PERKINS+WILL

Research Journal

2015 / VOL 07.02

SPECIAL ISSUE: FUTURE OF ARCHITECTURAL RESEARCH

ARCHITECTURAL RESEARCH CENTERS CONSORTIUM 2015 CONFERENCE

www.perkinswill.com

04.

URBAN MICROCLIMATES AND ENERGY EFFICIENT BUILDINGS

Pravin Bhiwapurkar, PhD, University of Cincinnati, *pravin.bhiwapurkar@uc.edu*

ABSTRACT

The challenges of a warm climate on urban buildings' energy needs for space conditioning are discussed by assessing the impact of intra-urban microclimatic changes, also called urban heat islands (UHI). This article analyzes the results of a simulation study on the energy consumption required for heating and cooling a small office building within five intra-urban microclimatic conditions of the Chicago metropolitan area. The study simulated a small office building per ASHRAE Standard 90.1-2013 with a whole-building energy simulation program and weather files that accounted for climatic changes due to urban development and synoptic weather conditions for selected locations. The results confirm that heating load decreases and cooling load and overheating hours increase as the office location moves from rural (less developed) to urban (developed) sites. However, these changes are influenced by the location's distance from downtown and from Lake Michigan. The article shows that prominent intra-urban climatic variations are an important factor affecting energy performance, examines detailed results for a typical small office located within the intra-urban climatic zones of the metropolitan area, and argues for the necessity of considering using weather files based on urban microclimates in designing buildings to safeguard their efficiency in the future.

KEYWORDS: lake effect, wind, cloud cover, solar radiation, heating and cooling energy

1.0 INTRODUCTION

Urban areas' climates are modified by high rates of urbanization resulting from drastic demographic, economic, and land use changes[1]. These modifications include increasing temperature and changing wind speeds, precipitation patterns, cloud cover, and solar irradiance. The most significant modification is the creation of urban heat islands (UHI), a term that refers to elevated temperatures over urban (developed) areas compared to rural (less developed) areas. UHIs are commonly studied under calm wind conditions during sunny days and have been found to be more prominent during nighttime, when wind speed is relatively lower than during the day. Paved urban surfaces and their configurations—for example, streets, sidewalks, parking lots, and buildings—are crucial in the formation of UHI because they absorb heat during the day and release it during the night. The lack of vegetation also reduces evapotranspiration. When studied using satellite thermal infrared images, surface heat islands are more prominent where the albedo and emissivity properties of paved urban surfaces are often intensified; vertical surfaces are often ignored[2]. The role that vertical urban surfaces, such as building facades, plays within dense urban environments is measured by Sky View Factor (SVF), which looks at the surface exposure to the sky that influences surface thermal balance[3,4]. In addition, the geography, topography, large bodies of water, land use, population density, and physical layout of the urban area all influence UHI[5]. Rapidly expanding urban boundaries constantly modify the rural landscape; the nature of the constantly evolving urban landscape also varies with land-use and land-cover changes. Furthermore, the increasing anthropogenic heat contribution of the urban environment is significant[6,7] and includes waste heat from buildings, industries, and transportation[7]. Therefore, this article focuses on the need to recognize the broader and more complicated range of intra-urban climatic conditions that influence building heating and cooling demand. The goal is to inform engineers and architects about lake effects—wind, cloud cover, and solar radiation—so that buildings will be designed to be more energy efficient.

UHI modify microclimatic conditions, increase air pollution[8], and exacerbate heat waves in urban areas[6]. Heat-related fatalities are observed globally[9]; in particular, the 1995-96 Chicago heat wave and the 2003 European heat wave are most reported in the literature. While the frequency of heat waves is increasing, mortality rates are decreasing where the use of air conditioners is prevalent[10-12]. The increased use of air conditioners to counterbalance this warming effect subsequently increases buildings' waste heat contribution and adds warmth to the urban environment. Although warm urban conditions reduce buildings' heating energy needs, they increase cooling energy needs. Internal heat load–dominated buildings operated during the daytime, like office buildings, are significantly affected. Therefore, UHI increases summertime peak electric demand that adds to the burden on the existing power infrastructure and increases greenhouse-gas emissions. However, the variation in peak demand within metropolitan areas is less recognized and this study investigates such variations within its microclimates.

Most UHI studies on building energy needs present air temperature as the climatic variable for energy impact and suggest increasing vegetation and albedo of pavements and roofs for energy savings[13]. Studies have also reported on the impact of air temperature and relative humidity on heating and cooling energy needs[14]. The wind speed is often associated with nighttime UHI, which prevents transportation of urban heat absorbed during the daytime by urban thermal mass, allowing it to rise above the city. Thermal properties of paved surfaces and their spatial organization within urban form[15] is critical for nighttime urban cooling. Buildings in warming climate benefit from night flushing and it is a suggested energy-saving strategy for office buildings[16]. However, variation in climatic elements within metropolitan area due to physical development and lake effect are less studied. For example, daytime and nighttime UHI variation, especially in the case of the Chicago metropolitan area, is not well established and has yet to show promising evidences[17]. Also, UHI studies are often reported during clear sky conditions with low wind speed; however, both of these conditions constantly change throughout the year.

To account for the combined influence of the urban environment and climate on building space-conditioning energy practices, especially in view of the synoptic weather conditions of the Great Lakes region, this article seeks answers to the following questions using average climatic data over a 30-year period (1980-2010) recorded in Typical Meteorological Year-3 format:

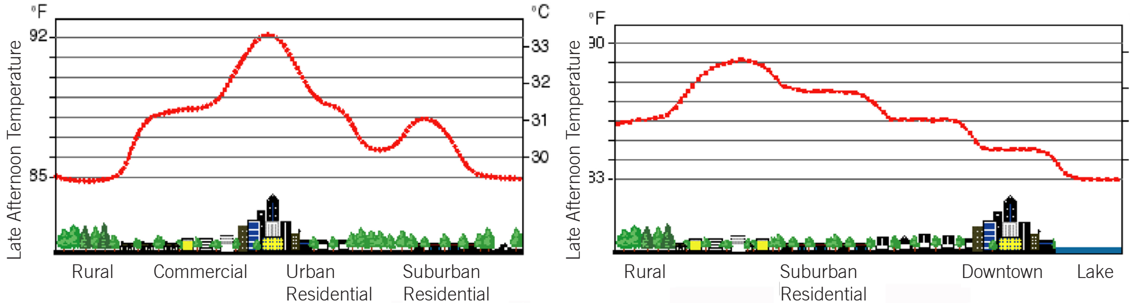
- Do intra-urban or microclimatic variations exist in the study area and how do they vary seasonally?
- How do intra-urban microclimatic changes influence peak building energy use and peak demand?

2.0 METHODS AND MATERIAL

2.1 Context

The Chicago metropolitan area lies on the flat Lake Michigan plain (41º52' north and 87º37' west) with minimal elevation changes of 176.5 meters (579 feet) to 205.1 meters (673 feet) above sea level. Chicago has a humid continental climate, with an average mean air temperature from May to September of 25.9ºC (1961–1990). In July and August, prevailing west-southwest (240º) winds average 13.2 km/h (8.2 mph) (1981–2010), transporting in warm humid air from the central and southern plains[18]. Tree cover plays an important role in moderating air temperatures in the region and the city of Chicago had an average tree canopy of 11 percent. Chicago falls within ASHRAE climatic zone 5A (cold and humid) and "Dfa", humid continental (hot summer, cold winter, no dry season, latitude 30-60ºN) per Köppen climate classification. While the 2010 population of the Chicago-Joliet-Naperville metropolitan statistical area was 9,461,105, the population of the city of Chicago was 2,695,598 per US Census. In 2010, Chicago had an average population density of 45.7 persons per ha (18.1 persons per acre) within the city limits. Researchers suggest that Chicago's current UHI patterns are likely to intensify with a warming climate and further urbanization in the region. This will significantly alter Chicago's micro-climate and increase its vulnerability to ecological and financial risks[19].

UHI effect is typically studied under calm wind conditions on clear, sunny days (Figure 1), in which urban heat rises above the built environment and raises the air temperature of the downtown area. However, the Chicago heat island often appears in the western suburbs, not in the downtown area[20]. The lake wind influences the transport of urban heat over the West Side development (Figure 2a). Gray and Finster reported an average about 3 to 5^{o}F temperature gradient between Lisle (located between 2 and 5 in Figure 2) and downtown Chicago in the summer months (June through August) from 1992 to 1996[20].



(a) (b)

Figure 1: (a) Typical urban heat island profile under calm wind conditions and (b) Chicago's heat island profile[20].

2.2 Climatic Data: Sources and Suitability

The weather stations monitored by the National Climatic Data Center (NCDC) are selected for investigating climatic variations in the Chicago metropolitan area for quality purposes (Figure 2). These stations are located at varying distances from Lake Michigan: Waukegan is 3.37 miles away, Midway 9 miles, O'Hare 13.5 miles, DuPage 31.5 miles, and Aurora 45 miles. The hourly climatic data obtained from these five weather stations in TMY-3 format are suitable for this study because they reflect the combined influence of land-use/land-cover changes, related anthropogenic heat from buildings, transportation and automobiles, and the lake effect[21]. In this way, the interaction of climatic variables and urban landscape is well accounted for in predicting energy needs.

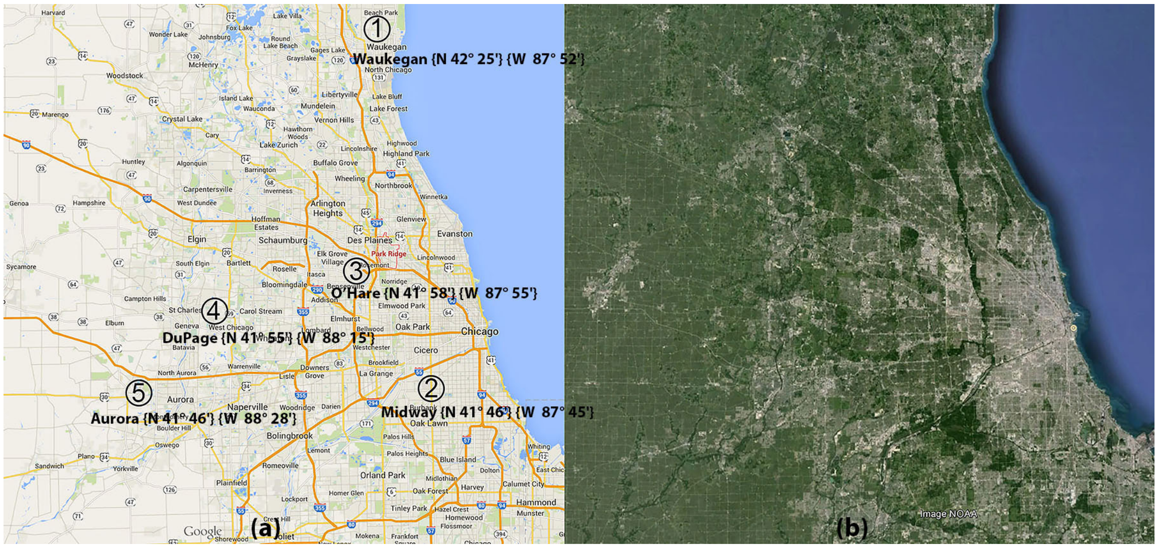


Figure 2: (a) Climatic data collection locations (Google Maps) and (b) LandSAT image of the Chicago metropolitan area showing urbanized to rural landscape pattern (Google Earth).

2.3 Physical Model Characteristics

A representative three-story, small-sized office building[22] of 1366 square meters (14,700 square feet) is modeled per ASHRAE Standard 90.1-2013, Climatic Zone: 5A[23] and Appendix G requirements to estimate energy needs. The building footprint of 21.30 meters x 21.3 meters (70 feet x 70 feet) is chosen for orientation neutrality[24] in which 40 percent of the area is allotted for open office space, 30 percent for enclosed/private offices, 10 percent for corridors, and five percent for a conference room; remaining areas include a printing/photocopying room, a stairwell, and electric/mechanical rooms. The perimeter and core zoning pattern is adopted for energy-modeling purposes and perimeter zone depth is 3.65 meters (12 feet). The floor-to-floor height is 3.96 meters (13 feet) and clear floor-to-ceiling space is 2.74m (9 feet). The floor-to-floor glazing of 40 percent (27 percent for floor-to-ceiling) is equally distributed on all sides and includes internal blinds that are 20 percent closed during occupied hours and 80 percent closed when unoccupied. The opaque building constructions in the small- and medium-sized office prototype include mass walls, a flat roof with insulation above the deck, and slab-on-grade floors. Windows are defined as manufactured windows in punch-style openings. These envelope constructions are common for small-office buildings in the United States[22,25] and are followed in the study. The building's operating hours are from 8 am to 5 pm Monday through Friday; it is closed on standard US holidays. Table 1 shows the building characteristics used for energy estimation purposes.

The baseline HVAC system for this building type and size and this climatic zone (5A) adopts ASHRAE 90.1-2013 Appendix G's suggestion on use of a (System3: PSZ-AC) constant volume packaged rooftop air conditioner. The space is conditioned by a packaged single-zone DX system with furnace. The efficiency of the packaged unit, EER, is 10 and the minimum efficiency of the furnace is 80 percent. Also, the natural gas nonresidential domestic hot-water system is modeled at 80 percent efficiency. The HVAC system maintains a 23.8ºC (75ºF) cooling set point and 21.11ºC (70ºF) heating set point during occupied hours. During off hours, the thermostat set point is 27.77ºC (82ºF) for cooling and 17.77ºC (64ºF) for heating. The economizer is set to maximum dry bulb temperature 70ºF.

2.4 Comparison Method

The distance from Lake Michigan and from downtown are significant factors for intra-urban microclimatic variation. Among the selected locations, Waukegan is less urbanized, less populated, and closer to the lake. It is far north of downtown and is not influenced by the UHI. The West Side developments, where summertime UHI influences are significant, host other study locations. The variations in UHI and related building heating and cooling energy needs on the West Side locations are compared here with the Waukegan location.

Climatic changes. The temperature influences of UHI among the selected locations are compared seasonally, particularly during the extremely hot week identified by the NCDC. The summer months are particularly cru-

Table 1: Office building characteristics.

Envelope		Lighting (w/ft^2)	
Roof	R-30ci (albedo 0.4, light)	Office (open/enclosed)	0.98 /1.11
Walls	R13+R10ci	Conference Room	1.23
Slab on Grade	R-15 for 24in	Restroom	0.98
Door	U-0.5	Corridor	0.66
Fenestration	U-0.42,	Mechanical	0.42
	SHGC-0.4	Copying Room	0.72
	VT-1	Plug Loads	0.75 [26]

cial due to an increase in cooling-related peak electric demand and energy. The summer months considered in this study are July through September; the winter months are January through March. The autumn and spring months are represented by October through December and April through June, respectively. The extremely hot week is from July 15 to 21 and the extremely cold week is from February 12 to 18. The average temperature of seasonal months is used to compare seasonal UHI. The average hourly temperature data is used to compare day and nighttime UHI. The day and nighttime hours are decided based on available global horizontal solar radiation, which is the sum of direct normal irradiance, diffuse horizontal irradiance, and ground-reflected radiation.

Annual energy use. A whole energy simulation program, eQUEST 3.65 (DOE, 2013), has been previously validated for its algorithm and published elsewhere, and is considered suitable for this study to estimate the energy performance of the small-office building, which was kept constant through the study. Keeping lighting, plug loads, and other energy needs constant throughout the study allowed the investigation to focus on shifting heating and cooling energy due to the changing climate. The weather files collected from the five stations in the Chicago metropolitan area were used to estimate intra-urban variations in energy use intensity (EUI), peak electric demand, and annual electric and heating energy use. The variations in intra-urban heating degree days (HDD) and cooling degree days (CDD) are also included in the study.

3.0 RESULTS AND ANALYSIS

The results and analysis of this investigation are presented in two sections: intra-urban climatic changes and building space conditioning energy needs. First, seasonal and diurnal temperature changes are discussed in relation to the lake effect and its impact on HDD and CDD. Second, microclimatic influences on energy use intensity (EUI), cooling energy, summertime peak demand, and heating energy are presented to inform decisions on energy efficiency of buildings.

3.1 Intra-Urban Climatic Changes

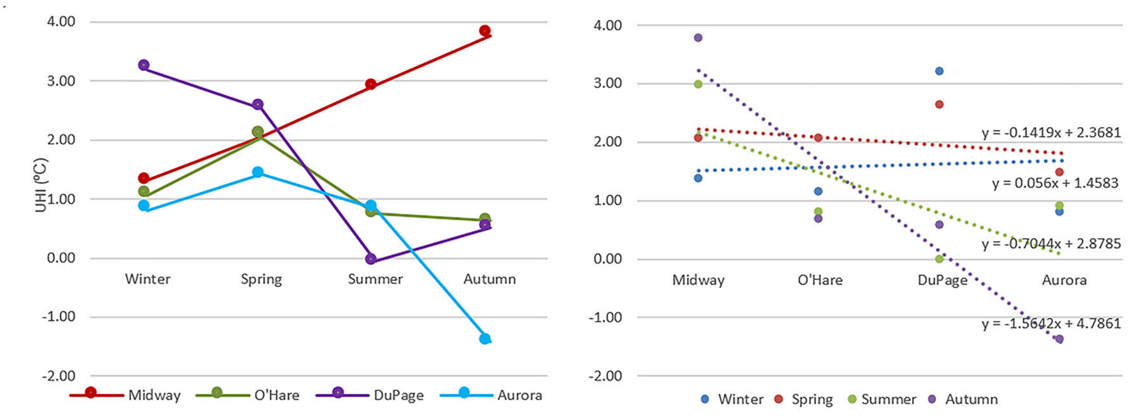
There is significant variation in average seasonal temperatures among all locations in Chicago metropolitan area. The average seasonal temperature includes hourly day and night temperatures for three months. The highest average temperature, 23.52°C, is observed during summer months at Midway; the lowest temperature, 20.6°C, is observed at Waukegan (Table 2). The temperature trends are opposite during winter months; DuPage (1.01°C) and Midway (-0.85°C) are warmer than Waukegan (-2.18°C). During spring months, DuPage (15.95°C) reports the highest temperature and Waukegan (13.42°C) is the lowest in the group. Although the average temperatures are lower at all locations during autumn, Midway reported the highest temperature at 7.13°C; Aurora showed the lowest among the group at -1.41°C. In general, average seasonal temperatures at Waukegan are lowest; thus it is a reasonable assumption for a baseline case when comparing intra-urban UHI.

Table 2: Seasonal UHI variation within the Chicago metropolitan area (°C).

	Waukegan	Midway	O'Hare	DuPage	Aurora
T (avg. summer)	20.60	23.52	21.34	20.54	21.44
ΔT (summer)		2.92	0.75	-0.05	0.85
T (avg. winter)	-2.18	-0.85	-1.11	1.01	-1.37
ΔT (winter)		1.33	1.07	3.19	0.81
T (avg. spring)	13.42	15.48	15.46	15.95	14.84
ΔT (spring)		2.06	2.04	2.53	1.42
T (avg. autumn)	3.37	7.13	4.00	3.89	1.96
ΔT (autumn)		3.76	0.63	0.52	-1.41

The highest seasonal intra-urban UHI variation among four locations is observed during autumn months and the lowest temperature variations are observed during spring months, ranging from 1.42°C at Aurora to 2.53°C at DuPage. When average temperatures are compared with those at Waukegan, the variation ranges from 3.76°C at Midway to -1.41°C at Aurora (Figure 3(a)). The negative temperature difference represents a cool island effect. This variation is consistent with its distance from the Lake Michigan as well as from the downtown area (Figure 3(b)). Thus, average wind direction and speed was analyzed at these locations. The average wind direction at Midway, O'Hare, DuPage, and Aurora is from southwest to northwest. The combined influence of wind direction and speed seems to minimize temperature gradient across the east-west axis, although industrial land use and a high percentage of paved areas exists in the West Side developments[20,27]. Based on this observation, it is expected that the downtown area will remain warmer during autumn months, although further evidences will be helpful.

The summertime UHI intensity of 2.92°C is highest at Midway, while the West Side locations, DuPage and Aurora, show marginal differences of -0.05°C and 0.85°C when compared with Waukegan (Table 2). When compared with Midway, the temperatures at O'Hare, DuPage, and Aurora are cooler by 2.18°C, 2.98°C, and 2.08°C. The lowest average summer temperature at DuPage is the most surprising result, as this location is on the West Side and closest to the center of the heat island reported by Gray and Finster[20]. These summertime temperature trends, like autumn observations, do not follow previously published trends of warmer climate in the West Side developments. One of the significant influences is that the prevailing west-southwest wind, which averages 13.2 km/h, transporting in warm, humid air from the central and southern plains[18], does not support the UHI phenomenon presented in Figure 1(b). In addition, while the major water body can provide summertime cooling, the distance of study areas from the lake may lessen its effect as evident in Figure 3(b). The lake's cooling influence also wanes in late summer when water temperature can reach as high as 26.7°C. The UHI effect is reported during day as well as night. Table 3 summarizes day and night average temperatures. The maximum seasonal day and night temperature difference (1.95°C) is observed at Aurora during summer, followed by spring (1.14°C), autumn (1.48°C), and winter (0.61°C). DuPage, O'Hare, and Midway follow a similar pattern, showing the lowest changes. Waukegan shows minimal change during the winter



(a)

(b)

Figure 3: (a) Seasonal UHI intensities within Chicago metropolitan area and (b) UHI intensities in relation to the distance from the lake.

and autumn months (1.91 to 2.1°C), while the spring and summer months show temperature differences in the range of 3.44°C to 3.76°C, respectively. Table 2 and Table 3 provide the average temperature differences of the seasons. In order to investigate non-averaged temperature differences, this study delves into an extremely hot week.

The extreme summer week varies by location, so an overlapping period of two weeks, from July 13 to 26, is considered for this analysis as seen in Figure 4. During this time, the maximum daytime temperature (40.0°C) was recorded at Midway on July 24 (with standard deviation of 12.81°C). The peak demand for the office building is observed on the same day at the Midway location. Similarly, high daytime temperature increases peak electric demand, although dates vary among the selected locations. The highest day and night temperature difference is observed at Aurora (19.00°C) followed by Waukegan (15.20°C), Midway (14.00°C), O'Hare (13.30°C), and DuPage (13.00°C). The weekly average day and night temperature difference is highest at Aurora (13.00°C), followed by O'Hare (10.64°C), DuPage (10.31°C), Midway (9.21°C), and Waukegan (9.06°C). The higher nighttime temperature, which minimizes day and night differences, is an indication of nighttime UHI. When compared with Waukegan, Midway shows high nighttime UHI and Aurora shows minimum nighttime UHI. Kolokotroni et al.[16] suggest that warm nighttime temperatures can improve nighttime ventilation opportunities in office buildings in a warming climate. The warm nighttime urban temperature may potentially increase use of air conditioners during evening hours, especially in residential buildings. However, spring and autumn might provide the most opportunities to benefit from natural ventilation as an energy-saving strategy. Since the small-office building under study is operating during the day (8 am to 5 pm), this discussion focuses on daytime hours. The following section explores the UHI influences on predicted energy needs.

The variation in intra-urban climatic conditions is changing annual heating and cooling degree days for each location as shown in Table 4. Midway location represents the most modified urban climate and it is observed in highest CDD (691) and lowest HDD (3106) among other locations. In comparison to Waukegan, Midway has 70 percent higher CDD and 17 percent lower HDD. While CDD and HDD are representative of climatic zone and does not account for specific building condition that may have unique indoor climatic conditions, the building cooling and heating hours vary

Table 3: Average day and night UHI variation.

	Waukegan	Midway	O'Hare	DuPage	Aurora
T (summer day-night)	3.76	3.02	4.20	4.54	5.71
ΔT* (summer day-night)		-0.74	0.44	0.78	1.95
T (winter day-night)	2.10	1.64	2.16	2.45	2.71
ΔT (winter day-night)		-0.47	0.06	0.35	0.61
T (spring day-night)	3.44	2.70	4.41	4.30	4.58
ΔT (spring day-night)		-0.74	0.44	0.78	1.95
T (autumn day-night)	1.91	2.06	2.47	3.38	3.39
ΔT (autumn day-night)		0.15	0.56	1.47	1.48

ΔT* is estimated in comparison to Waukegan significantly. The small-office building investigated in this study, shows 21 percent increase in building cooling hours and 22 percent decrease in building heating hours for Midway location. These changes are mainly due to external and internal gains. It is important to note that improved energy efficiency criteria of ASHARE 90.1-2013 allows for less building cooling hours (21 percent), however, it needs further study.

3.2 Building Heating and Cooling Energy Use

Energy Use Intensity (EUI). The annual building energy needs (gas, electric, and peak demand) of a three-story office building for selected locations in Chicago metropolitan area are discussed. For quality checks, the EUI at O'Hare location was compared with CBECS (2013) data for small buildings and then with EUI published by Pacific Northwest National Laboratory (PNNL) study on a small office building[24] that used a similar weather file. The EUI estimated at O'Hare in this study (26.75 KBtu/ft²) is lower than in the published PNNL study (27.40 KBtu/ft²), which applied advanced energy-saving strategies. This change makes sense for small office buildings because the PNNL study adopted ASHRAE 90.1-2004 and applied the version of Advanced Energy Design Guide for Small Office Buildings available at that time. The highest EUI (6.863 kWh/ft²-yr) is observed for Midway, the lowest EUI (6.559 kWh/ft²-yr) at Waukegan. The simulation results for EUI at O'Hare (6.781 kWh/ft²-yr) and Aurora (6.796 kWh/ft²-yr) are very similar, whereas EUI (6.825 kWh/ft²-yr) at DuPage is slightly higher, similar to Midway. The annual electric energy needs shown in Figure 5(a) follow a similar trend. The energy consumption categories are lights, miscellaneous equipment (plug loads), space cooling, pumps and auxiliary, and ventilation fans. The building energy consumption at Midway is highest at 100,879kWh, compared to Waukegan at 96,424kWh. O'Hare and Aurora show similar results at 99,682kWh and 99,899kWh, respectively.

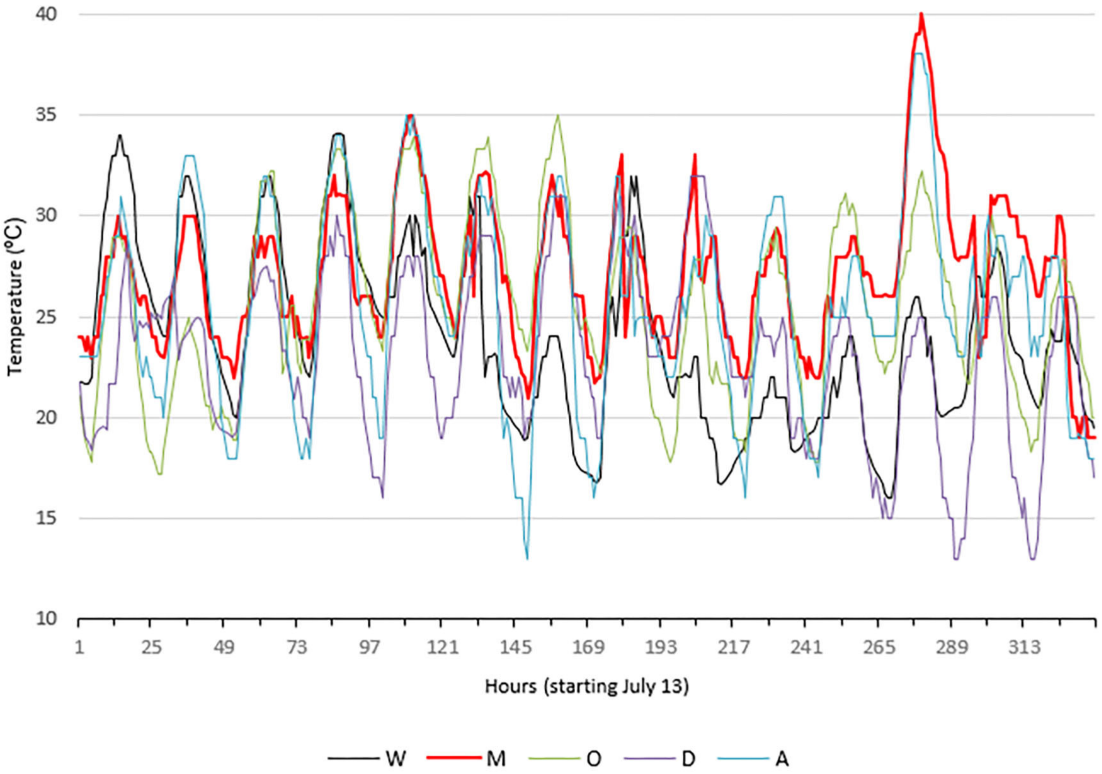


Figure 4: Day and night temperature variations during extreme summer week, July 13-26.

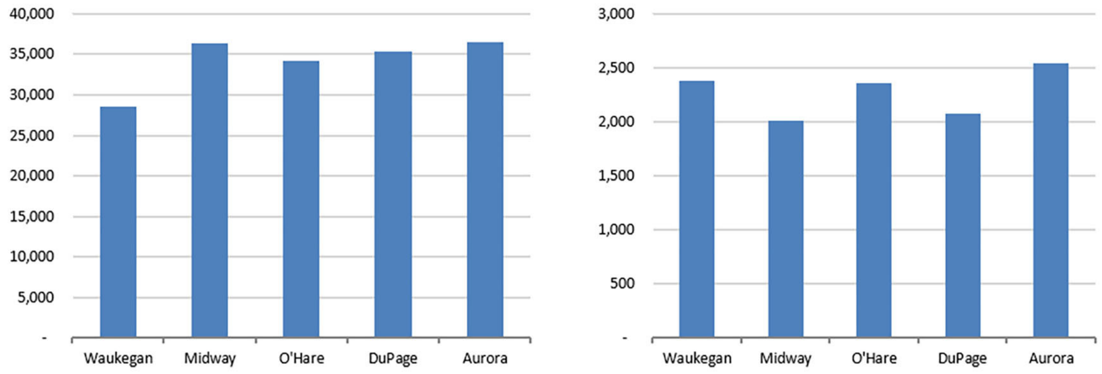
Cooling Energy. Cooling energy (kWh) needs are 34 to 37 percent of the total electric needs of the building. When annual cooling energy needs among Midway, O'Hare, DuPage, and Aurora are compared with Waukegan (Figure 5(a)), the energy needs are higher and cooling energy needs emerge as the most fluctuating energy category. In this category, the small office building at Aurora (28 percent) consumes the most energy, followed by Midway (27 percent), DuPage (24 percent), and O'Hare (19 percent). These variations are significant and affect overall EUI. Also, it is surprising to note that the Aurora location consumes more cooling energy than Midway. The main reason for such fluctuations is warm daytime starting conditions due to nighttime UHI as well as daytime UHI that is influenced by wind speed and direction in the metropolitan area. Furthermore, cloud cover plays an important role in the amount of global solar radiation received at these locations. Figure 6(a) shows the average hourly global horizontal solar radiation received at selected locations throughout the year. Aurora receives the most solar radiation (386 w/m²), whereas Midway (200 w/m²) receives almost half that amount because of high cloud cover. This affects external heat gain at Midway compared to Aurora, while internal heat gain remains constant for all locations.

Peak Demand. Cooling-related peak electric demand is significant for all intra-urban locations. Annually, it constitutes 41 to 44 percent of total electric demand, except for Waukegan (38 percent). This contribution increases to 52 to 56 percent during summer months and 46 to 51 percent, and 39 to 44 percent during spring and autumn months, respectively. Midway location requires 56 percent of the peak demand for cooling during summer, which is not very different from Aurora (55 percent), DuPage (54 percent), or even O'Hare (52 percent). This data clearly indicates the relationship between temperature and peak demand: higher temperature increases peak demand, which can test the susceptibility of power infrastructure to extreme heat

Table 4: Annual heating and cooling degree days.

	Waukegan	Midway	O'Hare	DuPage	Aurora
CDD (18°C baseline)	407	691	506	523	444
Increase in CDD*		284 (70%)	99 (24%)	116 (29%)	37 (9%)
Building Cooling Hours	877	1065	1098	1097	1072
Increase in Building Cooling Hours		188 (21%)	221 (25%)	220 (25%)	195 (22%)
HDD (18°C baseline)	3747	3106	3430	3300	3629
Decrease in HDD*		-641 (-17%)	-317 (-8%)	-447 (-12%)	-118 (-3%)
Building Heating Hours	1329	1042	1188	1137	1133
Decrease in Building Heating Hours		-287 (-22%)	-141 (-11%)	-192 (-14%)	-196 (-15%)

* Changes in CDD and HDD are in relation to Waukegan location

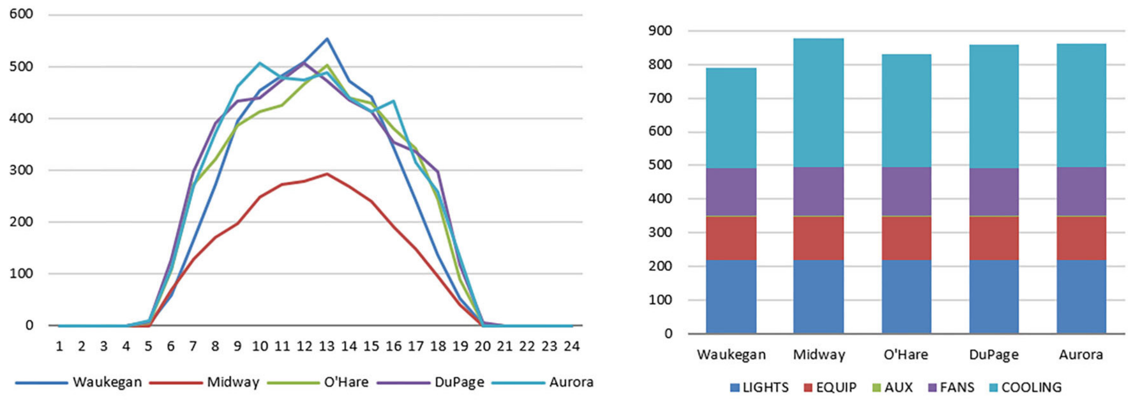


(a) (b)

Figure 5: (a) Annual cooling energy (kWh) and (b) Annual heating energy (Therms).

events. One of the major influences of climate change in the built environment is increased extreme hot- weather (and cold-weather) events. Extreme hot-weather events are observed during the spring and autumn months as well: early heat waves are reported in April, late heat waves in October. Thus, early warming trends in spring show significant cooling-related peak demand. Aurora and O'Hare locations need 51 percent peak demand for cooling; Midway and DuPage are at 49 percent and 46 percent respectively. During the autumn months, the Midway location shows the highest cooling-energy contribution to peak demand.

Heating Energy. High heating-energy needs at Waukegan (2382 Therms) are not surprising because of the location's proximity to Lake Michigan. The lake tends to increase cloudiness and suppress summer precipitation in the area. Winter precipitation is enhanced by lake-effect snow that occurs when winds blow from the north or northeast. These winds allow air to pass over the relatively warm lake, boosting storm-system energy and water content and leading to increased snowfall. Similarly, the far West Side location of Aurora shows high (2539 Therms) heating-energy needs, as north or northeast winds do not seem to be influenced by the UHIs (i.e., the combination of land use, land cover, and anthropogenic heat sources) that are decreasing heating-energy needs at the Midway and DuPage locations.



(a) (b)

Figure 6: (a) Average hourly global solar radiation (w/m²) and (b) Annual Peak Demand (kW) distribution by major categories.

4.0 CONCLUSION

This article investigates two research questions, focusing on intra-urban climatic change and its impact on building space conditioning energy demand in the Chicago metropolitan area. Four intra-urban locations (Midway, O'Hare, DuPage, and Aurora) are compared with the baseline location, Waukegan. The average climatic data over a 30-year period (1980-2010) recorded in Typical Meteorological Year-3 format is used for this purpose and to help estimate building energy demand. There are prominent intra-urban microclimatic zones within the Chicago metropolitan area; UHI intensity varies by location, season, and on a day-night basis. Overall, average intra-urban temperature is warmer through the year. These following conditions are summarized:

- The highest UHI intensity was reported at the Midway location during the autumn (3.76ºC) and summer (2.92ºC) months.
- The highest UHI intensity during the winter (3.19ºC) and spring (2.53ºC) months was reported at the DuPage location.
- The distance of study locations from the lake, wind pattern, cloud cover, and solar radiation are influencing UHI through the year. A linier relationship of distance from the lake and UHI is particularly significant during autumn and summer months
- The highest day-night UHI variation (19ºC) during the extreme summer week was observed at Aurora location.

These intra-urban climatic changes modified CDD (18ºC baseline) and HDD (18ºC baseline):

- The highest increase in CDD (70 percent) was observed at Midway in comparison to Waukegan. O'Hare, DuPage, and Aurora also showed an increase in CDD by 24 percent, 29 percent, and 9 percent, respectively.
- The highest reduction in HDD (22 percent) was observed at Midway. O'Hare, DuPage, and Aurora also reported decreased HDD by 11 percent, 14 percent, and 15 percent, respectively.

The changes in CDD and HDD modified building energy use:

- Annual cooling-energy needs increased by 27 percent, 19 percent, 24 percent, and 28 percent at Midway, O'Hare, DuPage, and Aurora, respectively.
- Cooling-related peak energy demand increased by 20.62 percent, 1.69 percent, 5.12 percent, and 14.24 percent at Midway, O'Hare, DuPage, and Aurora, respectively.
- In contrast, heating-energy needs decreased by 16 percent, 1 percent, 13 percent, and 8 percent at Midway, O'Hare, DuPage, and Aurora, respectively.
- Cooling energy is significantly affected by microclimatic variation during summer and it can reach up to 52 to 56 percent of total building energy.

The most significant finding of this investigations is the introduction of less widely known key climatic factors: wind speed, cloud cover, and solar radiation and the lake effect as a powerful influence on energy demand and energy efficiency.

Failing to account for urban-microclimatic temperature differences may lead to errors that are too large to overlook. Further, certification of the performance of the buildings within the framework of a building energy-rating scheme like LEED certification be affected if local climate modifications are not accounted.

By providing evidence on existing intra-urban climatic change and its influence on changing energy needs, this study is useful for making informed design decisions while selecting energy-efficient passive and active design strategies for new and existing construction projects. This study provides insights for other lakeside cities and is useful for deciding on climate-responsive strategies that will safeguard the energy efficiency of future buildings.

This study can be advanced by testing passive and active design strategies suggested for the urban area's climatic zone. Its impact on various building types and scales will help evaluate energy efficiency in urban microclimatic conditions.

REFERENCES

[1] Arnfield, A. J., (2003). "Two Decades of Urban Climate Research: A Review of Turbulence, Exchanges of Energy and Water, and The Urban Heat Island", *International Journal of Climatology*, Vol. 23, No. 1, pp. 1-26.

[2] Lo, C. P., Quattrochi, D. A., and Luvall, J.C., (1997). "Application of High-Resolution Thermal Infrared Remote Sensing and GIS to Assess the Urban Heat Island Effect", *International Journal of Remote Sensing*, Vol. 18, No. 2, pp. 287-304.

[3] Oke, T.R., (1988). "Street Design and Urban Canopy Layer Climate", *Energy and Buildings*, Vol. 11, pp. 103-113.

[4] Erell, E., Pearlmutter, D., and Williamson, T.J., (2011). *Urban Microclimate: Designing the Spaces between Buildings*, Washington, DC: Earthscan.

[5] Oke, T.R., (1987). *Boundary Layer Climate*, Vol. 2, New York, NY: Routledge.

[6] Stone, B., Hess, J. J., and Frumkin, H., (2010). "Urban Form and Extreme Heat Events: Are Sprawling Cities More Vulnerable to Climate Change than Compact Cities?", *Environmental Health Perspectives*, Vol. 118, No. 10, pp. 1425-1428.

[7] Sailor, D. J., (2011). "A Review of Methods for Estimating Anthropogenic Heat and Moisture Emissions in the Urban Environment", *International Journal of Climatology*, Vol. 31, No. 2, p. 189.

[8] Hankey, S., Marshall, J. D., and Brauer, M., (2012). "Health Impacts of the Built Environment: Within-Urban Variability in Physical Inactivity, Air Pollution, and Ischemic Heart Disease Mortality", *Environmental Health Perspectives*, Vol. 120, No. 2, pp. 247-253.

[9] McMichael, A. J., Woodruff, R. E., and Hales, S., (2006). "Climate Change and Human Health: Present and Future Risks", *Lancet*, Vol. 367, No. 9513, pp. 859-869.

[10] Bobb, J. F., et al., (2014). "Heat-Related Mortality and Adaptation to Heat in the United States", *Environmental Health Perspectives*, Vol. 122, No. 8, pp. 811-816.

[11] O'Neill, M. S., (2005). "Disparities by Race in Heat-Related Mortality in Four US Cities: The Role of Air Conditioning Prevalence", *Journal of Urban Health*, Vol. 82, No. 2, pp. 191-197.

[12] Davis, R. E., et al., (2003). "Changing Heat-Related Mortality in the United States", *Environmental Health Perspectives*, Vol. 111, No. 14, pp. 1712-1718.

[13] Akbari, H. and Konopacki, S., (2005). "Calculating Energy-Saving Potentials of Heat-Island Reduction Strategies", *Energy Policy*, Vol. 33, No. 6, pp. 721-756.

[14] Kapsomenakis, J., et al., (2013). "Forty Years Increase of the Air Ambient Temperature in Greece: The Impact on Buildings", *Energy Conversion and Management*, No. 74, pp. 353-365.

[15] Bhiwapurkar, P., (2007). Urban Heat Island Phenomenon, Urban Morphology, and Building Energy Use: The Case of Chicago, Chicago, IL: Illinois Institute of Technology.

[16] Kolokotroni, M., et al., (2012). "London's Urban Heat Island: Impact on Current and Future Energy Consumption in Office Buildings", *Energy and Buildings*, No. 47, pp. 302-311.

[17] Coseo, P. and Larsen, L., (2014). "How Factors of Land Use/Land Cover, Building Configuration, and Adjacent Heat Sources and Sinks Explain Urban Heat Islands in Chicago", *Landscape and Urban Planning*, Vol. 125, p. 117-129.

[18] Angel, J., (2009). "Climate of Chicago - Description and Normals", Illinois State Water Survey, Retrived on 11/20/2014 from http://www.isws.illinois.edu/atmos/statecli/general/chicago-climate-narrative.htm.

[19] Weinstein, M. P., and Turner, R. E., eds., (2012). *Sustainability Science: The Emerging Paradigm and the Urban Environment*, New York, NY: Springer.

[20] Gray, K., and Finster, M. E., (2004). The Urban Heat Island, Photochemical Smog, and Chicago: Local Features of the Problem and Solutions, Environmental Protection Agency.

[21] Wilcox, S., and Marion, W., (2009). Users' Manual for TMY3 Data Sets, Golden, CO: National Renewable Energy Laboratory.

[22] CBECS, (2012). Commercial Buildings Energy Consumption Survey 2012, Retrieved on 11/12/2014 from http://www.eia.gov/consumption/commercial/reports/2012/preliminary/index.cfm.

[23] ASHRAE, (2013). ANSI/ASHRAE/IES Standard 90.1-2013 — Energy Standard for Buildings Except Low-Rise Residential Buildings, Atlanta, GA: ASHRAE.

[24] Thornton, B., et al., (2010). Technical Support Document: 50% Energy Savings for Small Office Buildings, Richland, WA: Pacific Northwest National Laboratory.

[25] Richman, E. E., et al., (2008). National Commercial Construction Characteristics and Compliance with Building Energy Codes: 1999-2007, Richland, WA: Pacific Northwest National Laboratory.

[26] Mercier, C., and Moorefield, L.,(2011). Commercial Office Plus Load Savings and Assessment, California Energy Commission.

[27] Konopacki, S., and Akbari, H., (2002). Energy Savings of Heat-Island Reduction Strategies in Chicago and Houston, Berkeley, CA: Lawrence Berkeley National Laboratory, Environmental Energy Technologies Division.