Response to Anonymous Referee #1

(Note: Reviewer comments are listed in grey, and responses to reviewer comments are in black. Pasted text from the new version of the paper is in italics.)

The manuscript presents two sets of simulations realized with the model WRF-CHEM coupled with the Single Layer Urban Canopy Model, over the Los Angeles region for a 10 days period at the end of June-beginning of July 2012. One set of simulations is realized with the current land use, including the urban area of Los Angeles. The second set is realized replacing the urban area with shrub, representing the original vegetation (as claimed by the authors). The anthropogenic emissions are the same for both simulations. By comparing the results of the two simulations, authors derive the impact of urbanization on meteorology and air quality in the region.

We greatly appreciate the reviewer's helpful comments. We believe that addressing his/her comments have greatly improved the quality of our paper.

I have two main comments to this manuscript.

a) Authors rely heavily on previous work by the same team (mainly by Vahmani) to justify the set-up used, and the improvements obtained in simulating air temperature (for example due to the inclusion of the irrigation system). However, at lines 358-361, they say that all the previous simulations were performed without accounting for the shadowing effect in the street canyon, and with a different technique to estimate the surface temperature. On the contrary, the simulations presented in the manuscript consider shadowing and use the default formulation to estimate the surface temperature for impervious surfaces. The impact on the results of these different modeling choices seems important to the point that with the new approach urbanization decreases daytime temperature compared to the non-urban case, while with the previous set-up urbanization increased the daytime temperature. While I certainly agree that it is important to account for shadowing, I think that it is necessary to perform a more thorough validation of the simulations to get more confidence in the results, also because the RMSE, presented in table 1, is much larger than the urbanization effect. Therefore, I recommend making a separate analysis of urban and rural stations, and to separate between urban stations based on the different urban morphological characteristics. The validity of this study relies completely on the model capability to reproduce correctly the differences between urban and rural areas, so it is very important to show this comparison. For example, the following questions should be addressed: what are the RMSE and Mean Bias for the urban stations only? And for the rural stations? We have to be sure that the model is simulating correctly the urban areas AND the rural areas (in particular shrubs). Is the model able to capture the maximum and minimum temperature at each station? Is the model able to reproduce the differences between stations, and in particular the differences between the urban and the rural stations? (e.g., if at a certain hour higher temperature is measured in an urban station compared to a rural one, is the model doing the same? If rural stations measured lower minimum (maximum) than urban stations, is the model doing the same qualitatively and quantitatively? etc.).

We thank the author for bringing up these important points. Our detailed response is listed below.

Firstly, after a careful comparison among different model set-ups, we found that the parameterization of surface temperature is the more important factor that affects daytime air temperature compared to whether or not we account for shadow effects in urban canopies (i.e., see Figure S16 in the supplemental information). Therefore, we delete "and shading effects within urban canopies" in the sentence "In addition, increases in thermal inertia caused by use of manmade materials (e.g., pavements and buildings) and shading effects within urban canopies can contribute to simulated temperature reductions during the morning." We also modified the last paragraph in section 3.2.3 as below.

"Note that changes in air temperature during daytime shown here disagree with Vahmani et al. (2016). While our study detects daytime temperature reductions due to urbanization, Vahmani et al. (2016) suggests daytime warming. After detailed comparison of the simulations in our study versus Vahmani et al. (2016), we find that the differences are mainly associated with UCM configuration. First, our study uses model default calculations of surface temperature for the impervious portion of urban grid cells, whereas Vahmani et al. applied the alternative calculation proposed by Li and Bou-Zeid, 2014. Li and Bou-Zeid, 2014 intended the alternate surface temperature calculation to be performed as a post-processing step rather than during runtime. After a careful comparison among different model set-ups, we found that the parameterization of surface temperature is an important factor that affects simulated daytime air temperature (See Figure S16). Second, our study accounts for shadow effects in urban canopies, whereas Vahmani et al. (2016) assumes no shadow effects. (We note here that the default version of the UCM has the shadow model turned off. The boolean SHADOW variables in module_sf_urban.F needs to be manually switched to true to enable the shadow model calculations. With the shadow model turned off, all shortwave radiation within the urban canopy is assumed diffuse.) We suggest that it is important to include the effects of building morphology on shadows within the canopy, and to track direct and diffuse radiation separately, and therefore perform simulations in this study with the shadow model on. Note that the effect of shadowing is not as significant as the parameterization of surface temperature in our study, because the ratio between building height and road width is small."

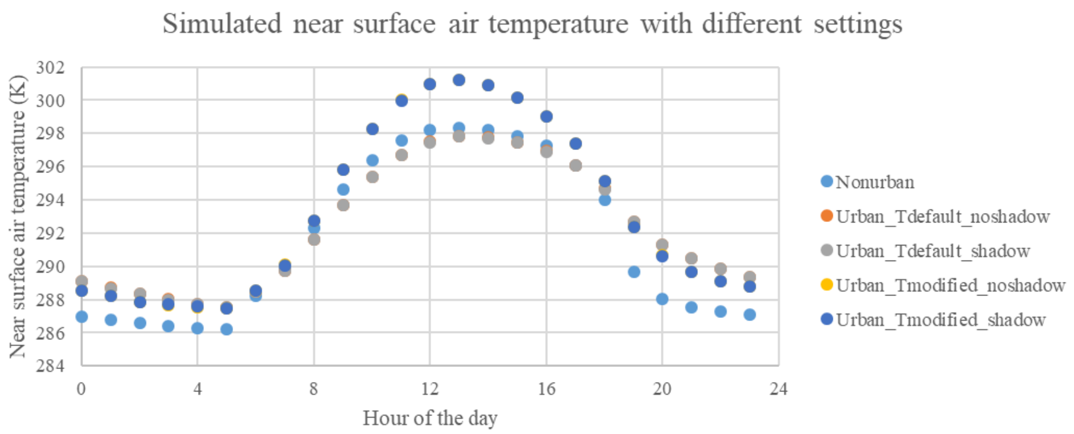

Figure S16. Diurnal cycle of near surface air temperature simulated with different model set-ups. "Tdefault" indicates that the simulation uses the default calculation of surface temperature in WRF, while "Tmodified" indicates that the simulation uses the calculation of surface temperature from Li and Bou-Zeid (2014) (which is also used in (Vahmani el al. (2016)). Dots for "Urban_Tdefault_shadow" and "Urban_Tdefault_noshadow" ("Urban_Tmodified_shadow" and "Urban_Tmodified_noshadow") are overlapping at every hour of the day because the simulation results with shadow on/off are very similar.

Secondly, we suggest that the comparison of urbanization impacts versus RMSE in Table 1 is not a robust comparison. Instead, to assess whether urbanization impacts are statistically distinguishable from zero, we added a new statistical analysis to the paper, using the paired Student's t-test with n = 7 days. We did the test to check 1) whether spatially averaged changes in regional meteorology and air quality are statistically significant within the simulation period, and 2) whether spatially resolved changes in regional meteorology and air quality are significant within the simulation period (i.e., for each urban grid cell). For 1), we edited the relevant sentences in the paper that refer to spatial average changes. For 2), we updated all figures with maps in the paper by adding black dots to grid cells with insignificant changes. Please see section 2.5 and section 3 in the paper for these changes. We haven't pasted the changes here because they are distributed throughout our results section, and would take up over 3 pages in this document.

Thirdly, we agree with the reviewer that the validation of urban sites, nonurban sites (shrubs in particular) and the difference between urban versus nonurban sites is important. In the main paper we only showed the validation of urban sites (i.e., we added a sentence to point this out in section 3.1.). Thus, we added a section in the supplemental information (section S2) discussing this topic. In general, our model can capture observations at nonurban sites, and the difference between urban versus nonurban sites. Thus, we believe the results we obtain based on this model set-up are reliable. The text in the paper are as follows (see below).

In the main paper:
"In addition, we only include observations from monitoring sites that are located in urban grid cells in the Present-day scenario. The validation of near surface air temperatures for both urban and nonurban sites are discussed in section S2 in the supplemental information."

Please see section S2 in the supplemental information for more details on the validation. We again do not paste it here because it is ~3 pages.

b) It must be made clear that the simulation with current anthropogenic emissions, but not the city, is a hypothetical one – there cannot be emissions without a city. In the last sentence of the manuscript (lines 570-574), authors say that their results "can be informative for decision making on sustainable urban planning to achieve a balance between climate mitigation/adaptation and air quality improvements". Honestly, I do not see how. This type of studies may have a scientific value, in the sense that they demonstrate the importance of taking into account the presence of the city in the simulation of air quality and meteorology (it would be interesting to see if the simulation with the city provides better results compared to measurements than the simulation without the city). But I do not see how they can be helpful for urban planning. Replacing the city with shrubs cannot certainly be considered a strategy to manage urban climate or improve air quality. The differences that authors estimated between the urban and the no-urban simulations are not the maximum difference that can be obtained managing the land use. They actually do not give any information about the impact of any realistic mitigation strategy based on land use management. I think it is very important that authors clarify what they have in mind because this is at the basis of the motivation of the whole manuscript.

We thank the reviewer for bringing this up. To emphasize that the "Nonurban" simulation is a hypothetical scenario, we added the following sentences to section 1, and revised sentences in section 2.5 and section 4.

Section 1

"In this paper, we aim to quantify the importance of historical land cover change on air pollutant concentrations, and thus the "Nonurban" scenario assumes current anthropogenic pollutant emissions. This hypothetical scenario cannot exist in reality, since current anthropogenic emissions would not exist without the city, but our intent is to tease out the relative importance of land cover change through urbanization (assuming constant emissions) on air pollutant concentrations."

Section 2.5

"Note that all three aforementioned scenarios adopt identical anthropogenic emission inventories described in Section 2.3. Using current anthropogenic emissions for "Nonurban" is a hypothetical scenario that cannot exist in reality, but allows us to tease out the effects of land surface changes via urbanization on meteorology and air pollutant concentrations."

Section 4

"The two main simulations of focus in this study are the real-world "Present-day" and the hypothetical "Nonurban" scenarios…"

We agree with the reviewer that the last sentence of the manuscript might not be an appropriate implication of the findings in this study. Therefore, we deleted that sentence, and added the following paragraph to the manuscript in section 4.

"This study highlights the role that land cover properties can have on regional meteorology and air quality. We find that increases in evapotranspiration, thermal inertia, and surface roughness due to historical urbanization are the main drivers of regional meteorology and air quality changes in Southern California. …Our findings indicate that air pollutant concentrations have been impacted by land cover changes since pre-settlement times (i.e., urbanization), even assuming constant anthropogenic emissions. These air pollutant changes are driven by urbanization-induced changes in meteorology. This suggests that policies that impact land surface properties (e.g., urban heat mitigations strategies) can have impacts on air pollutant concentrations (in addition to meteorological impacts); to the extent possible, all environmental systems should be taken into account when studying the benefits or potential penalties of policies that impact the land surface in cities."

Detailed comments:

1) Lines 64-66. Urban regions in semi-arid or arid surroundings have a weak (or non- existent) daytime UHI, but they have a very strong nocturnal UHI. I think authors missed the fundamental difference between daytime and nighttime UHI, (being the latter the most frequent).

Thank you for catching this mistake. We modified the sentence as follows.

"In particular, urban regions built in semi-arid or arid surroundings tend to have a weak daytime UHI or even a UCI, whereas those built in moist regions tend to have a larger daytime UHI (Fan et al., 2017; Peng et al., 2012)."

2) Line 168. On which basis authors claim that the period chosen is representative of summer conditions in Southern California?

Typical summer days in Southern California are clear or mostly sunny days without precipitation. The chosen simulation period has these characteristics. We added a figure in the supplemental information (Figure S8) showing the diurnal cycle of averaged (observed) near surface air temperature over JJA (June, July and August) and over our simulation period. We also added a sentence in the main paper.

"This simulation period is chosen as representative of typical summer days in Southern California, which are generally clear or mostly sunny without precipitation. A comparison of observed diurnal cycles for average near surface air temperatures over JJA (June, July and August) versus over our simulation period is shown in Figure S8 in the supplemental information."

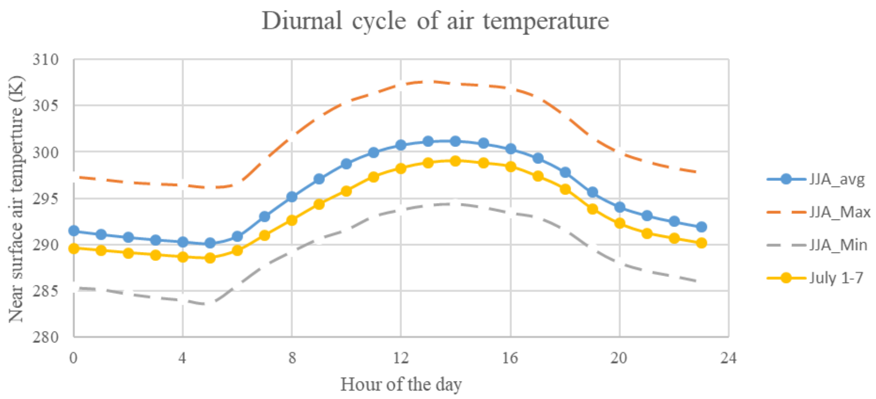

Figure S8. Diurnal cycles for observed near surface air temperature (K) over JJA (June, July and August) in blue, and over our simulation period in yellow. Observations are obtained from MesoWest (https://mesowest.utah.edu/), which are available at Mesonet API (https://developers.synopticdata.com/mesonet/). Mean values are derived by averaging over all observational sites available for the innermost domain and the aforementioned period for each hour of day. Orange and grey curves show the maximum and minimum air temperature at each hour of the day for JJA. Results show that our simulation period (July 1-7) is representative of summertime meteorology for our domain.

3) Line 174. Please provide the value of the depth of the lowest model level.

Thanks for the suggestion. We added it to the manuscript.

"The average depth of the lowest model level is 53 m for all three domains."

4) Line 215. Is the irrigation module implemented just for the pervious fraction of the urban cells, or also for the rural cells (to account for agricultural crops in the region)?

The irrigation module is just for the pervious fraction of the urban grid cells. The rural grid cells surrounding urban regions in Southern California are mostly natural land cover (e.g., shrub lands), and do not need to take irrigation into account. We added this information to the related sentence.

"Here we use an irrigation module developed by Vahmani and Hogue (2014), which assumes irrigation occurs three times a week at 2100 PST on the pervious fraction of urban grid cells."

5) Line 302. I would avoid indicating the percentage for temperature. This would depend on the unit (if you use Celsius or Kelvin). I would just put degrees.

Thanks for the suggestion. We have gone through the manuscript and changed all expressions of temperature in percentage to absolute values in Kelvin.

6) Line 303. On which basis authors claim that this is "acceptable".

We agree with the reviewer that "acceptable" is somewhat vague and unclear, so we modified the sentence as below, and added the comparison between our evaluation results and recommended model performance benchmarks to the supplemental information.

"The statistical results indicate that while model simulations underestimate near-surface air temperature, O_3 and $PM_{2.5}$ concentrations by 1.0 K, 22% and 31%, respectively. The comparison between our evaluation results and recommended model performance benchmarks is presented in supplemental information Table S2."

7) Section 3.2.3. I suggest studying the difference in sea breeze front progression between the two cases (urban and no-urban). This will give a better understanding of what is happening.

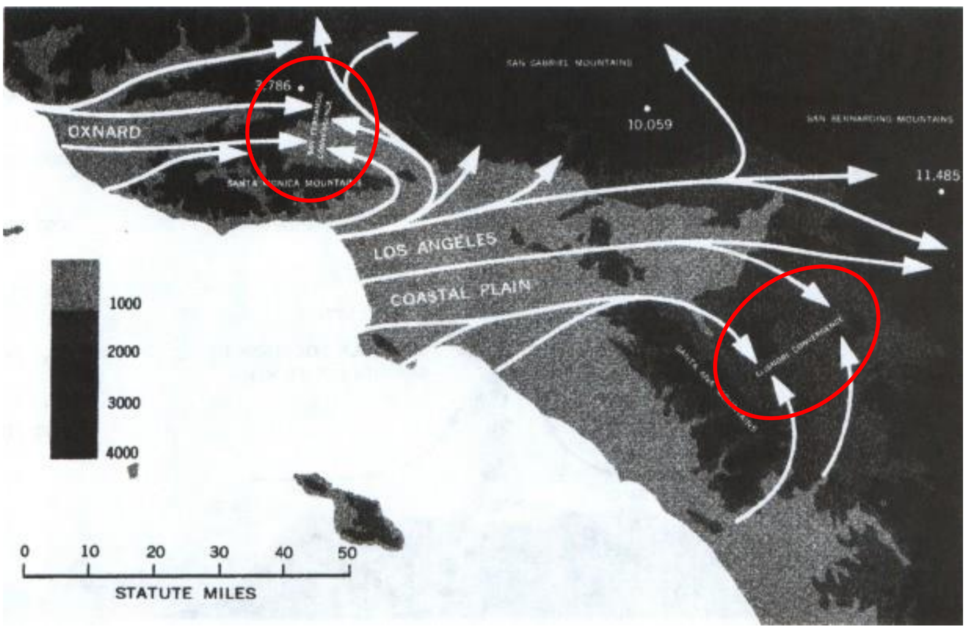

Figure R1.1 Sea breeze flow in the Los Angeles basin. Note the two sea breeze fronts formed at San

Fernando convergence zone (upper left), and the Elsinore convergence zone (lower right). (Figure adopted from: https://www.aviationweather.ws/097_Sea_Breeze_Soaring.php)

Figure R1.1 shows the two major sea breeze convergence phenomena in Los Angeles basin occurring in the San Fernando convergence zone and the Elsinore convergence zone. They are both formed by the meeting of two sea breezes that had flowed around the mountains. The sea breeze that flows across the Los Angeles coastal plain extends into the Mojave Desert. The sea breeze front of this branch of flow is not shown in our innermost domain. Therefore, we present here the difference in the wind vectors in the lowest model layer from 10 am to 5 pm instead of the progression of sea breeze front (Figure R1.2). The wind vectors are pointing towards the sea, which indicates that there is a significant decrease in wind speed in all hours of day presented here.

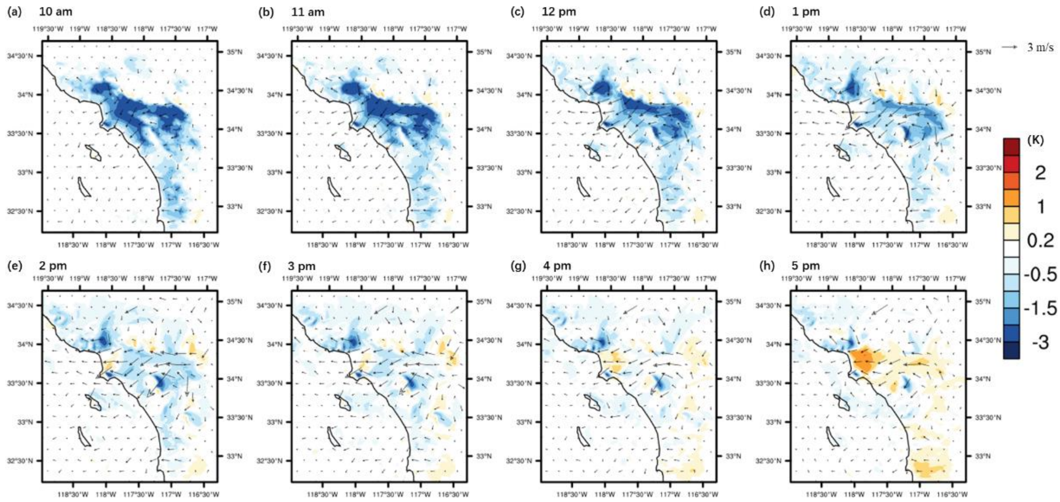

Figure R1.2 Wind vector plots for differences (Present-day – Nonurban) in temporally averaged wind speed in the lowest model layer from 10 am to 5 pm. The background plot shows the differences (Present-day – nonurban) in air temperature.

8) Lines 335-338. This is not clear. Before it is said that urbanization decreases temperatures and not increases.

The averaged temperature in the urban region decreases during the morning and afternoon. However, temperature changes vary spatially. While reductions in air temperature occur across the urban region during the morning, and in the inland urban region during the afternoon, temperatures actually increase in the coastal region during the afternoon. We specified the time when increases in temperature occur in the sentence.

"Note that the onshore sea breeze decreases in strength despite higher temperatures in the coastal region of Los Angeles during the afternoon, which would tend to increase the land-sea temperature contrast and thus be expected to increase the sea breeze strength."

9) Line 370. During nighttime atmosphere cools. The energy stored in the building during daytime (what authors call upward ground heat flux, I suppose) reduces the cooling. The higher PBL in the

urban simulation will reduce the cooling too because the effect of the surface cooling is distributed in a greater depth than in the no-urban case. The two mechanisms (energy stored in buildings, and high PBL), both reduce cooling. They do not compete they go in the same direction.

Thank you for catching this mistake. We revised the related sentences in section 3.2.4.

"The climate response to urbanization during nighttime is driven by the combined effects of (a) temperature increases from increasing upward ground heat fluxes, and (b) temperature increases from increasing PBL heights. Increased soil moisture (from irrigation) and use of man-made materials leads to higher thermal inertia of the ground; this in turn leads to increased heat storage during the day and higher upward ground heat fluxes and thus surface temperatures at night. Increasing PBL heights can also lead to warming because of lower air cooling rates during nighttime. Changes in PBL heights are associated with surface roughness changes since shear production dominants TKE at night. Coastal (inland) regions show larger (smaller) variation in roughness length (Figure 2e), which leads to larger (smaller) increases in PBL heights (Figure S14c). Despite larger increases in PBL heights in coastal versus inland regions, smaller air temperature increases occur in coastal versus inland regions, likely due to accumulative effects from coastal to inland regions with onshore wind flows."

10) Lines 375-376. Same as above, during the night there is not heating, there is cooling.

Please refer to our response to comment 9.