396: An Analysis of the Urban Heat Island of Sheffield – the Impact of a Changing Climate

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Abstract
The presence of a city has a major impact on its local environment in terms of the heat and water balance of the area. In particular, it has been widely observed that the centre of the urban area in a temperate climate tends to be of the order of 4 to 6 °C warmer than its rural surroundings (the Urban Heat Island effect). The paper describes the approach used by the SCORCHIO (Sustainable Cities: Options for Responding to Climate cHange Impacts and Outcomes) project to identify the Urban Heat Island and map the current land use for Sheffield, UK. This builds on previous work carried out by the ASSCUE (Adaptation Strategies for Climate Change in the Urban Environment) project to map the land use of Manchester. This paper highlights the variation in temperature across Sheffield derived from ground based and airborne measurements. Vulnerable areas that which would benefit from structural changes such as additional greenery or shading of the buildings are identified. Future studies should be able to adopt the methodology proposed here to apply to other similar cities.

Keywords: urban heat island, urban environment, SCORCHIO, climate change

1. Introduction

The urban environment has a profound effect on its surroundings. Oke [1] states that the process of urbanization produces radical changes in the nature of the surface and atmospheric properties of a region. It involves the transformation of the radiative, thermal, moisture and aerodynamic characteristics and thereby dislocates the natural solar and hydrologic balances. It is a well-known fact that the centre of an urban area tends to be warmer than outside, particularly during the early evening, and this is what is called the urban heat island effect - see Figure 1 [2]. This effect operates both at the micro-scale (street level) and at meso-scale (roof level), which in turn influences the climate "downwind" of a city. There is mounting evidence to suggest that urban heat islands affect the amount and distribution of precipitation, cloud type and amount and the diurnal temperature range in their vicinity [3]. There is also a greater awareness of the issue of climate change and how this is going to impact on the residents of cites [4, 5]. However, not only do cities have an impact on local weather and climate in terms of heat storage, wind speed and direction and intensification of the impact of rainfall events, but the weather and climate in turn influence the infrastructure and development of the city. Urban areas have distinct biophysical properties and climate change amplifies their distinctive behaviour. The impacts include a large building mass and associated heat storage capacity, reduced vegetation cover (reduced evaporative cooling, and rainwater interception and infiltration functions) and widespread hard surface cover causing a rapid runoff of precipitation.

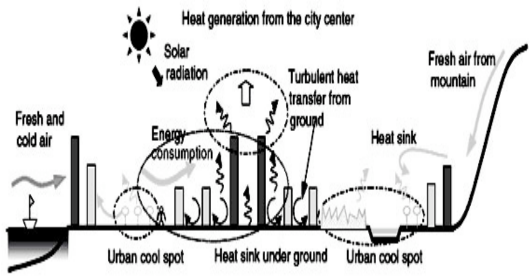

Fig 1. Urban impacts on the environment [2]

In the UK, 90% of the population now live in cities, as do 50% of the world's population. This figure is expected to rise to 60% (5 billion people) by 2030 [6]. These people have a major influence on the environment and the development of the urban infrastructure. At the same time as the population is growing the world is becoming increasing concerned with the impacts of a changing climate. The IPCC stated in its last report that there is no doubt that there is a continuing warming trend. *The understanding of anthropogenic warming and cooling influences on climate has improved since the Third Assessment Report, leading to very high confidence that the effect of human activities since 1750 has been a net positive forcing of +1.6 [+0.6 to +2.4] W m^{-2}* [7].
Over the last few years, there have been a number of major extreme weather events, which have reinforced these predictions. There is still caution about whether these events are directly attribute to climate change although the IPCC suggest with further studies, knowledge of this issue will improve [3]. Having said that, it is

considered by the IPCC very likely that there will be higher maximum temperatures, more hot days and heat waves over nearly all land areas, higher (increasing) minimum temperatures, fewer cold days, frost days and cold periods over nearly all land areas (very likely). In addition, more intense precipitation events are expected (very likely, over many areas) but at the same time it is considered likely that there will be increased summer drying over most mid latitude continental interiors and an associated risk of drought.

In terms of the direct impacts of these events on the urban population, there will be greater mortality caused by heat stress, and a shift in tourist destinations [8]. There will also be an increase in electric cooling demand and reduced energy supply reliability, decreased cold-related human morbidity and mortality along with reduced heating energy demand, increased flood, landslide, avalanche, and mudslide damage. Increased flood runoff could increase recharge of some floodplain aquifers and in turn increase pressure on government and private flood insurance systems and disaster relief. There will be more damage to building foundations caused by ground shrinkage, decreased water resource quantity and quality and an increased risk of forest fire. There are also expected to be some indirect effects due to crop damage by heat, water or pests and increased migration pressures as people move to more climatically acceptable regions [8]. Climate change may bring some benefits to city living but it also poses a significant threat to building integrity and human welfare. Furthermore, some aspects of the urban environment, such as urban green space, provide adaptation potential provided by the 'green infrastructure' in moderating climate change impacts.

The SCORCHIO (Sustainable Cities: Options for Responding to Climate cHange Impacts and Outcomes) project aims to address some of these issues. It seeks to develop tools that use the latest forecasts from the UK Climate Impacts Programme UKCIP (called the UKCIPnext scenarios) [9] to help planners, designers, engineers and users to adapt urban areas, with a particular emphasis on heat and human comfort. It follows on from a previous EPSRC funded project called ASCCUE (Adaptation Strategies for Climate Change in the Urban Environment) [10]. This was one of a number of projects within the EPSRC/ UK Climate Impacts Programme (UKCIP)/ Building Knowledge for a Changing Climate (BKCC) that looked at how climate change will affect different aspects of the built environment. SCORCHIO builds on ASCCUE by exploring the heat island phenomenon in Greater Manchester and Sheffield and its implications for building design and management.

There are a number of research objectives within SCORCHIO that include the following: an improvement in our understanding of the current and potential future UHI characteristics and to model buildings and their surroundings in order to develop a vulnerability index to account for building construction, form and layout. In addition, work is in progress to estimate heat emissions from buildings and emissions budgets and to understand the implications of different adaptation options. There is also development of GIS-based decision support tools and workshops have demonstrated the methods and tools through their application to selected case studies.

Some of the issues currently under investigation by SCORCHIO are the effects of the urban landscape on patterns of temperature in the city and the effects of heat released by human activities within cities. Neither of these has been considered in standard climate change projections, but these have been shown to be potentially very significant. SCORCHIO work that has been carried out to date includes producing two transects (airborne) of Manchester by Manchester University, along with three transects for Sheffield including one airborne transect. Data from the Sheffield transects will be presented in this paper. Further tasks planned by Sheffield include thermal simulations of a specific building and group of buildings in Sheffield within a case study site and to derive a thermal vulnerability index for use in Manchester and Sheffield. These simulations will use Design Builder [11], a software package that is, in effect, a user interface to the EnergyPlus dynamic thermal simulation engine. It enables building models to be created fairly quickly and simply. DesignBuilder can generate extensive data on environmental conditions within the building and resultant occupant comfort levels.

Sheffield City Council has played an active role in assisting SCORCHIO. Council employees have been very helpful in the provision of both meteorological data and energy usage data for council buildings. In addition, the Council is playing an active role in helping to shape the GIS-based decision support tools tool under development for the exploration of adaptation options for urban planning and design. They are also involved in selecting specific case study sites for more detailed analysis of the effects of increasing heat. The city of Sheffield is located in the centre of England (latitude: 53:22:59N, longitude: 1:27:54W) and is built on seven hills. It covers an area of 368 km^2 and it is unusual compared to many English cities in that one third of its boundary contains part of a National Park (the Peak District). It is also a very green city, with numerous parks and woods within its area. Figure 2 shows the green spaces within the Sheffield city limit, with most of the land in the western half of the map lying in the Peak District. It is an interesting city to compare with Manchester (latitude: 53:28:51N, longitude: 2:14:04W) because they share a similar latitude but Manchester is larger and much flatter with fewer green spaces.

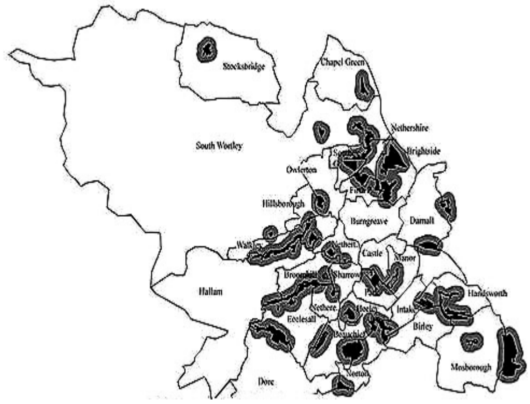

Fig 2. Green spaces within Sheffield city boundary (shaded in black)

The paper presents results obtained from ground based measurements of temperature and humidity for three different days in April and May 2008 within Sheffield. Areas of elevated temperature are identified within the city. Existing meteorological data have been gathered for Urban Heat Island modelling along with energy data for Council buildings and Universities. Land-use and planning data have also been acquired for the classification of buildings and urban land cover.

2. Methodology

2.1 Car transects

Three transects were undertaken, two with cars and one with an aircraft. These took place on 16th April, 22nd April and 7th May 2008. These days were selected, as they were dry with calm conditions. The 16th and 22nd April were both dry with sunny intervals and just one car was used. The 7th May was also dry and mostly sunny (although the sunshine was rather hazy). Both cars were fitted with a Rotronic AG HygrologNT sensor, which records temperature and humidity (Figure 3). The time interval was set to every five seconds. In addition, on 7th May a Cessna-182J flew overhead at the same time as the cars were recording on the ground (Figure 4). In order to link the temperature and humidity recorded each car also carried a GPS with a recording interval of 15 seconds. This provided latitude and longitude as well as altitude. A number of routes were recorded across the city. One car came in from the Northwest via Stocksbridge and Grenoside and then down through Hillsborough into the city centre and then along the A625. The other car came in along the A57 through Crosspool, Hillsborough and down into the city. It then headed northeast through Attercliffe and out to Meadowhall. It returned to the city through Wooley Wood, and down Barnsley Road through Ecclesfield (Figure 5) and back into the city. In addition to driving through the city, the cars also included Weston Park, which has a recognised Meteorological Office site, as well as the Geography Department at Sheffield University that has an automatic weather station on its roof. Furthermore, an additional site run by a company called Atomwide provided reference meteorological data on a minute-by-minute basis. These data can be accessed on the internet [12]. For the April transects the Rotherham site (53.4°N, 1.4°W) which is located not far from Meadowhall was used. The Sheffield site, (Lat 53.4°N, 1.5°W) southwest of the city centre in Heeley, was not in operation then, as it was undergoing final testing prior to going live. However, it was operational for the 7th May transect so this was used instead.

Fig 3. Car fitted with Rotronic AG HygrologNT sensor (arrowed), which records temperature and humidity

2.2 Air transect

This took place on 7th May. The pilot flew from Liverpool and approached Sheffield from the North. She then headed east and zigzagged over the city, including the city centre, flying at a height of 2000 ft (700m). It was difficult for the pilot to identify specific landmarks due to the hazy conditions but the centre of the city was included before the pilot headed off westwards. The plane used for the transects is a Cessna-182J, and the instrument providing the surface temperatures in a KT-19 infrared thermometer

Fig 4. Cesna-182J carrying KT19 sensor, which records temperature and humidity (arrowed)

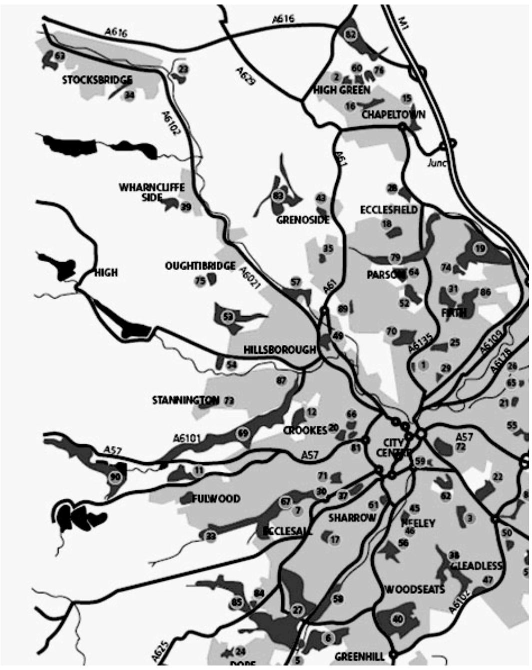

Fig 5. Major roads Sheffield - built-up areas are shown in light grey, parks in dark grey (courtesy of Sheffield City Council)

2.3 Temperature adjustments

When a 'parcel' of dry air rises, it cools at 9.8 °C per 1000 metres. This is known as the Dry Adiabatic Lapse Rate (DALR) [13]. In order to account for this decrease of temperature with height a lapse rate of 1°C per 100m is used for both the car transect data and the Atomwide data. For example, if a site were at 100m then the temperature would be increased by 1°C above its actual temperature in order to “standardise” it to sea level. Also, to account for the fact that the temperature is changing during the period of the transect the transect temperature data were adjusted in the same proportion to the Atomwide temperature data for a specific time of day. For example, if the 10.00 am temperature for the Atomwide site was 0.75 of the value of the final temperature recorded then the same proportion would be used to adjust the transect temperature at the same time.

3. Results

3.1 16th April 2008

A car transect was carried out on 16th April. The car travelled from Langsett, through Stocksbridge, down through Grenoside and Hillsborough into the City Centre. Table 1 shows the times and location details of specific sites along this transect. Note that the car was in the city centre between 12.09 (Campo Lane) and 12.52 (Sheffield Hallam University).

Table 1: Time and location details of specific sites along the Northern transect and north-eastern transect on 16.04.08

Time	Lat	Lon	Location details
10:36:00	53.50667	-1.698889	Langsett
10:45:00	53.48611	-1.611389	Stocksbridge 1
10:53:00	53.48111	-1.581667	Stocksbridge 2
11:01:00	53.48806	-1.508056	A616 layby
11:32:00	53.43000	-1.490000	Grenoside
11:45:00	53.40806	-1.494722	Hillsborough
11:57:00	53.83890	-1.488889	Geography
12:09:00	53.38317	-1.471639	Campo Lane
12:15:00	53.38622	-1.469250	Riverside
12:24:00	53.37478	-1.466778	Matilda Street
12:33:50	53.37933	-1.471556	Cross Burgess St
12:41:00	53.38022	-1.472389	Barkers Pool
12:52:00	53.37856	-1.464472	Hallam University
13:09:00	53.41469	-1.400361	Tinsley
13:15:00	53.41314	-1.375972	Meadowhall

The temperatures recorded, adjusted for altitude and time, are shown in Figure 6 along with the Atomwide (Rotherham) site (AW) temperatures. It can be seen from Figure 6 that when the car was in the city centre the temperatures were of the order of 1 to 2 degrees C greater than Atomwide (Rotherham). It is also interesting to note that the more rural areas were cooler than Atomwide (Rotherham) between the start of the transect 10.36 through to 11.32.

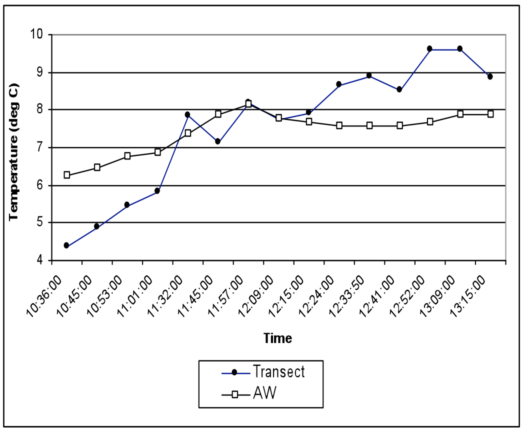

Fig 6. Temperature comparison between the Atomwide (Rotherham) site (AW) and the specific sites along the Northern transect to Meadowhall on 16.04.08

3.2 7th May 2008

Two car transects were undertaken on 7th May: a northern transect following the same route as 16th April and an additional route along the A57 through Crosspool and Broomhill down into the town centre and out on the north-eastern route to Meadowhall via Attercliffe. The weather on 7th May was mostly sunny but it started clouding over around 13.30. The western transect started at 11.14 and finished in the city centre at 12.08. The north-eastern transect started at 12.18 and finished at Meadowhall at 12.41. The second NE transect started at Meadowhall at 12.50 and finished in the city centre at 13.50. The Sheffield boundary was reached at 14.19. The northern transect started at 10.45 and finished at 12. The plane was over the city from 10.51 to 12.51. To show the spatial variation of the temperature across the city from the car transect data, 26 sites were selected and mapped using ArcGIS Figure 7 shows the results using the adjusted temperature (altitude and temporal) and inverse distance weighted option within ArcGIS.

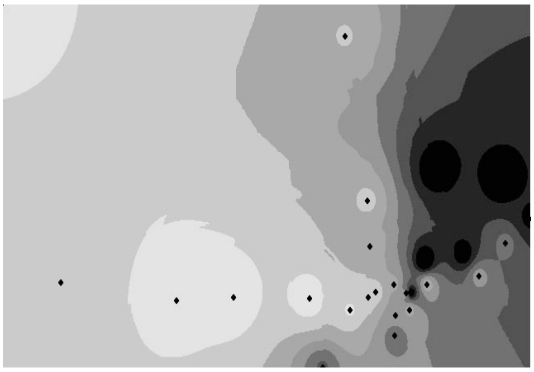

Fig 7. Spatial distribution of temperature across Sheffield on 07/05/08 - the black areas are 21° C and above and the white areas 14° C with the grey areas grading in between

It can be seen from Figures 6 and 7 that the highest temperatures of 18 to 22 °C during the period of the transects occurring in the centre and north-eastern parts of the city. This includes areas such as Attercliffe, Meadowhall and Ecclesfield. Along the Don Valley going up through Hillsborough, temperatures are around 16°C and then, moving westwards, decrease to 14°C. It is interesting to note that the areas which record the hottest temperatures are also the most deprived in the city (moving from Firth Park south-eastwards to the city centre). These areas are identified by Sheffield City Council within their Corporate Self Assessment report. Almost a third of Sheffield's population lives within the 10% most deprived wards in the country which occur in the north, east and central parts of the city [14].

4. Conclusion

This paper has introduced the SCORCHIO project and demonstrated the effect of the city of Sheffield on the local heat environment. It has highlighted particular vulnerable areas to a rising temperature. It would appear that the typical Urban Heat Island effect for Sheffield from the Spring transects is of the order of 2 degrees Celsius, which is less than Manchester (around 4 degrees Celsius in the middle of the day in summer). This may be due to seasonal differences or another possible reason is the presence of the parks and other green spaces within the city. Additional analysis of the humidity data and further ground and airborne transects performed at different times of the day during Summer 2008 will provide more detail. This additional data will also include radiant surface temperature that will be used in conjunction with heat emission data from satellite thermal imagery in order to determine specific “hot spots”. Such areas will form the focus of additional work. Design Builder will be used to demonstrate how the buildings and their layout in such areas may be improved for the benefit of the inhabitants.

6. Acknowledgements

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7. References

1. Oke, T.R. (1987) *Boundary layer climates.* Methuen, London
2. Murakami, S, (2006) Environmental design of outdoor climate based on CFD. *Fluid Dynamics Research*, 38: p. 108-126.
3. IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.*
4. McGregor, G.R. (2005) Climatic variability and change across Europe. In B.E. Menne, K. (ed.), *Climate Change and Adaptation Strategies for Human Health*, Springer, Dresden, p. 9-40
5. McEvoy, D. (2007) Climate Change and Cities. *Built Environment* 33: p. 5-8.
6. U.N. Secretariat (2005). World Population Prospects: The 2004 Revision. In *Population Division of the Department of Economic and Social Affairs*.
7. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., and Miller, H.L. (ed.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
8. McCarthy, J.J., Canziani, Osvaldo F., Leary, Neil A., Dokken, David J., White, Kasey S. (ed.) (2001) *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Summary for Policymakers*.
9. UK Climate Impacts Programme (UKCIP). [Online]
http://www.ukcip.org.uk/
10. Lindley, S.J., Handley, J. F, Theuray, N., Peet, E. and McEvoy, D (2006) Adaptation Strategies for Climate Change in the Urban Environment – assessing climate change related risk in UK urban areas. *Journal of Risk Research,* 9: p. 543-56.
11. Design Builder
[Online]
http://www.designbuilder.co.uk/content/view/7/13/
12. Atomwide [Online]
http://weather.atomwide.com/Default.aspx

13. Meteorological Office Education [Online] http://www.metoffice.gov.uk/education/higher/lapse_rates.html
14. Sheffield City Council [Online] http://www.sheffield.gov.uk/your-city-council/policy--performance/corporate-documents/performance-assessment/councils-assessment