KS1.1

LUKE HOWARD, TIM OKE AND THE STUDY OF URBAN CLIMATES

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1. INTRODUCTION

Urban climate research is concerned with the impacts that urbanized areas have on climate at all scales. The bulk of this research work has been carried out in the last sixty years. During this period progress has been hesitant with periods of rapid progress separated by periods of consolidation. The reasons for this pattern are manifold and are associated with asynchronous developments in theory and instrumentation. In the urban context these problems have perhaps been accentuated by the complexity of the urban atmospheric environment, the lack of dedicated researchers and their relative isolation from one another.

To a considerable extent many of the barriers to progress have been removed. Advances in theory, observation and models now allow urban effects to be explored at a very detailed level. Moreover, grappling with such a complex, spatially heterogeneous, landscape has stimulated research that has advanced boundary-layer studies generally. This has occurred as interest in the urban environment has increased because of the dramatic increase in the planet's urban population and the realization that urban-based activities have effects at the local, regional and global scales. As a consequence there is now a growing community of scholars focused on urban climate. This is evident in some of the large scale city projects that draw upon international teams to jointly examine urban effects (e.g. Rotach et al., 2005).

Nevertheless, there remain significant 'gaps' in the field. Oke (2006) outlined the stages in the development of an urban climate science: Conceptualization; Theory; Observation; Modelling; Validation; Application and; Evaluation. While the first three have advanced significantly, the others are less developed. In particular, the challenge of incorporating urban climate knowledge into planning and design practice remains.

In this paper I will look at the development of urban climate research with a particular focus on the study of the urban temperature effect. In doing so, I will discuss the respective approaches and contributions of Luke Howard and Tim Oke. Whereas Howard's research on the climate of London represents the beginning of the field, Oke's research is synonymous with the modern history of urban climate research.

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2. THE CLIMATE OF LONDON

Luke Howard (1772-1864) is most famous for his classification of clouds (Hamblyn, 2001). However, he is also the first to describe the development of the urban heat island effect over the course of a year and to suggest its causes (Mills, 2007). Both of these contributions are evident in his monumental work, The Climate of London, the second edition of which was published in 1833. The importance of this book for urban climatology is such that it has been republished by the International Association for Urban Climate (Howard, 2007).

From 1806 to 1830 Howard made daily recordings of the pressure, temperature, humidity, precipitation and evaporation at locations outside London. In addition he maintained a diary of his observations and collated newspaper articles on any event of meteorological interest. The first volume of both editions contains his analysis of climate and is organized according to each atmospheric property. The preface contains an extensive discussion of the instrumentation employed in making observations and includes his famous Essay on Clouds.

It is important to note that Howard was not concerned about the climate of the city of London but rather with climate generally as viewed from the vantage point of London. As such, he became concerned at the deviation between his recordings and those gathered at the Royal Society in central London (Figure 1). From his analysis he concludes that the: *Mean Temperature of the Climate, … is strictly about 48.50° Fahr.: but in the denser parts of the metropolis, the heat is raised, by the effect of the population and fires, to 50.50°; and it must be proportionately affected in the suburban parts. The excess of the Temperature of the city varies through the year, being least in spring, and greatest in winter; and it belongs, in strictness, to the nights; which average three degrees and seven-tenths warmer than in the country; while the heat of the day, owing without doubt to the interception of a portion of the solar rays by a veil of smoke, falls, on a mean of years, about a third of a degree short of that in the open plain.*

Howard identifies the UHI as the difference between the air temperature in the city and that in the country (ΔT_{u-r}) and hypothesizes that this difference must increase from the edge of the city toward its centre. His analysis also showed that ΔT_{u-r} is primarily a night-time phenomenon which is greatest in winter months.

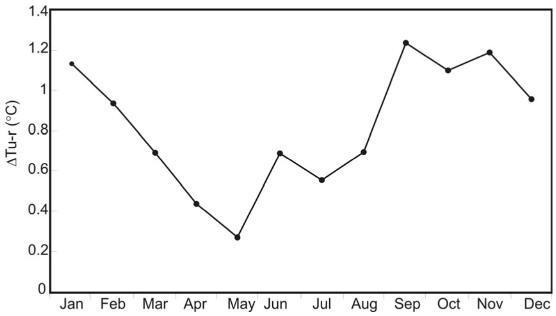

Figure 1. The difference between the average monthly mean temperatures for London and the country based on data for 1807-1816.

Howard goes on to suggest the causes of the UHI:
That the superior temperature of the bodies of men and animals is capable of elevating, in a small proportion, the Mean heat of a city or populous tract of country in a temperate latitude, is a proposition which will scarcely be disputed…But the proportion of warmth which is induced in a city by the Population, must be far less considerable than that which emanates from the fires: the greater part of which are kept up for the very purpose of preventing the sensation attending the escape of heat from our bodies. A temperature equal to that of Spring is hence maintained, in the depth of Winter, in the included part of the atmosphere, which, as it escapes from the houses, is continually renewed: another and more considerable portion of heated air is continually poured into the common mass from the chimnies; to which, lastly, we have to add the heat diffused in all directions, from founderies, breweries, steam engines, and other manufacturing and culinary fires. The real matter of surprise, when we contemplate so many sources of heat in a city is, that the effect on the Thermometer is not more considerable.

To return to the proportions held by the excess of London, it is greater in winter than in summer, and it sinks gradually to its lowest amount as the temperature advances in the spring, all which is consistent with the supposition, that in winter it is principally due to the heat diffused by the fires.

It appears that London does not wholly lose its superiority of temperature, by the extinction of most of the fires in Spring: on the contrary, it is resumed in a large proportion in the Sixth month, and continues through the warm season. It is probable, therefore, that the Sun in summer actually warms the air of the city more than it does that of the country around. Several causes may be supposed to contribute to this: the country presents for the most part a plain surface, which radiates freely to the sky, — the city, in great part, a collection of vertical surfaces, which reflect on each other the heat they respectively acquire: the country is freely swept by the light winds of summer, — the city, from its construction, greatly impedes their passage, except at a certain height above the buildings: the country has an almost inexhaustible store of moisture to supply its evaporation — that of the city is very speedily exhausted, even after heavy rain. When we consider that radiation to the sky, the contact of fresh breezes, and evaporation, are the three principal impediments to the daily accumulation of heat at the surface, we shall perceive that a city like London ought to be more heated by the summer sun than the country around it.

His analysis is superb as he has identified most of the causes for the UHI:
1. Anthropogenic sources of heat, particularly in winter.
2. The geometry of urban surfaces that 'traps' radiation and obstructs 'free radiation to the sky'.
3. The effect of urban 'roughness' in impeding the passage of 'the light winds of summer'.
4. The lack of evaporation in the country.

The only aspect of urban areas that he did not consider is the thermal properties of urban materials.

Elsewhere, Howard considers the rate at which the urban area warms and cools relative to the surrounding country: *But this effect is not produced suddenly. For while, in the forenoon, a proportion of the walls are exposed to the sun, the remainder are in shade, and casting a shadow on the intervening ground. These are receiving, however, in the wider streets, the reflected rays from the walls opposed to them; which they return to the former, when visited in their turn by the sun. Hence in the narrow streets, especially those that run East and West, it is generally cooler than in the larger ones, and in the squares. Hence too, in the morning of a hot day, it is sensibly cooler in London than in the country; and in the evening sensibly warmer. For the hottest time in a city, relatively to the hour of the day, must be that, when the second set of vertical surfaces having become heated by the Western sun, the passenger is placed between two skreens, the one reflecting the heat it is receiving, the other radiating that which it has received. Many of my readers must recollect having felt the heat of a Western wall, in passing under it long after sunset.*

In this passage he identifies the processes of multiple reflection of solar radiation and the exchange of terrestrial radiation within streets. Critically, Howard has correctly linked observations to the three-dimensional, micro-scale, urban context within which they are situated.

Unfortunately Howard did not examine the correspondence between clouds and the magnitude of the UHI (ΔT_{u-r}). Although he kept cloud observations he did not record cloud cover. If he had, he would have seen that ΔT_{u-r} was largest when cloud cover was least. He also did not have data on wind. While he recorded wind direction by observing a vane, he had no means of systematically observing wind speed. Again, an analysis would have shown that ΔT_{u-r} was largest when winds were light. Despite these misgivings, Howard had provided a cogent explanation for the UHI that few would equal a hundred and fifty years later.

3. UHI AND URBAN CLIMATE SCIENCE

Despite this start, sustained study of the urban climate effect did not begin until the late 1940's when researchers began to explore local variations in atmospheric properties, most notably air temperature. Table 1 presents a history of the field broken down by decade. Here, I select those contributions that I think represent critical developments in the field. The selections are not intended to be illustrative rather than comprehensive.

Period	Approach
1940-	Observation and description of urban effects using conventional meteor-ological equipment (e.g. thermometers).
1960-	Employment of statistical methods to test hypotheses; Move toward energy budget approach and explanation.
1970-	Application of computer modeling techniques; Observations of energy fluxes; More rigorous definition of urban 'surface', urban scales and observing urban effects.
1980-	Adoption of common urban forms for modeling and measurement; Use of scaled-physical models; Measurement of fluxes in different cities.
1990-	Establishing relationships between urban forms and their climate effect; Urban field projects examined by research teams.
2000-	Improved models of urban geometry; Increased links between modeling and measurement programs.

3.1 *Description and Hypotheses*

In 1950 Sundborg's study of the local climate of Uppsala was published (Sundborg, 1950, 1951). It is a remarkable study in many respects as he provides a spatial picture of the UHI by using a thermometer attached to a car (Figure 2). This work confirms Howard's hypothesis that the UHI grows in magnitude from the suburban margins to the urban centre. Moreover, he proposes the following relationship,

$$\Delta T_{u-r} = 2.8 - 0.10N - 0.38U - 0.02T + 0.03e$$

In words, the strength of the heat island is inversely related to cloud cover (N), wind-speed (U) and air temperature (T) and positively correlated with absolute humidity (e). Oke (1995) chose Sundborg's monograph on the urban climate of Uppsala (Sundborg, 1951) as a classic paper of its type because: *.. he seems to have seen very clearly where the study of urban climates must go, to higher levels of inquiry. His work is not only a superb example of descriptive (climatography) but it also takes us to the next stage of establishing statistical linkage between the phenomenon and related controls. Finally, he lays out the theoretical structure necessary to study the controlling physical processes which ultimately lead to a full process-response model.*

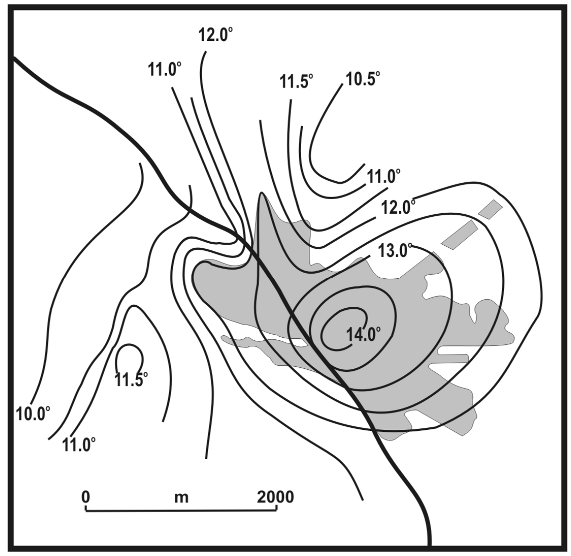

Figure 2. Isotherm map for August 30, 1948 at around 2000 hours. There were light wind ($1 ms^{-1}$) and little cloud. Redrawn from Sundborg (1950).

3.2 *Process*

Descriptive UHI studies continued to be done throughout the following decades however by the late 1960's the 'edge' of the field had shifted away from hypothesis testing, which linked meteorological variables, and toward an understanding of the processes responsible for the urban effect (Oke, 1968). This change is captured by the admonition of Terjung (1976), an urban climatologist, to his fellow physical geographers: *Physical geography could investigate the varying responses to different inputs, throughputs, and outputs of energy, mass, momentum, and information to portions of the environmental envelope of concern to mankind. I urge that this be the beacon towards which physical geographers set their sights… Climatologists, increasingly, should adopt the research level of physical process-response systems relevant to the world of man.*

The urban energy budget states that

$$Q^* + Q_F = Q_H + Q_E + Q_G,$$

where Q* represents net radiation, Q_F represents the anthropogenic heat flux, Q_H and Q_E represent turbulent sensible and latent heat exchanges with the overlying air and Q_G represents exchanges with the substrate. For simple surfaces (extensive, homogenous and flat) each of these terms can be parameterized using available meteorological data. The missing elements are the properties of the surface (albedo, roughness, wettedness) and the underlying substrate (conductivity and heat capacity). This allowed the development of simple surface energy budget models that 'solved' the budget (and balanced the terms of the equation) by iteratively seeking a surface temperature. By changing the surface properties to capture urban properties these models could provide an effective tool to simulate the UHI. Myrup (1969) was the first to apply this approach stating that, to this point in UHI research, *the complete absence of numerical estimates of the order of magnitude of the suggested mechanisms is striking.*

The resulting model produced an UHI (Figure 3) and allowed one to explore the consequences of changing surface and atmospheric parameters. However, ΔT_{u-r} was predicted to be strongest during the daytime, contrary to the observed UHI. In fact, some urban studies had shown the urban area to correspond to a 'cool' island during the daytime.

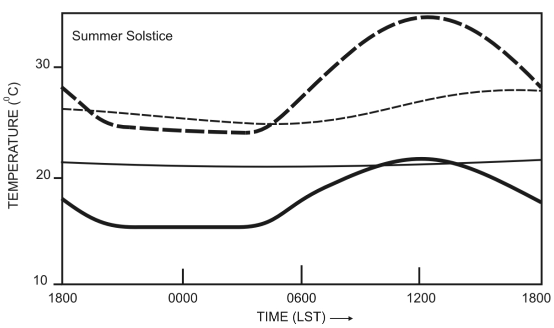

Figure3. City (dashed) and park temperatures for the air (heavy line) and soil. The park air temperature is 11.5ºC cooler at midday and 8.1ºC at dawn. Redrawn from Myrup (1969).

3.3 *Rethinking*

It was apparent that some elementary gaps remained in our understanding of the urban effect and that further conceptualizing, theorizing and observation work was required if the field were to progress. Oke et al (1972) commented that: f*aced with the enormous complexity of the city/atmosphere interface, the response of many meteorologists has been to avoid measurement, and to favor the construction of numerical or other models. This trend could lead to an unfortunate situation where research activity is divorced from physical reality.*

Analysis of the temporal development of the UHI showed it to be primarily a result of rates of night-time cooling, which occurs more quickly in rural areas (Figure 4). Coupled with the knowledge that ΔT_{u-r} is greatest under clear skies and calm conditions, this would suggest that

$$Q^* \approx Q_G ,$$

where Q* includes long-wave exchanges only. Thus a focus on the nature of radiation exchanges and on urban thermal properties would be a worthwhile pursuit.

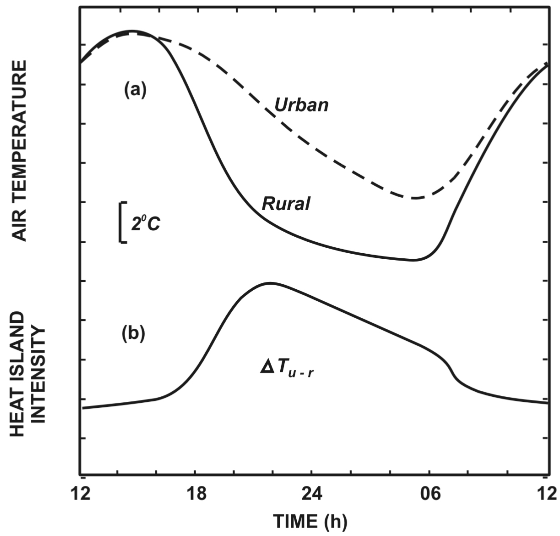

Figure 4. Typical temporal variation of rural and urban (a) air temperature and (b) the resulting heat island intensity under 'ideal' weather conditions (redrawn from Oke, 1987).

Absent from much of the discussion in this period is a consideration of the buildings and their layout that make up urban areas. Oke (1975) identified the lowest part of the UBL (that below the roof height of buildings) as belonging properly to an urban canopy layer (UCL). Observations made within this layer are strongly linked to the immediate environment – the walls and floor that comprise the street. Exchanges of radiation (Q*) in particular are regulated by the geometric properties of the street. Increasingly, simple street forms (or urban canyons) became the focus of research. This had the great benefit of linking UHI studies with those on street circulation and air quality (e.g. DePaul and Sheih, 1986).

The first measurements of the energy partitioning within an urban canyon were made by Nunez and Oke (1977): *Although progress has been made, there is still no comprehensive study available concerning the surface energy balance of an urban area… The present study was designed to investigate the energy input, partitioning and output of a characteristic urban canopy layer structure – an urban canyon* (Figure 5).

Since the 1980's the urban canyon has been employed as a fundamental structural unit of the UCL. It has proved a remarkably robust construct despite its obvious limitations and has yielded considerable insights into street microclimates and that part of the boundary layer experienced by humans. It has been employed extensively in both computational and physical modeling exercises but, until recently, there have been few observational studies. Nakmura and Oke (1988, Figure 6) is an exception. Since the 1990's other constructs of urban geometry, most notably cube forms, have been used to explore relationships between the urban 'surface' and overlying atmosphere.

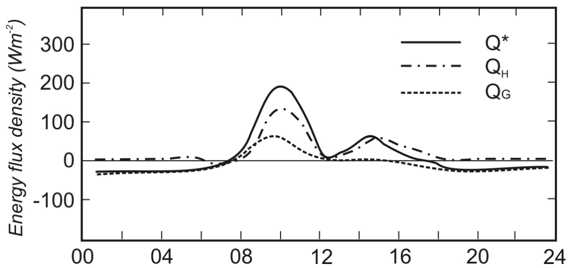

Figure 5. Diurnal energy balance for the east-facing wall of an urban street canyon based on mean hourly values for 9-11 September, 1973. Note that all the fluxes show two peaks, the first occurs as a result of direct solar receipt, the second as a result of reflection from the opposite wall. Redrawn from Figure 3a in Nunez and Oke, 1977).

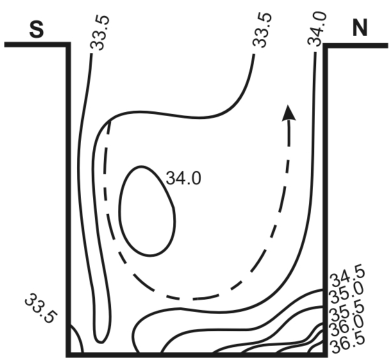

Figure 6. Isotherm (ºC) distributions across an east-west street canyon for the period 1450-1500 hours on 2 August 1983. Redrawn from Nakamura and Oke, 1988)

In addition to urban geometry, progress on the UHI required a more sophisticated approach to the thermal properties of urban materials which govern substrate exchanges. The thermal properties of manufactured construction materials, like concrete and asphalt, are distinct and consistent owing to both their density and dryness. However, the *thermal behavior of urban landscapes differs considerably from that predicted by the simple increased thermal inertia concept. The fundamental reason for this difference is the hollow structure of buildings which reduces the thermal mass of the interface compared with pavement properties* (Goward, 1981).

The combined issues of urban geometry and thermal properties continue to be problematic. For example, satellite thermal observations 'see' the roof (the base for the UBL) and street surfaces (the base of the UCL), each with distinct thermal properties and do not 'see' the walls (Voogt and Oke, 1997). Linking near-surface air and satellite observations is not obvious.

The observed maximum UHI ($\Delta T_{u-r(max)}$) for many settlements distributed in different climates shows a remarkable correlation with the ratio of building height to street width (H/W) in the center of that settlement. This relationship captures the effect of longwave 'recycling' that occurs within streets, and inhibits night-time surface (and air) cooling. Less apparent is that H/W is correlated with city 'size' and that the centre of settlements tend to correspond with highest property prices, where they may be few green spaces and taller buildings. Thus the relationship encompasses the geometry and material aspects of the urban thermal effect.

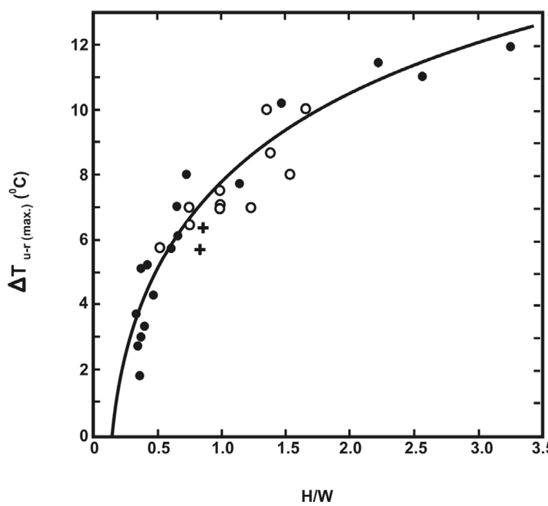

Figure 7. Maximum observed heat island ($\Delta T_{u-r(max)}$) can be related to the H/W ratio in the urban centre, $\Delta T_{u-r(max)}$ = 7.54 + 3.97 ln (H/W). Redrawn from Oke, 1987.

3.4 *Measuring the urban effect generally*

While much work on the UHI followed the 'forensic' path illustrated by the above examples, other work continued to examine the UHI using the same basic approach employed by Howard, that is, comparing air temperature measurements in urban areas against those made in a nearby rural setting (ΔT_{u-r}). Lowry (1977) examined this approach to assess the 'urban effect' problem. He identified three components in a set of measurements: the 'background' climate, the effects of the local climate and the effects of local urbanization. The individual components are not distinct and their relative contributions will vary with time depending on the frequency and duration of weather types experienced. Thus, it cannot be assumed that rural observations taken in the vicinity of an urban area represent pre-urban conditions and that rural-urban difference are the result of urbanization (Figure 6). This places considerable emphasis on the selection of both rural **and** urban sites. Lowry's work remains relevant, particularly as this is often the preferred method for establishing the degree of 'contamination' of temperature records by the urbanization process.

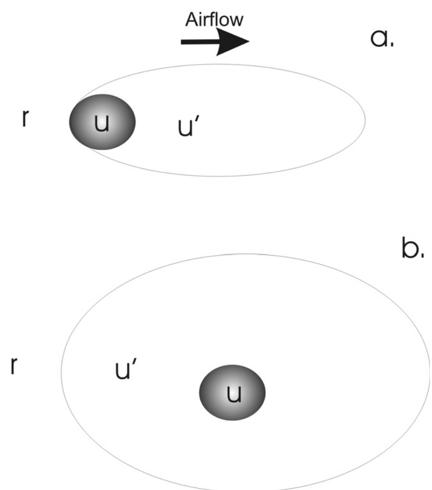

Figure 8. The urban effect is present in the urban area (u) and in a surrounding area (u'), whose shape and size depends on synoptic conditions. In a., the shape and size of u' is regulated by a particular weather event. In b., u' is defined by the sum of all weather events, that is, the climate of the area. (Adapted from Lowry, 1977).

3.5 *Urban Climatology after UHI*

To a considerable degree understanding the UHI was no longer central to the development of the field after 1990. Its exploration had forced a deeper examination of the roles of scale, geometry, materials and urban functions in creating the urban effect. It had also highlighted the need to place observations within the appropriate context in which they were made. The continuing need in the arena of urban observations is to broaden our information to include different types of cities located in different climates (Oke et al, 1992; Grimmond and Oke, 1995).

The period after 1990 has been characterized by considerable improvement in our understanding of the layers of the urban atmosphere and their interactions with the underlying urban surface (Oke, 2004). In addition, the treatment of this 'surface' has become more sophisticated so that observations can be plausibly linked to the surfaces from which their characteristics have derived (e.g. Grimmond and Oke, 1999; Schmidt and Oke, 1990).

4. DISCUSSION

Although separated by 150 years, I think that there are useful parallels to be drawn between the work of Luke Howard and that of Tim Oke that stand the test of time.

4.1 *The importance of good observations*

Howard was driven by the need to acquire observations rather than to speculate. He advocates the field of meteorology as one needing a 'greater store of facts': *Now, in no one department of Natural knowledge is the field less trodden, or the opportunity for a successful exertion of judgment in establishing general procedures greater, than in Meteorology, in its present state. …we are in want of more data, of a greater store of facts, on which to found Theory that might guide us to more certain conclusions; and the facts will certainly multiply together with observers*.

Of course, observations are only of value if the instruments are maintained and exposed correctly. In The Climate of London, Howard describes at length his concern for ensuring precise observations. It is perhaps for this reason that he is particularly disturbed at the attitude of the premier scientific organization, the Royal Society, for its published precipitation records. On comparing these with his own he finds there to be a difference of more than two inches in the annual totals. He supposes that the urban effect may contribute to this difference but finds that the data to be so poor as to be unworthy of publication. Until an instrument *shall be deemed worthy of daily use when Rain is falling, we shall in vain expect from this quarter the data needful even for the construction of the problem.*

One of the constants in Oke's work is the importance of carefully constructed and executed observational studies (e.g. Oke, 1981). These have been used effectively to distinguish the relative roles of the various processes responsible for the urban effect at different scales. Throughout his career he has employed a wide variety of methods and approaches to obtain useful data. Moreover, this experience has provided guidance for the routine gathering of (and reclaiming) valuable meteorological data gathered in non-ideal circumstances in urban areas (Oke, 2004).

4.2 *The importance of communication*

Howard uses diagrams and tables to convey temporal patterns and to illustrate the text. He justifies his use of Latin to name the clouds: *But the principal objection to English, or any other local terms, remains to be stated. They take away from the Nomenclature its present advantage of constituting, as far as it goes, an universal Language, by means of which the intelligent of every country may convey to each other their ideas, without the necessity of translation. And the more this facility of communication can be increased, by our adopting by consent uniform Modes, Terms,* *and Measures for our observations, the sooner we shall arrive at a knowledge of the phenomena of the atmosphere in all parts of the globe, and carry the science to some degree of perfection.*

The need for better communication both within urban climate and between it and cognate disciplines has been identified by Oke (2006) as essential to its maturation. *This includes standardization of symbols, terminology and indices, classification of phenomena, a protocol to generalize site description, adoption of principles of experimental design and the use of dimensional analysis and normalization to aid in the transferability of results*. The ultimate goal of urban climate science is to see its insights usefully employed by planners and designers to create more livable urban environments. Oke can reasonably claim to be among the few urban climate scientists that have attempted the difficult task of transferring scientific knowledge into practical guidelines (Oke, 1984, 1988).

The importance of scientific communities

Howard's work was a result of twenty-four years of gathering and analyzing daily observations. He was motivated by a desire to understand the vagaries of the climate and presented his work to his 'Fellow Citizens' to inform them of *what they may desire to know of the Climate and Seasons of the district in which they dwell*. He shared his insights with like-minded individuals, many of whom were gifted amateur scientists like him (Hamblyn, 2007). However, at the end of his endeavors, one gets the sense that Howard believes that his work has concluded and that others are unlikely to take on his project: *I have now… neither coadjutor nor encouragement. Science is become a mercenary scramble…Let posterity make use of the materials we have provided, and build on our foundations*.

Oke's presidential address to the 5th International Conference on Urban Climate (IAUC, 2003) described the recent history of urban climatology as one of 'reducing solitudes'. In the last forty years, the field has transformed from one characterized by individual researchers often working in isolation and meeting infrequently into one that has a healthy demographic profile and a vibrant research program. To a considerable degree this transformation has been led by Oke. While Howard may have become disillusioned by the lack of interest in continuing his work, Oke can have no such regrets. The trajectory of urban climate research outlined by Oke (1968) has been taken up by a new generation of scientists and is still yielding insights. Moreover, studies in the urban context are likely to have implications for the study of other spatially heterogeneous environments where conventional boundary-layer theory has limited application.

5. CONCLUSIONS

By comparison with the urban effect on radiation, precipitation, humidity, wind, etc., its effect on air temperature has occupied a disproportionate share of the research of urban climate science and the literature is replete with UHI studies. Few of these studies have contributed significantly to the development of the field, yet they have set the benchmarks for research in the field generally. Exploration of the UHI provided the spur for employing the urban energy budget and for establishing the roles of urban geometry and materials on the urban thermal effect at different scales. Consequently the UHI has a continued relevance to urban climate science, particularly as it must broaden its foundations to incorporate the urban climates of the rapidly urbanizing topical world.

The work of Luke Howard has a special place in the history of the field because he is the first to recognize the UHI and because his analysis proves so prescient. The International Association for Urban Climate (IAUC) presents the Luke Howard Award individuals that have made outstanding contributions to the field.

In 2004 Oke was selected as the recipient of the inaugural award for his unequalled contributions to the science of urban climate over four decades. He is *heir, in both stature and research to Luke Howard and Helmut Landsberg as one of the founding fathers of the science of urban climate* (IAUC, 2004). In addition to his scientific contributions, which are many, he has been central to the fostering the development of a scientific community in urban climatology where none existed hitherto. As such he is an active scientific citizen, interested in the pursuit of knowledge and its dissemination for everyone's benefit. Howard would be happy that 'posterity' had made use of the materials he had provided and had built upon his foundations.

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