City-Scale High-Resolution WRF-UCM Urban Weather Predictions Compared to a Dense Network of Ground-Based Weather Station Data for Assessment of Urban Building Energy Consumption

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ABSTRACT

Building energy consumption is highly influenced by weather conditions, thus having appropriate weather data is important for improving the accuracy of building energy models. Typically local weather station data from the nearest airport or military base is used for weather data input. However this is generally known to differ from the actual weather conditions experienced by an urban building, particularly considering most weather stations are located far from urban areas. The use of the Weather Research and Forecasting Model (WRF) coupled with an Urban Canopy Model (UCM) provides a means to be able to predict more localized variations in weather conditions. However, one of the main challenges associated with the assessment of the use of this model is the lack of availability of ground based weather station data with which to compare its results. This has generally limited the ability to assess the level of agreement between WRF-UCM weather predictions and measured weather data in urban locations. In this study, a network of 40 ground based weather stations located in Austin, TX are compared to WRF/UCM-predicted weather data, to assess similarities and differences between model-predicted results and actual data. Given that the WRF-UCM method also takes into account many input parameters and assumptions, including the urban fraction which can be measured at different scales, this work also considers the relative impact of the granularity of the urban fraction data on WRF-UCM predicted weather. As a case study, a building energy model of a typical residential building is then developed and used to assess the differences in predicted building energy use and demands between the WRF-UCM weather and measured weather conditions during an extreme heatwave event in Austin, TX.

INTRODUCTION

The occurrence of extreme heat events significantly impacts individual building energy demands and consumption, as well as the demand and consumption of cities where large numbers of buildings are located. Recent data indicates that 73% of electricity consumption and nearly 75% of peak electricity demands originate from residential and commercial

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buildings (U.S. Energy Information Administration). In extreme heat conditions, electricity demand and consumption are generally higher (Mirzaei and Haghighat 2010; Santamouris et al. 2015), due to the increased use of heating, ventilation and air conditioning (HVAC) systems which are present in over 83% of residential and nearly 100% of commercial buildings in the U.S. (U.S. Energy Information Administration, 2011). The significant increase in electricity demands can cause stress on the electric grid servicing these buildings. In such events, the electric grid must both have sufficient transmission capacity to service the areas of significant demand, and sufficient generation capacity to meet the demand levels. In some cases, such extreme heat events can require power plants with low efficiencies and high costs to operate to meet such demands, or in the worst cases, cause blackouts or brownouts if the grid is not able to handle the load. In summary, such events cause grid reliability issues, higher energy costs which are eventually passed to the consumer, as well as higher levels of pollution. As such, it is of significant benefit to develop methods to better model the electricity demands of buildings and cities, in part to better predict the resource adequacy of grid infrastructure.

To support assessing the electricity demand and use during extreme heat conditions, accurate evaluation and prediction of the local weather conditions in which buildings are located are needed, given that energy performance is highly dependent on the local weather, and in particular the outdoor temperature, in which buildings operate. Typically weather input data used for building energy simulations comes from weather data collected at airports (FAA 2014). However, the conditions at airports are not necessarily representative of the urban climate conditions experienced by buildings. In particular, as urbanization of the U.S. population has increased, people and buildings have increased in density, which has also increased the amount of man-made infrastructure that can absorb and retain heat, and the amount of heat sources (e.g. from cars, HVAC systems, people, equipment, etc). These factors create what has been called the urban heat island (UHI) effect in cities, which is typically defined as the increase in the ambient temperature of an urban area as compared to more rural areas. This effect has been documented over many decades (e.g., (Basara et al. 2010; Crawley 2008; Mirzaei and Haghighat 2010)).

In many cases airports are located outside of the city in locations with lower urban fractions, thus the weather data collected does not see the impacts of UHI effects that many of the buildings in that city may experience. There are several studies (Bhandari, Shrestha, and New 2012; Crawley 2008; Salamanca et al. 2011; United States Environmental Protection Agency) that highlight the importance of utilizing local weather data. However, given that the cost of installing a significant amount of ground-based weather stations to capture variations in climate conditions in a small geographic area is high, it is beneficial to explore the use of lower-cost methods to be able to capture the spatial variations in weather parameters, and variations in the presence of UHI effects within a city.

To capture localized climate characteristics in urban areas using modeling, the Weather Research and Forecasting (WRF) model (Skamarock et al. 2005) can be used. WRF is a nonhydrostatic atmospheric model. The WRF model can be coupled with an urban canopy model (UCM) (Bueno et al. 2014; Chen, Yang, and Zhu 2014) to capture more urban characteristics. UCMs are derived from energy balance equations which utilize urban parameters inputs including the land use and land cover information, amount of impervious surfaces, building sizes and heights, and the surface albedo, emissivity, and heat capacity of materials used in urban construction. There are several recent studies that have investigated the capability of a WRF-UCM model to simulate spatially varying weather conditions within a city. Chen et al. (Chen et al. 2014), compared multiple WRF models with different UCM inputs with a network of weather stations in Hangzhou, China during a single heatwave event. In another study by Miao et al. (Miao et al. 2009), a comparison between WRF-UCM results and 60 surface observation stations located in different land use types was conducted during a heatwave event in 2005 in Beijing, China. However, these studies mainly focused on a single heatwave event to evaluate the WRF-UCM model performance, even though extreme heat events often occur several times a year and across many years in warm climates. To our knowledge no recent studies have analyzed multiple heatwave events in non-contiguous periods to conduct comparative analysis. In addition, these recent studies were conducted in China rather than in the U.S. Given the significant differences in the building stock and city layouts associated with different countries, it is beneficial to study U.S. based cites as well.

In this research, a WRF model combined with input from a UCM model is used to predict weather conditions in the city of Austin, TX during 5 historical heatwave events. This is compared to a unique data set of historical measured weather data from a network of 40 ground-based weather stations within the city, to assess similarities and differences in model-predicted results and measured data across different spatial locations. Based on this comparison, parameters in the WRF model are then updated to improve agreement between modeled and measured data. Using the updated model results, a case study is conducted using a building energy model of a typical residential building in Austin TX, to assess the building energy implications of the utilization of a WRF-UCM model to predict urban, UHI-impacted weather as compared to airport-based data.

DATA SOURCES AND METHODOLOGY

Heatwave definition and occurrence selection

First, the specific heatwave events to be studied in the Austin area are identified. A review of the literature indicates that there are a large number (30+) of heatwave definitions. Many definitions consider a certain impacted group or sector (e.g., human health, wildlife, agriculture, bushfire–wildfire management, transportation, and electricity and power) in their development. For example, predicted mean vote (PVT)(Fanger and others 1970) and physiological equivalent temperature (PET) (Mayer and Höppe 1987) are indices used to measure human comfort during periods of excess heat. The World Meteorological Organization's (WMO's) Expert Team on Climate Change Detection and Indices (ETCCDI) developed eight of these different heatwave definitions (SU, TR, TXx, TNx, TX90p, TN90p, and WSDI) (Karl, T.R., N. Nicholls, A. Ghazi 2009). These indices can be used either by themselves or in combination to consider multiple elements of a heatwave such as the frequency, magnitude, and duration (Karl, T.R., N. Nicholls, A. Ghazi 2009). Some indices such as WSDI, TX90p, and TN90p consider data across the entire year for studying the number of consecutive days that the temperature exceeds certain thresholds. Other definitions such as SU, TR, TNx, and TXx (see Meehl and Tebaldi 2004 (Meehl 2004); Nairn et al. 2009(Nairn, Fawcett, and Ray 2009)) are based on a single season (summer), assuming that heatwaves can only occur during warm seasons. Several indices are percentile based, while some refer to an absolute temperature.

In the current study, four different definitions were applied to investigate the 69 years of historical weather data (1948 - 2017) available for the Austin, TX area, to capture the heatwave events that occurred in Austin throughout the studied time. Excess Heat Index (EHI), Warm Spell Duration Index (WSDI), Heatwave duration Index (HWDI), and the Meehl index are the four different definitions that are well-documented in the literature and were applied in this study. More detailed information about EHI and HWDI, are given in Perkins and Alexander (Perkins and Alexander 2013). The WSDI is adapted from the WMO (Karl, T.R., N. Nicholls, A. Ghazi 2009), and is based on an annual count of days with at least 6 consecutive days when the daily maximum temperature exceeds the 90th percentile of the daily peak temperature. The Meehl index which is adapted from Meehl and Tebaldi (Meehl 2004), is based on two percentile thresholds and maximum daily temperature.

Through checking historical temperature data for Austin from 1948 to 2017, considering the aforementioned definitions, various heatwave events were identified. However, among all of the various heatwave events identified by different definitions, only in five cases did all four definitions agree. Detailed information about the selected heatwave events is given in Table 1.

For each of these heatwave events, the WRF model was used to generate a temperature forecast for the Austin region at 1-km (0.62 mile) horizontal resolution over a 24-hour period. It should be noted that due to lack of archived model data used to initialize WRF for the year 2000, an alternative heatwave event that occurred from August 23-25, 2009 was identified. Using this alternate event conformed to the heatwave criteria using EHI, WSDI, and WHDI, but not the Meehl definition.

Table 1. Historical heatwave events in Austin selected by EHI, WHDI, WSDI and Meehl heatwave indices

No.	Date	Maximum Temperature (C)	Minimum Temperature (C)	Average Daily Temperature (C)
1	9/4/2000	42.8	27.8	35.3
	9/5/2000	43.3	26.1	34.7
	9/6/2000	40.0	26.1	33.1
2	6/26/2009	40.0	25.6	32.8
	6/27/2009	38.9	26.1	32.5
	6/28/2009	39.4	25.6	32.5
	6/29/2009	40.6	25.6	33.1
3	8/29/2011	42.2	27.2	34.7
	8/30/2011	40.6	26.7	33.7
	8/31/2011	38.9	26.1	32.5
4	8/8/2013	40.0	25.6	32.8
	8/9/2013	39.4	24.4	31.9
	8/10/2013	40.0	25.6	32.8
5	7/28/2017	40.0	24.4	32.2
	7/29/2017	41.1	25.0	33.1
	7/30/2017	40.6	26.7	33.7

Observational weather data

Two sets of weather data were used in this study. The first dataset is from Automated Surface Observing System (ASOS) sites, a part of a broad network of weather stations supported and maintained by the Federal Aviation Administration (FAA) and the National Weather Service (NWS) (FAA 2014). For this study, two ASOS stations were selected. The ATT site is located within the Austin urban area with an urban fraction of 0.9, at the site of the old Austin airport. The EDC site is located 19 km northeast of downtown Austin in a non-urban region at the current Austin airport. ASOS weather data is the data typically available for a city in the U.S., and is typically from an airport located in or near a city. The second set of data was adopted from weather data collected by weather stations maintained by a private company. This set of data is a part of a broader extended weather network of data, with more than 12,000 neighborhood-level sensors installed at schools, stadiums and businesses (Earth Network 2017).

WRF Model configuration

Due to high computational costs, it is not feasible to apply the WRF model with fine horizontal grid resolution on a large temporal and spatial scale. Therefore, in this study, the spatial boundary is limited to the city of Austin, Texas, and the time span for modeling is limited to a single day for each of the chosen heatwave events.

In order to capture the UHI effect that can vary spatially across an urban landscape, the WRF model (version

3.9)(Skamarock et al. 2005) coupled with a single layer UCM (SLUCM) is invoked with a relatively high grid resolution of 1 km (0.62 mile). The SLUCM used, consists of a single layer model that includes a 2-D street canyon and represents the physical process in the urban environment. In other words, the UCM is a simplified urban geometry that includes surface albedo, emissivity, and wind profile. In addition to the previously mentioned characteristics, the building shadow effect, and human-induced heat fluxes that are transferred to roads, walls, and roofs are also embedded in the UCM. To run WRF model with SLUCM, it is necessary to determine surface parameters, canyon dimensions, and physical constants. It should be noted that the WRF model was run for the historical heatwave events in Austin that are discussed in Heatwave definition and occurrence selection section using a series of nested grids of 36 km (22.37 mile), 12 km (7.46 mile), 4 km (2.49 mile), and 1 km (0.62 mile) resolution. The latter two grids were centered successively over central Texas and the Austin metro region. The coarsest (36-km (22.37 mile)) WRF domain was initialized at 12:00 UTC within the period of a given heatwave event using initial and boundary conditions from the Global Forecast System (GFS) acquired from the National Centers for Environmental Information of the National Oceanic and Atmospheric Administration.

WRF model assessment

To validate the WRF-UCM model as configured here, the WRF model hourly temperature forecasts are compared to the ATT ASOS data using the root mean square error (RMSE) for each of five selected heatwave events. Different variables such as building height, roof surface albedo, wall surface albedo, and the Akanda parameter were modified to enhance the model performance and get the lower RMSE values. UCM parameter default values are used with the exception of those listed in Table 2, the values of which are optimally chosen based on a series of preliminary WRF simulations. The obtained RMSE values for each event are compared with the range of RMSE values given in the literature involving similar mesoscale model studies (Chen et al. 2014; Miao et al. 2009).

Table 2. List of SLUCM parameter values that differ from WRFv3.9 default values

Note: Multiple entries indicate values respectively for low-density, high-density, and commercial urban fraction

Parameter	Symbol	Value	Unit
Roof level (building height)	z_r	5.0, 6.5, 6.5 16.4, 21.3, 21.3	[m] [ft]
Roof surface albedo	a_R	0.2	-
Wall surface albedo	a_W	0.2	-
Road surface albedo	a_G	0.2	-
Akanda parameter		0.3, 0,4, 0.5	-

After this validation step, the WRF model is used to determine the local weather for a range of spatial locations within the model domain across days with similar weather patterns and extreme heat, of interest in this work (i.e. other heatwaves). A comparison between the WRF model results and measured data is then conducted, considering a range of different locations for the five heatwave events. This includes 47 different comparison cases, considering the availability of measured data at each ground-based weather station. The RMSE values at each station for each 24-hour heatwave event are used to evaluate the WRF model results at a range of locations throughout the city of Austin.

To understand the potential impact of using WRF-created output for energy modeling as compared to the typically used weather data from ASOS sites at airports, the results from using the WRF model are extracted for the hottest location within the studied urban area during each heatwave. The hottest location was selecting as the point with the highest average daily temperature within the WRF domain. Using this location represents the maximum possible temperature difference between the temperatures experienced by buildings in the urban environment, as predicted by WRF, and that from an airport located in a non-urban area outside of the city. This comparison is made for all heatwave events. The differences between the WRF results and EDC ASOS measured data at the non-urban airport are reported in the results section.

Energy model configuration

The energy model is created in BEopt (Building Energy Optimization Tool (National Renewable Energy Laboratory (NREL)), which is based on EnergyPlus, to quantify the energy consumption change due to WRF-generated weather data and the weather data obtained from the EDC ASOS station, typical of weather data that would be used for energy modeling if only airport weather-generated weather files were available. The building characteristics for the energy model were taken from ResStock (National Renewable Energy Laboratory (NREL)), which provides housing stock data, including building characteristics such as building area, building insulation, type and rating of heating and cooling equipment, and lighting and electric equipment loads for residential buildings in U.S. by state. For this particular energy model the most common characteristics in the state of Texas were utilized. The energy model was run twice for each the heatwave event period. First, with the EDC ASOS data as the weather input and a second time with WRF generated weather data. Thus, ten energy simulation runs were generated for the 5 heatwave events.

RESULTS AND DISCUSSION

In this section, the results of the current study are reported in two subsections. In first section, the WRF model validation with ASOS measured data for the five different heatwave events are discussed and second section, covers the results of the developed energy model and the variation of the results due to different weather input.

Assessing WRF model results

To assess the WRF model performance, the simulation results are compared with the ASOS measured data during the five historical heatwave events in Austin (Table 1). It should be noted that due to the lack of Global Forecast System (GFS) output for the year 2000, as an input to the WRF model, an alternative heatwave event was used in which the heatwave was selected by the heatwave definitions EHI, WSDI, and WHDI. The elimination of the Meehl definition as a criteria increases the number of heatwave events to consider. Therefore, the heatwave event that occurred in August, 2009 was used as a substitute for the heatwave event in September, 2000. To validate the WRF model, the differences between hourly dry bulb temperature of the measured ASOS data and the WRF output were compared throughout the day that the heatwave event occurred. The RMSE values are shown in Table 3. As shown in this table, all the values are less than 1.72 which is within an acceptable range as compared to other recent literature (Chen et al. 2014; Miao et al. 2009).

Table 3. RMSE values for ASOS vs. WRF hourly drybulb temperature comparison for studied heatwave events

Heatwave events	8/23/2009	6/29/2009	8/28/2011	8/8/2013	7/28/2017
RMSE	1.57	1.41	1.56	1.72	0.7

To examine the performance of the validated model in various locations throughout the city of Austin, the comparison is conducted between WRF output and measured data. 47 ground-based weather stations had the data for the heatwave events that occurred in 2011, 2013, and 2017. As shown in Figure 1, all the RMSE values are in the range of 1 to 3 degrees which is similar to the range found in other studies (Chen et al. 2014; Miao et al. 2009). It should be noted that the data for the ground-based weather stations in Austin have been collected since 2011. Therefore, there is no data available for events in 2009. Moreover, as shown in Figure 1, the availability of the measured data for the studied heatwave events is not consistent for all the stations; at some stations there are missing data for that specific heatwave event.

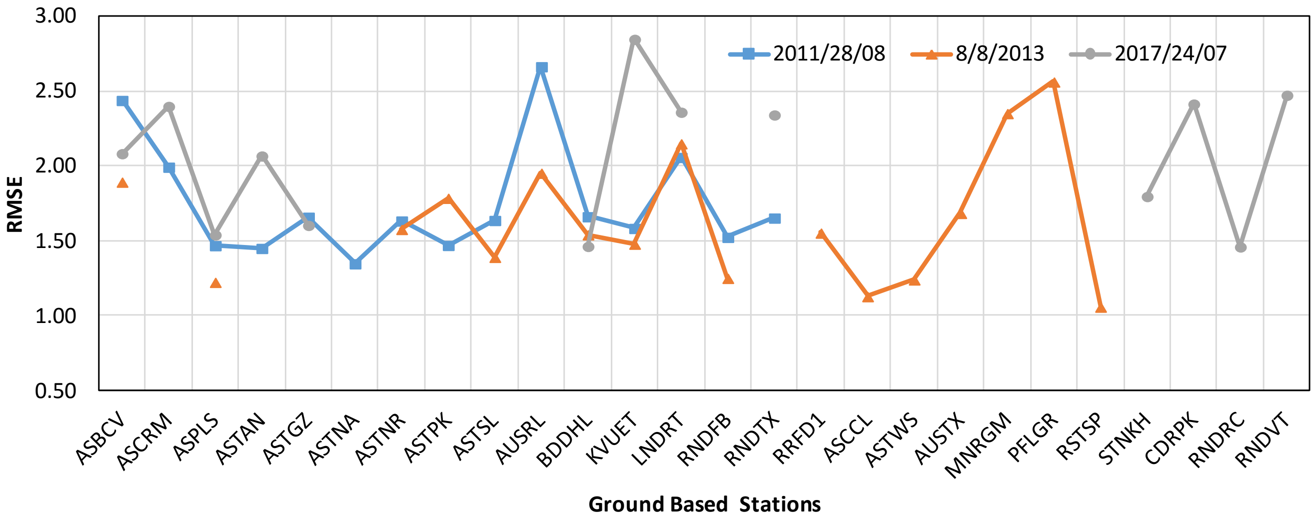

Figure 1. RMSE values for hourly temperature comparison between measured data at ground-based weather stations and WRF results extracted at the same location. *Note: The reported stations are those that had measured data for at least one of the studied dates.*

As per the discussion in WRF model assessment section, the WRF results were extracted for the hottest urban location for each heatwave event and compared to the measured temperature data at the EDC ASOS station (Figure 2).

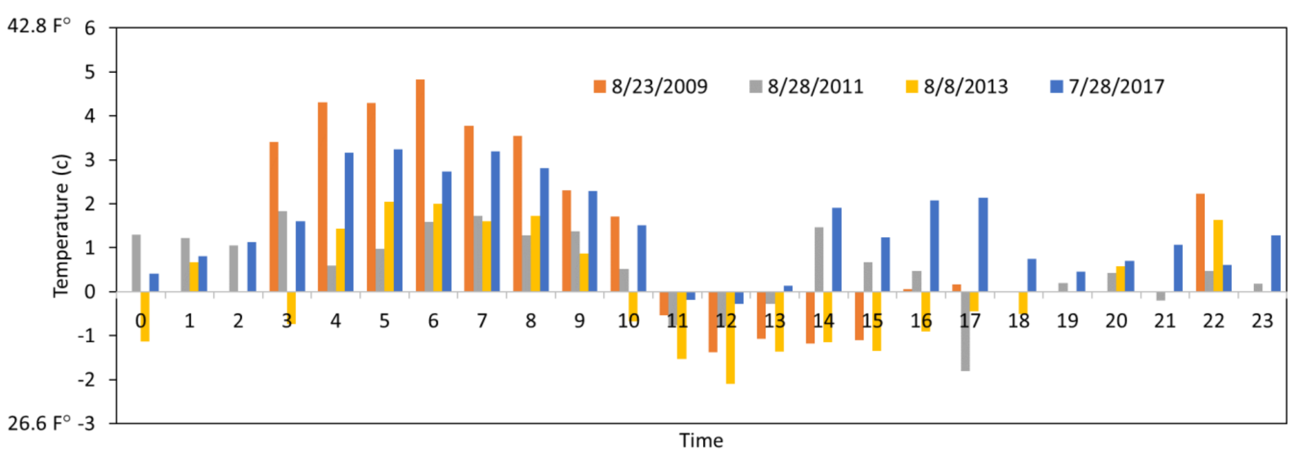

Figure 2. Hourly temperature differences between the WRF results at the hottest location in the city and EDC ASOS (airport) measured data. *Note: a positive value indicates the WRF temperature data is higher than the airport ASOS data;*

The results indicate that the WRF outputs for the locations within the city have a higher temperature from midnight to 10 am and from 5 pm to midnight. This makes sense given the urban fractions are much higher for the urban areas covered by WRF.

Effect of weather data on energy consumption

Comparing the results of energy models for each weather scenario, indicates the maximum possible variation in energy consumption due to the observed temperature differences. As shown in Table 4, in all the studied cases the total energy consumption using WRF weather inputs are higher than total energy consumption using EDC ASOS weather input. These differences are due in part to the differences in weather data input, including higher temperatures in the urban locations, due to UHI effects. However, the level of difference varies. Based on this analysis, an energy model of a typical Texas residential building would be predicted to consume up to 14% more energy using the WRF-based data.

Table 4. Energy consumption comparison for EDC ASOS weather data and WRF weather data

No	Heatwave event	Total energy consumption (kWh)		Total energy consumption difference (kWh)	% difference
		WRF	ASOS EDC	WRF -ASOS EDC	
1	7/28/2017	38.09	34.3	3.79	11%
2	8/8/2013	36.58	35.5	1.09	3%
3	8/28/2011	44.66	43.64	1.02	2%
4	6/29/2009	45.51	N/A	N/A	N/A
5	8/23/2009	41.78	36.64	5.15	14%

Note: The ASOS EDC measured data is missing for the date 6/29/2009

CONCLUSIONS

As in most cities, airports and thus their weather stations are located outside of the city. As such, the actual weather conditions experienced by buildings in a city may be different from the weather data recorded at the location of the traditional source of weather data used for energy modeling (airports). The airport weather data in these cases does not capture the UHI effects often present in a city. In Austin there is an ASOS site at the airport in a non-urban area and a dense network of 47 ground based weather stations located out through Austin urban area. A WRF model configuration coupled with a UCM was developed and calibrated using ASOS site-collected weather data, and then its output was compared to the ground based weather station network data, with RMSE values of 1 to 3 degrees. The validated WRF model results across 5 heat wave events indicate that a typical building in Austin, TX might consume 2-14% more energy in an extreme heatwave event in an urban area using urban weather data as compared to the airport data. This conclusion points to the importance of using local weather data. Based on the results, this research also indicates that the use of a WRF-UCM model appears to be beneficial in providing more appropriate weather data for buildings located in an urban region.

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