REVIEW ARTICLE

Green and blue-space significance to urban heat island mitigation

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Abstract: It has long been recognised that cities exhibit their own microclimate and are typically warmer than surrounding rural areas. This effect known as the urban heat island (UHI) results from the inadvertent modification of surface properties that lead to greater absorption of solar radiation, reduced cooling from slower wind speeds, and lower water evaporation rates. Cities contain fewer green and blue-spaces than rural areas, with the existing under constant threat from increasing population densities. The reduced water evaporation rates in cities as a result of the loss of such features is considered a major factor in increasing the magnitude of the UHI. This paper seeks to identify the fundamental principles of how green and blue-space affect canopy- and boundary-layer temperatures in the mitigation of urban heat risks. To address this, the paper presents a review of current understanding from city-planning, urban climatology, and heat island and climate change studies. The findings highlight recent research that suggests the cooling influence of both features are mainly relevant for canopy-layer conditions, with green-space offering greater heat stress relief when it is most needed. Any contribution to the cooling of the boundary-layer climate is attributed mainly to green-space increasing surface roughness that improves convection efficiency rather than evaporation, while little evidence exists for blue-space that support significant boundary-layer influence. This in turn has significant bearing on how these features should be used in future urban growth strategies that aim to deliver a reduced UHI and enhanced climate change resilience.

Keywords: Urban heat island mitigation; Urban cooling; Green-space; Blue-space; Evapotranspiration

1.0 INTRODUCTION

Urbanisation is widely acknowledged to be on an upward trend with 66 % of the global population expected to be living in cities by 2050 (UN, 2014). The expected warming of the climate, further increases in the frequency and severity of extreme weather events, and the unique phenomena affecting urban climates are all likely to amplify the challenges facing sustainable urban growth (IPCC, 2014). The relationship between land-use and the climate as a result has attracted greater attention from city-planners to policymakers as they attempt to identify, formulate, and eventually implement growth strategies that aim to enhance the wellbeing of urban populations. The purpose of this paper is to review the effectiveness of evapotranspiration from green (vegetation cover) and blue-space (waterbodies) in relieving heat related risks, and their future significance to urban planning strategies. This study is based on a synthesis of recently published research concerning green and blue infrastructure, and heat island and climate change mitigation approaches for urban areas. The evidence base considered is geographically focused on European and American sources principally, with examples from China and the surrounding region drawn upon to stress notable findings. The outcomes presented are aimed at providing useful evidence for the planning and design of urban areas to address sustainable growth and climate resilience objectives.

1.1 The energy balance and urban form

Luke Howard was the first climatologist to hypothesise that climate interactions of cities are determined by the nature of their surface energy exchanges (Howard, 1833). Sundborg (1951) later explained the uniqueness of the urban climate, and in particular, the heat island (UHI) phenomenon in terms of the 'urban energy balance' that accounts for the incoming and outgoing energy flows from the urban surface system. The First Law of Thermodynamics states that 'energy is always conserved', the energy absorbed by the urban surface system from solar radiation and generated by anthropogenic activity must therefore be physically balanced by warming the air above the surface, evaporated as moisture, and stored as heat in surface materials (Equation 1). The partitioning of this balance defines the nature of the climate experienced, which in turn affects how cities operate (use energy) and its inhabitants flourish (health and wellbeing) (Oke, 1988b).

Equation 1. *Net Radiation + Anthropogenic Heat = Convection + Evaporation + Heat Storage*

Although natural phenomena can affect the energy balance, anthropogenic surface modifications and activities are identified as the predominant influence in cities. The features that characterise an urban environment, increased surface area and roughness of built form, the use of engineered materials, improved drainage, and increased heat output from energy use affect all five components of the above urban energy balance (Equation 1). The formation of a heat island, the most prominent and distinct urban climatic feature, is the result of the net positive thermal balance of such alterations (Oke, 1987). In an ideal stable setting (calm weather), increased net radiation and anthropogenic heat (addition of thermal energy to the climate), combined with reduced evaporation and convection and increased heat storage (increased retention of thermal energy) create the positive thermal balance for the formation of a heat island (Oke, 1987; Gartland, 2008). Human activity in cities (energy use) influences anthropogenic emissions with the potential to increase thermal energy released to the urban climate. Weather and geographical features serve to vary intensities and diffusion. The urban features that modify energy flows relate to built-environment morphology and its materiality, and available green and blue-space features. While all these factors are relevant for a physically-based assessment of urban climates, this paper focuses on the impact of green and blue-space features.

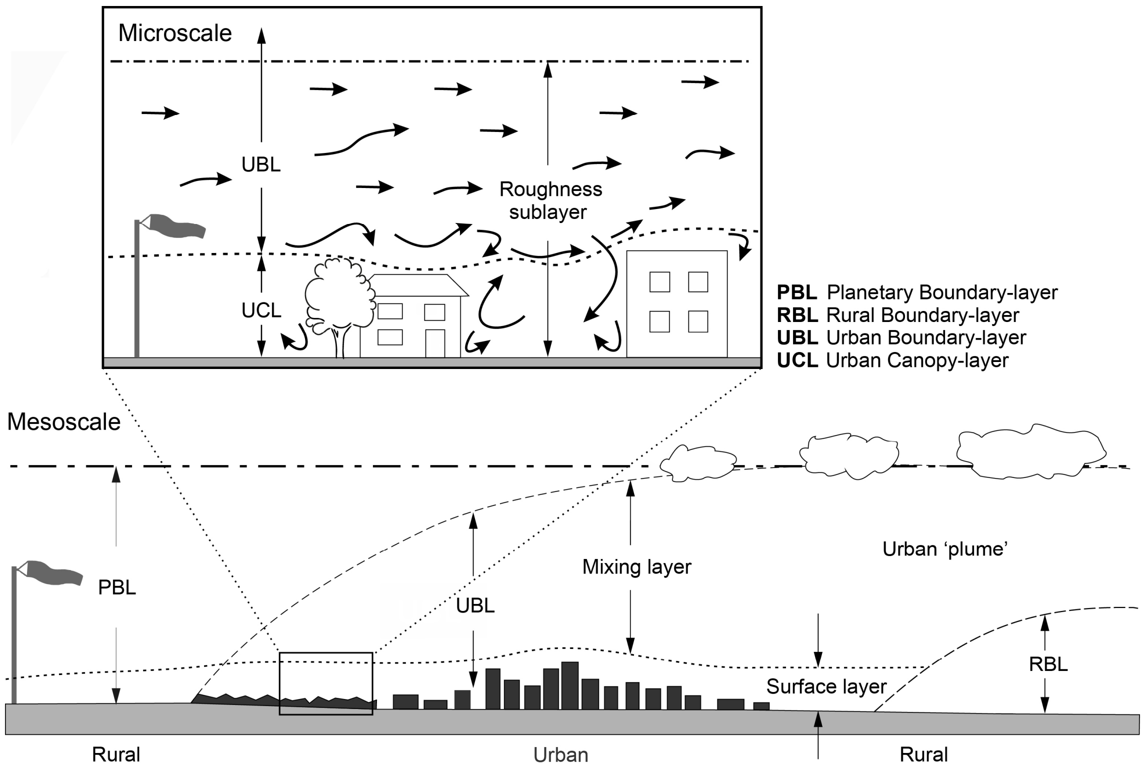

Figure 1. Illustration of the boundary-layer structures over a city resulting from increased surface roughness, based on Oke (1987)

Green and blue-space significance to the mesoscale urban climate is determined by the nature of their interactions with the structures of the urban atmosphere. The planetary boundary-layer (PBL) is a part of the atmosphere that is influenced by its contact with the planetary surface and is partitioned in urban areas into the urban boundary-layer (UBL) and the urban canopy-layer (UCL). The UBL is a mesoscale concept referring to the part of the atmosphere that is part of the PBL and situated directly above the UCL, with its qualities influenced by the presence of an urban area at its lower boundary. The UCL in contrast is a microscale concept that describes the part of the atmosphere consisting of the urban roughness elements (between the surface and the tops of buildings and trees), where the climate is dominated by the nature (materials and geometry) of the immediate surroundings (see Figure 1). The UCL represents the part of the atmosphere that people typically occupy and is as a result vital for ensuring human comfort, health, and wellbeing in cities (Oke, 1976). While any cooling value of green and blue-space is immediately significant to this stratum of the urban atmosphere, in order to influence the mesoscale urban climate and thereby mitigate the citywide warming of the UHI effect, this benefit must extend beyond the UCL in to the wider UBL.

2.0 GREEN AND BLUE-SPACE FEATURES

In urban climatology, the evaporation of water is significant for the transfer of energy from the urban surface to the atmosphere, thereby relating the surface energy balance to the hydrological cycle (Oke, 1988b). Combined with transpiration from vegetation, this process of heat transfer is referred to as 'evapotranspiration' and is influenced by the availability of moisture (vegetation cover, precipitation, irrigation etc.), humidity and wind velocity. It is estimated that annual global evapotranspiration can convert ~22 % of the total available solar energy at the top of the earth's atmosphere (Qiu *et al.*, 2013). A reduction in evapotranspiration alters the partitioning of the urban energy balance (Equation 1), as heat that would have otherwise been converted by this process instead contributes to the formation of the UHI. To mitigate the UHI, evapotranspiration can be increased by the addition of vegetation and significant waterbodies to an urban surface. The addition of such features enhances the conversion of sensible heating of the surface (Q_h) to latent heating (Q_e), which reduces its Bowen ratio (of sensible to latent heat fluxes) to present evaporative cooling ($B = Q_h/Q_e < 1$). When the Bowen ratio presents a negative value as in certain arid climate green and blue-spaces, the latent heat flux from the surface dominates the heat flux to the extent that it can create a 'heat sink' or 'oasis' effect (Taha, 1997).

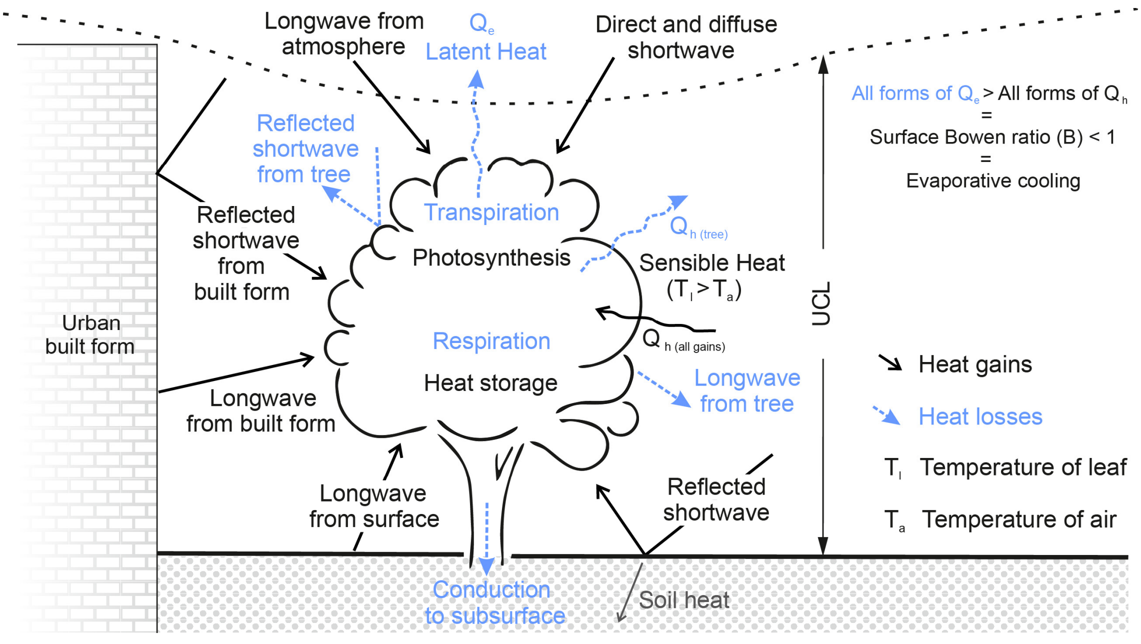

Figure 2. Daytime energy exchanges between a tree and urban form, based on Oke (1989)

2.1 Green-space

Green-space can take the form of urban forests, parks, street trees and verges, private gardens, vegetated roofs and walls and the like that provide varying ecosystem services to the urban environment. In addition to these benefits which include reduced surface run-off, flood alleviation, sustainable drainage, increased biodiversity, and general aesthetic and wellbeing enhancements, green-spaces have been found to create cooler microclimates (CCC, 2014). They are consequently regarded as critical environmental capital that can be utilised to mitigate the adverse effects of the UHI, extreme heat events, and climate change (Gill *et al.*, 2007). A recent study of Glasgow (maritime temperate Köppen climate) for example, suggested that an increase in green-space of ~20 % could eliminate between one third to half of the city's expected UHI effect in 2050 (Emmanuel and Loconsole, 2015). The introduction of such strategically planned interconnected networks of green-space offering social, economic, ecological, and climate resilience benefits is therefore promoted in city-planning discourse as 'green infrastructure' (Matthews *et al.*, 2015).

Vegetation differs from materials in urban areas in terms of moisture content, aerodynamics and thermal properties (Oke, 1989). These unique properties allow urban vegetation to modify temperatures through different yet complementing processes that prevent their immediate surroundings from being warmed (i.e. a relative cooling effect). The most discussed of such cooling processes is transpiration, where water transported through the plant is evaporated at their aerial parts by absorbing energy from solar radiation that increase latent rather than sensible heat to keep the foliage and the temperature of the surrounding atmosphere relatively cooler (Taha *et al.*, 1988). Transpiration occurs through leaf stomatal apertures that in most plant types are typically closed in the absence of solar radiation, and is therefore principally relevant to daytime (see Figure 2) rather than nighttime energy exchanges (Shashua-Bar and Hoffman, 2002). The species of vegetation considered is significant for the cooling potential achieved from transpiration. Drought-tolerant plants that utilise 'Crassulacean Acid Metabolism photosynthesis' for example, manage heat stress by keeping their stomata closed during the day, which in turn provides reduced cooling as a result of their minimal transpiration rates (Doick *et al.*, 2014). Shading from vegetation keeps the atmosphere cooler by acting as a solar radiation interceptor that absorbs radiant energy to enhance biological photosynthesis and thereby limit absorption by urban surfaces and eventual re-radiation into the canopy-layer atmosphere (Oke, 1989). The effectiveness of this shielding is determined by leaf size, crown shape, and density of the vegetation canopy, which is characterised in studies as the Leaf Area Index (LAI) and is defined as the single surface leaf area per unit of ground surface area (Santamouris, 2014). Trees, and to lesser extent shrubs, present higher shielding effectiveness in comparison to grass types. A tree canopy can therefore create a local microclimate beneath them as trunk-space cool spots, with cooling potential associated to canopy LAI (Bowler *et al.*, 2010). Depending on type and species, vegetation also modifies background wind flow to influence surface heat exchange processes. Canopy density and foliage features are similarly significant, with condensed clusters of trees identified to impede wind flow to the extent that they tend to retain warmer insulated air beneath the canopy, while dispersed clusters add to surface roughness affecting convective heat loss (Oke, 1987). Collectively, these processes of transpiration, solar shielding, and wind flow modifications provide a range of cooler conditions in green-spaces that add to the diversity of urban microclimates.

The effectiveness of the temperature modifications experienced is determined by the background climate of the vegetated area considered. As convective heat flow is dependant upon the temperature gradient, ambient temperature is a key variable that determines the rate of sensible heat released (Newton's Law of Cooling). Seasonal sensible heat flux from green-space is consequently found to be a minimum in winter, while the maximum is reached during the summer when the temperature gradient is typically higher. At greater wind speeds however, the convective heat transfer coefficient is primarily dependent on wind speed, with forced convection (greater efficiency) dominant over buoyancy-driven natural convection. Background moisture content is significant, with precipitation and/or irrigation providing greater water potential for transpiration. High atmospheric humidity however suppresses transpiration as the water potential gradient is reduced. Wind flow can be advantageous in such conditions as it assists to vacate accumulated saturation, with higher wind speeds reducing the 'leaf boundary-layer', which in turn enhances the water potential gradient and resulting latent heat flux (Santamouris, 2014).

The extent of the cooling influence provided by green-space is significant for understanding the likely comfort and public health benefits of urban greening proposals. A meta-analysis of studies on urban parks identified that on average they are 1 K cooler during the day, with evidence of this influence extending to the surroundings by varying degrees (Bowler *et al.*, 2010). To cool neighbouring areas, the cooler air in such green-spaces need to penetrate (diffuse horizontally) into the surrounding urban fabric. The formation and function of wind systems play a significant role in the distribution of this cooling potential. Prevailing wind direction affects downwind spread, aided by a combination of simple advection along aligned canyon geometries and turbulent mixing above roofs of cross canyons. This in turn establishes urban morphology features such as the sky-view factor as significant variables in modifying cooling diffusion (Chandler, 1965; Oke, 1989). As warm air rises from the surrounding urban area under stable conditions, advection currents have been identified to assist cooling diffusion by drawing air from the park as 'park breezes' (Jansson *et al.*, 2006). This park breeze effect can generate a centripetal thermal system, which completes its cycle by drawing warmer urban air from above into the park (Figure 3). The occurrence of this system may explain why the cooling rate within urban parks is seldom comparable to that of rural areas and is more closely associated with the surrounding urban context (Oke, 1989). It may also explain why parks seldom appear on UBL heat island intensity plots (e.g. Figure 4), as the occurrence of such centripetal systems are likely to hinder vertical cooling transport beyond the UCL. Vertical atmospheric stability is vital here as higher wind speeds (>5 ms^{-1}) tend to counteract cooling diffusion by disrupting buoyancy-driven effects through atmospheric mixing (Oke, 1989). Calm conditions typical of heatwaves and high UHI intensity in contrast favour the formation of buoyancy-driven centripetal systems (Oke, 1989). In a study of Kensington Gardens in London (maritime temperate) for example, cooling diffusion was observed to be at its greatest with low wind speeds and high vertical atmospheric stability. This in turn suggests that the canopy-layer cooling influence of green-space as being diffused greatest when it is most likely to be useful (during heatwaves and high UHI intensity) to relieve heat stress (Doick *et al.*, 2014).

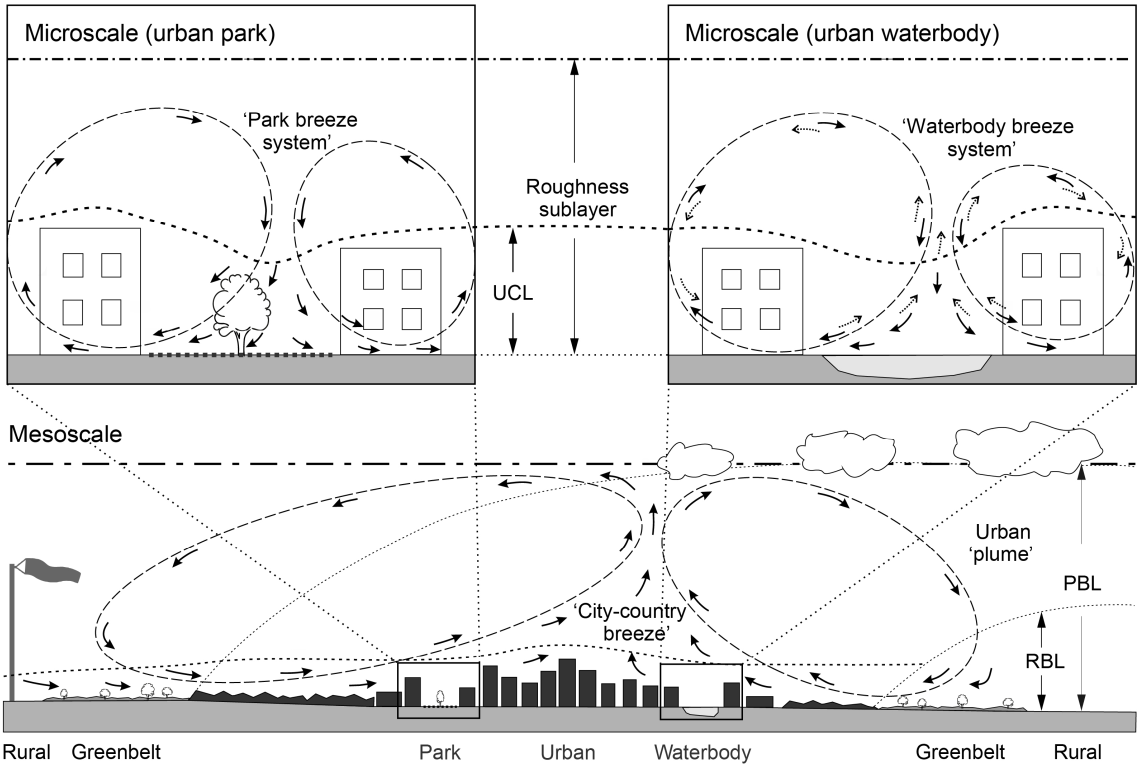

Figure 3. Illustration of green and blue-space interactions with the urban climate

The exact nature of how cooling diffuses into the surrounding urban area can differ significantly over time. An early study of Kensington Gardens and Hyde Park in London found a 3 K cooling influence extending up to 200 m beyond its boundaries (Chandler, 1965). A recent longitudinal study of Kensington Gardens highlighted a diverse nocturnal cooling range of 20-440 m (disregarding dominant south-westerly winds), with a mean summer temperature reduction of 1.1 K and a maximum reduction of 4 K observed on ceprtain nights. The study recorded an exponential decay in cooling diffusion with a substantial 83 % still observed 63 m (~half the range) from the park's boundary, which when averaged translates to a decay rate of 1.4 % per metre. Doick *et al.* (2014) argued that a higher proportion of the cooling effect seems to be maintained per metre beyond park boundaries for larger green-spaces. The magnitude of this diffusion, is dependent on the dominant vegetation profile, with cooling effectiveness typically reduced subsequent to heatwave or drought stress (Gill *et al.*, 2013). A recent modelling study consequently combined tree age and planting density as an adapted Leaf Area Index (LAIsp) as a means to calculate optimum cooling effect relative to park extents (Vidrih and Medved, 2013). The results of this modelling supported the previous finding of networks of smaller 0.2-0.3 km^2 green-spaces as providing effective cooling diffusion (Shashua-Bar and Hoffman, 2000; Vidrih and Medved, 2013). Doick and Hutchings (2013) however, argue that green-spaces smaller than 0.05 km^2 offer negligible cooling contribution, while an earlier study had suggested that green-space networks should be spaced <300 m apart to provide combined benefit (Honjo and Takakura, 1990).

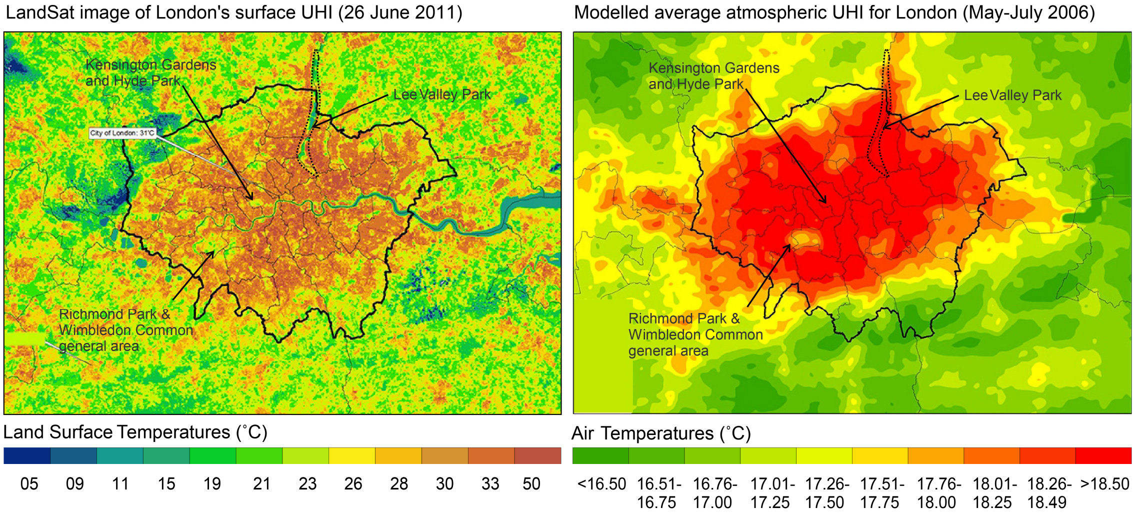

Figure 4. Summertime surface and modelled average atmospheric UHI for London (see ARUP, 2014, citing UK Space Agency (2011) and University College London (2011))

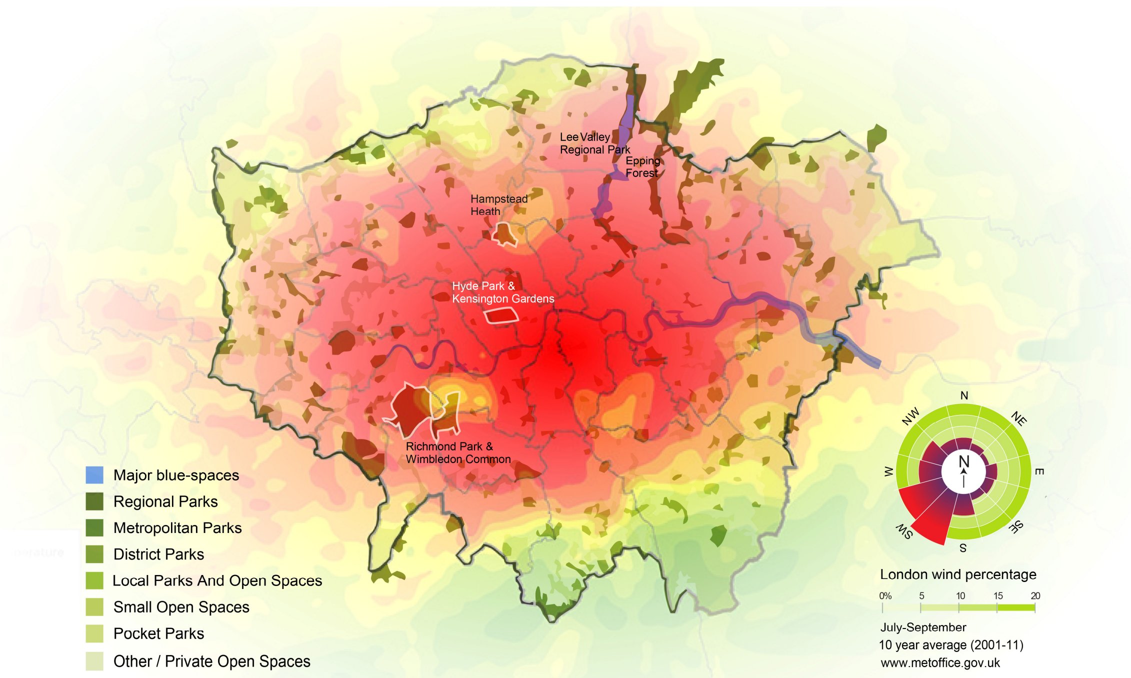

Figure 5. LUCID UHI simulation overlaid over London's green and main blue-spaces (compiled from the following sources: GLA (2012), Met Office (2012), atmospheric UHI simulation from Figure 4)

Even though larger parks with high and wide canopy trees have been shown to diffuse their cooling effect substantially, there is little quantitative evidence presented to clarify how such isolated cases affect the overall climate of a city (Bowler *et al.*, 2010). The need for clarity here is demonstrated by the comparison of a surface temperature map and an averaged atmospheric heat island simulation for London produced for relatively warm summers as part of the LUCID project (see Mavrogianni *et al.*, 2011). Accounting for predominant south-westerly winds, several areas of interest can be identified (see Figure 4). Kensington Gardens and Hyde Park's cooling influence is distinguishable at surface level, but at the atmospheric level, its significance is not apparent. The notable contributions distinguishable from examining both images represent the combined larger green-spaces of Richmond Park and Wimbledon Common, and to a lesser extent the network of green-spaces that includes Hampstead Heath (GLA, 2006). The linear Lee Valley Regional Park, which is approximately four times the size of Richmond Park, is not present in the atmospheric simulation. From these comparative observations, it can be hypothesised that the magnitude and geometrical distribution of a green-space has considerable bearing on mesoscale (citywide) UBL cooling. There is a significant gap in the literature presenting monitored vertical diffusion data for such green-spaces, which in turn makes a comprehensive assessment of the relationship between geometric parameters and the vertical transport of cooling within the mesoscale boundary-layer difficult. This lack of empirical studies could be attributed to the infrastructure necessary to carry out such vertical diffusion measurements particularly for longitudinal analyses, which are required to characterise the temporal variations of diffusion.

In contrast to most large cities, London is relatively green (Figure 5) with ~47 % of its area considered green, 33 % vegetated green-space, and 14 % as vegetated domestic gardens (ARUP, 2014). Such urban green-spaces however are under constant threat from various economic and spatial demands, particularly in urban centres where intensification of urban form is advocated by planning policy. Although the rate of decline has decelerated in recent years, urban green-space in the whole of England has reduced by 7 % (2001-13), with over two thirds of this loss due to the paving over of gardens, and the rest due to the development of greenfield sites. If further action is not taken, the Committee on Climate Change (CCC) has estimated that around 1,000 ha could be lost annually (CCC, 2014). The discussed environmental capital that green-spaces contribute to the urban setting suggests that it is sensible to conserve what already exists, and where possible to enhance green-cover in locations such as city centres, schools, and hospitals where heat stress relief is critical. It is argued that when opportunities arise to reconfigure urban areas as with regeneration projects, policy should seek to encourage their creation (Gill *et al.*, 2007).

A study of the city of Hong Kong (humid subtropical) highlights several ways to enhance urban greening in densely compacted arrangements, with tree planting emphasised as more beneficial than grass surfaces at a recommended coverage (based on Hong Kong morphology) of ⅓ of the urban area to achieve street-level temperature reductions of 1 K (Ng *et al.*, 2012). Relatively smaller tree planted green-spaces in particular are identified as being of greater use than larger grass ones, as they provide wider variety of urban greening that employs all the beneficial processes of vegetative cooling discussed earlier (Doick *et al.*, 2014). This approach also works well as an infilling strategy in urban densification schemes to create green wedges or corridors within achievable spatial demands (subject to effective geometry and width concerns discussed later). The Hong Kong study acknowledges that with extreme urban core densities, planar greening solutions such as green-roofs maybe the only viable approach (Ng *et al.*, 2012). Such planar greening strategies affect the urban thermal energy balance both directly and indirectly. It directly influences the climate by reducing surface temperatures, which in turn affects microclimate air temperatures. It indirectly modifies it by reducing heat transfer into occupied spaces and thereby reducing cooling loads and any resulting anthropogenic heat rejection to the urban climate. The Hong Kong study argued that the approach is less effective for street level comfort, particularly when typical morphology exceeds 10 m in height. In Hong Kong where the average building height is 60 m, this influence was deemed negligible (Ng *et al.*, 2012). A recent review of green-roofing studies similarly concluded proximity as significant to their cooling influence and suggested limited vertical diffusion potential, although there is little empirical evidence to support this as studies purposefully neglect monitoring beyond a canopy-layer range (Santamouris, 2014).

Studies considering vertical greening typologies have found the air temperature influence to not extend beyond their immediate foliage, and hence attributed their principal cooling purpose as a sunscreen that serves to reduce surface temperatures (Perini *et al.*, 2011). The coverage area considered by such studies however seems to be limited to either test-rigs or isolated facades. The effect of such solutions on canyon conditions, where surface temperatures are significant in modifying heat storage potential and subsequent nocturnal canopy-layer temperatures (Oke, 1988a; Bueno *et al.*, 2013), is not adequately discussed. Studies also focus on simulating or monitoring proximate canopy-layer interactions rather than vertical transport of cooling further up into the atmosphere. In general, significantly less material assesses the cooling benefit of vertical-greening solutions than horizontal, perhaps due to the limited availability of suitable case studies. The assessment of vertical greening cooling potential should therefore be considered as an emerging area of research interest.

Dispersed forms of urban development are typically criticised for increased land usage in comparison to compaction/densification strategies, with much of this usage likely to be greenfield land leading to green-space loss at the urban periphery (Echenique *et al.*, 2012). A US study has shown the rate of rural green-space loss in the most dispersing metropolitan regions to be more than double the rate in the most compact urban regions, with association made between the frequency of extreme heat events experienced and loss of regional vegetative land cover (Stone *et al.*, 2010). The significance of safeguarding peripheral green-space is further demonstrated by a study of Frankfurt's greenbelt (maritime temperate), which highlighted the zone as providing a beneficial cooling of 3-3.5 K. The study discusses this cooling influence with reference to the formation of a 'city-country breeze' (Bernatzky, 1982; 1989). Under stable conditions typical of high UHI intensity or heatwaves, this citywide system (Figure 3) is said to develop as the atmosphere at the core of the city heats and rises to the UBL to generate a low-pressure system, which then causes wind flow to advect in at canopy-layer level from the cooler surroundings of the greenbelt (Oke, 1987). Urban growth strategies that expand into such peripheral areas can reduce this beneficial breeze by modifying the energy balance at peripheries to reduce the city-country temperature gradient and potential of the system, and by preventing the supply of relatively cooler air that would otherwise been provided by greenbelt vegetation. In contradiction with the typical intentions of urban heat risk mitigation, compact forms of development that encourage higher UHI intensity by concentrating urban form, favours the formation of this cooling breeze while dispersed developments weaken it, subject to other energy balance factors.

Until recently, reductions in evapotranspiration were considered as the dominant contributor to the daytime UHI (Taha, 1997). A recent study considering cities across the US however, clarified this view by demonstrating that the daytime UHI is principally dependent on the relative effectiveness with which urban and rural areas convect heat to the climate, rather than by evaporative cooling contributions (heat storage remains dominant for the nighttime UHI). This climate modelling study suggests that if urban areas are aerodynamically smoother than surrounding rural areas, heat dissipation is relatively less efficient with potential for warming; and if reversed, could potentially lead to a cooling effect. This relative difference in convection efficiency between rural and urban conditions is said to be dependent on the background climate. In humid temperate climates, convection was found to be less efficient at dissipating heat from urban areas than from rural ones, as rural areas tend to be aerodynamically coarser than urban areas due to the presence of generally denser and coarser vegetation canopies. The study highlights urban form in such humid temperate US cities as having a reduced convection efficiency of 58 %, leading to temperature increases of up to 3.0 K that proportionally dominates their daytime UHI intensity. In dryer climates, the opposite is said to occur, as the built environment is coarser relative to the surrounding landscape, where drier conditions typically impede the growth of denser vegetation types. The study found that in such cities of the US, a 1.5 K decrease in UHI intensity was noted. In certain cities, this decrease resulted in lower urban temperatures indicating a daytime heat sink effect (Zhao *et al.*, 2014). This phenomenon had previously been explained with reference to the 'oasis effect' resulting from the enhanced evaporative cooling provided by urban trees and landscape gardening (Peng *et al.*, 2012). Zhao *et al.* (2014) however, argued that based on proportional contributions to the overall daytime UHI intensity (determined by their climate model and verified through remote-sensing surface temperature calculations), this evaporative cooling contribution is minimal in comparison to convection efficiency.

The findings of Zhao *et al.* (2014) suggest that the addition of vegetation with the principal aim of improving evapotranspiration qualities of the urban surface may prove to have lesser bearing on the mitigation of the daytime UHI than previously held. At the boundary-layer scale of the urban surface, the presence of vegetation seems to provide greater service to the cooling of the city by enhancing its surface roughness. In humid climates where daytime UHI warming is observed to be substantial, the addition of vegetation to increase inner-city surface roughness remains a viable strategy (Zhao *et al.*, 2014). If urban greening is to be utilised in this manner, tree planting with increased diversity of species suggests greater provision of roughness than planar greening approaches. The typologies of urban greening to be used therefore require consideration of not only transpiration potential, but also the roughness they deliver in their varied arrangements and seasonal forms. The planning of green infrastructure must recognise these typological diversities and their various arrangement options in the future deployment of green infrastructure. Certain planning processes have in recent times developed weighting systems that address the relative environmental capital of different green-space cover. The Green Area Ratio (GAR) implemented in Berlin and adapted in Malmo (Sweden) for example assigns weighting factors based on their relative climate change mitigation potential (Keeley, 2011). Such planning mechanisms however must be constantly updated with multidisciplinary evidence to ensure that greening strategies achieve their highest heat mitigation potential.

2.2 Blue-space

Urban blue-space refers to the general category of features that facilitate the presence of substantial bodies of surface water. In certain cities, their historical geopolitical significance has meant that substantial blue-spaces naturally exist as integral features of their geography. In the port city of London the River Thames is its dominant feature, which with other blue-space bodies such as tributaries, canals and reservoirs collectively represent ~2.5 % of the cities surface area

(ARUP, 2014). A study of the Thames found the air temperature at the riverside to be 0.6 K cooler on average than in neighbouring streets (Graves *et al.*, 2001). A recent meta-analysis of 27 studies has suggested that blue-space in general could provide a cooling effect of 2.5 K on average (including remote-sensing based studies) relative to their surroundings (Volker *et al.*, 2013). Studies considering the cooling benefits of such blue-space however are relatively fewer in comparison to green-space, with those available focusing on daytime influence. Air temperature monitoring studies are also notably limited in comparison to surface temperature studies. It is important to note that such remote-sensing based surface temperature studies only capture significantly larger bodies of water for a single moment in time and do not account for the conversion of sensible heat into latent heat (Sun and Chen, 2012; Volker *et al.*, 2013).

A waterbody's ability to modify surrounding temperatures is determined by its inherent properties and interactions with surrounding climate conditions. In literature, attention is directed predominantly to evaporative cooling where water absorbs thermal energy from ambient conditions to transform sensible heating to latent heating. The thermal properties of high specific heat capacity and enthalpy of vaporisation gives water a high thermal inertia, which plays a significant role in moderating temperatures and temporal variations that enable water to act as a thermal buffer (Oke, 1987). Surface reflectance (albedo) is significant for determining radiation exchanges. The albedo of blue-space is broadly considered as low (~0.09) at low to medium angles (predominant) of solar radiation incidence and varies daily with flow rate and dynamics (waviness) and the quantity of suspended particles (Oke, 1987; Taha *et al.*, 1988). This means that most of the incident shortwave solar radiation (ultraviolet, visible, and near infrared light between wavelengths ~0.1 µm - ~5.0 µm) is absorbed. The energy not released through evaporative (latent) cooling is re-radiated as longwave infrared radiation (wavelengths between 4 µm - 100 µm) back into the atmosphere after a time lag. The sensible cooling effectiveness of a blue-space is dependent on the net effect of this radiation balance and the sensible to latent heat conversion achieved (Hathway and Sharples, 2012). Static and dynamic types of blue-space achieve this in different ways. Dynamic types such as rivers or canals are able to carry by advection absorbed radiation downstream (subject to flow-dynamics) to release energy in different locations external to the urban climate system (Hathway and Sharples, 2012). Although this form of advective cooling is beneficial to an upstream city, the process can lead to thermal pollution and environmental concerns in ecological systems further downstream. As this form of advective energy discharge is limited in static bodies, they tend to demonstrate higher sensitivity to energy exchange modifications resulting from prevailing climate and seasonal conditions. Higher ambient temperatures in general translate to greater amounts of energy within the climate system, while higher surface temperature and humidity gradients increase the potential for sensible and latent cooling with increased capacity to transfer energy and moisture into the atmosphere. Increased wind velocity significantly alters the evaporative heat flux by advecting away thermal energy and moisture to enhance temperature and humidity gradients (Hathway and Sharples, 2012).

As discussed for green-space, the cooling effectiveness of blue-space may be argued as being dependant on the size and spread of bodies and the distance from them. Theeuwes *et al.* (2013) recently confirmed the significance of these parameters with the aid of a mesoscale model of hypothetical waterbodies simulated within an idealised city. The study highlighted that relatively large bodies demonstrate a greater cooling effect adjacent to their boundaries and in downwind areas. The size and length of the downwind spread is dependent on the wind velocity with the relative cooler air originating from a body transported by winds to generate plumes several kilometres long. The study also confirmed a previous remote-sensing study finding which suggested that several smaller regularly shaped waterbodies distributed equally within the urban area as having a smaller temperature effect (particularly during the day), although across a larger area of the city (Sun and Chen, 2012; Theeuwes *et al.*, 2013). The earlier Sun and Chen (2012) study of Beijing (humid continental) highlighted the geometry of a waterbody as significant with square or round-shapes providing higher cooling efficiency. They argued that the temperature and humidity gradient between a blue-space (or green-space) and its surrounding landscape is likely to be relatively smaller for a narrow-shaped feature, which in turn negatively affects cooling potential. Furthermore, they identified that surface temperatures around waterbodies located within surrounding built form tend to be substantially higher (owing to their typical materiality), which in turn assists to generate a steeper temperature gradient that positively affects cooling potential (Sun and Chen, 2012). The significance of width of a waterbody was also observed by a review of dynamic features in Beijing that highlighted urban river width as a principal factor affecting the temperature and humidity of nearby surroundings. They found that when the river width was >40 m, a significant and stable effect of decreasing temperatures and increasing humidity was evident (Zhu *et al.*, 2011). This significance of width may be one probable explanation for why the linear Lea Valley Park does not appear to be contributing a cooling benefit to the atmospheric UHI simulation for London discussed earlier (see Figure 4). It could be hypothesised that the linear geometry of the Park (of which a significant proportion is covered by reservoirs), does not provide a temperature and humidity gradient sufficient to generate the vertical diffusion of cooling necessary to modify mesoscale atmospheric conditions.

A longitudinal canopy-layer study of an urban river in Sheffield (maritime temperate) highlighted that the cooling effect tends to be greatest in the morning; with warm days in May demonstrating ~2 K cooling over the river and 1.5 K at the banks. At nighttime however, no significant cooling was observed, while towards late June even daytime cooling had notably diminished with similar ambient air temperatures (Hathway and Sharples, 2012). In support of such observations, the simulation study of a hypothetical city discussed above identified blue-space cooling as principally relevant during the daytime, while at night a 'warming effect' was probable (Theeuwes *et al.*, 2013). These diurnal-nocturnal and seasonal variations in cooling are explained by the thermal inertia of waterbodies and its interaction with the surface radiation balance. The energy absorbed and not released through latent cooling during the day is stored within the waterbody and re-radiated as longwave radiation back into the atmosphere at night. As evaporative cooling during the day increases atmospheric saturation, and the surrounding urban surfaces cool faster than the waterbody to reduce the temperature gradient, potential for nighttime evaporative cooling is diminished. Stability is significant as wind flow aids to vacate accumulated atmospheric saturation produced by the waterbody, the failure of which leads to a saturated boundary-layer that suppresses further evaporation by reducing the humidity gradient. Reduced nocturnal evaporative cooling and increased energy storage results in higher water temperatures. This acts to tip the net effect of thermal exchanges against evaporative cooling to facilitate greater re-radiation of longwave radiation resulting in atmospheric warming. The occurrence of these conditions are particularly apparent when waterbodies reach higher temperatures towards the end of the summer due to greater accumulation of stored thermal energy. Furthermore, Theeuwes *et al.* (2013) showed that when the diurnal cycle of water temperature is accounted for, this variation might result in a reduced duration of cooling in the evening and greater warming during the night.

The blue-space studies reviewed primarily focus on canopy-layer horizontal diffusion patterns as it is of greater significance to human health and comfort, with limited discussion of the characterisation of vertical diffusion. The Theeuwes *et al.* (2013) study provides the exception by considering two boundary-layer schemes modelled for a hypothetical lake. It is worth noting that the simulated lake in this study is notably large (covering 10 % of the city) and was influenced by their research plan to compare the diffusion sensitivity offered by the two different boundary-layer schemes. Notwithstanding subtle disparities, both schemes highlight the general trend where the greatest vertical transport of cooling is in the afternoon (at 3 PM), although in the morning (10 AM) and at nighttime (4 AM), the modest cooling and predominant warming was restricted to lower altitudes (<500 m). This limited vertical transport during the night may be influenced at the mesoscale level by the typically observed contraction of the nocturnal UBL, as the urban surface cools (Oke, 1987). At the microscale however, there is little explanation provided in studies. It is worth noting that none consider the possibility of whether the daytime advective cooling breezes diffusing out to the surroundings from the waterbody lead to the formation of a centripetal system similar to that of park breezes discussed earlier. If such a 'waterbody breeze' system were to form under similar stable conditions (Figure 3), it could be said to hinder vertical transport up in to the UBL, which possibly explains why waterbody influence is seldom evident in UHI studies such as the LUCID project simulation (Figure 4). The formation of a waterbody breeze system however, would be dissimilar to a park breeze due to the thermal inertia of water and its day-to-night cooling cycle leading to generally warmer nighttime temperatures than the surrounding urban landscape. The system could thus be expected to reverse during the night as warm air rises from the warmer waterbody to create a low-pressure system that in turn advects cooler air in from the surroundings. The completion of this nighttime centripetal cycle would be the settling of warmer and humid air back into the surrounding context at a higher canopy-layer level (see Figure 3). This in turn presents the possibility for an undesirable warming of the surrounding areas during stable climatic conditions (such as heatwaves and periods of peak nocturnal UHI intensity).

The canopy-layer trapping of heat presents significant threat to not only thermal comfort, but also to human health with nighttime temperatures epidemiologically established to be particularly oppressive (Kalkstein and Davis, 1989). Even during the day, the supposed cooling benefit from the dominance of evaporative cooling from waterbodies may prove to be somewhat misleading. A significant drawback of an evaporative cooling process is that it increases ambient humidity. The Theeuwes *et al.* (2013) study revealed that in some instances ~60 % of the comfort achieved by the sensible cooling effect of blue-space might be negated by this humidity modification. Considering such diurnal-nocturnal thermal exchange processes of blue-space, they may be said to work to warm urban environments when it is least desired (at night and stable conditions typical of high UHI intensity and heatwaves), and as such offer limited potential for urban heat risk mitigation when considered in isolation.

2.3 Synergistic cooling

Although green and blue-space is often highlighted for providing mutually dependent environmental capital (Hathway and Sharples, 2012; Volker *et al.*, 2013), comparative assessment of both features are uncommon in literature. A notable example is provided by a measured study of six parks and three lakes in Chongqing, China (humid subtropical) where cooling in parks was found to be more defined than at lakes with the maximum recorded at 3.6 K for parks and 2.9 K for lakes (Li and Yu, 2014). The study however considered this comparison in isolation, with little discussion on the integrated dynamics between the two features. Xu *et al.* (2010) in contrast considered such synergistic dynamics, although based on case study specific observations in Shanghai (humid subtropical) to propose a regression calculation to extend the observed 10-20 m zone of improvement in thermal comfort with the use of peripheral vegetation. Synergistic influence discussed by other studies are principally limited to recommendations of achievable enhancement based on generally acknowledged principles, or as explanations for identified anomalous cooling enhancements. The Hathway and Sharples (2012) study for example observed that the highest cooling diffusion at ~30 m from the river centre was evident at banks with greenery and street canyons opened-up to the river. Beyond such observations, there is little quantitative analysis offered to describe the synergistic processes involved, particularly for conditions where both features are integrated in to one infrastructural network. This in turn highlights a notable gap requiring further research. Observed forms of such further study however will be case study specific (as in Xu *et al.*, 2010), as no two urban infrastructural networks utilising both features are likely to be similar. For ascertaining more generally applicable principles, there is opportunity to consider scenario simulations, possibly based on percentage covers and archetypal arrangements. Similar to assessing horizontal canopy-layer diffusion, there is a need to ensure that vertical diffusion is assessed in order to ascertain whether interactions between the two features lead to beneficial mesoscale influence.

3.0 CONCLUSION

This paper has considered first principle observations on how green and blue-space features influence the mitigation of urban heat risks. By reviewing recent evidence, it highlights that:

- Evapotranspiration from vegetation contributes only marginally to the mitigation of the daytime UHI effect. This reduced emphasis however does not suggest that green-space is entirely ineffective. It only implies that evapotranspiration has less impact on the mesoscale boundary-layer climate (which determines the daytime UHI); while significant cooling effects at microscale canopy-layer climates remain valid, with relief established to extend (to varying degrees) beyond their boundaries.

- For both green and blue-space features, their microscale canopy-layer cooling effects are dependent on scale, geometry and spread of interventions, morphology of their immediate context, prevailing wind flow, and ambient temperature and humidity conditions. Green-spaces have been observed to extend their cooling effect greatest during conditions typical at high UHI intensity and heatwaves to provide relief when it is most likely to be required. Blue-spaces in contrast may provide a warming effect, particularly at night and towards the end of summer, when UHI intensity and risk from heat stress (epidemiologically identified) is most oppressive. This suggests that when considered in isolation, green-space is of greater benefit to heat risk mitigation than blue-space. However, when employed together both green and blue-space provide mutually dependent environmental capital that offer many benefits including synergistic cooling, although little quantitative evidence is presented by studies to validate this assertion.

- Where vegetation is utilised to mitigate urban heat risks, diverse tree planting is observed to offer greater surface roughness, shading, and evaporative cooling. For both green and blue features, the addition of multiple smaller interventions that take advantage of dominant wind patterns tend to offer greater effect across a larger canopy-layer area than with a solitary larger feature. This suggests that useful green and blue-space can be introduced as infilling features even in high-density compaction (regeneration) strategies. Furthermore, the addition of such green and blue infrastructural networks is aligned with the public health objective of providing greater access to cooler environments in addressing urban heat stress.

- The review highlights several key gaps in research. When considering urban greening solutions, there is greater need for empirical studies on how widespread vertical surface greening (particularly within canyons) influences canopy-layer temperatures. When considering urban blue-space, studies in general are comparatively fewer and particularly scarce for nighttime conditions. For both green and blue-space, there is little discussion offered on vertical transport and synergistic cooling, and no studies specifically addressing the impact of urban development approaches such as compaction or dispersal on green and blue-space distribution and resultant UHI mitigation.

- Geographical spread of studies reviewed suggest that in China and surrounding countries in the region there is a recent surge of interest in both green and blue-space strategies, fuelled by the need to address climate resilience challenges for their rapidly expanding cities and planned development of new cities. In the UK, compaction strategies are likely to remain the principal policy for urban development with attention given to safeguarding existing green and blue-space features from development pressures.

The study of green and blue-space features enable city-planners, engineers, and architects to determine the microclimatic qualities that are likely to protect and enhance the health and wellbeing of urban inhabitants, and citywide strategies that mitigate the mesoscale UHI to provide greater climate resilience. Key to assessing these features is to consider urban growth not only in terms of socioeconomic and political concerns, but also in terms of the physically-based consequences on the energy balance. This in turn would assist the development of strategic policies that address climate readiness and urban growth while acknowledging the energetic-basis of the climate challenges that influence how cities function and their inhabitants flourish.

4.0 BIBLIOGRAPHY

ARUP, 2014. *Reducing urban heat risk: A study on urban heat risk mapping and visualisation.* London: ARUP.

Bernatzky, A., 1982. The Contribution of Trees and Green Spaces to a Town Climate. *Energy and Buildings,* 5(1), pp. 1-10.

Bernatzky, A., 1989. *Tree ecology and preservation.* Third ed. Amsterdam: Elsevier.

Bowler, D.E., Buyung-Ali, L., Knight, T.M. & Pullin, A.S., 2010. Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape Urban Plan,* 97(3), pp. 147-155.

Bueno, B., Norford, L., Hidalgo, J. & Pigeon, G., 2013. The urban weather generator. *Journal of Building Performance Simulation,* 6(4), pp. 269-281.

CCC, 2014. *Managing climate risks to well-being and the economy.* London: Committee on Climate Change (Adaptation Sub-Committee).

Chandler, T.J., 1965. *The Climate of London.* London: Hutchinson & Co Ltd.

Doick, K. & Hutchings, T., 2013. *Air Temperature regulation by urban trees and green infrastructure.* Farnham: The Forestry Commission.

Doick, K.J., Peace, A. & Hutchings, T.R., 2014. The role of one large greenspace in mitigating London's nocturnal urban heat island. *The Science of the total environment,* 493, pp. 662-71.

Echenique, M.H., Hargreaves, A.J., Mitchell, G. & Namdeo, A., 2012. Growing Cities Sustainably: Does Urban Form Really Matter? *J Am Plann Assoc,* 78(2), pp. 121-37.

Emmanuel, R. & Loconsole, A., 2015. Green infrastructure as an adaptation approach to tackling urban overheating in the Glasgow Clyde Valley Region, UK. *Landscape Urban Plan,* 138, pp. 71-86.

Gartland, L., 2008. *Heat Islands: Understanding and Mitigating Heat in Urban Areas.* Oxford: Routledge.

Gill, S., Handley, J., Ennos, A. & Pauleit, S., 2007. Adapting Cities for Climate Change: The Role of the Green Infrastructure. *Built Environment,* 33(1), pp. 115-33.

Gill, S.E., Rahman, M.A., Handley, J.F. & Ennos, A.R., 2013. Modelling water stress to urban amenity grass in Manchester UK under climate change and its potential impacts in reducing urban cooling. *Urban Forestry & Urban Greening,* 12(3), pp. 350-358.

GLA, 2006. *London's urban heat island: a summary for decision makers.* London: Greater London Authority.

GLA, 2012. *Green infrastructure and open environments: the all London Green Grid.* London: Greater London Authority.

Graves, H.M., Watkins, R., Westbury, P. & Littlefair, P.J., 2001. *Cooling buildings in London: overcoming the heat island.* London: Construction Research Communications Ltd.

Hathway, E.A. & Sharples, S., 2012. The interaction of rivers and urban form in mitigating the Urban Heat Island effect: A UK case study. *Building and Environment,* 58, pp. 14-22.

Honjo, T. & Takakura, T., 1990. Simulation of thermal effects of urban green areas on their surrounding areas. *Energy and Buildings,* 15(3-4), pp. 443-446.

Howard, L., 1833. *The climate of London.* Second ed. London.

IPCC, 2014. *Climate Change 2014, Impacts, Adaptation, and Vulnerability, Summary for Policymakers.* New York: Cambridge University Press.

Jansson, C., Jansson, P.E. & Gustafsson, D., 2006. Near surface climate in an urban vegetated park and its surroundings. *Theoretical and Applied Climatology,* 89(3-4), pp. 185-193.

Kalkstein, L.S. & Davis, R.E., 1989. Weather and Human Mortality - an Evaluation of Demographic and Interregional Responses in the United-States. *Ann Assoc Am Geogr,* 79(1), pp. 44-64.

Keeley, M., 2011. The Green Area Ratio: an urban site sustainability metric. *Journal of Environmental Planning and Management,* 54(7), pp. 937-958.

Li, C. & Yu, C.W., Year. Mitigation of urban heat development by cool island effect of green space and water body. In: Proceedings of the 8th International Symposium on Heating, Ventilation and Air Conditioning, 2014. Springer, pp. 551-561.

Matthews, T., Lo, A.Y. & Byrne, J.A., 2015. Reconceptualizing green infrastructure for climate change adaptation: Barriers to adoption and drivers for uptake by spatial planners. *Landscape Urban Plan,* 138, pp. 155-163.

Mavrogianni, A., Davies, M., Batty, M., Belcher, S.E., Bohnenstengel, S.I., Carruthers, D., Chalabi, Z., Croxford, B., Demanuele, C., Evans, S., Giridharan, R., Hacker, J.N., Hamilton, I., Hogg, C., Hunt, J., Kolokotroni, M., Martin, C., Milner, J., Rajapaksha, I., Ridley, I., Steadman, J.P., Stocker, J., Wilkinson, P. & Ye, Z., 2011. The comfort, energy and health implications of London's urban heat island. *Build Serv Eng Res T,* 32(1), pp. 35-52.

Met Office, 2012. Southern England: Climate. Exeter: Met Office.

Ng, E., Chen, L., Wang, Y.N. & Yuan, C., 2012. A study on the cooling effects of greening in a high-density city: An experience from Hong Kong. *Building and Environment,* 47, pp. 256-271.

Oke, T.R., 1976. The distinction between canopy and boundary-layer urban heat islands. *Atmosphere,* 14(4), pp. 268-77.

Oke, T.R., 1987. *Boundary Layer Climates.* New York: Routledge.

Oke, T.R., 1988a. Street Design and Urban Canopy Layer Climate. *Energy and Buildings,* 11(1-3), pp. 103-113.

Oke, T.R., 1988b. The Urban Energy-Balance. *Progress in Physical Geography,* 12(4), pp. 471-508.

Oke, T.R., 1989. The Micrometeorology of the Urban Forest. *Philos T Roy Soc B,* 324(1223), pp. 335-349.

Peng, S., Piao, S., Ciais, P., Friedlingstein, P., Ottle, C., Breon, F.M., Nan, H., Zhou, L. & Myneni, R.B., 2012. Surface urban heat island across 419 global big cities. *Environmental science & technology,* 46(2), pp. 696-703.

Perini, K., Ottele, M., Fraaij, A.L.A., Haas, E.M. & Raiteri, R., 2011. Vertical greening systems and the effect on air flow and temperature on the building envelope. *Building and Environment,* 46(11), pp. 2287-2294.

Qiu, G.Y., Li, H.Y., Zhang, Q.T., Chen, W., Liang, X.J. & Li, X.Z., 2013. Effects of Evapotranspiration on Mitigation of Urban Temperature by Vegetation and Urban Agriculture. *Journal of Integrative Agriculture,* 12(8), pp. 1307-1315.

Santamouris, M., 2014. Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Solar Energy,* 103, pp. 682-703.

Shashua-Bar, L. & Hoffman, M.E., 2000. Vegetation as a climatic component in the design of an urban street - An empirical model for predicting the cooling effect of urban green areas with trees. *Energy and Buildings,* 31(3), pp. 221-235.

Shashua-Bar, L. & Hoffman, M.E., 2002. The Green CTTC model for predicting the air temperature in small urban wooded sites. *Building and Environment,* 37(12), pp. 1279-1288.

Stone, B., Hess, J.J. & Frum, H., 2010. Urban Form and Extreme Heat Events: Are Sprawling Cities More Vulnerable to Climate Change Than Compact Cities. *Environmental health perspectives,* 118(10), pp. 1425-28.

Sun, R. & Chen, L., 2012. How can urban water bodies be designed for climate adaptation? *Landscape Urban Plan,* 105, pp. 27-33.

Sundborg, A.A., 1951. *Climatological Studies in Uppsala. With special regard to the temperature conditions in the urban area.* Uppsala: Appelbergs Boktryckeri Aktiebolag.

Taha, H., 1997. Urban climates and heat islands: Albedo, evapotranspiration, and anthropogenic heat. *Energy and Buildings,* 25(2), pp. 99-103.

Taha, H., Akbari, H., Rosenfeld, A. & Huang, J., 1988. Residential Cooling Loads and the Urban Heat-Island - the Effects of Albedo. *Building and Environment,* 23(4), pp. 271-283.

Theeuwes, N.E., Solcerova, A. & Steeneveld, G.J., 2013. Modeling the influence of open water surfaces on the summertime temperature and thermal comfort in the city. *J Geophys Res-Atmos,* 118(16), pp. 8881-8896.

UN, 2014. *World Urbanization Prospects: The 2014 Revision, Highlights.* New York: United Nations, (ST/ESA/SER.A/352).

Vidrih, B. & Medved, S., 2013. Multiparametric model of urban park cooling island. *Urban forestry & urban greening,* 12(2), pp. 220-229.

Volker, S., Baumeister, H., Classen, T., Hornberg, C. & Kistemann, T., 2013. Evidence for the Temperature-Mitigating Capacity of Urban Blue Space - a Health Geographic Perspective. *Erdkunde,* 67(4), pp. 355-371.

Xu, J., Wei, Q., Huang, X., Zhu, X. & Li, G., 2010. Evaluation of human thermal comfort near urban waterbody during summer. *Building and environment,* 45(4), pp. 1072-1080.

Zhao, L., Lee, X., Smith, R.B. & Oleson, K., 2014. Strong contributions of local background climate to urban heat islands. *Nature,* 511(7508), pp. 216-9.

Zhu, C., Li, S., Ji, P., Ren, B. & Li, X., 2011. Effects of the different width of urban green belts on the temperature and humidity. *Acta Ecologica Sinica,* 31(2), pp. 0383-0394.