; Zajic et al., 2011), all of such phenomena should be properly approximated in parameterizations. Heat exchanges between the indoor and outdoor environments significantly influence the urban microclimatemicro-climate. Various studies have attempted to parametrize heat sources and sinks caused by buildings such as heat fluxes due to infiltration, exfiltration, ventilation, walls, roofs, roads, windows, and building energy systems (e.g. condensers and exhaust stacks) (Kikegawa et al., 2003; Salamanca et al., 2010; Yaghoobian and Kleissl, 2012). Therefore, a Building Energy Model (BEM)
- 10 is required to be properly integrated in an urban <u>microclimate micro-climate</u> model to take account of the impact of building energy performance on the urban <u>microclimate micro-climate</u> (Bueno et al., 2011, 2012b; Gros et al., 2014). This two-way interaction between the urban <u>microclimate micro-climate</u> and indoor environment can significantly affect Urban Heat Island (UHI) [K] and energy consumption of buildings (Salamanca et al., 2014).
- Urban vegetation can substantially reduce the adverse effects of UHI [K], particularly during heat waves, resulting in more 15 improved thermal comfort (Grimmond et al., 1996; Akbari et al., 2001; Armson et al., 2012). Urban trees can potentially provide shade and shelter, and therefore, change the energy balance of the individual buildings as well as the entire city (Akbari et al., 2001). A study of the local-scale surface energy balance revealed that the amount of energy dissipated due to the cooling effect of trees is not negligible and should be parameterized properly (Grimmond et al., 1996). In addition, the interaction between urban elements, most importantly trees and buildings, is evident in radiation trapping within the canyon
- 20 and most importantly shading impact of trees (Krayenhoff et al., 2014; Redon et al., 2017; Broadbent et al., 2019). Buildings and trees obstruct the sky with implications in long and shortwave radiation fluxes downward and upward that may create unpredictable diurnal and seasonal changes in UHI [K] (Kleerekoper et al., 2012; Yang and Li, 2015). Also, it has been shown that not only trees but also the fractional vegetation coverage on urban surfaces can alter urban temperatures with implications in UHI [K] (Armson et al., 2012). Trees, particularly those which are shorter than buildings, depending on their height and
- 25 <u>abundance relative to buildings, could</u> also exert drag and alter flow patterns within the canopy, however, this effect is not as significant as that the drag induced by buildings (Krayenhoff et al., 2015). Such complex interactions must be accounted for in successful urban microclimate micro-climate models.

1.1 Research Gaps

Numerous studies have focused on high fidelity urban microclimate high-fidelity urban micro-climate models with high
 spatiotemporal spatio-temporal flow resolution, capturing important features of the urban microclimate micro-climate with acceptable accuracy (Gowardhan et al., 2011; Soulhac et al., 2011; Blocken, 2015; Nazarian et al., 2018). Some example Computational Fluid Dynamics (CFD) models of this kind include Open-source Field Operation And Manipulation (OpenFOAM) (Aliabadi et al., 2017, 2018), Parallelized Large-Eddy Simulation Model (PALM) (Maronga et al., 2015; Resler et al., 2017), and ENVI-met (Crank et al., 2018). Despite the advances, however, high fidelity high-fidelity models capable of resolving

three-dimensional flows at microscale micro-scale are not computationally efficient and they are complex to implement for operational applications. As a remedy, lower-dimensional flow urban microelimate micro-climate models have been developed with many practical applications in city planning, architecture, and engineering consulting. For example, such bulk flow (single-layer) models as Urban Weather Generator (UWG) calculate the flow dynamics in one point, usually the centre of a hy-

- 5 pothetical urban canyon, which is representative of all locations (Mills, 1997; Kusaka et al., 2001; Salamanca et al., 2010; Ryu et al., 2011; Bueno et al., 2012a, 2014). Another bulk flow (single-layer) model is the Canyon Air Temperature (CAT) model, which utilizes standard data from a meteorological station to estimate air temperature in a street canyon (Erell and Williamson, 2006). The Town Energy Balance (TEB) calculates energy balances for urban surfaces, which is forced by meteorological data and incoming solar radiation in the urban site with no connection to rural meteorological conditions on top of the modeling
- 10 domain (Masson et al., 2002). The Temperatures of Urban Facets 3D (TUF-3D) model calculates urban surface temperatures with the main focus on three-dimensional radiation exchange, but it adopts bulk flow (single-layer) modelingwithout a connection to the surrounding rural area, and it is forced by meteorological data on top of its domain (Krayenhoff and Voogt, 2007). More recently TUF-3D was coupled to an Indoor-Outdoor Building Energy Simulator (TUF-3D-IOBES), but still-this model adopted a bulk flow (single-layer) parameterization (Yaghoobian and Kleissl, 2012). The multi-layer Building Effect
- 15 Parametrization-Tree (BEP-Tree) model includes variable building heights, the vertical variation of climate variables and the effects of trees, but it is not linked to a building energy model (Martilli et al., 2002; Krayenhoff, 2014; Krayenhoff et al., 2020). More recently, the BEP model has been coupled to a Building Energy Model (BEP+BEM) but it is forced with meteorological variables from higher altitudes above a city using mesoscale meso-scale models, instead of near surface meteorological variables measured outside the city (rural areas). An overview of the literature reveals an apparent paucity of an independent urban
- 20 microclimate micro-climate model that accounts for some spatiotemporal variation of meteorological parameters in the urban environment and considers the effects of trees, building energy, radiation, and the connection to the near-surface rural meteorological conditions measured outside a city, without the need for mesoscale meso-scale modeling, computationally efficiently and is operationally simple for practical applications.

1.2 Objectives

- 25 In this study, we present a new urban microelimate micro-climate model, called the Vertical City Weather Generator (VCWG), which attempts to overcome some of the limitations mentioned in the previous section. It resolves vertical profiles of climate variables, such as temperature, wind, and specific humidity, and turbulence kinetic energy in relation to urban design parameters. VCWG also includes a building energy model. It allows parametric investigation of design options on urban climate control at multiple heights, particularly if multi-storey building design options are considered. This is a significant advantage
- 30 over the bulk flow (single-layer) models such as UWG, which only consider one point for flow dynamics inside a hypothetical canyon (Masson, 2000; Kusaka et al., 2001; Dupont et al., 2004; Krayenhoff and Voogt, 2007; Lee and Park, 2008; Bueno et al., 2012a, 2014). The VCWG is designed to cycle through different atmospheric stability conditions that could be observed over the course of a day, but it is very computationally efficient with the capability to be run up to and beyond an entire year. The advantages of VCWG are as follows. 1) It does not need to be coupled to a mesoscale meso-scale weather model because

it functions standalone as a microelimate micro-climate model. 2) Unlike many UCMs that are forced with climate variables above the urban roughness sublayer (e.g. TUF-3D), VCWG is forced with rural climate variables measured at 2 m (temperature and humidity) and 10 m (wind) elevation above ground level (a.g.l.) that are widely accessible and available around the world, making VCWG highly practical for urban design investigations in different climates. Further, unlike UWG, VCWG

- 5 uses the Monin-Obukhov similarity theory in the rural area to consider effects of thermal stability and aerodynamicroughness length, temperature, and specific humidity roughness lengths to establish vertical profiles of potential temperature and specific humidity. 3) VCWG provides urban climate information in one dimension, i.e. resolved vertically, which is advantageous over bulk flow (single-layer) models. 4) VCWG is coupled with the building energy model using two-way interaction. 5) Unlike UWG, VCWG considers the effect of trees in the urban climate by modelling evapotranspiration (latent heat transfer), sensible
- 10 heat trasnfer, radiation transfer, drag, and other processes due to trees.

To evaluate the model, VCWG's predictions are compared to observation of the Basel UrBan Boundary Layer Experiment (BUBBLE) microclimate field campaign for two weeks starting 21 June 2002 (Christen and Vogt, 2004; Rotach et al., 2005). The model predictions of air temperature, wind speed, and specific humidity are compared to the observations. To explore the model, the VCWG is set to run to investigate the effects of building dimensions, urban vegetation, building energy configuration, radiation configuration, seasonal variations, and other climates.

1.3 Organization of the Article

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The paper is structured as follows. Section 2 describes the methodology. In Sect. 2.1, all, outlining the components of the VCWG and the way that they are integrated are presented. First, the Energy Plus model and their connections: the forcing EnergyPlusTM Weather (EPW) datasetis introduced, which is the background rural weather data used to force VCWG. Next,

- 20 the the Rural Model (RM), used to determine the potential temperature profile, specific humidity profile, friction velocity, and the horizontal pressure gradient in the rural area, is described. Then, details are discussed for the the one-dimensional vertical diffusion modelfor the urban environment, the building energy model, and the radiation model, which are forced by the RM to predict the vertical profiles of meteorological quantities in the urban area. Section ?? This section also describes the location and details of the BUBBLE field campaign used for model evaluation. Section 3 provides the results and discussion. It
- 25 starts with the detailed evaluation of VCWG by comparing simulation results with those of the BUBBLE field measurementsin Sect. 3.1... Then, results from other explorations, including effects of building dimensions, foliage density, building energy configuration, radiation configuration, seasonal variation, and different climate zones on urban climate are presented in Sect. ?? with limited evaluations against observed valuesbriefly presented with references to the supplementary material. Finally, Sect. 4 is devoted to conclusions and future work. Additional information about the sub-models and equations used are provided
- 30 in the appendix.

2 Methodology

2.1 Vertical City Weather Generator (VCWG)

Figure 1 shows the VCWG model schematic. VCWG consists of four integrated sub-models: 1) a Rural Model (RM) (Sect. 2.1.2) forces meteorological boundary conditions on VCWG based on Monin-Obukhov similarity theory (Paulson, 1970;

- 5 Businger et al., 1971; Dyer, 1974) and a soil energy balance model (Bueno et al., 2012a, 2014); 2) a an urban one-dimensional vertical diffusion model (Sect. 2.1.3) is used for calculation of the vertical profiles of urban microclimate micro-climate variables including potential temperature, wind speed, specific humidity, and turbulence kinetic energy, considering the effect of trees, buildings, and building energy system (e.g. condensers and exhaust stacks). This model was initially developed by Santiago and Martilli (2010) and Simón-Moral et al. (2017), while it was later ingested into another model called the Building
- 10 Effect Parametrization with Trees (BEP-Tree), considering the effects of trees (Krayenhoff, 2014; Krayenhoff et al., 2015, 2020); 3) a Building Energy Model (BEM) (Sect. 2.1.4) is used to determine the waste heat of buildings imposed on the urban environment. This model is a component of the Urban Weather Generator (UWG) model (Bueno et al., 2012a, 2014); 4) a radiation model with vegetation (Sect. 2.1.5) is used to compute the longwave and shortwave heat exchanges between the urban canyon, trees, and the atmosphere/sky. A summary of this model is provided by Meili et al. (2020) and references within.
- 15 The sub-models are integrated to predict vertical variation of urban <u>microclimate micro-climate</u> variables including potential temperature, wind speed, specific humidity, and turbulence kinetic energy as influenced by aerodynamic and thermal effects of urban elements including longwave and shortwave radiation exchanges, sensible heat fluxes released from urban elements, cooling effect of trees, and the induced drag by urban obstacles. The RM takes latitude, longitude, dry bulb temperature, relative humidity, dew point temperature, and pressure at 2 m elevationa.g.l., wind speed and direction at 10 m elevationa.g.l.,
- 20 down-welling direct shortwave radiation, down-welling diffuse shortwave radiation, down-welling longwave radiation, and deep soil temperature from an EPW file. For every time step, and forced with the set of weather data, the RM then computes a potential temperature profile, a specific humidity profile, friction velocity, and a horizontal pressure gradient as a function of friction velocity, all of which are forced as boundary conditions to the one-dimensional vertical diffusion model in the urban area. The potential temperature and specific humidity are forced as fixed values on top of the domain for the urban vertical
- 25 diffusion model in the temperature and specific humidity equations, respectively. The horizontal pressure gradient is forced as a source term for the urban vertical diffusion model in the momentum equation. It must be acknowledged that the model does not consider the horizontal advection from the rural area. The model assumes that the rural site is upwind of the urban site, and the top of the domain is above the urban boundary layer. While forced by the RM, the urban one-dimensional vertical diffusion model is also coupled with the building energy and radiation models. The three models have feedback interaction. The urban
- 30 one-dimensional vertical diffusion model calculates the flow quantities at the centre of control volumes, which are generated by splitting the urban computational domain into multiple layers within and above the urban canyon (see Fig. 2). The urban domain extends to three times building height that conservatively falls closer to the top of the atmospheric roughness sublayer in the urban area (Santiago and Martilli, 2010; Aliabadi et al., 2017), but within the inertial layer in the rural area, where Monin-Obukhov similarity theory can be applied (Basu and Lacser, 2017). In VCWG, buildings with uniformly-distributed

height, equal width, and equal spacing from one another, represent the urban area. The feedback interaction coupling scheme among the building energy model, radiation model, and the urban one-dimensional vertical diffusion model is designed to update the boundary conditions, surface temperatures, and the source/sink terms in the transport equations in successive time step iterations. More details about the sub-models are provided in the subsequent sections and the appendix.



Figure 1. The schematic of Vertical City Weather Generator (VCWG).

5 2.1.1 Energy Plus Energy PlusTM Weather Data

Building energy and solar radiation simulations are typically carried out with standardized weather files. EPW files include recent weather data for 2100 locations and are saved in the standard <u>EnrgyPlus-EnergyPlus</u> format, developed by US department of energy.¹ The data is available for most North American cities, European cities, and other regions around the World. The weather data are arranged by World Meteorological Organization (WMO) based on region and country. An EPW

10 file contains typical hourly-based data of meteorological variables. The meteorological variables are dry bulb temperature, dew point temperature, relative humidity, incoming direct and diffusive shortwave radiation fluxes from the sky, sun and sky, respectively, incoming longwave radiation flux, wind direction, wind speed, sky condition, precipitation (occasionally), deep soil temperature, and general information about field logistics and soil properties. Precipitation data is often missing in the EPW files.

¹https://energyplus.net/weather



Figure 2. Simplified urban area used in VCWG and corresponding layers of control volumes within and above the canyon. The height of the domain is three times of the average building height. A leaf area density (LAD) $[m^2m^{-3}]$ profile is considered to represent the treetrees.

2.1.2 Rural Model

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In the rural model, the Monin–Obukhov Similarity Theory (MOST) is used to solve for the vertical profiles of potential temperature, specific humidity, and friction velocity at 10 m elevation a.g.l. using meteorological measurements near the surface. MOST is usually applied to the atmospheric surface layer over flat and homogeneous lands to describe the vertical profiles of wind speed, potential temperature, and specific humidity as functions of momentum flux, sensible heat flux, and latent heat flux measured near the surface, respectively. Using MOST the gradient of potential temperature is given by

$$\frac{\partial \Theta_{rur}}{\partial z} \frac{d\Theta_{rur}}{dz} = \frac{Q_{sen,rur}}{\rho C_p \kappa u_* z} \Phi_H\left(\frac{z}{L}\right),\tag{1}$$

where $\overline{\Theta}_{rur}$ [K] is mean potential temperature in the rural area, $Q_{sen,rur}$ [Wm⁻²] is net rural sensible heat flux, ρ [kgm⁻³] is air density near the rural surface, C_p [Jkg⁻¹K⁻¹] is air specific heat capacity, u_* [ms⁻¹] is friction velocity, and $\kappa = 0.4$ [-] is the von Kármán constant. Φ_H [-] is known as the universal dimensionless temperature gradient. This terms term is estimated for different thermal stability conditions based on experimental data by (Businger et al., 1971; Dyer, 1974)

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$$\Phi_H\left(\frac{z}{L}\right) = \begin{cases} 1+5\frac{z}{L}, & \frac{z}{L} > 0(\text{Stable})\\ 1, & \frac{z}{L} = 0(\text{Neutral})\\ \left(1-\frac{16z}{L}\right)^{-1/2}, & \frac{z}{L} < 0(\text{Unstable}). \end{cases}$$
(2)

In the dimensionless stability parameter z/L [-], z [m] is height above ground and L [m] is Obukhov-Length given by

$$L = \frac{-\Theta_{rur,z=2m}u_*^3}{g\kappa \frac{Q_{sen,rur}}{\rho C_p}}.$$
(3)

It has been observed that there is a monotonic reduction in friction velocity with increasing stratification (Joffre et al., 2001). So, friction velocity in Eq. 1 is estimated from momentum flux generalization (Monin and Obukhov, 1957)

$$\frac{\partial S_{rur}}{\partial z} \frac{\partial S_{rur}}{\partial z_{max}} = \frac{u_*}{\kappa z} \Phi_M\left(\frac{z}{L}\right),\tag{4}$$

where \overline{S}_{rur} [ms⁻¹] is the mean horizontal wind speed in the rural area and Φ_M [-] is the universal dimensionless wind shear and is estimated for different thermal stability conditions based on experimental data (Businger et al., 1971; Dyer, 1974)

$$10 \quad \Phi_M\left(\frac{z}{L}\right) = \begin{cases} 1+5\frac{z}{L}, & \frac{z}{L} > 0(\text{Stable})\\ 1, & \frac{z}{L} = 0(\text{Neutral})\\ \left(1-\frac{16z}{L}\right)^{-1/4}, & \frac{z}{L} < 0(\text{Unstable}). \end{cases}$$
(5)

Friction velocity can be determined by integrating Eq. 4, iteratively, from the elevation of the rural aerodynamic roughness length z_{0rur} [m] to $\frac{10}{2} - d_{rur}$ [min an iterative process.], where z=10 m is the reference height for wind measurement and d_{rur} [m] is the zero displacement height. The aerodynamic roughness length and zero displacement height have been rigorously studied and parameterized in the literature as functions of obstacle height h_{rur} [m] and the type of rural area

15 (Raupach et al., 1991; Hanna and Britter, 2002). VCWG permits this specification, but the approximate values used in this study are $z_{0rur}=0.1h_{rur}$ and $d_{rur}=0.5h_{rur}$. This method provides a friction velocity that is corrected for thermal stability effects.

The potential temperature profiles are also obtained by integration of Eq. 1 (Paulson, 1970) –from rural roughness length for temperature $z_{\overline{\Theta},rur}$ [m] to $z-d_{rur}$ [m], where z [m] is the desired elevation above ground (here the top of the domain). A typical value of $z_{\overline{\Theta},rur}$ =0.1 z_{0rur} [m] is often used (Brutsaert, 1982; Garratt, 1994; Järvi et al., 2011; Meili et al., 2020).

Given the similarity of heat and mass transfer (sensible and latent heat fluxes), the same universal dimensionless temperature gradient can be used for the universal dimensionless specific humidity gradient, i.e. $\Phi_Q = \Phi_H$ [-] (Zeng and Dickinson, 1998). The net rural latent heat flux $Q_{lat,rur}$ [Wm⁻²] can either be directly measured or estimated using the Bowen ratio β_{rur} - β_{rur} [-] and the net rural sensible heat flux via $Q_{lat,rur}=Q_{sen,rur}/\beta_{rur}$ [Wm⁻²]. So the gradient of the specific humidity can be given by the following expression, employing latent heat of vaporization L_v [Jkg⁻¹], as

$$\frac{d\overline{Q}_{rur}}{dz} = \frac{Q_{lat,rur}}{\rho L_v \kappa u_* z} \Phi_Q\left(\frac{z}{L}\right),\tag{6}$$

which can also be integrated to give the vertical profile of specific humidity,

$$\frac{\partial Q_{rur}}{\partial z} = \frac{Q_{lat,rur}}{\rho L_v \kappa u_* z} \Phi_Q\left(\frac{z}{L}\right).$$

. This expression should be integrated from rural roughness length for specific humidity $z_{\overline{Q},rur}$ [m] to $z-d_{rur}$ [m], where z [m] is the desired elevation above ground (here the top of the domain). It is often assumed that $z_{\overline{Q},rur} = z_{\overline{\Theta},rur}$ [m] (Brutsaert, 1982; Järvi et al., 2)

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Meteorological information obtained from the weather station including direct and diffuse shortwave radiation, longwave radiation, temperature at 2 m elevationa.g.l., wind speed at 10 m elevationa.g.l., and deep soil temperature are used to calculate the net rural sensible and latent heat fluxes at the surface via the surface energy balance

$$Q_{S,rur} + Q_{L,rur} = Q_{sen,rur} + Q_{lat,rur} + Q_{grd},\tag{7}$$

10 where $Q_{S,rur}$ and $Q_{L,rur}$ [both in Wm^{-2}] are net shortwave and longwave radiation fluxes at the surface (positive with energy flux into the surface) and $Q_{sen,rur}$, $Q_{lat,rur}$, and Q_{grd} [all in Wm^{-2}] are net sensible, latent, and ground heat fluxes at the surface (positive with energy flux leaving the surface). Appendix A details the calculation of each term.

The rural model also outputs a horizontal pressure gradient based on the friction velocity calculation that is later used as a source term for the urban one-dimensional vertical diffusion momentum equation. The pressure gradient is parameterized as $\rho u_*^2/H_{top}$ [kgm⁻²s⁻²], where H_{top} [m] is the height of the top of the domain (Krayenhoff et al., 2015; Nazarian et al., 2020),

here three times the average building height.

After calculating potential temperature and specific humidity at the top of the domain by the rural model, these values can be applied as fixed-value boundary condition at the top of the domain in the urban one-dimensional vertical diffusion model in the temperature (energy) and specific humidity transport equations.

20 2.1.3 Urban Vertical Diffusion Model

Numerous studies have attempted to parameterize the interaction between urban elements and the atmosphere in terms of dynamical and thermal effects, from very simple models based on MOST (Stull, 1988), to the bulk flow (single-layer) parameterizations (Krayenhoff and Voogt, 2007; Masson, 2000; Kusaka et al., 2001; Bueno et al., 2014), to multi-layer models (Hamdi and Masson, 2008; Santiago and Martilli, 2010; Krayenhoff et al., 2015, 2020) with different levels of complexity. The multi-

- 25 layer models usually treat aerodynamic and thermal effects of urban elements as sink or source terms in temperature(energy), momentum, specific humidity, and turbulence kinetic energy equations. Parameterization of the exchange processes between the urban elements and the atmosphere can be accomplished using either experimental data or CFD simulations (Martilli et al., 2002; Dupont et al., 2004; Kondo et al., 2005; Kono et al., 2010; Lundquist et al., 2010; Santiago and Martilli, 2010; Krayenhoff et al., 2015; Aliabadi et al., 2019). CFD-based parameterizations proposed by Martilli and Santiago (2007), Santiago
- 30 and Martilli (2010), Krayenhoff et al. (2015), and Nazarian et al. (2020) use results from Reynolds-Averaged Navier-Stokes (RANS) or Large-Eddy Simulations (LES) including effects of trees and buildings. These parameterizations consider the CFD results at different elevations after being temporally and horizontally averaged.

For the one-dimensional vertical diffusion model, any variable such as cross- and along-canyon wind velocities (U and V $[ms^{-1}]$, respectively), potential temperature (Θ [K]), and specific humidity (Q $[kgkg^{-1}]$) is presented using Reynolds averaging. The one-dimensional time-averaged momentum equations in the cross- and along-canyon components can be shown as (Santiago and Martilli, 2010; Krayenhoff, 2014; Krayenhoff et al., 2015; Simón-Moral et al., 2017; Nazarian et al., 2020; Krayenhoff et al., 2020)

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$$\frac{\partial \overline{U}}{\partial t} = -\underbrace{\frac{\partial \overline{u}\overline{w}}{\partial z}}_{I} - \underbrace{\frac{\partial \overline{P}}{\partial x}}_{II} - \underbrace{\frac{D_{x}}{\partial x}}_{III},\tag{8}$$

$$\frac{\partial \overline{V}}{\partial t} = -\underbrace{\frac{\partial \overline{vw}}{\partial z}}_{I} - \underbrace{\frac{1}{\rho} \frac{\partial \overline{P}}{\partial y}}_{II} - \underbrace{\frac{D_{y}}{D_{II}}}_{III},\tag{9}$$

where P [Pa] is time-averaged pressure. The terms on the right hand side of Eqs. 8 and 9 are the vertical gradient of turbulent flux of momentum (I), acceleration due to the large-scale pressure gradient (II), and the sum of pressure, building form,
10 building skin, and vegetation drag terms (III). The parameterization of the latter term is detailed in Appendix Aand is not reported here for brevity. K-theory is used to parameterize the vertical momentum fluxes, i.e. ∂uw/∂z = -K_m∂U/∂z and ∂vw/∂z = -K_m∂V/∂z (the same approach will be used in temperature (energy) potential temperature and specific humidity equations), where the diffusion coefficient is calculated using a k-ℓ turbulence model

$$K_m = C_k \ell_k k^{1/2},\tag{10}$$

15 where C_k [-] is a constant and ℓ_k [m] is a length scale optimized using sensitivity analysis based on CFD (Nazarian et al., 2020). Note that the plan area density λ_p [-] in this study is greater than the limit considered by Nazarian et al. (2020), so we assume that the parameterizations extrapolate to this value of λ_p [-]. More details on C_k [-] and ℓ_k [m] are provided in Krayenhoff (2014) and Nazarian et al. (2020). The turbulence kinetic energy k [m²s⁻²] can be calculated using a prognostic equation (Krayenhoff et al., 2015)

$$20 \quad \frac{\partial k}{\partial t} = \underbrace{K_m \left[\left(\frac{\partial \overline{U}}{\partial z} \right)^2 + \left(\frac{\partial \overline{V}}{\partial z} \right)^2 \right]}_{I} + \underbrace{\frac{\partial}{\partial z} \left(\frac{K_m}{\sigma_k} \frac{\partial k}{\partial z} \right)}_{II} - \underbrace{\frac{g}{\Theta_0} \frac{K_m}{Pr_t} \frac{\partial \overline{\Theta}}{\partial z}}_{III} + \underbrace{\frac{S_{wake}}{V}}_{V} - \underbrace{\varepsilon}_{V}, \tag{11}$$

where g $[ms^{-2}]$ is acceleration due to gravity and Θ_0 [K] is a reference potential temperature. The terms on the right hand side of Eq. 11 are shear production (I), turbulent transport of kinetic energy parameterized based on K-theory (II), buoyant production/dissipation (III), wake production by urban obstacles and trees (IV), and dissipation (V). Parameterizations of the last two terms are presented in more detail in Appendix A and by Krayenhoff (2014)and are not reported here for brevity. σ_k [-] is the turbulent Prandtl number for kinetic energy, which is generally suggested to be $\sigma_k=1$ [-] (Pope, 2000). To calculate the vertical profile of potential temperature in the urban area, the energy transport equation can be derived as

$$\frac{\partial\overline{\Theta}}{\partial t} = \underbrace{\frac{\partial}{\partial z} \left(\frac{K_m}{Pr_t} \frac{\partial\overline{\Theta}}{\partial z} \right)}_{I} + \underbrace{S_{\Theta R} + S_{\Theta G} + S_{\Theta W} + S_{\Theta V} + S_{\Theta A} + S_{\Theta waste}}_{II}, \tag{12}$$

where Pr_t [-] is turbulent Prandtl number, the first term on the right hand side is turbulent transport of heat (I), and the heat sink/source terms (II) correspond to sensible heat exchanges with roof (S_{Θ R}), ground (S_{Θ G}), wall (S_{Θ W}), urban vegetation S_{Θ V}, and radiative divergence S_{Θ A} [all in Ks⁻¹]. These terms are detailed in appendix A and by Krayenhoff (2014)and-are

5 $S_{\Theta V}$, and radiative divergence $S_{\Theta A}$ [all in Ks⁻¹]. These terms are detailed in appendix A and by Krayenhoff (2014)and are not reported here for brevity. Contribution of the waste heat emissions from building Heating Ventilation and Air Conditioning (HVAC) system $S_{\Theta waste}$ [Ks⁻¹] is parameterized by

$$S_{\Theta waste} = F_{st} \frac{1}{\rho C_p \Delta z} Q_{HVAC},\tag{13}$$

where Q_{HVAC} [Wm⁻²] is total sensible waste heat released into the urban atmosphere per building footprint area, F_{st} [-] is 10 the fraction of waste heat released at street level, while the remainder fraction $(1-F_{st})$ [-] is released at roof level, and Δz [m] is grid discretization in the vertical direction. Depending on the type of building, waste heat emissions can be released partially at street level and the rest at roof level, which can be adjusted by changing F_{st} [-] from 0 to 1. For the BUBBLE campaign, it is assumed that all waste heat was released at roof level, which is more typical in most energy-retrofitted mid-rise apartments (Christen and Vogt, 2004; Rotach et al., 2005). Term Q_{HVAC} [Wm⁻²] is calculated by the building energy model as

15
$$Q_{HVAC} = \underbrace{Q_{surf} + Q_{ven} + Q_{inf} + Q_{int}}_{Q_{cool}} + W_{cool} + Q_{dehum} + Q_{gas} + Q_{water}, \tag{14}$$

$$Q_{HVAC} = \underbrace{(\underbrace{Q_{surf} + Q_{ven} + Q_{inf} + Q_{int}}_{Q_{heat}})/\eta_{heat} + Q_{dehum} + Q_{gas} + Q_{water},}_{\text{Heating waste heat}}$$
(15)

under cooling and heating modes, respectively. Under cooling mode Q_{HVAC} [Wm⁻²] is calculated by adding the cooling demand (Q_{cool} [Wm⁻²]), consisting of surface cooling demand, ventilation demand, infiltration (or exfiltration) demand, and internal energy demand (lighting, equipment, and occupants), energy consumption of the cooling system ($W_{cool}=Q_{cool}/COP$

- [Wm⁻²]) (accounting for Coefficient of Performance (COP [-])), dehumidification demand (Q_{dehum} [Wm⁻²]), energy consumption by gas combustion (e.g. cooking) (Q_{gas} [Wm⁻²]), and energy consumption for water heating (Q_{water} [Wm⁻²]). Under heating mode, Q_{HVAC} [Wm⁻²] is calculated by adding the heating waste heat (Q_{heat} [Wm⁻²]), consisting of surface heating demand, ventilation demand, infiltration (or exfiltration) demand, and internal energy demand (lighting, equipment, and occupants) (accounting for thermal efficiency of the heating system (η_{heat} [-])), dehumidification demand (Q_{dehum} [Wm⁻²]), energy consumption by gas combustion (e.g. cooking) (Q_{gas} [Wm⁻²]), and energy consumption for water heating (Q_{water} [Wm⁻²])
- energy consumption by gas combustion (e.g. cooking) (Q_{gas} [Wm⁻²]), and energy consumption for water heating (Q_{water} [Wm⁻²]).

To complete the urban one-dimensional vertical diffusion model, the transport equation for specific humidity is

$$\frac{\partial \overline{Q}}{\partial t} = \underbrace{\frac{\partial}{\partial z} \left(\frac{K_m}{Sc_t} \frac{\partial \overline{Q}}{\partial z} \right)}_{I} + \underbrace{\frac{S_{QV}}{S_{II}}}_{I}, \tag{16}$$

where \overline{Q} [kgkg⁻¹] is time-averaged specific humidity. The turbulent transport of specific humidity (I) is parameterized based on K-theory, Sc_t [-] is the turbulent Schmidt number, and source term S_{QV} [KgKg⁻¹s⁻¹] (II) is caused by latent heat from vegetation detailed in appendix A and by Krayenhoff (2014)but not reported here for brevity.

2.1.4 Building Energy Model

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In this study, the balance equation for convection, conduction, and radiation heat fluxes is applied to all building elements (wall, roof, floor, windows, ceiling, and internal mass) to calculate the indoor air temperature. Then, a sensible heat balance equation, between convective heat fluxes released from indoor surfaces and internal heat gains and sensible heat fluxes from the HVAC system and infiltration (or exfiltration), is solved to obtain the time evolution of indoor temperature as

$$V\rho C_p \frac{dT_{in}}{dt} = \underbrace{Q_{surf} + Q_{ven} + Q_{inf} + Q_{int}}_{Q_{cool/heat}},\tag{17}$$

where V [m³m⁻²] is indoor volume per building footprint area, T_{in} [K] is indoor air temperature, and Q_{cool/heat} [Wm⁻²] is cooling or heating demand as specified in Eqs. 14 and 15. More details on parameterization of the terms in Eq. 17 can be found in appendix A and by Bueno et al. (2012b)but are not reported here for brevity.

- A similar balance equation can be derived for latent heat to determine the time evolution of the indoor air specific humidity as well as the dehumidification load Q_{dehum} [Wm⁻²], which is parameterized in Bueno et al. (2012b)but is not detailed here for brevity. Note that energy consumption by gas combustion (e.g. cooking) Q_{gas} and water heating Q_{water} [both in Wm⁻²] does not influence indoor air temperature or specific humidity, but such energy consumption sources appear in the waste heat Eqs. 14 and 15. These terms are determined from schedules (Bueno et al., 2012b).
- 20 The building energy model is a single-zone model with respect to both the indoor and outdoor (urban canopy) environments. That is, only a single temperature is assumed for indoor air, and only a single potential temperature is assumed for outdoor air by integrating the potential temperature profile from the street to roof levels. Further, all wall temperatures are assumed to be uniform with height.

2.1.5 Radiation Model with Vegetation

In VCWG, there are two types of vegetation: ground vegetation cover and trees. Ground vegetation cover fraction is specified by δ_s [-]. Tree vegetation is specified by four parameters: tree height h_t [m], tree crown radius r_t [m], tree distance from canyon walls d_t [m], and Leaf Area Index (LAI) [m²m⁻²], which is the vertical integral of the Leaf Area Density (LAD) [m²m⁻³] profile. VCWG considers two trees spaced from the walls of the canyon with distance d_t [m]. Trees cannot by be higher than the building height. Both types of vegetation are specified with the same albedo α_V [-] and emissivity ε_V [-]. The VCWG user can change these input parameters for different vegetation structures. The radiation model in VCWG is adapted from the model developed by Meili et al. (2020). The net all-wave radiation flux is the sum of the net shortwave and longwave radiation fluxes

$$R_n = S^{\downarrow} - S^{\uparrow} + L^{\downarrow} - L^{\uparrow}, \tag{18}$$

where S[↓], S[↑], L[↓], and L[↑] [all in Wm⁻²] represent the incoming shortwave, outgoing shortwave, incoming longwave, and
outging longwave radiation fluxes. The incoming shortwave radiation fluxes (direct and diffuse) and the longwave radiation flux from the sky are forced by the EPW file. The absorbed (net) shortwave radiation on surface i is given by

$$S_{n,i} = (1 - \alpha_i) \left(S_i^{\downarrow} \right) = (1 - \alpha_i) \left(S_i^{\downarrow direct} + S_i^{\downarrow diffuse} \right), \tag{19}$$

where α_i is the albedo of the surface and $S_i^{\downarrow \text{diffuse}}$ [Wm⁻²] are the direct and diffuse incoming shortwave radiation fluxes to surface i. Here i can be S, G, V, W, or T for sky, ground, ground vegetation, wall, and tree. The amount of direct shortwave radiation received by each urban surface is calculated considering shade effects according to well-established methodologies for the case with no trees (Masson, 2000; Kusaka et al., 2001; Wang et al., 2018) and with trees (Ryu et al., 2016). Sky view factors are used to determine the amount of diffuse shortwave radiation that reaches a surface from the sky. Infinite reflections of diffuse shortwave radiation are calculated within the urban canyon with the use of view factors for each

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$$L_{n,i} = \varepsilon_i \left(L_i^{\downarrow} - \sigma T_i^4 \right),$$
 (20)

pair of urban surfaces (Wang, 2010, 2014). The absorbed (net) longwave radiation for each surface is calculated by

where ε_i [-] is the emissivity of the surface, $(1-\varepsilon_i)$ [-] is the reflectivity of the surface, L_i^{\downarrow} [Wm⁻²] is the incoming longwave radiation flux, $\sigma = 5.67 \times 10^{-8}$ Wm⁻²K⁻⁴ is the Stefan Boltzmann constant, and T_i [K] is the surface temperature. Infinite reflections of longwave radiation within the urban canyon are considered with the use of reciprocal view factors. These view factors are derived analytically for the case with no trees (Masson, 2000; Lee and Park, 2008; Wang et al., 2013). If trees are present, the view factors are calculated with a simplified two-dimensional Monte Carlo ray-tracing algorithm (Wang, 2014;

20 present, the view factors are calculated with a simplified two-dimensional Monte Carlo ray-tracing algorithm (Wang, 2014; Frank et al., 2016). More details about the radiation model are provided in appendix A and by Meili et al. (2020)but are not reported here for brevity.

2.2 Experimental Field CampaignCampaigns

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To evaluate the model, VCWG's predictions are compared to observation of observations from the Basel UrBan Bound-25 ary Layer Experiment (BUBBLE) microclimate field campaign (Christen and Vogt, 2004; Rotach et al., 2005)for two weeks starting 21 June (Christen and Vogt, 2004; Rotach et al., 2005), which was conducted for eight months from December 2001 to July 2002. The model predictions of air temperature, wind speed, and specific humidity are compared to the observations. The urban microclimate urban micro-climate field measurements were conducted in Basel, Switzerland, a typical quasi twodimensional urban canyon (47.55°N and 7.58°E). An EPW file is used to force the VCWG simulations with rural measurements.

30 The rural measurements are conducted at correspond to a site 7 km south-east of the city (47.53°N and 7.67°E concurrent with the urban measurements). The average building height for the urban area is $H_{avg}=14.6$ m, and the plan area density is $\lambda_p=0.54$

[-]. The urban canyon axis is oriented in the northeast-southwest direction with canyon axis angle of $\theta_{can} = 65 = 65^{\circ}$. The x and y directions are set to be cross- and the along-canyon, respectively. The frontal area density is $\lambda_f = 0.37$ [-]. In BUBBLE, wind speed was measured at elevations z = 3.6, 11.3, 14.7, 17.9, 22.4, and 31.7 m a.g.l.; potential temperature was measured at elevations z = 2.6, 13.9, 17.5, 21.5, 25.5, and 31.2 m a.g.l.; and relative humidity was measured at elevations z = 2.6 and 25.5 m -a.g.l. The dataset provides the measurements averaged every 10 min.

3 Conclusions and Future Work

The Vertical City Weather Generator (VCWG) is an urban microelimate model designed to calculate vertical profiles of meteorological variables including potential. The model predictions of air temperature, wind speed, specific humidity, and turbulence kinetic energy in an urban area. The VCWG is composed of four sub-models for ingestion of urban parameters and meteorological variables in a rural area (as input and boundary conditions) and prediction of the meteorological variables in a

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nearby urban area and specific humidity are compared to the observations on an hourly basis.

3 Results and Discussion

In this section, first the VCWG model results are evaluated against micro-climate field measurements. Next, the model performance is explored by various parametric simulations. A uniform Cartesian grid with 2 m vertical resolution is used.

- 15 The flow is assumed to be pressure-driven with the pressure gradient of ρu²_{*}/H_{top} [kgm⁻²s⁻²], which is decomposed into the x and y directions based on the wind angle. In this equation, the adjustment for wind angle is made based on canyon orientation and the incoming wind angle at the top of the domain. This pressure gradient is forced as source terms on the momentum Eqs. 8 and 9. The boundary condition for potential temperature and humidity equations (Eqs. 12 and 16) are determined from the rural model (see Fig. 1). Thus, the VCWG is aimed to calculate momentum and energy exchanges for the centre of each cell
- 20 in the vertical direction based on the boundary conditions obtained from the rural model, the building energy model, and the radiation model.

3.1 Detailed Model-Observation Comparison

3.1.1 Model Input Variables

The results of the VCWG are compared to the measured data from the BUBBLE campaign. The input parameters representing
the urban area are listed in Table 1. The input parameters are inferred from variables, datasets, and simulation codes in the literature that pertain to the BUBBLE campaign and associated models as well as general assumptions found in the literature (Raupach et al., 1991; Garratt, 1994; Hanna and Britter, 2002; Christen and Vogt, 2004; Järvi et al., 2011; Bueno et al., 2012a; Faroux et a . In this table, note that the choices of average building height H_{avg}=14.6 [m], street width w=18.2 [m], and building width to street width ratio b/w=1.1 [-] provide λ_p=b/(w+b)=0.52 [-] and λ_f=H_{avg}/(w+b)=0.38 [-], which are remarkably

30 close to morphometric variables reported by Christen and Vogt (2004). The simulations are conducted for eight months from

December 2001 to July 2002. Usually the first 24 hours of each month are treated as the model spin-up period. For analysis of each month, the simulation time is approximately 1 min, however it can vary slightly depending on the grid spacing and time step.

3.1.2 Potential Temperature

- 5 To compare VCWG results with measured meteorological variables from the BUBBLE campaign, the BIAS, Root Mean Square Error (RMSE), and coefficient of determination R² are computed for pairs of model versus observed values every hour for available altitudes and months. This analysis is performed for wind speed, potential temperature, and specific humidity. Figure 3 and Table 2 show the scatter plots of the observed versus simulated values of potential temperature as well as the statistical metrics used for the comparison. Over all altitudes and months, on average, the BIAS, RMSE, and R² for potential
- 10 temperature are 0.25 K, 1.41 K, and 0.82, respectively. These statistics are comparable to what has been reported in the literature for similar models that were compared against observations. For instance, Lauwaet et al. (2016) reported BIAS, RMSE, and the short and longwave radiation transfer processes. VCWG combines elements of several previous models developed by Santiago and Martilli (2010), Bueno et al. (2014), Krayenhoff (2014), Krayenhoff et al. (2015), R² of 0.76 K, 1.32 K, and 0.88, respectively, near ground by comparing model and observation values in a summer. Meili et al. (2020)
- 15 reported BIAS, RMSE, and R² of -0.1 K, 2.2 K, and 0.98, respectively, near ground by comparing model and observation values in a full year. Mussetti et al. (2020) reported BIAS, RMSE, and R² of 0.40 K, 1.53 K, and 0.95, respectively, near ground by comparing model and observation values in a summer. Ryu et al. (2016) reported BIAS and RMSE of 0.67 K and Meili et al. (2020) to generate a model with the ability to predict vertical profiles of urban meteorological variables, forced by rural measurements, 0.99 K, respectively, near ground by comparing model and observation values in a summer.
- 20 Bueno et al. (2012a) reports average BIAS and RMSE of 0.6 K and with two-way coupling with both building energy and radiation models. 0.9 K near the ground for June 2002. VCWG predicts the BIAS, RMSE, and R² of -0.1 K, 0.72 K, and 0.95, respectively, near the ground. This comparison reveals that the BIAS and RMSE are improved compared to the predecessor UWG model.

To evaluate VCWG, its predictions

- 25 Figure 4 shows the diurnal variation of the observed versus simulated values of potential temperature averaged for every hour of the day for the available months. The diurnal patterns in temperature reveal that the model has a similar level of success in predicting the potential temperature at all hours in lower elevations (z=3.6 to 14.7 m). This performance is comparable to other models that show a well-behaved diurnal variation of potential temperature at low altitudes (Bueno et al., 2012a; Krayenhoff et al., 2020; M . However the diurnal pattern in temperature can deviate between the model and observations at higher elevations (z=17.9 to
- 30 31.7 m), especially during midday hours. This can be attributed to more complex flow patterns in the above-roof-level space due to heat advection, horizontal heterogeneity of the urban site, and the above-roof-level shear layer.

3.1.3 Wind Speed

Table 1. List of input parameters used in VCWG for model evaluation; input variables are extracted from assumptions, datasets,and simulation codes available from Raupach et al. (1991), Garratt (1994), Hanna and Britter (2002), Christen and Vogt (2004), Järvi et al. (2011) Bueno et al. (2012a), Faroux et al. (2013), Ryu et al. (2016), Yang et al. (2017), Meili et al. (2020), andMussetti et al. (2020).

Parameter	Source	Symbol	Value
Latitude [°N]	Christen and Vogt (2004)	lat .	47.55
Longitude [°E]	Christen and Vogt (2004)		7.58
Average buildings height [m]	Christen and Vogt (2004)	Havg	14.6
Width of canyon [m]	Christen and Vogt (2004)	$W_{x} = W_{y} = W$	18.2
Building width to canyon width ratio [-]	Christen and Vogt (2004)	$D_{x}/W_{x} = D_{y}/W_{y} = D/W$	1.1
Leaf Area Index [m ² m ⁻²]	Faroux et al. (2013), Yang et al. (2017), Mussetti et al. (2020)		0-1~
Tree height [m]	Ryu et al. (2016)	h_t	8~
Tree crown radius [m]	Ryu et al. (2016)	rt	2.5
Tree distance from wall [m]	Ryu et al. (2016)	dt	$\frac{3}{\sim}$
Ground vegetation cover fraction	<u>Ryu et al. (2016)</u>	δ_{s}	$\overset{0}{\sim}$
Building type	Christen and Vogt (2004), Prome et al. (2012a)	~	Mid rise apartment
Urban albedos (roof, ground, wall, vegetation)	Bueno et al. (2012a) Bueno et al. (2012a), Ryu et al. (2016)	$lpha_{ m R}, lpha_{ m G}, lpha_{ m W}, lpha_{ m V}$	0.15, the building energy performance variables, 0.15, 0.15, 0.2
Urban emissivities (roof, ground, wall, vegetation)	Bueno et al. (2012a), Ryu et al. (2016)	$\varepsilon_{\rm R}, \varepsilon_{\rm G}, \varepsilon_{\rm W}, \varepsilon_{\rm V}$	~~ 0.95, 0.95, 0.95, 0.95
Rural overall albedo	Bueno et al. (2012a)	$lpha_{ m rur}$	0.2
Rural overall emissivity	Bueno et al. (2012a)	$\varepsilon_{ m rur}$	0.95
Rural aerodynamic roughness length [m]	Raupach et al. (1991), Bueno et al. (2012a)	$z_{0rur}=0.1h_{rur}$	0.2
Rural roughness length for temperature [m]	Garratt (1994), Meili et al. (2020)	$z_{\overline{\Theta},rur} = 0.1 z_{0rur}$	0.02
Rural roughness length for specific humidity [m]	Järvi et al. (2011). Meili et al. (2020)	$z_{\overline{Q},rur}=0.1z_{0rur}$	0.02
Rural zero displacement height [m]	Hanna and Britter (2002)	d _{rur} =0.5h _{rur}	1
Rural Bown ratio [-]	17 Christen and Vogt (2004)	$\beta_{\rm rur}$	0.9
Ground aerodynamic roughness length [m]	Bueno et al. (2012a)	z_{0G}	0.02



Figure 3. Scatter plots of observed (BUBBLE) versus simulated (VCWG) values of potential temperature for different altitudes and months; each data point corresponds to a 1-hour comparison between the model and observation.

Figure 5 and Table 3 show the scatter plots of the observed versus simulated values of wind speed as well as the statistical metrics used for the comparison. Considering all altitudes and months, the average BIAS, RMSE, and R^2 are 0.67 ms⁻¹, 1.06 ms⁻¹, and 0.41, respectively. Although the comparison reveals a reasonable BIAS and RMSE, the R^2 is lower than values reported for comparisons of potential temperature and specific humidity. This can be explained by the fact that the urban

- 5 morphology is highly heterogeneous, the measurement of wind is location specific, and that the wind speed and direction can change considerably within each hour. Heterogeneous urban morphology results in great spatial variability of the components of wind velocity vector as a function of wind direction and wind speed (Klein and Clark, 2007; Klein and Galvez, 2015; Afshari and Ramire . On the other hand, forced by hourly rural measurements, VCWG assumes a regular urban morphology and predicts the volume-averaged horizontal wind velocity components. So it is expected to obtain lower R² values. Other models also often
- 10 report lower R² values for wind speed compared to potential temperature and specific humidity (Mussetti et al., 2020). Overall our BIAS, RMSE, and R² values are in agreement with values reported in the literature. For instance, Lemonsu et al. (2012) reported a range in BIAS of -0.16 to 0.56 ms⁻¹. They also reported a range in RMSE of 0.40 to 0.69 ms⁻¹. Mussetti et al. (2020) reported the BIAS, RMSE, and R² of 0.61 ms⁻¹, wind speed 1.31 ms⁻¹, and 0.70, respectively.

3.1.4 Specific Humidity

Table 2. BIAS [K], RMSE [K], and R^2 [-] for VCWG predictions of potential temperature against the BUBBLE observations for different altitudes and months.

Altitude z [m]	Statistic	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	July	Average
3.6	BIAS [K]	0.35	0.16	0.58	0.25	0.78	0.81	-0.1	-0.25	0.32
	RMSE [K]	1.10	1.02	1.78	1.90	1.72	1.59	0.72	0.90	1.34
	\mathbf{R}^2	0.97	0.70	0.80	0.72	0.62	0.89	0.95	0.88	0.82
	BIAS [K]	0.11	-0.19	0.60	0.23	0.50	0.87	-0.22	-0.23	0.21
11.3	RMSE [K]	1.07	1.17	1.7	1.84	1.59	1.34	0.79	0.96	1.31
	\mathbf{R}^2	0.97	0.68	0.81	0.69	0.68	0.90	0.93	0.86	0.81
	BIAS [K]	0.20	-0.22	0.70	0.34	0.57	1.03	-0.12	-0.16	0.29
14.7	RMSE [K]	1.16	1.25	1.78	1.84	1.57	1.33	0.97	1.11	1.38
	\mathbf{R}^2	0.96	0.66	0.81	0.70	0.71	0.89	0.92	0.87	0.82
	BIAS [K]	0.26	-0.21	0.75	0.36	0.55	0.99	-0.35	-0.35	0.25
17.9	RMSE [K]	1.19	1.27	1.82	1.85	1.54	1.30	1.14	1.31	1.43
	\mathbf{R}^2	0.96	0.68	0.81	0.69	0.73	0.90	0.93	0.86	0.82
	BIAS [K]	0.29	-0.22	0.77	0.38	0.56	0.99	-0.45	-0.42	0.24
22.4	RMSE [K]	1.20	1.30	1.85	1.88	1.50	1.30	1.29	1.49	1.48
	\mathbf{R}^2	0.96	0.68	0.81	0.68	0.74	0.90	0.93	<u>0.86</u>	0.82
31.7	BIAS [K]	0.28	-0.28	0.78	0.37	0.58	0.95	-0.64	-0.57	0.18
	RMSE [K]	1.17	1.35	1.87	1.90	1.52	1.31	1.43	1.69	1.53
	R^2	0.96	0.67	0.81	0.65	0.68	0.89	0.93	.0.84	0.81
Average	BIAS [K]	0.25	-0.16	0.70	0.32	0.59	0.94	-0.31	-0.33	0.25
	RMSE [K]	1.15	1.23	1.8	1.87	1.57	1.36	1.06	1.24	1.41
	\mathbf{R}^2	0.96	0.68	0.81	0.69	0.69	0.90	0.93	0.86	0.82

Figure 6 and Table 4 show the scatter plots of the observed versus simulated values of specific humidity as well as the statistical metrics used for the comparison. Note that specific humidity data were only available in June-July 2002. Over all altitudes and the available months, on average, the BIAS, RMSE, and R² for specific humidity are compared to observation of the Basel UrBan Boundary Layer Experiment (BUBBLE) microclimate field campaign for two weeks starting 21 June 2002

5 (Christen and Vogt, 2004; Rotach et al., 2005). The results obtained from VCWG agree reasonably well with the measurements. The averageBIAS and RMSEfor wind speed, temperature, and specific humidity are -0.20 ± 0.50 , $+0.11 \pm 1.73$, and $+0.0011 \pm 0.0016 \pm 0.00057$ kgkg⁻¹, 0.0010 kgkg⁻¹, and 0.85, respectively. The temperature BIASis improved compared to the predecessor UWG model (-0.6 K (Bueno et al., 2012a)) These statistics are comparable to what has been reported in the literature for similar models that were compared against observations. For instance, Mussetti et al. (2020) reported BIAS,

10 <u>RMSE</u>, and R^2 of -0.00109 kgkg⁻¹, 0.00152 kgkg⁻¹, and 0.74, respectively, above the urban canopy for comparisons of



Figure 4. Comparison between the observed (BUBBLE) versus simulated (VCWG) values of potential temperature; the hourly means are shown; nighttime indicated with shaded regions; solid line: model and dashed line: observation; times in Local Standard Time (LST).

model and observations in summer. Lemonsu et al. (2012) reported a range in BIAS of -0.00116 to -0.0005 kgkg⁻¹. They also reported a range in RMSE of 0.00081 to 0.00172 kgkg⁻¹. VCWG-predicted mean and standard deviation

Figure 7 shows the diurnal variation of the observed versus simulated values of specific humidity averaged for every hour of the day for June-July 2002. While the diurnal variation is predicted by the model, some deviations are noted between the model

5 and the observation. The model over predicts the observations at night, while it under predicts the observations during mid day, especially at z=25.5 m. This could be due to the assumptions of the rural model to generate the vertical profile of specific humidity. In this model the latent heat flux in the rural area is parameterized as a function of the sensible heat flux and a fixed Bowen ratio. However, the Bowen ratio can vary diurnally (Kalanda et al., 1979). This can result in a slight miscalculation of the latent heat flux and a forcing boundary condition for specific humidity on top of the modeling domain.

10 3.1.5 Urban Heat Island (UHI)



Figure 5. Scatter plots of observed (BUBBLE) versus simulated (VCWG) values of wind speed for different altitudes and months; each data point corresponds to a 1-hour comparison between the model and observation.



Figure 6. Scatter plots of observed (BUBBLE) versus simulated (VCWG) values of specific humidity for different altitudes and months; each data point corresponds to a 1-hour comparison between the model and observation.

Altitude z [m]	Statistic	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	July	Average
	$\underset{}{\underline{BIAS}}[\mathrm{ms}^{-1}]$	-0.5	-0.6	-0.59	-0.49	-0.59	-0.40	-0.51	-0.49	-0.52
3.6	$\underbrace{RMSE}_{[\mathrm{ms}^{-1}]}$	0.41	0.49	0.46	0.41	0.47	0.33	0.40	0.40	0.42
	\mathbb{R}^2	0.55	0.19	0.59	0.47	0.32	0.07	0.43	0.34	0.37
	$\underset{\text{WMS}}{\text{BIAS}} [\text{ms}^{-1}]$	-0.24	-0.35	-0.43	-0.24	-0.28	-0.38	-0.17	-0.18	-0.28
11.3	<u>RMSE [ms⁻¹]</u>	0.22	0.27	0.38	0.21	0.23	0.35	0.18	0.18	0.25
	\mathbb{R}^2	0.55	0.26	0.44	0.5	0.43	0.39	0.29	0.35	0.4
	$\underbrace{\text{BIAS}}_{\text{MAS}} [\text{ms}^{-1}]$	0.69	0.43	0.83	0.55	0.54	0.48	0.88	0.87	0.66
14.7	<u>RMSE [ms⁻¹]</u>	0.53	0.36	0.74	0.46	0.47	0.37	0.74	0.79	0.56
	\mathbb{R}^2	0.5	0.29	0.56	0.56	0.47	0.08	0.43	0.48	0.42
	$\underset{\text{BIAS}}{\text{BIAS}} [\text{ms}^{-1}]$	0.99	0.65	1.27	0.73	0.72	0.73	1.13	1.15	0.92
17.9	<u>RMSE [ms⁻¹]</u>	0.73	0.56	1.00	0.64	0.63	0.67	0.97	1.08	0.79
	\mathbb{R}^2	0.56	0.30	0.52	0.58	0.4	0.21	0.43	0.51	0.44
	$\underset{\text{WAS}}{\text{BIAS}} [\text{ms}^{-1}]$	1.7	0.94	2.3	1.2	1.25	1.23	1.96	1.93	1.56
22.4	$\underbrace{\mathbf{RMSE}[\mathrm{ms}^{-1}]}$	1.27	0.82	1.83	0.97	0.99	1.03	1.67	1.69	1.29
	\mathbb{R}^2	0.51	0.38	0.54	0.52	0.50	0.28	0.4	0.46	0.45
	$\underset{\text{WAS}}{\text{BIAS}} [\text{ms}^{-1}]$	1.96	0.98	2.63	1.24	1.24	1.39	2.10	2.08	1.70
31.7	$\underbrace{\mathbf{RMSE}[\mathrm{ms}^{-1}]}$	1.50	0.95	2.11	1.18	1.09	1.30	1.78	1.85	1.47
	R^2	<u>0.47</u>	<u>0.14</u>	0.58	0.49	<u>0.41</u>	<u>0.17</u>	0.51	.0.47	0.41
	$\underline{BIAS} [\mathrm{ms}^{-1}]$	0.77	0.34	1.00	0.50	0.48	0.51	<u>0.90</u>	0.89	0.67
Average	RMSE [ms ⁻¹]	0.78	0.58	1.09	0.64	0.65	0.68	0.96	1.00	1.06
	\mathbb{R}^2	0.52	0.26	0.54	0.52	0.42	0.20	0.42	0.43	0.41

Table 3. BIAS $[ms^{-1}]$, RMSE $[ms^{-1}]$, and R^2 [-] for VCWG predictions of wind speed against the BUBBLE observations for different altitudes and months.

To compare VCWG results with measured UHI [K] from the BUBBLE campaign, the BIAS, RMSE, and \mathbb{R}^2 are computed for pairs of hourly model versus observed values for the available months. UHI [K] for the observation is computed by considering the difference between the temperature measurements inside the canyon at z = 3.6 m and those temperatures provided by the EPW dataset. For VCWG, UHI [K] is calculated by considering the difference between the temperature prediction inside the canyon at z = 3 m and those temperatures provided by the EPW dataset. Figure 8 and Table 5 show the diurnal variation

- 5 canyon at z = 3 m and those temperatures provided by the EPW dataset. Figure 8 and Table 5 show the diurnal variation of UHI (for both observations and simulations) as well as the statistical metrics used for the comparison. On average, the BIAS, RMSE, and R² for UHI are +1.59 and 1.46[K] are 0.36 K, respectively, in reasonable agreement with observations reporting a mean and standard deviation for 1.2 K, and 0.35, respectively. VCWG predictions of UHI of +1.72 and 0.91 [K] are more successful for months of December, January, April, May, June, and July (R² > 0.3) than for months of February and
- 10 March ($R^2 < 0.2$). The deviations in predicting UHI [K] may be attributed to several factors. The heterogeneity of the urban

Table 4. BLAS $[kgkg^{-1}]$, RMSE $[kgkg^{-1}]$, and R^2 [-] for VCWG predictions of specific humidity against the BUBBLE observations for different altitudes and months.

Altitude z [m]	Statistic	Jun.	July	Average	
	$\underset{\text{BIAS}}{\text{BIAS}} [\text{kgkg}^{-1}]$	0.00081	0.00056	0.00069	
2.6	$\underbrace{RMSE}_{W}[\mathrm{kgkg}^{-1}]$	0.0012	0.00086	0.0010	
	\mathbf{R}^2	0.86	0.84	0.85	
25.5	$\underset{\text{CMAS}}{\text{BIAS}} [\text{kgkg}^{-1}]$	0.00049	0.00042	0.00045	
	$\underbrace{RMSE}_{Kgkg^{-1}}$	0.0014	0.00074	0.0010	
	\mathbf{R}^2	0.84	0.86	0.85	
	$\underset{\text{CMAS}}{\text{BIAS}} [\text{kgkg}^{-1}]$	0.00065	0.00049	0.00057	
Average	$\underbrace{RMSE}_{Kgkg^{-1}}$	0.0013	0.0008	0.0010	
	R^2	0.85	0.85	0.85	



Figure 7. Comparison between the observed (BUBBLE) versus simulated (VCWG) values of specific humidity; the hourly means are shown; nighttime indicated with shaded regions; solid line: model and dashed line: observation; times in Local Standard Time (LST).

Table 5. BIAS [K], RMSE [K], and R² [-] for VCWG predictions of UHI [K] against the BUBBLE observations for different months.

Statistic	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	July	Average
BIAS [K]	0.35	0.16	0.58	0.25	0.78	0.81	-0.1	0.06	0.36
RMSE [K]	1.04	0.92	1.63	1.72	1.48	1.42	0.66	0.57	1.2
\mathbb{R}^2	0.32	0.37	0.16	0.12	0.50	0.51	0.37	0.47	0.35

environment and placement of urban sensors may result in sensing slightly warmer or colder temperatures than the spatial average due to the spatial variability of temperature (Mussetti et al., 2020). Also the relative position of the rural site with respect to the urban site, variation of dominant wind directions over different seasons, and horizontal advective transport of heat from the rural area may confound the prediction of UHI. Given that VCWG does not consider all such variations due

5 to simplifying assumptions, it is expected to predict different values of UHI [K] over different seasons in comparison to the observations. Nevertheless, overall, the statistics of UHI [K] comparison are in reasonable agreement with those reported by other models. For example, Mussetti et al. (2020) reported BIAS, RMSE, and R² values of -1.88 K, respectively1.66 K, and 0.55, respectively, for near-ground predictions of UHI [K] in the summer.
The prefermance

The performance

10 3.2 Model Exploration and Comparison with Limited UHI Observations

In this section we explore the capability of the VCWG is further assessed by conducting several types of explorations for model to predict urban climate for investigations of the effects of building dimensions, urban vegetation, building energy configuration, radiation configuration, seasonal variations, and other climates. These results are reported in the supplementary material in detail. Here only brief references to the analysis are made. Many explorations consider both nighttime and daytime

- 15 urban microclimatemicro-climate. First, we investigate how the urban geometry, which is characterized by plan area density λ_p [-] and frontal area density λ_f [-], can affect the urban microclimatemicro-climate. An increase in λ_p from 0.46 to 0.54 [-] is associated with lower air temperatures (due to shading) and reduces wind speeds speed within the urban canyon during daytime - A configuration with higher (see Fig. S1). An increase in λ_f from 0.37 to 0.51 [-] also increases shading effects and consequently reduces daytime temperatures, but it increases nighttime temperatures due to more heat released from urban
- surfaces that is trapped in the canyon -(see Fig. S2). The cooling effect of the urban vegetation is also evaluated by changing the Leaf Area Density (LAD [m²m⁻³]) profiles within the canyon. Increasing the average LAD from 0.1 to 0.2 [m²m⁻³] shows heat removal from the canyon alongside with lower wind speeds speed due to the drag induced by trees The VCWG is also run (see Fig. S3). VCWG simulations are also conducted for different building types (a mid-rise apartment and a hospital), cooling system Coefficient of Performance (COP)-[-], and heating thermal efficiency (η_{heat} [-]), and location of building waste heat
- 25 release F_{st} . The results show that a hospital generates more waste heat fluxes associated with cooling and gas consumption, which increase urban temperatures - (see Fig. S4). The analysis of different cooling systems also reveal and heating systems also reveals that less-efficient systems (lower COP from 3.13 to 1 [-] and η_{heat} from 0.8 to 0.4 [-]) result in more



Figure 8. Hourly mean and standard deviation (band) of UHI [K] in each month for the observed (BUBBLE) and predicted (VCWG) values; nighttime indicated with shaded regions; times in Local Standard Time (LST).

waste heat emission and slightly higher temperatures –(see Fig. S5). It is found that releasing building waste heat at street level contributes to a higher UHI [K], by 1 K, than releasing the waste heat at roof level (see Fig. S6). This can be due to more effective heat removal from the urban roughness sublayer when the heat is released at roof level. The radiation model is assessed by running the VCWG VCWG simulations for different canyon aspect ratios and axis angles. The radiation fluxes at

- 5 the road and walls show differences according to canyon aspect ratio and axis angle, while the fluxes at the tree canopy and roof are less sensitive to the canyon aspect ratio and axis angle . Another exploration made for all months of the year (see Figs. S7 and S8). VCWG is also evaluated against the observations of Runnalls and Oke (2000) in Vancouver, Canada, justifies the ability of the VCWG to predict the urban microclimate in different seasons. The results show the expected diurnal variation of in the urban site. Also for a period from 1991 to 1994, for daily maximum and minimum UHI [K] values are in agreement with
- 10 observations of Runnalls and Oke (2000) over an entire year. The average BIAS and RMSE, RMSE, and R^2 for daily maximum and minimum UHI [K] are -0.5 K, and 0.45 K, respectively. The and 0.97, respectively (see Figs. S9 and S10). Seasonal variations of the vertical profiles of potential temperature, wind speed, specific humidity, and turbulence kinetic energy reveal that the seasonal variations in potential temperature and specific humidity are higher than those associated with wind speed and turbulence kinetic energy (see Fig. S11). Finally, the ability of the model to predict UHI ranging from diurnally-averaged values
- 15 of 1.00 to 1.78 [K] in different cities with different climate zones is assessed. The case studies are Buenos Aires, Vancouver, Osaka, and Copenhagen (see Fig. S12). All exploration results obtained from the VCWG are reasonably consistent with the previous observations in the literature.

In this study, it is shown-

4 Conclusions and Future Work

20 The Vertical City Weather Generator (VCWG) is an urban micro-climate model designed to calculate vertical profiles of meteorological variables including potential temperature, wind speed, specific humidity, and turbulence kinetic energy in an urban area. The VCWG is composed of four sub-models for ingestion of urban parameters and meteorological variables in a rural area (as input and boundary conditions) and prediction of the meteorological variables in a nearby urban area, the building energy performance variables, and the short and longwave radiation transfer processes. VCWG combines elements of several previous models developed by Santiago and Martilli (2010), Bueno et al. (2014), Krayenhoff (2014), Krayenhoff et al. (2015), and Meili et al. (2020) to generate a model with the ability to predict vertical profiles of urban meteorological variables, forced

by rural measurements, and with two-way coupling with both building energy and radiation models.

To evaluate VCWG, its predictions of potential temperature, wind speed, and specific humidity are compared to observation of the Basel UrBan Boundary Layer Experiment (BUBBLE) micro-climate field campaign for eight months from December

30 2001 to July 2002 (Christen and Vogt, 2004; Rotach et al., 2005). The model evaluation indicates that the VCWG predicts vertical profiles of meteorological variables in reasonable agreement with field measurements. The average BIAS, RMSE, and R² for potential temperature are 0.25 K, 1.41 K, and 0.82, respectively. The average BIAS, RMSE, and R² for wind speed are 0.67 ms⁻¹, 1.06 ms⁻¹, and 0.41, respectively. The average BIAS, RMSE, and R² for specific humidity are 0.00057 kgkg⁻¹.

0.0010 kgkg⁻¹, and 0.85, respectively. In addition, the average BIAS, RMSE, and R² for Urban Heat Island (UHI) are 0.36 K, 1.2 K, and 0.35, respectively. Based on the evaluations, the model performance is comparable to the performance of similar models. The performance of the model is further explored to investigate the effects of urban configurations such as plan and frontal area densities, varying levels of vegetation, building energy configuration, radiation configuration, seasonal variations,

5 and different climate zones on the model predictions. The exploration results also show acceptable performance in agreement with known urban physical processes and observations.

This study shows that the urban microclimate micro-climate model VCWG can successfully extend the spatial dimension of the preexisting bulk flow (single-layer) urban microclimate micro-climate models to one-dimension in the vertical direction, while it also considers the relationship of the urban microclimate micro-climate model to the rural meteorological measure-

- 10 ments and the building energy conditions. The effect of the key urban elements such as building configuration, building energy systems , and vegetation (e.g. location of condensers and exhaust stacks), surface vegetation, and trees are considered, but there is still opportunity to improve VCWG further. The urban site is simplified as blocks of buildings with symmetric and regular dimensions, which can be more realistically represented if more considerations are to be taken into account about nonuniform distribution of building dimensions. Also the building energy model in VCWG is a single-zone model, assuming a uniform
- 15 temperature with height in both indoor and outdoor environments. This limitation can be overcome by improving the radiation model, urban vertical diffusion model, and the building energy model so that wall and indoor temperatures can vary with height, allowing the development of a multi-zone building energy model. In addition, the horizontal advection from the rural area can be considered and parameterized in future work. Future studies can also focus on improvement of flow-field parameterization or including additional source/sink terms in the transport equations to model horizontal motions, eddies, and flow fluctuations
- 20 in the urban area, which is realistically very three-dimensional and heterogeneous. Urban hydrology can be added to VCWG in the future to account for precipitation effects. At present, the developed VCWG model can account for the spatial variation of urban microclimate micro-climate in a computationally efficient manner independent of an auxiliary mesoscale meso-scale model. This advantage is really important for urban planners, architects, and consulting engineers, to run VCWG operationally fast for many projects for operationally-fast VCWG simulations.
- 25 Code and data availability. The VCWG v1.3.0 is developed at the Atmospheric Innovations Research (AIR) Laboratory at the University of Guelph: http://www.aaa-scientists.com. The source code is available under GPL 3.0 licence: https://opensource.org/licenses/GPL-3.0 (last access: October 2020) and can be downloaded from https://www.zenodo.org/ with DOI: 10.5281/zenodo.4255225.

Appendix A

A1 Surface Energy Balance in the Rural Area

In Eq. 7 the net shortwave solar radiation flux absorbed at the surface can be calculated from

$$Q_{S,rur} = ((1 - F_{veg})(1 - \alpha_{rur}) + F_{veg}(1 - \alpha_V))(S^{\downarrow direct} + S^{\downarrow diffuse}),$$
(A1)

5 where F_{veg} [-] is the fraction of the rural area covered by vegetation, α_{rur} [-] is overall albedo of the rural area, α_V [-] is the albedo of vegetation (here considered to be the same for rural and urban vegetation), and $S^{\downarrow direct}$ and $S^{\downarrow diffuse}$ [Wm⁻²] are the forcing direct and diffuse shortwave radiation fluxes from the EPW file, respectively. The net longwave solar radiation flux absorbed at the surface can be calculated from

$$Q_{L,rur} = L^{\downarrow} - L^{\uparrow} = \varepsilon_{rur} \left(L^{\downarrow} - \sigma T_{s,rur}^4 \right), \tag{A2}$$

10 where L^{\downarrow} [Wm⁻²] is the forcing longwave radiation flux from the EPW file, L^{\uparrow} [Wm⁻²] is the longwave radiation flux leaving the rural surface at temperature $T_{s,rur}$ [K], and ε_{rur} [-] is rural surface emissivity. The net sensible heat flux is calculated using Louis (1979)

$$Q_{sen,rur} = \rho C_p \frac{\kappa^2}{\left(\ln \frac{z}{z_{0rur}}\right)^2} \frac{1}{R} \overline{S}_{rur,z=10m} \left(\overline{\Theta}_{rur,s} - \overline{\Theta}_{rur,2m}\right) F_h\left(\frac{z}{z_{0rur}}, Ri_B\right),\tag{A3}$$

where R [-] is a model constant, Ri_B [-] is the bulk Richardson number, and F_h [-] is the stability function for sensible heat flux 15 defined by Louis (1979). The net latent heat flux is calculated using the Bowen ratio β_{rur} [-] such that $Q_{lat,rur}=Q_{sen,rur}/\beta_{rur}$ [Wm⁻²]. The ground heat flux drives the conduction equation at the upper most upper-most soil layer via (Bueno et al., 2012a)

$$dC_v \frac{dT_1}{dt} = C(T_2 - T_1) + Q_{grd},$$
(A4)

where d [m] is the soil layer thickness, C_v [Jm⁻³K⁻¹] is volumetric heat capacity of soil, T₁ = Θ_{rur,s} [k] is soil upper
layer temperature (the same as soil surface temperature), C [Wm⁻²K⁻¹] is the soil thermal conductance, and T₂ [K] is soil temperature in the second layer under ground. In the lowest layer (n) of soil the conduction equation is forced by a deep soil temperature T_{deep} [K]

$$dC_v \frac{dT_{n-1}}{dt} = C(T_{deep} - T_{n-1}).$$
(A5)

A2 Source/Sink Term in the 1-D Model

The pressure and skin drags exerted on the flow in Eqs. 8 and 9 are formulated as follows (Santiago and Martilli, 2010; Krayenhoff, 2014; Krayenhoff et al., 2015; Simón-Moral et al., 2017; Nazarian et al., 2020; Krayenhoff et al., 2020)

$$D_x = \underbrace{\frac{1}{\rho} \frac{\partial \tilde{P}}{\partial x}}_{II} + \underbrace{\nu(\nabla^2 \tilde{U})}_{II},\tag{A6}$$

5
$$D_y = \underbrace{\frac{1}{\rho} \frac{\partial \tilde{P}}{\partial y}}_{I} + \underbrace{\nu(\nabla^2 \tilde{V})}_{II},$$
 (A7)

where term I represents dispersive pressure variation (form drag) induced by vegetation and building and term II represents the dispersive viscous dissipation (skin drag) induced by horizontal surfaces. The former can be parameterized as below-

$$\frac{1}{\rho}\frac{\partial P}{\partial x} = \left(B_D C_{DBv} + LAD\Omega C_{DV}\right)\overline{U}_{expl}\overline{U},\tag{A8}$$

$$\frac{1}{\rho}\frac{\partial P}{\partial y} = \left(B_D C_{DBv} + LAD\Omega C_{DV}\right)\overline{V}_{expl}\overline{V},\tag{A9}$$

10 where $B_D [m^{-1}]$ is sectional building area density, C_{DBv} [-] is sectional drag coefficient in the presence of trees, LAD $[m^2m^{-3}]$ is leaf area density in the canyon, Ω [-] is clumping factor, C_{DV} [-] is the drag coefficient for tree foliage, and \overline{U}_{expl} and $\overline{V}_{expl} [ms^{-1}]$ are wind velocity components in x and y directions from a previous numerical solution, respectively, which are assumed explicitly as constants to linearize the system of equations to be solved. The skin drag can be parameterized as follows

15
$$\nu(\nabla^2 \tilde{U}) = \frac{1}{\Delta z} c_d f_m \overline{U}_{expl} \overline{U},$$
 (A10)

$$\nu(\nabla^2 \tilde{V}) = \frac{1}{\Delta z} c_d f_m \overline{V}_{expl} \overline{V},\tag{A11}$$

where c_d [-] is skin drag coefficient and f_m [-] is a function of stability from Louis (1979).

The terms related to wake production S_{wake} and dissipation rate ε [both in $m^2 s^{-3}$] in Eq. 11 can be parameterized as

$$S_{wake} = \left(B_D C_{DBv} + LAD\Omega C_{DV}\right) \overline{U}_{expl}^3,\tag{A12}$$

20
$$\varepsilon = C_{\varepsilon} \frac{k^{\frac{3}{2}}}{\ell_{\varepsilon,dissip}},$$
 (A13)

where Ω [-] is clumping factor, C_{ε} [-] is a model constant and $\ell_{\varepsilon,\text{dissip}}$ [m] is a dissipation length scale obtained by sensitivity study using CFD (Nazarian et al., 2020). Note that plan area density λ_p [-] in this study is greater than the limit considered by Nazarian et al. (2020), so we assume that the parameterizations extrapolate to this value of λ_p [-].

The heat source/sink terms, terms in Eq. 12, caused by roof $(S_{\Theta R})$ and ground $(S_{\Theta G})$ [both in Ks⁻¹] are calculated based on 25 the study by Louis (1979) and the heat flux from the wall $(S_{\Theta W} [Ks^{-1}])$ is formulated in Martilli et al. (2002). The two other source/sink terms can be parameterized as below

$$S_{\Theta A} = \frac{4\rho_{abs}k_{air}}{\rho C_p v_L} \left[(1 - \lambda_p)L_A \right],$$

$$S_{\Theta V} = \frac{2g_{Ha}c_{PM}}{\rho C_p v_L} \left[LAD(1 - \lambda_p)(\overline{\Theta}_V - \overline{\Theta}) \right],$$
(A14)
(A15)

where L_A [Wm⁻²] is the absorbed flux density of longwave radiation in the canyon, ρ_{abs} [kgm⁻³] is the density of absorbing
molecules, k_{air} [m²kg⁻¹] is their mass extinction cross section, v_L=(1-λ_p) [-] is the fraction of total volume that is outdoor air, g_{Ha} [molm⁻²s⁻¹] is conductance for heat, c_{PM} [Jmol⁻¹K⁻¹] is the molar heat capacity for the air, and Θ_V [K] is the temperature of tree foliage.

In the specific humidity Eqn. 16, the source/sink term can be calculated using the following equation

$$S_{QV} = \frac{\Lambda_M g_v \Omega}{\rho \Lambda v_L} \left[LAD(1 - \lambda_p) \left(s[\overline{\Theta}_V - \overline{\Theta}] + \frac{D}{P} \right) \right]$$
(A16)

10 where Λ_M [Jmol⁻¹] is molar latent heat of vaporization, Λ [Jkg⁻¹] is latent heat of vaporization, g_v [molm⁻²s⁻¹] is the average surface and boundary-layer conductance for humidity for the whole leaf, s [K⁻¹] is derivative of saturation vapour pressure with respect to temperature divided by pressure, D [Pa] is the vapour deficit of the atmosphere, and P [Pa] is atmospheric pressure.

A3 Building Heat Exchanges

15 The heat fluxes in Eq. 17 can be parameterized as bellow-

$$Q_{surf} = \Sigma h_i A_i (T_{si} - T_{in}) \tag{A17}$$

$$Q_{inf} = \dot{m}_{inf}C_p(T_{out} - T_{in}) \tag{A18}$$

$$Q_{vent} = \dot{m}_{vent} C_p (T_{supp} - T_{in}) \tag{A19}$$

where $h_i [Wm^{-2}K^{-1}]$ is convective heat transfer coefficient (or u-value) for surface i and $A_i [m^2m^{-2}]$ is surface area for surface i per building foot print area. Surface i can correspond to indoor elements such as ceiling, walls, floor, building mass, and windows. $T_{si} [K]$ is the temperature of the inner layer of elements, $T_{in} [K]$ is indoor temperature, $T_{out} [K]$ is the outdoor temperature averaged over building height, $T_{supp} [K]$ is supply temperature, $\dot{m}_{inf} [kgs^{-1}m^{-2}]$ is mass flow rate of infiltration (exfiltration) per building footprint area, and $\dot{m}_{vent} [kgs^{-1}m^{-2}]$ is mass flow rate of ventilated air in the HVAC system per building footprint area.

25 A4 Radiation Model

A summary of details for the radiation model is provided here from Meili et al. (2020), while mathematical calculations are not provided here for brevity. The direct and diffuse shortwave radiation fluxes absorbed by each urban element are computed

as functions of urban canyon height, width, tree shape, and albedo. The urban geometry creates shading effects by blocking a portion of the incoming direct solar radiation flux. This flux is further decreased by the sky view factor, which reduces the incoming diffuse solar radiation flux and traps reflected solar rays within the canyon. Two steps are involved to calculate the net shortwave radiation flux: 1a) the direct shortwave radiation flux received by each urban element is calculated as a function

- 5 of the sun position and shading effects created by buildings and trees; 1b) the diffuse shortwave radiation received by each urban element is computed as a function of the corresponding sky view factor; 2) infinite radiation reflections within the urban canyon are calculated using view factors and the net shortwave radiation flux for each urban element is then calculated. All urban elements are assumed to be Lambertian with isotropic scattering and reflections. If there are no trees, the view factors are computed analytically. Otherwise a Monte Carlo ray tracing algorithm is used. No obstructions are considered for roofs,
- 10 i.e. trees cannot be taller than buildings. The model computes the net shortwave radiation flux due to both direct and diffuse radiation, allowing to investigate effects of shade and albedo in detail. The energy associated with the shortwave radiation exchange on each urban element is conserved.

For net longwave radiation flux on each urban surface, the difference between the incoming and outgoing longwave radiation fluxes are considered. These fluxes depend on surface temperatures. Infinite reflections of longwave radiation within the urban

15 canyon are considered. Again, no obstructions are considered for roofs, i.e. trees cannot be taller than buildings. The canyon air does not impact the radiation exchange. The energy associated with the longwave radiation exchange on each urban surface is conserved.

For the case of no trees, analytical view factors are calculated using standard equations (Masson, 2000; Lee and Park, 2008; Ryu et al., 2011; Wang et al., 2013), while for trees the method of Ryu et al. (2016) is used. View factors meet a set of three

- 20 requirements: 1) the self view factor of a flat surface is zero, 2) energy at the surface is conserved, and 3) view factors are reciprocal. The view factors for the case with trees are calculated using a Monte Carlo ray tracing algorithm (Wang, 2014; Frank et al., 2016). This algorithm performs a probabilistic sampling of all rays emitted by an urban element. The relative frequency of rays remitted emitted by one element that hit another element is an estimation of the view factor between the two elements. On each element, a large number of randomly distributed emitting points are considered. These view factors are also
- 25 corrected for the three requirements mentioned above.

30

Author contributions. MM wrote the paper with significant conceptual input from ESK and AAA and critical feedback from all co-authors. BB and LKN developed the base Urban Weather Generator (UWG) program in MATLAB. CM and SV translated UWG from MATLAB to Python. NN and ESK provided their code for the one-dimensional vertical diffusion model for the urban climate that was integrated into VCWG. MM and AAA developed the Vertical City Weather Generator (VCWG) program in Python by integrating various modeling components developed by BB, LKN, CM, SV, ESK, and NN. BD, AN, MKN, and MRN edited the manuscript.

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