A Framework for Outdoor Mean Radiant Temperature Simulation: Towards Spatially Resolved Thermal Comfort Mapping in Urban Spaces

Tarek Rakha[1], Pouya Zhand[1] and Christoph Reinhart[2]
[1]School of Architecture, Syracuse University, Syracuse NY, USA
[2]Department of Architecture, Massachusetts Institute of Technology, Cambridge MA, USA

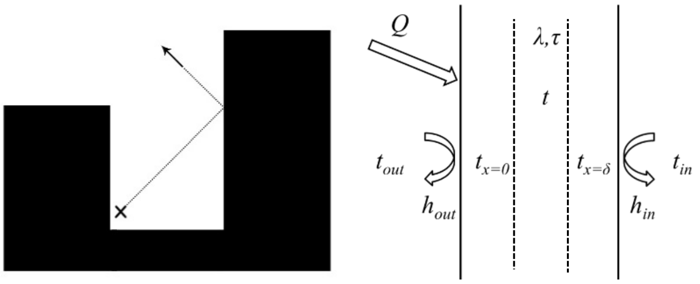
Abstract

Mean Radiant Temperature (MRT) is a critical physical quantity that indicates how human beings experience radiation in their surrounding environment. If taken outdoors, MRT depends on the temperature of the sky, ground, vegetation and surrounding buildings, and is therefore difficult to predict reliably. An additional challenge for designers is that publically available simulation tools do not produce reliable outdoor MRT outcomes within a design environment. Hence, this paper presents a raytracing-based simulation methodology for spatially and temporally resolved MRT mapping and consequent outdoor thermal comfort assessment. Following a description of the simulation workflow, the method is applied to a case study of an outdoor space in Syracuse, NY, USA.

Introduction

The form and function of the ever-growing cities that humankind erects and inhabits influence various microclimatic aspects within built environments. If parameters that affect urban microclimates were better understood and properly manipulated, then urban dwellers' quality of life could be improved dramatically (Erell, Pearlmutter, & Williamson, 2011), given that local governments would implement change through lessons learned. Designers strive to create spaces that encourage outdoor activities, and it is well understood, that outdoor thermal comfort conditions influence how residents use public spaces for day-to-day interactions and enjoyment (Brown, 2010). Activities such as walking and cycling are influenced by people's comfort in, and consequent satisfaction with, outdoor environments. That is why measures for evaluating pedestrian environmental comfort and computer-based design tools are gradually gaining interest among architects and urban planners. The motivation for using these tools is to test the performance of buildings and their influence on various public spaces (Robinson, 2011). The need to incorporate design-decision support tools in robust and reliable workflows has become essential. As described in the following review, there are a number of tools available to model outdoor thermal comfort conditions. However, these tools require advanced expertise to simulate microclimatic aspects and are only capable of modelling a few moments in time, as opposed to a full year.

A number of simulation tools have been previously developed to simulate urban microclimates, with a specific focus on the MRT (Fanger, 1970). MRT is challenging to model, since it relies on heat transfer principles to produce surface temperatures for the required period of analysis in the examined space. It also needs geometric analysis capabilities in order to create accurate form factors for the analysis nodes to trace how much each nodes "sees" from all surrounding surfaces in the environment, as well as the sun and sky. A recent and relevant development to model MRT accurately is CityComfort+, which presents a method to simulate the spatial variation of MRT in dense urban environments (Huang, Cedeno-Laurent, & Spengler, 2014). The method is rigorous and has found good agreement between simulated and measured data. However, the workflow assumes that urban surfaces fall within four categorizations of sunlit and shaded walls and ground, with no spatial resolution. This creates a lack in variations that urban surfaces exhibit in reality through change in short-wave and long-wave radiation values in an open space, which could be modelled explicitly to get finer and more reliable representation, which lend themselves to spatially more nuanced urban design interventions such as where to best place a parkbench. ENVI-met is a software package that focuses on urban microclimates (Toudert-Ali, 2005). It is constantly under development, and it can compute MRT in various urban situations, as well as other microclimate aspects such as wind speed and directions and comprehensive comfort metrics such as Predicted Mean Vote (PMV). In its latest release at the time of writing of this paper, ENVI-met is able to calculate radiation at every grid level. Unfortunately, it cannot process vector-based geometries, and works through pixel-based modelling. This makes its use tedious in design, as buildings, topography and vegetation are modelled over raster images. It is also a computationally expensive workflow, where a 24-hour simulation can take 24 hours to simulate, with limitations of predicting long-wave radiation fluxes. The RayMan model is a simulation platform that aims to calculate radiation flux densities, sunshine duration, shadow spaces and thermo-physiologically relevant assessment indices using only a low number of meteorological and other input data (Matzarakis, Rutz, & Mayer, 2010). The model's limitations are lack of compatibility with low solar angels, and its inability to account for reflected short-wave radiation. Another development is the SOLWEIG model



$$\begin{cases} \dfrac{\partial t}{\partial \tau} = a\dfrac{\partial^2 t}{\partial x^2} \\ -\lambda \dfrac{\partial t\big|_{x=0}}{\partial x} = h_{out}\left(t_{out} - t\big|_{x=0}\right) + Q \\ -\lambda \dfrac{\partial t\big|_{x=\delta}}{\partial x} = h_{in}\left(t\big|_{x=\delta} - t_{in}\right) \end{cases}$$

Figure 1: Exterior façade backwards raytracing workflow and heat diffusion calculations.
Where: Q = Solar Radiation (W/m^2) h = convection coefficient (W/m^2.K) t_{out}= External Temperature (°C) t_{in}= Internal Temperature (°C) τ = Time (Minutes) λ = Conductivity (W/m.K) a = Diffusivity (s/m^2) x = Depth (m)

(Lindberg, Holmer, & Thorsson, 2008), which uses Digital Elevation Models (DEMs) as a GIS compatible pixel-based geometry input. This method uses simplified workflows for 3D geometry and microclimate elements such as diffused and reflected solar radiation, and it is also limited with density simulated. There are multiple other methods that were developed and were either not scientifically validated against measured data, or are not available for public use. Hence, there is a need for simulation tools that aid designers in exploring their design decision impacts on various aspects of outdoor microclimates, in a robust and timely manner, which is the focus of this work.

This paper presents a new simulation methodology for spatially and temporally resolved outdoor thermal comfort assessment. The tool is developed as a Grasshopper component within the 3D Computer Aided Design (CAD) software Rhino3D (Robert McNeel & Associates, 2016). Grasshopper is a visual scripting environment which support the geometric manipulation and environmental analysis of objects in a Rhino scene. The MRT simulation process is divided into 3D modelling as a first step to produce what is called an "Urban Surfaces" model. Hourly surface temperatures are then simulated using annual radiation falling on all subdivisions of Urban Surfaces, to become an input for Heat Diffusion Equations used to calculate surface temperatures. The tabulated results for every hour of the year are then recalled as part of a workflow to calculate MRT through analysis nodes. To compute MRT, the analysis nodes also use raytracing for surface temperatures, as well as short-wave/long-wave sun and sky radiation.

Simulation Method

To predict comfort metrics in urban environments, the simulation method combines multiple approaches that include Radiance-based backwards raytracing, and a custom admittance model to estimate mean radiant temperatures over time. The following sections detail the components of the presented simulation methodology, focusing on Urban Surface temperature simulation and consequent MRT calculations.

Façade / Ground Thermodynamics and Simulation

A three-dimensional model in Rhinoceros 3D is used to model the outdoor urban environment. The simulation workflow utilizes a custom module in Grasshopper that meshes each building and ground surface for surface temperature simulations. The Radiance-based (Ward, 1994) Daysim (Reinhart & Walkenhorst, 2001) program is used to calculate hourly radiation values on a grid of outward facing sensors that are laid across all urban surfaces in the model. Exterior radiation values are then used to compute surface temperature using the thermal admittance method (Heat Diffusion Equation) (Lienhard V & Lienhard IV, 2011). The admittance method (façade and ground) includes several components that comprise solar radiation, outdoor convection, conduction through surfaces and indoor convection. Conduction presents a challenge through its three dimensionality. However, conduction through urban surfaces can be simplified as one dimensional heat transfer through the heat diffusion equation. The simplified heat transfer process of the façade is shown in Figure 1, which shows three equations that define heat transfer inside the wall, external boundary conditions and internal boundary conditions. They translate into the heat transfer equation (1), which calculates temperature within each wall layer for simulation purposes. The façade depth is discretized into a number of layers (k) with a thickness of Δx, and temporal temperature change is also discretized into Δτ. For each layer a heat balance equation is built up:

$$h\left(t_f^k - t_1^k\right) - \lambda\frac{t_1^k - t_2^k}{\Delta x} = \rho c\frac{t_1^{k+1} - t_1^k}{\Delta \tau}\frac{\Delta x}{2} \qquad (1)$$

Where:

ρ = density (kg/m3)

c = specific heat capacity (J/K)

The resultant surface temperatures are then tabulated with reference to the meshing geometry in a database to be recalled for temporal MRT calculations.

MRT Simulation

MRT sums up all short and long wave radiation fluxes (both direct and reflected) to which the human body is exposed to (Thorsson, Lindberg, Eliasson, & Holmer, 2007). Figure 2 shows the main factors influencing MRT, which are broken down to short-wave radiation (direct, diffuse and reflected solar radiation) and long-wave radiation (sky and urban surfaces). For a 3D model a number of sensor nodes are generated to compute MRT as a step to simulate thermal comfort. The workflow is based on simplified twofold method (Kessling, Engelhardt, & Kiehlmann, 2013):

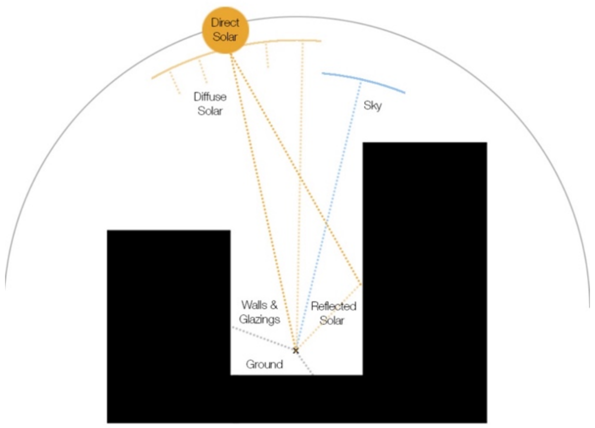


Figure 2: Built Environment and Environmental Parameters influencing MRT in an urban canyon.

- Direct and Diffuse Solar Radiation

Solar radiation has a significant influence on MRT. To be accurately represented, direct and diffused short-wave solar radiation need to be simulated. For the direct radiation component, analysis nodes are used as input for radiance to raytrace these components using Daysim's hourly irradiation method using Rhino3D plugin DIVA for Grasshopper. Daysim uses solar radiation data input from a weather station, which is typically reported as global horizontal radiation that is split into direct normal irradiance and diffuse horizontal irradiance using the Reindl method (Reindl, Beckman, & Duffie, 1990). The output is hourly radiation for each analysis node. With the short-wave solar radiation simulated, the MRT component is then calculated for each hour of the year based on the Stefan-Boltzman law:

$$MRT_{dir} = \sqrt[4]{f_p \cdot a_{s} \cdot \frac{I^*}{\varepsilon_p \cdot \sigma}} \tag{2}$$

$$MRT_{diff} = \sqrt[4]{\sum_{i=1}^{n} a_{s} \cdot \frac{D_i}{\varepsilon_p \cdot \sigma} \cdot F_i} \tag{3}$$

Where:

a_s = the short wave absorption coefficient of a person.

σ = the Stefan–Boltzmann constant (5.67•10-8 Wm-2K-4)

I^* = radiation intensity of the sun.

F_i = angle factor.

D_i= diffuse radiation.

ε_p = emission coefficient of clothing or skin.

- Long Wave Radiation

Sensors are used as input for Radiance to send spherical rays out from each sensor to raytrace with 0 bounces all surrounding surfaces. This means that the sensor is attempting to detect the first surface each ray hits. A database is created in reference to each node and the number of surfaces traced. Using this database view factors are computed based on the number of rays that hit each surface, which is controlled by the user as an accuracy level input, and the temperature of the traced surface is looked up in the surface temperature database previously simulated.

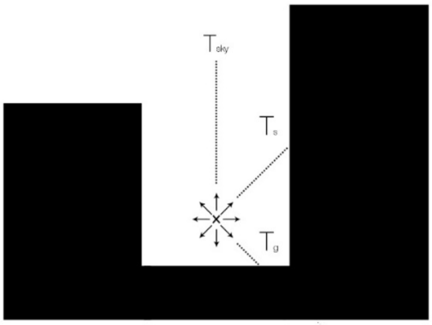


Figure 3: Sensor nodes and view factor raytracing workflow in an urban model.

For each node and time step the long-wave MRT is then calculated using the following formula:

$$MRT_{lw} = \sqrt[4]{T_1^4 F_{p-1} + \cdots + T_n^4 F_{p-n}} \tag{4}$$

Where:

T_n= Surface Temperature for surface "n" (Kelvin).

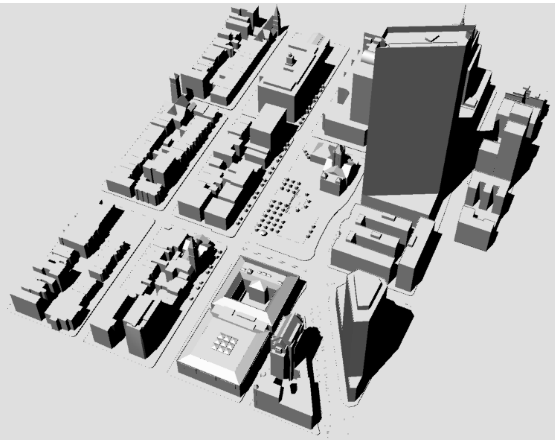
F_{p-n}= angle factor between sensor node and surface "n."

- MRT Calculation

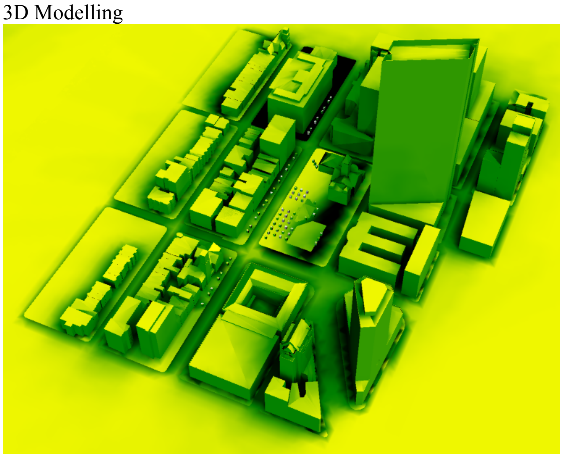
MRT is computed by adding the short-wave and long-wave MRT components:

$$MRT = \sqrt[4]{MRT_{dir}^4 + MRT_{diff}^4 + MRT_{lw}^4} \tag{5}$$

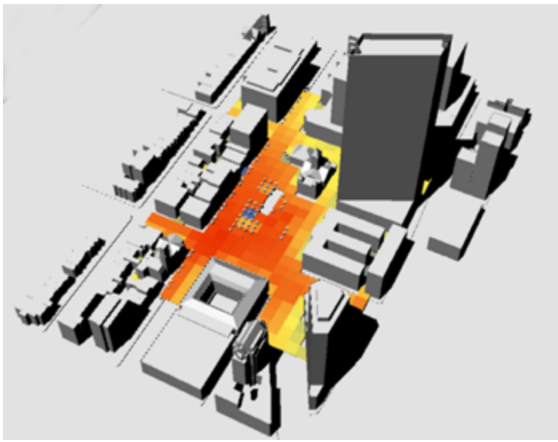
After MRT simulation, calculation of various comfort metrics such as PMV, Universal Thermal Climate Index (UTCI) and the like becomes achievable. Other parameters needed such as dry bulb temperature and relative humidity are extracted from weather data files, and wind speed, metabolic rates and clothing can be assumed. An example case of Copley Square in Boston is presented in Figure 4 to demonstrate the entire methodology's workflow, from 3D model creation, to surface temperature simulation and MRT calculations and mapping.



3D Modelling



Surface T Simulation



MRT Calculation

24 68 °C MRT

Figure 4: MRT simulation workflow applied to a 3D model of Copley Square, Boston, MA, USA on June 21st at 12 PM.

Example Case Study

As a proof of concept, a 3D model of Downtown Syracuse NY was built with the aim of mapping MRT performance across seasons and times. 102 buildings were modelled, including glazing and surrounding context of streets and sidewalks, which included 3006 surfaces (Figure 5). All buildings were assumed to have the same thermal properties as detailed in Table 1. 2582 nodes were generated for spatially resolved simulation purposes, set approximately 3.5m apart. Wind speeds' impact on convection coefficients was assumed to be constant.

Table 1: Urban Surfaces Model simulation inputs.

MATERIAL PROPERTY		
Wall	Thickness	0.3 m
	Density	1700 kg/m^3
	Heat Capacity	840 J/K
	Heat Conductivity	0.84 W/m.K
Glazing	Thickness	0.06 m
	Density	3000 kg/m^3
	Heat Conductivity	0.9 W/m.K
Indoor Temperature		26 ℃
Indoor Convective Efficiency		8 W/m^2.K
Outdoor Convective Efficiency		25 W/m^2.K
Ground Temperature		10 ℃
Ground Depth		10 m
Initial layers tested for each material		50
Meshing resolution for urban surfaces		8 m

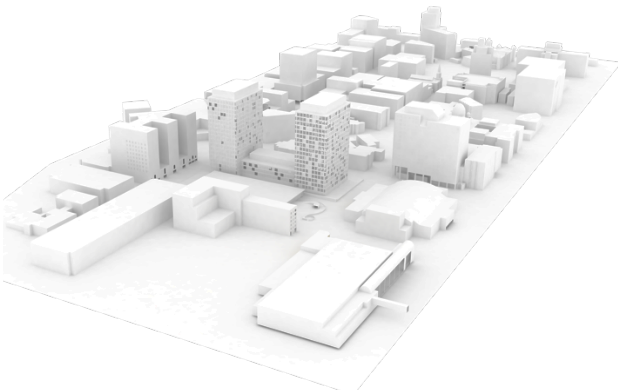


Figure 5: 3D Model of Downtown Syracuse NY USA.

Results

The developed method was applied on the Syracuse, NY case and ran successfully for 8 hours on an IMac Core i7 4ghz with 16gb ram. Figure 6 shows example spatially-resolved summer analysis for the case study area, where solar radiation has a direct influence on reduced sensation of MRT. Shadow patterns show a reduction in the order of 10 C MRT. In the June 20th simulation, intermediate sky conditions show minimum variation in MRT. In contrast, the July 4th simulation output under clear sky conditions show significant decrease in MRT values in shaded areas in the morning and noon simulations, which is a direct influence of solar radiation blockage by buildings. It is worth noting that simulation time scales linearly with the number of surfaces simulated, as well as the number of analysis grid points.

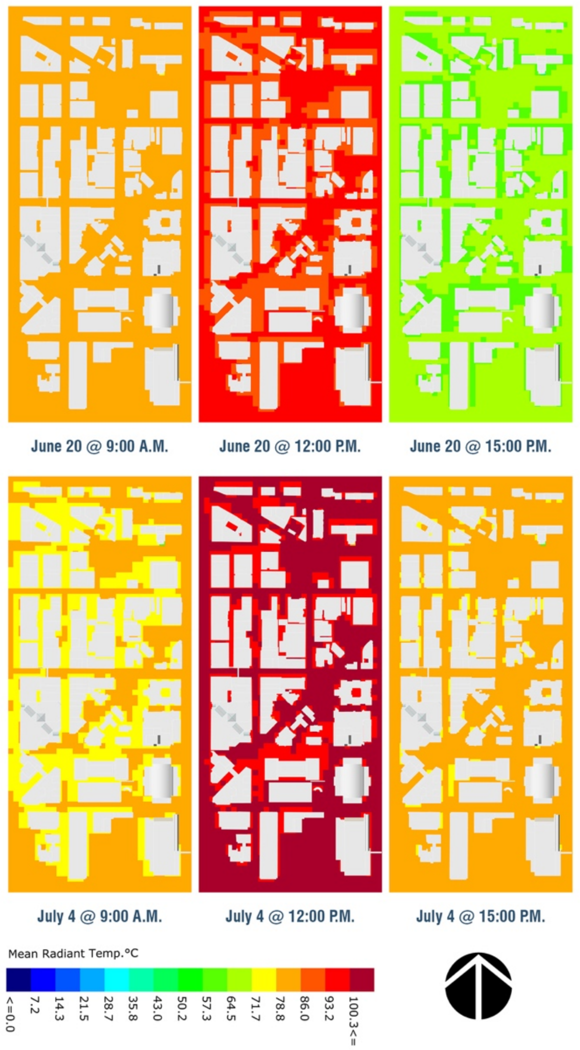


Figure 6: MRT simulation of Downtown Syracuse NY USA in representative summer days of June 20th with an intermediate sky cover and July 4th with a clear sky condition.

Discussion

The outcome of this simulation workflow is spatially resolved MRT, which translates to daily MRT values mapped in urban spaces, as demonstrated in Figure 7. While such an outcome is specifically interesting for seasonal design interventions, annual visualization of 8760 hours of an entire year is needed in order to understand impacts over different seasons and time, which should be further developed.

While thermal comfort metrics are typically static, and can be considered a potential prediction of a snapshot in time, our human sensations and perceptions are spatiotemporal. There is a need for dynamic interpretations of thermal comfort that comprehends diurnal, weekly and seasonal patterns. Figure 8 demonstrates a limited annual mapping approach that is challenged when spatio-temporal relationships need more in-depth detail. A snapshot in time in relevance to annual performance renders analysis mapping performing roughly the same way through the entire massing. The consistency of the legend range does not offer deeper insight into potential understanding of performance of outdoor spaces for different users and in different scenarios.

Outdoor thermal comfort is vital for public spaces. A walk down a comfortable street, or activities taking place in a public park require suitable microclimates for such undertakings, and designers have a say in the creation of these spaces. Human perception of the radiant environment is an important component in our sensation of comfort. Previously, architects and planners used design intuition, manual calculations, or computer tools that were not fully integrated in the design process to make informed outdoor comfort design decisions. The outcome may be inaccurate due to the outdated workflows, or cumbersome to interpret due to the technical know-how required to run such tools. Therefore, the simulation workflow presented in this paper was developed as a novel, robust method to calculate surface temperature and consequent MRT in urban spaces, with integration in the design environment of Rhino 3D and the Grasshopper plugin. While the use of raytracing significantly reduces simulation time, there is still development needed to produce reliable integration of long-wave radiation simulation. Although the method is based on previously validated building science, a validation experiment is needed to verify the accuracy of simulation outputs. There is also a need to develop a more holistic approach that would include other climatic factors such as wind speed, and its effect on comfort sensation

Figure 7: 3D representation of MRT simulation mapping in Downtown Syracuse NY USA. Cyan colours represent thermal "relief" as MRT values drop in shaded areas at the time simulated time.

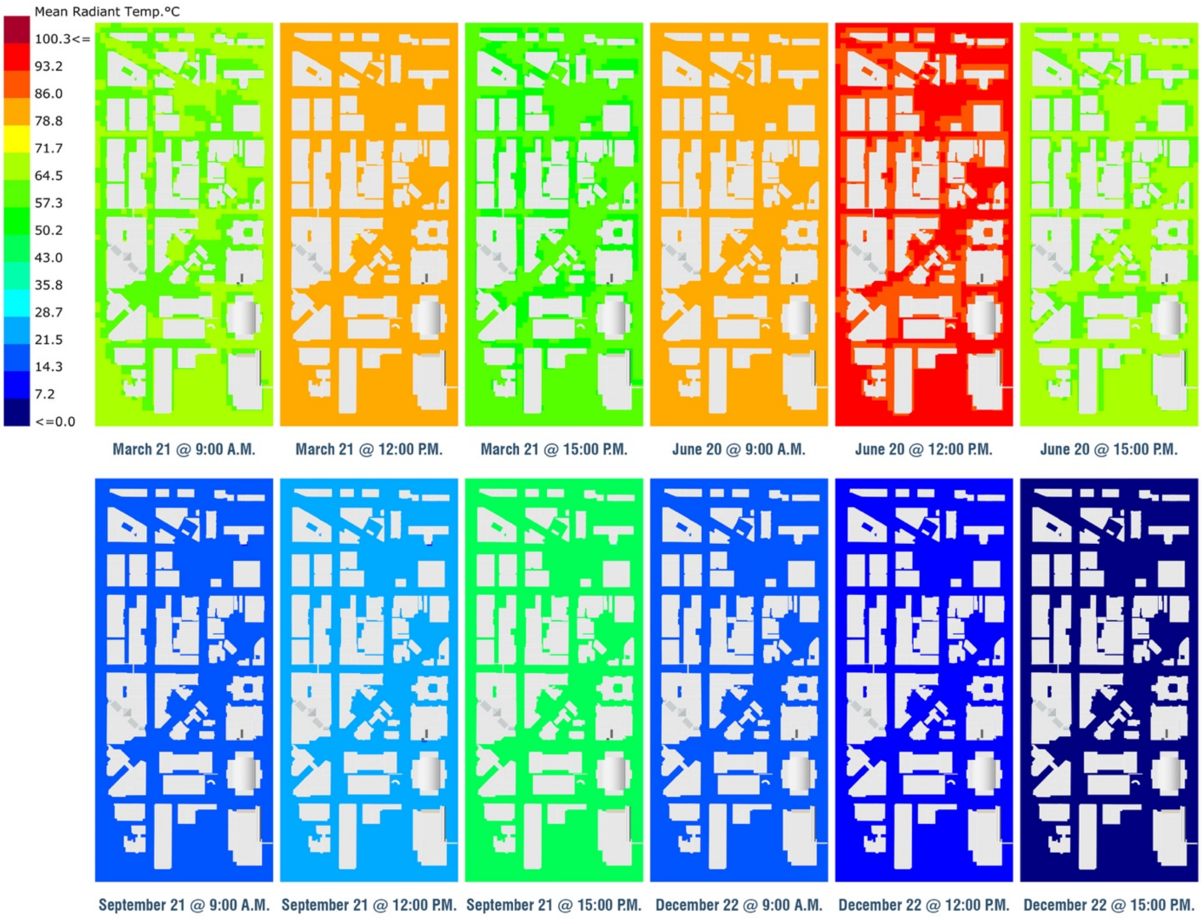


Figure 8: Annual representation of MRT performance in Downtown Syracuse NY USA. Due to the high range in annual MRT performance, spatial resolution is limited, where performance is not representing significant variations within a single instance of simulation (e.g. Dec 22nd all single solid color).

Conclusion

This paper presented a simulation workflow for MRT with the goal of creating an integrative design decision support tool to aid architects and planners in the creation of comfortable outdoor spaces. The workflow amalgamated building physics through heat transfer equations and computational raytracing to generate urban surface temperatures and mapping MRT in outdoor spaces. Future studies should focus on validation of the simulation framework by comparing simulated and measured MRT using greyglobe thermometers in different urban canyon configuration, and the development of dynamic outdoor thermal comfort metrics.

Acknowledgement

The simulation experiment for Syracuse NY is based on work supported in part by the New York State Energy Research and Development Authority (NYSERDA) and New York State Department of Transportation (NYSDOT), grant no. 83182. The opinions, results, findings, and/or interpretations of data contained therein are the responsibility of the authors and do not necessarily represent the opinions, interpretations, or policy of the State, NYSERDA, and NYSDOT. The authors would like to thank Timur Dogan and Bing Wang for their contributions to the development of the surface temperature simulation component of the workflow.

References

Brown, R. D. (2010). *Design with Microclimate: the Secret to Comfortable Outdoor Space*. Washington DC: Island Press.

Erell, E., Pearlmutter, D., & Williamson, T. (2011). *Urban Microclimate: Designing the Spaces Between Buildings*. London: UK: Earthscan.

Fanger, P. O. (1970). *Thermal comfort. Analysis and applications in environmental engineering*. New York: McGraw-Hill.

Huang, J. (2013). *Microclimate, Thermal Comfort and Urban Form*. Cambridge, MA: Doctoral dissertation.

Huang, J., Cedeno-Laurent, J. G., & Spengler, J. D. (2014). CityComfort+: A simulation-based method for predicting mean. *Building and Environment* (80), 84-95.

Kessling, W., Engelhardt, M., & Kiehlmann, D. (2013). The human bio-meteorological chart – a design tool for outdoor thermal comfort. Passive Low Energy Architecture Conference (PLEA). Munich.

Levitt, B., Ubbelohde, M., Loisos, G., & Brown, N. (2013). Thermal Autonomy as Metric and Design Process. *CaGBC National Conference and Expo: Pushing the Boundary–Net Positive Buildings*, (pp. 47-58). Vancouver.

Lienhard V, J. H., & Lienhard IV, J. H. (2011). *A Heat Transfer Textbook*. Meneola: New York: Dover Publications.

Lindberg, F., Holmer, B., & Thorsson, S. (2008). SOLWEIG 1.0–Modelling spatial variations of 3D radiant fluxes and mean radiant temperature in complex urban settings. *International journal of biometeorology*, 52(7), 697-713.

Matzarakis, A., Rutz, F., & Mayer, H. (2010). Modelling radiation fluxes in simple and complex environments: basics of the RayMan model. *International Journal of Biometeorology*, 131-139.

Reinhart, C., & Walkenhorst, O. (2001). Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. *Energy and Buildings*, 33(7), 683-697.

Reindl, D. T., Beckman, W. A., & Duffie, J. A. (1990). Diffuse fraction correlations. Solar energy, 45(1), 1-7.

Robert McNeel & Associates. (2016, 12 17). Rhinoceros. Retrieved from https://www.rhino3d.com/

Robinson, D. (2011). *Computer Modelling for Sustainable Urban Design: Physical Principles, Methods & Applications*. London: UK: Earthscan.

Thorsson, S., Lindberg, F., Eliasson, I., & Holmer, B. (2007). Different methods for estimating the mean radiant temperature in an outdoor urban setting. *International Journal of Climatology*, 27(14), 1983-1993.

Toudert-Ali, F. (2005). *Dependence of outdoor thermal comfort on street design in hot and dry climate*. Doctoral thesis. Freiburg: Universitätsbibliothek.

Ward, G. J. (1994). The RADIANCE lighting simulation and rendering system. *Proceedings of the 21st annual conference on Computer graphics and interactive techniques*. Orlando.