Response to Reviewers

Note:

(1) In this response, the text in *italic type* is the original comments from the reviewers, and the text in blue, headed with "Reply", is the response from the authors.

(2) In the manuscript, the words in blue indicate the sentence is improved or revised. Some of them are mentioned in this response via the page and line number.

PART 1: Response to Reviewer #1

The authors show an excellent job of coupling an urban model to the VIC model to improve the capability of this global land surface model. The manuscript is well organized, with concrete results demonstrating the advantages of the VIC-urban model. I think it should be accepted after considering the following minor issues.

Reply: We thank the reviewer for the positive comments. The replies can be seen below.

1. The authors are suggested to give more information about the base map and urban maps. Did the authors update different urban maps during the study period? Because the study period was a time of high urbanization, the urban maps should have changed significantly over time.

Reply: Thanks. We have indeed updated the land cover maps and related parameters every five years during the 2005-2020 period. The land cover distribution maps used in this work are shown in Fig.1 below. Moreover, we employed Global LAnd Surface Satellite (GLASS) products to update parameters, including Leaf Area Index (LAI), downward shortwave radiation, Fraction of Vegetation Cover (FVC), and albedo, on a daily scale. This approach ensured the model to capture changes in land surface. **We added related statements and the fig in the manuscript. Please see L253-258 and Supplemental Figure 1.**

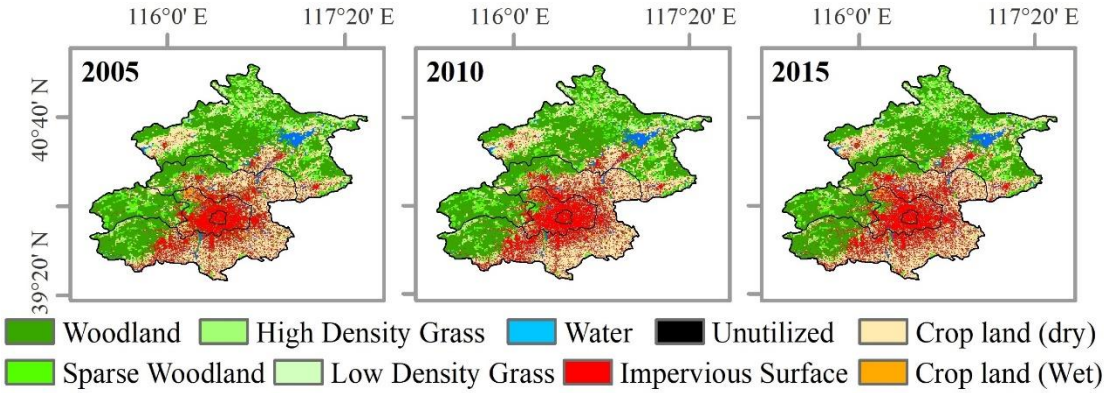

Fig. 1 Land cover maps during 2005-2020 period used in the study.

2. More details about the Beijing simulation are needed. What is the simulation resolution of the VIC model? The resolution of the various data used in the model is inconsistent, what methodology did the authors use to standardize the resolution.

Reply: Thanks. The spatial resolution and temporal resolution of the VIC model is 0.0625° and 3 hours. To ensure consistency, all input data were adjusted to match the 0.0625°/3h resolution through a linear interpolation. Additionally, we considered temperature changes according to elevation differences during the interpolation. **We elaborated on this process in more detail in the revised manuscript. Please see L261-263.**

3. It is better to show more details about the urban parameters, for example, the spatial distribution maps of the parameters of the urban model of Beijing.

Reply: Thanks for the suggestion. We made a figure to show the spatial distribution maps of the urban parameters of Beijing (Fig. 2 below). These maps will offer insights into the spatial variability of the parameters. It is important to note that we updated land cover maps and related parameters every five years (As mentioned in the Question 1), and Fig. 2 shows an example of urban parameters of 2015. The figure and related statements are added in the supplementary document. **We added related statements and the fig in the manuscript. Please see L241-242 and Supplemental Figure 2.**

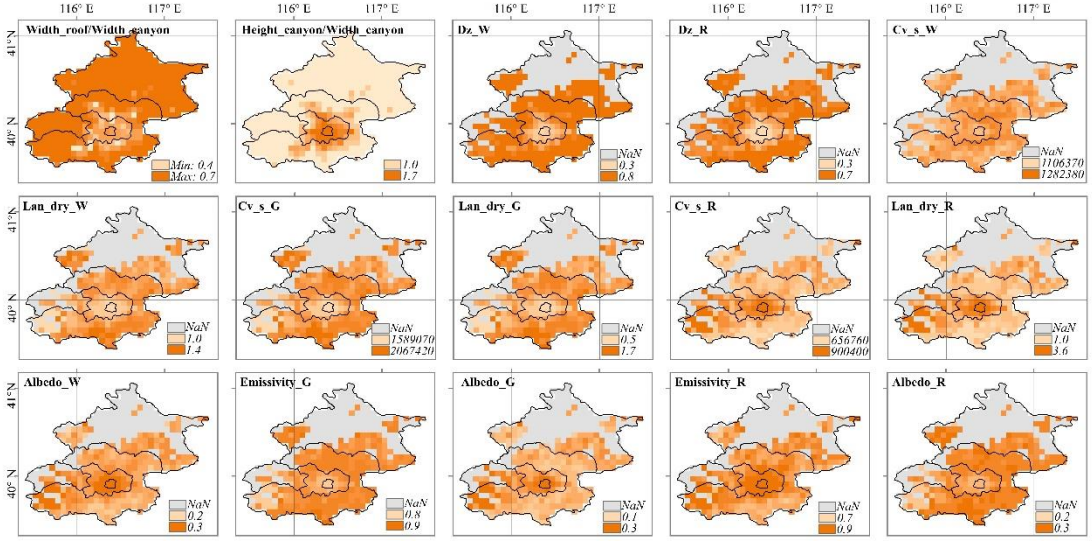

Fig. 2. The spatial distribution maps of the urban parameters used in our work, using urban parameters in 2015 as an example.

4.For figure 6 and table 3, can the authors show the results in daily scale?

Reply: We made a new figure and table to show the results in daily scale (Fig. 3 and Table 1). However, we kept the monthly scale results in the manuscript due to the slight differences observed between the daily and monthly scales. Moreover, adopting the daily scale tends to artificially inflate *R* values.

It is worth noting that the urban parameters of VIC-urban model are calibrated based on the MODIS land surface temperature (LST), not the LST values of these 14 sites. The figures are used to highlight the better performance of VIC-urban over VIC.

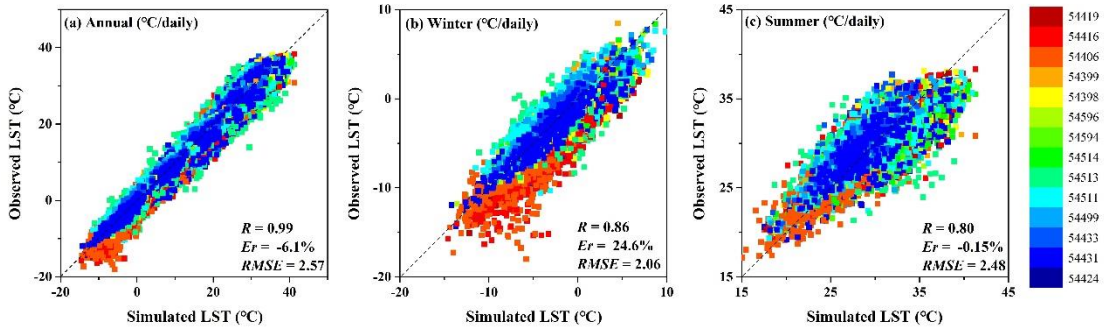

Fig. 3 Daily simulated LST validated against 14 ground-based observation stations, which are marked in different colours.

Table 1. The simulated LSTs from VIC-urban and VIC-orig models are validated by 14 ground-based observations in daily scale.

Station	***Er (%)***		***R***		***RMSE***	
	VIC-urban	**VIC-orig**	**VIC-urban**	**VIC-orig**	**VIC-urban**	**VIC-orig**
54419	-7.78	-9.56	0.99	0.98	2.44	3.07
54416	-11.28	-10.58	0.99	0.98	2.81	3.03
54406	-8.37	-12.75	0.99	0.97	2.41	3.55
54399	0.29	8.61	0.99	0.98	2.15	2.78
54398	-8.5	-13.82	0.98	0.98	2.72	3.47
54596	-6.54	-5.29	0.99	0.99	2.4	2.8
54594	-7.1	-3.77	0.99	0.98	2.53	2.58
54514	-5.21	1.18	0.99	0.99	2.55	2.46
54513	-5.45	-3.54	0.97	0.96	3.49	3.7
54511	-1.38	-0.41	0.98	0.98	2.41	2.52
54499	-1.88	-1.72	0.98	0.99	2.32	2.36
54433	-1.2	3.09	0.98	0.98	2.32	2.53
54431	-5.24	-7.59	0.99	0.98	2.31	2.82
54424	-11.74	-12.44	0.98	0.98	2.98	3.24

PART 2: Response to Reviewer #2

This is a nice manuscript with a good attempt to include urban characteristics in VIC to make VIC usable for urban regions. I have a few comments, which the authors may address:

Reply: We appreciate your positive assessment of our study in integrating urban characteristics into VIC. The replies can be found below.

1. Urban models should have a strong human component characterized by human behavior and it is difficult to consider the same in VIC. THis is my major concern. The data requitement for development such module is also huge. The authors need to consider this very seriously.

Reply: Thanks for the concern regarding the strong human component in urban modeling. We fully recognize the pivotal role of human factors in shaping urban environments.

In the VIC-urban model, human behavior is partly addressed through several key parameters: land surface changes, indoor temperature, and anthropogenic heat/water input. Land cover is derived from Liu et al. (2010), Wang et al. (2020), and Global Land Surface Satellite (GLASS) products. Indoor temperature, assuming that heating or cooling of building interior is occurring, ranges between *Tmin* and *Tmax*, with values determined based on regional conditions (de Munck et al., 2018). For our study area, *Tmin* and *Tmax* are defined as 5℃ and 29℃, respectively. The anthropogenic heat input is maintained as a constant value, and the anthropogenic water input is represented by 12 monthly cycle values which can be defined by users. In this study, these parameters are set with reference to the UT&C model.

Moreover, urban-related parameters, except for the highly-sensitive ones (e.g., height-to-width ratio, layer thickness), are referenced from Jackson et al. (2010). These highly sensitive parameters are manually calibrated based on MODIS and runoff observation data. **We described these parameters in more detail in the revised manuscript. Please see L249-258 (land surface changes), L126-129 and L157-159 (indoor temperature), L162-163 and L195-197 (anthropogenic heat/water input).**

We acknowledge the challenges associated with integrating human components into VIC, and admit that there are still many factors have not been fully addressed, such as infrastructure dynamics. Your feedback is greatly appreciated, and we are dedicated to continually enhancing our model to better represent urban systems.

Liu, J. et al., 2010. Spatial patterns and driving forces of land use change in China during the early 21st century. Journal of Geographical Sciences, 20(4): 483-494.

Wang, Y. et al., 2020. Quantifying the response of potential flooding risk to urban growth in Beijing. Science of the total environment, 705: 135868.

de Munck, C., Lemonsu, A., Masson, V., Le Bras, J. and Bonhomme, M., 2018. Evaluating the impacts of greening scenarios on thermal comfort and energy and water consumptions for adapting Paris city to climate change. Urban Climate, 23: 260-286.

Jackson, T.L., Feddema, J.J., Oleson, K.W., Bonan, G.B. and Bauer, J.T., 2010. Parameterization of Urban Characteristics for Global Climate Modeling. Annals of the Association of American Geographers, 100(4): 848-865.

2. For urban heat balance, the anthropogenic heat plays a major role, and I am not sure how do the authors consider them. There are weekly variations in energy budget, like in weekends the office areas will have low energy requirements. The transportation component have a strong sub-daily variations. These are very important and I am a bit curious how to consider them in VIC.

Reply: Thank you for emphasizing the importance of anthropogenic heat and its variations in the urban environment. Addressing the factor is indeed essential for accurately modeling urban heat dynamics within VIC.

The VIC-urban model proposed in this study simulates the hydro-thermal dynamics independently at the grid scale, the magnitude of anthropogenic heat can be defined by users according to factors such as building density, population density. Therefore, there is spatial heterogeneity in anthropogenic heat distribution, such as variations between office areas and transportation areas. Unfortunately, temporal changes in anthropogenic heat were not considered in the model, because of the difficulty in obtaining input data and uncertainty in the formulation. Like other urban models, the VIC-urban applied a constant value to represent anthropogenic heat. This is a general limitation in urban models e.g., UT&C, and BEPS (Building Energy Prediction and Simulation).

To remedy this limitation: the model included temporal changes of indoor and outdoor conductive heat fluxes, and the model was calibrated with observed urban heat fluxes and land surface temperatures. **We added related statements in the manuscript, please see L504-509.**

3. The same point is applicable for water use as well.

Reply: For the anthropogenic water input, similar to the anthropogenic energy input, we considered its spatial heterogeneity, and took into account its monthly variations. However, we did not consider diurnal-scale temporal variations in anthropogenic water inputs.

We acknowledge that several water-related factors, such as drainage and industrial wastewater, have not been fully addressed in the model. It's important to note that addressing these issues are highly related to the availability and accuracy of data sources. **We added related statements in the manuscript, please see L504-509.**

4. There are existing models like SUEWS, how is the proposed model bettter than SUEWS frameowrk.

Reply: There are substantial differences between the SUEWS model and the VIC-urban model. First, SUEWS mainly focuses on water and energy balances in urban land cover (i.e., impervious surface), but VIC-urban is able to simulate water and energy balances for multiple land cover types (e.g., impervious surface, bare land, water bodies, agriculture, and forests). Second, SUEWS is generally applied at small spatial scale, such as a single city, but VIC-urban is suitable for large-scale applications (e.g., regional

and global scales). And third, SUEWS is primarily used to quantifying urban microclimate condition, but VIC-urban can be used in land surface hydrothermal environments, including regional and global water/energy balance estimation, and land cover/climate change impact assessments. **We added related statements in the manuscript, please see L481-486.**

PART 3: Response to Reviewer #3

The paper makes a significant contribution by modifying the Variable Infiltration Capacity (VIC) model to account for heterogeneous urban parameters, offering valuable insights into urban environment simulation. However, I have two major concerns regarding the validation process:

Reply: Thank you for your valuable feedback on our paper. We would like to address the concerns you raised below.

The primary contribution of this paper is incorporating various urban parameters. Despite this, the study was validated using data from only three stations, which may not be sufficient to represent the complexity of urban environments.

Reply: Thanks for the concern regarding the validation process. The simulated turbulent heat fluxes (latent and sensible heat) were evaluated using three ground-based observations. These are all the data for Beijing that can be obtained at present. To compensate this limitation, the VIC-urban model was further evaluated using land surface temperature data derived from the MODIS product (which covers the entire study domain), alongside 14 ground-based observations. Moreover, the simulated runoff was validated using streamflow data from three hydrological observations. Therefore, the evaluation or validation was done with respect to various hydrothermal fluxes and state, which guarantee the reliability of VIC-urban in representing the complexity of urban environments.

We acknowledge it is important to obtain more data to evaluate the model in future studies, and **added relevant statements in the manuscript. Please see L516-520**: *"The validation of the turbulent heat flues was not sufficient to reflect the model performance due to the scarcity of station data. However, the model was further validated using runoff and LST data obtained from gauge stations and MODIS product. These hydrothermal fluxes and states can be cross-verified based on the principles of water and energy balance, proving the reliability of VIC-urban in representing the complexity of urban environments."*

2. The authors claim that the VIC-urban model outperforms the standard VIC model. However, the results presented in Figure 9 show no significant difference in performance between the two models for two out of the three validation stations.

Reply: Among the three stations shown in Figure 9, the Miyun and the Daxing stations are located in suburban areas. Please note the improvements of the VIC-urban model primarily focuses on the urban areas rather than the suburban areas. Consequently, the VIC-urban and VIC models show similar performances at the two sites. We mainly focus on the Beijing station, which is located at the site with high-degree urbanization. VIC-urban performs better compared to the original VIC. Specifically, in comparing the sensible heat flux observed at the Beijing Station, the simulated values of VIC-urban model yielded a smaller RMSE (~12.7 W/m^2) than that of the VIC model (~15.7 W/m^2), with a higher correlation (~0.93) than the VIC model (~0.81).

We added relevant statements in the manuscript. Please see L390-396: "*As shown in Figure 9, the simulation results of the VIC-urban and the VIC models showed similar patterns at the Miyun and Daxing stations, as the two stations are located in suburban areas. The VIC-urban model mainly focuses on improving the model performance in urban areas rather than suburban areas. For the Beijing station, which is located at the site with a high degree of urbanization, VIC-urban provided a better performance. Specifically, the VIC-urban model yielded a smaller RMSE (~12.7 W/m^2) for the sensible heat flux than that of the VIC model (~15.7 W/m^2), and attained a higher correlation (~0.93) than the VIC model (~0.81).*"

To highlight the improvement, we provided a figure similar to the Figure 9 but exclusively using the data from the Beijing Station. The new figure is presented as Figure 1 below. But in the manuscript, we still use Figure 9 for completeness.

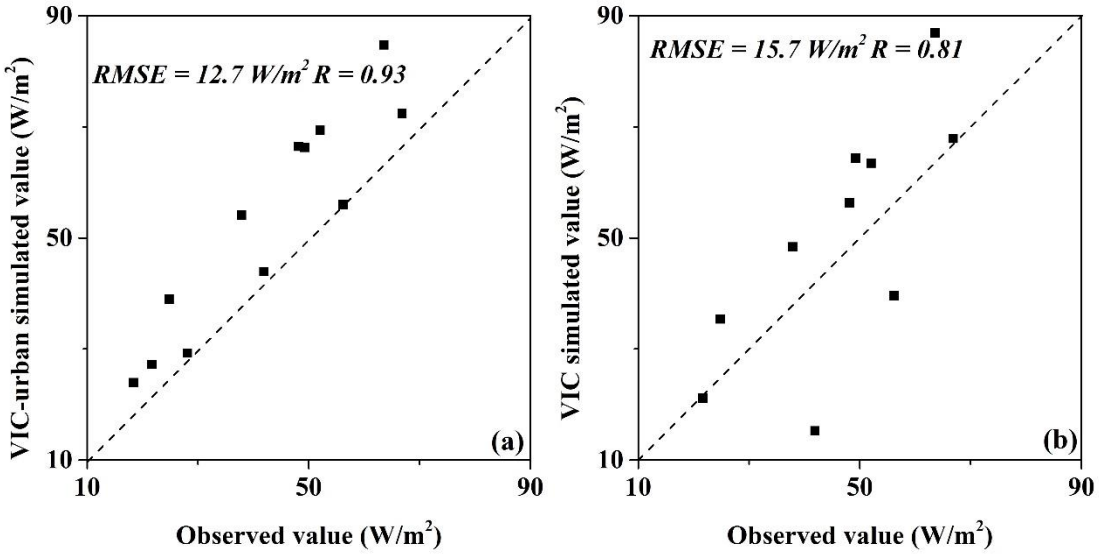

Figure 1. Simulated yearly turbulent heat fluxes of the VIC-urban (left) and the original VIC models (right) compared to the observed data at the Beijing station.

Relevant changes in the manuscript

Lines	Contents
L126-129	In addition, the urban module accounts for human impacts, including indoor temperature, and artificial heating and irrigation. We present core formulations of the urban processes and related parameters in Subsections 2.2-2.5. A more detailed explanation is included in the Supplementary Document and Meili et al. (2020).
L157-159	T_{int} is the interior building temperature, which can be calculated from the outdoor and indoor temperatures based on the thermal conductivity parameters
L162-163	Q_{can} is anthropogenic heat, which can be prescribed according to associated observations or estimated from other formulations.
L195-197	Q [mm h^{-1}] is the anthropogenic water input, and currently can be prescribed by user-defined 12 monthly-cycle values, but this prescription can be improved with dynamic values according to observations.
L241-242	Supplementary Figure 2 illustrates the spatial distribution maps of the urban parameters.
L249-258	The base maps were obtained from Liu et al. (2010), which were created by merging Landsat TM digital images with a spatial resolution of 1 km and 12 land cover types. The urban maps were obtained from Wang et al. (2020), which were created by the Classification Regression Tree (CART) method using Landsat images with a spatial resolution of 30 m. The land cover parameters were obtained from Zhu et al. (2020). To better reasonably reflect the land cover changes in modeling, our study updated land cover maps and related parameters (e.g., the thermal conductivity, volumetric heat capacity) every five years. Moreover, four satellite datasets, namely, Downward Shortwave Radiation (DSR), albedo, LAI, and Fraction of Vegetation Cover (FVC), were incorporated in the modelling process (Zhang et al., 2019; Liang et al., 2021) to better identify land conditions and calculate turbulent heat fluxes.
L253-258	To better reasonably reflect the land cover changes in modeling, our study updated land cover maps and related parameters (e.g., the thermal conductivity, volumetric heat capacity) every five years. Moreover, four satellite datasets, namely, Downward Shortwave Radiation (DSR), albedo, LAI, and Fraction of Vegetation Cover (FVC), were incorporated in the modelling process (Zhang et

al., 2019; Liang et al., 2021) to better identify land conditions and calculate turbulent heat fluxes.

L261-263 The spatial/temporal resolution of the VIC modelling is defined as 0.0625°/3 hours in this study. To ensure consistency, all model input data were adjusted to match the same spatial resolution through a linear interpolation.

L390-396 As shown in Figure 9, the simulation results of the VIC-urban and the VIC models showed similar patterns at the Miyun and Daxing stations, as the two stations are located in suburban areas. The VIC-urban model mainly focuses on improving the model performance in urban areas rather than suburban areas. For the Beijing station, which is located at the site with a high degree of urbanization, VIC-urban provided a better performance. Specifically, the VIC-urban model yielded a smaller RMSE (~12.7 W/m2) for the sensible heat flux than that of the VIC model (~15.7 W/m2), and attained a higher correlation (~0.93) than the VIC model (~0.81).

L481-486 Most UCMs, such as the Surface Urban Energy and Water Balance Scheme (SUEWS) (Järvi et al., 2011), are primarily focus on water and energy balances on urban impervious surface, and generally applied at small spatial scale, such as a single city. Moreover, UCMs often neglect heterogeneity within urban areas (Kusaka et al., 2001; Meili et al., 2020). In contrast, the VIC-urban model is able to simulate hydrothermal processes for multiple land cover types, and has the strength for large-scale applications beyond urban areas (e.g., regional and global scales).

L504-509 The model also simplifies anthropogenic heat and water impacts, which are user-defined and represented by a constant setting and 12-month cycle values, respectively. However, these anthropogenic influences fluctuate over time, such as anthropogenic heat input in office areas varying between weekdays and weekends. These factors may impose a significant impact on the urban environment, and need to be further studied given the availability and accuracy of data and the feasibility of methods.

L516-520 The validation of the turbulent heat flues was not sufficient to reflect the model performance due to the scarcity of station data. However, the model was further validated using runoff and LST data obtained from gauge stations and the MODIS product. These hydrothermal fluxes and states can be cross-verified based on the principles of water and energy balance, proving the reliability of VIC-urban in representing the complexity of urban environments.