Environmental Impact Assessment Review 56 (2016) 139–144

Contents lists available at ScienceDirect

Environmental Impact Assessment Review

journal homepage: www.elsevier.com/locate/eiar

An energy and mortality impact assessment of the urban heat island in the US

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ARTICLE INFO

Article history:
Received 14 May 2015
Received in revised form 19 October 2015
Accepted 20 October 2015
Available online 31 October 2015

Keywords:
Urban heat island
Mortality impact energy impact
Heat related deaths
Cold related deaths

ABSTRACT

Increased summer energy use and increased summer heat related mortality are the two most cited detrimental impacts of the urban heat island (UHI). An assessment of these impacts was made that considered the annual impact of the UHI, not just the summer impact. It was found that in north of the US there was a net decrease in energy use from the UHI, as heating energy reductions were larger than the increase in cooling energy. In the south there was a net energy increase from the UHI. The impact of the UHI on heat related deaths was an estimated increase of 1.1 deaths per million people. The impact of the UHI on cold related deaths was an estimated decrease of 4.0 deaths per million people. These estimates are caveated by the acknowledgement that compounding factors influence mortality. Hypothermia related death rates were three times higher in rural areas than urban areas. This is surprising as the homeless population is usually considered the most at risk, yet they mostly live in urban areas.

1. Introduction

The urban heat island (UHI) effect has been known for 200 years. Luke Howard made temperature measurements in 1815 in and around London that not only identified the phenomenon but also most of the causes (Howard 1818). As identified by Howard the urban heat island effect raises the ambient air temperature compared to surrounding, less urbanized areas. The main contributor to the UHI is the extensive use of manmade materials (concrete and asphalt) that effectively store short wave radiation (Solecki et al. 2005; Rizwan et al. 2008; EPA (US Environmental Protection Agency) 2015a).

The detrimental impacts of the UHI are usually listed as (EPA (US Environmental Protection Agency) 2015b):

1. Increased energy consumption as cities use more electricity for cooling in summer.
2. Increased emissions of air pollutants and greenhouse gases associated with the above.
3. Increased mortality from heat related deaths in summer.

A less cited impact is the heating of stormwater runoff (EPA (US Environmental Protection Agency) 2015b). Warmer water has less dissolved oxygen and can impact temperature sensitive fish species.

It can be assumed that most if not all cities in the US are aware of the UHI. Many cities are developing or implementing plans to mitigate the UHI impact. For example, Hewitt et al. (2014) details the UHI mitigation strategies and results in 26 US cities. Some common approaches include reflective roofs; vegetated (green) roofs; porous pavement; shade trees and increasing urban vegetation in general.

Apart from projects specifically planned with the UHI in mind, numerous projects in a city will cite UHI reduction as a benefit. For example New York City has a large green infrastructure program whose main focus is on reducing Combined Sewer Overflows (CSO's) (NYC EP (New York City Environmental Protection) 2014). However most of the initiatives also act to reduce the UHI and this is cited as a benefit on the first page of the NYCEP report.

Assessment measures help guide the development of UHI strategies, and then help track their effectiveness once implemented. One problem with existing assessments of the UHI is that only detrimental effects are considered. Note that the list above considers only summer impacts, not winter or annual. An accurate assessment should at least cover an annual range.

This paper attempts to assess the UHI impact on an annual basis in the US. The list above basically falls into two categories: energy and mortality. Emissions are directly linked to energy use. The next section describes the energy calculation for New York City, and then this method is expanded to the US. Mortality impacts are addressed from both the heat and cold perspective.

2. Annual energy impact of the UHI on New York City

The urban heat island (UHI) in New York City has been studied extensively (e.g. Kirkpatrick and Shulman 1987; Childs and Raman 2005; Gaffin et al. 2008). The UHI typically has a diurnal signal and is stronger at night (EPA (US Environmental Protection Agency) 2015a). Gedzelman et al. (2003) analyzed a large amount of local data and

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http://dx.doi.org/10.1016/j.eiar.2015.10.004
0195-9255/

concluded an average value of the UHI was 3 °C in the winter (Dec, Jan., Feb) and 4 °C in the summer (Jun, July, Aug).

The long term monthly average temperatures for New York City Central Park are given in Table 1 (NOAA (National Oceanic and Atmospheric Administration) 2015). These values would include the UHI effect. Using monthly temperature the heating degree days (HDD) and cooling degree days (CDD) can be calculated. These are referenced from 18 °C. HDD is the (18 °C − monthly temperature) × (days in the month). If the monthly temperature is above 18 °C then CDD is calculated as (monthly temperature − 18 °C) × (days in the month). Based on these calculations there are 2460 heating degree days, and 609 cooling degree days.

It has been shown that energy consumption is highly correlated with heating and cooling degree days (Quayle and Diaz 1980; Le Comte and Warren 1981, Sailor and Muñoz 1997). Sivak (2008) also points out that there may be secondary variables that influence the need for heating and cooling, such as the differences in the tolerance for heat and cold, differential home insulation across the country and the energy efficiency of heating and cooling systems.

The last point in particular is worth paying attention to. If the efficiency of heating and cooling systems are compared using a coefficient of performance (COP), then cooling systems are typically more efficient (Sivak 2013). Based on new device efficiencies Sivak concluded that the energy impact of one HDD was twice that of one CDD.

However this ratio could change dramatically if other factors were considered. For example the efficiencies of systems are highly dependent on age and maintenance level, with cooling systems degrading more rapidly than heating (NREL (National Renewable Energy Laboratory) 2006). The reported efficiencies of new systems are based on standard calculations and vary widely in actual use (Stein and Meier 2000; Pérez-Lombard et al. 2009). The distribution efficiency of the system, as opposed to just the heating/cooling unit, is also a factor. A hydronic heating system is extremely efficient compared to losses in air ducts, for example (NREL (National Renewable Energy Laboratory) 2006).

So while it is probable that the energy related consumption of one HDD and one CDD are not the same, it is difficult to derive a realistic estimate of what the ratio should be. So for the analysis presented here the energy related consumption of one HDD and one CDD is assumed to be equal.

Table 2 shows the monthly average temperatures reduced by the values reported by Gedzelman et al. (2003). The heating and cooling degree days are then recomputed. The spring and fall use averages of the summer and winter UHI intensity values (i.e. 3.5 °C). Summer and winter generally represent the two extremes of the UHI (Schatz and Kucharik 2014) and studies have shown ~linear variations between the two (Gallo and Owen 1999).

The results from Tables 1 and 2 indicate the net energy effect of the UHI is a decrease in annual heating of 3068.9–2460.4 = 608.5 heating degree days. Conversely the UHI causes an increase in cooling requirements of 609–170.5 = 438.5 cooling degree days. This means there is an annual energy benefit of the UHI of 608.5 − 438.5 = 170°days.

Table 1
Heating and cooling for NYC including UHI.

Month	Avg temp (°C)	Heating degree days	Cooling degree days
Jan	0.4	547.2	
Feb	1.8	453.6	
Mar	5.9	375.1	
Apr	11.3	201.0	
May	17.1	29.5	
June	22.0		120.0
July	25.2		221.7
Aug	24.4		196.9
Sept	20.4		70.5
Oct	14.2	117.8	
Nov	8.7	279.0	
Dec	3.3	457.3	
		2460.4 total	609.0 total

Table 2
Heating and cooling For NYC excluding UHI.

Month	Avg temp (°C)	Heating degree days	Cooling degree days
Jan	−2.7	475.9	
Feb	−1.2	470.4	
Mar	2.4	483.6	
Apr	7.8	306.0	
May	13.6	138.0	
June	18.0		0.0
July	21.2		97.6
Aug	20.4		72.9
Sept	16.9	34.5	
Oct	10.7	226.3	
Nov	5.2	384.0	
Dec	0.3	550.3	
		3068.9 total	170.5 total

This result is not unexpected for a city with the climate of New York, which has more months requiring heating than cooling. The official heating season is 8 months long, Oct. 1–May 31 (NYS (New York State) Division of Housing 2015).

Using this methodology the energy impact of the UHI across the US is assessed in the next section.

3. Mapping energy impact of the UHI in the US

Remote sensing technology has enabled the estimation of the UHI in many cities in the US (Streutker 2002; Xian and Crane 2006; Yow and Carbone 2006; Yuan and Bauer 2007; Imhoff et al. 2010; Gallo and Xian 2014). In addition the EPA has compiled information on various cities (EPA (US Environmental Protection Agency) 2014).

Whether remote sensing is an accurate method to assess the UHI has been the subject of numerous papers. Many papers have concluded the validity of the method (for example Hu et al. 2014). Some papers have noted differences between measured air temperature and remote sensing results. For example Zhang et al. (2014) noted that although overall agreement was good, some particular situations were not (midday summer UHI for cities in forested areas, for example). Others have also noted the issues with observed air temperature measurements (for example Oke 1982; Stewart 2011). This further complicates the comparison of results. For the purposes of this paper the remote sensing estimates of the UHI are assumed to be accurate enough to complete the analysis presented.

Using the available UHI information and monthly NOAA temperature data, the annual energy impact of the UHI was computed for cities throughout the continental US. The same approach as above for New York City was utilized. Due to the large number of cities involved (42), it is not feasible to show all the individual tables in this paper. The spatial distribution of the cities considered is shown in Fig. 1. The results are summarized in Table 3. A city that would use less energy as a result of the UHI (e.g. New York City) is listed as positive UHI impact. A city that will use more energy as a result of the UHI is listed as negative UHI impact. In some cases the heating energy reductions and the cooling energy increases tend to offset each other. These cases are listed as neutral UHI impact.

The results indicate that cities in more northern areas will show a net energy benefit of the UHI, as a result of colder climates. Conversely cities in southern areas will be negatively impacted by the UHI as a result of their warmer climate. The results are mapped in Fig. 2. Also shown in Fig. 2 is an approximate location of the zero gain line — where there is neither a significant net energy gain nor loss.