MODELING THE URBAN HEAT ISLAND EFFECT'S IMPACT ON RESIDENTIAL HEATING AND COOLING LOADS IN THE UNITED STATES FROM 1960-2010

by

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ABSTRACT

The urban heat island effect is a phenomenon wherein the dark, hard surfaces prevalent in heavily-developed urban areas absorb and re-radiate heat, leading to measurably higher air temperatures in urban areas than in surrounding rural areas. A primary consequence of the urban heat island effect is a shift in energy consumption patterns, as increased urban air temperatures lead to greater summertime air conditioning demand and lower wintertime space heating demand.

This study takes a three-step approach to characterizing the historical extent of space conditioning demand in the United States, using these results to model residential space heating and cooling loads, and identifying the share of these quantities attributable to the urban heat island effect. First, daily average temperature records dating back to 1960 were compiled from 9,417 U.S. climate stations listed in NOAA's Global Historical Climatology Network and converted into heating and cooling degree days. Individual climate stations were then cross-referenced with regional housing characteristics such as recommended insulation levels, housing square footage, space heating fuel types, and air conditioner unit types. Then, climate stations' degree day tallies were used to model the total annual BTU or kWh demanded for space heating and air conditioning over a range of insulation levels and furnace and air conditioner efficiencies. Finally, modeled loads were averaged for climate stations inside and within a 50-mile radius beyond the boundary of the country's 20 largest metropolitan areas (ca. 2010) and compared in order to determine the relative rise or fall in load due to the urban heat island effect.

Results demonstrate: (1) a general warming trend from 1960-2010, expressed through a respective decrease and increase in heating and cooling degree days over time; (2) confirmation of the relative warming of urban areas, as they record more cooling degree days and less heating degree days than rural areas; and (3) a logical distribution of space heating and air conditioning loads for modeled homes with regards to geography. For the 20 largest metropolitan areas in 2010, the urban heat island effect was measured to reduce space heating demand by an average of 5.26-7.68 MMBTU and \$91-\$134 in associated expenditures, as well as increase air conditioning demand by 155-210 kWh and \$16-\$21 in associated expenditures. These figures suggest that the urban heat island effect has a larger impact on the bottom line for space heating than for air conditioning. By modeling individual households, these results possess a scalability that can easily be incorporated into future studies aiming to examine urban heat island-induced increases or decreases in energy expenditures, demand for electricity, natural gas, other space conditioning fuels, and/or greenhouse gas emissions for an entire city or country.

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1. *Introduction and purpose*

The urban heat island effect is the phenomenon wherein the dark, hard surfaces prevalent in urban areas, such as concrete, asphalt, and steel, absorb and re-radiate heat. This can lead to surface temperatures in cities that are 50 to 90 degrees hotter than the ambient air temperature (Berdahl and Bretz, 1997), which in turn can render urban areas between 1.8 and 5.4 degrees warmer than outlying rural or vegetated areas during the day (Oke, 1997) and more than 20 degrees warmer at night, as elevated temperatures on the hard surfaces take much longer to cool off than vegetated areas whose surfaces metabolize solar radiation (Oke, 1987).

The slight rise in urban air temperatures has many effects on various natural and man-made systems. Principal amongst these is a shift in patterns of energy consumption, with elevated urban temperatures causing an uptick in summertime air conditioning loads. In fact, a study performed by

Akbari et al. (2001) estimates that the urban heat island effect's contribution to peak electricity demand ranges from five to 10 percent. Peak electricity loads, attained during the afternoon hours of the hottest months of the year, are primarily caused by widespread air conditioner use, which sets off a cascading array of side effects that starts with the spike in expelled indoor air associated with peak air conditioner use. Urban canyons—the visual and atmospheric corridors created by the tightly-packed frontage of buildings along the streets of densely-developed downtown areas—trap and reflect this exhaust along with solar or thermal radiation to exacerbate the overall heat gain on the street level (Sailor and Fan, 2002). Urban canyons also serve to trap in amplified levels of ozone, which is formed from the reaction of tailpipe-sourced NO_x and VOCs in sunlight and is thus exacerbated by elevated air temperatures (Cardelino and Chameides, 1990). What is more, the well-documented rise in ambient air temperatures over the previous century (Jones et al., 1999) due to growing atmospheric concentrations of carbon dioxide and other heat-trapping greenhouse gases from natural and anthropogenic sources (Stott et al., 2000) will continue to raise the magnitude of the urban heat island effect in the coming decades. Because peak electricity demand coincides with the heaviest use of electric power plants, the urban heat island effect makes a considerable contribution to the release of greenhouse gas emissions sourced from electricity generation. Taking these things together, the urban heat island effect can thus be seen to incite a vicious cycle in which many major issues, such as increased air pollution and compromised human comfort, are significantly exacerbated by spurring more of the behavior that gives rise to such issues in the first place.

As the cascading fallout from the urban heat island effect begins primarily with increased energy consumption, any examination aimed at quantifying the different side-effects of the urban heat island effect must necessarily consider building energy usage. This is because patterns of indoor space conditioning are largely correlated with fluctuations in outdoor air temperature (Sailor and Pavlova, 2003). Of the many functions to which energy is applied in buildings, including lighting, cooking, and appliances, almost half of building energy consumption is tied to space heating and air conditioning (Energy Information Administration [EIA] [a], 2010). Indeed, the corollary to higher urban summertime cooling demand is that urban areas also experience lower wintertime space heating demand than rural areas. Given that residential and commercial buildings combine to consume over 40 percent of total primary energy use in the United States (EIA [b] , 2010), it is thus highly likely that the urban heat island effect contributes significantly to national levels of energy consumption, energy expenditures, and greenhouse gas emissions.

The purpose of this study is to develop a simplified building energy flow model that isolates the end-uses of space heating and air conditioning that can be used to determine the space conditioning loads that result from empirical temperature measurements. Between the residential and commercial sectors, buildings grouped in the residential sector are preferred for the goal of modeling space conditioning loads because they demonstrate far less intra-sector variability in terms of size, occupancy, energy end-uses, and function than buildings grouped in the commercial sector (Randolph and Masters, 2008). Because space conditioning loads are a function of outdoor air temperature and the heat loss of the space, comparing the modeled space conditioning loads of a standardized residential building located within and directly outside of densely-developed urban areas should tease out the shift in energy consumption attributable to the urban heat island effect. Quantifying the actual magnitude of the urban heat island effect in terms of dollars and energy consumption will display one of the major consequences of being a nation in which 80 percent of the population lives in urban areas. It will also present a basis for the direct consideration of the costs, benefits, and relative efficacies of different heat island mitigation strategies.

2. Methods

The simplified model of residential space heating and air conditioning was built according to a three-step approach: (1) characterizing the historical distribution of degree days in the United States; (2) cross-referencing degree day data with regional housing characteristics such as recommended insulation levels, average square footage, space heating fuels, and air conditioning types, and using these parameters to model household space conditioning loads; and (3) comparing average modeled space conditioning loads for a household in a given urbanized area with a household directly beyond the boundary of that urban area.

Model inputs and parameters were developed around empirical temperature readings from land surface climate stations listed on the National Oceanic and Atmospheric Administration (NOAA)/National Climatic Data Center's (NCDC) Global Historical Climatology Network-Daily (GHCN-D). The GHCN-D is an integrated database of daily climate summaries from over 75,000 stations in over 180 countries and territories that report such variables as maximum and minimum temperature, total daily precipitation, snowfall, and snow depth. Specific variables reported by a given station vary, as does a station's temporal range of coverage. Geographic coordinates of the GHCN-D stations are given in decimal degrees and provide a basis for siting temperature data.

2.1. Characterizing degree day distributions

The first step was to characterize the historical distribution of degree days in the United States. Degree days are a measure that relate outdoor air temperature to thermal indoor comfort, and represent the difference between outdoor air temperature a standard measure of comfort that must be compensated for via space heating or air conditioning. Degree days are calculated on a daily basis by subtracting the average daily temperature (in Fahrenheit) from 65 degrees. The baseline temperature of 65 degrees is widely accepted as the threshold between heating and cooling, assuming that most houses are set to maintain a 72-degree temperature on average, and that the radiative heating provided by humans, pets, and appliances make up the difference between the set temperature and the thermal conditioning the furnace or air conditioner must provide (Randolph and Masters, 2008).

Degree days are grouped either into categories of heating degree days (HDDs) or cooling degree days (CDDs) depending on if the difference between 65 degrees and the average daily temperature is positive or negative. Positive values represent HDDs, while negative values represent CDDs. For instance, if the difference between 65 degrees and the average daily temperature is positive, space heating would theoretically have to be turned on to maintain a consistent level of comfort, so the absolute value of this difference would be grouped in the HDD category. (The same holds true for negative differences, air conditioning, and CDDs).

Average daily temperatures were calculated by averaging the daily minimum and maximum temperature values recorded by stations on the GHCN-D. Stations on the GHCN-D exhibit great intra- and inter-year data coverage, in that some stations listed on the GHCN-D have complete temperature records spanning more than 175 years, while other stations might have only a few years of coverage, less than one year of coverage, or have a span of continuous coverage interrupted by a mutli-year gap. Stations were selected from the GHCN-D for use in the analysis if they met a number of criteria. First, only stations in the contiguous United States were considered. Second, stations had to have records of both minimum and maximum daily temperature. Finally, stations had to contain at least one full year of data coverage. In all, 9,417 stations listed on the GHCN-D were identified in the contiguous United States that met these criteria (Figure 1). Stations whose records contained coverage gaps within a given year were completed via linear interpolation if the gaps broke up otherwise consistent coverage in that year, i.e., if the gaps were bookended with records at the beginning and ends of the year rather than being isolated at the beginning or end of the year. This was done to limit the assumptions being made about inter-seasonal temperature variations from one year to another. Average daily temperature values for the selected stations were converted to degree days and then summed by degree day type (HDD or CDD) on an annual basis for each station.

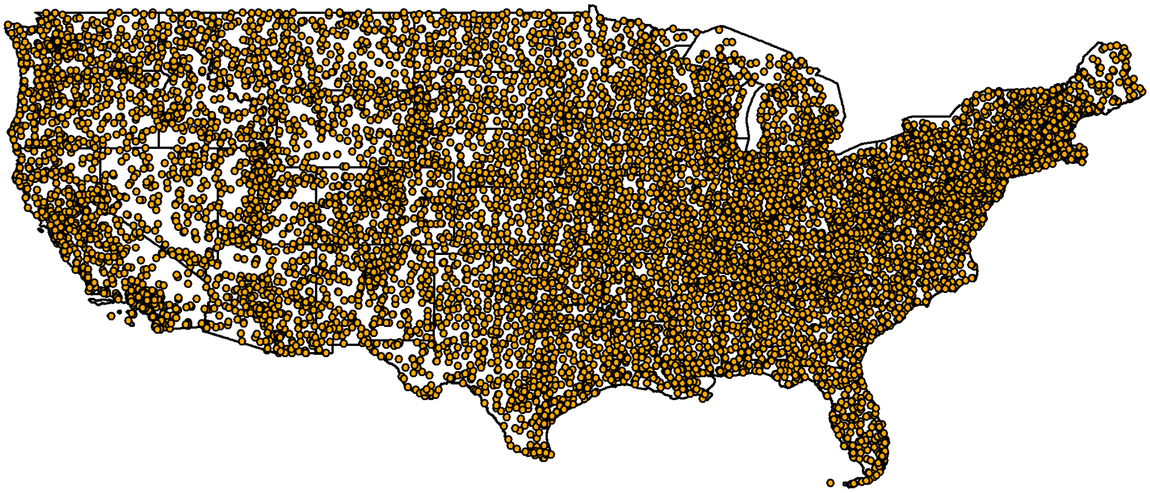


Figure 1. Distribution of GHCN-D stations (n=9,417) in the contiguous United States

After determining annual HDD and CDD tallies for each station, stations were separated based on their location relative to urbanized-area boundaries delineated by the corrected 2000 US Census (US Census Bureau [a], 2009; Figure 2). The US Census defines urban areas, including urbanized areas and urban clusters, to encompass densely settled territory consisting of core census block groups or blocks that have a population density of at least 1,000 people per square mile, surrounded by census blocks that have an overall density of at least 500 people per square mile (US Census Bureau [b], 2011). Urbanized areas differ from urban clusters on the basis of population: urbanized areas have minimum populations of 50,000, whereas urban clusters are areas that fit the aforementioned population density criteria with minimum populations of 2,500 (US Census Bureau [c], 2011). Including urban cluster stations in the "urban" category would have the effect of diluting positive temperature anomalies that exist between urban and rural areas, as many small rural towns are designated as urban clusters. Because of this study's primary focus on densely-developed metropolitan areas, stations were divided into urbanized and un-urbanized categories. For simplicity's sake, "un-urbanized" will be referred to as "rural" hereafter.

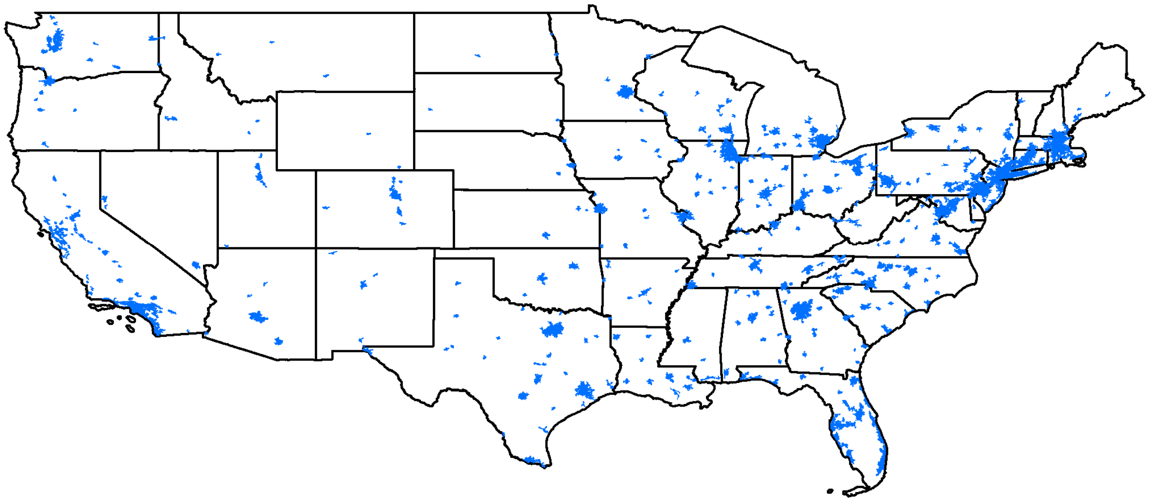


Figure 2. Distribution of urbanized areas (n=464) in the contiguous United States, from the Corrected 2000 US Census, used to sort GHCN-D stations into urbanized and un-urbanized (rural) groups.

Pooled annual tallies of urbanized and rural HDDs and CDDs were first considered on a national basis from 1960 through 2010 to test two hypotheses: that all areas of the country have experienced a general warming trend over the previous half century, and that urbanized areas have recorded higher temperatures than rural areas during this time. The former hypothesis would be expressed through an increasing trend of CDDs and a decreasing trend of HDDs over time, while the latter would be expressed through greater amounts of CDDs and lesser amounts of HDDs in urbanized areas than in rural areas. National plots were created by averaging annual station sums of HDDs and CDDs for each year from 1960 to 2010. The 9,417 GHCN-D stations in the contiguous United States were divided into urbanized and rural groups of 1,294 and 8,123 stations, respectively. However, the actual number of stations included in annual HDD and CDD averages vary from year to year, as well as by degree day type, due to inconsistencies in intra- and inter-year data coverage, and because of the fact that a number of rural stations are located at latitudes or elevations that only record HDDs (Table 1).

Average Number of Stations in Annual Averages		
Geographic Division	HDD	CDD
All Lower 48	5,024.76	5,024.76
Un-Urbanized Areas	4,362.08	4,318.06
Urbanized Areas	662.65	662.61

Table 1. Average number of stations included in annual degree day averages, by geographic division and degree day type.

2.2. Building the "typical" American house

The primary driver of space conditioning demand is the thermal equilibration of conditioned indoor air with ambient outdoor air. The rate at which this equilibration occurs is dependent not only on the differential between the desired indoor air temperature and that of the outdoor air—a quantity expressed by degree days—but also on the rate of heat transfer through the enclosure of the conditioned space (Randolph and Masters, 2008). Essentially, space conditioning can be seen as the continual replacement (or removal) of heat lost (or gained) through the equilibration of the temperature differential between indoor and outdoor air, which can be expressed in terms of the heat input needed to maintain a consistent indoor temperature in light of this heat transfer:

$$\text{(i)}\quad Q_{DELIVERED}\left(\frac{BTU}{year}\right) = DDs\left(\frac{°F - day}{year}\right) * UA_{TOTAL}\left(\frac{BTU}{hr - °F}\right) * \ 24\left(\frac{hr}{day}\right)$$

$$\text{(ii)}\quad Q_{FUEL}\left(\frac{BTU}{year}\right) = \frac{Q_{DELIVERED}}{AFUE_{FURNACE} * \eta_{DISTRIBUTION}} \quad \text{for space heating}$$

$$\text{(iii)}\quad Q_{FUEL}\left(\frac{kWh}{year}\right) = \frac{Q_{DELIVERED}}{EER_{A/C\ Unit} * \eta_{DISTRIBUTION}} \quad \text{for air conditioning}$$

where **$Q_{DELIVERED}$** is the heat content that must be provided to (or removed from) the space
DDs is the annual sum of degree days
UA_{TOTAL} is the total leakage rate (*U; U = 1/R*) of the materials that constitute the space enclosure, which is proportional to their area (*A*)
Q_{FUEL} is the total heat content of the fuel or total electricity needed to meet space heating or air conditioning demand, respectively, given the efficiencies of the furnace or air conditioning unit ($AFUE_{FURNACE}$; $EER_{A/C\ Unit}$) and that distribution system ($\eta_{DISTRIBUTION}$)
AFUE is a the annual fuel utilization efficiency, or the ratio of heat output to fuel input, of a given furnace
and **EER** is the energy efficiency ratio of air conditioning units, which is a measure of the amount of BTUs removed per watt hour of energy consumed by the unit (higher EER = higher efficiency)
(from Randolph and Masters, 2008)

While degree days serve as the primary driver of space conditioning demand, overall demand is a function of other variables such as the size of the space and the transfer of heat through its enclosure, as shown in Equation (i), as well as the efficiency of the equipment providing the conditioned air, as shown in Equations (ii) and (iii). However, just as the number of HDDs and CDDs vary according to region, so too do the building materials, construction styles, and space conditioning equipment that constitute residential buildings in different parts of the country. A focus on key regional housing characteristics such as insulation levels, square footage, space heating fuel types, and air conditioning unit types requires a model of a standardized American house that provides a foundation for the seamless interchangeability of these features independent of the degree day inputs that are processed into modeled space conditioning loads. This model's foundation is "standardized" because it is "built" using assumptions of the most common layouts and building materials found in the "typical" American house. To this end, the standardized American house model parses down all stories and internal walls into a basic cubic space with a given number of windows and doors to maintain a level of simplicity. All of these variables remain constant regardless of region in order to provide a consistent basis on which to examine the interplay between degree days, regional space enclosure characteristics and equipment efficiency, and the resulting modeled space conditioning loads. Table 2 displays the name of the materials and their R-values that were used in the construction of the space.

Once the basic structure of the standardized house model has been set, individual GHCN-D stations are cross-referenced with regional housing characteristics provided by 2005 EIA Residential Energy Consumption Survey (RECS) data (EIA [c], 2005), as well as recommended insulation levels for new homes provided by the US Department of Energy (D.O.E.) (US D.O.E., 2008). Housing characteristics provided by 2005 EIA RECS data include average household square footage (Table 3), space heating fuel types (Table 4), and air conditioning types (Table 5). These are divided into regional figures based on US Census Divisions (US Census Division [d], 2011; Figure 3). D.O.E.-recommended insulation levels for ceilings, wall cavities and sheathings, and floors (Table 6) are based on the climate region in which a given station is located (Figure 4). By filling out the standardized housing framework with important, location-dependent housing characteristics and insulation levels, a unique modeled house is essentially developed for each GHCN-D station. This serves as the main model parameter in the calculation of space conditioning loads that result from a station's annual record of HDDs and CDDs.

R-Values of Space Components			
Components (Ceiling / Wall / Floor)	Ceiling	Wall	Floor
Exterior air film	0.17	0.17	1.23
Wood Bevel Siding	No siding	0.80	No siding
Air Space (between siding and sheathing)	No air space	0.94	No air space
Air barrier/Sheathing/0.75" Plywood Subfloor	Climate Zone	Climate Zone	0.93
Cavity insulation (Fiberglass Batt)	Climate Zone	Climate Zone	Climate Zone
0.5" Drywall/Carpet + Rubber Pad flooring	0.45	0.45	3.31
Interior Air Film	0.61	0.68	0.92
Single-Pane Glass Windows - R-Value	No windows	0.91	No Windows
Square footage per window	No windows	15	No Windows
Total number of windows	No windows	4	No Windows
Total window area, ft^2	No windows	60	No Windows
Wooden Studs - R-Value	4.38	4.38	4.38
Board width, inches	2	2	2
Number of boards in stud	1	1	1
total individual stud width	2	2	2
Stud spacing, inches on-center	16	16	16
Hollow Core Wooden Door, 1.75" - R-Value	No Doors	2.17	No Doors
Square footage per door	No Doors	32	No Doors
Total number of doors	No Doors	2	No Doors
Total door area, ft^2	No Doors	64	No Doors
% Frame	12.50%	12.50%	12.50%
% Cavity	87.50%	87.50%	87.50%

Table 2. R-values and other characteristics of space components that comprise the standardized American house model. “Climate Zone” entries represent insulation components listed in Table 6 that change based on station location relative to the climate zone map in Figure 4. Total assembly R-value = 1 / (Assembly U-value) = 1 / ((U of frame x %frame) + (U of cavity x %cavity)). All values from ColoradoEnergy.org’s (2011) R-Value Table (with the exception of Wall Air Space and Floor Interior Air Film, from BuildItSolar.com [2006]).

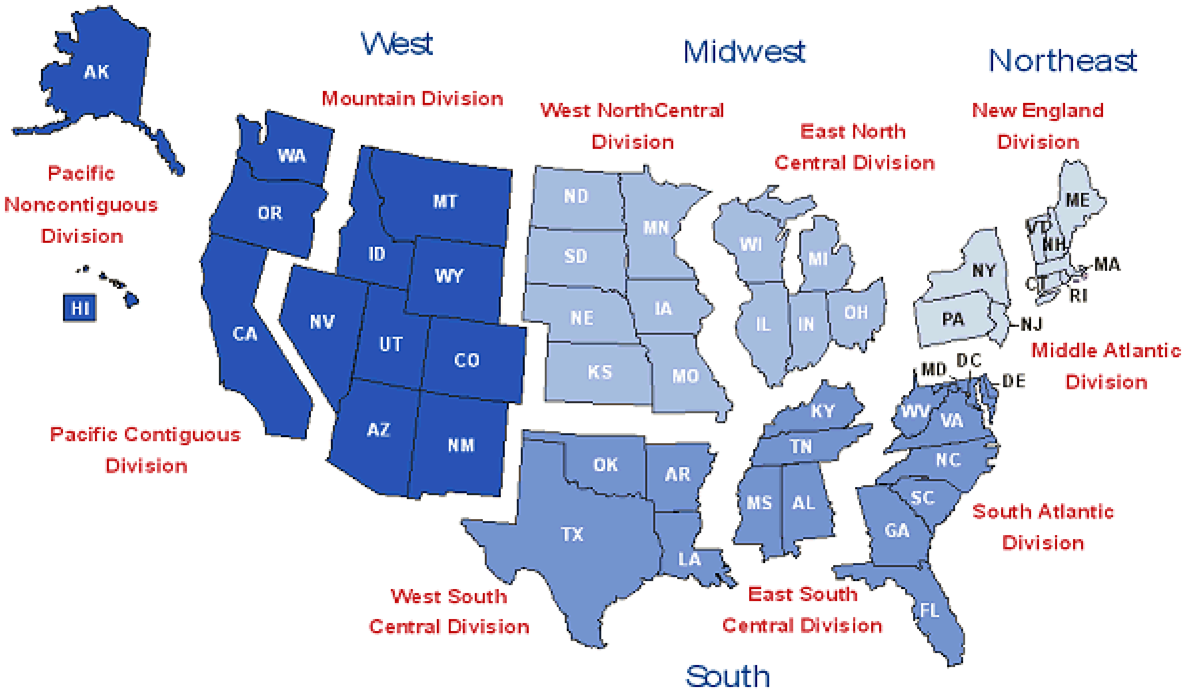


Figure 3. Map of US Census Divisions used by 2005 EIA RECS to separate regional data (Pacific Noncontiguous Division not included in this analysis; Pacific Contiguous Division referred to as Pacific). Abbreviations of Census Regions used henceforth are as follows: New England (NE); Middle Atlantic (MA); East North Central (ENC); West North Central (WNC); South Atlantic (SA); East South Central (ESC); West South Central (WSC); Mountain (MTN); and Pacific (PAC).

HOUSING SPACE AREA CHARACTERISTICS						
Census Division	number of housing units per region	average sq footage per region, ft^2	one house side length, ft	area of one wall, ft^2	**total wall area, ft^2**	**total wall area w/o windows or doors, ft^2**
New England	5,500,000	2,472	49.72	596.63	**2,386.52**	**2,262.52**
Middle Atlantic	15,100,000	2,284	47.79	573.49	**2,293.98**	**2,169.98**
East North Central	17,700,000	2,483	49.83	597.96	**2,391.83**	**2,267.83**
West North Central	7,900,000	2,281	47.76	573.12	**2,292.47**	**2,168.47**
South Atlantic	21,700,000	2,243	47.36	568.32	**2,273.30**	**2,149.30**
East South Central	6,900,000	2,137	46.23	554.73	**2,218.93**	**2,094.93**
West South Central	12,100,000	2,028	45.03	540.40	**2,161.60**	**2,037.60**
Mountain	7,600,000	1,951	44.17	530.04	**2,120.17**	**1,996.17**
Pacific	16,600,000	1,708	41.33	495.94	**1,983.74**	**1,859.74**
story height, ft	12					

Table 3. Housing space area characteristics by US Census Division, from 2005 EIA RECS.

US Census Region	NE	MA	ENC	WNC	SA	ESC	WSC	MTN	PAC
Natural Gas, %	42%	60%	74%	67%	26%	33%	47%	61%	61%
Electricity, %	5%	9%	12%	18%	62%	49%	43%	24%	28%
Heating Oil, %	44%	25%	4%	0%	2%	0%	0%	0%	0%
Wood, %	4%	2%	2%	4%	1%	3%	2%	4%	3%
Propane, %	0%	2%	6%	10%	5%	13%	7%	8%	2%

Table 4. Percent of primary space heating fuels by US Census Division, from 2005 EIA RECS.

US Census Region	NE	MA	ENC	WNC	SA	ESC	WSC	MTN	PAC
Do not have cooling, %	31%	16%	10%	4%	4%	3%	2%	41%	44%
Central system, %	15%	34%	64%	76%	81%	75%	77%	51%	39%
1 wall unit, %	25%	19%	16%	15%	6%	12%	7%	7%	14%
2 wall units, %	20%	21%	8%	4%	5%	10%	8%	0%	2%
3 or more wall units, %	11%	11%	3%	0%	4%	3%	8%	0%	0%

Table 5. Percent of air conditioner type by US Census Division, from 2005 EIA RECS.

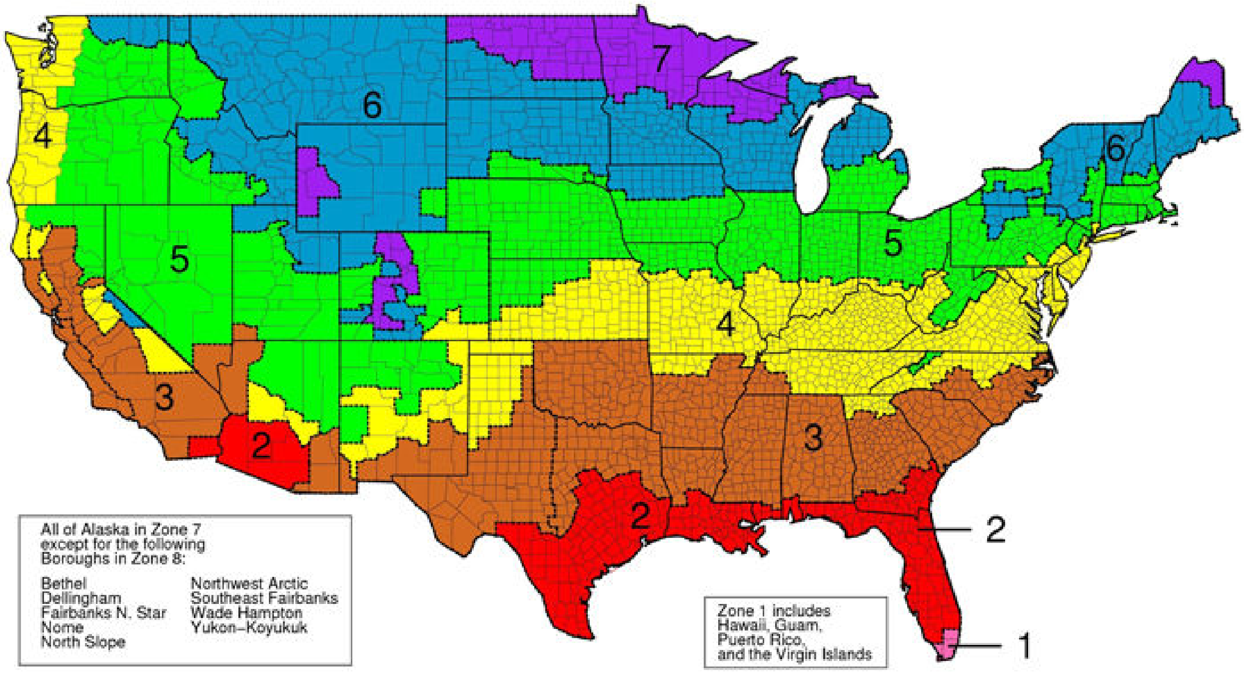


Figure 4. Map of climate zones used as the basis for D.O.E.-recommended insulation levels.

D.O.E.-Recommended Cavity Insulation, Air Barrier, and Sheathing R-Values for Ceilings, Walls, and Floors										
	ceiling cavity		ceiling air barrier		wall cavity		wall sheathing		floor cavity	
Zone	low	high	low	high	low	high	low	high	low	high
1	30	49	0	0	13	15	0	0	13	13
2	30	60	0	0	13	15	0	0	13	25
3	30	60	0	5	13	15	0	5	25	30
4	38	60	2.5	6	13	15	2.5	6	25	30
5	38	60	2.5	6	13	21	2.5	6	25	30
6	49	60	5	6	13	21	5	6	25	30
7	49	60	5	6	13	21	5	6	25	30

Table 6. D.O.E.-recommended R-values of various space components based on climate region map shown in Figure 4.

2.3. Modeling space conditioning loads

Modeled space conditioning loads are determined by first solving for the heat content needed to be delivered to or removed from the space, which is calculated in BTU per year based on the differential between indoor and outdoor air temperatures and the space's size and rate of heat loss (Equation [i]). This quantity is then corrected for the amount of conditioned air lost to through the conversion of fuels or electricity into heating and cooling, as well as losses incurred by the distribution of conditioned air to the space through leaky ductwork or conduction (Equations [ii] and [iii]; Randolph and Masters, 2008). For space heating considerations, furnace efficiencies are measured in annual fuel utilization efficiency (AFUE), which is a standard ratio of the heat output by the system to the heat input to the system by various fuels. The product of a furnace's AFUE and the distribution efficiency can be directly applied to correct the quantity of annual space heating demand to determine the annual heat content of the fuel needed to meet this demand given the heat losses of the various systems.

Air conditioning calculations are rendered slightly different because units are rated in terms of their energy efficiency ratios, or EERs. EER is a measure of the BTUs of heat a unit removes from a space (i.e., cooling provided) per watt hour (Wh) of electricity consumed by the unit. EER essentially describes a unit's rate of cooling rather than a traditional measure of efficiency, and it thus cannot correct the quantity for annual air conditioning demand to show the BTU content of heat needed to meet demand in light of efficiency losses as AFUE does for space heating. However, dividing annual air conditioning demand by EER directly quantifies the annual number of Wh consumed by a unit through the removal of a given annual amount of BTUs. Because conditioned air from window units does not enter the space through a distribution system, only the EER for central air conditioners is corrected for distribution losses.

2005 EIA RECS data pertaining to space heating fuels and air conditioner unit types allow for the regional mix of space conditioning equipment to be accurately represented in the housing models developed for individual stations. Instead of limiting the analysis to a single baseline scenario for furnace and air conditioner efficiency, space conditioning loads were modeled for a range of high to low efficiency. This helps compensate for the model's disregard of household age and the relative penetration of high efficiency furnaces and air conditioners. High and low efficiency ranges are coupled by the high and low insulation levels listed in Table 6, rendering the range of the two modeled scenarios to be high space conditioner efficiency, high insulation to low space conditioner efficiency, low insulation. Duct efficiency is set at 75% for all scenarios (Brookhaven National Laboratory, 1999). The range of furnace and air conditioner efficiencies used in the high and low scenarios are divided by fuel or unit type and shown in Table 7.

FURNACE EFFICIENCY RANGE		
Type	Minimum Federal AFUE	High Efficiency
Natural Gas	78%	97%
Electricity	97%	97%
Heating Oil	78%	89%
Wood*	40%	90%
Propane	78%	97%

AIR CONDITIONER EER RANGE		
Type	Low Efficiency	High Efficiency
Central System	10	12
Window Unit	8	10

Table 7. Furnace and air conditioner efficiency levels used in modeling low and high equipment efficiency scenarios. *Wood stoves used for low-efficiency furnace scenarios, while wood pellet furnaces are used for high-efficiency scenarios.

2.4. Urban heat island effect calculations for individual metropolitan areas

After modeling household space heating and air conditioning loads for individual GHCN-D stations, the urban heat island effect can be parsed out through direct comparisons of modeled loads for stations within urbanized areas and directly outside of urbanized areas. It is assumed that a radius of 50 miles beyond the boundaries of urbanized areas provides a distance over which increased urban air temperatures will be sufficiently attenuated, but also one over which it can be assumed that air temperatures would be held relatively constant if the urbanized area did not exist. Stations are identified within these two delineated geographic areas, and their modeled space conditioning loads are averaged to create an area-wide space conditioning load for a given year from 1960 to 2010. Subtracting the annual average space heating load of a given urbanized area from that of the area directly outside it renders the relative increase in rural space heating that results from the urban heat island effect. Similarly, subtracting the annual average cooling load of a given 50-mile radius outside an urbanized area from that of the urbanized area itself represents the relative increase in air conditioning caused by the urban heat island effect.

Expenditures resulting from space heating and air conditioning loads can be calculated for individual modeled households and for the load anomaly created by the urban heat island effect. Annual modeled space heating and air condition loads for individual households are expressed in BTU of heat content and Wh of electricity, respectively. Expenditures are thus calculated by multiplying these quantities by the per-BTU price of different space heating fuels and the per-kWh price of electricity for each US Census Division (Tables 8-11). Prices for residential natural gas, electricity, propane, and no. 2 heating oil were compiled from 2010 EIA data, while wood cord and wood pellet prices were taken from an EIA heating fuel comparison calculator (EIA [d], 2010). Average annual natural gas and electricity prices are provided for each state, and are used to calculate a regional average for individual US Census Divisions. An average 2010 price for no. 2 heating oil was calculated for each state by taking the average of weekly prices. Due to insufficient state-level data, the 2010 propane price is calculated by taking the average of weekly national average prices. Regional variations in space heating fuel types require the regional percentages of each fuel type to be multiplied by their per-BTU price and summed to create a region-wide per-BTU price for space heating.

FUEL PRICES		Census Division								
Fuel	unit	NE	MA	ENC	WNC	SA	ESC	WSC	MTN	PAC
2010 residential NG	$/Mcf	15.11	13.26	10.16	9.48	13.76	11.62	11.30	10.03	11.55
2010 residential electricity	$/kWh	0.162	0.158	0.114	0.096	0.110	0.096	0.107	0.105	0.123
2010 residential no. 2 heating oil	$/gal	2.96	3.08	2.74	NONE	3.01	NONE	NONE	NONE	NONE
wood	$/cord	200	200	200	200	200	200	200	200	200
wood pellets	$/ton	250	250	250	250	250	250	250	250	250
2010 residential propane	$/gal	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59

Table 8. Fuel prices used in space conditioning expenditure calculations, divided by US Census Region.

UNIT CONVERSIONS		
fuel	heat content of fuel	
natural gas	1,025	Btu/cf
	1,025,000	**Btu/Mcf**
electricity	**3,412**	**Btu/kWh**
heating oil	6,287,000	Btu/Barrel
	149,690.48	**Btu/Gallon**
wood (cord; pellets)	**22,000,000**	**Btu/Cord**
	16,500,000	**Btu/Ton pellets**
propane/LPG	3,836,000	Btu/Barrel
	91,333.33	**Btu/Gallon**

Table 9. Conversion factors used to express fuel prices in terms of heat content (BTU).

FUEL PRICES PER BTU ($/BTU)	Census Division								
fuel	NE	MA	ENC	WNC	SA	ESC	WSC	MTN	PAC
NG	$0.000015	$0.000013	$0.000010	$0.000009	$0.000013	$0.000011	$0.000011	$0.000010	$0.000011
electricity	$0.000048	$0.000046	$0.000033	$0.000028	$0.000032	$0.000028	$0.000031	$0.000031	$0.000036
no. 2 heating oil	$0.000020	$0.000021	$0.000018	NONE	$0.000020	NONE	NONE	NONE	NONE
wood	$0.000009	$0.000009	$0.000009	$0.000009	$0.000009	$0.000009	$0.000009	$0.000009	$0.000009
wood pellets	$0.000015	$0.000015	$0.000015	$0.000015	$0.000015	$0.000015	$0.000015	$0.000015	$0.000015
propane	$0.000028	$0.000028	$0.000028	$0.000028	$0.000028	$0.000028	$0.000028	$0.000028	$0.000028

Table 10. Fuel prices used in space conditioning expenditure calculations in terms of heat content, separated by US Census Region. Per-BTU prices were calculated by multiplying fuel prices found in Table 8 by the conversion factors found in Table 9 to express prices in terms of heat content.

Space Heating Fuel Prices per BTU	
Census Division	Price per BTU
NE	$0.0000179
MA	$0.0000178
ENC	$0.0000141
WNC	$0.0000147
SA	$0.0000254
ESC	$0.0000217
WSC	$0.0000209
MTN	$0.0000160
PAC	$0.0000182

Table 11. Regional Per-BTU space heating fuel prices calculated for each Census Division. Overall regional prices were determined by summing the products of a given space heating fuel's regional price-per-BTU found in Table 10 by the regional percentage of that space heating fuel type found in Table 4. Regional per-kWh prices for electricity used in determining air conditioning expenditures are taken directly from Table 8.

The model is set up so that these calculations can be performed on an annual basis for any of the 464 urbanized areas listed in the Corrected 2000 US Census located in the contiguous United States. For the sake of brevity, and for the ease of presenting results, however, only the 20 largest metropolitan areas in the United States for the year 2010 are examined herein (Figures 5 and 6).

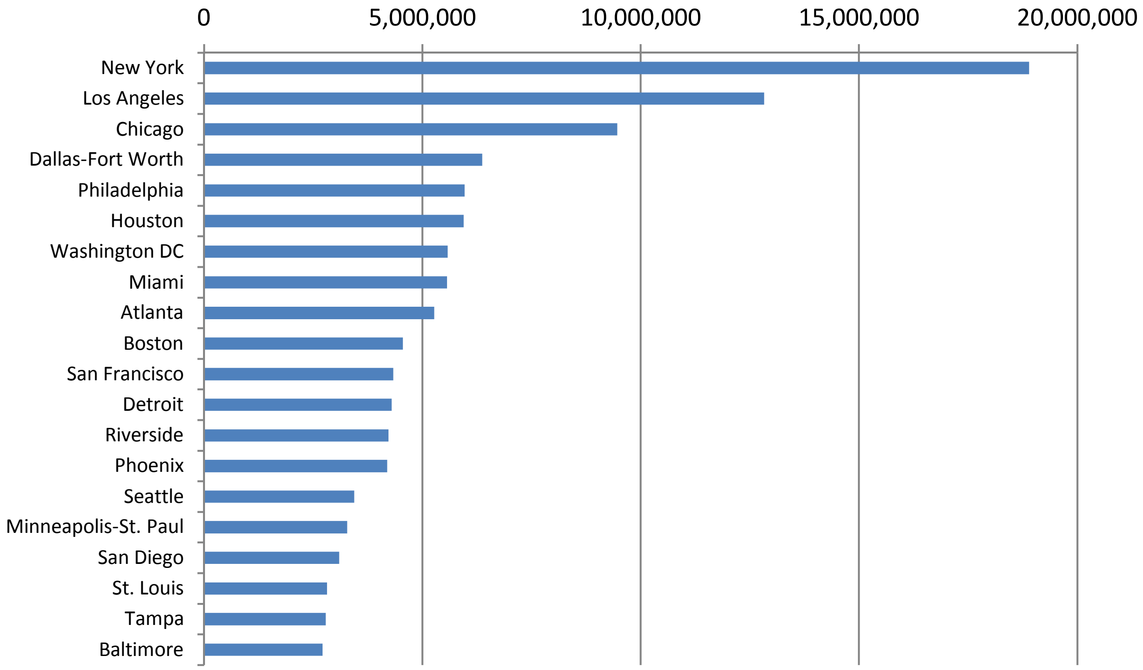


Figure 5. The 20 largest metropolitan statistical areas by population, according to 2010 US Census.

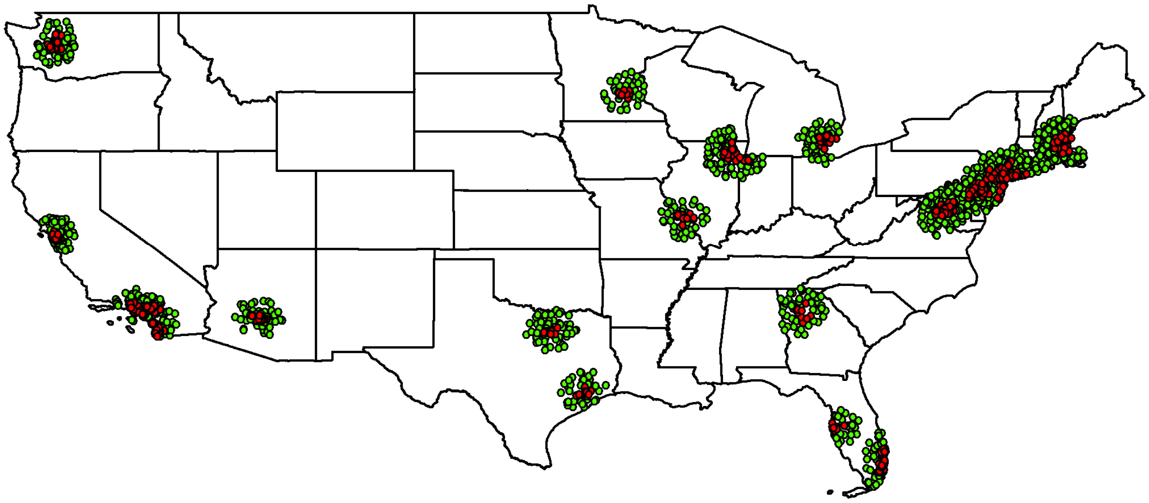


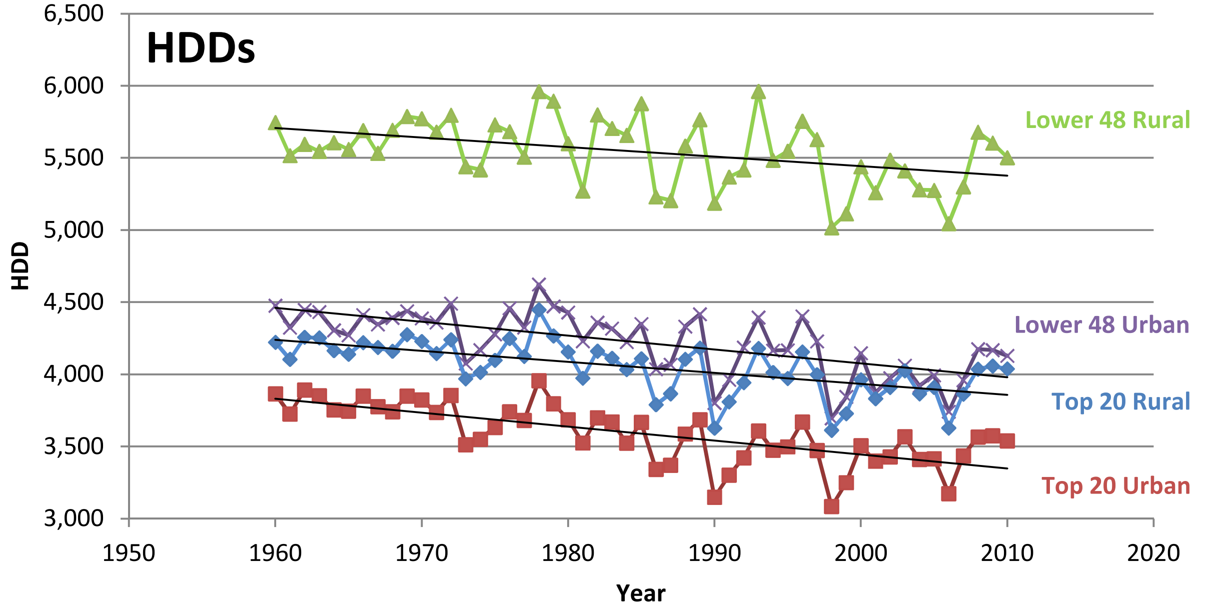
Figure 6. GHCN-D stations located inside (red) and within a 50-mile radius of urban boundaries (green) of 20 largest metropolitan statistical areas by population according to 2010 US Census.

3. Results

Results are organized and reviewed as follows: (1) plots of the historical distribution of HDDs and CDDs in the contiguous United States; and charts displaying the modeled ranges of (2) space heating and (3) 2010 air conditioning demand and expenditures for individual households in the 20 largest metropolitan areas, and the share of these quantities attributable to the urban heat island effect.

3.1. Historical distribution of degree days from 1960 – 2010

Figure 7 contains graphs of the historical distribution of HDDs and CDDs in, respectively, in the contiguous United States from 1960 to 2010. Each graph contains four plots of the degree day variable separated into groups of urbanized and rural areas throughout the entire contiguous United States (Lower 48 Urban and Rural), as well as areas within and directly outside of the urban boundary of the 20 largest metropolitan areas (Top 20 Urban and Rural).



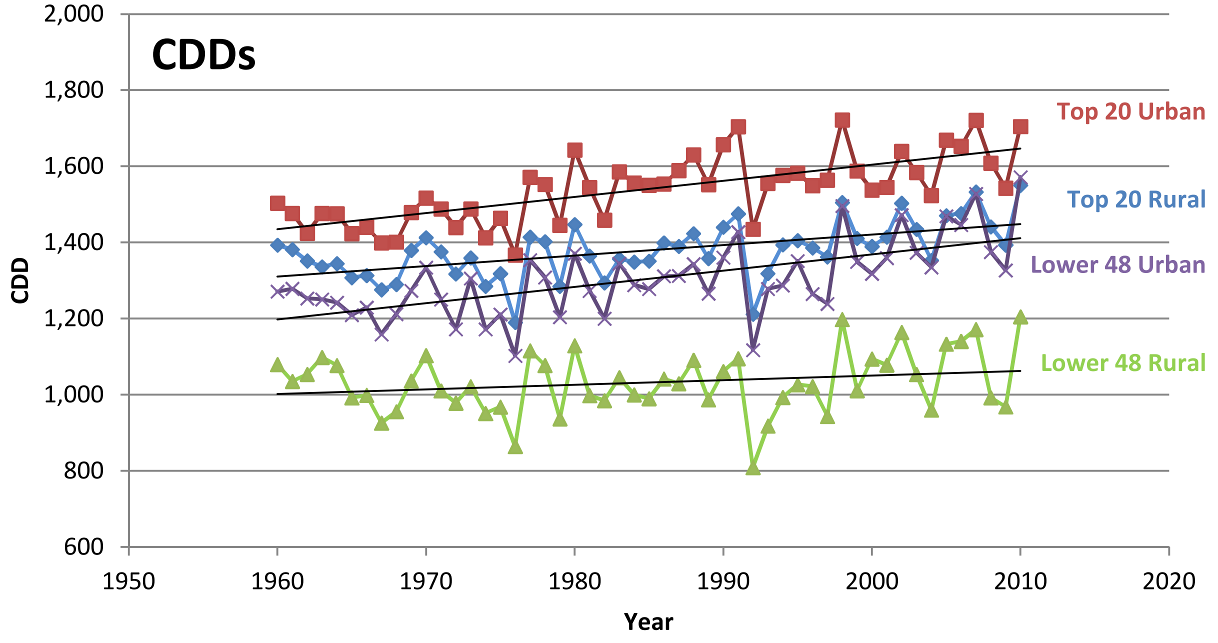


Figure 7. Graphs of annual average HDDs and CDDs from 1960-2010 divided into individual plots of urbanized and rural areas over the entire contiguous United States (Lower 48 Urban and Rural), as well as areas inside and within a 50-mile radius from the boundary of the 20 largest metropolitan areas in the United States (Top 20 Urban and Rural). Plots display a general trend of warming temperatures over the time period, in that annual records of HDDs and CDDs are decreasing and increasing, respectively, and also confirm assumptions regarding the positive temperature anomaly between urbanized and rural areas.

Figure 7 confirms the hypotheses relating to the expression of general climate warming trends in annual average degree day counts: specifically, that HDDs have decreased and CDDs have increased over time. Figure 7 also confirms the hypothesis that urbanized areas have recorded more CDDs and less HDDs than rural areas, with the plots of Top 20 CDDs and Lower 48 HDDs occupying the highest counts on their respective graphs. What the plots interestingly demonstrate however is that rural areas within a 50-mile radius of the top 20 metropolitan areas' boundaries are warmer than all urbanized areas aggregated throughout the contiguous United States. This suggests that the urban heat island effect may be amplified on some non-linear or logarithmic scale depending on a given urbanized area's relative level of development, in that heavily urbanized areas are demonstrably projecting heat-island related gains in air temperature well beyond their boundaries.

What is more, the absolute values of average HDD records were two to three times more than that of average CDD records over the entire period from 1960 to 2010 (Table 12). This is partially explained by the presence of GHCN-D stations in locations where relatively few urbanized areas are found, especially at high elevations and the interior and northern regions of the country (See Figure 1). The extent to which warming trends are being expressed in the growth of degree day records, as represented by the slopes of plot trend lines (Table 13), are commensurately disparate: the trend of HDD reduction is occurring at more than twice the rate of CDD addition for both urbanized and rural areas. Urbanized areas are also found to be warming at a faster rate than rural areas, judging from their greater annual reduction of HDDs and greater annual addition of CDDs.

HDDs		**ave**	min	max	stdev
Top 20	Urban	**3,589.2**	3,084.7	3,956.3	203.8
	Rural	**4,047.8**	3,613.3	4,448.1	182.6
Lower 48	Urban	**4,220.4**	3,695.1	4,623.0	216.4
	Rural	**5,541.3**	5,017.3	5,961.8	231.2

CDDs		**ave**	min	max	stdev
Top 20	Urban	**1,540.8**	1,367.5	1,722.0	89.3
	Rural	**1,379.3**	1,190.3	1,550.7	73.7
Lower 48	Urban	**1,304.5**	1,102.6	1,571.6	99.1
	Rural	**1,031.9**	809.1	1,205.3	80.9

Table 12. Summary statistics for Figure 7 degree day plots. Comparisons of Top 20 versus Lower 48 breakdowns show that rural areas within a 50-mile radius of a top 20 metropolitan area are warmer than urbanized areas aggregated on a contiguous national scale. Average annual HDD records are also around two to three times greater than average annual CDD records.

Geographic Scale	HDD		CDD	
	Urban	Rural	Urban	Rural
Lower 48	-9.62	-6.61	4.26	1.21
Top 20	-9.67	-7.62	4.25	2.75

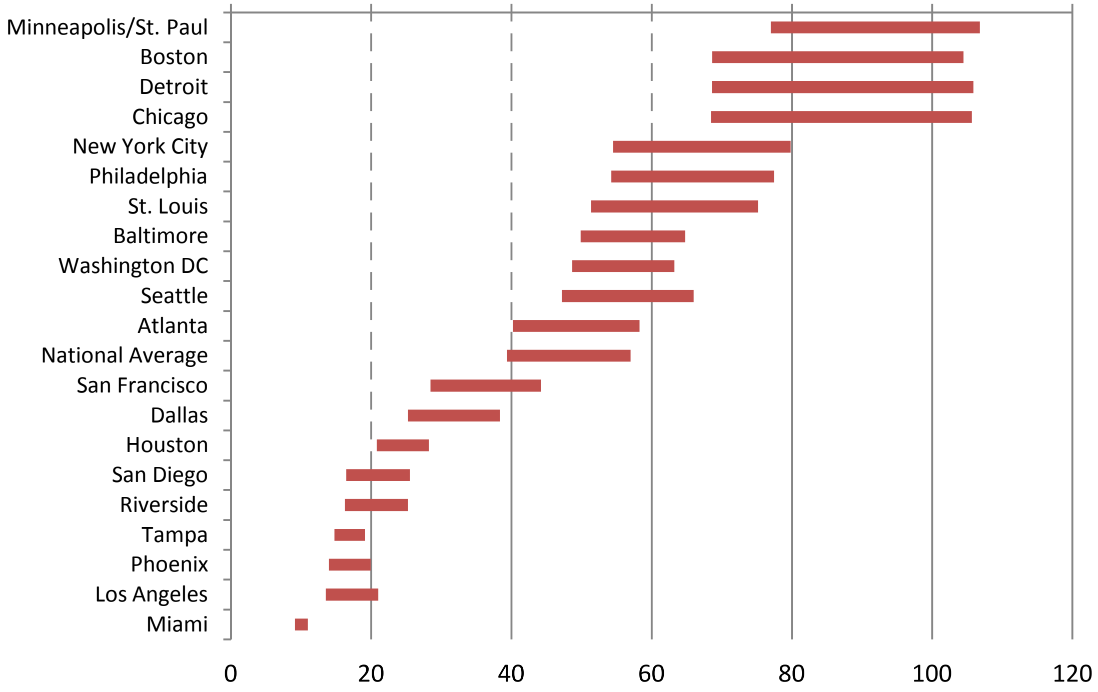
Table 13. Slopes of linear trend lines for Figure 7 degree day plots. Values indicate a general trend of warming from 1960 – 2010, as well as a trend of HDD reduction that is occurring at more than twice the rate of CDD addition for both urban and rural areas. Urban areas are also found to be warming at a faster rate than rural areas, judging from their greater annual reduction of HDDs and greater annual addition of CDDs.

The next two sections of results are organized by first displaying the range of overall 2010 space heating and air conditioning loads and expenditures for modeled houses located within the boundaries of the 20 largest metropolitan areas. Then, the share of modeled space heating and air conditioning loads and expenditures attributable to the urban heat island effect is displayed by taking the difference between houses located within and up to 50 miles beyond the boundary of a given metropolitan area.

3.2. Space heating

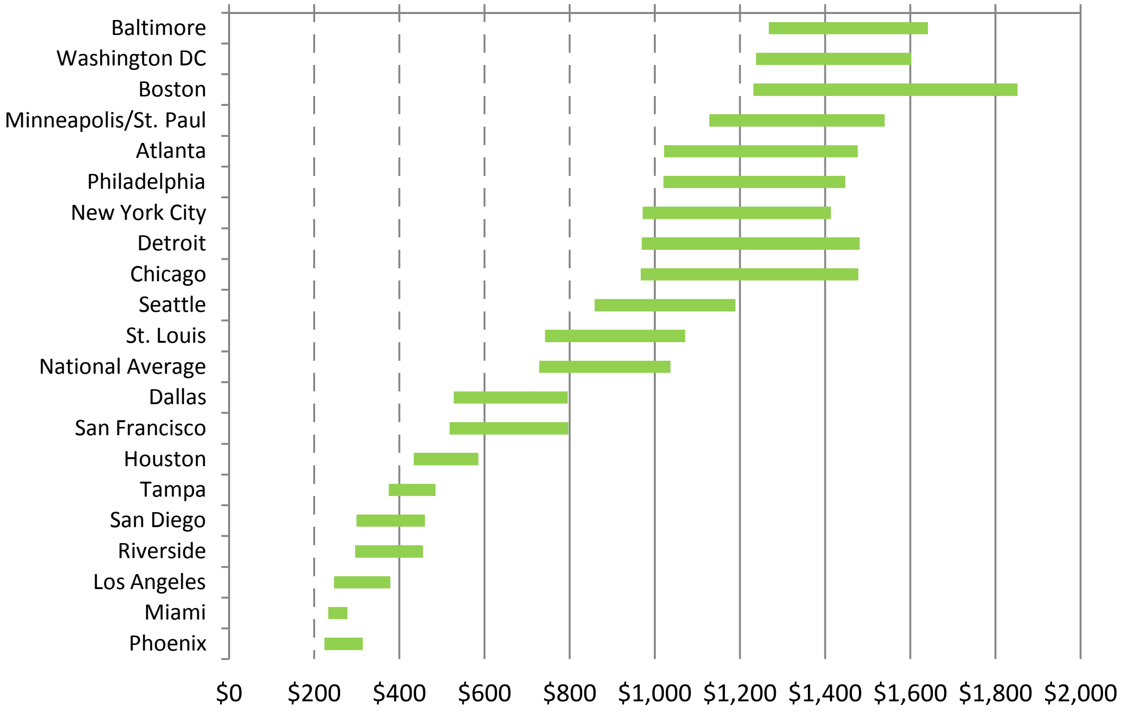
3.2.a. 2010 Space Heating Demand (MMBTU/yr/home)

Range of High Insulation/High Furnace ɳ to Low Insulation/Low Furnace ɳ



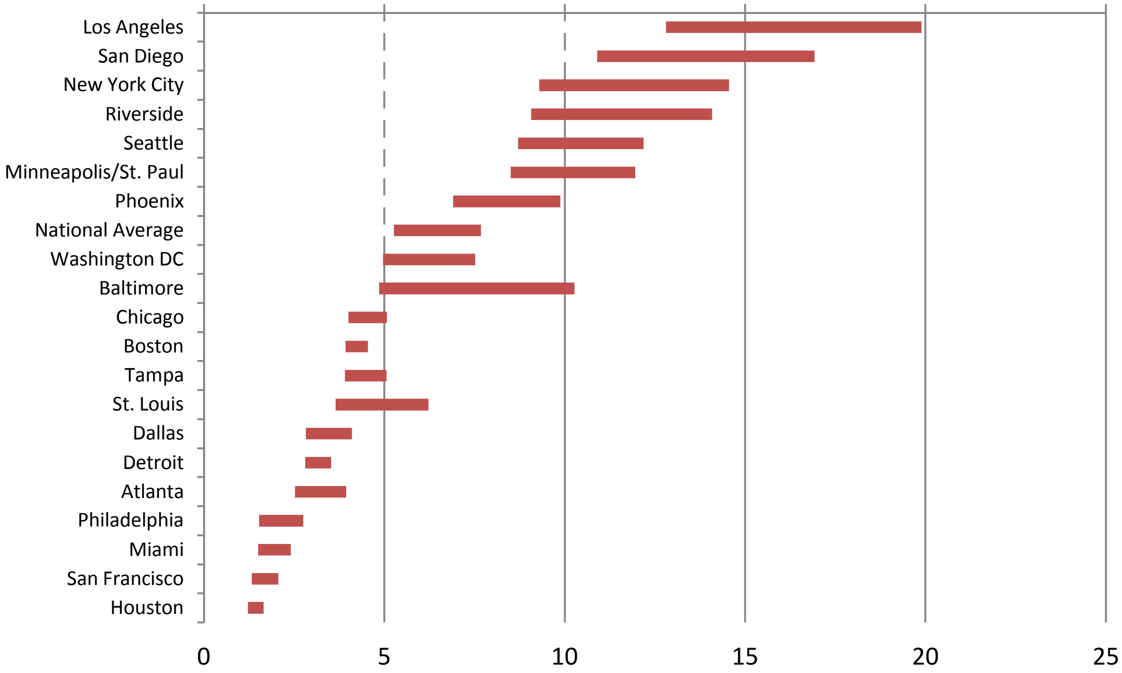
3.2.b. 2010 Space Heating Expenditures ($/yr/home)

Range of High Insulation/High Furnace η to Low Insulation/Low Furnace η



3.2.c. 2010 Reduction in Space Heating Demand (MMBTU/yr/home) Relative to Outlying Rural Areas due to Urban Heat Island Effect

Range of High Insulation/High Furnace η to Low Insulation/Low Furnace η



***3.2.d.* 2010 Reduction in Space Heating Expenditures ($/yr/home) Relative to Outlying Rural Areas due to Urban Heat Island Effect**

Range of High Insulation/High Furnace Ƞ to Low Insulation/Low Furnace Ƞ

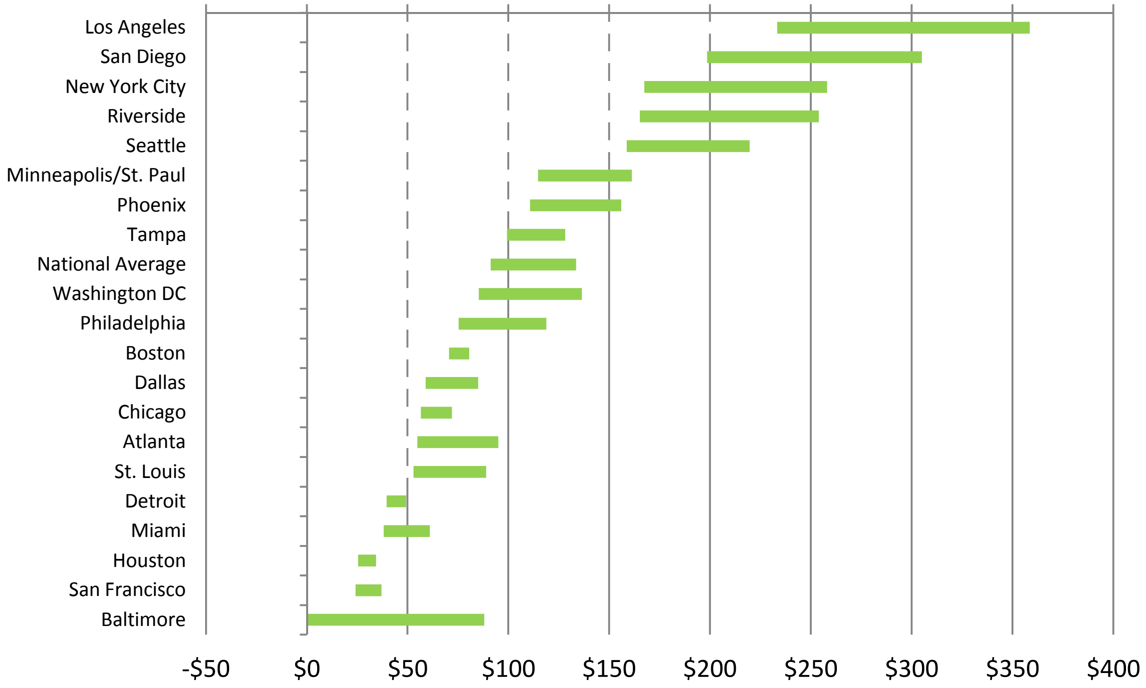


Chart 3.2.a. displays reasonably expected results in terms of the range of space heating loads of modeled homes in given metropolitan areas, with the cities displaying the five largest levels of 2010 space heating demand located in the Northeast and Upper Midwest, and the cities showing the lowest levels occurring in the South and Coastal California. Minneapolis/St. Paul recorded the highest 2010 household space heating load, with between 77 and 107 MMBTUs of demanded heat. However, when demand is translated into expenditures (Chart 3.2.b.), the Atlantic Coast cities of Baltimore, Washington DC and Atlanta break into the top five, with Baltimore recording the highest annual space heating expenditures of between $1,268 and $1,642. This is explained by the fact that the price for electricity in the South Atlantic Census Division, in which all of the urbanized stations in these three metropolitan areas are located, is at least one-and-a-half times greater than the price of all other space heating fuels in that division on the basis of heat content (Table 10), and that more than 60% of space heating in the South Atlantic division is provided by electric furnaces (Table 4). As such, the combined regional per-

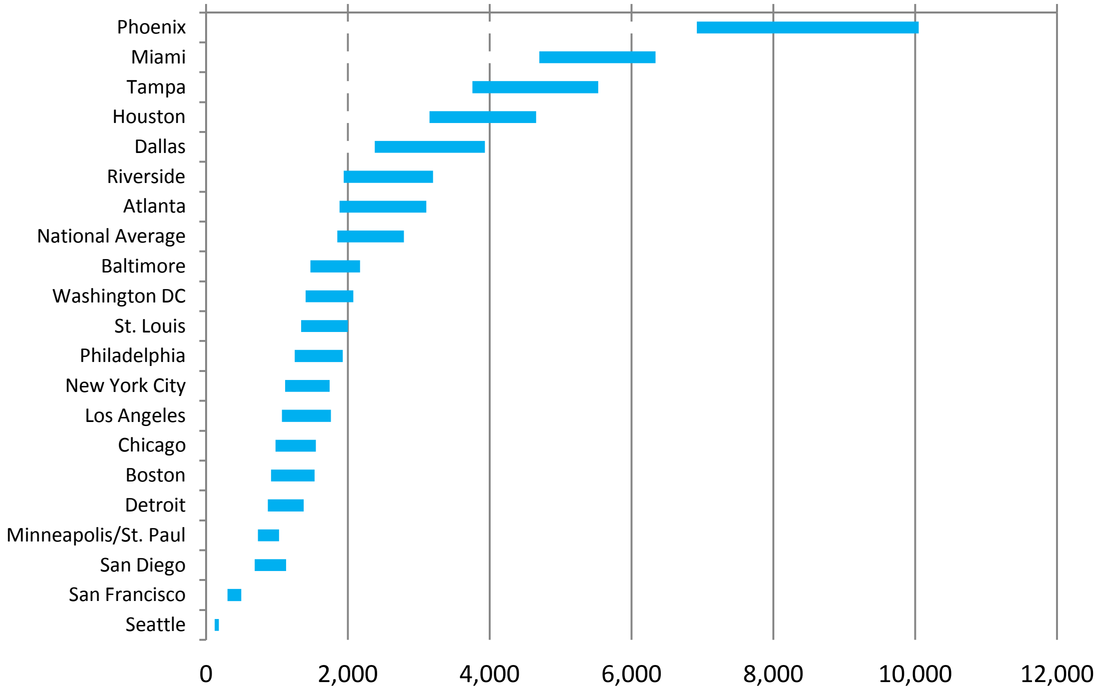
BTU price for space heating is more expensive in the South Atlantic division than all other divisions (Table 11).

Results for urban heat island-induced reductions in urban space heating loads and expenditures (Charts 3.2.c. and 3.2.d., respectively), however, show no clear qualitative correlation with geography. This is not only evidenced by the fact that the cities that recorded the five highest levels of overall demand in 2010 are scattered randomly throughout the chart, but especially because homes in the Pacific Coast cities of Los Angeles, San Diego, Riverside and Seattle are modeled to have four of the five highest levels of urbanization-related reductions in space heating demand. This is most likely attributable to the fact that air temperature in these coastal cities tends to remain much closer to 65 degrees than areas further inland, which experience much greater temperature variations than at the coast. As such, Los Angeles records the largest heat island-related household reduction in space heating demand (between 12.81 and 19.89 MMBTUs) and expenditures (between $233 and $538).

3.3. Air conditioning

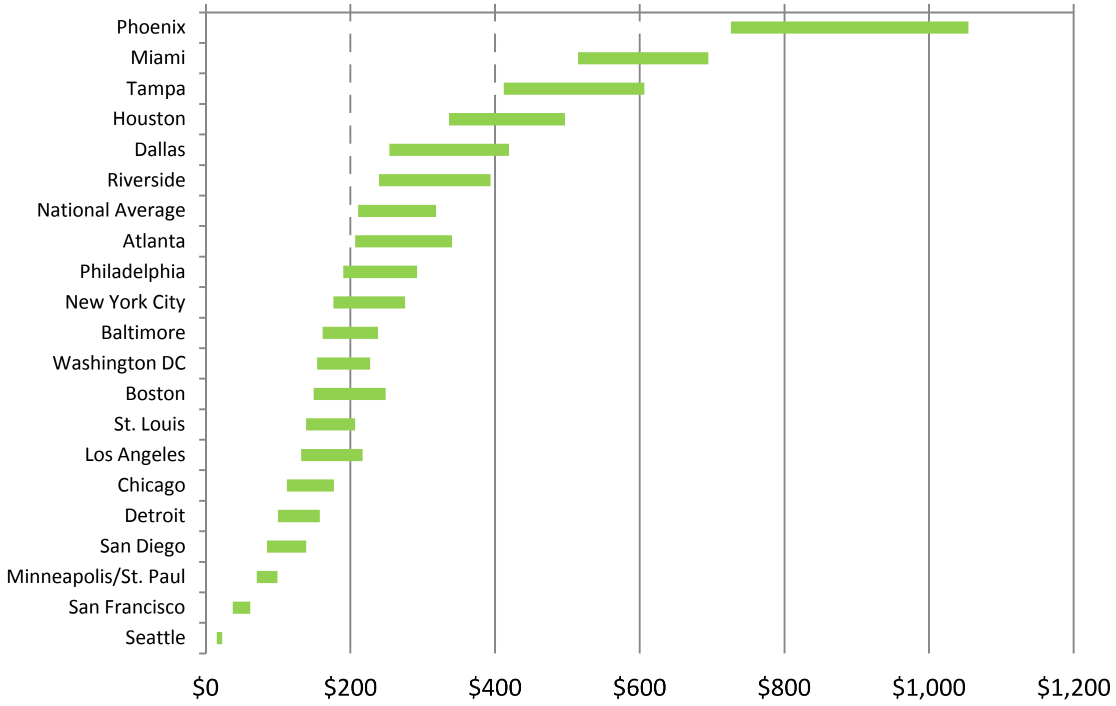
3.3.a. 2010 Air Conditioning Demand (kWh/yr/home)

Range of High Insulation/High Furnace η to Low Insulation/Low Furnace η



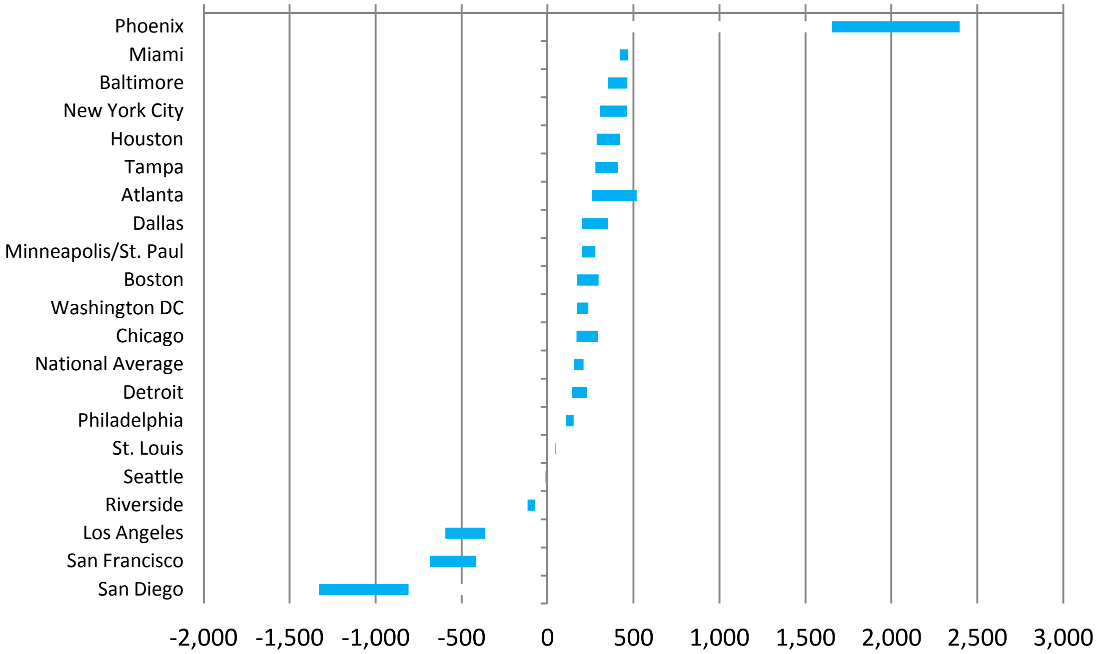
3.3. b. 2010 Air Conditioning Expenditures ($/yr/home)

Range of High Insulation/High Furnace η to Low Insulation/Low Furnace η



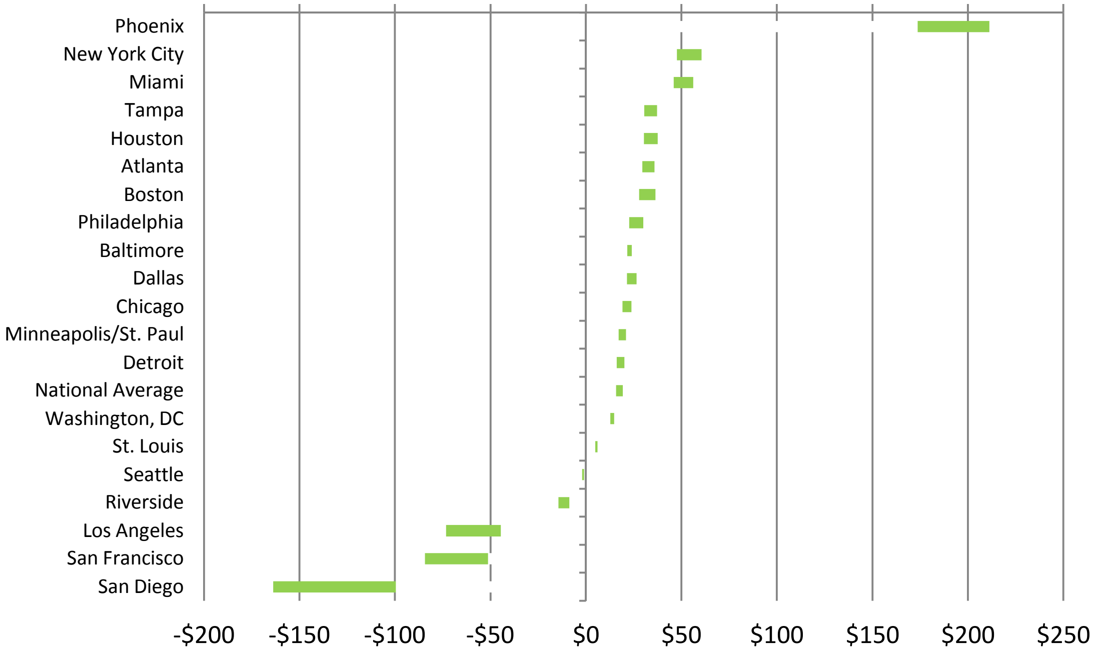
***3.3.c.* 2010 Increase in Air Conditioning Demand (kWh/yr/home) Relative to Outlying Rural Areas due to Urban Heat Island Effect**

Range of High Insulation/High Furnace η to Low Insulation/Low Furnace η



***3.3.d.* 2010 Increase in Air Conditioning Expenditures ($/yr/home) Relative to Outlying Rural Areas due to Urban Heat Island Effect**

Range of High Insulation/High Furnace η to Low Insulation/Low Furnace η



Charts 3.3.a. and 3.3.b. display reasonably expected results in terms of the range of air conditioning loads and expenditures modeled for homes in the 20 largest metropolitan areas, with the five largest figures for 2010 demand and expenditures located in Southern cities, and the lowest occurring in Upper Midwestern and Pacific Coast cities. Many of the cities' 2010 air conditioning expenditures fell in the vicinity of \$100 to \$300; however, these cities exhibit a large disparity with Phoenix, which recorded 6,921 to 10,051 kWh of air conditioning demand equating to \$726 to \$1,054 in related expenditures.

The difference between the extremes of Phoenix and the moderate demands of most other top 20 cities is exacerbated through the consideration of Charts 3.3.c. and 3.3.d. A house located inside metro Phoenix is modeled to demand 1,655 to 2,397 kWh more in electricity—and pay \$174 to \$211 for it—than a house directly outside of it. This is compared with an average increase in demand and expenditures for the top 20 cities with positive anomalies of 307 to 446 kWh and \$34 and \$41, respectively. Cities with negative anomalies display the same impact of the temperate Pacific coast: because air temperature in coastal cities hovers around 65 degrees, subtracting modeled air conditioning demand for urban areas from that of adjacent rural areas will lead to negative urban heat island indicators, as these rural areas are further inland and are thus subject to more extreme variations in temperature.

4. Discussion

Overall, results for historical degree day distributions and modeled space condition loads demonstrated the things that were anticipated of them: that air temperature has been rising over time; that, averaged on a national scale, urbanized areas are warmer than rural areas; and that cities located in hot areas use significantly more air conditioning than cities in cold ones, and vice versa. These expected results were best served by this study through verifying their validity and quantifying the extent of such assumptions. By modeling individual households, these results possess a scalability that can easily be incorporated into future studies aiming to examine urban heat island-induced increases or decreases in energy expenditures, demand for electricity, natural gas, other space conditioning fuels, and/or greenhouse gas emissions for an entire city or country. This model could also be scaled to serve in studies on the impact of urban heat islands on the stability of the electric power grid.

Of the unexpected outcomes that were found in the results, a number of them could be considered the true teachings of this study. For instance, a far greater number of HDDs have been recorded in the contiguous United States than CDDs. The average modeled quantities of overall space heating demand and expenditures (as well as those quantities caused by the urban heat island effect) are as such far greater than the average modeled quantities for air conditioning (Table 14). This disparity suggests that the higher absolute rates of HDD reductions than CDD additions in both urbanized and rural areas in the Lower 48 (Table 12) is simply an expression of the general warming trend within the larger pool of demand indicators (i.e., degree days). Another unexpected outcome was the replacement of the two metropolitan areas with highest modeled space heating demand, Minneapolis/St. Paul and Boston, with two other cities, Baltimore and Washington DC, on the list of space heating expenditures. This result hinted at the model's sensitivity to EIA's assignment of space heating, air conditioning, and square footage characteristics on the basis of US Census Divisions. If stations in these two urbanized areas were cross-listed with characteristics of the Middle Atlantic Census Division, with 9% of space heating demand met through electric furnaces instead of the 62% of the South Atlantic division (Table 4), there is a good chance that the top five cities for overall space heating expenditures would closely replicate that of overall demand. Experimenting with high-resolution housing characteristic data, perhaps those provided on a city-by-city basis by the US Census' American Housing Survey (AHS), would help to verify the accuracy of such a regional approach.

Top 20 Metro Area Averages for 2010 Space Heating				
Area	Demand (MMBTU)	Expenditures ($/yr)	Urban Heat Island Decrease (Rural - Urban)	
Urban	39.37 - 57.01	$729 - $1,037	Δ Demand (MMBTU)	**5.26 - 7.68**
Rural	44.63 - 64.70	$820 - $1,171	Δ Expenditures ($/yr)	**$91 - $134**
Top 20 Metro Area Averages for 2010 Air Conditioning				
Area	Demand (kWh)	Expenditures ($/yr)	Urban Heat Island Increase (Urban - Rural)	
Urban	1,851 - 2,790	$211 - $318	Δ Demand (kWh)	**155 - 210**
Rural	1,697 - 2,580	$195 - $297	Δ Expenditures ($/yr)	**$16 - $21**

Table 14. Average ranges of the 20 largest metropolitan areas for overall space heating and air conditioning demand and expenditures, as well as the relative increase or decrease in each attributable to the urban heat island effect.

Yet, other outcomes served only to highlight some of the shortcomings of the model's assumptions. The very pronounced effect of the temperature anomaly between urban areas on the Pacific Coast and adjacent rural areas further inland highlights one of the model's critical assumptions: that anomalies between the air temperatures of urbanized and rural areas are completely determined by the urban heat island effect and lack the influence of other geographic factors like elevation, latitude, and microclimates that exist on local and regional scales. These things are of course active drivers of air temperature, and the model makes no attempt to correct for these confounding variables. Future use of the approach laid out heretofore would benefit from an attempt to take these different factors into account. Improvements to the approach would focus on attempts to better characterize degree day distributions by accessing temperature data with a higher resolution or better coverage than that provided by stations on the GHCN-D. One possibility would be to integrate thermal bands of satellite imagery into the analysis in order to empirically examine the radiation of heat off of the hard surfaces in urban areas. This would open the possibility to better map and analyze patterns of the urban heat island effect within urban areas and between urban and rural areas. For the purposes of this model, remote sensing would allow for higher precision in locating degree day data, and could help investigate relationships between geography, urban development, and air temperature—something completely ignored by the model as it is presented herein.

Remote sensing would also assist in characterizing the percent spread of different housing types located in a given neighborhood or city. Of course, one of the major issues with this model is that it calculates conditioning loads for a space that is shaped as a simple cube and made from the same basic materials. 2005 EIA RECS data, as well as US Census AHS data, contain housing characteristics that were far too vast and detailed for the scope of this study. Some examples include the number of rooms per house, the material used on the outside of the house (stucco, bricks, etc.), the relative amount of time space heating or air conditioning equipment is used, and so on. With more time and sophistication, a comprehensive suite of these characteristics could be built into the model to present a more accurate mix of the housing types, housing characteristics, and building materials that work together to determine the space conditioning loads that result from higher-resolution degree day records. Assuming a more accurate mix of housing types would also improve the ability to use these results in studies aimed at characterizing certain side-effects of the urban heat island effect, be it energy consumption, greenhouse gas emissions, or grid stability, on a scale larger than a household.

5. Acknowledgements

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