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Downwind footprint of an urban heat island on air and lake temperatures

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The urban heat island (UHI) effect was first documented ~200 years ago, making it the longest recognized anthropogenic effect on climate. Although anomalous heating in cities has been meticulously characterized, less is known about how the UHI affects surrounding regions. It is hypothesized that downwind of cities a “heat plume” forms due to the advection of urban heat. This heat transport may have impacts beyond heating of the surface, such as disrupting atmospheric convection and influencing boundary layer structure, which influences weather, air quality, and human health. Here, a lagrangian atmospheric transport model, forced with archived data from a numerical weather model, is used to generate a three-dimensional map of an urban heat plume for a major city, Chicago. We document significant heating 100–200 m above the surface and 70 km downwind of the city. Over Lake Michigan, the scale of the plume is truncated nearly in half (~40 km), suggesting the lake is acting as a sink for the exported urban heat. Using satellite lake surface temperatures, we observed a disruption of the diurnal pattern of lake temperature beneath the plume, which supports a possible role of the lake in absorbing the heat plume. The results provide unique quasi-observational evidence for a significant footprint of cities on regional atmospheric structure and potentially on adjacent aquatic bodies.

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INTRODUCTION

The UHI effect is the condition that describes higher temperatures in urban areas than surrounding areas of less development.^{1,2} This phenomenon is attributed primarily to the replacement of permeable surfaces with dryer impermeable surfaces which influences energy availability and leads to a higher Bowen ratio at the land surface and therefore warmer temperatures.^{3,4} The intensity of the UHI is related to regional climate and variations in urban morphology that include characteristics of density, land use type, heterogeneity, and properties of the urban surface, such as surface roughness, permeability, and albedo.^{4–6} The UHI effect impacts energy consumption, greenhouse gas emissions, and air pollution by increasing the demand for cooling during hot summer months. It also puts human health and comfort at risk by intensifying extreme summer weather conditions and heat waves. For example, in 1995, a 5-day heat wave in Chicago brought sustained temperatures above 36 °C⁷ and led to over 500 deaths.⁸

Much of the research on the UHI has focused on measurements of heating at the urban surface, with less emphasis on the regional impact of heating on the atmosphere beyond the urban environment. Previous work has taken advantage of land surface temperature retrievals from satellite^{6,9–12} and meteorological data collected at fixed or mobile weather stations throughout developed areas.¹³ These results show that effects from the UHI can impact local climates within the urbanized region. This heating contributes to warming within the urban canopy layer, the turbulent roughness layer near the surface of the urban environment, which is then transferred to the boundary layer as an atmospheric urban heat island.¹⁴ The advection of this heat may lead to indirect effects on regional climate that are missed

when only surface data is analyzed. As UHIs strengthen, surrounding regions may be impacted through both direct surface warming and atmospheric changes that influence convection in the boundary layer and mesoscale circulation patterns such as lake-breezes.¹⁵ These changes can affect boundary layer height, cloud formation, precipitation,¹⁶ and intensify air pollution.¹⁷

Previous research has shown that the UHI can impact temperatures in an area as great as 2–4 times that of the city itself.¹⁸ The potentially large spatial scale of the UHI's impact is important to understand as it may influence regional climate conditions in megapolitan regions where large urban areas are clustered together in continuous development. Modeling of the effects of continued development of megapolitan regions in the US have led to predictions that urban expansion could contribute to local warming of up to 4 °C¹⁹ and mesoscale regional warming of 1–2 °C.²⁰ Regionally, these temperature changes can be a factor of two greater than projected warming from greenhouse gas emissions alone. Quantification of this regional-scale impact of the urban environment is important because it may impact the hydrologic and radiation balance within megacities,²¹ it can influence agriculture and natural ecosystems outside of cities and is useful for developing solutions for urban adaptation in the face of future climate change.

Our current understanding of the vertical structure of the UHI is based on a conceptual model proposed by Oke (1982) where an urban boundary layer is defined by its increase in thickness over urban areas of enhanced roughness and sensible heat flux.²² Oke (1982) described the UHI as influential in the development of an urban heat ‘dome’ that moves vertically over the city and is then exported to the region beyond as a “plume” of unstable air.^{23,24} The distance over which the heat transport is considered significant has been estimated to be on the scale of “tens of

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Fig. 1 Schematic diagram of experimental setup. Lagrangian atmospheric transport model (HYSPPLIT) is run within gridded meteorological data, North American Mesoscale Forecast System (NAM), that represents the atmospheric state during analysis period. The grey area in the 'Land Surface Model' represents an urban domain. The NAM forecast system consists of the weather research and forecasting—nonhydrostatic mesoscale model (WRF—NMM). Surface conditions are defined within the WRF—NMM system with the Noah Land Surface Model (Noah LSM) and Urban Canopy Model (UCM)

kilometers,” with its magnitude related to city size.⁴ The impact of this boundary layer warming downwind of the city has been documented through observational networks, such as the Birmingham Urban Climate Laboratory (BUCL). These observations suggest the effect can extend, on average, 4–12 km from the urban center, with temperature increases of 1–2 °C,¹⁴ while modeling studies have shown the effect to potentially extend up to 40 km²⁵ and to contribute to temperature increases up to 2.5 °C.²⁶

We present here a detailed analysis of the scale and seasonal variability of the heat plume for the city of Chicago, which has a typical mid-latitude climate. Located next to Lake Michigan, the region has mesoscale and microclimatic features associated with land–lake interactions.²⁷ The water body acts as a regional heat source during the winter and heat sink in the summer, its thermal inertia generating a lag relative to the adjacent land surface. Chicago provides an ideal test bed to study the atmospheric footprint of the UHI because: (1) it has a strong UHI,^{28,29} (2) it lacks significant topography, which simplifies atmospheric circulation in the region, and (3) the area in the prevailing upwind and downwind footprint of Chicago does not include other major metropolitan regions, which would complicate a clear delineation of its singular effect. Lastly, from one direction Chicago borders a major water body and in the other direction, a fairly homogenous agricultural landscape,³⁰ providing a test of how the scale of the UHI and regional heat balance is affected by both aquatic and terrestrial surfaces. Lake breeze dynamics contribute additional complexity to the urban climate (i.e. patterns of diurnal cooling, increased humidity,³¹ pollution dispersion, and precipitation) but represent conditions that are common in other lake and ocean bordering cities where the UHI has been observed and thus increases the generality of our findings.²⁸

RESULTS AND DISCUSSIONS

In order to assess the regional footprint of the UHI, we used a three-dimensional simulation of heat transport from Chicago using a lagrangian approach. We consider heat as it is introduced into the atmosphere above the city of Chicago and moves away from the urban environment. Trajectories were seeded at ground level (0 km) and two heights above the city (0.5 and 1 km) and temperature variations were tracked as air masses traveled away from the city (Methods). We conducted the analysis for June 2012–June 2014 using 17,400 trajectories at each of two study sites: the urban center of Chicago (UL) and a non-urban site (NUL) located in similar proximity to Lake Michigan, which served as a control by providing an opportunity to explore how the lake affects atmospheric temperatures³¹ and terrestrial–aquatic heat exchange in the absence of a city.

Archived meteorological data was used as boundary conditions for the lagrangian atmospheric transport simulations (Fig. 1) at four time intervals throughout each day in the study period (Methods). The weather dataset provides a generalized regional picture of temperature conditions but the lagrangian approach is required to isolate whether an air parcel in the region had directly interacted with the UHI. The specific approach was chosen for computational efficiency and by using archived operational weather model outputs, it also aids in evaluation of the model outputs used for daily weather prediction in urban environments. In addition, the weather model is a public archive, which enables similar analysis to be reproduced without running new weather simulations. The use of an operational product differs from higher resolution micro-scale analyses of the urban environment³² and uses generic classifications for urban grid cells associated with building density, height, building material, and surface permeability. It does not, however, include specific information on individual buildings. Furthermore, while the model does include anthropogenic heat sources as a component of the surface energy

a. Trajectory density histogram

b. Chicago metropolitan region

c. Δ Temperature - Summer

d. Δ Temperature - Winter

Fig. 2 **a** Density histogram showing spatial distribution of trajectory data points in relationship to the UL site. More than 10,000 trajectory data points were recorded east of the UL site, just over Lake Michigan. **b** Map showing the extent of urbanization in the Chicago metropolitan region. Development intensity categories are derived from the National Land Cover Database classification for 2011. **c** Horizontal spatial analysis of trajectories within 200 and 2 km above ground level (AGL) of the Chicago urban center during nighttime in the summer. Plot shows the change in temperature from the initial air parcel temperature. The pattern of heating evident here corresponds with the developed area. Location of Chicago is designated by 'a' and the location of Milwaukee is designated by 'b'. **d** Horizontal spatial analysis of trajectories within 200 and 2 km AGL of the UL site initiation point in the Chicago urban center during nighttime in the winter. Plot shows the change in temperature from the initial air parcel temperature

balance in the urban canopy model (Methods), these sources are not associated with specific sectors or neighborhoods. On the one hand, the input weather data provides only a coarse depiction of the urban atmosphere, thermal dynamics, and urban surface in the region. On the other hand, because the weather model assimilates observational data it can produce realistic depictions of the atmospheric state despite known limitations in the model physics and land surface parameterizations. Nonetheless, because the scale of this study is on the order of 10's of kms and the focus is on general features, these limitations are not likely to significantly impact the findings.

The effect of the city on atmospheric temperatures is demonstrated by mapping the change in temperature as air masses leave the city. The dominant trajectory of air masses leaving Chicago is over the lake, but a significant number of trajectories also moved to the west over land (Fig. 2a). We focus on an area 200 km around the city center and at a height from the surface to 2 km above ground level (AGL). Fig. 2c, d show surface

maps of the average difference in temperature as air parcels leave the initiation point in the center of the city for summer and winter, respectively. These maps are an interpolation of all trajectory data points, regardless of original seed height and show a temperature average for the entire vertical profile in plan view. Fig. 2c shows the map associated with summer nights and illustrates the presence of an area of heating around the urbanized area that persists for ~70 km from the city center during the summer. This pattern can be compared against the area of urban development in the region shown in Fig. 2b. The area of urban development is approximately half the size of the excess heat area, and provides an approximate scale for the urban plume. We test whether this apparent radial pattern is significant by calculating the average rate of temperature decay from the initiation point and compare it against both randomly shuffled temperatures (using data from the same matrix in Fig. 2c) and against the temperature pattern generated from this period at the NUL site. The results show that the pattern is different from random at both the UL and NUL sites

Fig. 3 **a** Temperature decay pattern assuming the heat source is from the initiation point for both the UL and NUL sites. **b** The rate of change of temperature moving away from the initiation point averaged for all directions and integrating all heights. The gray bars indicate the range of possible slopes derived by randomly shuffling the temperature patterns shown in Fig. 1c, d 5000 times. The black and green dots are the slopes for the UL and NUL sites, respectively. The error bars are the standard error of the slope. In cases where the slope deviates from the gray bar, this means there is a change in temperature from initiation that exceeds random. In cases where black has a larger absolute value than green, this means the decline in temperature is not from the effect of the lake alone and suggests a different mechanism, which we presume to be the presence of the city. This analysis suggests that summer nights are the only time when atmospheric temperatures at all heights retain a strong regional signature associated with the Chicago UHI

and the decay is significantly greater at UL than NUL (Fig. 3). The result confirms there is a statistically significant radial decay pattern that cannot be explained purely by Chicago's proximity to the lake. One potential source of uncertainty is the presence of Milwaukee, located ~150 km north of the Chicago urban center. Air movement in this direction will be impacted by this additional

heat source and further analysis is necessary to understand its specific influence on this regional system. That being said, prevailing wind directions in the area are from the west, and therefore the effect of Milwaukee on the results presented here should be minimal.

A similar analysis is shown for the winter months in Fig. 2d. During the winter, sensible heat flux from the land surface is at its annual minimum whereas sensible heat flux from the lake is high. During this period, warming from Lake Michigan dominates atmospheric temperature patterns near Chicago, and the gradient between lake and air temperatures is increased (Fig. 2d). Under these conditions, air over the lake surface appears to have cooled less (by 0 to -3°C) than air moving over the land surface (by 1 to -5°C). This can be clearly observed visually but is tested for significance using the method described above where the rate of radial temperature decline (data from the same matrix in Fig. 2d) is compared against both a random temperature pattern and from the map produced at the same time at the NUL site (Fig. 3). Figure 3a shows the temperature decay pattern assuming a heat source is present at the initiation point whereas Fig. 3b shows the rate of change of temperature compared to the random pattern. The pattern shown in Fig. 2d is distinct from random but is not different from the NUL site, suggesting the pattern observed is caused by the presence of the lake.

The vertical structure of heating detected from the urban atmosphere is shown in Fig. 4. We show only nighttime conditions, when the shallow boundary layer and reduced mixing focuses the heat plume within a narrower atmospheric window near the surface. The trajectories are divided into those that move away from Chicago over land (Fig. 2a, b) and those trajectories that move away from Chicago over Lake Michigan (Fig. 2c, d). Because of the nature of the lagrangian analysis and that trajectories were seeded at three fixed heights, the maps of temperature are not continuous and only include data where the seeded trajectories traveled. We identify structure in these maps by calculating the rate of change of temperature from the initiation point for each height and assess whether the temperature change is significantly different than if the grid cells were randomly distributed (Supplementary Fig. 1). This is a comparable statistical assessment described in Fig. 3 but with vertical layers now discretized. During the winter, the UL site shows prominent heating of the urban atmosphere between 0 and ~400 m AGL, persisting for up to ~70 km beyond the city center (Fig. 4a). This can also be seen as a statistically significant decline in temperature at multiple heights between 0 and 200 m moving away from the initiation point (Supplementary Figure 1). Air parcel temperatures in this zone are between ~5 and ~10 $^{\circ}\text{C}$ warmer than the atmosphere above. A comparison with the NUL site for the same conditions (Fig. 4b) shows the absence of a comparable heat plume and a lack of any heights where the decline in temperatures was statistically significant (Supplementary Fig. 1).

For air parcels moving over the lake (Fig. 4c, d), the results also suggest the presence of a heat plume emanating from Chicago over the lake for 40–48 km away from the city. The magnitude of the heat plume is smaller for the lake site but still emerges as a statistically significant decline in temperature focused at a height of around 200 m (Supplementary Figure 1). A comparison with the NUL site for the same conditions (Fig. 4d) shows an absence of a statistically significant decline in temperature, suggesting the heat plume can be attributed to the presence of the urban environment at the UL site.

The results provide a quasi-observational depiction of the magnitude and scale of the urban heat plume associated with the city of Chicago. Assuming a constant heat source from the city, the truncated length of the plume over the lake suggests it is absorbing this added heat. At first, this seems counterintuitive because the lake broadly acts as a regional heat source during the

Fig. 4 Temperature of air parcels as distance increases from Chicago over land at UL **a** and NUL **b** sites and over Lake Michigan at UL **c** and NUL **d** sites for winter nighttime. Heat movement is shown within 100 km of trajectory initiation point. The vertical axis shows height above ground level (AGL) plotted on a logarithmic scale. Atmospheric heating is evident in both UL analyses (**a** and **c**) but not for the NUL analyses **b** and **d**. The heat plume extends further over land **a** than over Lake Michigan **c**. Key maps are provided to the right of each panel to show area of trajectory movement that was used to generate each mapping scenario

Fig. 5 **a** Relationship between MODIS lake surface diurnal temperature and bathymetry. The best-fit power law fit (dotted black line) is shown along with the distribution of the data visualized in Supplementary Figure 5. Lake surface temperatures in proximity to Chicago fall below the fitted curve and demonstrate an anomaly from the expected relationship between diurnal temperature range and water depth. Marker shows average of data <40 km from Chicago. **b** Average diurnal cycle anomaly normalized to bathymetry. The deviation in day night temperatures from what would be predicted based purely on bathymetry is shown. Near Chicago, the diurnal temperature change is much smaller than predicted, suggesting the impact of urban heating

winter.³³ However, previous studies made this assessment of sensible heat flux from the lake based on the whole lake and did not consider local urban heating, which we suggest may alter the sign of the heat flux. To assess possible impacts of urban heating on the lake, we analyzed lake skin temperatures using the MODIS land surface temperature product from 2003 to 2014 (Methods). A small temperature anomaly in skin temperatures is observable near the city (Supplementary Figure 5a), though this effect appears restricted to a single grid cell (~1 km) adjacent to the city. We instead look for the urban influence through analysis of the difference between day and night lake surface temperatures (ΔTemp) as our results show that the heat plume is most prominent at night (Figure 4). ΔTemp is strongly affected by bathymetry, such that it is larger in shallower coastal regions and this effect needs to be removed in order to isolate the anomalous

conditions near Chicago. ΔTemp was first regressed against bathymetry using all the Lake Michigan grid cells and the residuals from this model were used to detect regions where ΔTemp strongly deviated from the expected influence of bathymetry (Fig. 5). Within 30–40 km of the city, a prominent reduction in ΔTemp can be observed relative to that which would be expected based on the shallow water in the region. This result suggests a modification in lake energy balance near Chicago, with a spatial scale that is consistent with that which was independently derived from the atmospheric measurements (Fig. 4c). However, we note that these deviations in ΔTemp could also be the result of other factors, such as runoff from the city that was heated through interaction with pavement or industrial processing.³⁴ This would also have the effect of reducing ΔTemp because pavement retains daytime temperature signals through the night and industrial processing would generate thermal pollution both day and night thus homogenizing the diurnal cycle.

Further study is needed to assess the relative importance of atmospheric absorption and surface heating of runoff on the anomalous lake temperature conditions we document near the city. For example, added heat to the lake surface from urban runoff would have the effect of reducing the capacity for the lake to absorb exported atmospheric heat from the city. This could, in turn, enhance the regional scale of the heat plume. Lake Michigan's effect on the Chicago UHI has been previously noted, for example, during the 1995 heat wave, when the near surface air temperature of locations near the shore were more than 3.7 °C cooler than locations farther inland.³⁵ However, the city's influence on the lake temperatures has not previously been documented. We hypothesize that this effect has gone unnoticed largely because it is only apparent when viewed using ΔTemp as opposed to absolute temperatures of the lake.

It is critical to understand the impact of cities on regional climates, as this effect can be as large or even larger than that which is associated with the greenhouse effect. By combining archived numerical weather model outputs with an atmospheric transport mode, we show the presence of a prominent atmospheric temperature plume emanating radially from Chicago (Fig. 6). This feature leaves a clear signature on regional atmospheric temperatures during summer and winter nights and may have an impact on the sensible heat flux from the region of Lake Michigan that borders the city. The results have important implications for how urban development coupled with climate change will impact regional climates. Firstly, the results support the theory that export of heat is a non-negligible component of the UHI.^{4,22,36} The findings compliment results by Zhao et al. (2014), which suggest the scale of the UHI effect is strongly determined by convection efficiency, or the ability of an urban surface to move heat upward into the atmosphere and away from the city. The urban heat transport documented in this analysis provides evidence for this displaced heat. The results presented here suggest that UHI mitigation strategies attempting to increase convective efficiency may also need to consider the regional atmospheric impacts of these efforts. Secondly, the results confirm that the UHI has an impact that extends well beyond the local urbanized area. This regional effect has been shown through previous observational and modeling studies,^{14,18,25,26} but these studies did not place a spatial (both vertical and horizontal) constraint on this feature. These results extend our understanding of warming beyond that of near surface air temperatures.^{13,37,38} While surface conditions have the most direct effects on human and ecosystem health, modification of the atmosphere above the surface has indirect effects for which less measurement and documentation exists. For example, the temperature anomalies located 500–1000 m above the surface (a boundary layer UHI) can contribute to the formation of inversions that increase atmospheric stability at the surface and cap pollution not only within the city but also above the peri-urban and rural regions surrounding cities. These capping events

Fig. 6 Conceptual diagram showing the scale of the Chicago urban 'plume' as derived from the analyses presented here. **a** Heating from the urban atmosphere is transported over land for up to ~70 km and up to ~40 km over Lake Michigan (**b**). Modified from Oke (1976) and Clarke (1969)

can affect air quality by intensifying pollution in the urban atmosphere, though they may also lead to improved air quality through enhanced mixing.^{22,37} Our preliminary results on boundary layer heights in the region surrounding Chicago show increased boundary layer heights that extend beyond the urban center, which suggests these capping events may be observable (Supplementary Fig. 6). Thirdly, the analysis shows an impact of the city on water temperatures in the adjacent lake at a scale of 30–40 km. The exact mechanism transferring the signal from city to lake is not identified here but the results nonetheless document a regional-scale thermal signature of the city on the large lake system. We hypothesize that similar effects would be observable in other cities that are adjacent to large water bodies (e.g. Toronto). While the changes are subtle, they can theoretically affect air–water interactions that feedback onto the scale of the heat plume and may influence thermal gradients that control circulation of contaminants and nutrient cycling of the lake.^{39,40}

While this study emphasized the Chicago UHI, the results are applicable elsewhere, though may be less clearly visible in more complex topographical domains such as Los Angeles or Mexico City. The analysis presented here can help define the scale of future studies on urban climates and is critical to understanding the movement of air out of the urban center, which has implications for UHI mitigation strategies. Ultimately, the mapping of the Chicago atmosphere described here provides an additional perspective of the UHI, necessary for considering its effects not only on land surface temperature but also as it contributes to regional air pollution through the modification of the boundary layer structure. The results provide compelling evidence for a regional above-surface signature of the UHI though future studies would benefit from the use of multiple weather models of varying resolutions to test the scale, amplitude, and variability of these features.

METHODS

Regional climatic conditions of Chicago are defined by its mid-latitude location on the interior of North America. At the synoptic scale (1000–2500 km), winter weather patterns are influenced by the polar jet stream and arctic air masses that can move southward into the region.⁴¹ Summer is defined by hot and humid conditions resulting from high-pressure subtropical systems that migrate over the continent from the Atlantic Ocean, causing anti-cyclonic circulation and transport of moisture from the Gulf of Mexico into the Midwest.⁴¹ At the mesoscale (80–160 km), regional temperatures are influenced by the Great Lakes and proximate

agricultural land use characteristics. Reductions in daily maximum temperatures in the region are hypothesized to be related to its surroundings and have been observed in previous research at similar latitudes in the northeastern United States.³⁰ The microclimate of Chicago is influenced by its proximity to Lake Michigan, which moderates temperatures, creates lake breeze scenarios and influences variability in precipitation.²⁷

The annual average for Chicago temperatures from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) derived from historical data at Chicago O'Hare Airport over the period of 1981–2010, is 9.9 °C, with an average maximum summer temperature of 27.7 °C, and an average minimum winter temperature of −7.2 °C.⁴² The direction of prevailing winds during the winter is from the west, while summer months are dominated by winds from the southwest.⁴³

Three-dimensional assessment of the Chicago UHI is gained through the coupling of an atmospheric transport model and gridded meteorological data (Fig. 1). Atmospheric circulation patterns and meteorological characteristics of air parcel histories in the Chicago are area characterized using the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (ARL) Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) within 12 km gridded numerical meteorological fields from archived data sets of the North American Mesoscale (NAM) Forecasting System. The resolution of this meteorological dataset is coarse in comparison to more detailed analyses of urban micro and meso climates but, as it is publicly available, it has advantages for replication and ease of analysis. Further, the scale of the methodology is too large to resolve the urban canopy and urban geometries. However, since the research explores processes occurring on the 10–100 km scale, the model scale is considered appropriate.

The position and characteristics of an air parcel are computed along a trajectory and can be calculated in a forward or backward direction from the starting point. Air parcel trajectories were calculated for each day at 6-h intervals (00z, 06z, 12z, 18z) for both forward and backward movements for 24 h. The forward trajectory direction describes the movement of an air parcel from the initiating point away from the city to an unknown ending point. The backward trajectory direction describes the movement of the air parcel from an unknown starting point 24 h prior to the initiation time, as it moves towards the established initiation point in the Chicago urban center. Meteorological data was extracted along trajectories at 30-min intervals in each direction in time. Both backward and forward trajectories were initiated for each interval from 0, 500, and 1000 m. These heights were chosen to represent air moving from the surface of the urban center at 0 m, air just above the roughness sublayer of the urban boundary layer at 500 m, and air moving above or within the urban boundary layer at 1000 m. Building heights within the city of Chicago fall within the 0–500 m layer of the Chicago urban boundary layer, with the tallest building, the Willis Tower, standing at 443 m.⁴⁴ These heights are not necessarily reflected in the parameterization of urban surface geometry that is

Table 1. HYSPLIT parameter settings (from Hysplit User Guide⁴⁹)

HYSPLIT parameter	Set point	Definition
Integration time step	30 min	Interval at which program computes change in meteorological variables along trajectory length.
Advection stability ratio	0.75	Fraction of a grid cell that a trajectory can traverse in one time step. Set at default value.
Meteorological subgrid	10	Minimum size in grid units of the meteorological subgrid over which calculation occurs. Set at default value.
Top of model	10,000 m	Vertical limit of the internal meteorological grid. Set at default value.
Vertical motion method	0, equal to input model data	Vertical motion calculation method. Uses the vertical velocity fields from the meteorological model. Set at default value.
Boundary layer height	Provided by NAM 12 km data	Uses value provided by the input meteorological data. If not available, boundary layer height is computed from the temperature profile. Set at default value.

represented in the weather dataset described below, though provide rationalization for the vertical scope of the analysis zone.

The NAM data is archived at 12 km resolution (though run at 4 km) from daily forecast files over the US along hybrid pressure–sigma hybrid levels.⁴⁵ The NAM forecasting system consists of the weather research and forecasting—nonhydrostatic mesoscale model (WRF-NMM).⁴⁶ Land surfaces are defined within the WRF-NMM system with the Noah land surface model.⁴⁶ Further, this model is coupled with the urban canopy model (UCM) to provide a description of the lower boundary conditions of the urban regions. The UCM model simplifies urban geometry (e.g. building heights, building coverage ratio) and features of heat exchange and transfer (e.g. anthropogenic heat, moisture availability, heat capacity, and albedo of surfaces) within the three-dimensional environment into a single layer model.⁴⁶ Urban parameters vary by grid cell with different land use classifications across Chicago that can be accessed at <http://www.wudapt.org/>. Sharma et al.³² provide a sensitivity analysis for the WRF model in the region that gives an example of variations in the parameter settings as may be used in this version of the model. NAM is publicly archived and datasets are accessible for reproduction of the analysis. Within this domain, the model runs a nested 4 km resolution contiguous United States (CONUS) domain.⁴⁷ The model is initialized in a continental domain that is defined by the Rapid Refresh short-term weather forecast system that is updated every hour with data assimilation from real-time observations (e.g. commercial aircraft sensors, radiosondes, surface reporting stations, buoys).⁴⁸ This process assimilates hourly outputs of the model run to coordinate with actual measurements. Forecasts are calculated using a sequence of grid-point statistical interpolation (GSI) analyses.⁴⁵ Forecasts are generated every 6 h.⁴⁵ For the purpose of this study, the output from the weather model is treated as the true state of the atmosphere. While this assumption is not strictly valid, because these outputs are the result of assimilated data and are evaluated against observations, they are likely to be close to the actual atmospheric state in locations where many observations, including atmospheric measurements from aircraft, are available (such as Chicago).

The lagrangian atmospheric transport simulations were computed from the UL and at a NUL for comparison. Air parcel trajectories for the UL site were initiated from the Chicago downtown “loop” area (41.88°N, 87.63°W). The NUL site was located ~2 latitudinal degrees north (~250 km) of Chicago at 43.93°N, 87.73°W, and approximately halfway in between Sheboygan, Wisconsin and Manitowoc, Wisconsin. This site is located in rural Wisconsin, over 100 km north of Milwaukee, WI. The initiation point for both UL and NUL simulations was 1 km west of the Lake Michigan shore in order to capture similar land–lake boundary circulation conditions. The proximity of the two sites and consistent relationship to Lake Michigan is assumed to yield comparable meteorological conditions.

HYSPLIT simulations for forward and backward trajectories were run within the gridded NAM 12 km meteorological data. The diagram shown in Fig. 1 describes the relationship between the trajectory simulation and the archived weather data in the model environment. The settings used for the HYSPLIT simulations are detailed in Table 1. The majority of the parameters were maintained at their default position or value. Each model simulation output a .csv file of meteorological variables (e.g. temperature, humidity, wind speed) along the life of the trajectory at each time step at the specified interval.

The trajectory analysis produced ~17,400 trajectories for each study site. Many of these trajectories, because of a particular atmospheric state, rapidly moved to the upper troposphere. The data sets for each study site

were grouped into four clusters using a *k*-means clustering algorithm in MATLAB (R_2015a). The distance measure used in the algorithm was squared Euclidean distance. The trajectories were clustered based on height (km AGL). 77% of the trajectories fell into two clusters that maintained heights within 3 km AGL and were used for the analysis. The figures provided here only show mapping of heating within 2 km AGL which are the result of the interpolation of the temperature values of trajectory data points from within these two clusters. The remaining 23% of trajectories fell into clusters that contained trajectories with long travel paths and vertical movement up to 10 km AGL. Trajectories in these two clusters were excluded from the analysis.

Values of meteorological variables output along trajectories from HYSPLIT were first used to group datasets based on time of day, time of year, latitude, longitude, height AGL, distance from the initiation point, etc. and then a surface fit was interpolated in order to visualize these data. The results include air moving towards and away from the city (backward and forward trajectories), assuming that air moving in and out of the urban atmosphere is similarly affected by urban heating. Two-dimensional surface fits for the mapping of each variable were generated using the Curve Fitting Toolbox in Matlab_R2015A. The surface fit was generated using the linear interpolant method and the fit was scaled so that the *x* and *y* values were normalized by their mean and standard deviation. Matrices were generated from the evaluation of these surface fits on a grid and used for further analysis and comparison. The resolution of the surface mapping (Figs. 2 and 4; Supplementary Figures 2, 3 and 4) is finer than that of the 12 km NAM data and should therefore be considered only an approximation of atmospheric temperature structures during the analysis period.

Lagrangian simulations of the Chicago atmosphere were completed for June 2012–June 2014. Simulations were divided into Summer (JJA): June, July and August; and Winter (DJF): December, January, and February. Diurnal differences were captured for periods of high and low boundary layer conditions, excluding transitional periods. The maximum height of the mean boundary layer height during the study period was 1385 m, occurring at 3 p.m. The minimum height of the mean boundary layer height was 7 a.m. at 554 m. Based on these heights, “night”, was defined as from 1 a.m. to 7 a.m. “Day,” was defined as 12 p.m. to 6 p.m.

Statistical analysis of the plan view (Fig. 2; Supplementary Figures 2 and 3) and vertical maps (Fig. 4 and Supplementary Figure 4) was done by assuming the presence of the city would generate a decline in temperature than emanates in a radial pattern. We compare the slope of the temperature change (dTemp/dDistance) to either the change in temperature if all the temperatures observations were randomly shuffled and to the rate of change in temperature between the UL and NUL site. For the former analysis, the temperature maps were shuffled randomly 5000 times and the slope calculated for each. The range of slopes are represented by the error bars shown in Fig. 3. If the slope of the observations deviates from the range of slopes calculated from this randomly shuffled population, it can be assumed that there is a decline of temperature moving from the initiation point. If the slope is larger at the UL than the NUL site, it can be assumed that the city effect is larger than the effect of the lake.

Lake surface diurnal temperatures and bathymetry for Lake Michigan were obtained from Moderate-resolution Imaging Spectroradiometer (MODIS) data for 2003–2014.⁵⁰ Daily surface temperatures over the lake at a spatial resolution of 4.6 km × 4.6 km were obtained and screened for quality.⁵¹ The differences between daytime and nighttime surface

temperatures over the same grid were used to compute the diurnal cycle. The daily diurnal temperature for each of the lake's grid cells was plotted against the NOAA Great Lakes bathymetry data (<https://www.ngdc.noaa.gov/mgg/greatlakes/greatlakes.html>) to generate an empirical model for the bathymetric control on the diurnal cycle of lake temperatures (Fig. 5). The results revealed large diurnal cycles in shallow regions, as expected. A sigmoidal model was used to characterize this relationship between bathymetry and diurnal temperatures and residuals from the model indicated locations where the diurnal cycle significantly deviated from a pure bathymetric control.

DATA AVAILABILITY

NAM 12 km data can be accessed here: <https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/north-american-mesoscale-forecast-system-nam>. Processed data available on request from authors.

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AUTHOR CONTRIBUTIONS

M.B. and A.C. designed the research. A.C. completed the simulations and data analysis. M.B. and A.C. drafted the manuscript.

ADDITIONAL INFORMATION

Supplementary information accompanies the paper on the *npj Climate and Atmospheric Science* website (<https://doi.org/10.1038/s41612-018-0055-3>).

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REFERENCES

- Howard, L. *The Climate of London*, Vols. I–II 1–10 (Harvey Dorton, London, 1833). Republished by IAUC.
- Mills, G. Urban climatology: history, status and prospects. *Urban Clim.* **10**, 479–489 (2014).
- Arnfield, A. J. Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *Int. J. Climatol.* **23**, 1–26 (2003).
- Oke, T. R. The energetic basis of the urban heat island. *Q. J. R. Meteorol. Soc.* **108**, 1–24 (1982).
- Debbage, N. & Shepherd, J. M. The urban heat island effect and city contiguity. *Comput. Environ. Urban Syst.* **54**, 181–194 (2015).
- Zhao, L., Lee, X., Smith, R. B. & Oleson, K. Strong contributions of local background climate to urban heat islands. *Nature* **511**, 216–219 (2014).
- Livezey, R. E. & Tinker, R. Some meteorological, climatological, and micro-climatological considerations of the severe U.S. heat wave of mid-July 1995. *Bull. Am. Meteorol. Soc.* **77**, 2043–2054 (1996).
- Semenza, J. C. et al. Heat-related deaths during the July 1995 heat wave in Chicago. *N. Engl. J. Med.* **335**, 90 (1996).
- Holderness, T., Barr, S., Dawson, R. & Hall, J. An evaluation of thermal Earth observation for characterizing urban heatwave event dynamics using the urban heat island intensity metric. *Int. J. Remote Sens.* **34**, 864–884 (2012).
- Mackey, C. W., Lee, X. & Smith, R. B. Remotely sensing the cooling effects of city scale efforts to reduce urban heat island. *Build. Environ.* **49**, 348–358 (2012).
- Weng, Q. Remote sensing of impervious surfaces in the urban areas: requirements, methods, and trends. *Remote Sens. Environ.* **117**, 34–49 (2012).
- Yuan, F. & Bauer, M. E. Comparison of impervious surface area and normalized difference vegetation index as indicators of surface urban heat island effects in Landsat imagery. *Remote Sens. Environ.* **106**, 375–386 (2007).
- Coseo, P. & Larsen, L. How factors of land use/land cover, building configuration, and adjacent heat sources and sinks explain Urban Heat Islands in Chicago. *Landsc. Urban Plan.* **125**, 117–129 (2014).

- Bassett, R. et al. Observations of urban heat island advection from a high-density monitoring network. *Q. J. R. Meteorol. Soc.* **142**, 2434–2441 (2016).
- Smith, K. R. & Roebber, P. J. Green roof mitigation potential for a proxy future climate scenario in Chicago, Illinois. *J. Appl. Meteorol. Climatol.* **50**, 507–522 (2011).
- Baik, J. J., Kim, Y. H., Kim, J. J. & Han, J. Y. Effects of boundary-layer stability on urban heat island-induced circulation. *Theor. Appl. Climatol.* **89**, 73–81 (2007).
- Patz, J. A., Campbell-Lendrum, D., Holloway, T. & Foley, J. A. Impact of regional climate change on human health. *Nature* **438**, 310–317 (2005).
- Zhou, D., Zhao, S., Zhang, L., Sun, G. & Liu, Y. The footprint of urban heat island effect in China. *Sci. Rep.* **5**, 2–12 (2015).
- Georgescu, M., Moustau, M., Mahalov, A. & Dudhia, J. Summer-time climate impacts of projected megapolitan expansion in Arizona. *Nat. Clim. Chang.* **3**, 37–41 (2013).
- Georgescu, M., Morefield, P. E., Bierwagen, B. G. & Weaver, C. P. Urban adaptation can roll back warming of emerging megapolitan regions. *Proc. Natl Acad. Sci. USA* **111**, 2909–2914 (2014).
- Kennedy, C. A. et al. Energy and material flows of megacities. *Proc. Natl. Acad. Sci. USA* **112**, 5985–5990 (2015).
- Barlow, J. F. Progress in observing and modelling the urban boundary layer. *Urban Clim.* **10**, 216–240 (2014).
- Clarke, J. F. Nocturnal urban boundary layer over Cincinnati, Ohio. *Mon. Weather Rev.* **97**, 582–589 (1969).
- Oke, T. R. The distinction between canopy and boundary-layer Urban Heat Islands. *Atmosphere* **14**, 268–277 (1976).
- Bohnenstengel, S. I., Evans, S., Clark, P. A. & Belcher, S. E. Simulations of the London urban heat island. *Q. J. R. Meteorol. Soc.* **137**, 1625–1640 (2011).
- Heaviside, C., Cai, X. M. & Vardoulakis, S. The effects of horizontal advection on the urban heat island in Birmingham and the West Midlands, United Kingdom during a heatwave. *Q. J. R. Meteorol. Soc.* **141**, 1429–1441 (2015).
- Hayhoe, K. et al. An integrated framework for quantifying and valuing climate change impacts on urban energy and infrastructure: A Chicago case study. *J. Great Lakes Res.* **36**, 94–105 (2010).
- Hu, L. & Brunell, N. A. A new perspective to assess the urban heat island through remotely sensed atmospheric profiles. *Remote Sens. Environ.* **158**, 393–406 (2015).
- Conry, P. et al. Chicago's Heat Island and climate change: bridging the scales via dynamical downscaling. *J. Appl. Meteorol. Climatol.* **54**, 1430–1448 (2015).
- Bonan, G. B. Observational evidence for reduction of daily maximum temperature by croplands in the Midwest United States. *J. Clim.* **14**, 2430–2442 (2001).
- Theeuwes, N. E., Solcova, A. & Steeneveld, G. J. Modeling the influence of open water surfaces on the summertime temperature and thermal comfort in the city. *J. Geophys. Res. Atmos.* **118**, 8881–8896 (2013).
- Sharma, A. et al. Urban meteorological modeling using WRF: a sensitivity study. *Int. J. Climatol.* **37**, 1885–1900 (2017).
- Rouse, W. R. et al. The role of Northern Lakes in a regional energy balance. *J. Hydrometeorol.* **6**, 291–305 (2005).
- Herb, W. H., Janke, B., Mohseni, O. & Stefan, H. G. Thermal pollution of streams by runoff from paved surfaces. *Hydrol. Process.* **22**, 987–999 (2008).
- Changnon, S. A., Kunkel, K. E. & Reinke, B. C. Impacts and responses to the 1995 heat wave: a call to action. *Bull. Am. Meteorol. Soc.* **77**, 1497–1506 (1996).
- Haeger-Eugensson, M. & Holmer, B. Advection caused by the urban heat island circulation as a regulating factor on the nocturnal urban heat island. *Int. J. Climatol.* **19**, 975–988 (1999).
- Basara, J. B., Hall, P. K., Schroeder, A. J., Illston, B. G. & Nemunaitis, K. L. Diurnal cycle of the Oklahoma City urban heat island. *J. Geophys. Res. Atmos.* **113**, D20 (2008).
- Peterson, T. C. Assessment of urban versus rural in situ surface temperatures in the contiguous United States: no difference found. *J. Clim.* **16**, 2941–2959 (2003).
- Beletsky, D. & Schwab, D. J. Modeling circulation and thermal structure in Lake Michigan: annual cycle and interannual variability. *J. Geophys. Res. Ocean* **106**, 19745–19771 (2001).
- Rao, Y. R. & Schwab, D. J. Transport and mixing between the coastal and offshore waters in the Great Lakes: a review. *J. Great Lakes Res.* **33**, 202–218 (2007).
- Hayhoe, K., VanDorn, J., Croley, T., Schlegal, N. & Wuebbles, D. Regional climate change projections for Chicago and the US Great Lakes. *J. Great Lakes Res.* **36**, 7–21 (2010).
- National Oceanic and Atmospheric Administration National Centers for Environmental Information. *Climate Data Online: Data Tools: 1981–2010 Normals for Chicago O'Hare International Airport, IL US*. <https://www.ncdc.noaa.gov/cdo-web/datatools/normal>. Accessed 2017.
- NCDC, National Climatic Data Center. *Climatic Wind Data for the United States*. <https://www.ncdc.noaa.gov/sites/default/files/attachments/wind1996.pdf>. Accessed 2017 (1998).

44. Willis Tower, Office of the Building. "Fact Sheet: Willis Tower." <http://www.willistower.com/building-information/history-and-facts> Accessed 20 Oct 2016 (2015).
45. NOAA-ARL, National Oceanic and Atmospheric Administration Air Resources Laboratory. *North American Mesoscale (NAM) Analysis and Forecast System Characteristics*. http://www.emc.ncep.noaa.gov/mmb/mmbpll/misc/nam_2014_specs/index.html (2014).
46. Tewari, M., Chen, F., Kusaka, H. & Miao, S. *Coupled WRF/Unified Noah/urban-canopy Modeling System*. NCAR WRF Doc. NCAR, Boulder 122, (2007).
47. NOAA-NCEI, National Center for Environmental Information. North American Mesoscale Forecast System (NAM). <https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/north-american-mesoscale-forecast-system-nam>. Accessed 26 Jan 2016 (2015).
48. NOAA-ESRL, National Oceanic and Atmospheric Administration Earth System Research Laboratory. *Rapid Refresh (RR)*. <http://rapidrefresh.noaa.gov/> (2016).
49. Draxler, R., Stunder, B., Rolph, G., Stein, A., & Taylor, A. *HYSPLIT4 User's Guide*. https://www.arl.noaa.gov/documents/reports/hysplit_user_guide.pdf (2016).
50. N. A. S. A. Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group. Moderate-resolution Imaging Spectroradiometer (MODIS) Terra Sea Surface TemperatureData; 2014 Reprocessing. NASA OB.DAAC, Greenbelt, MD, USA. 10.5067/TERRA/MODIS_OC.2014.0 Accessed in 2014 and

2015 provided with time variable by the Integrated ClimateData Center (ICDC, icdc.cen.uni-hamburg.de). University of Hamburg, Hamburg, Germany.

51. Kilpatrick, K. A. et al. A decade of sea surface temperature from MODIS. *Remote Sens. Environ.* **165**, 27–41 (2015).

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