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Representation and evolution of urban weather boundary conditions in downtown Chicago

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ABSTRACT

This study presents a novel computing technique for data exchange and coupling between a high-resolution weather simulation model and a building energy model, with a goal of evaluating the impact of urban weather boundary conditions on energy performance of urban buildings. The Weather Research and Forecasting (WRF) model is initialized with the operational High-Resolution Rapid Refresh (HRRR) dataset to provide hourly weather conditions over the Chicago region. We utilize the building footprint, land use, and building stock datasets to generate building energy models using EnergyPlus. We mapped the building exterior surfaces to local air nodes to import simulated microclimate data and to export buildings' heat emissions to their local environment. Preliminary experiments for a test area in Chicago show that predicted building cooling energy use differs by about 4.7% for the selected date when compared with simulations using TMY weather data and without considering the urban microclimate boundary conditions.

Introduction

Building energy (residential and commercial) constitutes around 40% of the total US delivered energy according to the 2017 US Energy Information Administration report (EIA 2018). Urbanized areas account for 67–76% of the global final energy consumption (Guneralp et al. 2017) and the growing urban density significantly impacts urban energy use. Urban scale building energy modelling is an emerging field that requires modelling the buildings' interconnection with their surrounding urban microclimate. Higher fidelity simulations with new enhancements to the building energy models are gaining more and more interest in the scientific community.

Urbanweather boundary conditions such as temperature, pressure, wind speed, solar radiation and humidity greatly influence the building energy simulation models and ultimately the understanding of final results and conclusions. Yet in traditional building energy simulation, weather data is obtained from measurements at nearby airports, local-weather stations, or historical datasets, and compiled as a typical meteorological year (TMY) weather file (Wilcox and Marion 2008). A TMY dataset provides hourly data for one year, composed of 12 typical calendar months selected from historic meteorological measurements in a specific region over a period of decades. These TMY weather data tend to come from weather stations located at remote open areas (e.g. airports) that do not represent the actual meso- or micro-climates of the city and are prone to produce erroneous results for focused studies of a few city blocks or a specific region. Yet individual buildings operate within these local regions, and the dynamic range of local-weather, topologies, building types, and building densities is significant across any major city, and thus city-wide averages cannot adequately forecast energy performance of specific buildings or districts. As more data related to local urban weather is collected and more accurate forecasting models are developed, traditional building energy modelling can be both improved and scaled up from individual buildings to districts or entire cities, considering the actual urban weather conditions. This will require that building energy simulation engines evolve to integrate this new information into calculations, and that the two types of models run in parallel, coupled by the exchange of data throughout the course of a simulation.

Literature review

Many researchers have expressed concerns over the accuracy of the TMY methodology and selection. Sun, Li and Xiao (2017) performed a sensitivity study involving three TMY dataset and four cities of China and report a 10–20% variation in building energy calculations. They also reported the finding that static metrics such as daylight factor are insensitive, whereas dynamic metrics such as daylight autonomy and useful daylight index are very sensitive to the TMY year used in the simulations. In another study of Hangzhou, China (a sub-tropical city with high humidity), Bourikas et al. (2016) demonstrate that micro-climate plays an important role in computing building heating and cooling loads. They demonstrate the shortcomings of weather datasets such as the TMY, by using the actual measurement of air temperature and relative humidity at 26 sites within a 250-m radius. Variations of up to 20% were observed in the final heating and cooling loads computed with/without micro-climate considerations.

Research by Dorer et al. (2013) use a detailed building energy modelling (BEM) for a typical office building in an urban canyon, finding that local-weather can also have a significant impact on the heat exchange between buildings, and thus on their energy demand, with further variation based on the geometries and construction types of individual buildings. Pisello et al. (2015) used in-field monitoring campaigns and degree-day or degree-hour methods to show the influence of local-weather boundary conditions on building heating and cooling requirements of urban, suburban and rural areas in central Italy. Takane et al. (2017) examined the impact of urban air temperature dynamics and electricity demand for Osaka, Japan, using downscaled numerical weather prediction models at 2nd nest domain(d02) with 1 km resolution and 126 grid points to improve the accuracy of building energy consumption prediction. Their simulations fix the problem of under-estimation of surface air temperature (2°C in winter heating season) and over-estimation of electricity demand, quantifying the significance of local-weather models for building energy prediction.

Conry et al. (2015) demonstrated a coupling study using the Weather Research and Forecasting Model (WRF) (Skamarock et al. 2008) and a simple building energy model, looking at the present and potential future climate conditions in Chicago. Despite forecasts of stronger winds and lake-breeze effect, they indicated about 26% increase in daytime building energy use by the end of the century (about 2080) assuming the climate change scenario of a 4.7°C increase in average temperature. In a more recent study, Sharma et al. (2017) explored the sensitivity of high-resolution mesoscale simulations of urban heat island (UHI) in the Chicago metropolitan area and its environs to urban physical parameterizations, with emphasis on the role of a lake-breeze. Their results show the WRF model, with appropriate selection of urban parameter values, was able to reproduce the measured near-surface temperature and wind speed reasonably well.

Many researchers have incorporated more dynamic local-weather conditions in building energy simulations with the use of the Urban Weather Generator (UWG) software detailed by Nakano et al. (2015). In an interesting research by Hammerberg, Vuckovic, and Mahdavi (2017), a study comparing the climactic output from WRF and UWG is presented, they find that UWG is slightly more accurate and cite the high computational costs associated with running WRF. Both WRF and UWG require tuning of several parameters for accurate simulations. The main underlying initialization data for UWG are TMY files, whereas, for WRF it is the weather data files. The initialization conditions for weather models are as critical for their performance of WRF simulations. The publically available North American Mesoscale Forecast System (NAM), the High Resolution Rapid Refresh (HRRR) (EMB 2018) or outputs from other weather models can be utilized to initialize WRF boundary conditions. HRRR is a relatively new hourly 3-km resolution data, while NAM is 6-hourly 12-km resolution dataset. Both HRRR and NAM cover the contiguous United States. Recently, Blaylock, Horel, and Liston (2017) made past archives (July 2016–present, HRRRDATA 2018) of HRRR dataset available to the public. Although a recent update of the NAM model includes 5-km resolution forecasts over the continental United States, the HRRR model is the highest-resolution weather model that can provide forecasts up to 18 h. One of the major advantages of the high-resolution HRRR dataset is the ability to explicitly resolve convection, leading to better forecasting of precipitation events and thus moist flow evolution, which are important atmospheric processes for the Chicago lake areas.

In all the literature indicated above, as well as the work outlined in this paper, we find that high-fidelity coupling between building energy models with atmosphere models is important to understand the impacts of urban weather conditions on cities at the building or city-block level resolutions. Our work presents a coupling methodology and results of one-way coupling where WRF provides local-weather data to the EnergyPlus building energy model for a test area within the city of Chicago.

Modelling tools

EnergyPlus (USDOE 2018a) is the US Department of Energy's flagship building energy software for simulating the dynamic energy and environmental performance of buildings. An EnergyPlus model performs a period (typically from one day to a full year) of calculations on a sub-hourly basis, reporting energy use results monthly, hourly or as frequent as one minute per time step. Applied to urban energy modelling, EnergyPlus simulations calculate the overall thermal conditions of the building in terms of the exterior surface temperatures and the emitted heat from the building, which can be used as the boundary conditions of the urban atmosphere models. New features in EnergyPlus version 8.8 allow input and output from urban weather boundary conditions (Hong and Luo 2018), including variables such as outdoor air temperature, humidity, wind speed and direction. This enables the use of local outdoor air conditions for the calculations of heat and mass balances at the exterior building surface and building zone level resolutions. The implementation allows EnergyPlus to leverage this information to either simulate a single building using a pre-simulated micro-climate or to co-simulate a group of buildings.

The WRF model is one of the most commonly used numerical weather forecasting tools in the atmospheric and climate science community. It includes a rich suite of physics packages such as microphysics, radiation, cumulus, and planetary boundary layer parametrization. Its nesting capability enables the model to capture atmospheric motions on scales ranging from continents to near buildings. Powers et al. (2017) survey a wide range of WRF applications, such as short-long term synoptic to mesoscale weather prediction, large-eddy simulations, cyclone modelling, air pollution studies, solar-energy impact, hydrology study, fire modelling, and urban meteorology.

WRF can perform simulations using statistically modelled meteorological data or actual measurements in which case a pre-processing stage interpolates land-use, topography and meteorological data into the model domain. Higher-resolution measurements, data assimilation technologies, and parameterizations have yielded significant improvements simulating urban weather and climate. With these new approaches, WRF simulations can capture the passage of dry and precipitating frontal systems in summer and winter seasons as well as the land-breeze formations which might be a factor to erode urban heat island effect. Despite these developments, WRF does not have mechanisms to incorporate data from building energy models.

WRF is originally developed for mesoscale ($\sim$1–2 km) resolutions and above, whereas urban models operate below 100 m, and even finer scales if turbulence is to be incorporated. The integrated WRF-urban modelling system was introduced by Chen et al. (2011) to bridge the gap between mesoscale and microscale modelling. The model integrates urban canopy models with localized city morphology datasets and provides lumped building/structure effect parametrization, and includes procedures to incorporate/couple high-resolution land, atmosphere, and other urban data. These changes provide accurate modelling of winds, temperature and humidity for urban areas – as these have impacts on the urban atmospheric boundary layer which in turn may influence the mesoscale motions.

In this work, we use WRF simulation results initialized with HRRR data on over 3 km to 120 m resolution range to feed EnergyPlus simulations with weather data. Previous versions of EnergyPlus used building level resolution with one weather data point per building. Here the resolution is surface level (window or a wall), about 5–10 m for EnergyPlus. As noted earlier, the computational costs of higher resolution models drive trade-offs such as omitting building geometry details and turbulence effects. The work described here is part of a larger effort within the USDOE Exascale Computing Program (USDOE 2018b) to explore the extent to which factors influence building energy demand, and thus what are the optimal spatial and temporal resolutions for such coupled models.

The rest of this manuscript is organized as follows: we first present the methodology, the overall workflow, WRF and EnergyPlus simulations setup, next we detail the results and findings, and finally, we discuss the results followed by conclusions.

Methodology

In this section, the details of model preparation, setup of the numerical weather prediction and building energy codes along with a scheme to couple the two models are presented. The focus of this work has been on utilizing the High Performance Computing (HPC) platforms to perform high-fidelity calculations and develop a data-exchange mechanism for small and larger target models.

Model preparation

The City of Chicago open data portal (CHI-DATA 2018) provides the building footprint, location, building ID, and other useful data for simulations. Our chosen initial target area is a small subset of this database; we filter this entire city data using the QGIS software. An initial file in geojson (Butler et al. 2016) format providing a footprint for each building in the target area is obtained from QGIS (QGIS 2018); associated building height, vintage and usage data are added to create the input data files (IDF) for running building energy simulations with EnergyPlus. Our focus area for this work is a subset of the area surrounding the Goose Island on the north branch of the Chicago River, part of a planned 600-acre redevelopment project called North Branch Framework (NBIC 2018). Figure 1 shows the target area used in this paper.

Overall workflow

Figure 2 shows the initialization data and output dumps for both WRF and EnergyPlus. It also shows the coupler, which is the central data translation engine from one simulation to another. The workflow involves preprocessing WRF initialization data, followed by running WRF simulations and generating time-series of state variables for temperature, wind-speed, radiation and other output variables, which are used by the coupler to query and interpolate the WRF results onto EnergyPlus simulations. The coupler coordinates simulations and performs an hourly file-based transfer of values from WRF to EnergyPlus simulation. EnergyPlus outputs the final energy use and exhaust heat produced by the buildings.

WRF simulation set-up

The WRF model (version 3.9) is used to simulate the weather and airflow of a 2-day summer case over Chicago. We initialize the model for 16th to 18th August 2017 with HRRR input data

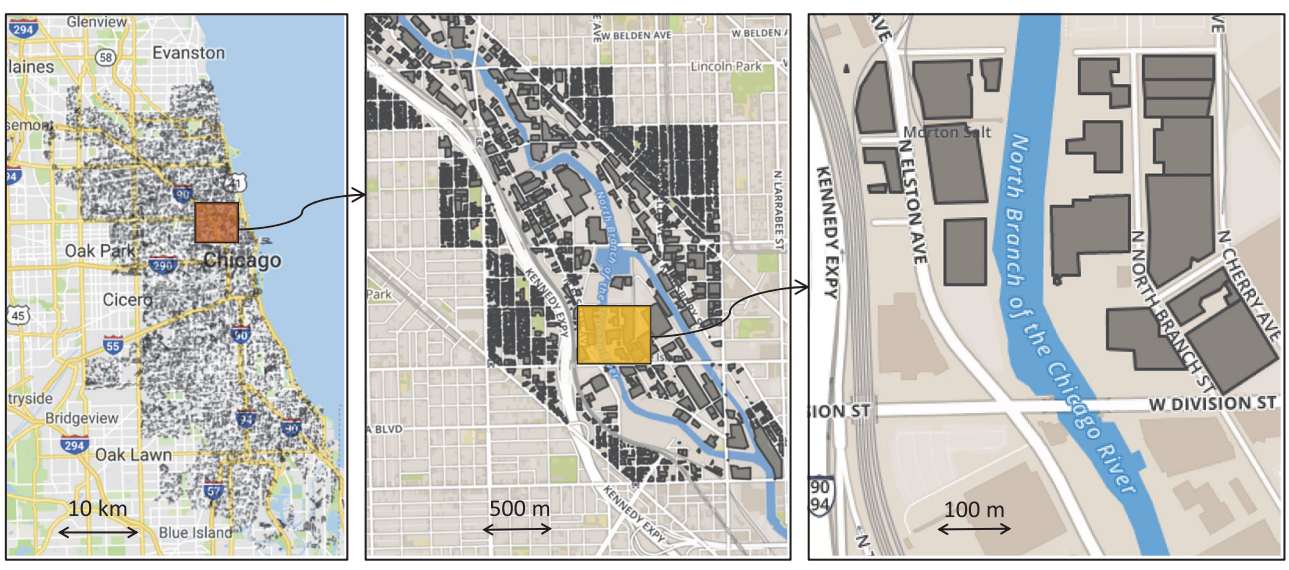


Figure 1. Left: footprint (city of Chicago). Centre: Goose Island Region with $\sim$20,000 buildings. Right: a small subset of Goose Island with 20 buildings (target area).

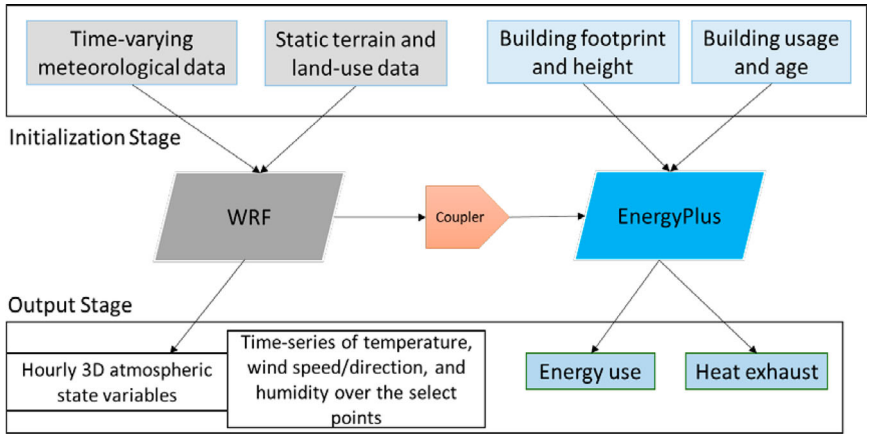


Figure 2. Data flow from WRF to EnergyPlus.

at every 3 hours. The USGS 30 arc seconds ($\sim$1 km) topography dataset is utilized. Three domain configurations are set up to capture weather evolution over parts of Illinois, Michigan, Indiana and Lake Michigan as shown in Figure 3 (left panel). Although the figure shows the fourth domain (d04) which is configured to run at 24-m resolution, we omitted this domain for the current study due to its large computational requirements. The first domain (d01) covers a region of 600 $\times$ 450 km, the second domain (d02) 240 $\times$ 180 km and the third domain (d03) 96 $\times$ 72 km. These one-way nested domains have a horizontal resolution of 3 km, 600 m, and 120 m, respectively. All three domains have 42 vertical layers with fine spaced layers being close to the surface. The time step of integration is 15, 3 and 0.6 s for the three regions, scaled down with the same ratio 5:1 as in the horizontal resolutions.

In addition to the common dynamics options, we employed various physics schemes, namely, the Mellor-Yamada-Janjic boundary layer parameterization scheme (Janjic 1994) and Goddard scheme (Tao, Simpson, and McCumber 1989) to explicitly resolve microphysics of clouds and precipitation. Long and shortwave radiations are resolved using the RRTMG-based schemes (Iacono et al. 2008) which is an essential component of real-case simulations to capture atmospheric heating and cooling effects. The surface physics is treated with the unified Noah land-surface model (Chen and Dudhia 2001). No urban canopy model parameterization is enabled; therefore, impacts of trees, buildings, and other anthropogenic sources are not taken into consideration.

We configured the model to output basic atmospheric variables at every hour for two days' simulation. A horizontal map view of surface winds and temperature at 16 August 21 UTC forecast time is shown in the right panel of Figure 3. The model produces about uncompressed 2.5 GB per output which totals a dataset over 100 GB per simulation. It takes about two days to simulate the two-day case on eight nodes (36 cores per node) Intel Broadwell processors. Including the finest scale d04 domain, it would require approximately one month of computing time on the same platform, and can easily produce a TB dataset. Expanding the simulations to cover longer periods necessitates careful planning of model setup which addresses both large data volume and computational challenges.

Energyplus simulation set-up

As introduced previously, EnergyPlus version 8.8 adapts the local-weather conditions in building energy modelling at the surface and zone resolution. EnergyPlus uses the urban climate-related data in simulations for exterior surface heat balance calculation, air infiltration and ventilation in zone heat balance calculation, and building system air flow network calculation. As Figure 4 shows, the buildings' exterior surfaces simulated in EnergyPlus models serve as the boundary between the buildings' thermal zones and the exterior urban atmosphere. The building exchanges mass and heat with the surrounding environment through the thermal boundaries by conduction, convection, infiltration and ventilation. The buildings also exhaust heat and mass from building systems to the local environment, including exhaust air from fans, DX condensing units, cooling towers, boilers, etc.

To import local outdoor air condition from the urban atmosphere model, we set up a series of local Air Nodes in the simulation domain and modelled them at external air nodes in EnergyPlus models. As Figure 5 shows, an Air Node can contain environmental data including temperature, humidity, wind velocity and direction. The exterior surfaces in a building model are linked to an external local Air Node. A surface object gets it local-weather condition from the linked Air Node as the input to run the energy simulation. At each time step, the surface objects in each building model provide mass and heat flux rate to the Air Node for the urban weather model.

Figure 6 shows the simulation components (Building Surface, Building Zone and Canopy Cell) and data exchange units (Zone Node, Surface Node and Building Node) of the simulation scenario allowing each EnergyPlus model with external input from WRF data. Each Surface and Zone object allows inputs from an Air Node object to consider local climate conditions simulated by the urban atmosphere model.

As WRF also provides local solar radiation data, we modify the EnergyPlus IDF model to allow overwriting the Direct Normal Solar Radiation (W/m^2) and Diffuse Solar Radiation (W/m^2) at the building level. Specifically, we added two Energy Management System actuators, namely EnergyManagementSystem: Environment, Weather Data, Diffuse Solar (W/m^2), and Energy-

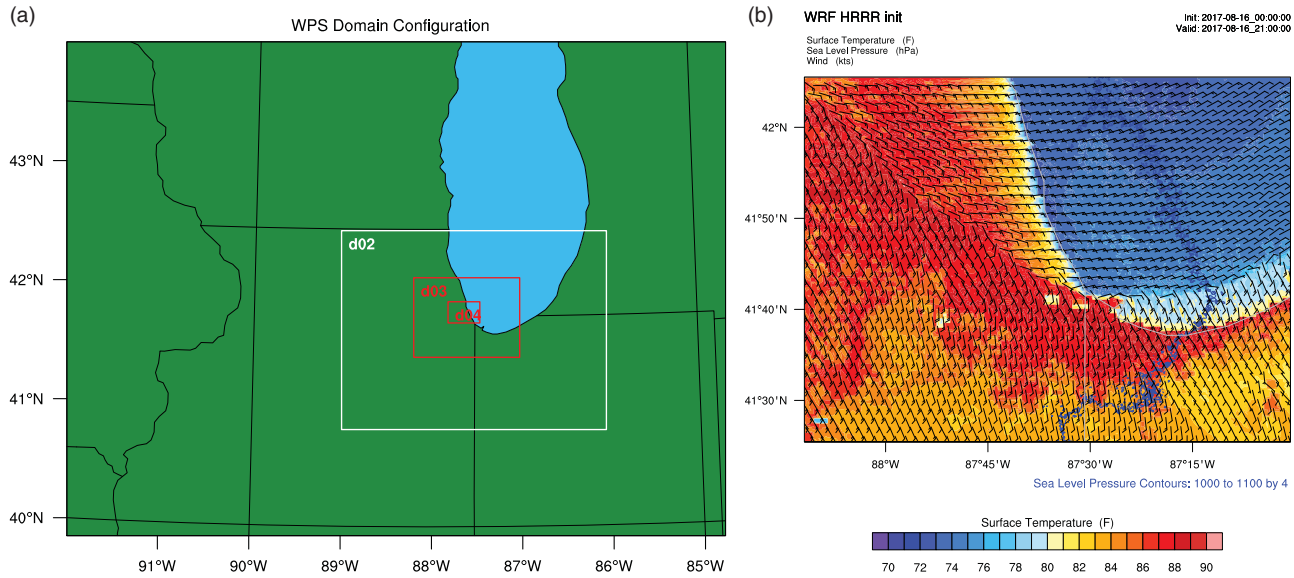


Figure 3. Domain configurations in WRF simulation which are centered over Chicago downtown: d01-dx/dy = 3000 m; d02-dx/dy = 600 m; d03-dx/dy = 120 m (leftd01 covers a region of 600 × 450 km, d02 240 × 180 km, and d03 96 × 72 km. Note that although d04-dx/dy = 24 m is shown, this domain was not activated in simulations. Horizontal map view of surface winds and temperature profile at forecast time 21 UTC (right).

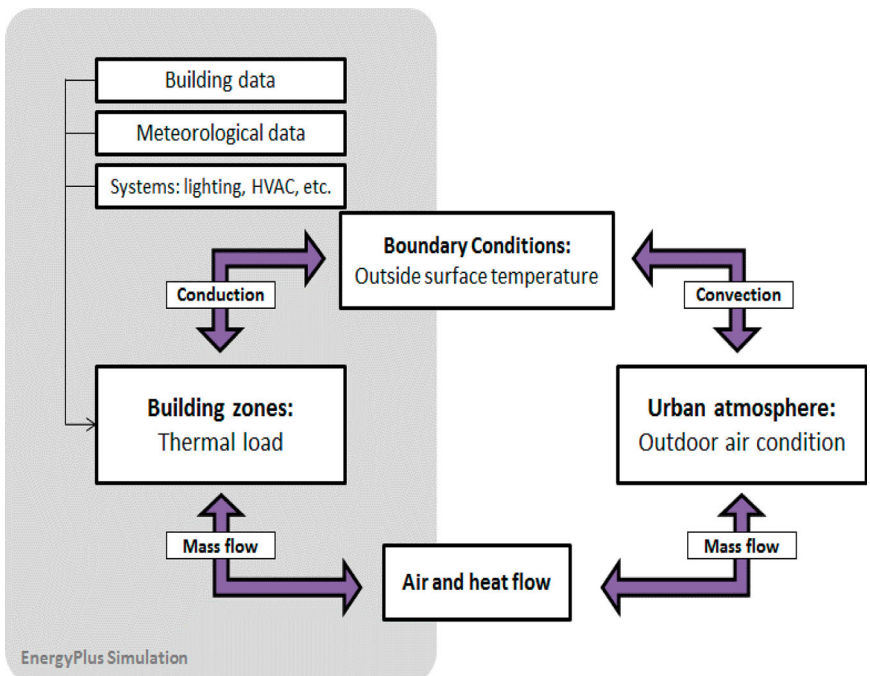


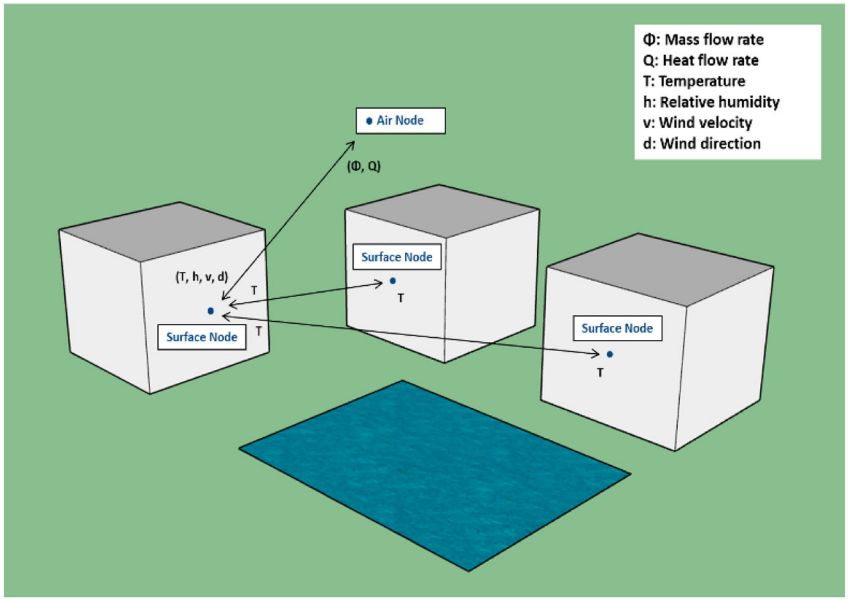
Figure 4. EnergyPlus data exchange with the urban atmosphere model.

ManagementSystem: Environment, Weather Data, Direct Solar (W/m^2) to import the external schedules of solar radiation at each time step. The long wave radiation between building surfaces to the sky and ground are considered. However, as the modelled block consists only of low-rise buildings, the long wave radiation between building surfaces are neglected in this simulation case.

To evaluate the impact of heat exchange between buildings and urban weather condition, we also script the model to output hourly energy meters and building heat emission to the urban boundary. The heat emissions contain:

- Convection heat from exterior surfaces (walls, roofs, windows) to the ambient air
- Heat emission from exhaust air and exfiltration of zones to ambient
- Heat emission from HVAC exhaust/relief air
- Condenser exhaust heat by fans of DX systems
- Heat emission from the exhaust air of cooling towers

As demonstrated in the previous section, we choose the city block in the Chicago Goose Island Region along the Michigan River to conduct the simulation case study, as shown in Figure 7.

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  "z_coord": 3.0,
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},
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Figure 5. Left: external inputs for a building model from a local Air Node. Right: snippet of the hourly JSON data for an air-node from WRF to EnergyPlus.

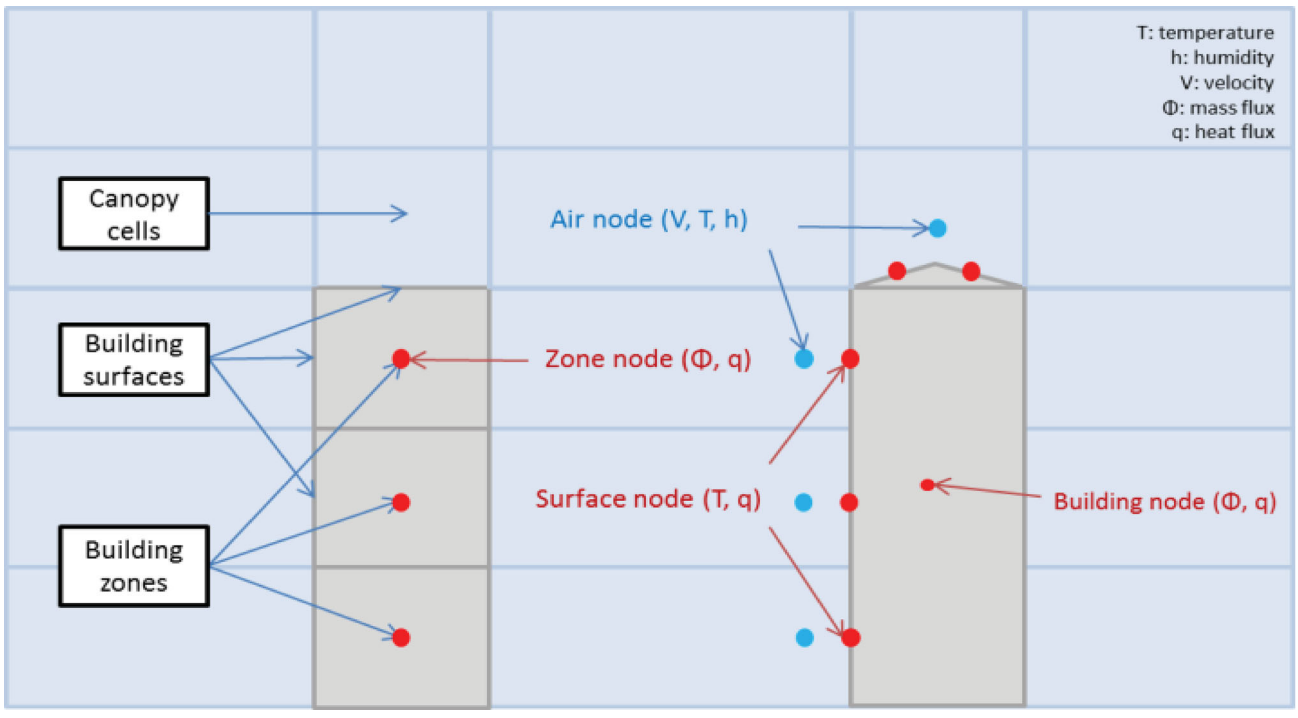

Figure 6. Local outdoor air conditions at the zone and surface levels.

The block contains 20 buildings, of which 14 are office buildings and six are retail buildings. We use City Building Energy Saver (CityBES) (Hong et al. 2016; Chen, Hong, and Piette 2017) to generate the EnergyPlus IDF models based on the building footprint and a number of floors, visualized as the aqua extruded polygons. For thermal zoning, each floor is divided by core and perimeter thermal zones matching the building footprint according to the requirements of ASHRAE 90.1-2013 Appendix G Table G3.1-8 (ASHRAE Standard 90.1, 2013). In modelling, we adopted the occupancy, lighting, equipment, heating and cooling setpoint schedules used by the DOE reference buildings for office and retail buildings. For building systems, small offices are equipped with gas furnaces providing hot air for space heating, and packaged single zone roof top air conditioners for cooling. For medium office and medium retail buildings, gas boilers are used for space heating, and packaged rooftop variable air volume (VAV) with reheat systems are used for cooling. CityBES also models the neighborhood buildings as shading surfaces in EnergyPlus to consider the solar overshadowing effect between buildings.

Figure 7 also maps out the locations of the 15 local Air Nodes used as ambient air conditions from the WRF simulated data. Each Air Node has an absolute physical coordinate with a latitude, longitude and height in meters (x, y, z). The 15 nodes are

Figure 7. Building models in the city block of the Goose Island Region.

selected based on the layout of streets and the flow of the river using a single Z layer at 3.0 m. For each building exterior surface and exterior zone, we calculate its absolute physical coordinates and mapped it to its nearest air node out of the 15 pre-defined ones by distance. For example, during simulation, all surfaces at the east façade of Buildings 1 and 2, and the west façades of Buildings 5 and 6 use the local-weather condition at Air Node 4. The environmental data stored at each Air Node is generated from the WRF model and extracted by its physical coordinate.

Results

WRF simulations

The WRF model typically outputs vertical profiles from land surface height to $\sim$4 km above sea-level. The vertical grid is staggered to capture the variations close to the land. There are a total of 42 vertical grid points with 29 points in the first one kilometer. Figure 8 shows a clear 2.5-degree difference in the HRRR and NAM initialized simulations of vertical profiles of temperature for $\sim$300 m above the surface. A sharp increase in temperature is seen from 50 to 100 m height in the HRRR simulation. Without observed temperature profiles for the selected area, it is difficult to speculate which model has a better prediction. It must be noted that the comparison of results for only node 5 is shown, as other nodes show a very similar pattern. This can be attributed to the fact that the target area does not have any tall urban buildings and that the total area simulated is less than 400×400 m^2, which does not yield high meteorological variability, hence, the difference observed in vertical temperature profiles of nodes is minimal. The higher-resolution HRRR simulations may be performing better in terms of capturing thermally and mechanically driven boundary layer profile which is obtained at 4 PM local time.

Figure 9 shows the locations of three measurement stations used for hourly measurements of wind speed, temperature, and relative humidity obtained for 16 August 2017. The first observation is at the O'Hare international airport (Obs-ORD); this is typically used in EnergyPlus TMY weather profile creation for the entire Chicago region. The second observation, which is the closest station to our target region (Obs-city2, Goose Island), is obtained from the website – http://mesowest.utah.edu, this the closest to our target region and the third observation is along Foster Ave., which is located right by the lake shore drive in Chicago. In Figure 10, we compare the WRF simulated time-series of temperatures at ORD (d03-ORD) and lat:41.91, lon:−87.66 (d03-city) with the data measured by sensors. The d03 values cover the time range of 0Z on 16 August to 20Z on 17 August 2017 (Chicago local time: 19:00 on 15 August to 15:00 17 August). Due to numerical instabilities, the last 3 h of the simulation was disregarded, therefore only 45 simulated hours is used throughout the study. Obs-ORD and d03-ORD closely match at all times except the first 10 hours, which might be due to model spin-up time to adjust to the initialization data, a bias in the init data, or the model is not able to represent physical processes reasonably.

In general, we observe that the city is slightly warmer during the night hours due to the westerly advection of warm moist air over the lake effect. Between morning to late evening hours, WRF reasonably captures the warming at ORD which is caused by southerly winds. The city is cooler compared to ORD at these

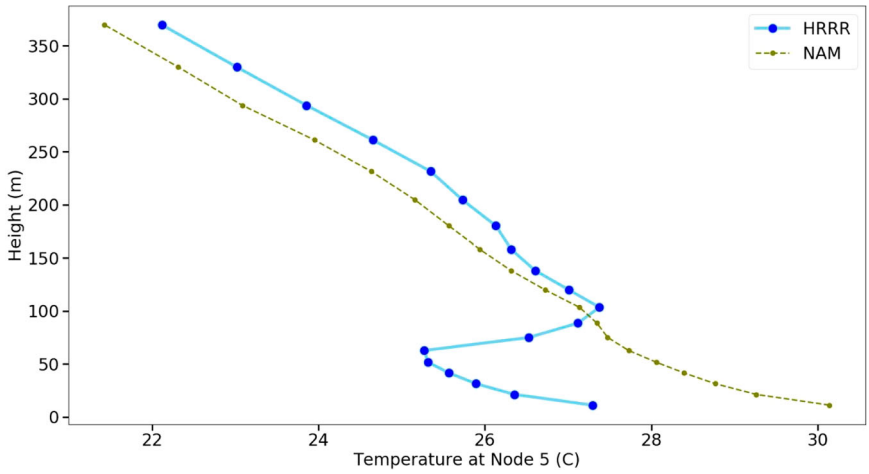

Figure 8. For node 5, as shown in Figure 7, the plot shows a vertical profile temperature (^oC) obtained by HRRR and NAM initialized simulations for 16th Aug 2017 at 21 UTC (4 PM local time).

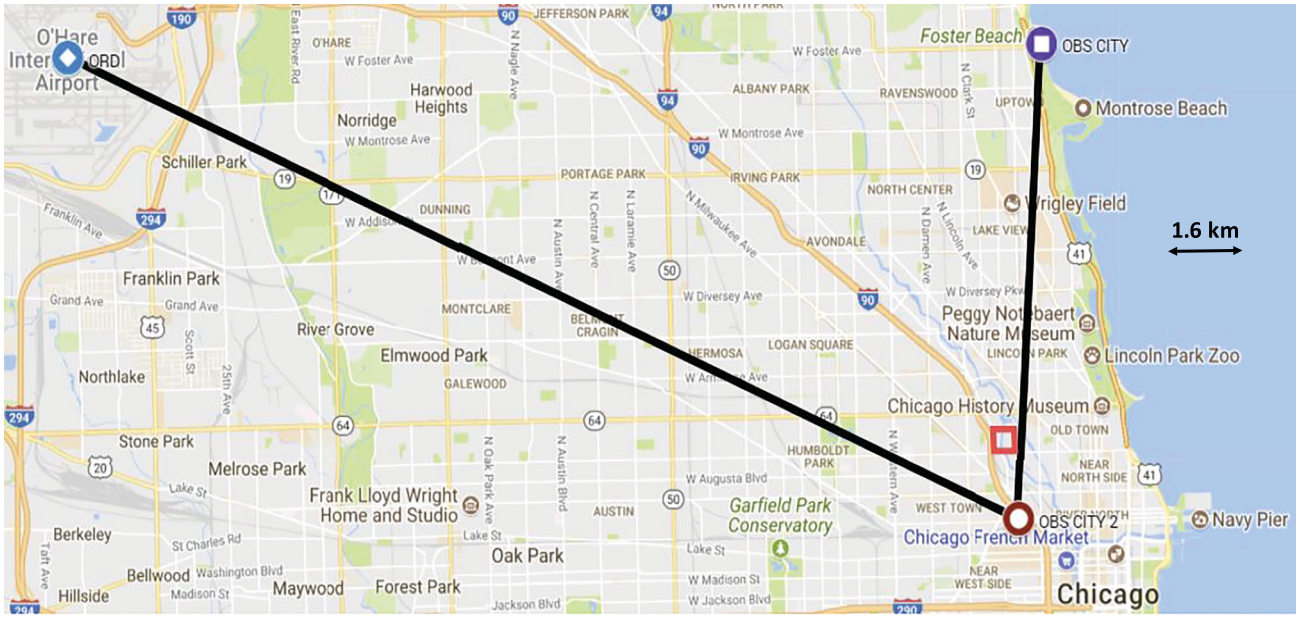

Figure 9. The square shows the target area, along with the three observation locations: (1) Chicago O'Hare airport, (2) Observation location close to Goose Island, and (3) Lakeshore drive that are used for the plot in Figure 10.

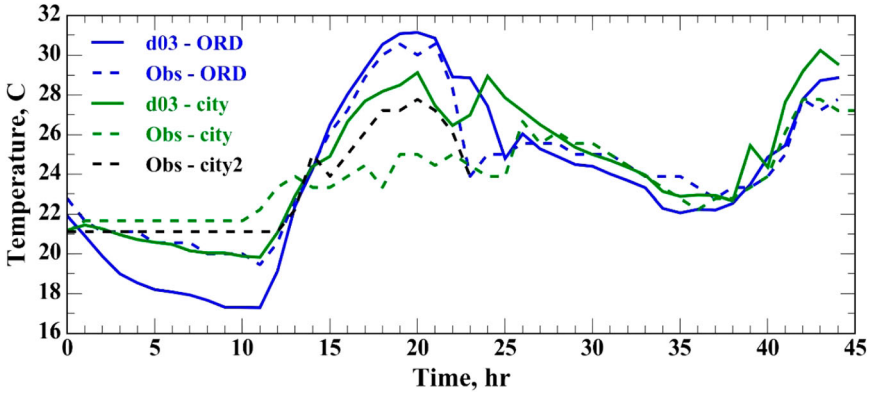

Figure 10. Comparison of WRF simulated temperature results with observations for three stations shown in Figure 9 for 0Z August 16th to 20Z August 17th (Chicago local time: 19:00 on August 15th to 15:00 August 17th).

times, because of the strong lake breeze. We note that d03-city and Obs-city values are located a few kilometers apart and the temperature difference is significant. Also, Obs-ORD, Obs-city and Obs-city2 show variation around hours 10–25 which are corresponding to the local afternoon and night period. This result is a good motivation for a dense instrument deployment in the Goose Island region to perform better fidelity high-resolution simulations and validations. Obs-city and Obs-city2 and d03-city show a difference of 2–3 degrees around 18 h, while at this time ORD measurements show 4–5 degrees higher temperatures. The cooler measured and simulated city temperatures are resulted by the strong lake breeze which dominates most the lower west coast of the Lake Michigan. The latter part of simulations (25–45) shows a good agreement and the model has good skill when local weather is synoptically driven. Under these conditions, the location of temperature measurements is not very important, as local effects like the lake breeze or urban heat island effects are relatively weaker. The variations in temperature as a result of mesoscale weather processes and mechanical and thermal building effects in a city block show that high-resolution simulations and observations are necessary to capture local-weather variability. In the next sections, we will highlight how these simulations and measurements impact the building energy simulations and overall energy requirement calculations.

Building energy simulation

We first compare the climate condition difference among (1) TMY data: the TMY3 weather data from the weather station of Chicago O'Hare, which is traditionally used in EnergyPlus simulations (2) WRF data: the average local-weather data of the 15 nodes at the day of 2017-08-16 simulated by the WRF model, and (3) OBS data: the local climate data observed at the nearby weather station (River West Station, Elev. 600 ft, 41.89°N, 87.65°W). The TMY3s are data sets of hourly values of solar radiation and meteorological elements for a 1-year period, representing only typical conditions. The simulation day we choose, however, is a special boundary condition case. The weather was mostly fair during the morning, but mostly overcast and cloudy after 14:00 in the afternoon and evening. Figures 11 and 12 show the daily dry bulb temperature and relative humidity, comparing the TMY, WRF, and OBS data. Throughout the day, the observed dry-bulb temperature is generally higher than the typical condition by two to five degrees, and the WRF simulation captures the trend. The simulation result of the relative humidity agrees with both the observed and the typical condition on this day. The difference is expected to affect the energy consumption and heat emission of buildings to the urban environment.

Besides, as Figure 13 (wind speed) and Figure 14 (hourly solar radiation rate) show, the WRF simulated values agree with the

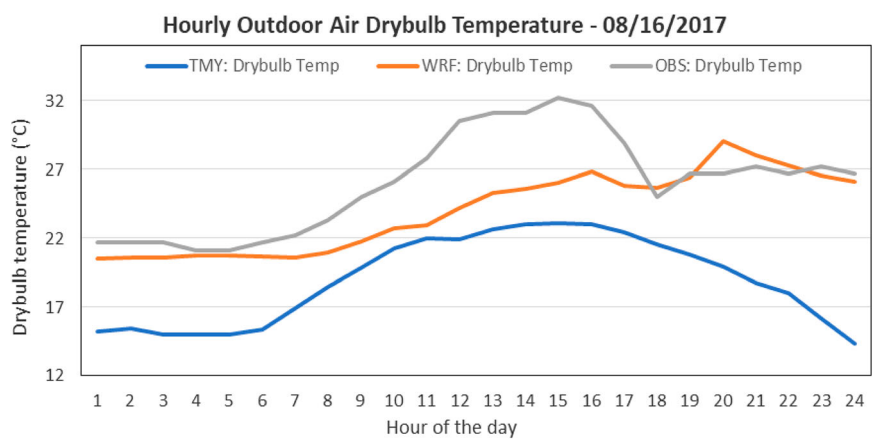

Figure 11. The daily dry-bulb temperature TMY, WRF and OBS data.

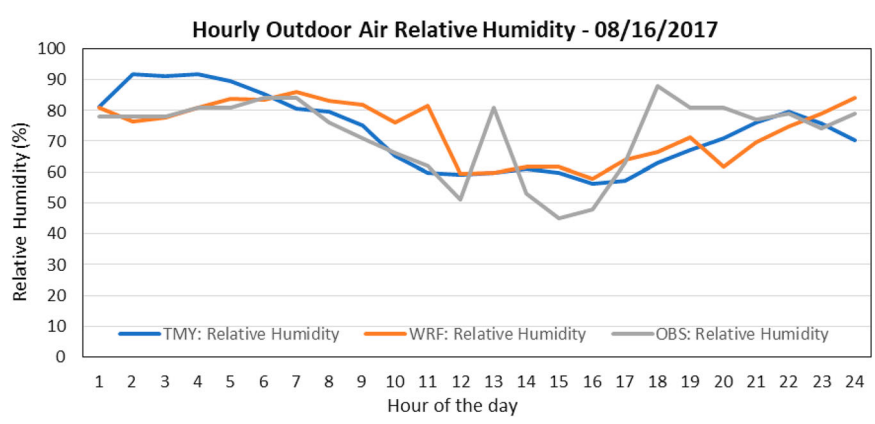

Figure 12. The daily relative humidity of the TMY, WRF and OBS data.

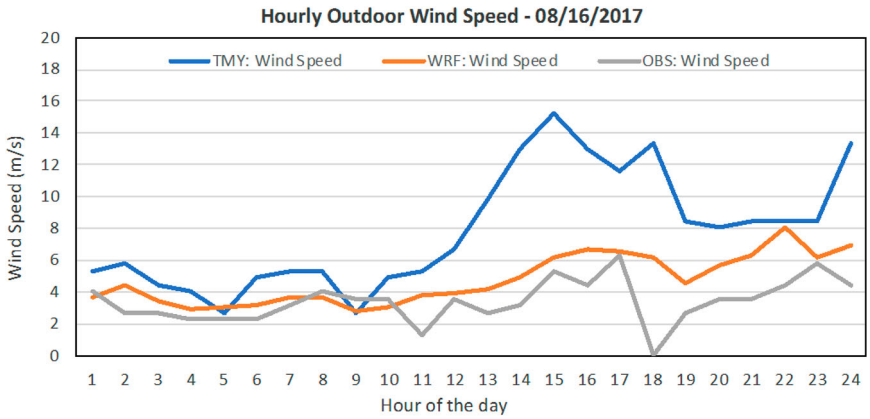

Figure 13. The daily wind speed of the TMY, WRF and OBS data.

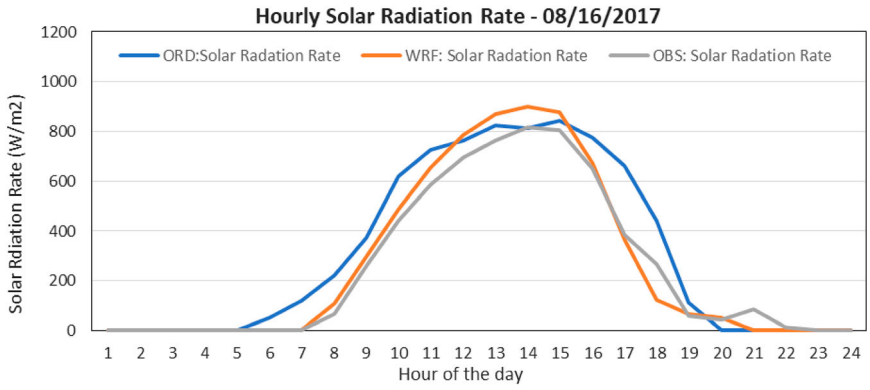

Figure 14. The daily short wave solar radiation rate of the TMY, WRF and OBS data.

observed local data, but the TMY data deviates from the local conditions. The air flow condition would affect the heat convection and infiltration from the surrounding environment to the buildings.

In August, cooling load is dominated in Chicago, among all energy demand. In order to evaluate the sensitivity of the energy use to the local environmental data, Figure 15 compares the hourly building energy use intensity in watt-hour simulated with TMY and WRF data. In general, the WRF simulated local temperature on this day is higher than the TMY data, the solar radiation is higher during the noon time, and the wind speed is lower. Consequently, the cooling energy demand is higher. On average, the total energy usage of these 20 buildings simulated using the WRF data is 4.7% higher than the results simulated using the TMY data. In this experiment, the buildings with larger surface-to-volume ratios are more sensitive to local-weather conditions,

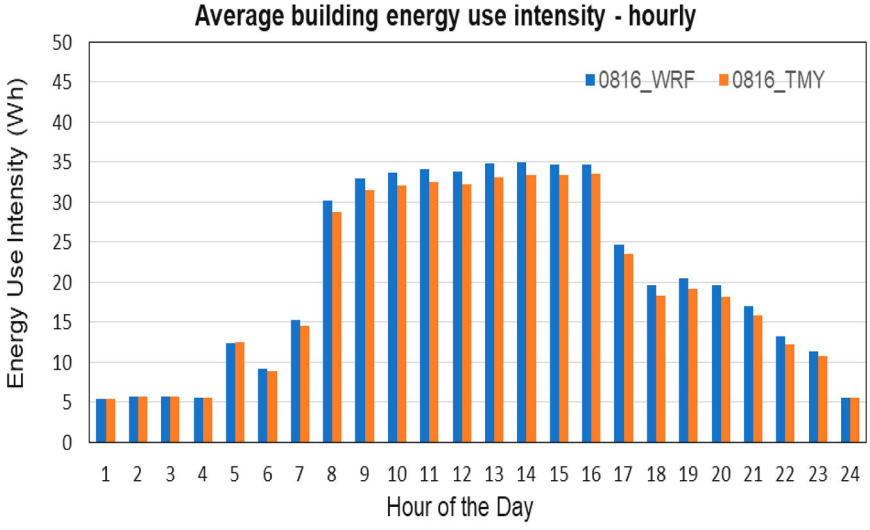

Figure 15. The average building energy use intensity of the 20 buildings for two simulation scenarios.

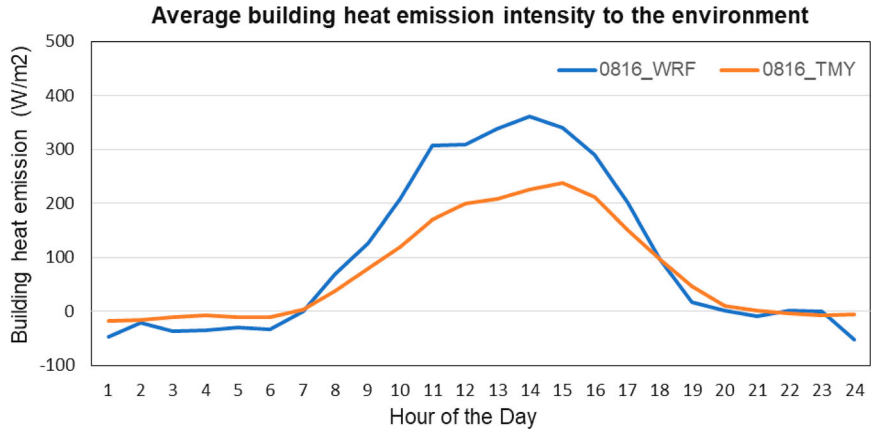

Figure 16. Average building heat emission intensity of the 20 buildings to the urban atmosphere for two simulation scenarios.

such as Building 2 in Figure 7 with a 9.11% higher total energy use and a 32.0% higher cooling consumption.

To evaluate the impact of buildings in the urban context on the local-weather, for all exterior walls, windows, and roofs of each building, we calculated the building heat emission as described in the previous sections. Figure 16 shows the heat emission curves averaging the 20 buildings on the simulation day using the TMY weather station data and WRF simulated data. The positive values indicate the heat transfer from the surrounding environment to the outside face, while the negative values indicate the opposite. In this study, the building heat emission consists of heat convection through building surfaces, building HVAC system heat rejection, heat transfer through zone exhaust air and building mechanical system relief to the local climate. Simulated with the WRF data, the difference between building the indoor and outdoor temperatures is higher, and the cooling demand is higher, driving the heat emission to be higher throughout the day. For the simulated day, the average aggerated heat emission to the environment simulated with WRF data is 40.4% higher than that simulated with TMY data.

Discussion

Our study shows the potential and need for higher fidelity simulations and coupled calculations for more accurate building energy modelling in the urban context, with which deeper insights and conclusions can be drawn to aid the city planners and architects. We specifically find out that this can be achieved with the use of high performance computing. First, our methodology for simulation data flow shown in Figure 2 is based on data transfer using an intermediate json file. For longer duration simulations and superior performance, the in-memory data-exchange capability will be required. Second, in our models, we use National Urban Database with Access Portal Tool (NUDAPT) for urban land characteristics, and further improvements to this can be made with the addition of true-resolution topography leading to more accurate weather and airflow prediction. This methodology can be further extended to include other models and enable the two-way feedback.

The recent advances in HRRR initialized WRF, when compared to NAM, are showing a promise of improved and more detailed variation in urban boundary layer regions. One-way data coupling between EnergyPlus and WRF and the methodology developed here is scalable and is found to be more realistic in comparison to traditional standalone simulations. However, we note that a finer-scale computational fluid dynamics (CFD) model resolving the turbulence around the buildings could be more accurate than this work. CFD models offer a more exhaustive investigation of urban areas providing insights into pollutant concentration distribution, temperature distribution, and various other mixing and air quality impacts. More importantly, due to the heavy computing burden of the urban atmosphere simulation, the study is performed at a small spatial scope of a sampled district using one-day WRF data during the cooling season. Simulation scenarios should be considered in the future combining various cases of local-weather conditions of difference seasons. Other building types and typologies, such as high-rise buildings in a dense urban area, or residential districts, are highly potential to show different results from the specific building block modelled in the study. We note that feedback from live sensor data, such as continuous temperature, humidity, and wind speed can be used to further make the coupled simulation more accurate. This is established by results in Figures 11–14, which highlight the substantial difference in observations from sensor data at three different locations in the city.

For the test case in this study, we use measurements at $z = 3.0$ m, because the target area has low-rise buildings that are approximately that height. In future studies, we intend to use the World Meteorological Organization (WMO) indicated heights of $z = 1.5$–2.0 m for our simulations and coupling. For generating the input models, we manually fix the building footprint data according to the satellite map data. This process of fixing the buildings in GIS platforms is tedious and intractable for city-scale models, thus we are investigating reasonable alternatives to address this issue by automatically generating accurate 3D models with other data sources such as LIDAR data for the city. Currently, the limited data resource allows us to model the building only at the limited level of details (extruding polygons). When more accurate building geometry, configuration and system related data are obtained, the building energy modelling can be considerably improved.

Conclusions

Thiswork develops a high-fidelity coupling methodology involving building energy and urban atmospheric models. A one-day coupled simulation for a chosen area in the city of Chicago, along with the challenges and benefits involved in developing such coupled models are presented. Our results for a small test area in Chicago clearly show that utilizing WRF provides more accurate urban weather boundary conditions such as temperature, windspeeds, humidity and radiation when compared to traditional TMY datasets typically used as inputs to EnergyPlus. Although the computational cost is high, the resolution and accuracy of the predictive total energy consumed by the building are improved. For 16 August 2017, a typical summer day, we find out that on average, the total building energy use differs by about 4.7% and the average aggregated heat emission to the environment simulated with WRF data is 40.4% higher than the EnergyPlus simulated results using the TMY weather data. We predict that for days with severe weather events our methodology will produce more accurate results and the variation in computed energy differences will be large. In the future, we plan to cover more area and time duration to further validate our tools and findings. Also, trees and other green vegetated sources cover only a small fraction of the studied urban area. Given the selected days of the simulation is dominated by strong background flow, the neglect of such sources may have a few percent variabilities in the results. We expect this variability to become larger with quiescent weather conditions. Three major conclusions for this work are: (1) Three kilometers to 120 meters' domain configurations which are initialized with the HRRR dataset, allow the WRF model to drive building energy models with a reasonable accuracy, (2) The representation and resolution of the urban weather boundary conditions used in building energy simulation have a significant impact on the space cooling loads and energy consumption, and (3) The building's heat exhaust to the surrounding environment is influenced by the local climate conditions, and vice-versa has an impact on the urban boundary conditions.

The methodology developed here is capable of using measured data. Also, such high-fidelity analysis will aid the design of IoT systems for controlling the climate of the building to help policy makers and electricity suppliers in order to better optimize the urban systems for the city. For better evaluation of the performance of the coupling approach, longer-term datasets (ranging from days to months) should be used to analyse and reduce the weather-related local variations.

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