Evaluating the ENVI-met microscale model for suitability in analysis of targeted urban heat mitigation strategies

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Abstract:

Microscale atmospheric models are increasingly being used to project the thermal benefits of urban heat mitigation strategies (e.g., tree planting programs or use of high-albedo materials). However, prior to investment in specific mitigation efforts by local governments, it is desirable to test and validate the computational models used to evaluate strategies. While some prior studies have conducted limited evaluations of the ENVI-met microscale climate model for specific case studies, there has been relatively little systematic testing of the model's sensitivity to variations in model input and control parameters. This study builds on the limited foundation of past validation efforts by addressing two questions: 1) is ENVI-met grid independent; and 2) can the model adequately represent the air temperature perturbations associated with heat mitigation strategies? To test grid independence, a "flat" domain is tested with six vertical grid resolutions ranging from 0.75 to 2.0 m. To examine the second question, a control and two mitigation strategy simulations of idealized city blocks are tested. Results show a failure of grid independence in the "flat" domain simulations. Given that the mitigation strategies result in temperature changes that are an order of magnitude larger than the errors introduced by grid dependence for the flat domain, a lack of grid independence itself does not necessarily invalidate the use of ENVI-met for heat mitigation research. However, due to limitations in grid structure of the ENVI-met model, it was not possible to test grid dependence for more complicated simulations involving domains with buildings. Furthermore, it remains unclear whether existing efforts at model validation provide any assurance that the model adequately captures vertical mixing and exchange of heat from the ground to rooftop level. Thus, there remain concerns regarding the usefulness of the model for evaluating heat mitigation strategies, particularly when applied at roof level (e.g. high albedo or vegetated roofs).

Keywords

ENVI-met, urban climate, heat mitigation strategies, grid sensitivity, model validation

1. Introduction

Global climate change coupled with the urban heat island effect continues to be a catalyst for cities to implement measures to reduce air temperature in the urban core (Mills, 2007). These measures collectively mitigate the urban heat island effect and are mechanisms by which policymakers seek to minimize the local effects of climate change. Mitigation strategies can take on a myriad of forms (including vegetation, urban canyon adjustments, shade structures, etc.), but in relation to reducing urban air temperatures, one popular approach is the use of highly reflective (high albedo) urban surfaces (Grimmond et al., 2010). The ability to design or modify the built environment to reduce air temperatures during heat waves is important to cities as urbanization and climate change continue to increase air temperatures in urban areas (IEA, 2014; IPCC, 2013).

Vegetative cover has been extensively considered as an urban cooling strategy by planners and microclimate modelers (Ali-Toudert and Mayer, 2007; Lindberg and Grimmond, 2011). While vegetation offers local atmospheric cooling and provision of shade, initial cost, irrigation needs, and maintenance requirements introduce implementation challenges for city planners. Increase in pavement albedo is another commonly considered urban heat mitigation strategy. High albedo paving, however, can be more costly and also introduces concerns about reflected solar radiation (Santamouris, 2013). Mitigation strategies that focus on increasing albedo at the rooftop level are promising in that they have relatively little impact on the current urban form, and can be implemented as part of routine roof replacement with little to no marginal cost (Botham-Myint et al., 2015; Taleghani et al., 2016). Roof albedo modification offers the additional benefit of directly reducing summertime air conditioning loads for modified buildings; however, the effect that roof-level modifications have on near-surface ambient air temperatures is likely less than that achieved by ground-level albedo modification. The challenge for planners and developers is to quantitatively weigh the costs of each of these types of strategies against their likely benefits (Georgescu et al., 2014). While the urban cooling benefits of these mitigation strategies have been tested in computational models, variability in the magnitude of the modeled benefits casts doubt on their accuracy (Santamouris, 2014).

Significant obstacles to the deployment of these mitigation strategies include the cost of city-wide implementation and the general lack of quantitative observational data regarding their performance in reducing air temperatures. Therefore, researchers have turned to computational models to represent the urban built environment and its atmosphere. These models are able to explore the effectiveness of mitigation strategies in a variety of scenarios, such as testing these strategies across entire domains or in smaller, targeted regions of the urban area—which may be a more cost-effective strategy for city planners (Ambrosini et al., 2014; Santamouris, 2014; Taleghani et al., 2015, 2014).

A variety of computational models are currently available for use in urban microclimate applications (spatial resolution between 1 and 4 m). These models use different approaches to represent the governing flow equations and the urban surface energy balance. Some approaches only consider the radiation budget and ignore the impact of fluid flow through the urban canyon (e.g., RayMan and TEB) (Pigeon et al., 2008; Thorsson et al., 2007). Other models use large eddy simulation (LES) to resolve fluid flow around individual buildings within the urban canyon, in addition to modeling the radiation budget (e.g., TUF-3D) (Krayenhoff et al., 2007). Some urban models use Reynolds Averaged Navier-Stokes (RANS) equations—an approach with reasonable accuracy, but at a lower computational cost than LES (Mirzaei and Haghighat, 2010). Among the RANS modeling approaches, FLUENT, OpenFOAM, and Star-CCM+ are sophisticated computational tools, requiring extensive training on the part of the user (Blocken et al., 2007; Botham-Myint et al., 2015; Chen et al., 2009). Other codes, such as ENVI-met and SOLWEIG, are more user-friendly and accessible by less experienced users (Elnabawi et al., 2013; Lindberg and Grimmond, 2011; Samaali et al., 2007)—a characteristic that has both advantages and significant disadvantages.

A literature search of published research using atmospheric microclimate modeling in the urban environment led to 46 search results since 2006. About 30% of these results (14) used or reference ENVI-met explicitly, with RayMan being the next most commonly cited model with 8 results. The general preference for using ENVI-met in these sorts of studies is likely due, in large part, to a balance of sophistication, user-friendliness, and lower computational costs, of the model (Ali-Toudert, 2005; Chow and Brazel, 2012; Roth and Lim, 2017; Singh and Laefer, 2015). An additional reason for the use of ENVI-met is the dynamic coupling of the atmospheric processes with vegetation/soil moisture processes with the model. The search also revealed a general trend toward using spatial resolutions of ~2 m per cell to accommodate for the neighborhood size.

ENVI-met is a Computational Fluid Dynamics (CFD) model that relies on RANS equations to solve for atmospheric flow and heat transfer in urban settings. This model was initially developed by Bruse during his dissertation work in Germany in the late 1990’s (Bruse and Fleer, 1998). The model has evolved and transformed into its latest version (v.4), released in the summer of 2016 (www.envi-met.com). The model’s user-friendly interface and relatively simple input scheme allows most researchers to be able to run this software with minimal training or expertise. The highly-touted feature of the model is its ability to model complex urban geometries and vegetation while also allowing for energy inputs such as waste heat from vehicles and the effects of water features.

As pointed out by Maggiotto et al., (2014), the majority of literature on the topic of ENVI-met addresses model accuracy and suitability in a rather superficial manner. One important test of model suitability is grid independence testing, which is used to confirm that the discretized model resolution is sufficient such that further refinement of the model grid does not substantially alter model output. However, such testing is lacking in prior investigations involving ENVI-met. Most researchers who seek to evaluate the ENVI-met model use air temperature observations from a limited number of locations in the domain to verify model accuracy (Ali-Toudert, 2005; Emmanuel and Fernando, 2007; Samaali et al., 2007; Yang et al., 2013). Measurements of other atmospheric variables to validate ENVI-met's performance have been collected by some researchers, but were generally not considered in their analysis of ENVI-met model performance (Middel et al., 2014; Ng et al., 2012). The lack of thorough testing of the model's limits and abilities is a serious concern for those attempting to use the software to model prospective changes in the urban surface, such as implementation of urban heat mitigation strategies. Therefore, the present study seeks to fill this knowledge gap by testing the grid independence of ENVI-met to further assess its usefulness for evaluating urban heat mitigation strategies such as increasing albedo of roof and pavement surfaces. First, we explore the historical literature to assess the extent to which ENVI-met has previously been validated. Then, we focus on two questions: 1) is ENVI-met grid independent; and 2) can the model adequately represent the air temperature perturbations associated with heat mitigation strategies?

2. Past Validation Efforts

The popularity of ENVI-met among urban climate researchers over the past twenty years has led to a copious number of publications that use ENVI-met in some capacity to represent the urban environment (Singh and Laefer, 2015). Yet, among the published studies, few (Elnabawi et al., 2013) have conducted a rigorous investigation into the model's numerical stability and most (Salata et al., 2016; Singh and Laefer, 2015; Yang et al., 2013) refer to the work of the model developers as justification for the model's fitness for use. Some research studies have taken steps to compare results produced by ENVI-met with measurements taken in the physical environment (Acero and Arrizabalaga, 2016; Buccolieri et al., 2015; Conry et al., 2015); however, only a select few have done so with a critical eye for how the model represents atmospheric variables beyond air temperature (Maggiotto et al., 2014; Middel et al., 2014).

Urban climate research has used ENVI-met to simulate the effects of complex urban geometries and materials on air temperature, wind flow, and relative humidity in many locations around the world, including desert and arid climates (Ali-Toudert, 2005), tropical humid climates (Emmanuel and Fernando, 2007; Roth and Lim, 2017), and mid and high latitude urban climates (Conry et al., 2015). Many of these studies used air temperature data within the canyon to verify ENVI-met output. However, most do not consider sensitivity of model output to perturbations in model input parameters or model grid structure. The default parameters within the model are often acceptable or preferred settings for specific applications; however, there is little justification provided within the literature regarding use of default or custom settings.

Challenges are associated with the albedo enhancement approach that is common in the literature and used with this study. The albedo of individual surfaces does not remain constant over time, rather low albedo surfaces tend to become more reflective as the surface ages (e.g., consider new vs. aged asphalt paving). On the other hand, high albedo surfaces will become less reflective over time as dirt is deposited and the surface is worn through use (e.g., consider a white membrane roof). Additionally, any shaded surfaces will function differently than unshaded surfaces, even with the same albedo. This can reduce the impact of albedo enhancement if shading is a predominant urban feature where the enhancement occurs.

While there have previously been a limited number of studies that have rigorously tested ENVI-met, some scientists have begun to take up this concern and analyze their results in a more critical light, considering how use of model default mechanisms and assumptions might affect the results. One example of this type of analysis is the work of Maggiotto et al. (2014) who conclude that, despite ENVI-met's ability to represent building geometry and vegetation, it requires significant tuning in order to accurately represent heat transfer processes in complex urban canopies. This gives rise to a concern that ENVI-met may perform well at representing a limited sample of measured temperatures near the surface without necessarily providing a good representation of heat transfer and vertical mixing processes that are crucial to determining the effects of mitigation strategies. Best practices in using ENVI-met from the literature focus on collecting in situ measurements and creating domains with large buffer zones between the edge of the domain and the areas of interest (Middel et al., 2014; Salata et al., 2016). However, the intentional analysis of the model itself is not apparent in the literature. Some studies have investigated the role of physical extent of mitigation strategies as well as the relative magnitude of the simulated change in the urban form (Taleghani et al., 2015, 2014), yet even these analyses do not directly consider the role of model-specific features.

Computational fluid dynamics (CFD) modeling is dependent on suitable representation of the conservation of mass, energy, and momentum. Hence, CFD modelling of the atmosphere typically involves simplifying the environment into a discretized 3D grid box. The output from the model is tied to the spacing between computational grid box center points. If the grid is sufficiently fine in resolving the environment, then the resulting model output should remain stable when further refining the model grid. This type of analysis is referred to as grid sensitivity or grid independence testing and is commonplace for the CFD modelling community (American Society of Mechanical Engineers., 2007; Blocken et al., 2007); however, past studies of ENVI-met have not performed these types of analyses for grid sensitivity. Given that vertical transport processes can be quite sensitive to grid resolution, and that these processes are key to determining the relative impacts of various heat mitigation strategies, it is crucial to test this aspect of model performance prior to using it for analysis of heat mitigation strategies. Therefore, the present study seeks to apply grid independence testing to an idealized urban setting to evaluate whether the modeled effects of changes in roof-level albedo on pedestrian-level air temperature are grid independent. Whether the model simulations of urban heat mitigation scenarios are grid independent or not, the final question that we strive to address is whether model variability introduced by grid dependence is significant relative to the effects of modeled pedestrian-level air temperature reduction.

3. Methods

ENVI-met is an easy to use CFD modeling software, commonly used by stakeholders and researchers in a variety of disciplines focused on the urban environment (e.g., urban planning, landscape architecture, civil engineering, and urban climate). The foundational code of ENVI-met is a microclimate fluid dynamics model of the urban environment. This code has evolved into the latest version (4.3), updated in 2018. ENVI-met relies on RANS equations to solve the model physics. The design of the model interface is intuitive and simple enough for any researcher to be able to quickly set up an experimental domain and begin to conduct simulations with the software.

To test the grid independence of the model and its sensitivity to spatial grid resolution, we selected version 4. All research previously cited in this manuscript used version 3 for research and testing. Version 4 offers domains that are more customizable in that multiple soil profiles, surface materials, wall characteristics, and roof features can be used. The ability to create user-defined materials is another option provided within version 4. The model generates output in the form of two- and three-dimensional vectors, as well as optionally outputting raw data.

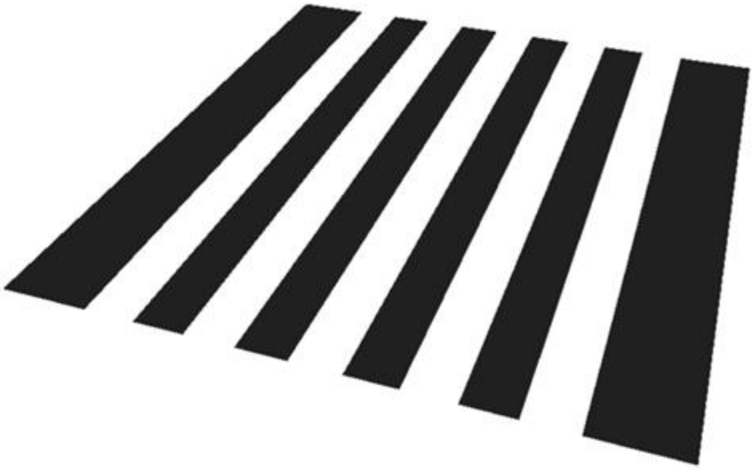

Figure 1. The domain layout of the ENVI-met simulation for grid independence testing. The surface is made up of two types of road surface, a low albedo asphalt (dark in color, α = 0.20), and a high albedo asphalt (light in color, α = 0.80).

This modeling study looks at two over-arching questions: is ENVI-met grid independent, and can the software adequately represent the air temperature perturbations associated with heat mitigation strategies. A “flat” domain with no topographical variation is designed to study the first question, and a uniform grid of buildings is used to develop an initial assessment of the second. For the first question, the flat domain includes alternating strips of dark and light asphalt with albedo of 0.2 and 0.8, respectively, which help to introduce vertical mixing associated with variations in resulting surface temperatures (Fig. 1). Six vertical resolutions were modeled: 0.75, 1.00, 1.25, 1.50, 1.75, and 2.00 m (Table 1), with x-y dimensions of 100 m by 100 m. For the second question, we investigated a base case and mitigation cases, following the approach of Botham-Myint et al. (2015) by modeling a simple 5 by 5 grid of square buildings. The only changes made for the two mitigation cases relative to the control case is in the albedo of different surfaces.

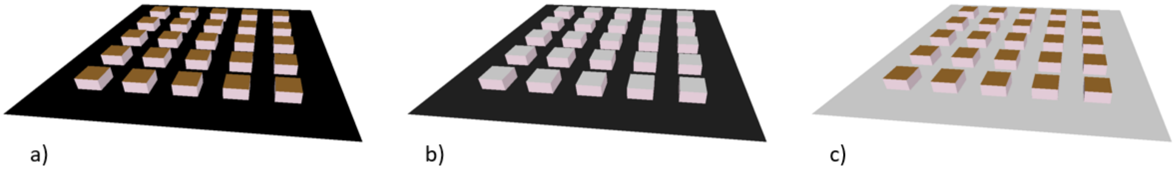

Figure 2. Three building simulations in ENVI-met to determine the software's capability to represent effects of heat mitigation strategies. (a) is the control case, (b) is the high albedo roof, and (c) is the high albedo pavement

Table 1 Summary of simulation domain characteristics.

Vertical Grid Resolution (m)	Height of Domain (m)	Ground Grid Independence Simulations	Control Simulation	High Albedo Roof Simulation	High Albedo Pavement Simulation
0.75	18.38	X	--	--	--
1.00	24.50	X	--	--	--
1.25	30.63	X	--	--	--
1.50	36.75	X	--	--	--
1.75	42.88	X	--	--	--
2.00	49.00	X	X	X	X

Air temperature values were extracted from the output files of each simulation for every horizontal grid cell at two heights (grid cells just above and below 2 m). We then linearly interpolated between the two levels to obtain an estimate for 2 m air temperature across the entire domain for each case. The data were then imported into RStudio to create bootstrapped statistics for all nine cases (the six grid independence testing cases and the three mitigation strategy testing cases), and the upper and lower confidence intervals (the 2.5 percentile and the 97.5 percentile) were calculated.

The standard mode for implementing the ENVI-met software version used in this study allows for a total of 30 levels in the vertical. Six different vertical resolutions for testing were selected to determine whether the default implementation mode is grid independent. The flat domain was used for this testing due to a limitation in the grid-spacing/resolution in ENVI-met that would result indifferent simulated building heights for different model vertical resolution. Specifically, regardless of the user's specified roof height, the software automatically adjusts this height so that the roof level aligns with a discrete level in the model. The default vertical resolution in ENVI-met is 1 m, although the ENVI-met users' guide recommends that the domain height be at least twice the height of the tallest object in the domain and a minimum of 30 m. As a result, it is not possible to conform to these guidelines using vertical resolutions any finer than 0.75 m. Simulations involving finer resolutions were attempted, but resulted in computational instabilities, crashing the model with a floating point error message.

This "flat" domain is configured to represent urban surfaces in a street-like pattern, perpendicular to the wind flow in the domain (Fig. 1). This configuration, as well as the chosen atmospheric input data (summarized in Table 2), allows for some variation in vertical mixing between parts of the domain, which helps in highlighting potential differences between vertical resolutions.

***Table 2**. Atmospheric input and configuration settings selected for the nine simulations.*

Simulation Day (DD.MM.YYYY)	22.08.2011
Simulation Start Time (HH:MM:SS)	4:00:00
Total Simulation Time (hr)	24
Wind Speed at 10 m above ground (m/s)	2
Wind Direction (°, clockwise from 0:N)	270
Roughness Length z_0 (m)	0.01
Initial Atmospheric Temperature (K)	295
Initial Relative Humidity (%)	50
Output interval main files (min)	60
Output interval log files (min)	30
Include Nesting Grids in Output	No

Location	Portland, Oregon (45.5º N, 122.7º W)

To test the performance of mitigation strategies, similar to the work of Botham et al. (2015), we explore a low albedo control simulation, a high albedo roof test simulation, and a high albedo pavement test simulation of an idealized urban environment (Fig. 2). All domains consist of a 5x5 array of buildings, where each building is 8x8 m with a height of 3 m. The street widths between buildings are also 8 m. The horizontal spatial resolution of all simulations is 1 m and the vertical resolution is 2 m (Table 1). The buildings are composed of default hollow concrete blocks. The control simulation has terracotta roofs with an albedo of 0.15 and an asphalt surface with an albedo of 0.20 (Fig. 2a).

The high albedo roof test simulation maintains the same features as the control, except for increasing roof albedo to 0.85 from 0.15 (Fig. 2b). All other roof characteristics remain unchanged from the defaults of ENVI-met's predefined terracotta roof. This allows for examination of targeted heat mitigation strategies without the possibility of other variables changing or affecting the simulation. The high albedo pavement test simulation replicates the roof test simulation approach, but for the ground. The only difference between the control and high albedo pavement test is a surface albedo of 0.90 (Fig. 2c).

We used the ENVI-met application tool Leonardo for visualizing and analyzing model output. Air temperatures were output at the z-levels (vertical levels) just above and below 2 m and were then interpolated to get air temperature data at 2 m across the domain. The output must be interpolated to 2 m since the model's vertical levels change with vertical resolution as discussed earlier. This interpolation approach is used for all simulations in this study. The vertical resolution of the mitigation cases (with buildings) remains the same, though this interpolation is still used to compare the impact of parameterization to simulation physical environmental changes. Statistical analysis to quantify the significance of the results uses the interpolated air temperatures for 2 m. The simulations are then compared to one another using the statistical analysis to test for grid independence, the efficacy of mitigation strategies, and the relative magnitude of their impacts. Due to non-normality in the distributions of air temperature, the statistical approach of bootstrapping is selected to compare the mean air temperatures across simulations.

The Bootstrapping approach allows for comparison of samples from different sources by using a large number of repetitions in resampling the data to obtain a normal distribution of some population statistic (Efron, 1981). Bootstrapping produces a non-parametric test statistic that is predicated on resampling with replacement. A test statistic is then obtained from this re-sampled distribution. The Central Limit Theorem dictates that this test statistic will be normally distributed, no matter the size or distribution of the underlying population. This allows us to then compare mean air temperature results from the various simulation cases.

Standard procedure when using the bootstrapping approach is to use a repetition number of at least 1,000. For the purposes of this research, a repetition number of 10,000 is used (20,000 was tested with similar results). The mean near-surface air temperature of each simulation is calculated by taking the values from each grid cell at the interpolated 2 m height (8400 cells per domain) and averaging. The mean is then resampled with replacement 10,000 times using the 8400 cells per domain. This creates a distribution of mean temperatures for each simulation. If the mean of each grid resolution simulation is statistically similar to the other simulation means, then it cannot be concluded that the simulations are statistically different and the simulations are deemed to be grid independent. The same statistical methodology is applied to the mitigation strategy simulations.

4. Results and Discussion

Interpolated 2 m air temperature histograms of the six grid resolution simulations (using the “flat” domain) for mid-afternoon (15:00) are plotted in Fig 3. Mid-afternoon temperature values were selected as a representation of peak heating, balancing the timing of maximum solar radiation and maximum air temperatures. While the effects of albedo may also have an influence on nocturnal air temperatures, the simulation found no appreciable difference in temperature between the simulations at night. The values from this single time step range from 29° to 30°C; however, when comparing the histograms of the different simulations, none of the distributions follow a normal distribution. Therefore, bootstrapping is used to generate the 95% Confidence Interval (CI) of mean temperature results from each simulation (Fig. 5). Of the six simulations, only two (the 0.75 m vertical resolution and the 1.00 m vertical resolution) are not significantly different from each other (Fig. 5).

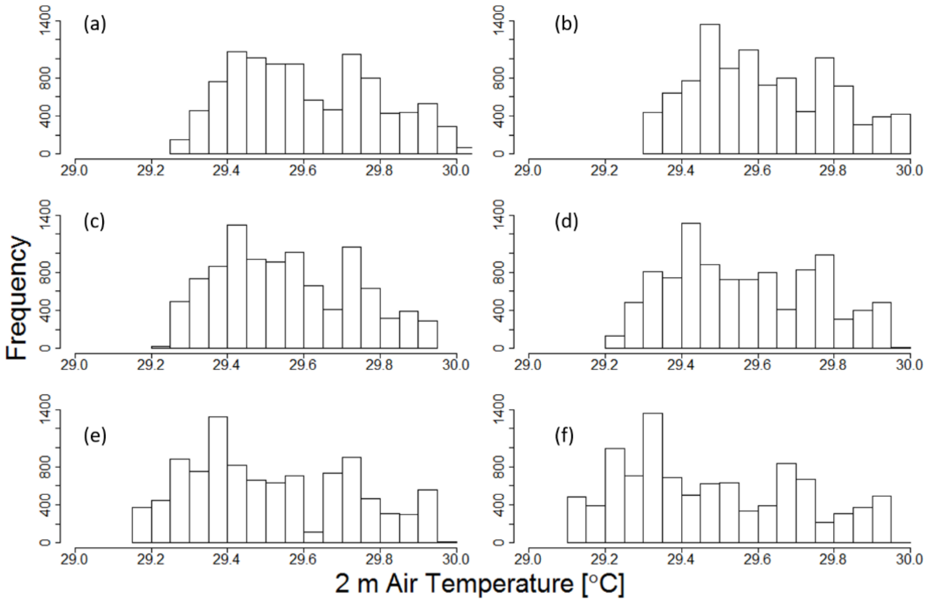

Figure 3. The interpolated 2-meter air temperature distributions from the six grid independence testing simulations for vertical resolutions of (a) 0.75 m , (b) 1.00 m, (c) 1.25 m, (d) 1.5 m, (e) 1.75 m, and (f) 2.00 m.

Using the building grid domain (Fig. 2), three simulations were run to explore the impact of mitigation strategies: a base case, a high albedo roof case, and a high albedo pavement case. The distribution of each simulation’s interpolated 2m air temperature is plotted in Fig 4. As the results for each simulation were not normally distributed, the data were bootstrapped to obtain the 95% CI of the mean temperature results (Fig. 6).

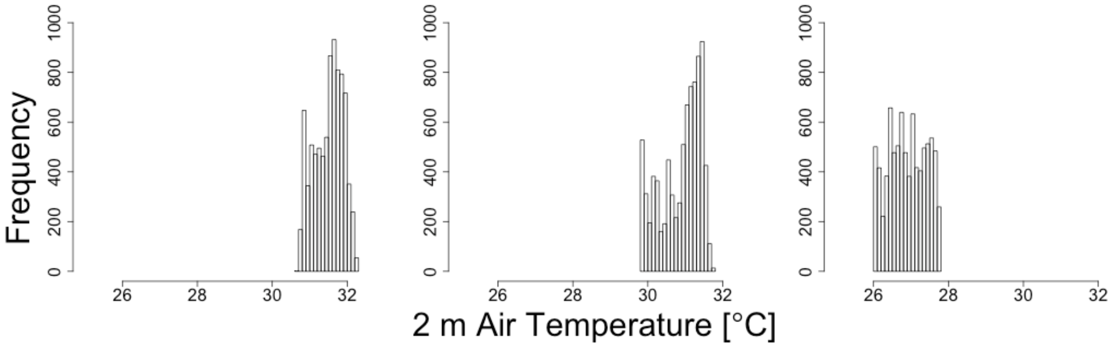

Figure 4 is the interpolated 2-meter air temperature distribution for mitigation strategy simulations (and their control simulation). (A) is the control simulation, (B) is the high albedo pavement simulation, and (C) is the high albedo roof simulation.

The results clearly indicate that 2 m air temperatures from the control and two mitigation strategies are statistically significantly different from each other (Fig. 6). This result leads to the final question as to whether the magnitude of projected difference in air temperature for the mitigation strategies is large enough that the grid independence shortcomings are important. Comparing Figure 5 with Figure 6, the air temperature changes resulting from the mitigation strategies is 10 to 40 times larger than errors introduced by the grid-sensitivity to vertical resolution.

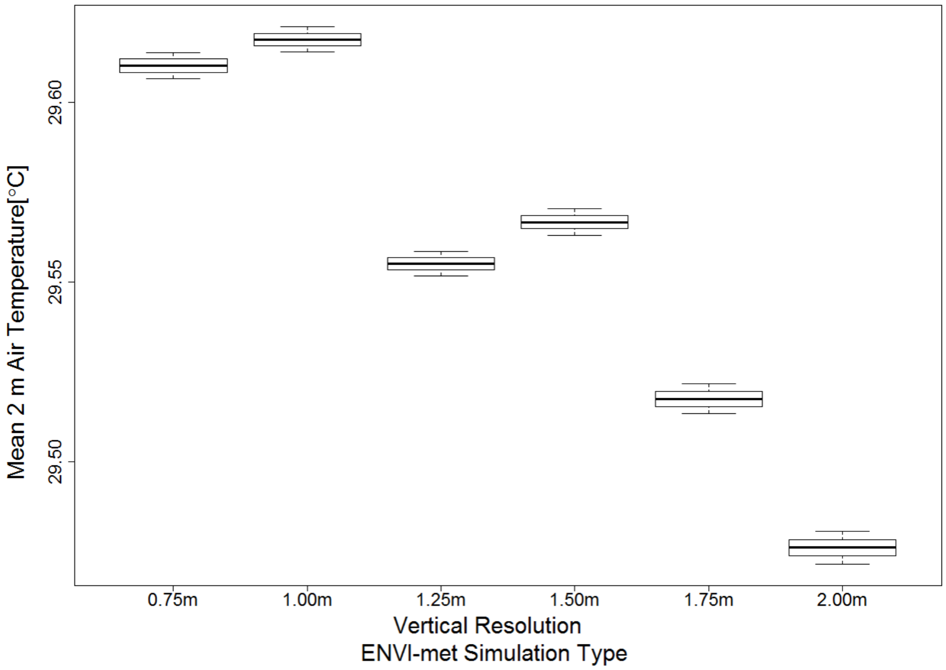

Figure 5 Mean +- 95% confidence interval for grid independence test simulations. The confidence intervals are from the averaged 2 m air temperatures that are bootstrapped for each simulation. The plots have a box around the 25-75th quartile, with a bar at the mean, and small bar at the top and bottom for the 2.5 and 97.5 percentiles (composing the 95% CI).

Figure 6 shows that in regard to pedestrian-level cooling benefits, strategies that involve increasing the albedo of the urban surface, result in lower air temperatures at the pedestrian level with the largest decrease in air temperature occurring with the high albedo pavement (4-5 °C reductions). Although the magnitude of change is smaller, our simulations also show a statistically significant decrease in air temperature when the albedo on roofs (at a 3 m height) are increased (0.5-1 °C reductions).

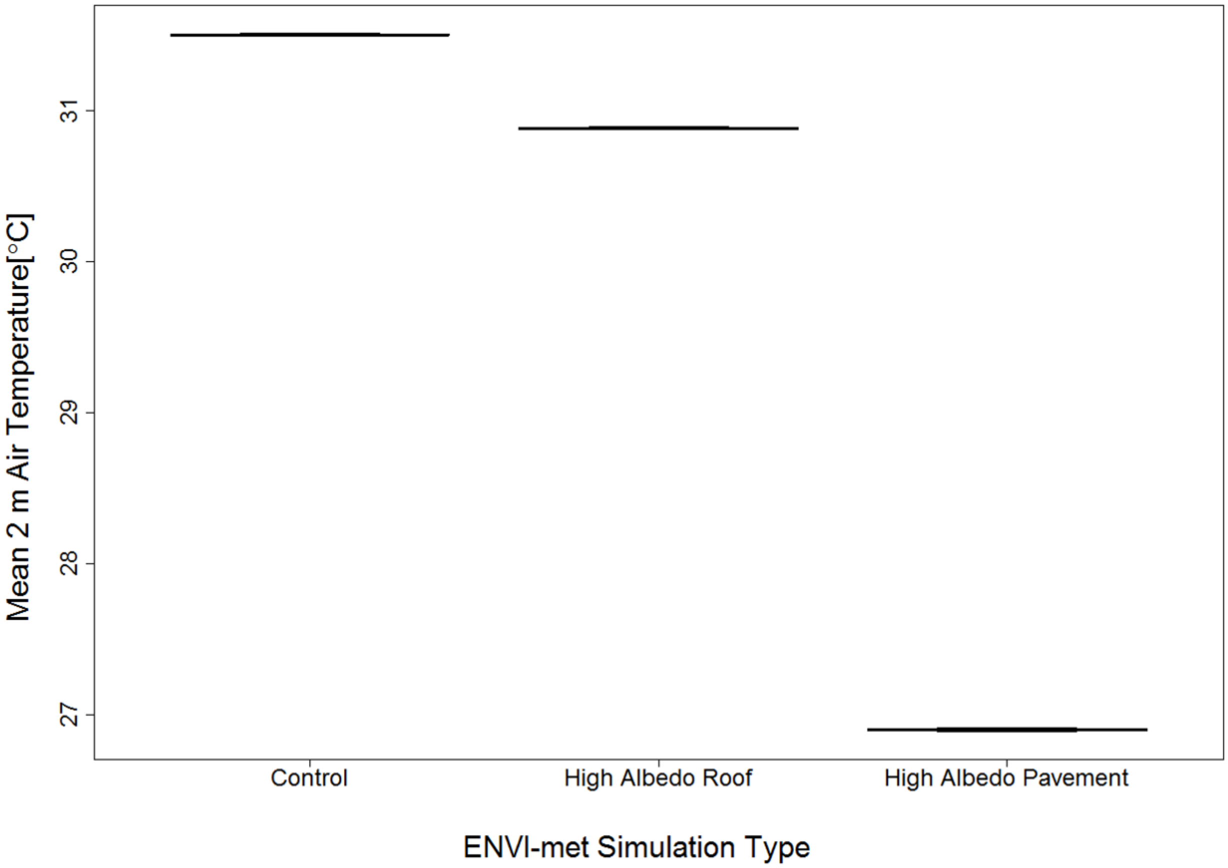

Figure 6 Mean +- 95% CI of the averaged 2 m air temperatures that are bootstrapped for the control, high albedo roof, and high albedo pavement simulations. The plots have a box around the 25-75th quartile, with a bar at the mean and small bar at the top and bottom for the 2.5 and 97.5 percentiles (composing the 95% CI).

5. Limitations

Despite the extensive use of ENVI-met over the past decade to answer questions pertaining to the urban surface and its influence on the urban atmosphere, there have not been many studies that seriously considered the limits of the software in relation to the sensitivity of the scale at which the model is run. Some researchers use measured vs. modeled error metrics to qualify their results for air temperature, but have not analyzed the sensitivity of the model to its own parameters (Chow and Brazel, 2012; Emmanuel and Fernando, 2007; Middel et al., 2014; Yang et al., 2013). Other researchers are more skeptical of ENVI-met's performance in representing heat transfer between buildings and the atmosphere, and therefore have also called for more rigorous testing of numerical modeling of the atmosphere (Buccolieri et al., 2015; Maggiotto et al., 2014).

Our results confirm the concerns voiced by Maggiotto et al. (2014) who found other issues with heat flux and neighborhood air temperature results from ENVI-met. They suggest rigorous model tuning to improve the performance; however, the reservations that the model may not produce consistent results when the grid resolution is changed also sheds light on a limitation regarding tuning the model for improved prediction of the heat flux and air temperature. This study shows that there are statistical differences between models; however, these differences are less than the magnitude of the change in surface albedo. Thus, the relative magnitude of the error associated with model resolution is less than the modeled differences of mitigation strategies.

Under a similar design set up to that of Botham-Myint et al. (2015), our results show a weaker effect of heat mitigation strategies on air temperature (~0.15 – 0.2° C) at the pedestrian level (Fig. 6). This magnitude of change is somewhat lower than other research which suggests temperature reductions of 0.5-1.5° C, depending on scale (Botham-Myint et al., 2015; Zhang et al., 2016). Shade may have a small influence on the results; however, with building heights at 3 m and sun angles being high due to simulation design, the influence of shade by building is minimal. The lower effect may be due to some of the limitations we experienced in using ENVI-met.

A key issue was finding the correct wind profile set up in the model configuration to prevent the model from crashing due to turbulence related to vertical motion near the beginning of the model run. This may have resulted in key model physics differences between our work and Botham et al. (2015) that contributed to differences between the model results. Specifically, the wind profile in ENVI-met (v4.3) cannot represent shifts in the predominant wind pattern that are commonly observed in urban settings and poorly represent the influence of surrounding urban infrastructure. These limitations are known (Bruse, 2009), but must be reiterated as another potential improvement in the modeling of urban climates. Additionally, the grid spacing and resolution of the buildings and the domain were different as well due to the previously mentioned limitations in the capacity of the ENVI-met code.

While this research focuses on the importance of model grid independence, ENVI-met suffers from additional limitations with respect to how buildings are created in the SPACES application of ENVI-met. These limitations are easily avoided through careful study design and therefore are things that are guiding principles when working with ENVI-met. Specifically, while the user is allowed to create a building of any height, during simulation, the software adjusts the building height to the closest vertical level without any warning to the user that this change has occurred. This limitation in ENVI-met makes it impossible to fully test grid-independence for realistic domains, as any change in grid resolution also changes the modeled heights of buildings. This issue also limits any use of ENVI-met to flat roofs as a pitched roof would require multiple heights for a single building at a fine scale.

Additionally, while the model allows for vertical mesh refinement near the ground surface, the inability to have a refined mesh adjacent to all horizontal and vertical surfaces in the model domain limits the accuracy of representation of heat transfer processes at walls and at the rooftop level. Accurate representation of the impact of rooftop mitigation strategies on the pedestrian level atmosphere depends on several things, including, the vertical transport of heat being modeled accurately. However, due to the large number of factors influencing observed temperatures within any urban canyon, it is possible for validation efforts to reveal good agreement between computer models and observations, without necessarily capturing this vertical transport with any fidelity. Other principles include issues and usage of wind profiles and the estimation of boundary conditions which have been brought up in previous literature as well (Middel et al., 2014).

6. Conclusions

The questions of ENVI-met's validation in regard to the surface energy balance, grid sensitivity/independence, and efficacy for evaluating rooftop level mitigation strategies were investigated through a study of the literature as well as through idealized simulations designed, first to isolate the effect of grid resolution, and then to isolate the impact of the mitigation strategies. The results indicate that although ENVI-met is not grid independent, the magnitude of the software's dependency on grid resolution is less than the magnitude of the simulated effects of the mitigation strategy. Therefore, we believe ENVI-met-projected impacts of heat mitigation strategies on air temperature are not being overshadowed by the impact of grid sensitivity to changes in vertical resolution.

The published literature does not reveal a significant amount of research into the accuracy of ENVI-met for atmospheric variables other than air temperature. This gap in the literature was not fully explored within our research but remains an area for future study. Research in this arena must consider new ways of measuring and testing ENVI-met's ability to represent atmospheric variables in the urban environment other than through air temperature. A specific need is future research that evaluates the performance of ENVI-met with respect to modeling the surface energy balance, including latent and sensible heat fluxes. These fluxes also depend on the thermal mass of the urban form. Currently, ENVI-met does not represent this within its calculations. Therefore, the surface energy balance is limited in its ability to represent the urban environment. Furthermore, additional studies should be undertaken to quantify the ability of the model to accurately represent vertical mixing from ground to roof level.

Our results suggest that ENVI-met is not grid independent even when there are no buildings in the domain. This is not in accordance with best practices in the CFD modeling community, which demand grid independence (Blocken et al., 2007). However, lack of grid independence itself does not necessarily invalidate the use of ENVI-met for heat mitigation research.

Specifically, as long as the magnitude of the uncertainty introduced by the grid sensitivity is small relative to the magnitude of the modeled effects of the tested heat mitigation strategy (which is the case in this study), the use of ENVI-met for heat mitigation may not be inhibited by grid sensitivity. Given that ENVI-met cannot be tested for grid independence for simulations involving buildings, modelers should still use ENVI-met with caution, particularly when simulating heat mitigation strategies applied at the roof-level. A possible method for future modeling designs is to measure multiple points within a domain and study other atmospheric variables, such as moisture content, wind, and radiation to confirm the quality of ENVI-met simulations.

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