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REPLY

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This article is a reply to a comment by Velasco (2020), https://doi.org/10.1029/2020JD033301.

Key Points:

- The published work is a state of the art scientific study
- The commenter's accusations are addressed with facts and scientific evidence
- Model limitations acknowledged in the published work are reiterated

Correspondence to:

X.-X. Li,
lixx98@mail.sysu.edu.cn

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Reply to Comment by Velasco on "High-Resolution, Multilayer Modeling of Singapore's Urban Climate Incorporating Local Climate Zones"

M. O. Mughal[1], Xian-Xiang Li[2], Tiangang Yin[3,4], Alberto Martilli[5], Oscar Brousse[6], Maria Angela Dissegna[7], and Leslie K. Norford[8]

[1]CENSAM, Singapore-MIT Alliance for Research and Technology, Singapore, Singapore, [2]School of Atmospheric Sciences, Sun Yat-sen University, Zhuhai, China, [3]Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA, [4]NASA Goddard Space Flight Center, Greenbelt, MD, USA, [5]CIEMAT, Madrid, Spain, [6]Department of Earth and Environmental Sciences, KU Leuven, Leuven, Belgium, [7]Future Cities Laboratory, Singapore-ETH Center, Singapore, Singapore, [8]Department of Architecture, Massachusetts Institute of Technology, Cambridge, MA, USA

Abstract In response to the comment on our paper "High-resolution, multilayer modeling of Singapore's urban climate incorporating local climate zones," we provide detailed response to each of the incorrect accusations with scientifically based evidence. We have evaluated our model using all the available observational data, and the results showed good agreement. Our modeling study includes assumptions, as all modeling work does, and we have discussed their rationales and possible implications.

1. Introduction

The research presented in Mughal et al. (2019) was supported by the National Research Foundation Singapore (NRF) under its Campus for Research Excellence and Technological Enterprise (CREATE) programme and its Intra-CREATE Collaborative Grant "Cooling Singapore."

Overall, the commenter stressed validation, and indeed more validation is better. But in an urban context, with such large heterogeneity, it will be almost impossible to validate the model for all the different urban configurations. Even if the model is validated for a low-rise neighborhood of Singapore, it does not necessarily mean that the model will perform well for a high-rise, densely developed district. Similarly, obtaining temperature measurements in the urban canopy conforming with the standard requirement for urban measurement sitting (Oke et al., 2006) may be difficult due to the strong spatial variability of the temperature field. The spatial applicability of the point measurement in the canopy will be then limited, and, in principle, we could not directly compare point measurements of temperature against the 300-m spatial average provided by the mesoscale model. This means that in urban areas the model will be inevitably used for configurations where it has not been fully validated. But does this mean that model results are useless in these cases? We do not think so. Numerical models are grounded on physical principles and convey our best understanding of how the atmosphere interacts with the earth surface. They can be used to interpret measurements and to guide new field campaigns. If models show counterintuitive results in some places, this can be a motivation to perform dedicated field campaigns to check if the model is right, and if it is not these results can be used to improve the model formulation or set-up.

The commenter asserts that environmental point measurements are the "real world." This is generally true, but the information given by point measurements is necessarily incomplete in space and time. For many applications, we need a complete representation of the atmosphere in space and time, and this is something that, today, can be accessed only with models. A well-tested and well calibrated simulation model can be a good representation of the three-dimensional real world, its dynamics and its responses to the possible future perturbations (Zannetti, 1970). Even in environmental research, models are often validated against other models of different theoretical backgrounds as opposed to full-scale measurements; for example, computational fluid dynamics are usually tested against wind tunnel studies.

Table 1
Locations and Elevations of the Meteorological Stations Used for Model Validation

ID	Longitude	Latitude	Elevation above mean sea-level (m)	Elevation above ground level (m)
S24	103.9826	1.3678	15	2.3
S104	103.7853	1.4438	27	6.9
S106	103.9673	1.4168	27	6.4
S107	103.9619	1.3133	9	3.5
S108	103.8703	1.2799	15	10.9
S109	103.85	1.3792	53	27.7
S111	103.8365	1.3105	115	91.6
S115	103.6379	1.2884	6	3.0
S116	103.7545	1.2823	26	25.8
S121	103.7114	1.3858	38	22.4
S122	103.8251	1.4172	26	2.
S43	103.8881	1.3406	36	16.8
S44	103.6833	1.3452	84	48.1
S50	103.7761	1.3317	69	33.6
S60	103.8275	1.2504	37	20.9

2. Our Definition of Urban Canopy Layer Heat Island Is Scientifically Sound and Widely Used

The urban canopy layer heat island intensity is defined as the temperature difference between the urban canopy (a loosely defined layer comprised between the roof level and the ground) and the surface layer of the rural site, usually near standard screen height (1.25–2 m above ground). Behind this common definition, however, there is the implicit assumption that this UHI intensity represents the urban impact on local climate. It is this assumption that makes the UHI intensity relevant from the scientific point of view. For a dense city like Singapore, surrounded by inhomogeneous rural areas, and the sea, it is almost impossible to find a rural reference good enough so that the difference between the urban and rural air temperatures represents the impact of the urban area on climate. Lowry (1977) formalized the method for deriving UHI intensity and explained that to estimate urban-rural difference (more correctly the impact of an urban area), making model simulations with and without the urbanized surface was considered a valid approach. This method is widely used in mesoscale simulations and can avoid the effects of sea breezes, cloud impacts, and topography in the model which might alter the surface temperature (Bohnenstengel et al., 2011; Li et al., 2013, 2016).

Indeed, the choice of the land use type to replace the city could be questioned. We chose the majority land use type of rural weather stations (S106, S107, and S122), dense forest, which is a clear cut term referring to the only forest type in the region, the evergreen broadleaf forest, as seen from Table 1 in Mughal et al. (2019). We consider that this choice is justified and transparent (it gives readers the information needed to understand the study). The statistics in Mughal et al. (2019) reveal that our model can accurately reproduce the local climates of forest areas. In the land surface model (NOAH) used in Weather Research and Forecasting (WRF) model, the 2-m air temperature is interpolated using Monin-Obukhov Similarity Theory (MOST) for rural areas. It is correct that it does not represent the temperature below the tree crown. However, none of existing mesoscale models give this information to our knowledge, and it was not the aim of this article to develop a new vegetation scheme.

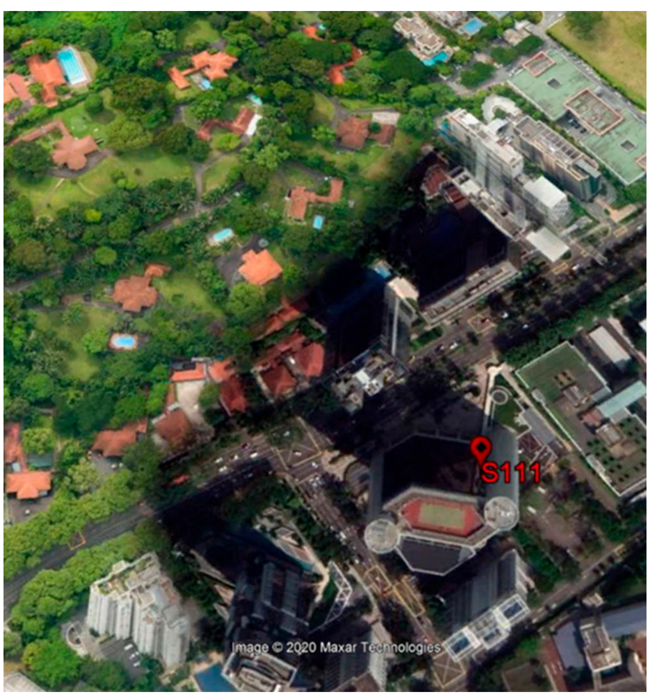

Figure 1. Surrounding environment of the S111 station from Google Earth.

The overall accuracy of the Local Climate Zone (LCZ) map (compared with Google Earth) is specified clearly in the manuscript as 70%; therefore, it is possible that the model misinterpreted some points such as station S111 in the land use, due to the process of aggregating 100 m resolution LCZ map to 300 m resolution of WRF model grid. During this aggregation process, a dominant LCZ type was used to represent the 300 m grid box. By checking the surrounding environment of station S111 (Figure 1), we can clearly see some parks and sparse buildings. Therefore, the classification of the grid where station S111 is located may not be wrong but station S111 may not accurately represent spatially averaged air temperature simulated by the model. This is quite common in urban stations in Singapore, due to many factors.

3. Not All Urban Stations Are Located at the Top of Buildings

In Multilayer Urban Canopy Model (MLUCM), the 2 m temperature and 10 m winds have been forced equal to the lowest model level. This is mainly for two reasons: a) the MOST is arguably not valid in the urban canopy, so that it is impossible to derive the 2 and 10 m values

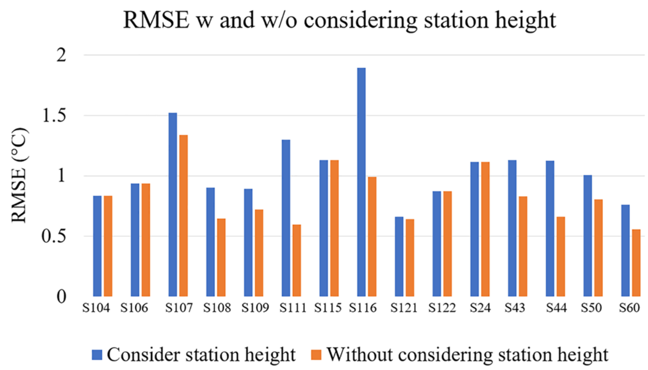

Figure 2. RMSE of WRF simulated temperature compared to measured temperature with and without considering the measurement height.

using the log-law, and b) to run WRF/MLUCM it is necessary to have a very high vertical resolution (5–10 m) to resolve the canopy, so the differences between the lowest model level values and the 2 and 10 m values are expected to be small. WRF uses an Arakawa C grid and it stores temperature at the half model level. In our simulations, the lowest level for temperature is about 5.5 m a very high vertical resolution for mesoscale model standards.

The weather stations used in the assessment are shown in Table 1 (Meteorological Service Singapore, 2017). As we have pointed out, "some of the stations are not properly located (e.g., at the roof top) according to the World Meteorological Organization (WMO) standards" (Mughal et al., 2019).

Table 1 shows that only a few stations lie at the top of buildings while the rest are within the urban canopy layer. In Mughal et al. (2019), the comparison of WRF results measurements was done using data from the lowest model level, at about 5.5 m above the ground level, regardless of the actual height of the measurements. For example, station S109 (Ang Mo Kio) is 53 m above mean sea level, the WRF output at 53 m above mean sea level is extracted and compared with the measurement. Since the terrain height at station S109 is 25.3 m (i.e., 25.3 m above mean sea level), the temperature at $53 - 25.3 = 27.7$ m above ground is extracted from WRF. The RMSE between WRF simulated temperature and the measured temperature is then calculated. Choosing the correct model level to compare against a roof top measurement is not trivial. The temperature at the measurement height is influenced by the height above sea level, the height above ground, and the height above the roof (because the temperature is certainly affected by the heat flux from the roof). To perform this, we need to add the uncertainty given by the fact that the grid averaged topography height used by the model may differ from the actual height of the ground where the building that has the measurement on roof is, and the fact that the urban morphology used by the model for that grid cell (derived from the LCZ of the cell) may not correspond to the actual urban morphology at that location (and so not represent adequately the presence of the building's roof where the measurement is). In any case, with the aim to assess the variability due to these uncertainties, Figure 2 shows the comparison of RMSE calculated with and without considering the height of measurement for April 2016. Overall, the RMSE differences are small for all but one station, S116 (Pasir Panjang). This could be due to the special land use around S116, which is a maritime port with many shipping containers. There is no urban category in WRF that parameterizes the metal surface properties of shipping containers.

4. We Studied a Special Month With No Energy Balance Data Available

The commenter misquoted Mughal et al. (2019) that it was the first time the model was applied in a tropical city. Mughal et al. (2019) clearly stated that there are other studies (Liao et al., 2014; Valdés, 2018; Wang et al., 2017) in the tropics which have utilized WRF/MLUCM. More generally, in our view, the fact that WRF/MLUCM has never been applied before to a city that has the same latitude of Singapore, does not mean that the validations that have been done for other cities are completely irrelevant, given that the model is grounded on physical principles, and not a parameter fitting. We have explained that we have compared our results of energy balance (including Q_F), sea breeze pattern and UHI intensities with those reported in the available literature, where applicable. Some caveats should be noted, though. While our study focuses on a hot month in April 2016 and emphasizes utilizing LCZs, those studies (Boehme et al., 2015; X. X. Li, 2018; Pokhrel et al., 2019; Wang et al., 2018) reported in the literature are not completely compatible with our spatial or temporal coverage, which affects the interpretation of the comparison.

Without the flux data noted above, we have not validated all the components of an energy balance. However, we compare Q_F and solar irradiation with all available observational data. In addition, most of the mesoscale models do not evaluate models against an energy balance but against such state variables as air temperature. Though useful, indirect measurement of anthropogenic flux derived from unbalance of flux measurements is susceptible to errors due to uncertainties in each of the measured flux terms (Grimmond et al., 2010)

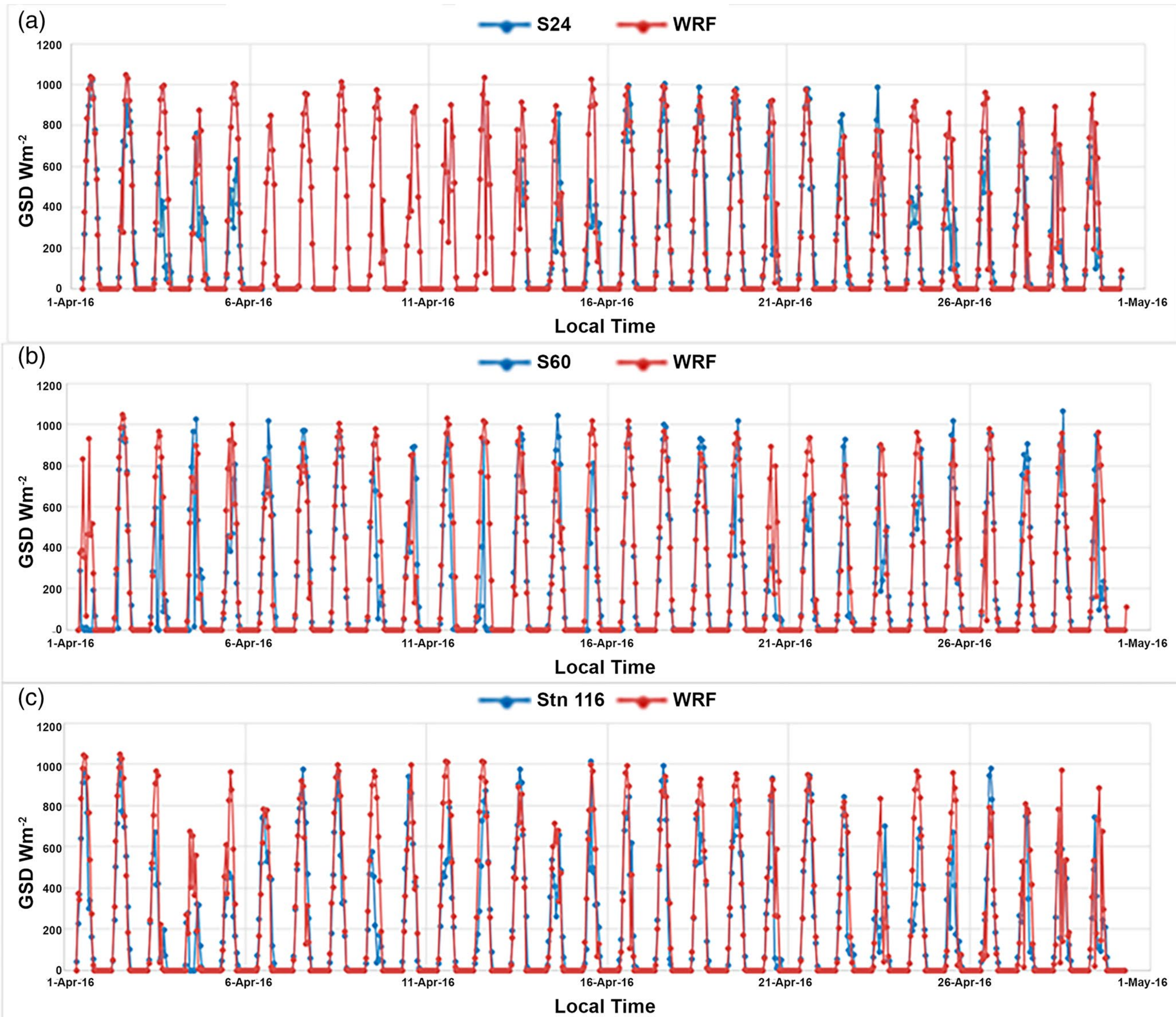

Figure 3. Time series plot for WRF simulated and observed values of global radiation at (a) S24, (b) S60, and (c) Stn 116.

Information related to heatwaves in April 2016 was removed from the revised manuscript, as this was not the focus of the current study. Singapore Meteorological Services have listed April 2016 as the hottest April since 1929 (Meteorological Service Singapore, 2016).

5. We Used All Available Radiation Data

In our paper (Section 3.2), we explained that the discrepancy between simulated and observed solar radiation is partly attributed to their different temporal averaging methods. For stations run by Meterological Service Singapore (MSS) (i.e., S24 and S60), the observational data were averaged within each hour (with an interval of 1 minute), while the simulated results and the observational data from other stations (Stn 116, 307, 315, and 322) were instantaneous values at each hour. The large discrepancy observed at S24 (Figure 8a in our paper) was largely due to this difference, not by model errors. The agreement between our simulated results and Stn 116, 307, 315, and 322 is much better than S24 and S60. Figure 3 shows the time series of observed global radiation data. The broken irregular curves clearly demonstrate the existence of clouds or thunderstorms, a difficult phenomenon to model that may have a strong stochastic component.

Admittedly, we do not have observational data of other components of radiation to compare with our simulation results. However, the albedo, emissivity and thermal conductivity values of different urban facets were taken from Li et al. (2013, 2016) and Liu et al. (2017), the latter of which has been carefully validated against observations of different components of radiations as well as other energy balance components.

6. Air Conditioning Is a Major Source of Anthropogenic Waste Heat in Nonindustrial Regions During the Studied Period

In our paper, we have clearly specified that the Building Effect Parameterization (BEP)/Building Energy Model (BEM) only considers the anthropogenic heat (AH) from the buildings including the metabolic heat of occupants, which was the major source of AH in non-industrial regions. The model did not consider the heat emissions from traffic or industry.

In BEM, several assumptions were made: (1) The indoor temperature is fixed at 21°C, which is the set temperature for most office and commercial buildings in Singapore (Damiati et al., 2015) and (2) all of Singapore's urban areas are air-conditioned and all the air conditioner (AC)s are in operation for 24 hours every day.

BEM in WRF accounts for diffusion of heat through walls, roofs, and floors; natural ventilation; the radiation exchanged between indoor surfaces; the generation of heat due to occupants and equipment; and the consumption of energy due to air conditioning systems. By accounting for these urban heat fluxes, BEM supports analysis of the impact on urban climate of a change in the urban structure, which would not be possible by imposing an estimated AH.

However, due to the BEM's limited capability in handling the different timing for ACs in different urban areas (e.g., the timing of AC operations in residential buildings differs from that of office and commercial buildings), and the fact that it is difficult to obtain the specific set temperatures for different urban areas, a single AC configuration was applied to all urban areas. The impact of these assumptions on AH from ACs will also vary in different areas at different time of the day.

It is true that our simulated Q_F is much higher than that reported in Quah and Roth (2012). However, the results of Quah and Roth (2012) were based on a 181-day average from Oct 2008 to Mar 2009, with no data in April or May (typically two hot months in Singapore), while our results were for a hot month of April in 2016. In addition, Quah and Roth (2012) only studied three neighborhoods in Singapore, which are not enough to represent the highly heterogeneous urban environment, though they were claimed to be representative. The two are not directly comparable in terms of their different spatial and temporal coverage. We have also compared our results with other data sets for Singapore. In a separate project, we estimated the AH in Singapore based on energy consumption, traffic and dynamic population data in 2015, and found that the AH from buildings (mostly from energy consumption) can be as high as 663 W m^{-2} at the central business district at 17:00–18:00. It is worth noting that the spatial density (at the scale of the grid size of the mesoscale model) of the anthropogenic heat from AC is strongly influenced by the volume of the buildings (e.g., the number of floors—the more floors that must be cooled, the larger the total emitted heat), and the building density.

We performed a sensitivity test (for the entire April 2016) by using a higher thermostat temperature (25°C), which should correspond to the temperature used in most residential areas. This case is termed as "increased thermostat indoor temperature" (ITTT). The difference of Q_F between the Control and ITTT cases is between 20 and 50 Wm^{-2} (Figures 4a and 4b). The temperature and UHI differences are generally between −0.2 and 0.4°C (Figures 4c, 4d, and 5). This suggests that the errors introduced by a low thermostat temperature are not so significant as to seriously impact our major conclusions in this manuscript. The future research in Cooling Singapore will focus on a more thorough validation of the BEM, to better assess weaknesses and strengths of the approach, and will also refine the definition of the parameters, for example by considering the day time scheduling of thermostat set point temperature.

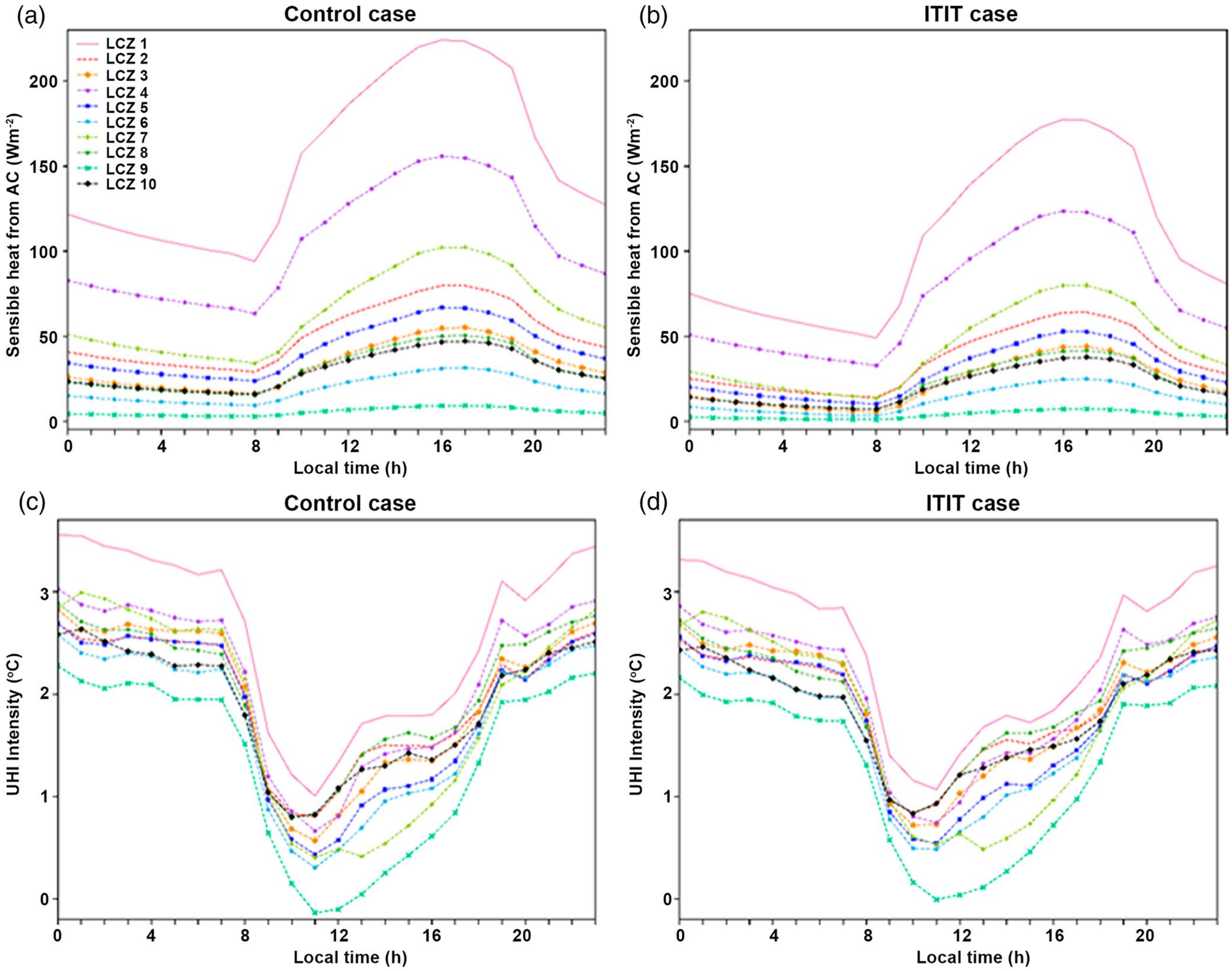

Figure 4. Comparison of (a) and (b): The sensible heat flux from the AC systems and (c) and (d): UHI intensity of each LCZ class for Control and increased thermostat indoor temperature (ITIT) cases. The diurnal cycles are calculated as the ensemble-mean during April 2016.

7. Trees' Evapotranspiration and Shading Effects Are Small in Mesoscale Models

The research by Liu et al. (2017) indeed showed that tree evapotranspiration is important in reproducing the latent heat flux in Singapore using an "offline" single-layer urban canopy model (SLCUM). However, a follow-up research using coupled ("online") WRF/SLUCM showed that the improvement in latent/sensible heat flux did not strongly impact the 2-m air temperature and humidity. In addition, the hydrological processes have not been implemented in the MLUCM. Therefore, our paper did not include the evapotranspiration effects of trees within the urban fraction of the grid cell.

8. A Validated Model Can Be Used as an Explorative Tool

The highly heterogeneous urban contexts make model validation a challenging task. This means that in urban areas the model will be used for configurations where it has not been fully validated. However, this should not restrict using the model—instead it should be used as exploratory tool to detect relevant features that may eventually be confirmed or found false by detailed measurements (which may be inspired by model results).

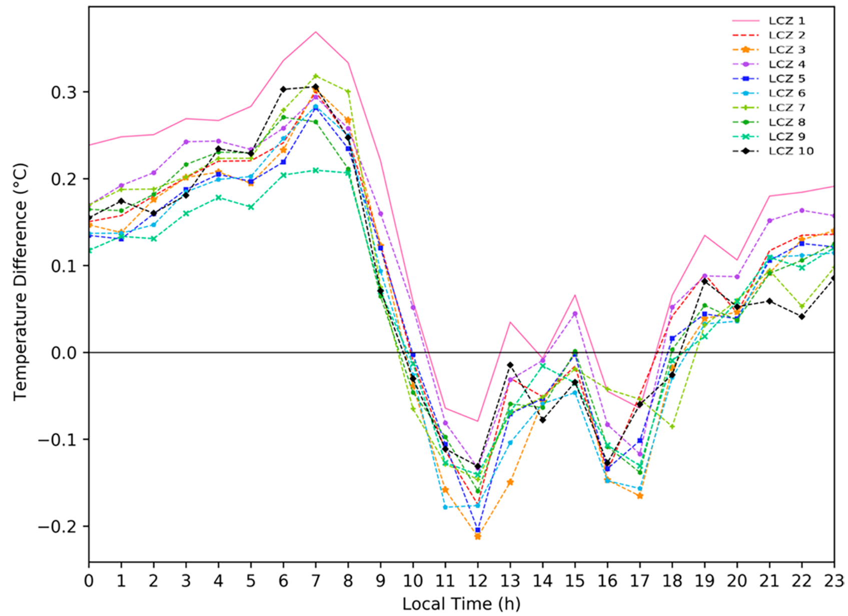

Figure 5. Comparison of diurnal variation of temperature difference between the Control and ITIT cases.

9. Concluding Remarks

We consider the technical skills employed in the published study to be comparable to the state of the art demonstrated in the relevant scientific literature. We have explained the assumptions made in the study and their possible implications in the original paper.

We welcome comments and critics from a scientific standpoint of view from everyone who has carefully read the paper.

Data Availability Statement

All other data used have been properly cited. The results data used in the analysis are available at https://doi.org/10.5281/zenodo.4456134.

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