

The impact of trees on passive survivability during extreme heat events in warm and humid regions

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Abstract: Communities are increasingly affected by excessive heat. The likelihood of extreme heat events is predicted to increase in the Midwest region of the United States. By mid-century (2036–2065), one year out of 10 is projected to have a 5-day period that is 13°F warmer than a comparable earlier period (1976–2005). The frequency of high humidity/dew point days (“extra moist tropical air mass days,” MT++ synoptic climate classification system) has also increased significantly during a similar period (1975–2010) and between 2010 and 2014 included 8 of 26 heat events. This impact is exacerbated by the fact that many residences in low-income neighbourhoods in the US do not have central air-conditioning systems (e.g., up to 50% of low-income homes in Polk County, the location of our study in the US Midwest). Modifications to urban landscapes by the addition of trees can modify temperatures in the nearby environment, which is important for reducing summer heat loads on building surfaces. Trees can reduce energy use and improve indoor and outdoor comfort for cooling in summer by casting shade and providing evapotranspirational (ET) cooling. This paper presents a methodology to combine spatially explicit three-dimensional tree morphology and estimates of ET rates with building location and wall characteristic data to test their relative contribution to building energy consumption. Based on a comprehensive tree inventory for our Midwestern study neighbourhood, tree morphology and building data have been integrated in a three-dimensional array in the “Urban Modeling Interface” (*umi*) to estimate cooling due to interception of sunlight. We then perform a series of parametric computational fluid dynamics (CFD) studies to simulate ET cooling for various tree morphologies and relative locations to walls. We resolve conventional mesh generation challenges associated with CFD by introducing a novel, immersed boundary framework based on adaptive octree meshes. This approach can seamlessly include trees and buildings at arbitrary locations with minimal human effort. This model was run with and without trees to quantify the relative impact of that process in the microenvironment. The paper presents first results of CFD modeling for latent heat transfer near urban trees.

Keywords: climate adaptation, passive cooling, urban forest, computational fluid dynamics model, evapotranspirational cooling

1. Introduction

Globally, communities are increasingly affected by excessive heat, which can lead to increased human morbidity and mortality. The likelihood of extreme heat events is predicted to increase markedly in the Midwest region of the United States. By mid-century (2036–2065), one year out of 10 is projected to have a 5-day period that is 13°F warmer than a comparable earlier period (1976–2005; Melillo et al. 2014). Current average annual 5-day maximum temperatures range from about 87°F along the Canadian border to 97°F in Missouri. The frequency of high humidity/dew point days (“extra moist tropical air mass days,” classified as MT++ according to the synoptic climate classification system; Sheridan 2018) has also increased significantly during a similar period (1975–2010) and between 2010 and 2014 included 8 of 26 heat events. Seven out of 12 MT++ days caused a 10% to 30% increase in daily human mortality by the fifth day of extended heat events of 90°F or more (Kalkstein 2014). This impact is exacerbated by the fact that many residences in low-income neighbourhoods in the US do not have central air-conditioning systems (e.g., up to 50% of low-income homes in Polk County; PCHD 2018).

Our research team is developing novel hybrid data-physics models to assimilate weather, building, and near-building microclimate data to integrate with a building energy simulator to forecast building interior temperatures during real-time events or to create scenarios to enhance community preparedness (Hashemi et al. 2018). This approach can combine data across spatio-temporal scales (i.e., satellite, community, home, and individual) with physics-based models of near-building and indoor environments for real-time identification and predictions of locations most affected by extreme heat events.

Members of the project team have conducted relevant research on occupant-building-microclimate relationships and validation of CFD models for urban energy dynamics (Mutti 2014; Deza et al. 2015). They have analyzed multi-phase convective heat transfer in complex geometries (Sharma et al. 2018), symbolic abstraction for optimization of energy efficient buildings (Sarkar et al. 2012, 2013), and human-machine interactions (Lore et al. 2015, 2016). Additional work focused on algorithms for urban heat island modeling and impacts on building energy use (Zhou et al. 2012; Guneralp et al. 2017). In addition, this work has included investigations of the effect of human-building interactions on building energy performance (Kalvelage et al. 2015, 2016), climate change predictions for urban systems (Rabideau et al. 2012), and their integration in the urban modeling interface (umi) to understand impact of weatherization in future climates (Jagani & Passe 2017).

2. Background – Urban Heat and Comfort at the Extreme

The Polk County Health Department (PCHD) (with jurisdiction over Iowa's capital, Des Moines, and adjacent suburban/rural communities) has indicated a critical need for improved knowledge about vulnerability of residents to extreme heat. Preliminary measured data for homes in the Bank neighbourhoods of Des Moines showed that temperatures inside non-shaded, poorly insulated, or non-ventilated homes can be even higher than ambient temperature, conditions that are common in resource-limited neighbourhoods and thus hinder comfort at these extreme conditions. Those uncomfortable conditions are even detrimental to health and wellbeing of occupants, particularly during heat events of extended duration (Lomas & Porritt 2017).

In the US Midwest, events above 90°F for 3 days or more are considered significant heat events, also called "heat waves." A significant impact of excessive heat is increased human mortality (for example, 670 people died during the 1995 Chicago heat wave). As indicated, increasing frequency of MT++ days have resulted in 10% to 30% increases in daily heat-related mortality (Kalkstein 2014). Peak dew points on the most oppressive days have also increased over time, from 72° to 74°F. The World Meteorological Organization has called for development of HHWS alerts at neighbourhood-specific scales (due to variable characteristics within urban areas and temperature increases caused by heat island effects), for increased knowledge of heat-related indoor conditions (temperature and relative humidity) as they relate to human health, and for improved integration of urban and rural heat alerts (WMO 2015). HHWS should thus be re-designed to focus at finer spatial scales and also better address needs in rural areas. Predicting interior temperature of buildings which lack active mechanical systems is a complex thermo-physical challenge (Lomas & Porritt 2017).

Trees in the Urban Landscape Context & Evapotranspirational (ET) cooling

While it has long been known that vegetation in near-building environments reduces reflected radiation, affects surface heat fluxes, and increases evapotranspiration (e.g.,

Tabares-Velasco & Srebric 2012 and citations therein), efforts to integrate these effects in combined building-microclimate energy models have only recently been made (Taleghani et al. 2016) and models validated with local data remain rare (TNC 2016). In fact, little empirical research has focused on near-building environments using a comprehensive approach to assess the role of urban trees for building energy consumption. Nowak and co-workers (2008, 2017) studied avoided energy use for cooling and highlighted the need for additional research relating specific tree characteristics (such as dimensions, distance/direction from buildings, and evapotranspiration rates) on those dynamics. Other studies have demonstrated that tree placement (affecting radiation intensity and interception of sunlight) and tree morphology (tree size, canopy size and shape, leaf area, and leaf density) are important determinants of building energy use for cooling (Holmes 2015; Hwang et al. 2017). Others have called for additional research to incorporate such investigations with studies of building heat balances in non-air-conditioned structures (e.g., TNC 2016).

The integration of such data into building energy analyses and visualization tools such as the urban modelling interface (*umi*) (Reinhart et al. 2013) could significantly improve model predictions for building thermal performance in existing urban neighbourhoods, that have tree canopy cover but where buildings lack air conditioning. *umi* is a Rhinoceros-based design environment for architects, engineers, and urban planners interested in modeling the performance of neighbourhoods and cities with respect to operational and embodied energy use, walkability and daylighting potential.

3. Methodology

3.1 Study area

The study area is in Polk County, Iowa, within the limits of the City of Des Moines, and includes a portion of a municipally-recognized area known as the Capital East neighbourhood, relatively close to the city's downtown. It was chosen as a test case because of specific social and economic characteristics that limit residents' ability to control the temperatures within their homes. We developed empirical databases describing both the characteristics of the buildings (340) and the trees (1142) in a portion of this neighbourhood (Hashemi et al. 2018).

3.2 Assessment of tree location and morphology

Tree data were collected in an inventory of a portion of the neighbourhood during summer 2017: 1,142 neighbourhood trees were catalogued using a Trimble Geo 7X Handheld GNSS receiver. Data collected include tree species, trunk diameter, tree height, canopy shape/height, canopy width in two dimensions, and latitude/longitude coordinates.

3.3 Assessment of buildings

We developed a Geographic Information Systems (GIS) shapefile integrating parcels, building footprints, and elevation data for an area within the neighbourhood. Grasshopper 3-D, the Meerkat plug-in, and GIS shapefiles were used to create a 3-D model of the buildings. We used GIS files for building footprints, elevations, and parcels, which were obtained from records maintained by City of Des Moines' Assessor's office. After preparing the shapefiles for buildings and trees, which contained required information to create the model, we imported them into Rhinoceros 3-D. To do so, we used Meerkat (a GIS data-parsing plug-in) to import shapefile data into Rhinoceros 3-D. This plug-in allows selection and cropping of shapefile layers for a specific area of interest. The result is a layered collection of 2-D linework that can then be further manipulated in Grasshopper or Rhino. These steps led to a similar

base map for all necessary geometries (buildings and trees). A shadow range analysis of the whole neighbourhood including tree geometries and location for May-September was simulated by Hashemi et al. 2018 (Figure 1). The hours of direct sunlight received by buildings increases from dark to light colours; buildings indicated in blue had more than 5% reduction in cooling demand for the scenario with trees based solely on shading.

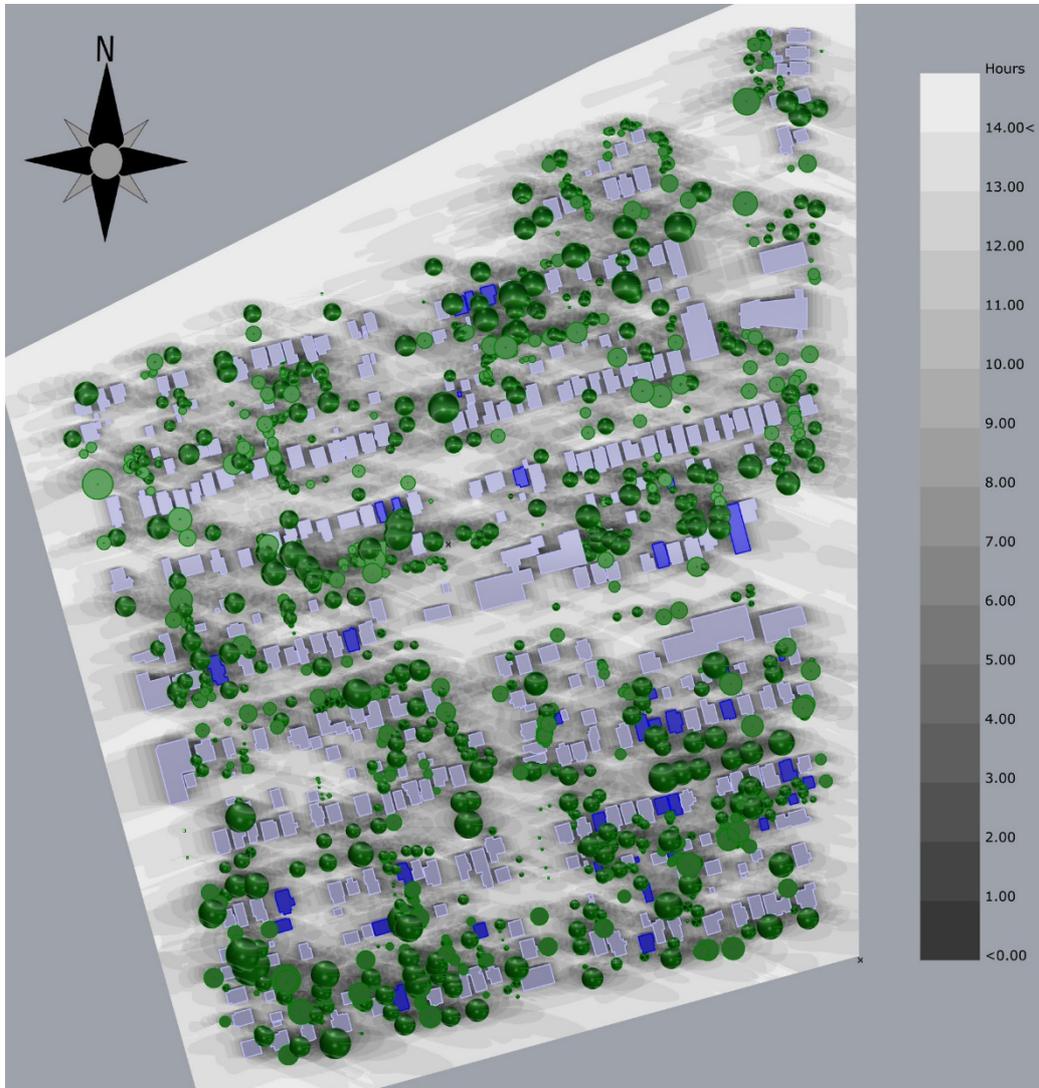


Figure 1. Shadow range analysis of neighbourhood including tree geometries and location (May-September) (Hashemi et al 2018). Hours of direct sunlight received by buildings increases from dark to light colours; buildings indicated in blue are those with more than 5% reduction in cooling demand for the scenario with trees.

3.4 CFD using Immersed Boundary Method

To understand the impact of position of trees relative to position of the built environment requires a parametric study consisting of multiple tree configurations that must be reliably simulated. A major burden of such parametric studies is the need to manually construct high resolution body-fitted meshes that include complex objects. Studies have shown that such manual mesh generation of analysis suitable geometries takes up 80% of time and effort thus precludes detailed parametric analysis (Cottrell et al. 2009). We circumvent this bottleneck by relying on an Immersed Boundary Method (IBM) for Computational Fluid Dynamics (CFD) modeling. The IBM embeds the solid geometry (e.g., trees, buildings) into a background

Cartesian mesh without conforming the background mesh to the objects, and the effect of the immersed boundary on the fluid field is accounted for by distributing the boundary conditions of the immersed geometry on the background Cartesian mesh. Since the IBM does not require a conforming mesh, it becomes computationally convenient to simulate different kinds of configurations while avoiding a cumbersome boundary-fitted meshing process. In addition to the background Cartesian mesh, each discrete object (tree, building) is represented as a Computer-Aided Design (CAD) object. This enables seamless integration into downstream analysis and visualization tools (like the urban modeling interface, *umi*). The B-rep surface defined by the CAD model is triangulated to a stereolithography (STL) format, with the size of the triangle (refinement level) pre-determined to match the resolved scale of numerical simulation (the size of the Cartesian mesh). Each discrete object is completely independent and can be placed anywhere in the Cartesian mesh, which is dynamically refined (see next section). This leads to ease of constructing meshes for a whole neighbourhood, with and without the presence of trees (Figure 2). This mesh construction is fully automatic and requires no manual intervention.

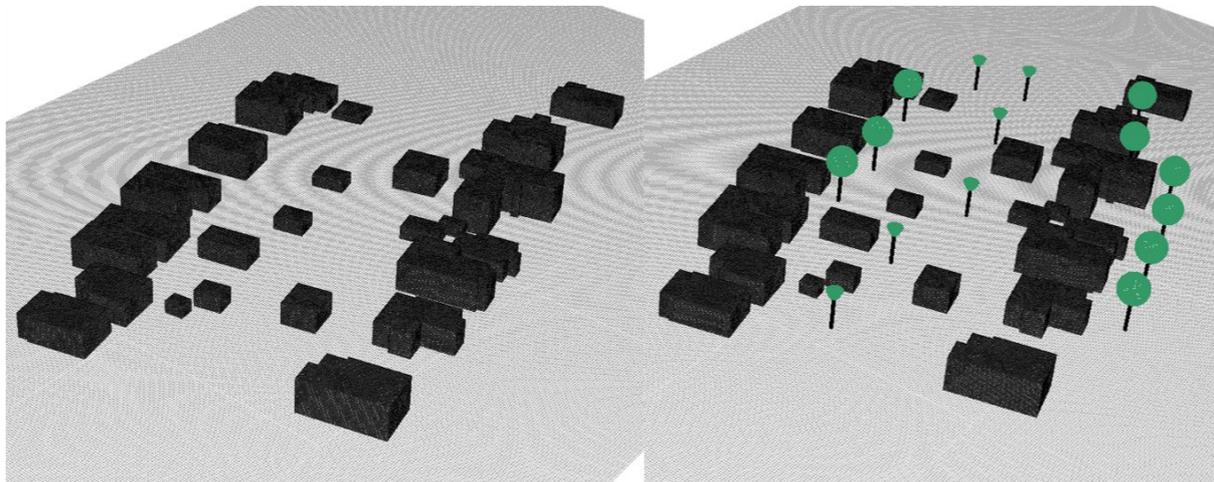


Figure 2: Neighbourhood without trees on the left and the same neighbourhood with trees on the right.

3.5 Incorporation of trees into the urban Computational Fluid Dynamics (CFD) model

Depending on thermal conditions, buoyancy driven thermal plumes exist due to evapotranspiration from trees. The accurate modelling of this phenomenon is critical to evaluating impact on the near- building environment and requires a refined mesh near the tree surface to capture the heat transfer and boundary-related physics. Similarly, accurately capturing the boundary layers on the walls requires a refined mesh close to those boundaries. We used an octree-based Cartesian meshing scheme that enables efficient, parallel and fast mesh generation and refinement. Starting from a coarse uniform mesh, each cell in the mesh was refined if an STL surface (tree or house) passed through it. Here, refinement means subdivision of a cell into its eight constituent octants. Since the refinement happens in a cell-local fashion, this step is parallel and instantaneous. The refinement is repeated until a preselected level of accuracy is achieved. To ensure numerical accuracy and stability, it has been shown that the refinement level between neighbouring cells cannot be drastically different (i.e., a very coarse cell next to a fine cell will cause numerical instabilities). This is ensured by using

2:1 balancing so that no two neighbouring octants differ in size by more than a factor of two. The complete mesh is represented as a graph, which enables easy domain decomposition and parallel distribution (shown for a representative tree-building configuration in Figure 3). More details of this framework are available at DENDRO (Sundar et al. 2008).

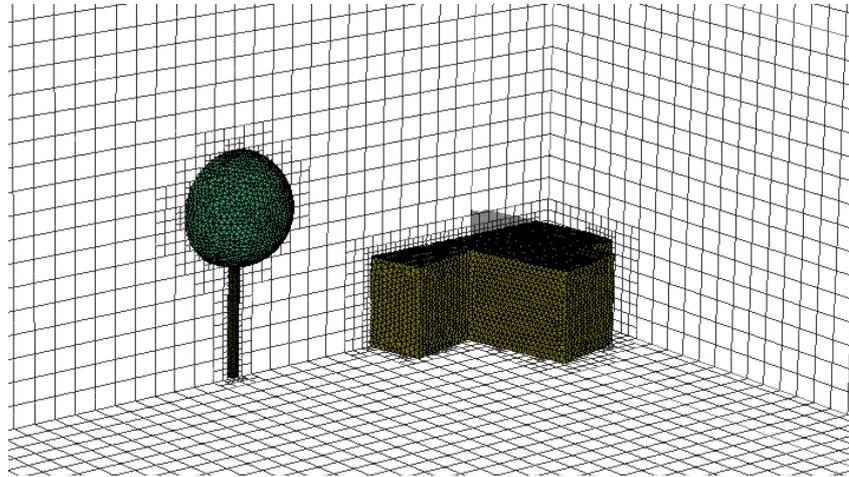


Figure 3. Mesh with adaptive refinement around the interfaces of immersed geometries with enforced 2:1 balancing

3.6 Simulation of tree surface temperature and evapotranspiration

We reviewed the literature to make determinations of surface temperatures for tree leaves and trunks. In hot and humid climates, leaf surface temperatures are generally above ambient temperatures due to absorbed solar radiation. Leaves reduce the effects of solar heating via re-radiation, convection and conduction with the air, and through transpiration and evaporation (Gates 1962). Leaf temperature, in turn, influences rates of respiration, photosynthesis, and transpiration, although the exact numerical influence on each is unknown (Leuning et al. 1995; Blonder & Michaletz 2018). Leaves in hot and dry conditions are generally closer to ambient temperature than leaves in hot and wet conditions because ambient humidity slows the escape of water from leaf surfaces (Lin et al, 2008, Blonder and Michaletz, 2018). Wind speeds have significant effects on leaf temperatures, reducing surface temperatures compared to ambient temperatures by up to 50% (Gates, 1962; Ansari 1959; Vogel, 2009). Further, leaves in direct sunlight have been reported to be from 2 to 20 °C above ambient temperatures, while leaves in shade may be as much as 1.5 °C below ambient (Gates, 1964; Gates, 1962; Pincebourde and Woods, 2012; Vogel 2009; Smith and Carter, 1988; Lin et al, 2008). Based on these general observations we determined that leaf surface temperatures for the tree species found in the Capitol East neighbourhood would be approximately 10 °C above ambient temperature at noon on a typical sunny June day with average wind speeds of 5 mph. The temperatures of the tree's trunk would be very similar to the ambient temperature.

We then created a 3 x 3 matrix of estimated evapotranspiration (ET) values for a representative small, medium, and large tree across three seasons (spring, summer, and fall). We used the 'K_c-ET_o' method of estimating ET (Allen 1998; FAO ET calculator) and published crop coefficients (K_c) for select tree species using the following equation:

$$ET = K_c ET_{ref}$$

where ET is evapotranspiration (for a tree), K_c is the crop coefficient, and ET_{ref} is the reference evapotranspiration (also known as ET_0).

We chose three species to serve as “proxies” for the small, medium, and large trees that occur in the neighbourhood to estimate the crop coefficient for each (Johnson et al 2000, Irmak et al 2012). The species and K_c values we used (Table 1) were selected from the limited literature on ET for trees and reflect similarity in tree form, leaf morphology, and degree of maturity compared to the trees for which they serve as proxies.

Table 1: K_c values for small, medium, and large trees for representative monthly conditions in spring, summer, and fall. K_c is a unitless coefficient.

Season	K_c values by tree species and size		
	Small	Medium	Large
Spring (April)	0.4	0.5	1.1
Summer (July)	1.0	1.2	0.9
Fall (September)	0.9	1.6	1.1

We determined reference evapotranspiration (ET_{ref}) based on estimated ET from a field of uniform grass under normal and non-stressed conditions calculated according to the FAO Penman-Monteith equation (Allen 1998) using the FAO ET calculator. Historical weather data were obtained from Weather Underground data for a nearby neighbourhood. Then ET_{ref} was calculated for three dates, representing typical conditions in spring (April 22, 2017; cool and low humidity), summer (July 17, 2017; hot and high humidity), and fall (September 15, 2017; warm and moderate humidity; Table 2).

Table 2: Reference ET for spring, summer, and fall based on historical Weather Underground station data.

Parameter	Season		
	Spring	Summer	Fall
Representative date	April 22, 2017	July 21, 2017	September 15, 2017
Reference ET (mm/day)	3.9	6.5	4.7

Tree ET was then estimated for each season as a flux for each representative tree selected from the Capitol East tree inventory (Table 3). These ET values can be used to estimate the total daily volume of evapotranspiration by a single tree using the tree’s canopy area.

Table 3: Estimated ET flux for small, medium, and large trees for spring, summer, and fall.

Season	ET (mm/day) by representative tree species/ size		
	Small	Medium	Large
Spring	1.6	2.0	4.3
Summer	6.5	7.8	5.9
Fall	4.2	7.5	5.2

3.7 Simulation details and boundary conditions

A total of 18 + 1 configurations are simulated for this study. A house was selected from the neighbourhood by identifying a building with average size and moderate complexity. The height of the house was normalized to 1 (dimensionless height). The tree was generalized as

a cylinder-shaped trunk and a spherically-shaped canopy. The trees in our simulations are parametrized into three different sizes and three different placements (Table 4).

Table 4: Size and placement of tree (H is height of house).

Size of tree (trunk height/canopy diameter)		
Small	Medium	Large
1.25/1	1.5/1.25	1.75/1.5
Placement of tree (distance from front of house)		
1.5	2.5	5

We placed the tree and house within a computational domain of size 20*20*5, with the house at the bottom center (10, 10, 0) (Figure 4). We chose such a large computational domain to ensure that there are no boundary-induced effects, and to ensure that any wakes developed behind the structures are accurately captured.

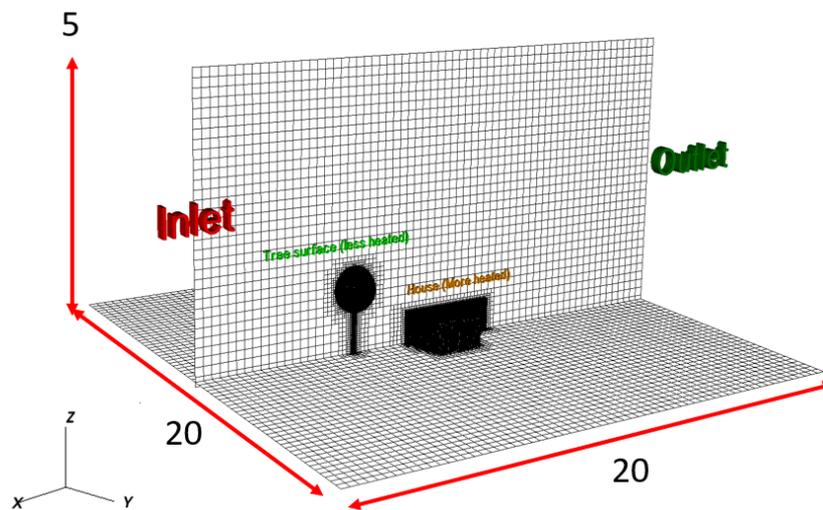


Figure 4. Domain of the simulation (not to scale).

The boundary conditions include a velocity inlet condition of 0.25 (a dimensionless velocity), at a direction normal to the boundary with the temperature of the incoming flow at ambient temperature. The pressure outlet for outflow boundary (a dimensionless pressure) is 0. A no-slip wall was created for the ground at ambient temperature. A zero-gradient, adiabatic wall was created for the top, front and back boundary of the building. The internal house temperature was set at 30°C above ambient temperature. For the simulations without evapotranspiration cooling trees consisted of two parts, the trunk at ambient temperature, and the canopy at 10°C above ambient temperature. We solve all equations in their non-dimensional form. Consequently, the flow physics determining parameter for this geometry is the Rayleigh number, which is of the order of 1e7.

4. Results

All simulations were performed on a high performance computing system (TACC Stampede). The simulations were run on 24 Skylake nodes. The average x (Figure 5) and z (Figure 6) air movement velocity for the house and tree were calculated for four cases: a house only, a

small tree close to the house, a medium tree close to the house, and a large tree close to the house. Incoming air flow from the left is obstructed and deflected by the tree. For the z velocity comparison the medium-sized tree has a larger influence on air flow than the large tree, possibly because the canopy of the large tree is further away from the house and has less effect on air movement close to it. Temperature iso-surfaces were also developed for same comparisons (Figure 7). The effect of the buoyancy-driven wake is clear in the house-only configuration as the temperature iso-surface shows an upward movement in the z-direction. With a tree in front of the house, the temperature surface is changed dramatically, and as the size of the tree increases, the temperature iso-surface increases in length in the x-direction (Figure 7).

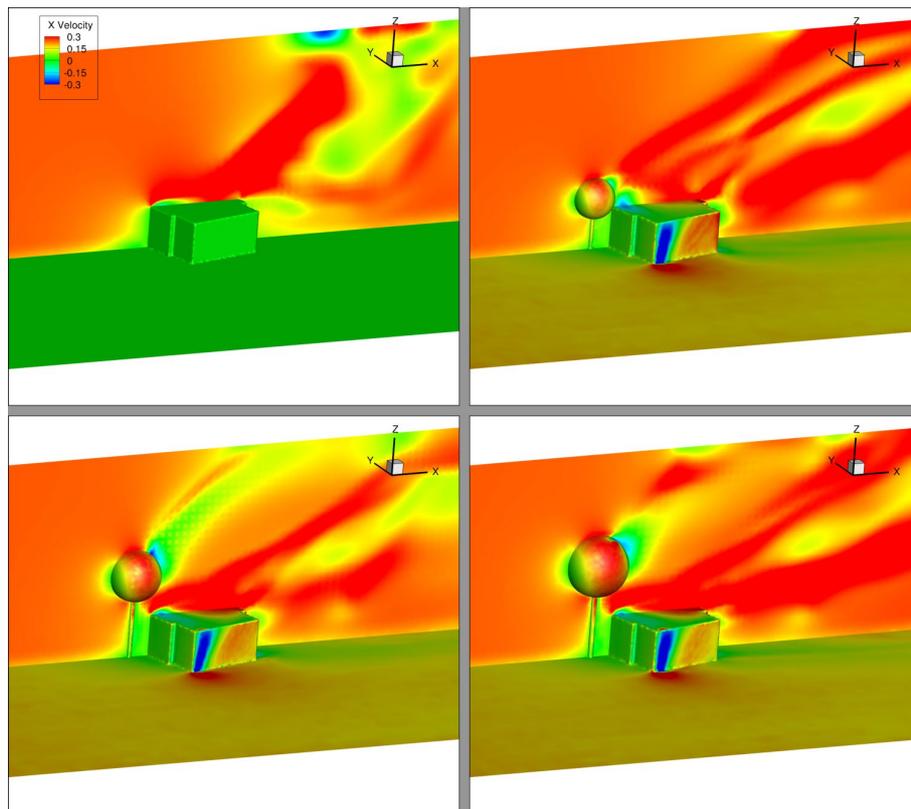


Figure 5. Comparison of x-velocity of house only (top left) and three different size trees close to the house

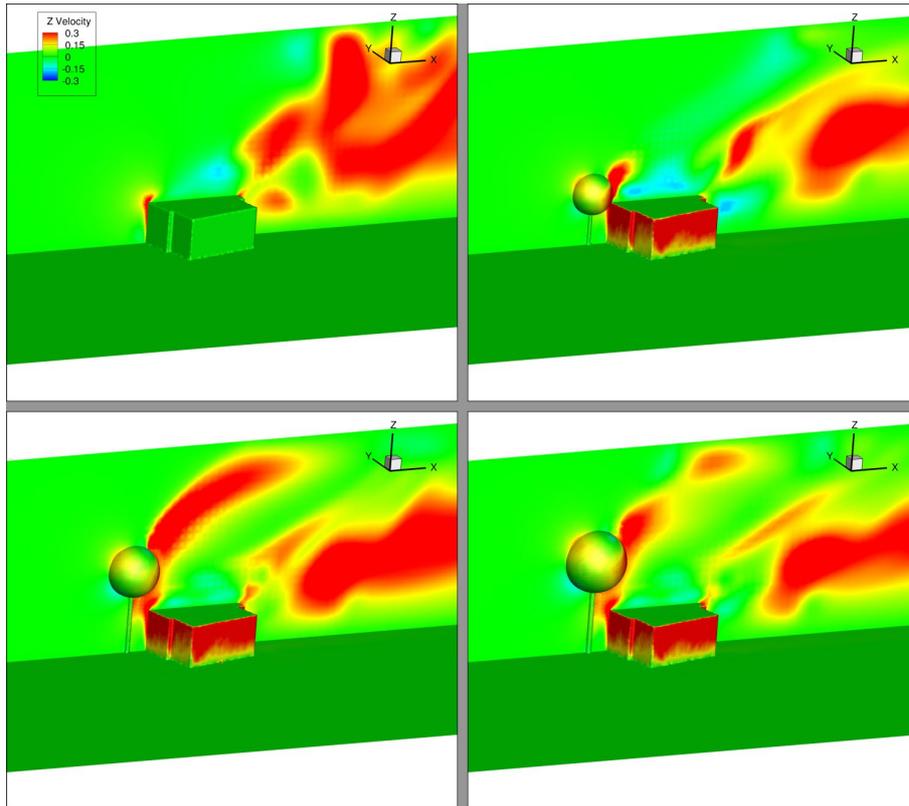


Figure 6. Comparison of z-velocity of house only (top left) and three different size trees close to the house

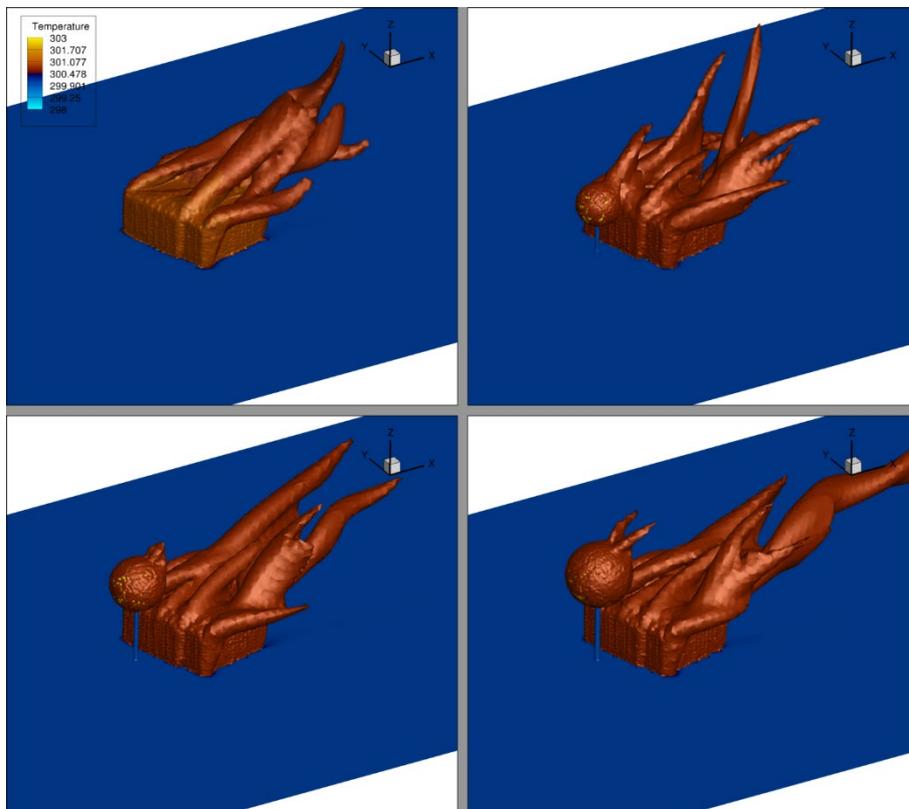


Figure 7. Comparison of temperature iso-surface of house only (top left) and three different size trees close to the house

We also compared effects of the same-sized tree at different distances from the building by examining the z-velocity for a small tree at three different locations (Figure 8). The upward movement of air flow due to warming of the canopy can be seen clearly in the moderate and far configurations, while air flow past the canopy in the closest configuration is mixed with upward-moving flow from the house itself, generating a very different flow configuration. The temperature contour of the same comparison indicates that the closest distance configuration has the biggest impact on the temperature contour above the house (Figure 8). The upward moving boundary layer above the house shows an earlier separation with the presence of a tree at moderate and more distant locations compared to the house- only configuration.

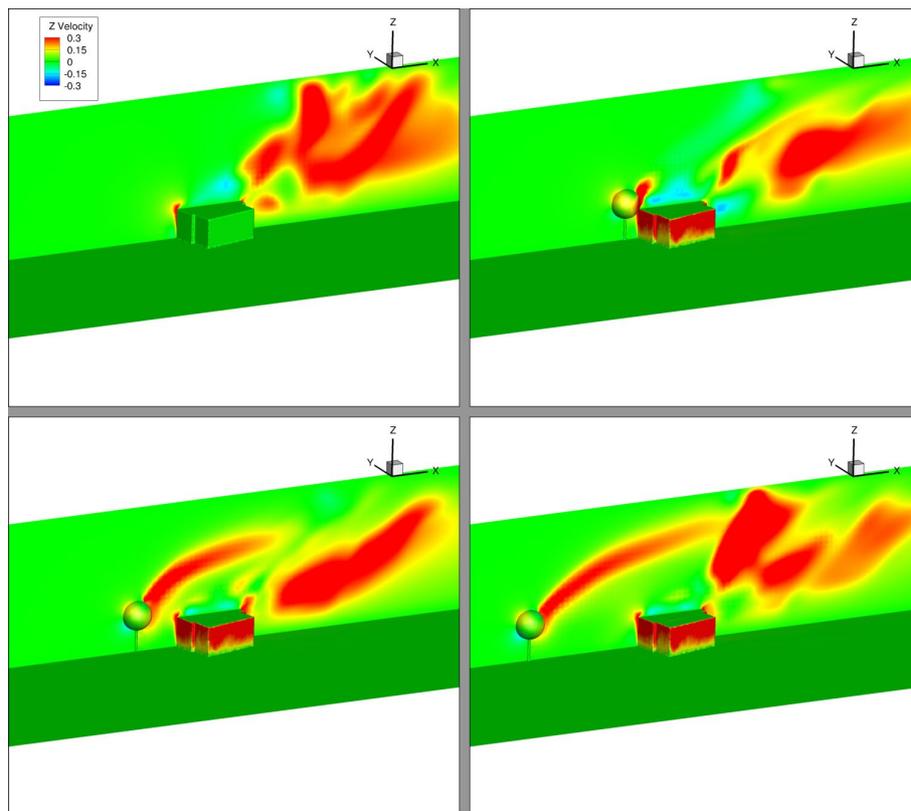


Figure 8. Comparison of temperature iso-surface of house only (top left) and three different size trees close to the house

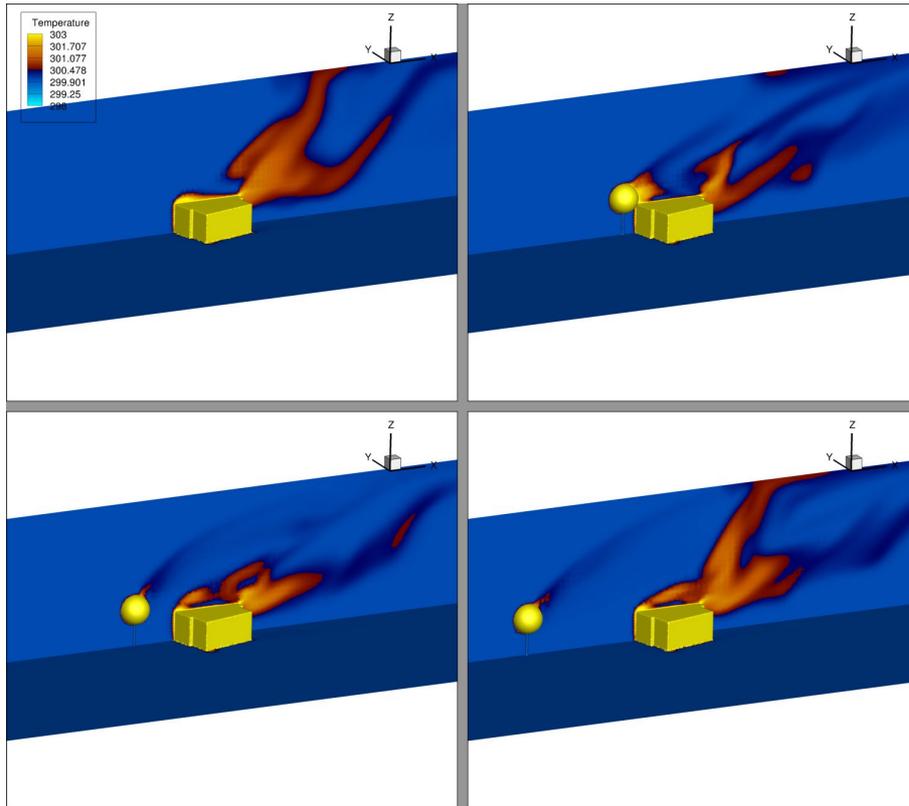


Figure 9. Comparison of temperature iso-surface of house only (top left) and three different size trees close to the house

5. Discussion and Conclusion

This paper reports first results of a simulation framework to integrate the impact of trees in an urban context in energy performance evaluation for buildings and neighbourhoods. Trees can reduce energy use and improve indoor and outdoor comfort for cooling in summer by casting shade and providing evapotranspirational (ET) cooling. This paper presents a methodology to combine spatially explicit three-dimensional tree morphology and estimates of ET rates with building location and wall characteristic data to test their relative contribution to building energy consumption. Based on a comprehensive tree inventory for our Midwestern study neighbourhood, tree morphology and building data have been integrated in a three-dimensional array in the urban modelling interface" (umi) to estimate cooling due to interception of sunlight. We then performed a series of parametric computational fluid dynamics (CFD) studies to simulate ET cooling for various tree sizes and different distances to walls. We resolved conventional mesh generation challenges associated with CFD by introducing a novel, immersed boundary framework based on adaptive octree meshes. The preliminary results shown in this paper highlight the important fact that trees provide improvement in situations of extreme heat via two mechanisms (a) shading and radiation blockage, (b) ET-based local cooling. The preliminary results also indicate the dynamic nature of the tree-building interaction, which will influence window placement on walls and roof to enhance natural ventilation strategies in a warming climate. The ET cooling potential related to roof openings seem particularly noteworthy as it could reduce overheating specifically in upper residential floors. The dynamic nature of these current results also indicate the need to conduct further simulations. Therefore, a seasonal matrix will be simulated next.

The models we have developed allow us to discern the relative impact of tree shading in relation to building characteristics and according to tree size and distance from the home, as well as the potential effect of evapotranspiration for the same scenarios. We observed distinct patterns for air movement and temperature profiles that are likely to influence building energy dynamics and suggest landscape configurations for trees and buildings that could contribute to more effective passive temperature control within dwellings in this neighbourhood. The potential to integrate these specifics into design configurations for this and similar neighbourhoods can provide significant benefit to reduce building interior temperature conditions in situations of extreme heat events. Thus future work in our team will now combine radiation blockage as complement to the CFD simulations.

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