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Urban heat island and its impact on climate change resilience in a shrinking city: The case of Glasgow, UK

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ABSTRACT

Given its long urban history of growth and decline, Glasgow, UK, provides a historically significant opportunity to study the local climatic changes brought about by urban variables. This study investigates the changes in air temperature within the central area of Glasgow using three data sources: the UK Meteorological Office historical data for Glasgow (climate normals and running data for a 50-year period), the Weather Underground network; MIDAS Surface Weather Stations network of the British Atmospheric Data Centre (BADC). Three approaches were used to evaluate Glasgow's local climate change: assessment of mean air temperature increases based on two concurrent climate normals, traditional UHI approach (i.e. differences between a 'rural' and an 'urban' site) and observed temperatures in locations with different land cover characteristics (using the Local Climate Zone LCZ concept. Planning and building scale implications for other shrinking cities are explored.

1. Introduction

Cities are home to over half of the global population [1]. The current growth trajectories indicate that by 2050, nearly 70% of humanity (6.3 billion out of an estimated global population of 9.1 billion) will live in urban areas [1]. The local, regional and global climate implications of such rapid urban growth are complex: On the one hand, cities are major consumers of energy and materials as well as generate vast amounts of waste. They are also major centres of innovation and finance – which could enable them to be at the forefront of climate mitigation actions. At the same time, the nature of climate change with its long lag-times mean that cities need to prepare themselves now, to act as the first line of defence against catastrophic effects of local and global changes expected in the near future. Given the twin realities of potential innovation in mitigatory action as well as adaptive capacity and need in the face of burgeoning urban population, urban areas are beginning to receive a long overdue attention from climate change scientists and policy makers [2,3]. In these efforts, the role of urban climate change in both contributing to and augmenting global change is a key unknown that needs careful attention. Could there be opportunities to use the mitigatory potential of urban fabric to reduce the effects of urban warming with a view to providing some relief to the wider and more extreme weather events spawned by global climate change?

A further reality confounding the issue is urban decay. Major centres of urban population have already begun to lose population and even those that are yet growing continue to sprawl, leading to lowering urban densities in many parts of the world. What effects will shrinking cities as well as de-densification have on local climate change? What lessons can we learn from the local climate change trajectories of mature cities to plan better the still growing cities of the world?

In this paper, we analyse the trends and local differences in air temperature in and around the mature urban area of Glasgow, UK (55°51′N, 04°12′W). Using historical weather data from three different sources we determine the effect of local climate zones [4] on microclimate and postulate what lessons could be learnt by other mature and/or shrinking cities and how the city of Glasgow could benefit from these changes in its quest for a sustainable and low carbon future.

2. Background

2.1. Urban heat island in mature cities

Urban warming and its links to regional and global warming have been well documented in several mature cities in Japan, Europe (especially in the UK) North America and Sweden. Fujibe's work in Japan [5,6] epitomises these efforts. Reviewing data from

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561 meteorological stations established in Japanese cities in the early 20th Century, Fujibe [6] found that there is a warming trend of 0.3–0.4 °C/decade even for locations with low population density (<100 people per square kilometre), indicating that the recent temperature increase is largely contributed by background climate change. However, an anomalous warming trend is detected for stations with larger population density (in the order of 100–300/km^2) where the anomalous trend is 0.03–0.05 °C/decade [6]. Furthermore the recorded rate of temperature increase tends to be larger at night than during the daytime, although in the case of a megacity (Tokyo) widespread urban warming in the hinterland during afternoons of the warm season is seen as a result of extensive urbanization that enhances daytime surface heating.

Among the European mature cities, the heat island effect in London is one of the most well studied (see Ref. [7] for a comprehensive review). On the positive side, heating energy consumption in central London is 65–85% of the heating required for the same building based outside the Urban Heat Island [8]; conversely, cooling energy consumption is 32–42% higher in the city. Given the fuel mix for heating and cooling (gas for heating and coal for electricity, [8]), the carbon implications of UHI to London are negative. An estimate of the heat island effect in major population centres in the UK (based on the UK Met Office historical weather data, see UK Met Office, 2011) was developed by Kershaw et al. [9]. Table 1 shows the seasonal and annual average UHIs for several UK cities.

The heat island effect on outdoor thermal comfort at a mature city (Göthenburg, Sweden) was studied by Thorsson et al. [10]. Statistically downscaling climate change projections to the city street-levels, Thorsson et al. [10] showed that urban geometry could cause large intra-urban differences in Mean Radiant Temperature (T_{mrt}), on hourly, daytime and yearly time scales. In general, open areas are warmer than adjacent narrow street canyons in summer, but cooler in winter. The combination of regional warming coupled with augmentation by urban geometries will triple strong/extreme heat stress (to approx. 20–100 h a year, depending on geometry). Conversely, the number of hours with strong/extreme cold stress will decrease by 400–450 h. Furthermore, the number of hours with no thermal stress will increase by 40–200 h a year. Considering both winter warming and summer cooling potential of judicious arrangement of urban geometry, Thorsson et al. [10] conclude that a densely built urban structure will mitigate extreme swings in T_{mrt} and in the generally adopted thermal comfort index 'physiologically equivalent temperature' (PET), improving outdoor comfort conditions both in summer and in winter.

Table 1
Seasonal and annual average UHI values (° C) for UK cities.

City	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)	Annual
New castle upon-Tyne	1.8	1.9	2.0	1.8	1.9
Portsmouth	1.3	1.73	2.0	2.0	1.8
Central London	1.3	1.7	1.9	1.6	1.6
Liverpool	1.1	1.4	1.7	1.5	1.4
Glasgow	1.0	1.5	1.5	1.2	1.3
Edinburgh	1.1	1.4	1.4	1.3	1.3
London Suburbs	0.9	1.2	1.4	1.1	1.1
Plymouth	0.9	1.2	1.2	1.1	1.1
Sheffield	0.9	0.9	1.1	0.9	1.0
Manchester	0.8	1.1	1.2	0.8	0.9
Bristol	0.6	1.0	1.2	0.9	0.9
Middlesbrough	0.8	1.0	0.9	0.8	0.9
York	0.8	0.8	1.0	0.9	0.9
Cardiff	0.5	0.9	1.1	0.6	0.8
Leeds-Bradford	0.6	0.7	0.8	0.8	0.7
Nottingham	0.5	0.7	0.9	0.6	0.7
Bournemouth	0.6	0.8	0.8	0.5	0.7
Birmingham	0.4	0.5	0.7	0.6	0.6
Coventry	0.4	0.5	0.7	0.4	0.5
Belfast	0.4	0.5	0.3	0.3	0.4
Leicester	0.0	0.2	0.1	0.1	0.1

Note: UHI values are given as three-month average temperature difference between a city centre weather station and a nearby rural station.
Winter = December, January and February (DJF); Spring = March, April and May (MAM); Summer = June, July and August (JJA); Autumn = September, October and November (SON). Source: Based on Kershaw et al., 2010.

2.2. Climate change and urban heat island

Given the small fraction of land occupied by cities (all urban sites including green as well as built-up areas cover only 2.8 per cent of the Earth's land area [11]) it is unlikely that cities have a direct bearing on global climate change. However, cities indirectly drive global climate change on account of their insatiable appetite for energy and material (and associated waste and pollution). Furthermore, an increasing urban population will lead to the expansion of land covered by cities, at which point the direct influence of cities on regional and perhaps global climate may not be insignificant.

There is increasing evidence to the scale of urban influence on the global climate to be in the order of El-Nino Southern Oscillation (ENSO) [12]. The significance of the signal from urban climate change on the global climate led Hansen et al. [13] to term it as "urban warming." A key difficulty in untangling the urban warming from global climate changes is the computational and parametric difficulties associated with representing urban areas in climate models. Yet it is increasingly recognised that climate models provide a good approach for assessing the global consequences of the urban climate modifications [14].

Given the lack of detailed land cover information and computing power, most climate models generally do not include a representation of urban areas, and therefore their climate projections are likely to underestimate the heat island phenomenon [9]. The general consensus appears to be that the UHIs are likely to augment the temperature anomaly arising from global warming [2,9].

A recent study commissioned by the World Bank shows that modern patterns of city growth are increasingly land intensive [15]. Average urban densities have been declining for the past two centuries. As transportation continues to improve, the tendency is for cities to use up more and more land per person [15]. In developing countries, cities of 100,000 or more are expected to triple their built-up land area to 600,000 km^2 in the first three decades of this century. Cities in developed countries expand at an even faster rate per resident, despite their smaller population size and lower rate of population growth. They will increase their built-up land area by 2.5 times between 2000 and 2030. At that point, they will occupy some 500,000 km^2 [15]. These may have direct consequences to global climate.

Even if the urban effects on global climate change remain weak, the influence of UHIs on regional climates is clearer. Lamptey [16] attempted to untangle the sensible and latent heat partitioning associated with different land cover classes in Chester County and surroundings near Philadelphia, Pennsylvania, USA. The urban effect became more important as the fraction of urban land cover to the total increased. When the urban land cover increased from 11% to 19% in 9 years it led to the largest proportionate sensible (21.4 Wm^{-2}) and latent (14.2 Wm^{-2}) heat fluxes during winter. During summer, urban and vegetation land cover produced the largest proportionate sensible heat (59.2 Wm^{-2}) while urban land cover produced the second largest proportionate latent heat flux (39.5 Wm^{-2}). The regional climatic implications of these energy partitioning cannot be ignored.