Spatiotemporal Variability in Building Energy Use in New York City

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Abstract

Data on building energy use for large and dense cities is not yet available at adequate spatial and temporal scales. The energy consumption from buildings significantly influences the local climate and this impact is not adequately integrated into regional or local scale weather models. The primary objective of his study is to understand and map building energy consumption and quantify its impact on the urban environment; here, New York City (NYC) is used as a test case. The project involved a detailed classification of buildings in NYC using a high-resolution landuse/landcover dataset. The customized classification was then coupled with a single building energy model (SBEM) to estimate the building energy use. The developed model matched the annual energy use of NYC within 5% of the observed value. Coupled energy simulations were then performed with the Weather Research and Forecasting (WRF) model. The results show that heat released from building's heating and air conditioning system during extreme heat events can be as high as 18% of the overall available energy. Finally, a comparison between the average annual energy use, the urban heat island intensity (UHI) and the landcover/landuse fraction for various parcels during extreme heat events indicated that neighborhoods surrounding the highly-commercialized zones were disproportionately impacted by high UHI values. The increase was related to advection of heat.

1. Introduction

Over the last three decades energy consumption and the corresponding greenhouse gas emissions around the world have increased by approximately 49% and 43% respectively [1,2]. Energy usage of developing countries is projected to rise 3.2% annually, eventually surpassing the developed nations by 2020 [1]. The unabating consumption pattern will have adverse consequences on both energy sustainability and improving climate resiliency [3,4]. One area of importance is the building energy sector; currently, residential and commercial buildings in the US account for 41% of the total energy consumed and 47% of the greenhouse gas emissions [5]. In China, 43% of the total energy consumption comes from building energy use [6]. In a dense urban environment, such as New York City (NYC), buildings account for more than two-thirds of total energy consumption [7]. The waste heat released from the buildings amplify the local air temperature contributing to urban heat island effects and increases the probability of extreme heat events in dense cities during the warm season [8,9]. Various studies have demonstrated the feedback between electricity consumption and urban heat island intensity (UHI) [10,11]. Akbari et al. (2009) showed that for every 1˚C increase in air temperature, 2-4% more energy is required to cool the indoor spaces for a large urban agglomeration. In addition to local impacts, urban energy use also influences regional-scale water and energy cycles [12]. Currently various city, state and federal administrations around the world have created various strategies to reduce the overall energy consumption, restrict green house gas emissions, and moderate urban heat island impacts [13-17]. However, without a clear understanding of the spatiotemporal correlations between building energy use and its environmental impact, one cannot suitably address this issue. The primary objective of this article is to understand the spatial and temporal pattern of building energy use and its impact on the local environment in the densely populated New York City. The research also aims to correlate the building energy use to urban landcover/landuse pattern to identify land parcels for urban heat moderation strategies.

Recent studies have used both top-down and bottom-up approaches to predict energy consumption in major cities with statistical analysis and estimations based on building functions [7]. Sailor et al. (2004) used top-down approach using observations of electricity consumption for different states in the U.S. to model temporal and spatial variability in energy consumption. The model proved to be effective and found energy use to be highly dependent on population density, which is highly variable and uncertain [18]. On a City scale, Howard et al. (2012) developed a model to estimate the energy use for each tax lot in NYC. The model demonstrated that energy consumption is highly dependent on the function of the building and not on the building construction material [7]. Similar modeling approaches have also been used and proved to be effective elsewhere outside of the United States. Momonoki et al. (2017) assessed the effectiveness of bottom-up approach by evaluating energy use in residential sectors for Japan creating a model based on building energy-use parameters (i.e. heating/cooling equipment, insulation, weather). Simulation results were comparable to the statistical data for the residential sector for the given modeling approach [19]. Menezes et al. (2014) studied the efficacy of bottom-up approaches at a smaller scale, estimating the energy consumption of small power equipment in office buildings in United Kingdom (UK). The model based on building function, equipment used, and usage schedule demonstrated good correlation when compared to metered data in the UK [20]. However, there are two main issues with inventory energy analysis: one, the temporal resolution is highly restricted and two, there is a lack of data at fine spatial scales.

Another useful tool to conduct energy analysis is the single building energy model (SBEM). The single building energy model created by the Department of Energy is a numerical scheme that uses conductive and radiative heat transfer equations and numerous parametrizations that account for occupancy, fenestration, heating and cooling efficiency to compute the energy load for a given indoor and outdoor condition. The physical characteristics of the building, like roof albedo, wall insulation and building material can all be independently parameterized. The model is widely used by building operation managers and researchers to study and forecast energy use. Heiple et al. (2008) simulated building energy consumption in Houston, Texas with SBEM and found good agreement at individual building level [8]. Zerrough et al. (2015) compared electricity consumption from SBEM models to real data for individual buildings in Albuquerque, New Mexico and concluded that SBEM can be used to model energy consumption for single buildings [21]. Their results showed that the difference between SBEM and observations of electricity consumption differed by approximately 4% on an annual basis. Lately, the single building energy scheme is also used in regional climate models [21]. Ortiz et al. (2006) used the coupled scheme to study the increase in energy load in NYC for heatwave episodes [22]. The models are currently run at 1-3 km spatial resolution and hence the surface cover is parametrized using bulk properties. As the spatial resolution of these models increase there is a greater need to assess the scalability of the single building energy model to represent building envelope-environment interactions.

Here we use the single building energy model integrated with a high-resolution building dataset to study the spatial and temporal pattern of energy use in the densely populated New York City. The analysis will include a detailed classification of buildings using local morphological characteristics. Additionally, the energy use pattern will be coupled with a high-resolution landcover dataset to identify land parcels that offer high potential for microclimate mitigation strategies. The analysis will answer the following questions:

- What is the spatial and temporal variation in building energy consumption and heat rejection in NYC?
- How is the energy consumption or demand partitioned between various commercial and residential buildings?
- Can the single building energy model be scaled to represent energy use at neighborhood and city scale?
- What neighborhoods/parcels within the city offer best potential for urban heat moderation strategies?

2. Methods and Validation

Herein we detail the methods used in this investigation. The analysis presented here utilizes a SBEM coupled to a localized building classification scheme to map the building energy use at high spatial resolution. The SBEM output is validated using observations from a residential and a commercial building. The energy model is then coupled to WRF to quantify the impact of building energy use on the environment.

2.1. Land Cover and Land Use Classification

The study coupled publicly available data from the New York City Department of Planning database also known as PLUTO (Public Land Use and Tax Lot database) with the single building energy model [23]. The PLUTO database contains extensive information about buildings in NYC that are preserved and updated by city organizations on a periodic basis. For each building, the PLUTO database records its area, age, function, and other morphological parameters [23]. With this data, a detailed building classification scheme was implemented to represent the complex local morphology. The buildings in the City were subdivided based on their primary use: residential, commercial, or mixed. Each of these categories were then divided based on physical characteristics such as building height (number of floors). Each residential, commercial, and mixed building was divided into Low-rise (0-5 Floors), Mid-rise (6-20 Floors), and High-rise (20+ Floors). The classifications were then modeled into a building energy model independently. For each building model, a factor for electricity consumption per unit area was derived. With this scaling factor, a bottom-up approach was implemented, which was shown to be effective in other studies [8]. Utilizing the scaling factor obtained from simulations, we computed the energy consumed and heat rejected utilizing the footprint of each building that fits our classification scheme from the PLUTO database. The building energy model simulation was carried out for year 2012. The classification scheme developed here is best suited for New York City and will be different for other cities. Table 1 below illustrates the distribution of the buildings in NYC. The categorization developed accounts for approximately 91 percent of the total buildings in NYC (See Table 2). Buildings not included are: hospitals, parking lots, and empty locations with an undefined building function.

NYC is primarily composed of residential buildings. Downtown and Midtown Manhattan, specifically Times Square and Financial District areas, is dominated by commercial and mixed building functions. In Brooklyn, the Williamsburg area and Flushing in Queens are populated by commercial buildings. The commercial buildings in The Bronx are not concentrated in a specific area, but are distributed around the borough (figure 2 illustrates the location of these neighborhoods on the NYC map).

In addition to the PLUTO database that is used to classify the buildings, high resolution spatially distributed land cover dataset, provided by NYC Department of Parks and Recreation [24] is used here. The dataset, which has a spatial resolution of ~0.9 m, is derived using LiDAR observations (from 2010) and 4-band orthoimagery, employing Object-Based Image Analysis (OBIA) techniques. Around 23% of NYC land is covered by greens, ~31% by buildings and ~17% by roads and pavements. In this analysis, we converted the data to the permeability fraction according to the hydrological soil groups defined by the Department of Environment Protection (DEP) guidelines [25]. For impervious surfaces, permeability fraction is assumed to be 0 and for natural surfaces it varies between 0 - 100.

2.2. Single Building Energy Model (SBEM) and Model Validation

The energy simulation was conducted using DOE-2 engine with eQuest as the front end [26]. The building energy model was validated with data from a commercial and a residential building before upscaling using PLUTO. Monthly electricity consumption data from a two-story residential building and a high-rise commercial building were obtained. The building characteristics were modeled using data from the PLUTO database and the energy use was simulated for a full year. The building properties were obtained from the DOE-2 in-built baseline criteria for each of the respective building functions. Other factors that influence energy consumption such as schedules, internal heat gains, as well as other building characteristics, were determined based on the DOE-2 baseline model for respective building functions [26]. Nine models were created in the SBEM; three for each of the respective building functions (residential, commercial, and mixed) based on the building height (i.e. Low-rise, Mid-rise, High-rise). The end-uses included in the calculation of energy consumption for each SBEM simulation were also determined based on the building functions. The end-uses include: area lighting, task lighting, miscellaneous equipment, ventilation fans, refrigeration, and space cooling [26]. As with electricity consumption, heat rejected from the cooling system is an output generated from the DOE-2 simulations. It is dependent on the HVAC system in use, which is different for commercial and residential buildings. The single-zone DX coils cooling was used for residential and mixed buildings and a chilled water loop cooling system was used for commercial buildings. Table 3 shows the building properties used for the energy consumption simulations.

Fig. 1a illustrates the comparison between the modeled and observed electricity consumption for a residential building. The results from the simulation follow the monthly trend for the entire year reasonably well (See Fig. 1a). The coefficient of determination (R^2) is 0.74 and the RMSE value is 1.68 kWh, which indicates a reasonably strong correlation between the simulated and measured values. Similarly, Fig. 1b illustrates the comparison of electricity consumption between high-rise model and the observations. The coefficient of determination (R^2) is 0.73 and the RMSE value is 2.28 kWh. The trend for electricity consumption on a month by month basis is very similar between the model and the real building. Given the local scale variability, related to albedo, emissivity, insulation thickness, fenestration, occupancy and variability in forcing data, the model performs reasonably well in estimating the monthly usage.

2.3. Urban Climate Simulation

The single building energy model simulation is a 1-way coupling and does not include the vital feedbacks between energy use and its associated impacts on the environment. To enable this, Weather Research and Forecast (WRF) model coupled with the building energy model and the PLUTO database was used to simulate a 10-day period in 2012, between July 11 to July 21. It should be noted that while the coupled simulations can quantify the impact of building energy use on the environment, it is computationally expensive to perform lengthy simulations. Here, we have focused on a 10-day period in mid-July that includes a heatwave scenario to capture the impact of building energy use on the thermodynamic state of the urban environment. WRF is a non-hydrostatic primitive Eq.-based model that has multiple options for parameterizations [27]. Fig. 3 shows the nested domains used for the simulation; 3 domains with grid resolutions $9 \times 3 \times 1$ km and 60 vertical grids centered on NYC were used. The North American Regional Reanalysis (NARR) data at 6-hr intervals was used to drive the model and the North American Land-use Category Dataset (NLCD) 2011 was used to determine the landuse type and the surface properties. For New York City, the NLCD parameters were replaced by data from the PLUTO database, which included building height, building area fraction and building surface ratio. The simulation used the following physical parameterization schemes: (i) the rapid radiative transfer model scheme for longwave radiation [28]; (ii) the Dudhia scheme for shortwave radiation [29]; (iii) the 2D Smagorinsky scheme for horizontal diffusion [30]; (iv) the mosaic Noah land surface model for non-urban surfaces; (v) the Mellor−Yamada−Janjic PBL scheme [31] along with the modified Zilitinkevich relationship for thermal roughness length parameterization [32]; (vi) the BEP-BEM for urban parameterization. Cumulus parameterization schemes are not used in the inner domain; however, they are enabled in the 2 outer domains. The model has been thoroughly validated for the New York area using surface weather stations [22]

3. Results and Discussion

3.1. Spatial & Temporal Variability

The electricity consumption per unit area was obtained using the SBEM simulations, forced by the DOE-2 built-in weather input file (Typical Meteorological Year version 2 (TMY2)). The output was then integrated with our custom building classification scheme (detailed section 2.1) and scaled up to city-level. Fig. 2 shows the spatial distribution of annual energy consumption.

The open spaces in the map indicate parks and airports. It is strikingly clear that the commercial zones in downtown Manhattan consume the most electricity throughout the year (over 150 Megawatts-Hour). This area is occupied by densely packed commercial buildings. Other areas of high electricity consumption include downtown Brooklyn near Williamsburg Bridge and Astoria in Queens. These areas consume over 15 GWh of electricity on an annual basis. Areas predominantly occupied by small residential houses had extremely low energy footprints compared to the lower section of Manhattan. Overall, the commercial sector consumes approximately ten times more electricity than the residential and mixed sectors for each of the respective classifications, and much of this consumption is in Manhattan. Thus, in areas dominated by commercial buildings, electricity consumption is higher than a predominantly residential area during the daytime period. Fig. 3 illustrates the total electricity consumption for each of the building classifications in this study for each of the respective boroughs in NYC. Apart from Manhattan, in the outer boroughs the residential energy consumption is higher compared to the commercial sector. In the Bronx and Queens residential high-rise buildings have the highest consumption; whereas, in Brooklyn and Staten Island the consumption is much more evenly distributed. In Manhattan, high-rise commercial and mixed buildings consume the most electricity.

Heat rejected is an important parameter to study the anthropogenic impact on urban heat island effects. We quantified the heat rejected from buildings using the same procedure used to determine the electricity consumption. The heat rejected in NYC due to building energy consumption follows the same spatial distribution as observed in Fig. 2. The categories consuming the most electricity are also the categories responsible for rejecting the most heat into the surroundings. Staten Island heat rejection is much lower than the other four boroughs because it is comprised of primarily residential houses that are approximately 1 to 5 stories high. The borough of Manhattan rejects the most heat out of all the boroughs, followed by Brooklyn, Bronx, Queens, and Staten Island. In total 555 GWh was rejected during 2012 which averages around 5.6 kWm^{-2}.

The Summer months had the highest electricity consumption; from June to August the total energy use averaged to 3 Terawatt-hours for all three building types. From October to March it averaged around 2 Terawatt-hours. The ratio of energy consumption between commercial and residential buildings was 1:3, year around. Since most of the heat during the year is rejected over the summer period, further analysis was conducted to understand how the heat rejected varies depending on the daily conditions over an average summer day (Mean 23 ℃, Max 25 ℃) in contrast to a heat wave day (Mean 31 ℃, Max 34 ℃). In NYC, any 3 consecutive days with a daily maximum temperature exceeding 32 ℃ is considered a heat wave day [33]. The total heat rejected over the average summer day was 4.47 Wm^{-2} while during a heat wave day the heat rejected per unit of area was 9.33 Wm^{-2}. The difference between the average temperature between the two days is 9 ℃. Highly commercialized zones such as Times Square rejected much more heat than a residential area in Staten Island. For example, on a heat wave day, the highly commercial zone of Times Square rejected twice as much heat, 16 Wm^{-2}. The heat rejected from these zones could potentially impact areas that are downstream. NYC experiences strong Southerly winds during daytime periods in the summer [34]. Hence much of the heat rejected in the Downtown regions will impact the Upper Manhattan neighborhoods that have high concentration of residents without air-conditioning.

Overall the results obtained provide a general picture of energy use pattern in NYC for the different building categories and neighborhoods. According to New York Independent Systems Operator (NYISO), the total electricity consumed in 2012 for NYC is 54 TWh [35]. Buildings in NYC account for two-thirds of the total annual electricity consumption [36]. Thus, out of the 54 TWh, building energy consumption alone accounts for approximately 36 TWh. Based on our model simulation, the annual electricity consumption for 2012 is 34 TWh, which is remarkably close and differs from the actual electricity consumption by a mere 5%. As noted before, the building classification used from the PLUTO database does not account for 9% of the buildings in NYC (Hospitals, Warehouse, etc.). The exercise has shown that the single building energy model can be scaled to represent neighborhood and even city scale consumption with the help of a detailed building dataset and a suitable building classification scheme.

3.2. Coupled Simulation:

From the two-way simulations of the WRF model coupled with the building energy model, we studied the relationship between building energy use and its impact on the surrounding environment during a 10-day period in July 2012. Fig. 4a shows the average peak hour (1200 - 1700 local time) air conditioning demand for the New York Metropolitan area (the encapsulated space shows the innermost domain of the simulation of 1 km resolution). Similar to the SBEM, the WRF simulation also shows high energy consumption in most of Manhattan, dominated by tall structures and commercial buildings. A distinct gradient can be deduced as we move away from the center of the City. The neighborhoods in Brooklyn and Queens, dominated by 2-story residential houses have much lower energy footprint. The energy demand fades from 26-27 Wm^{-2} in Midtown Manhattan to 10-12 Wm^{-2} in Brooklyn and Queens. The gradient reduces to 3-4 Wm^{-2} as we move further North East to Long Island which is mostly a suburban neighborhood with high vegetative fraction. The area to the west of the City in New Jersey is a highly industrialized zone and also includes Jersey City and Hoboken. The air-conditioning demand in the region averages around 12-14 Wm^{-2}, equivalent to Brooklyn and Queens. Overall the peak hour AC demand for Manhattan averages around 1.36 GW for the entire City

Fig. 4b shows the fraction of energy contributed by waste heat release from the air conditioning unit to the overall available energy. The available energy can be interpreted from the urban surface energy budget as defined below;

$$R_n - \Delta G = H + LE + Q_A \quad (1)$$

In the above Eq., R_n represents net radiation and the ΔG represents storage heat flux. H and LE are the surface energy fluxes and Q_A represents the anthropogenic heat. The left-hand or the right-hand side of the Eq. 1 is collective referred to as the available energy. The fractional contribution was the calculated using the following Eq.;

$$\frac{Q_A}{R_n - \Delta G} \quad (2)$$

It should be noted that the anthropogenic heat in Eqs. 1 and 2 is only from the air conditioning system. Heat from transportation and other anthropogenic sources are not included as the current modeling framework does not account them. In NYC heat released from transportation could be high due to the substantial underground rail network that connects the entire City.

It is evident from Fig. 4 that nearly 18% of the available energy in the city center (Manhattan) is directly due to heat released from the HVAC system. The fractional contribution decreases marginally in the outer Boroughs, dropping to 8-11 %. As we move away from the City, the contribution reduces to less than 2%. The numbers indicate considerable heat added in to the urban boundary layer from air conditioning use. The heat released from the air conditioning system is transported within the Urban Boundary Layer (UBL) as sensible heat, which highly influences the near surface air temperature and any increase in sensible heat will directly lead to increase in air temperature, which will reduce the efficiency of the HVAC system, thereby creating a negative feedback loop. It should be noted that the air temperature is also affected by various other parameters like the turbulence structure of the urban boundary layer, humidity in the lower atmosphere and other geophysical factors.

As discussed above, the building energy demand is highly dependent on the meteorological and thermodynamic state of the urban environment. The panel plots in Fig. 5 compare building energy use and air temperature during an average summer day and a heatwave day; the barbs indicate wind direction and wind speed at 10 m. Here July 13, 1700 local time and July 18, 1700 local time are chosen to represent normal and heatwave conditions. Heatwaves are mesoscale events caused by continental scale blocking and regional scale imbalances in energy-water budgets. The temperature contours during a regular day show a high of around 31˚C in much of Manhattan and the temperature gradually decreases as we move towards the coast; the temperature reduces to 27-26 ˚C in neighborhoods surrounding the coast. The wind barbs show presence of a strong sea breeze during the normal day (Fig 5a). The coastal winds penetrate through much of NYC, reaching far in to New Jersey. As we move east, in NYC the air temperature gradient strictly follows the urban parcels proximity to the coast. During the regular day, the building energy demand in NYC has a peak value of around 22-24 Wm^{-2}, the neighborhoods in outer boroughs and those close the coast average between 6-10 Wm^{-2}. This observed reduction in AC demand is potentially related to both land cover characteristics as well as the stronger influence of the coast. During the heatwave episode, panels b and d in Fig. 5, the near surface air temperature in Manhattan averages around 36-38˚C and the neighborhoods close to the coast experience an average temperature of around 31˚C. Most interestingly there is a marked shift in wind direction, the sea breeze normally witnessed during regular days does not penetrate deeper in to NYC. The Manhattan and the adjacent neighborhoods witness westerly land breeze, a common phenomenon during heatwave episodes. This shift in wind direction and subsidence of warm air due to high pressure blocking increases the air temperature and invariably escalates building energy demand. The AC demand in the highly dense Manhattan neighborhoods sharply increases to 34-35 Wm^{-2}. We also see increases in Queens and Brooklyn Neighborhoods where the demand jumps to 12-18 Wm^{-2}. On average, the results show that a 5˚C jump in air temperature leads to 12 Wm^{-2} increase in AC energy demand in Manhattan and around 7 Wm^{-2} increase in the outer boroughs, which represents an overall 50% - 70% jump in energy demand during heatwave episodes. Overall the coupled simulations reveal a complex system of heat transport in NYC. As expected high density urban parcels in Manhattan experience high temperatures due to their morphological characteristics and presence of tall commercial and residential buildings that overwhelmingly contribute to anthropogenic heat emissions. The heat released from these parcels penetrate the neighboring parcels located in Brooklyn, Queens, The Bronx and even to Upper Manhattan neighborhoods that are cut-off from coastal winds during heatwave episodes.

3.3. Landcover, Landuse and Building Energy Consumption

This section explores the relationship between building energy consumption and urban land cover land use. Various cities are promoting and administering measures to optimize energy consumption and improve climate resiliency which primarily involves reducing urban heat island effect using different green infrastructure strategies like cool roofs, urban greening, porous pavements etc. Apart from the plans that focus on roofs, all other strategies are constrained by space availability. Herein we analyze how building energy consumption and urban heat island intensity varies in different land parcels in NYC and its relationship to the surrounding landcover. The analysis is purported to identify areas within the city that will maximize the benefits of green infrastructural interventions. Fig. 6 shows the relationship between annual energy consumption and permeability fraction for different urban parcels. At each zip-code of the City, the weighted average of permeability fraction was calculated and mapped in Fig. 7a. The box plot (Fig. 6) shows a direct exponential relationship between permeability and total energy use for both commercial and residential buildings. On average residential buildings located in predominantly impervious parcels consume 30000 kWh compared to 1500 kWh for buildings surrounded by vegetative cover. This relationship also holds for commercial buildings. The relationship establishes that higher vegetative cover in a given parcel could have a direct impact on energy consumption. This effect is mainly tied to the surface energy balance of a given parcel. Impervious surfaces have higher heat storage capacity and overwhelmingly redistribute available energy in to sensible heat as opposed to latent heat. The sensible heat will directly lead to an increase in near surface air temperature which will increase the energy load of HVAC systems.

Fig. 7 a, b and c show permeability fraction, annual energy use and UHI for various zip codes in NYC, which indicates the administrative boundaries of the City. Apart from the mid and lower Manhattan areas shown in lighter shades of green and the parks indicated in darker green shades, much of NYC land parcels have a permeability fraction between 20-50%. Most of Brooklyn and The Bronx area averages around 20-30% whereas Queens has an average impermeability of around 50%. The difference is related to land use characteristics; Brooklyn and The Bronx boroughs have many industrial parcels and Queens is dominated by residential neighborhoods. Similarly, the annual energy consumption in much of Brooklyn averages around 0.2 - 0.4 GWh and in Queens, most of the parcels average between 0.1 - 0.22 GWh. Most of the high-energy consumption parcels are in lower Manhattan area.

The permeability index is a static variable and is solely determined by land cover characteristics. The UHI and energy use indices are dependent on various meteorological factors. Here the 1-week simulation data was used to calculate the UHI, which is the difference between the 2-m air temperature in the urban parcels and the rural parcel. The 2-m air temperature is commonly used as an indicator of ground conditions. The rural grid cells were located at 50 km north-west of NYC in comparable elevation and dominated by vegetative cover. It should be noted that the UHI pattern shown here is only applicable to summertime peak demand period, particularly during extreme heat episodes when the energy demand is high. The UHI contours show high values in much of Manhattan, including the upper Manhattan neighborhoods which have relatively less heat rejection compared to lower Manhattan parcels. Also, the parcels in Queens, Brooklyn and The Bronx, closer to Manhattan experience high UHI. Parcels close to the coast experience relatively weaker UHI. The UHI pattern is consistent with the sea breeze pattern, wherein the parcels adjacent to the coast experience weaker UHI compared to parcels in Manhattan and Bronx.

Cumulatively the results show that along with commercial zones in Manhattan, the neighborhoods that are adjacent to Manhattan also experience very high UHI. This is mainly because of heat advection from the center of the city to downwind areas. Also during extreme heat days, the sea breeze does not reach these neighborhoods. While most land parcels within Manhattan have very high impervious cover, the neighborhoods adjacent to the City have relatively higher fraction of pervious surfaces. In South Bronx, the permeability fraction ranges between 30-50%. The parcels in Queens and Brooklyn that are closer to Manhattan have at least 40-50% permeability. From geophysical perspective, these neighborhoods that experience disproportionately high UHI should be targeted for energy efficiency and climate moderation strategies. Additionally, building level mitigation efforts such as upgrading the HVAC system and increasing the reflectivity and insulation thickness of the roof and wall facets in commercial districts would also potentially reduce the UHI in the surrounding neighborhoods.

Overall our results reveal that local near surface air temperature in a large urban agglomeration is not a simple function of local land use and land cover characteristics. In fact, the near surface air temperature in coastal NYC depends on multiple factors such as sea-breeze/land-breeze impacts and proximity to heat sources.

4. Conclusion

Given the growing population and the increasing demand for energy in urban environments, high-resolution energy models are crucial to establish the energy-environment feedbacks. In order to prepare dense cities to better cope with extreme heat events, energy consumption and the corresponding heat released needs to be quantified. Our study integrated coupled energy modeling with high resolution land cover land use dataset to understand the spatio-temporal variability in energy use pattern and its impact on the environment in the densely populated NYC. The results shown here demonstrate that SBEM combined with high-resolution landcover database can be used to quantify the energy use pattern at multiple spatiotemporal scales. Our investigation highlighted that during extreme heat events the heat released from buildings is doubled compared to regular days. To understand the environmental impacts of energy consumption, the SBEM was coupled to a high-resolution urban numerical weather prediction model. The simulations revealed that the heat released due to building energy consumption is 18 % of the total energy in the urban boundary layer. The coupled simulation study indicated that during extreme heat events, areas around the high energy consuming commercial zones were greatly impacted by heat advection. The residential areas downwind of the commercial zones experienced disproportionately high UHI's. These regions should be the focus of urban heat mitigation efforts. Furthermore, improving the HVAC efficiency of buildings located in commercial zones will potentially benefit the entire city.

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Tables

Table 1
Distribution of buildings in NYC extracted from the PLUTO database and classified by building function. (B.) Stands for buildings.

Building Function	# of Building in NYC	% of Building in Manhattan (43,465 B.)	% of Building in Bronx (90,008 B.)	% of Building in Brooklyn (278,127 B.)	% of Building in Queens (324,611 B.)	% of Building in Staten Island (123,530 B.)
Residential	706,880	47.91	79.06	80.48	87.31	87.15
Commercial	24,528	12.14	3.44	2.53	2.14	1.77
Mixed	48,711	23.61	4.13	7.91	3.47	1.19
Other	79,621	16.34	13.37	9.08	7.08	9.89

Table 2
Distribution of buildings in NYC classified by the number of floors. (B.) Stands for buildings.

Building Height Category	Range of Floors	% of Building in Manhattan (36,133 B.)	% of Building in Bronx (77,613 B.)	% of Building in Brooklyn (252,066 B.)	% of Building in Queens (290,936 B.)	% of Building in Staten Island (110,483 B.)
Low-rise	0-5	69.58	96.60	98.58	99.28	99.92
Mid-rise	6-20	27.09	3.36	1.39	0.72	0.08
High-rise	21+	3.33	0.04	0.03	0.01	0.00

Table 3
Building properties for the SBEM used for energy consumption simulations for each building type.

Properties	Residential	Commercial	Mixed
Albedo (%)	0.6	0.6	0.6
Thermal Capacity (W/m °K)	0.519	0.346 - 0.5363	0.519
Thermal Conductivity (J/kg °K)	132.2 - 279.06	133.88 - 2467.97	133.88 - 1744.31
Wall Insulation (m^2- °K / W)	2.58	1.52	1.52
Coefficient of Performance	2.72	2.9	2.9

Figures

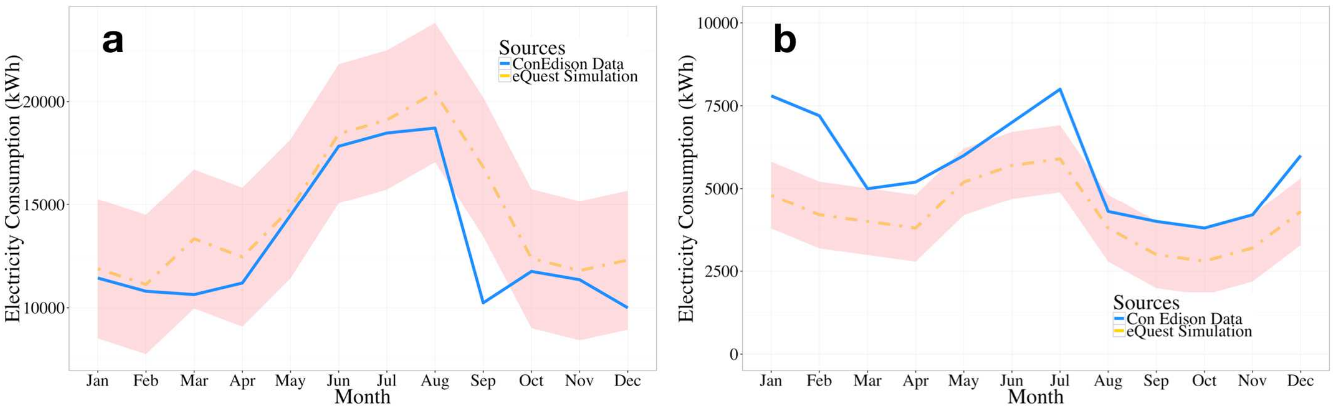

Fig. 1. Comparison of electricity consumption between energy model simulation and real data from Con Edison for an entire year (a) Residential building (b) Commercial building.

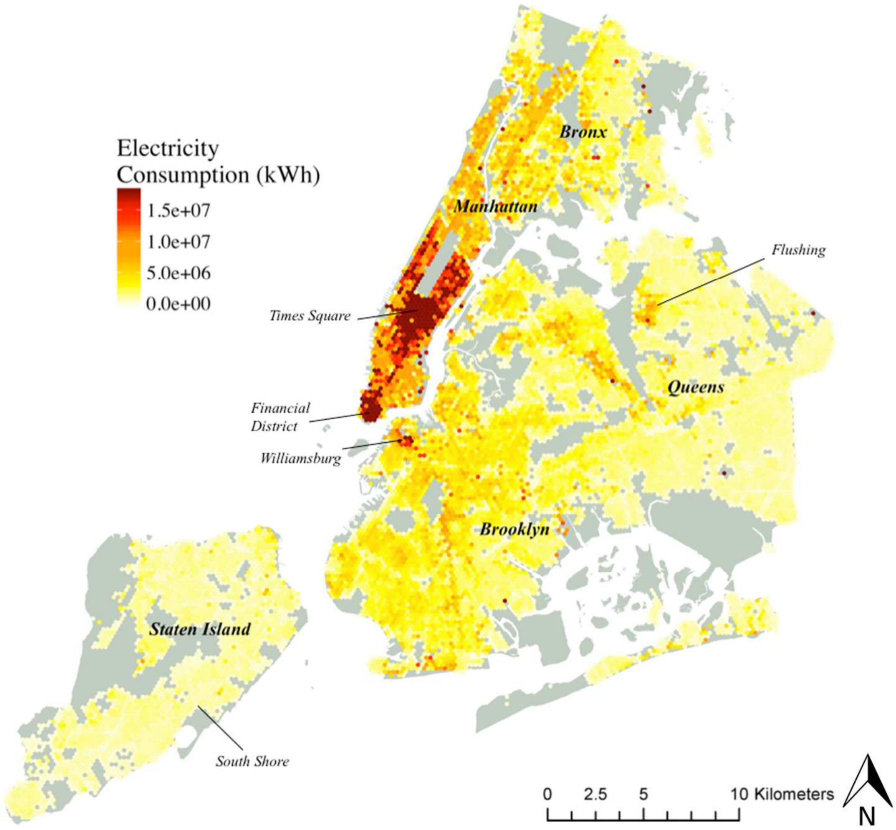

Fig. 2. Spatial distribution of the electricity consumed in NYC for one year.

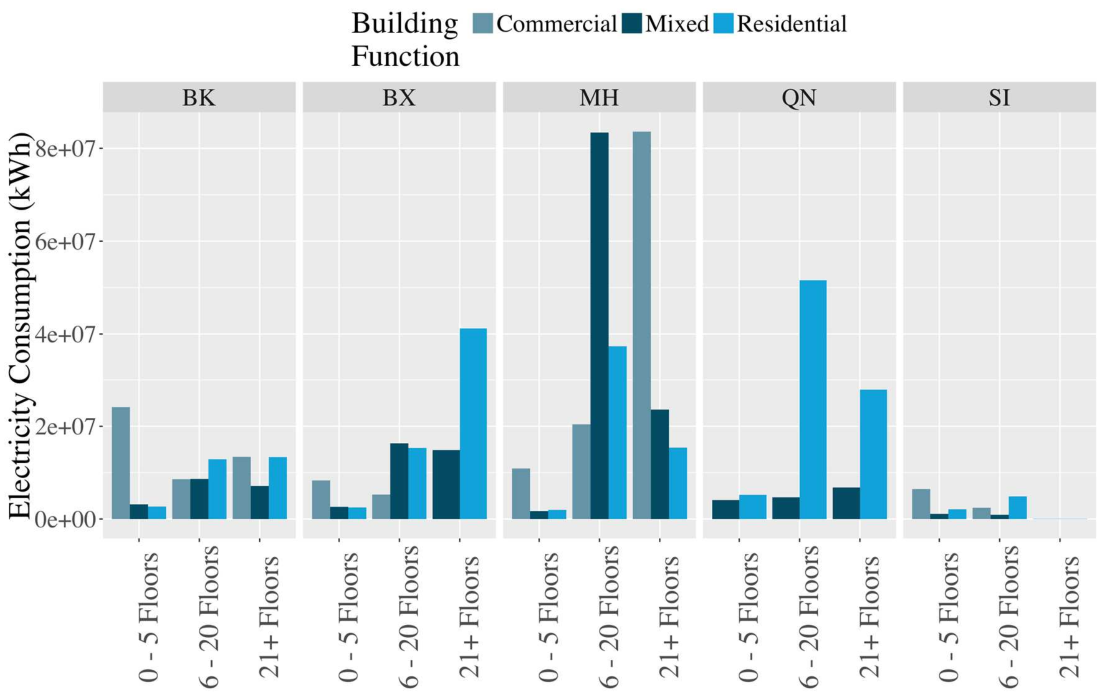

Fig. 3. Total annual electricity consumption for each building function and category.

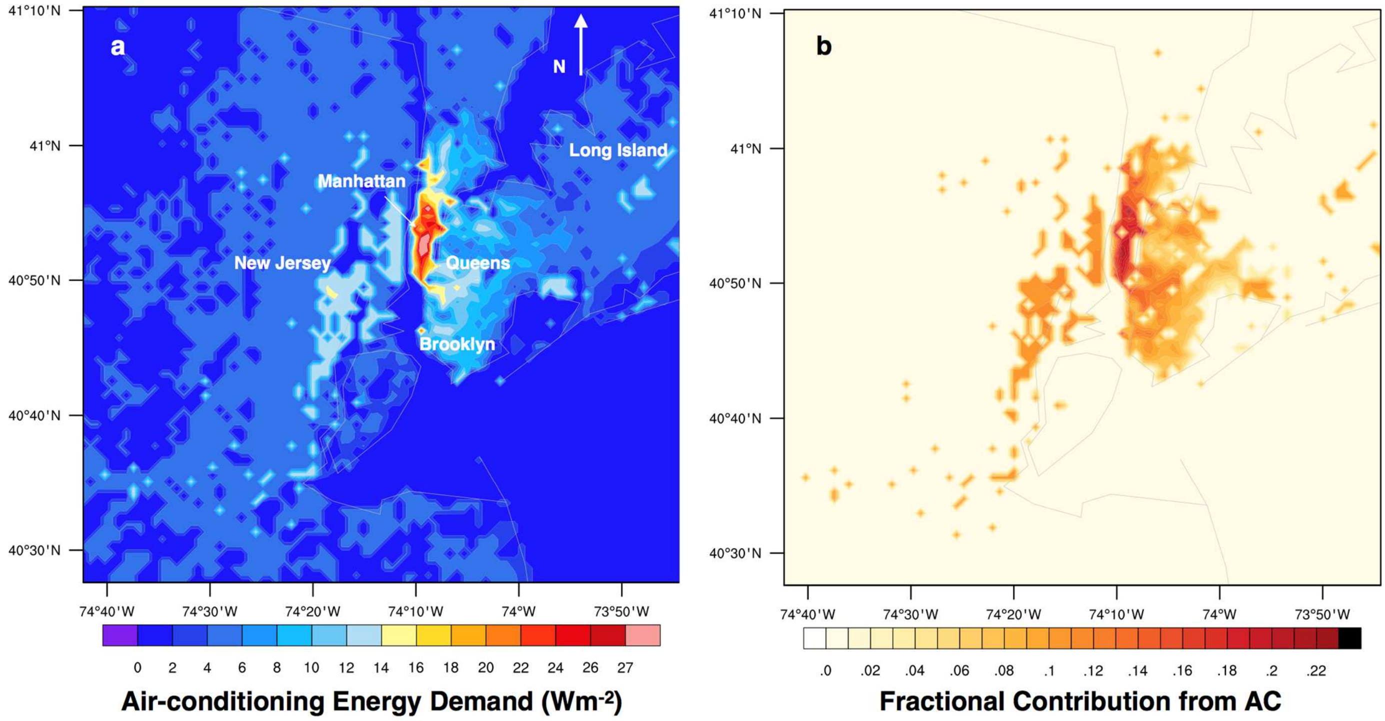

Fig. 4. (a) Average air conditioning demand for New York City (b) Fraction of energy contributed by waste heat release from the air conditioning unit to the overall available energy.

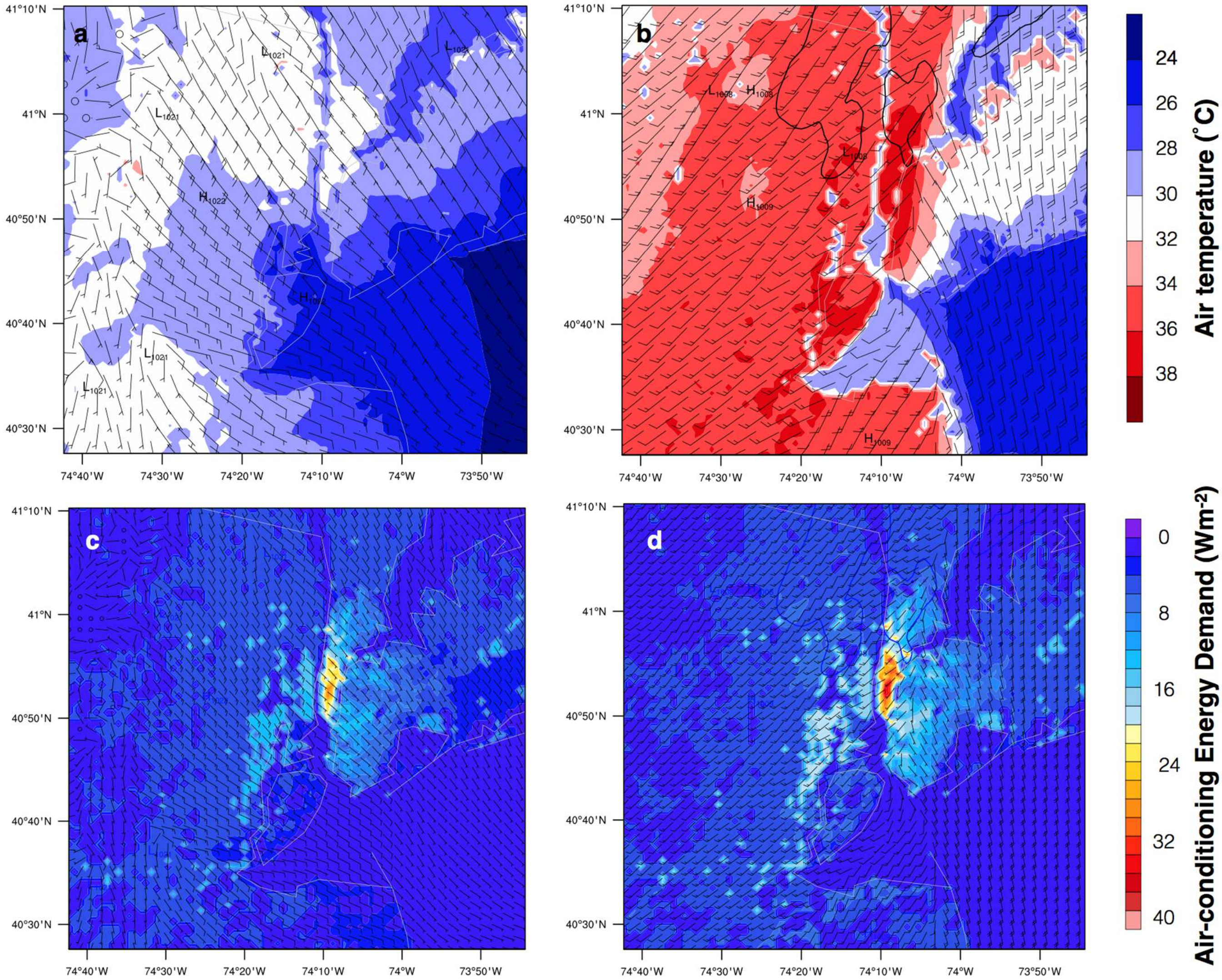

Fig. 5. (a) Air temperature during an average summer day (b) Air temperature during a heatwave day (c) Building energy use during an average summer day (d) Building energy use during a heatwave day

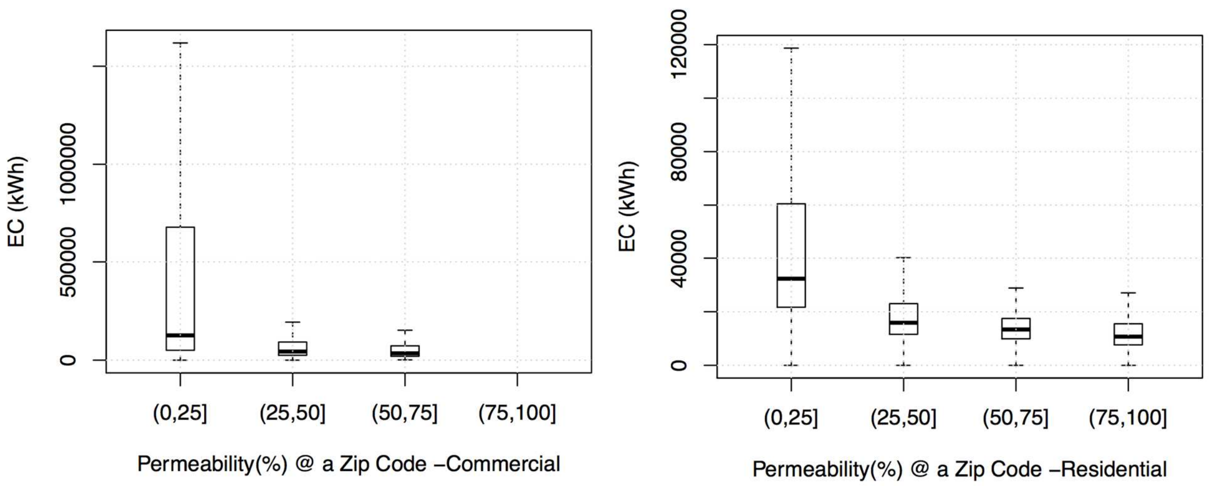

Fig. 6. Annual energy consumption and permeability fraction for commercial and residential buildings.

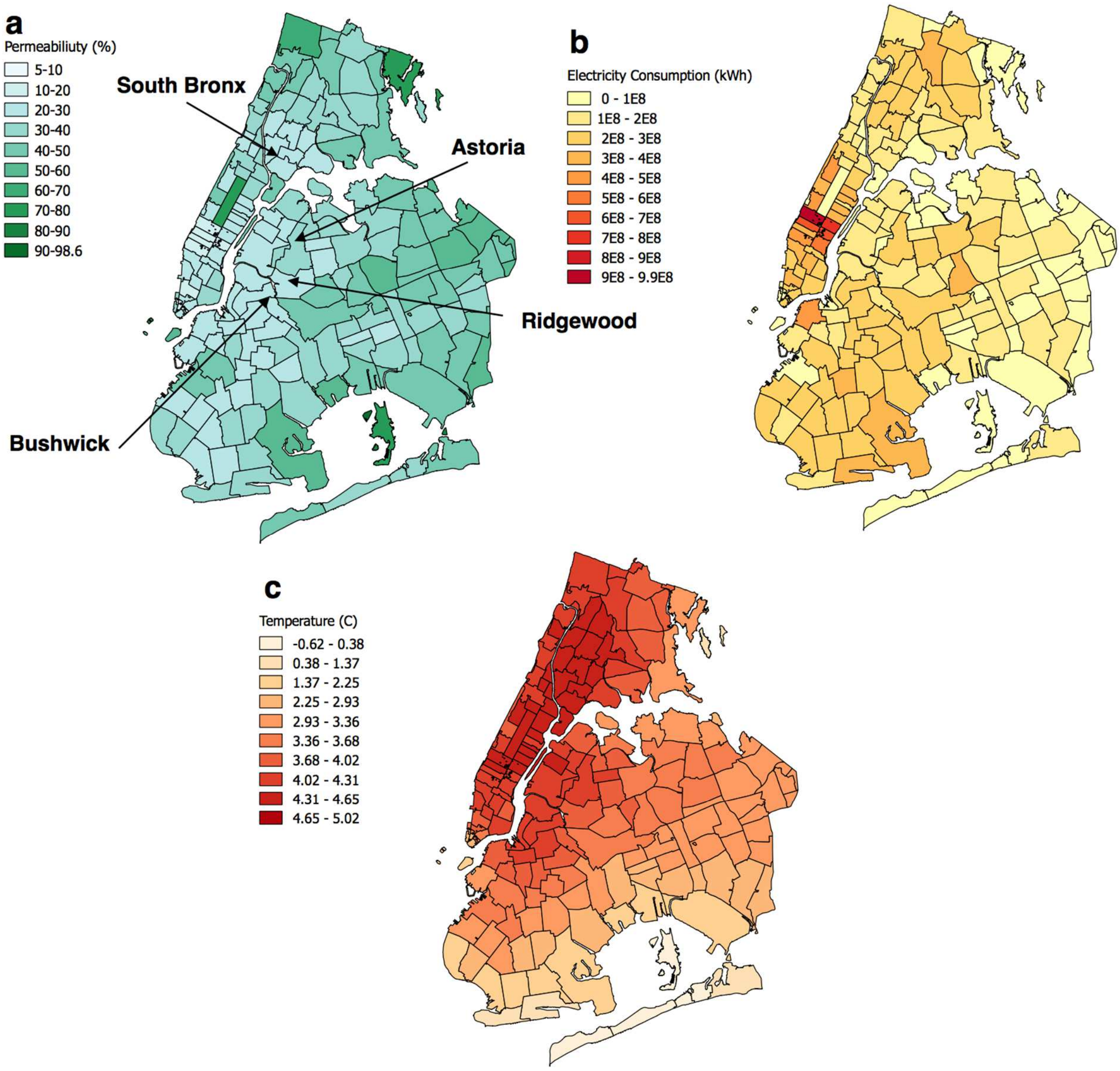

Fig. 7. Permeability coefficient, annual energy use and UHI for various zip codes in NYC.