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Utilising green and bluespace to mitigate urban heat island intensity

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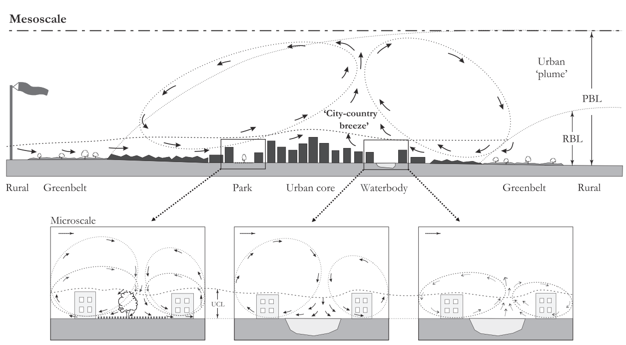
HIGHLIGHTS

- The influence of green and bluespace on urban canopy/boundary-layer temperatures.
- Tree-dominated greenspace offers greater heat stress relief when most required.
- Badly designed bluespace, may exacerbate heat-stress during oppressive conditions.
- Boundary-layer cooling is attributed to greenspace increasing surface roughness.
- The influence of geometry and diversity of green/bluespaces requires more research.

GRAPHICAL ABSTRACT



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ABSTRACT

It has long been recognised that cities exhibit their own microclimate and are typically warmer than the surrounding rural areas. This 'mesoscale' influence is known as the urban heat island (UHI) effect and results largely from modification of surface properties leading to greater absorption of solar radiation, reduced convective cooling and lower water evaporation rates. Cities typically contain less vegetation and bodies of water than rural areas, and existing green and bluespace is often under threat from increasing population densities. This paper presents a meta-analysis of the key ways in which green and bluespace affect both urban canopy- and boundary-layer temperatures, examined from the perspectives of city-planning, urban climatology and climate science. The analysis suggests that the evapotranspiration-based cooling influence of both green and bluespace is primarily relevant for urban canopy-layer conditions, and that tree-dominated greenspace offers the greatest heat stress relief when it is most needed. However, the magnitude and transport of cooling experienced depends on size, spread, and geometry of greenspaces, with some solitary large parks found to offer minimal boundary-layer cooling. Contribution to cooling at the scale of the urban boundary-layer climate is attributed mainly to greenspace increasing surface roughness and thereby improving convection efficiency rather than evaporation. Although bluespace cooling and transport during the day can be substantial, nocturnal warming is highlighted as likely when conditions are most oppressive. However, when both features are employed together they can offer many synergistic ecosystem benefits including cooling. The ways in which green and bluespace infrastructure is applied in future urban growth strategies, particularly in countries expected to experience rapid urbanisation, warrants greater consideration in urban planning policy to mitigate the adverse effects of the UHI and enhance climate resilience.

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1. 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 greatest urbanisation is anticipated to be in Africa and Asia, where some countries are expected to experience greater than a five-fold increase in urban populations by 2050. Projections of climate change show increasing frequency and severity of extreme weather events, such as heatwaves. Such events, coupled with the UHI are likely to amplify the challenges facing this urban growth (IPCC, 2014). For these reasons, the relationship between land-use and the urban climate has attracted ever-increasing 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. This paper reviews the effectiveness of green (areas dominated by vegetation cover) and bluespace (areas dominated by surface waterbodies or watercourses) in reducing the risks of heat related illness from high urban temperatures and their significance to future urban planning strategies. Results are considered in relation to urban morphology and growth. City-planners have devised many models for conceptualising urban development that describe contrasting land-use morphologies and distributions. Of the many such models, the two theoretical extremes considered in relation to this paper are the 'compaction' and 'dispersal' models. Both have widely featured in city-planning and urban growth discourse, with a comparative preference directed towards the compaction model as offering a more sustainable framework for growth (Williams, 2014). This paper utilises these models to discuss green and bluespace deployment and to compare results from recent studies.

A preference for urban containment has its origins in the long-held desire to safeguard the countryside from encroachment and unrestricted sprawl. The 'compact city' and its merits were promoted in the UK largely by the Urban Task Force, which resulted in a UK Government White Paper that eventually translated to various policy measures (Rogers, 1999). In the USA, similar principles have been advocated under the 'smart growth' model (Williams, 2014). The aim of such compaction approaches to urban design is to promote efficient land-use with the aid of integrated and well-served public transport services. Higher urban density is considered to reduce resource consumption and lower economic and environmental costs (CO_2 emissions). The legacy of such urban compaction policies is evident in modern England, where ~80% of the population occupies only ~20% of the land and over 70% of new development takes place on brownfield land at relatively high densities (ONS, 2015; Rogers, 2005). Further advantages of urban compaction include the revitalisation of historic buildings and spaces, efficient use of existing infrastructure, use of non-car travel (promoting health and psychological wellbeing), improved safety from natural surveillance and increased variety and frequency of social and cultural experiences (Rogers, 1999). Since the late 90s, such advantages have been regarded as the essential features of a thriving urban environment (Williams, 2014). A sustainable urban setting is therefore often credited by the environmentally conscious to these features of the compact city, although often with little quantitative evidence cited (Echenique et al., 2012).

By contrast, the dispersed urban model is promoted by economically conscious, free-market advocates who argue that if land-supply (greenbelt) restrictions are liberalised to satisfy market demand, land will become more affordable and socially accessible (Williams, 2014). Evolving socioeconomic patterns seem to favour this model, with the decline of the singular urban centre and the emergence of polycentric nodes in many cities (particularly in Europe) seen as shifting urban planning agendas to a dispersed approach to growth (Kasanko et al., 2006). However, allowing market forces to manage land-supply and demand is treated with scepticism by policymakers, as it is suggested to lead to urban sprawl and low-density developments with high dependency on resource usage (Bruegmann, 2005). Furthermore, sprawl is associated with increased energy consumption, reducing greenspace and biodiversity, increased infrastructural networks, and often leading to social inequity (Echenique et al., 2012).

Sprawl or compaction can result from application of concerted urban planning policies or from a complete lack of any clear policy framework. What is clear, however, is that whether urbanisation is dense or sprawling, it creates distinctive relationships between climatic variables and land-use, urban energy consumption, and the efficiency of buildings.

2. The urban energy balance and its partitioning

Luke Howard was the first climatologist to hypothesise that the climate of cities and their interactions with the surrounding areas 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 urban heat island (UHI) phenomenon in terms of an 'urban energy balance' based on the analysis of incoming and outgoing energy flux from an urban surface system. The energy absorbed by this urban surface system from solar radiation and generated by anthropogenic activity is therefore physically balanced by warming the air above the surface (convection and radiation), the evaporation of moisture, and storage of heat in surface materials. The partitioning of this energy balance defines the nature of the urban climate, which in turn affects how cities use energy and the comfort and wellbeing of citizens (Oke, 1988).

The increased surface roughness of cities creates different structures or 'layers' in the urban atmosphere (see Fig. 1). The planetary boundary layer (PBL), which is a part of the atmosphere that is influenced by its contact with the planetary surface, is partitioned above urban areas into the urban boundary layer (UBL) and urban canopy layer (UCL). The UBL is a mesoscale concept referring to the part of the atmosphere that is part of the PBL and overlying 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 between the surface and the tops of buildings and trees, where the local climate is dominated by the materials and the geometry of the urban environment, (generally known as 'urban roughness') and is the zone typically occupied by people. The UCL consequently represents the part of the atmosphere that is vital for ensuring human comfort, health and wellbeing in cities (Oke, 1976).

The formation of an UHI is dependent on several climatic processes and may be described in terms of the phenomena occurring in either the UBL or the UCL. The UBL is governed by processes relevant at the mesoscale with the higher altitude thermal inversion dominant during the daytime, while the latter by those at the microscale with the lower altitude inversion dominant during night-time (Oke, 1976). The UHI is most potent under anticyclonic (high-pressure) conditions with reduced wind velocities and cloud cover. Thus UHI intensity is observed to be greatest in summer when increased solar radiation increases the energy available within the urban system, and at night heat release from the urban form becomes the dominant heat source (Grimmond et al., 2010; Oke, 1987). Anthropogenic features and human activities within the UCL are the main influence on the net positive thermal balance that gives rise to the heat island (Oke, 1987). Human activities in cities result in anthropogenic emissions that have the potential to increase the quantity of thermal energy released to the urban climate, while weather, urban and geographical features serve to vary the intensity and distribution of this release. The main urban features that modify energy flux relate to the morphology and materiality of the built environment and available green and bluespace features. This paper focuses on the effects of greenspace and bluespace, through a meta-analysis of relevant studies, in an attempt to identify whether cooling is extended beyond the UCL to the UBL and thereby reduces the citywide UHI.

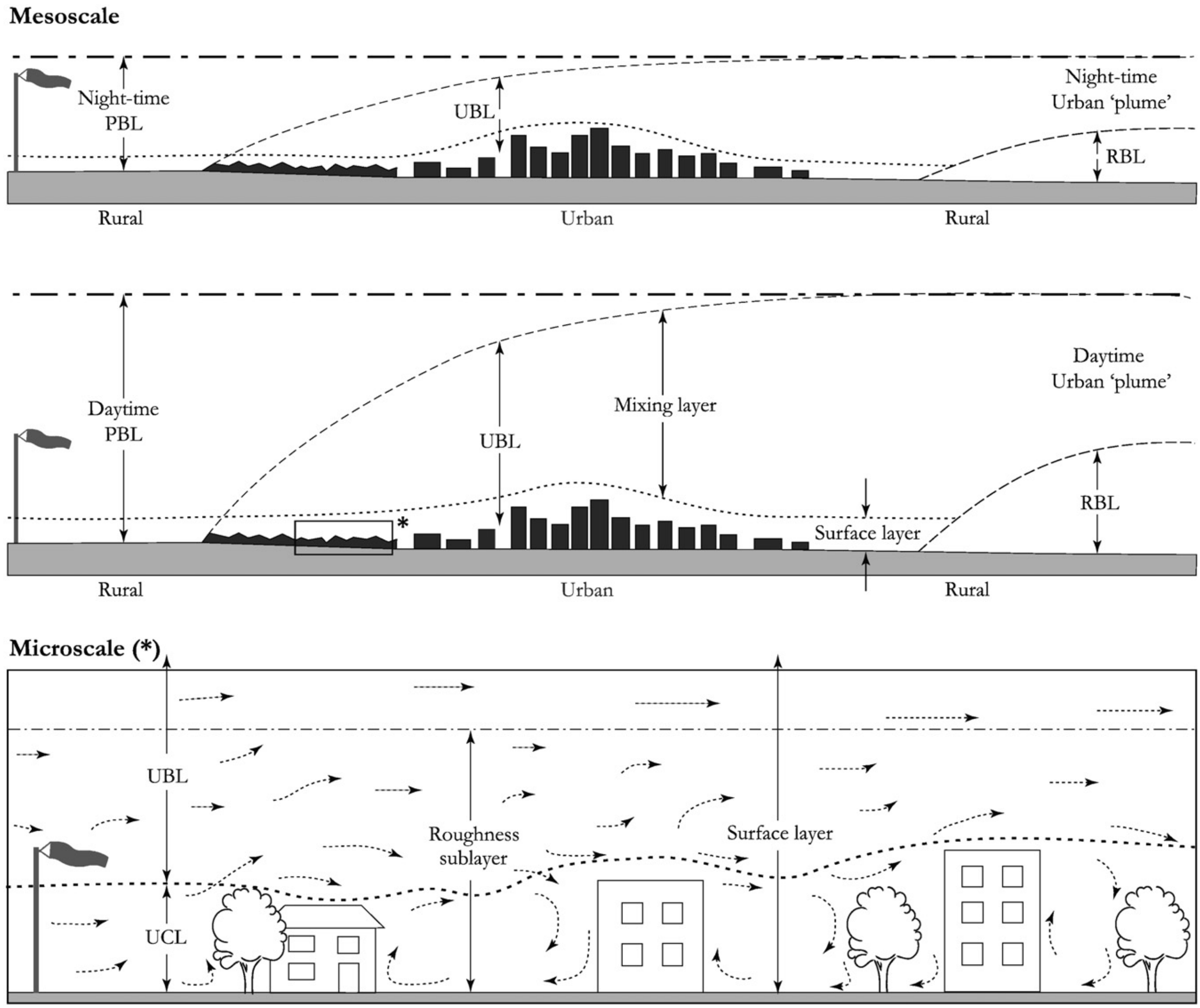

Fig. 1. Boundary-layer structures over a city resulting from increased surface roughness, based on Oke (1987).

3. Thermal regulation by green infrastructure

Greenspace can take many forms, including for example: urban forests, parks, street trees and verges, private gardens, fringes of transport corridors and vegetated roofs and façades. All types of greenspace provide varying ecosystem services to the urban environment including; reduced surface runoff, flood relief, sustainable drainage, general aesthetic and wellbeing enhancements and the modification of local microclimates (CCC, 2014). Urban greenspace can also harbour important biodiversity, not just urban generalist species. Greenspace is consequently 'environmental capital' that can be utilised to mitigate the adverse effects of the UHI, extreme heat events, and climate change (Gill et al., 2007). For example, a recent study of Glasgow (maritime temperate Köppen-Geiger climate) advocated that an increase in greenspace of 20% above the current level could eliminate between a third and a half of the city's expected UHI effect in 2050 (Emmanuel and Loconsole, 2015). Strategically planned interconnected networks of greenspace offering ecological, social and economic benefits and engendering climate resilience are referred to in city-planning discourse as 'green infrastructure' (Matthews et al., 2015).

Energy is transferred from the urban surface to the atmosphere through the evaporation of water, thereby linking the urban energy balance to the hydrological cycle (Oke, 1988). 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, humidity, etc.) and wind flow. It is estimated that annual global evapotranspiration consumes ~22% of the total available insolation at the top of the Earth's atmosphere (Qiu et al., 2013). Reducing evapotranspiration alters the partitioning of the urban energy balance, 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/or waterbodies to an urban surface, thereby replacing 'sensible heating' (Q_h) with 'latent heating' (Q_e), which in turn reduces the 'Bowen ratio' (of sensible to latent heat flux) leading to evaporative cooling ($B = Q_h/Q_e < 1$). In extreme oasis conditions, the latent heat flux can be sufficiently large to reverse the sensible heat flux, thereby creating a negative Bowen ratio, i.e. the air above and from drier surroundings supplies sensible heat to the moist oasis (Taha, 1997).

Vegetation affects the thermal energy balance in cities both directly and indirectly. It directly influences the microclimate by reducing surface and local air temperatures, which in turn affects air temperatures over wider areas. It also indirectly modifies it by reducing heat transfer into occupied spaces and thereby reducing mechanical cooling loads and any resulting anthropogenic heat emissions back into the urban climate. The most discussed of such vegetation-based cooling processes is transpiration, where water transported through the plant is evaporated at the aerial parts by absorbing energy from solar radiation that increases latent rather than sensible heat to keep the foliage and the temperature of the surrounding atmosphere relatively cooler (Taha et al., 1988). For most vegetated systems, 99% of the water and over half the energy absorbed is typically used for transpiration (Oke, 1987). The species of vegetation considered is significant for the cooling potential achieved. Most plants in cool and wet climates have what is known as a 'C3 photosynthetic metabolism'. This requires the regular opening of leaf pores (stomata) and the transpiration of significant volumes of water. Many plants in much warmer climates operate what is known as a Crassulacean Acid Metabolism or 'C4' photosynthetic metabolism which enables them to retain water by greatly reducing transpiration. They tend to keep their stomata closed during the day (open at night), which in turn provides reduced daytime cooling owing to negligible transpiration rates (Doick et al., 2014). In most plant species of all types, leaf stomatal apertures are typically closed in the absence of solar radiation. Latent cooling from transpiration is therefore principally more relevant during daytime (see Fig. 2) than night-time energy exchanges (Monteith and Unsworth, 2013; Shashua-Bar and Hoffman, 2002). The rates of transpiration achieved during the day depend many features of plants including: crown area, Leaf Area Index (LAI) defined as the single surface leaf area per unit of ground area, height of the leaves above ground level, stomatal resistance, hydraulic resistances of the shoots and roots and soil conditions: water content and availability, compaction, and hydraulic conductivity (Armson et al., 2012). The effectiveness of transpiration effectiveness is also influenced by the background weather and climate, rates being actively controlled by plants by reducing or closing stomatal openings (moisture is required for guard cell turgidity) to manage heat stress and water loss (Monteith and Unsworth, 2013). It follows that the cooling effectiveness of plants reduces subsequent to protracted heatwaves or drought conditions (Gill et al., 2013).

Shading by vegetation keeps the air cooler by acting as a solar radiation interceptor that reflects and absorbs radiant energy, thereby limiting shortwave absorption by urban surfaces and re-radiation of heat to the canopy-layer atmosphere (Oke, 1989). Rural vegetated areas are estimated to reflect ~20–25% and 15% of the incoming shortwave radiation back to the atmosphere by grass and trees respectively (Armson et al., 2012). Part of the absorbed shortwave energy is utilised by phyto-active chemicals in vegetation for biological photosynthesis, while the residual is stored as heat. The effectiveness of this shading effect is determined by leaf size, crown area and LAI of the vegetation canopy (Santamouris, 2014). Trees, and to lesser extent shrubs, present higher shading effectiveness in comparison to grass types. Tree canopies can therefore create a microclimate beneath them (Bowler et al., 2010). Vegetation canopies modify surface roughness and background wind flow altering convective heat exchange. Canopy density and foliage features are similarly significant here; grasses provide a barrier of stagnant air near the ground and dense forests impede wind flow to retain warmer insulated air beneath the canopy. Dispersed groves with canopy heterogeneity improve surface roughness to generate mechanical turbulence and thereby enhance convective heat loss (Oke, 1987; Zhao et al., 2014). With isolated trees, convective loss tends to be greater as they protrude into the UBL to present greater surface area exposure and increased opportunity for contact with drier air flowing from non-vegetated areas to increase evapotranspiration. The three-dimensional form and exposure presented by plants is therefore significant for the effective dissipation of their heat flux (Armson et al., 2012).

In addition to the above processes of transpiration, solar shading and modification of wind flow, pollution filtering and reduction of runoff by vegetation also indirectly assist the cooling of the climate. Pollution filtering is largely achieved by dry deposition, a process where the pollutant molecules or particles impact upon and stick to vegetation surfaces such as canopy leaves, while gaseous pollutant can be absorbed directly by leaves (McPherson et al., 1994). The removal of such pollutants reduces atmospheric scattering and absorption of shortwave radiation and longwave infrared radiation, which in turn influences the radiation balance and the rates of atmospheric warming or cooling. Larger canopy

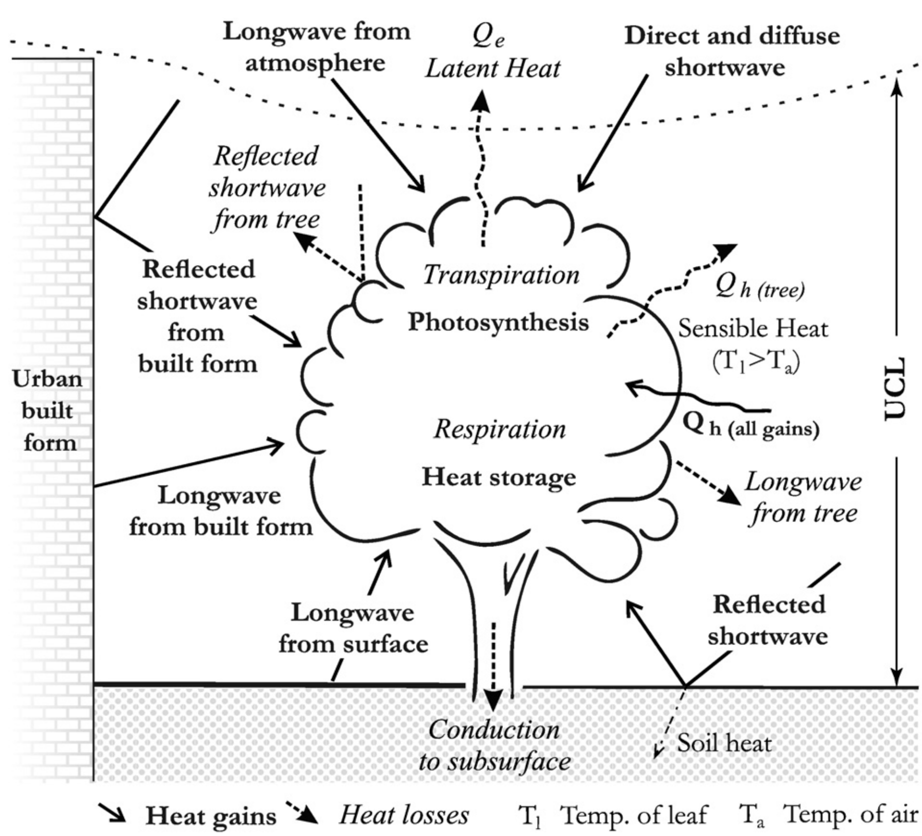

Fig. 2. Daytime energy exchanges between a tree and urban built form, based on Oke (1989).

trees unsurprisingly filter out more pollutants per unit land area than other types of vegetation. A modelling study for example estimated that the tree cover of the West Midlands (UK) was likely to reduce urban particulate matter ≤10 μm (PM_{10}) concentration levels by 4% (McDonald et al., 2007). The vegetation canopy also reduces runoff by the interception of rainfall. At the surface, their root spread and the typical (often softer) landscaping also aid in the reduction of runoff rates and encourage greater absorption, hence providing increased soil moisture content for evapotranspiration.

The effectiveness of vegetative cooling is determined by the background climate of the vegetated area. Soil and atmospheric moisture content are particularly significant; precipitation and/or irrigation provide greater soil water potential for transpiration, while high atmospheric humidity suppresses transpiration as the water potential gradient is reduced (Santamouris, 2014). The availability of moisture also characterises the typical vegetation growth that results, with greater water availability resulting in denser growth that generates greater surface roughness relative to drier climates (Zhao et al., 2014). Ambient temperature is a variable that determines the rate of sensible heat released from the vegetated surface. Seasonal sensible heat flux is consequently found to be a minimum in winter, while the maximum heat flux occurs during the summer when the vegetation-to-atmosphere temperature gradient is typically higher. Wind velocity, however, is significant in modifying both these climate variables. At greater wind velocities, the convective heat transfer coefficient is primarily dependent on wind velocity as forced convection dominates heat transfer to aid greater sensible heat loss irrespective of the temperature gradient. Wind flow is also advantageous in high humidity conditions as it assists to advect away accumulated saturated air; and higher wind velocities reduce the leaf boundary-layer and enhance the water potential gradient and resulting latent heat flux (Santamouris, 2014). These background variables of moisture content, ambient temperatures and their interaction with wind flow together influence the typical vegetation profiles that occur in a given area. This in turn defines the availability and effectiveness of the cooling processes discussed above, their distribution is discussed next.

3.1. Extent of UCL cooling provided by greenspace

The spatial extent of the cooling influence provided by greenspace is significant in 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 their surroundings by varying degrees (Bowler et al., 2010). 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 nocturnal cooling range of 20–440 m, with 83% of influence evident 63 m (~half the range) from the boundary, mean summer temperature reduction of 1.1 K, and a maximum reduction of 4 K observed on certain nights (Doick et al., 2014). The exact nature of greenspace cooling influence observed can vary significantly both spatially and temporally. If vegetation is to be utilised for the purpose of cooling urban areas, the variables that affect cooling distribution (horizontal and vertical transport) into the surrounding context must be examined.

The formation and function of wind systems plays a significant role in the distribution of cooling from vegetated spaces. Macro-to-mesoscale prevailing wind flow and direction over the city affect downwind spread, aided by a combination of simple advection along aligned canyon geometries and turbulent mixing above roofs of canyons aligned across the flow. This in turn establishes urban morphology features: the sky-view factor and canyon aspect ratio and orientation as significant variables in modifying cooling distribution (Chandler, 1965; Oke, 1989). The formation of microscale systems have been shown to play a significant role in horizontal cooling distribution. Under conditions with low wind velocities typical of anticyclonic conditions, thermals rising from the surrounding urban areas generate low-level advection currents that draw air from cooler green areas as 'park-breezes' (Jansson et al., 2006; Oke, 1989). This park-breeze effect can generate a centripetal thermal system, which completes its cycle with the subsidence of warmer urban air from above into the greenspace (see Fig. 6). The occurrence of this system may explain why the cooling rate within urban parks is seldom comparable to that of rural areas but rather is strongly affected by the surrounding urban context (Oke, 1989). It may also explain why parks seldom appear on UHI intensity plots (e.g. Fig. 3) as the occurrence of such centripetal systems are likely to hinder the vertical transport of the cooling plume. Dynamic stability is vital for such conditions to manifest, as higher wind velocities (>5 ms^{-1}) tend to impede vertical movement and disrupt buoyancy-driven effects by introducing rapid turbulent mixing (Oke, 1989). In a study of Kensington Gardens (London, UK) for example, horizontal cooling distribution was observed to be disrupted with higher wind velocities (Doick et al., 2014). Low wind velocities evident under anticyclonic conditions typical of heatwaves and high UHI intensity consequently favour the formation of such buoyancy-driven centripetal systems (Oke, 1989). This suggests that the canopy-layer cooling influence of greenspace is assisted by such microscale processes to offer their greatest distribution when it is most likely to be useful in relieving heat stress, a significant advantage to bear in mind when comparing against alternative heat mitigation strategies (Doick et al., 2014).

In review of the transport of greenspace cooling across urban areas, a higher proportion of the cooling effect is said to be maintained per metre beyond park boundaries of larger scale bodies (Doick et al., 2014). This significance of scale could be attributed to increased potential of the park-breeze system, either due to increased temperature gradient or else increased fetch (length of area over which a given flow has contact) than smaller scale parks. Geometry is significant here, with square or round-shapes said to provide higher cooling efficiency and distribution. This is explained with reference to the greater opportunity for increased temperature and humidity gradients and fetch between the body and its surrounding landscape (Shi et al., 2011; Sun and Chen, 2012). The range of distribution experienced is also dependent on the vegetation profile (trees, shrubs or grass) and its heterogeneity (Gill et al., 2013). A recent modelling study combined tree age and planting density as a composite Leaf Area Index (LAIsp) as means to calculate optimum cooling effect relative to park size (Vidrih and Medved, 2013). The results of this modelling supported the findings of Shashua-Bar and Hoffman (2000), that networks of smaller 0.2–0.3 km^2 greenspaces can provide effective cooling distribution (Vidrih and Medved, 2013). An earlier study that considered the scale and interval between areas of greenspace suggested that such network or cluster arrangements should be spaced <300 m apart in order to provide their combined benefit (Honjo and Takakura, 1990). There is however, a minimum effective size of greenspace areas to consider, with Doick and Hutchings (2013) highlighting greenspace smaller than 0.05 km^2 as offering negligible cooling contribution. This gives weight to the hypothesis that a certain fetch is required to create a park-breeze system and that larger parks are able to create larger park-breezes allowing for greater cooling transport into the surrounding urban fabric, even for a minimal temperature gradient. More research is required to examine if the same breeze effects can be achieved by networks of smaller greenspaces and the necessary size and interval required in relation to urban surface roughness features.

3.2. Extent of UBL cooling provided by greenspace

Although numerous studies of urban parks have demonstrated the horizontal distribution of their cooling effects, 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 studies of London (UK). In contrast to most large cities,

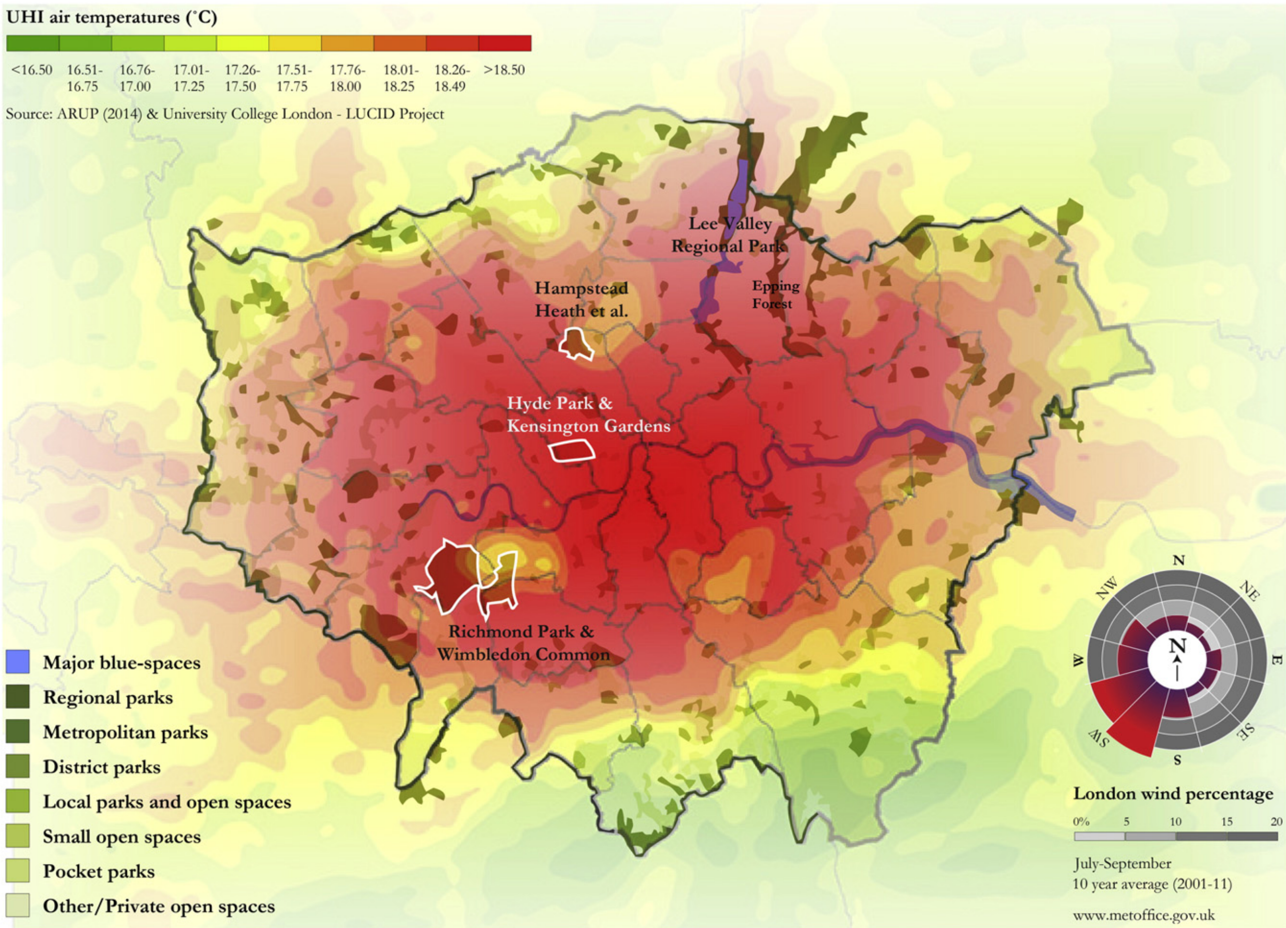

Fig. 3. LUCID UHI simulation overlaid over London's green and main bluespaces, compiled from the following sources: GLA (2012), Met Office (2012), and atmospheric UHI simulation from ARUP (2014) and University College London – LUCID project.

London is relatively green (Fig. 3), with ~47% of its total area considered green, 33% vegetated greenspace and 14% as vegetated private domestic gardens (ARUP, 2014). However, examination of an averaged atmospheric heat island simulation produced for relatively warm summers (see Fig. 3) as part of the LUCID project (see Bohnenstengel et al., 2011; Mavrogianni et al., 2011) reveals complex cooling penetration patterns. Accounting for predominant south-westerly winds, several areas of interest can be identified. Although Kensington Gardens' and Hyde Park's cooling potential can be observed at the surface level (ARUP, 2014), at the higher atmospheric level its significance is not apparent. Notable cooling contributions represent the combined larger greenspaces of Richmond Park and Wimbledon Common, and to a lesser extent, the cluster of greenspaces that includes Hampstead Heath. The linear Lee Valley Regional Park, which is around four times the area of Richmond Park, is remarkably absent in the atmospheric simulation. It can therefore be hypothesised that the magnitude and geometrical distribution of greenspace has significant bearing on the citywide (UBL) cooling expected. It could be suggested that the relative linear geometry and limited fetch of the Lee Valley Regional Park (~1 km width, compared with 5 × 7.5 km dimensions of Richmond Park and Wimbledon Common, see Table 1) potentially impedes the development of strong temperature and humidity gradients necessary to effect citywide cooling. Another contributing factor to this condition could be that a significant proportion (~22%) of this Park is taken up by reservoirs, the significance of which is discussed later. Observation of Hampstead Heath and its context forwards the hypothesis, that clustering of greenspaces is potent enough to produce the transport necessary to effect citywide cooling. There is however, a significant gap in the literature presenting monitored vertical cooling distribution data, preventing a comprehensive assessment of the relationship between geometric parameters and the vertical transport of cooling within the UBL. This lack of empirical data is generally attributed to the infrastructural cost necessary to carry out such vertical measurements particularly for longitudinal analyses, which are required to characterise the temporal patterns of vertical transport. The majority of recent studies therefore present and discuss findings in relation to canopy-layer cooling, almost entirely with reference to horizontal distribution and transport.

3.3. Greenspace in relation to urban compaction and dispersal

Dispersed urban development is typically criticised for increased land usage in comparison to compaction or densification strategies, with much of this usage likely to be greenfield land leading to peripheral loss of greenspace and tree coverage (Echenique et al., 2012). A study in

Table 1
Significant greenspaces in London and approximate dimensions for comparison with Fig. 3. Compiled from the following data sources: *Parliament UK (2016); **GiGL (2016); ***LVRPA (2016); and Google Maps (2016).

Greenspace	~Area (km^2)	~East-west span (km)	~North-south span (km)
Hyde Park + Kensington Gardens*	2.5	2.5	1.0
Hampstead Heath**	3.2	1.7	1.8
Richmond Park*	9.6	4.0	4.5
Epping Forest**	24.8	2.7 (widest)	8.8 (linear)
Lee Valley Regional Park***	40.5	1.4 (widest)	42.0 (linear)

the USA has shown the rate of rural greenspace loss in the most actively sprawling urban regions to be more than double the rate in the most compact urban regions, and there are correlations between the frequency of extreme heat events experienced and loss of regional vegetative cover (Stone et al., 2010). The significance of safeguarding peripheral greenspace is further demonstrated by a study of the Frankfurt greenbelt (maritime temperate), which highlighted the greenbelt as providing a beneficial cooling of 3–3.5 K between the greenbelt and the city core. The study discusses this cooling influence with reference to the formation of a mesoscale city-country breeze, also referred to as UHI flow (Bernatzky, 1982, 1989). Under anticyclonic conditions, this city-wide system (Fig. 4) develops as thermals at the core of the city rise to the UBL to generate advection flow 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. Interestingly, compact forms of development that encourage higher UHI intensity by concentrating heat-absorbing built mass also favour the formation of these cooling breezes (by enhancing the city-country temperature gradient), while dispersed developments weaken it.

The degree of any cooling shortfall at the centre of a city that may be expected from a dispersing arrangement into its peripheral greenbelt is dependent on the distribution, typology and spread of vegetation lost. It is significant to note that while future dispersal growth can be reasonably quantified in terms of magnitude, its market-driven distribution seems less straightforward to anticipate, as demonstrated by a systematic modelling of Toulouse, France (maritime temperate) (Masson et al., 2014). Although the framework proposed in this Toulouse study allows assessment of compaction-to-dispersal influences on greenspace and resultant cooling, this is beyond the scope of this paper, presenting an opportunity for future study.

Until recently, reduction of evapotranspiration was considered as the dominant contributor to the daytime UHI in cities (Taha, 1997). However, a study of cities across the US (Zhao et al., 2014) argued that the daytime UHI was in fact principally dependent on the relative effectiveness with which urban and rural areas convect heat to the climate, rather than on precipitation (and potential evapotranspiration). Heat storage remains the dominant determinant of night-time UHI. It was also found that in areas with greater precipitation the increased availability of moisture had an effect on the daytime UHI, although the trend was not consistent for all regions. The modelling study also suggested that if urban areas are aerodynamically smoother than surrounding rural areas (due to dense vegetation in the latter and its relative absence in the former), heat dissipation is relatively less efficient resulting in potential for warming; and increasing surface roughness in urban areas, could potentially lead to a cooling effect.

This relative difference in convection efficiency between urban and rural conditions in different cities and parts of the world is generally considered to be dependent on the background climate and its effect on vegetation cover in rural areas. In humid temperate climates in the US, Zhao et al. (2014) found convection to be less efficient at dissipating heat from urban form than from rural land, as rural areas tend to be aerodynamically coarser than urban areas due to the presence of generally denser and coarser vegetation canopies. The study highlighted urban form in such humid temperate US cities as having a reduced convection efficiency of 58% relative to adjacent rural areas, leading to relative temperature increases of up to 3.0 K, dominating their daytime UHI intensity. In drier climates the opposite was noted, as the built environment was coarser relative to the surrounding landscape, where drier conditions typically impeded 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 presented a daytime heat sink effect. This phenomenon had previously been explained with reference to the 'oasis effect' resulting from evaporative cooling provided by urban trees and soft landscaping (Peng et al., 2012). Zhao et al. (2014), however, argued that based on proportional contributions to the overall daytime UHI intensity as determined by their climate model and verified through remote-sensing surface temperatures, the evaporative cooling contribution to UHI reduction was minimal in comparison to the effects of convection.

The above findings suggest that the addition of vegetation with the principal aim of improving evapotranspiration qualities of the urban surface may prove to be less effective in mitigating the daytime UHI than previously believed. 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. This provides another insight into the results presented in Fig. 3, where Richmond Park and Wimbledon Common presents a pronounced UHI reduction effect in contrast to Hyde Park and Kensington Gardens, not only for the fact that they are larger in area, but also because their surfaces are significantly rougher. In humid climates where daytime UHI warming is observed to be substantial, the addition of vegetation to increase inner-city surface roughness could therefore be a feasible strategy (Zhao et al., 2014). It can be hypothesised that if urban greening is to be undertaken for this purpose, tree planting with an increased diversity of species would provide a greater provision of roughness than more planar greening approaches (such as mown grasslands). The typologies of urban greening to be used therefore require consideration of not only transpiration potential, but also the roughness they deliver in their

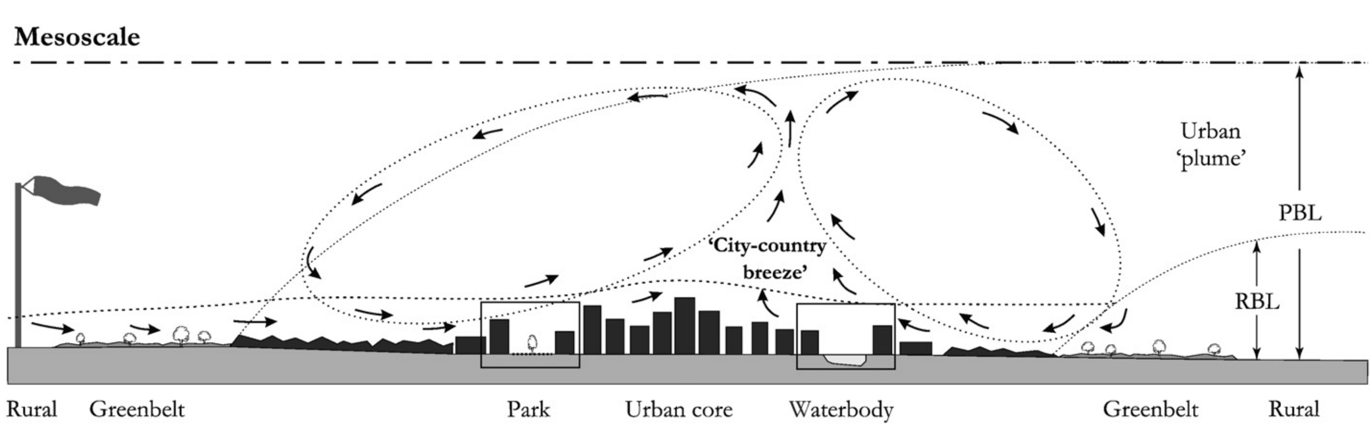

Fig. 4. UHI formation flow, also referred to as the city-country breeze, the highlighted regions are expanded in Fig. 6.

varied arrangements. Planners of green infrastructure should therefore address these typological diversities and their various arrangement options in the future deployment of green enhancements.

Certain planning processes have in recent times developed weighting systems that address the relative abilities of different greenspace cover types to deliver cooling and other benefits. The Green Area Ratio (GAR) implemented in Berlin (Germany) and adapted in Malmo (Sweden) for example assigns weighting factors to different urban greenspace cover types based on their relative climate change mitigation potential (Keeley, 2011). In the District of Columbia, USA, GAR provides weightings to greenspace typologies that reflect a much fuller range of urban ecosystem services. Such planning mechanisms however should be constantly tested against the latest multidisciplinary scientific evidence and updated as necessary to ensure that greening strategies achieve their optimum balance of ecosystem services.

3.4. Contribution from green building envelopes

Subject to effective geometry and width, tree-planting schemes to create green wedges or corridors may be effective in some urban zones or areas where densification is proposed. A study of Hong Kong (China) (humid subtropical), highlighted several effective means to enhance urban greening in compacted arrangements, tree cover being stated to be more beneficial than grass cover. The study recommended greenspace coverage (based on Hong Kong morphology) of a third of a given urban area to achieve street-level temperature reductions of 1 K (Ng et al., 2012). Similarly, greenspaces planted with trees were considered by Doick et al. (2014) to be more effective in terms of urban cooling per unit area than grass-covered ones, as they contribute to more of the beneficial processes of vegetative cooling discussed earlier. An increasing number of advocates of vegetal architecture also argue for trees and shrubs to be incorporated onto buildings as either retrofits or replacements. Particular examples of such approaches include the Park Royal Hotel on Pickering Avenue, Singapore, The Kensington Roof Garden, London, and Boso Verticale in Milan (Italy).

However, a systematic modelling assessment of future urban growth has argued that enhanced greening of this nature is unlikely to be achieved in many already compacted urban centres (Masson et al., 2014). The Hong Kong study (Ng et al., 2012) acknowledges that with extreme urban core densities and limitations on roof load-bearing capacity, planar greening solutions such as herbaceous sward green-roofs may be the only viable approach. The same study however argues that this form of green-roof provision is less effective than street level vegetation for street level cooling, particularly when typical urban morphology exceeds 10 m in height. In the case of Hong Kong where the average building height is 60 m, the street-level cooling influence of herbaceous sward green roofs was deemed negligible (Ng et al., 2012). Another review of green-roofing studies similarly concluded that proximity is significant to cooling influence and suggested limited vertical transport, although there seems to be little empirical evidence to support this as studies purposefully avoid considering thermal effects beyond an immediate canopy-layer range (Santamouris, 2014). It should however be noted that the cooling by herbaceous roof swards may be significant for users of roof gardens in dense urban areas, and that herbaceous sward green roofs provide many other benefits including runoff attenuation and habitat for flora and fauna different to that which inhabits shrub and tree covered areas.

The influence of green-roof strategies on energy use, through modification of heat transfer to/from occupied spaces that affects cooling or heating loads and the resulting heat rejection back to the urban climate, is well-documented (Huang et al., 1987; William et al., 2016). Such impact on cooling or heating loads is predominantly assessed by studies in comparison to the alternative strategy of cool-roofing (altering the albedo of the roof). The William et al. (2016) study demonstrated that both cool and green-roofs can provide comfortable internal temperatures in summer, but that cool roofs can provide greater UCL cooling than green-roofs through reflection of heat away from the urban surface, however, green-roofs were shown to result in lower annual energy costs. The overall energy saving generally increases with increased vegetation LAI and in the case of cooling-dominated buildings, it is highlighted as the critical parameter (Sailor et al., 2011). The use of such approaches to vegetated architecture, however, needs to be based on holistic cost-benefit analysis, considering the balance of thermal insulation, runoff reduction, carbon uptake and all of the ecosystem services being offered by the vegetation and the relative value of different urban habitats to different target species of flora and fauna that are considered desirable co-denizens of urban areas with people.

Studies considering vertical greening typologies have found the air temperature influence to not extend beyond their immediate foliage zone, and attribute their principal cooling purpose as shading devices to reduce surface temperatures (Perini et al., 2011; Wong et al., 2010). When considering living-wall approaches that include irrigation systems, air temperature influence is evident, although the range is restricted to < 1 m from the green vertical surface in question (Wong et al., 2010). The technology behind living-wall design is however constantly evolving and generalisations are risk-laden. For example, the Rubens Hotel near Victoria Station in London supports a 350 m^2 soil-based living-wall that is also a vertical sustainable drainage system. The evaporative cooling effect of this system is likely to be measurable and could be of particular benefit in cooling local air prior to drawing into buildings through the ventilation system. As such, assessment of cooling potential and contingent delivery of other ecosystem services, particularly in dense urban settings should be considered as an emerging area of research interest.

4. Thermal regulation by blue infrastructure

The terms 'urban bluespace' and 'urban waterbodies; refer to all substantial bodies of static or dynamic surface water found in urban areas. Substantial bluespaces naturally exist as integral features of the geography of many cities because of their historical geopolitical significance. In the port city of London for example, the River Thames is a dominant feature, which with other bluespace represents ~2.5 % of the city's surface area (ARUP, 2014). Urban bluespace is often also created and/or managed specifically to provide key ecosystem services. These include canals for transport and more recently sustainable drainage and rainwater harvesting systems such as at the East Village in Stratford, London.

4.1. Thermal effects of bluespace

City planners and architects have long considered waterbodies as vital components of any strategy to minimise urban heat stress (Coutts et al., 2012). Studies considering the cooling benefits of bluespace however are relatively fewer in comparison to greenspace and tend to focus on the daytime influence on urban temperatures. Air temperature monitoring studies are also notably limited in comparison to surface temperature studies. The findings of such surface temperature studies based on remote sensing should be treated with caution, as such images inspect only significantly larger bodies for a single moment in time and do not account for the conversion of sensible heating into latent heating (Sun and Chen, 2012; Volker et al., 2013). A recent meta-analysis of 27 studies (including such remote-sensing based studies) concluded that the bluespaces studied could provide a cooling effect of 2.5 K on average relative to their context (Volker et al., 2013).

A waterbody or watercourse's ability to modify surrounding temperatures is determined both by its inherent properties and by its interactions with surrounding climate conditions. Most published studies appear to focus on evaporative cooling, where absorbed thermal energy transforms sensible heating to latent heating with the production of water vapour. However, the thermal properties of high specific heat capacity and enthalpy of vaporisation give water a high thermal inertia, which plays a significant role in moderating temperatures and temporal variations allowing waterbodies to act as a thermal buffer (Oke, 1987). For larger bodies such as oceans, on an annual basis, >90% of the available radiation balance may be used to evaporate water, while for smaller bodies this conversion is likely to be >50%. Although on average this translates to lower Bowen ratios for such surface waterbodies, the evaporative flux is characterised by diurnal variations rather than seasonal variations for oceans. For a large part of the morning, absorbed energy primarily warms the water. Towards the afternoon when the water surface temperature and the water-to-air vapour pressure deficit reaches their peak, a strong evaporative flux is generated. The energy stored within the body is adequate to sustain this evaporative flux even throughout the night, although with diminishing intensity (Oke, 1987).

Radiative exchange is determined by the reflectance (albedo) of the water surface, which is considered low (~0.09) at low to medium angles (predominant) of solar radiation incidence and varies daily with flow rate and dynamics (waviness), biochemical make-up and the quantity of suspended particles present (turbidity). This means that most incident shortwave solar radiation (wavelengths from ~0.1 to ~5.0 μm) is absorbed leading to warming of the waterbody (Oke, 1987; Taha et al., 1988). Longwave infrared radiation (wavelengths from 4 to 100 μm), is almost entirely absorbed at the surface with hardly any reflection, while the outgoing longwave flux remains constant throughout the day for larger bodies, due to limited diurnal variation in surface water temperatures. The fluid properties of water enable the absorbed radiation energy to be transferred within waterbodies by conduction, radiation, convection, and advection processes that in turn contribute to efficient heat transport and mixing. This permits heat gains or losses to be efficiently diffused throughout a large surface volume, maintaining surface water temperatures within a limited diurnal range (Oke, 1987); and also means that the outgoing longwave flux remains relatively constant throughout the day.

The sensible cooling effectiveness of a bluespace is dependent on the net effect of the radiation balance, the climate variables that encourage the sensible-to-latent heat (evaporative) conversion, and its atmospheric advection (Hathway and Sharples, 2012). The greater the water-to-atmosphere temperature gradient the greater the sensible heat flux; while the water-to-atmosphere moisture gradient or vapour pressure deficit (VPD) determines the potential for moisture to transfer into the atmosphere. Relatively drier air above the body enhances the evaporation rate, while the presence of humid air has the opposing effect (Oke, 1987). Increased wind velocity above the body can significantly alter both the sensible and evaporative heat flux by advecting away both heat and moisture, enhancing temperature and humidity gradients (Hathway and Sharples, 2012). Similar to greenspace, relatively high wind velocities hinder extensive lateral cooling distribution by enhancing atmospheric mixing (Theeuwes et al., 2013).

The sensible cooling effectiveness of dynamic (open) and static (closed) types of bluespace differ owing to their respective fluid flow characteristics. The thermal properties of dynamic bluespaces such as rivers, streams, and canals are influenced by both fluid flow variables and climate parameters. Their fluid flow enables them to carry absorbed radiation by advection downstream and release energy external to the urban system (Hathway and Sharples, 2012). Observations of such bodies have identified increased downstream daily water temperatures. Galli (1991) for example observed in Washington DC (USA) (humid subtropical) that stream temperatures increased with impervious surface cover, a measure used to classify urbanisation. In Long Island (USA) (humid subtropical), urban streams were found to be 5–8 K warmer in summer and 1.5–3 K cooler in winter than rural streams. This study also noted diurnal temperature fluctuations to be greater in urban streams, with notable contribution from summertime storm water runoff from heated impervious surfaces leading to 10–15 K warmer temperatures than recorded simultaneously in nearby rural streams (Pluhowski, 1970). Although this form of storm runoff has a beneficial cooling influence on upstream urban surfaces, the process may also lead to thermal pollution and resulting biochemical concerns further downstream (Paul and Meyer, 2001).

Similar to static waterbodies the energy balance of a river is typically dominated by the net shortwave balance, followed by the net longwave balance and evaporative flux (Caissie, 2006; Evans et al., 1998). A study of River Exe in Devon (UK) (maritime temperate) for example demonstrated the net radiation balance to account for 56% of the heat gain and 49% of heat loss (Webb and Zhang, 1997). As most such watercourses are of limited depth for most of their course, thermal exchanges at the riverbed-water interface may also require attention particularly during seasonal changeover periods. A study of River Blithe in Staffordshire (UK) (maritime temperate) for example found that 82% of the energy exchange occurred at the atmosphere-water interface, while ~15% occurred at the riverbed-water interface (Evans et al., 1998). In smaller streams, the influence of other energy partitioning factors may gain greater proportional significance, which also applies to hydrological factors such as discharge and groundwater exchange. For larger dynamic bodies (watercourses) however, high exposure to solar radiation input and wind flow is likely to lead to dominant heat exchange at the atmosphere-water interface. This means that their water temperatures are principally modified by local weather conditions and their diurnal and seasonal cycles, with the possible exception of sizeable discharges from external sources such as power station cooling outfalls (Gu et al., 1998). As dynamic instability is restricted in static waterbodies due to limited water movement, they tend to be more sensitive to energy exchange modifications at the atmosphere-water interface from local climatic conditions.

For deep static waterbodies such as deep lakes and reservoirs, thermal inputs lead to temperature and density changes resulting in thermal stratification of the water column. In such bodies, the thermally active zone (the epilimnion or surface layer and upper part of the thermocline) is principally responsible for thermal exchange with the climate above. Several mixing mechanisms can affect the thermal moderation of this active zone. At the very surface of a waterbody, evaporative flux generates instability bringing warmer water to the surface to maintain a relatively constant surface temperature (Oke, 1987). Far greater significance to surface mixing is the mechanical energy transferred by wind shear stress at the water surface that produces fields of waves and turbulence. The strength of this mixing depends on wind flow conditions such as fetch and the presence of littoral obstructions. Strong wind-driven turbulence may in certain instances transfer turbulent kinetic energy to the lower layers to destabilise stratification (Coates and Folkard, 2009; Song et al., 2013). In addition to these forms of surface mixing, a diurnal mixing current can be generated at the littoral zone of a waterbody. As the shallower littoral slope heats faster than the open water during the day, a horizontal current is generated from the zone towards open water, while cooler water from the open water depth is drawn up the slope. As the zone cools faster than open waters at night, the current is reversed. This diurnal littoral zone current however is typically not potent enough to destabilise stratification of the entire waterbody, and is mostly significant for biochemical processes (Stefan et al., 1989).

Seasonal changes in temperate climates provide conditions for buoyancy-driven overturning of the stratified layers of lakes and at least once a year water is mixed to the extent that temperature changes little with depth (so-called 'holomictic' waterbodies). The threshold temperature for this overturning is ~4 °C, when pure water reaches maximum density (Oke, 1987). In spring, surface water that is cooler than this starts to warm, increase in density and drops to generate convective instability. This overturning occurs until the epilimnion reaches ~4 °C, after which warming increases stability and restricts vertical mixing to restore stratification. In the autumn as the surface water cools, its density increases to generate convective instability and overturning (Oke, 1987). Other than during this seasonal overturning, waterbodies maintain their stratification for the majority of the year.

When a waterbody is stratified, the entire thermal capacity of the waterbody is not available for thermal exchange to the atmosphere above. Greater thermal capacity depth is only likely to become available towards the end of the summer, when internal conduction and radiation aids the transport of warming further down the water column to increase the thermally active surface layer volume.

In shallower static waterbodies, with reduced thermal capacity and inertia, the peak surface temperature and resulting latent flux can be reached relatively sooner than for a deeper body (Oke, 1987). The reduced volume of shallower static waterbodies also means that the conduction of heat across the water-bank boundary into the surrounding littoral zone, wind-driven mixing and heat storage from absorption by aquatic flora, fauna and other matter are likely to be more pronounced than in a deeper waterbody (Oke, 1987; Song et al., 2013). The result will be that the proportion of the net radiation converted to the evaporative flux is likely to be lower.

Nevertheless, the latent flux in shallow static waterbodies is still likely to be substantial. The study of a shallow lake in the Hudson Bay lowlands (Canada) (subarctic) for example determined that on average 55% of the daily net radiation balance was converted to evaporative flux from the lake (Stewart and Rouse, 1976). In addition to thermal exchange at the atmosphere-water interface, shortwave radiation can generally penetrate to the bed and often at sufficient intensity to heat the bed substrate, leading to potential warming of the waterbody from the bed.

Given the greater potential penetration of wind-driven mixing than in deeper waterbodies, shallower water bodies have typically been described as unlikely to display thermal stratification but rather to show a well-mixed epilimnion extending from surface to bed. Recent studies, however, have highlighted that during warm and calm periods (typical of heatwaves and high UHI intensity), even quite shallow waterbodies (<1 m) can exhibit stratification frequently and for substantial periods (Abis and Mara, 2006; Song et al., 2013).

The creation of smaller and shallower ponds as part of sustainable drainage systems (SuDS) is of late becoming common practice particularly within largescale development plans. The urban setting specifically affects the thermal properties of such ponds. Key factors in this regard include the inflow of surface runoff from surrounding heated hard surfaces, anthropogenic discharges (thermal pollution) and the morphology of adjacent buildings that may inhibit wind-driven surface mixing. These influences in turn may present the opportunity for thermal stratification to develop in such ponds. For example, a study by Song et al. (2013) of ten shallow urban ponds in Ontario (Canada) (subarctic and humid continental) identified that the density changes produced by daytime heating are not always dissipated depending upon surrounding environmental and subsurface conditions. Instead relative stability and stratification can pertain over relatively extended periods during the mid-summer months with vertical temperature differences >3–4 K between top and bottom layers being recorded. Song et al. (2013) attributed this strong and persistent stratification, to the turbidity of water columns (high levels of suspended sediments common in such ponds, increasing their heat-absorption characteristics) and the reduced wind stress recorded at their surfaces. In terms of dimensional parameters of small waterbodies to consider, the ratio between surface area and perimeter (shape factor) and the maximum depth are both identified as significant. Ponds of relatively large area but with simple geometry can display pronounced stratification whereas larger lakes with longer fetch are typically associated with reduced stratification and greater mixing (Mazumder and Taylor, 1994). Maximum depth demonstrates the strongest correlation to stratification, with only bodies <1 m typically identified as relatively isothermal (Song et al., 2013). This means that very shallow bodies utilise their entire water column's thermal capacity for climate exchanges, while deeper waterbodies typically do not. This is of some benefit in that creation of substantial waterbodies is often unlikely as part of a compact urban design, but the implementation of shallow SuDS features is much more likely. If shallow waterbodies such as ponds, swales and water-gardens, which utilise all their available thermal capacity, are distributed throughout an urban area, these may prove to be of greater benefit in terms of urban cooling than more localised but larger/deeper individual bodies. This is because the latter do not utilise all of their thermal capacity (during summertime) and which may be shaded and sheltered by surrounding buildings, thereby further reducing cooling propagation effectiveness. One potential limitation of shallow waterbodies as effective cooling components of urban bluespace is that they require frequent inputs of water to retain a water column; and may be dry and provide no daytime evaporative cooling when most needed, such as during a summer heatwave. On the other hand, they will also provide no heating or increased humidity at night as a larger urban water body would. Beyond these limnological observations, the research considering urban waterbody temperature structures, particularly in relation to such small shallow artificial waterbodies remain distinctly limited.

4.2. Bluespace characteristics that influence the distribution of thermal effects

As for greenspace, the cooling effectiveness (magnitude and distribution) of bluespace is influenced (inter alia) by the size and spread of such spaces and the distance from them. Theeuwes et al. (2013) constructed a mesoscale model of hypothetical waterbodies simulated within an idealised city. The study highlighted that relatively large waterbodies demonstrate greatest cooling effect adjacent to their boundaries and in downwind areas. The size and length of the downwind spread was dependent on the wind velocity, with relatively cooler air originating from a large urban waterbody 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 an urban area generate smaller temperature effects (particularly during the day) than a single larger waterbody of similar total volume, although across a larger area of the city (Sun and Chen, 2012; Theeuwes et al., 2013). The study however offered little discussion on how the distance from the urban core affects cooling distribution. This presents an opportunity for further study.

The Sun and Chen (2012) study of Beijing (China) (humid continental) recognised waterbody geometry as being significant for cooling distribution with square or round geometries highlighted as providing greater efficiency than more irregular shapes. As discussed earlier in relation to greenspace, this was attributed to the increased temperature and humidity gradients that are likely to result between such wider-shaped waterbodies and their surrounding landscape (Sun and Chen, 2012). Furthermore, regular geometries present consistent fetch distances, which in turn presents greater opportunity for atmospheric advection. The significance of width of a given bluespace 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 the riparian zone. They found that when the river width was >40 m, significant and stable effects of decreasing temperatures and increasing humidity in surrounding urban areas were evident (Zhu et al., 2011). This significance of width may be one probable explanation for why the river Lea in the Lee Valley Regional Park (<30 m wide through much of the park) does not appear to be contributing a cooling benefit to the atmospheric UHI simulation for London discussed earlier (see Fig. 3).

The urban context is significant for modifying the climate variables that influence a waterbody. The Sun and Chen (2012) study for example noted substantially higher surface temperatures around bodies with surrounding built form, owing principally to the typical surface materiality of the built form. This in turn helps create steeper temperature gradients between the centre of the waterbody and its surrounding context and enhances cooling distribution (Sun and Chen, 2012). The surrounding urban morphology can influence this cooling distribution by shading the waterbody and/or obstructing wind flow. Shading affects the net radiation balance, to reducing the temperature gradient and availability of energy to evaporate water. Obstructing wind flows reduces the opportunity for atmospheric advection and surface mixing from waves. As discussed in relation to greenspace, morphology also plays a role in directing or blocking advected cooling distribution from the body and in enhancing turbulent mixing. The influence of shading or sheltering is discussed further in Section 5.

4.3. Local thermal influence of bluespace by day and night

Cooling distribution for bluespace is observed to demonstrate diurnal and seasonal variations. For example, a longitudinal canopy-layer study of an urban river in Sheffield (UK) (maritime temperate) highlighted that the cooling effect of the river tends to be greatest in the morning, with warm days in May demonstrating ~2 K cooling over the river and 1.5 K in the riparian zone. At night however, no significant cooling was observed. Towards late June even daytime cooling had notably diminished for similar ambient air temperatures (Hathway and Sharples, 2012). In agreement with such observations, the simulation study of a hypothetical city discussed above, identified bluespace cooling primarily during the daytime, while at night and particularly towards the end of the summer, the modelling showed that a warming effect was more probable (Steeneveld et al., 2014; Theeuwes et al., 2013).

This diurnal and seasonal variation can be explained by variation in the evaporative flux. The moderate instability of the atmosphere in the morning hours increases evaporative flux to the immediate atmosphere above increasing its moisture content. The early afternoon period often marks the peak of atmospheric convective instability, water surface temperature and evaporative flux, although the vapour content of the immediate atmosphere above the bluespace is reduced as the increased buoyancy of warmer vapour transports it to higher altitudes where concentrations are diluted and mixed (Oke, 1987). This convective instability during the day gradually reduces towards the evening and at night as the surface atmosphere cools gaining stability and resistance to vertical transport. The evaporative cooling during the evening period therefore leads to saturation of this stabilising air mass above the waterbody thereby reducing vertical transport of water vapour to higher altitudes, reducing the moisture gradient and hence evaporative flux. In summary, diurnal evaporative heat flux is expected to peak during the day as the air warms, reducing towards evening and then continues throughout the night at a reduced rate (Oke, 1987). This is reflected in the diurnal profile of the cooling provided, and by night in the warming of the water's surface due to reduction in evaporative flux. The differential cooling rates of a waterbody and the surrounding urban surfaces (that cool faster), reduces the waterbody-to-context temperature gradient. This in turn reduces the potential for night-time horizontal distribution by advection currents and prevents evacuation of the saturated stable air mass above the body. This warming effect is particularly pronounced when urban waterbodies reach higher temperatures towards the end of the summer from accumulated thermal energy. Theeuwes et al. (2013) demonstrated that when the thermal diurnal cycle of water is accounted for, this variation (although within a limited range) results in reduced cooling duration in the evening and greater warming duration during the night.

Summarised results of Theeuwes et al. (2013) simulations (see Fig. 5):

- Morning (10 am) – cooling at lower altitudes (<500 m), warming at higher altitudes.
- Afternoon (3 pm) – modest cooling at all altitudes, greatest vertical transport.
- Night (4 am) – predominant warming but at lower altitude only, vertical transport minimal.

The different thermal properties of waterbodies and their surrounding context are observed to generate distinct breeze systems. These are particularly highlighted in earlier research addressing sea, lake and land-breeze fronts (a front is defined as the boundary between two masses of air of differing densities). For example, a study of Tokyo (Japan) (humid subtropical) found that sea-breeze propagation into a coastal region is slower when the coastal region is urban than when it is rural (Yoshikado and Kondo, 1989). A subsequent simulation attributed this deceleration to collision and convergence with UHI flow (mesoscale boundary layer flow, city-breeze) (Yoshikado, 1990). Studies considering lake-land-breeze fronts have generally been concerned with very large bluespaces simply for the reason that the fronts and the effects observed are then more pronounced. Lake Michigan (USA) (humid continental) for example has been the subject of several historical studies examining this breeze system (e.g. Keen and Lyons, 1978; Lyons, 1972; Ryznar and Touma, 1981). A recent study examining the Lake Michigan breeze system identified strong correlation between the deceleration of the front's inland propagation and the maximum night-time UHI magnitude of Chicago (Keeler and Kristovich, 2012). This suggests that the altitude (100–400 m) of the frontal propagation of the land breeze is at a height that permits interference and convergence with the flow of the canopy-layer thermal inversion of the night-time UHI. The same study however noted no significant association between frontal propagation and the daytime UHI magnitude (Keeler and Kristovich, 2012). This suggests that the altitude of the sea breeze inflow has minimal opportunity to modify the daytime UHI, where the thermal plume mostly occurs at a higher altitude at the top of the UBL. There is therefore a notable difference in altitude between

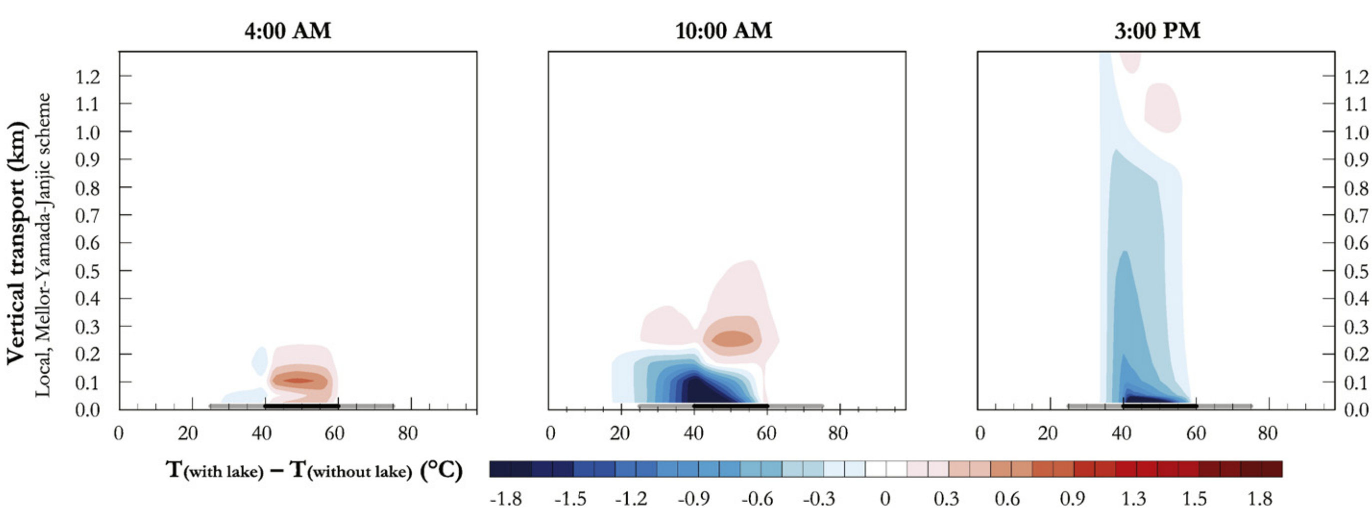

Fig. 5. Vertical transport for a hypothetical urban lake from Theeuwes et al. (2013).

daytime and night-time breeze systems. The daytime lake-breeze is able to take advantage of stronger thermals developed over land to achieve greater vertical distribution (100–1000 m), while the relatively weaker night-time thermals developed over the waterbody lead to a relatively contracted distribution (100–400 m).

To understand these distributions and their interaction with UHI thermal inversion plumes, a study of vertical temperature structures in the atmosphere is necessary. The Keen and Lyons (1978) study of Lake Michigan for example offered some data gathered from aircraft traverses, while Ryznar and Touma (1981) provided more reliable representation from neighbouring towers. The latter study however acknowledged that the towers were not representative of the conditions over the lake itself, which is essential in order to gain a better understanding of these systems and their vertical distribution. Apart from these historic studies from the 70s–90s of larger sea and lake relationships with urban areas, there seems to have been few studies of atmospheric feedback from waterbodies, and even fewer of the vertical transport and temperature structures above smaller scale urban bluespaces.

It is possible to hypothesise the occurrence of a microscale centripetal system similar to park-breezes discussed earlier in relation to greenspace, although, this is not addressed in the literature. The possible formation of such a waterbody-breeze system would in theory differ from a park-breeze system owing to the thermal inertia of water and its diurnal cooling cycle that leads to night-time water temperatures being generally higher than the surrounding urban landscape. The system could also be expected to reverse during the night in situations where warm saturated air rising from the warmer waterbody, causing cooler air from the urban surroundings to advect towards the body (see Fig. 6). This sort of phenomenon could be considered a smaller scale version of the land-breeze system discussed earlier. The completion of this hypothetical waterbody-breeze centripetal cycle would be the subsidence of warmer and humid air back to the surrounding context at night, as occurs in the case of a land-breeze system. This presents the possibility for the horizontal transport of an undesirable warming effect into the surrounding areas. The trapping of heat within the urban canopy layer poses a significant threat to not only thermal comfort, but also to human health and wellbeing with night-time temperatures epidemiologically established to be particularly oppressive (Kalkstein and Davis, 1989).

Even during the day, the suggested cooling benefit from the dominance of evaporative cooling from waterbodies is somewhat misleading. A drawback of evapotranspirative cooling is that it increases atmospheric water vapour (humidity), which is a greenhouse gas (Oke, 1987). This applies to both greenspace and bluespace, but with the latter the water vapour is at ground level rather than aerial. Increased humidity can inhibit human thermoregulation by reducing sweat evaporation rates, but also by altering the emissivity of the surrounding air leading to greater absorption, re-radiation and trapping of heat at street level. The Theeuwes et al. (2013) study revealed that in some instances ~60% of the comfort achieved by the sensible cooling effect of bluespace might be negated by this humidity modification. Through consideration of the diurnal thermal exchanges, the evidence suggests that bluespace can in fact warm urban environments when it is least desirable (at night and under anticyclonic conditions typical of high UHI intensity and heatwaves) and as such offer limited potential for urban heat risk mitigation if considered in isolation.

5. Synergistic cooling

Although greenspace and bluespace is often highlighted as providing significant ecosystem services (i.e. functions as environmental capital) (Hathway and Sharples, 2012; Volker et al., 2013), comparative assessment of both together is uncommon in climate studies. A notable example is provided by a study of six parks and three lakes in Chongqing (China) (humid subtropical). Here cooling within parks (mixed landscape types) was found to be more defined than for lakes, the maximum recorded cooling being 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 synergistic dynamics based observations from case studies in Shanghai (humid subtropical). They proposed a regression model to extend an observed 10–20 m zone of improvement in thermal comfort through the use of littoral vegetation.

Synergistic cooling discussed within other climate studies are principally limited to recommendations of achievable improvements based on acknowledged first principles, or as hypothetical explanations for identified anomalous cooling enhancements. The Hathway and Sharples (2012) study for example observed that the most extensive cooling distribution at ~30 m from the river centre was evident at street canyons that were opened-up to provide access to riparian areas with greenery. Beyond such observations, there is little analysis offered to describe the synergistic processes involved, particularly for conditions where both greenspace and bluespace are purposefully integrated as green and blue infrastructure.

Synergistic processes are mostly discussed in the specific fields of potamological (studies of watercourses) and limnological (studies of waterbodies) research, where attention is given to biochemical implications of the thermal impacts of interactions between greenspaces and bluespaces. The majority of potamological studies are concerned with agricultural and forested areas. For example, a study of 20 streams in Washington (USA) highlighted the influence of riparian vegetation in reducing the net radiation balance of rivers by reducing exposure to both solar radiation incidence and wind flow. They found that clearcutting of this vegetation increased air temperature above the streams by up to 4 K within one winter and that preserved vegetated buffers provided some protection against air temperature increases mid-summer, while even greater protection was observed both early and late in the summer (Dong et al., 1998). Following the removal of such riparian vegetation, vapour density at a stream is likely to increase

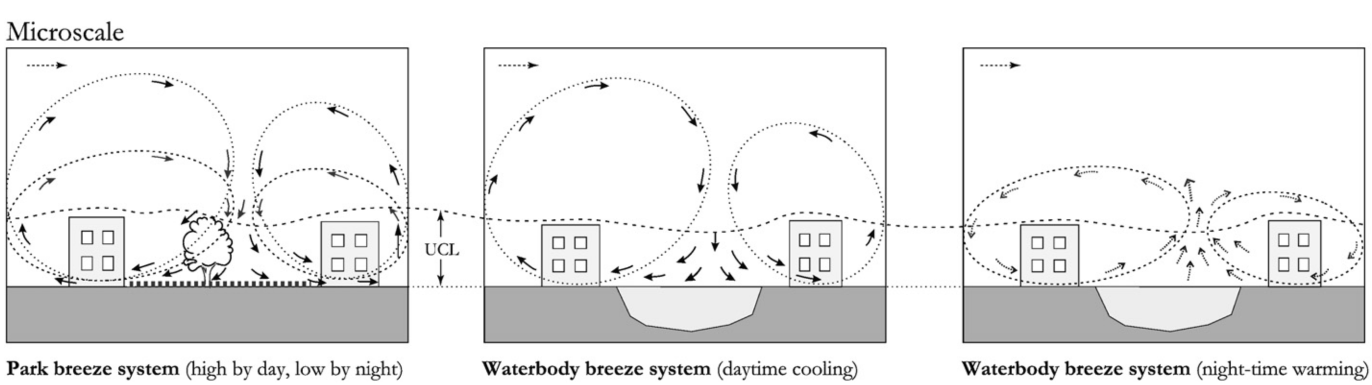

Fig. 6. Illustration of greenspace and bluespace interactions with the urban climate, expanded from Fig. 4.

as higher air temperatures lead to greater evaporation and increased transpiration rates from remaining riparian vegetation (assuming sufficient airflow to vacate humid air). These moisture reductions from the surface of watercourses and corresponding increases in the atmosphere are likely to have bearing on the local water-cycle (Brosofske et al., 1997). The influence of urbanisation on this cycle is mainly discussed in the literature in terms of impervious surface cover altering pathways of water movement that can lead to significant declines in the urban watertable (Groffman et al., 2003).

For static bodies, various forms of aquatic vegetation (macrophyte) occur. These vegetation types range from terrestrial plants, wet marginal and emergent plants (e.g. reeds), free-floating leaved plants (e.g. waterlilies) and submerged plants (e.g. milfoils) (Coates and Folkard, 2009). In addition to their numerous biological and chemical functions, these vegetation types are significant for moderating the thermal properties of the waterbodies they inhabit. Shading by such vegetation, besides modifying the radiation balance of a waterbody as noted earlier, can cause differential heating and cooling, resulting in internal convection flows that aid mixing. Where edge vegetation density and LAI is extensive, shading can be expected to reduce water temperatures in this littoral zone (Herb and Stefan, 2005). For example, a study of Priest Pot, a lake in the Lake District National Park (UK) (maritime temperate) found that the dominant solar radiation influence was modified by vegetation, altering light penetration into the water, thereby encouraging mixing and reducing stratification. They note that the interactions between radiation penetration in the littoral zone, vegetative shading and internal mixing are complex and unique to each waterbody and can produce either lower, or higher relative littoral zone temperatures (Coates and Folkard, 2009).

Littoral vegetation reduces wind-stress induced water column mixing, as does aquatic vegetation, which results in a reduced surface layer depth and potential strengthening of temperature stratification (Herb and Stefan, 2005). Significant to the degree of mixing generated is both the cover of vegetation present and fetch. For larger lakes with increased fetch, littoral vegetation serves to dampen surface-generated turbulent kinetic energy from penetrating the water column. A study of the aforementioned Priest Pot found that wind mixing was usually damped owing to its extensive surrounding tree cover, while at the neighbouring Esthwait Water lake, with its larger open setting and fetch, active turbulence developed over open water, save for damping in the littoral zone by vegetation (Coates and Folkard, 2009; Folkard et al., 2007). The effectiveness of damping is dependent on plant separation, with higher plant density achieving greater damping. A study of Lake Purrumbete in Victoria (Australia) (maritime temperate) identified that greater littoral plant spacing reduced its damping influence to the extent that flow and turbulence was similar to open water (Coates and Folkard, 2009).

Examining empirical data from Australia and corresponding numerical simulations, Hipsey and Sivapalan (2003) examined the effect of littoral windbreaks (both artificial and natural) on evaporation from small waterbodies. The study showed that reduced wind speeds and increased turbulence immediately downwind of a shelter promoted the accumulation of moisture in the air above the water surface, thereby reducing the humidity gradient and resulting evaporative flux. The area where the waviness of the water surface and surface area (roughness) in contact with the atmosphere is reduced was described as the 'quiet zone'. Wind speeds (u) further downwind of this remain reduced, although turbulent intensity increases as flow recovers to its upwind structure. This turbulent wake exhibits increased moisture and heat transfer. It was found that a greater degree of wind protection reduces the wind speed experienced by the waterbody and therefore reduces evaporative cooling, although the corresponding increase in surface water temperature was minimal. While no explanation was provided by the study, it can be hypothesised that this could be due to increased radiative output, or increased conductive heat loss between the water surface and the moisture saturated air that forms above the water surface.

For a windbreak of height H, subjected to initial wind speed u_0, the wind speed u at distance x downwind of the windbreak was found to be:

$$\hat{u} = 1-(1-\hat{u}_{min})[\exp(c_D(\xi-\xi_{min}))] \tag{1}$$

where, $\hat{u}$ is the normalised wind velocity $\hat{u} = u/u_0, \xi = x/H$ and ξ_{min} is the location of $\hat{u}_{min}$, the minimum value of the velocity profile. The location of $\hat{u}_{min}$ varies linearly with the height of the windbreak such that $\xi_{min} \approx 3$ ($x_{min} = 3H$). c_D is an empirically determined decay coefficient given by:

$$c_D = \frac{1}{120} \ln\left(\frac{H}{z_{o1}}\right) - 0.16 \tag{2}$$

where, z_{o1} is the upwind surface roughness length (typically defined as 1/10th the height of roughness elements). It is significant to note that the region between the windbreak and the position of minimum air velocity x_{min} is not necessarily a quiet zone. However, the two were found to be related such that:

$$x_{quiet} = 1.5 + 0.92x_{min} \tag{3}$$

Hipsey and Sivapalan (2003) also found that evaporation off the water surface varied with the diurnal cycle. At night when the Richardson number (the ratio between buoyancy and flow shear or equivalently the ratio between natural and forced convection) was suggestive of instability, the decay coefficient c_D is increased and the sheltering effect of a windbreak was reduced (Hipsey and Sivapalan, 2003).

The sheltering effect of natural (e.g. trees) and artificial (e.g. buildings) windbreaks in the littoral zone is likely to be another reason why the Lee Valley Park does not appear to affect the UHI shown in Fig. 3. Owing to the geometry of the Park and surrounding trees, the water surface may be completely sheltered (i.e. within the quiet zone shown in Fig. 7), thereby reducing the wind speed over the surface and resulting evaporative cooling. Even within the wake zone, vertical transport will be reduced despite evaporation being increased due to increased turbulence. This implies that extra thought has to be given to the placement of bluespace in relation to dominant wind direction and surrounding littoral windbreaks and buildings, so as not to create localised areas that exhibit higher night-time temperatures (due to thermal inertia) and higher humidity (due to reduced horizontal and vertical transport away from the water surface).

It is clear that predicting the synergistic cooling effect of greenspace and bluespace within urban areas is complicated due to the varied sheltering of vegetation and water surfaces. The nature of the surrounding surface roughness thus seems to be a very significant factor in predicting evapotranspiration and synergistic cooling potential. It can be hypothesised that if the diameter of the waterbody is <3× the height of the surrounding obstructions (e.g. buildings or trees), i.e. entirely within the quiet zone then it will act to create a localised pocket of warm humid air. If such conditions are of concern in an urban area (depending on background climate) consideration needs to be given to ensuring that there is reasonable permeability to windflow to facilitate cooling by breezes. This will be generally easier to achieve in dispersed urban arrangements where surrounding structures are typically not as tall and where the urban fabric is more permeable to wind flow than in more densely developed urban areas.

In addressing the UHI phenomenon in the context of future urban growth, patterns of urban development must be considered, which in turn will also provide an indication of the surface roughness patterns expected. Table 2 provides a summary of the influence of greenspace and bluespace on the thermal environment both compaction and dispersal urban growth patterns. Dispersal development of cities should in theory allow greater liberty to plan and integrate greenspace and bluespace features with greater consideration for surface roughness

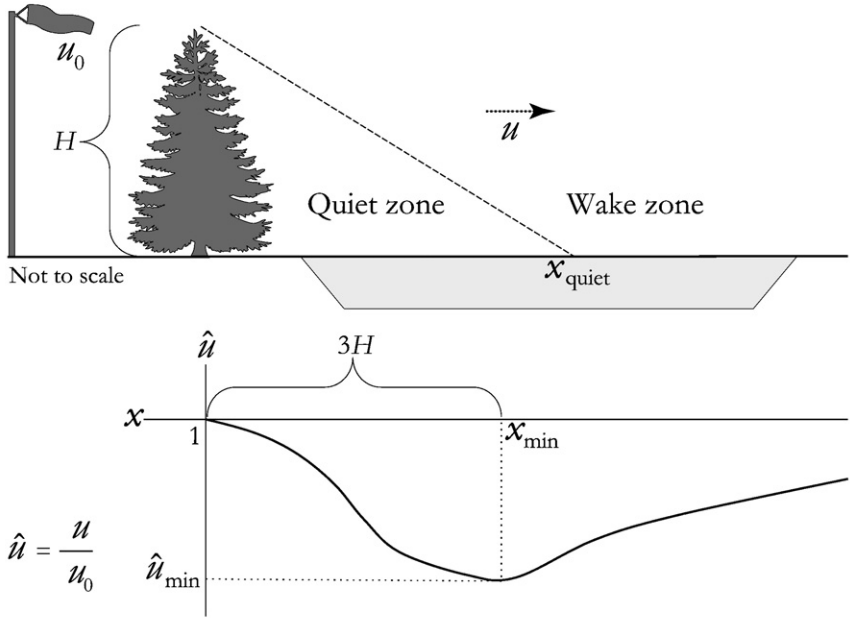

Fig. 7. Illustration of the effects of sheltering on downwind wind speed (u) above a water surface with distance (x) from a wind break, based on Hipsey and Sivapalan (2003).

implications. In strategies of urban compaction however, the creation of thermally effective blue and green infrastructure remains challenging, as existing roughness elements are likely to present rigid constraints. In such instances, successful strategies are more likely to take the approach of adapting existing bluespace through the introduction of additional 'infill' greenery, and through the inclusion of deep-soil building envelopes in vegetated architecture, able to support trees and shrubs rather than simpler and more planar herbaceous cover.

Within all of these studies it would be even better to improve urban design further by co-modelling the thermal benefits of green and blue infrastructure design along with the effects on all other ecosystem services (including psychological aspects) that pertain. Achieving a correct balance and character of green and blue infrastructure elements would seem to be particularly significant in relation to biophilic design and the eco-psychological benefits (Kellert et al., 2011).

Supplementary tables of the literature reviewed and summaries of results and conclusions are presented (online only) for greenspace (Table 3), bluespace (Table 4) and for joint studies of both greenspace and bluespace investigating synergistic cooling (Table 5).

6. Conclusions

This paper has considered first principle observations on how greenspace and bluespace features influence the mitigation of urban heat risks. Through a meta-analysis of various studies several key conclusions may be drawn.

Table 2
Urban development model influence on the thermal environment.

Greenspace & bluespace features	Compaction	Dispersal
Scale	Relatively smaller scale interventions generally feasible, apart from one or two exceptions. Substantial scale required to exhibit mesoscale influence.	Scale varies, with a number of larger features possible. Potential to act synergistically with existing rural features.
Typical arrangement	Planned, ordered, and managed arrangements.	Fragmented with planned and managed arrangements coexisting with undeveloped greenfield land and unplanned development.
Expansion impact	Compaction can lead to decline in inner-city greenspace and bluespace.	Loss of rural greenspace.
Day and night UCL health and impact on thermal comfort impact	Loss of greenspace is more likely and critical than bluespace (but higher land values suggest bluespace reclamation may be considered in certain circumstances).	Greenspace loss is more critical and likely than bluespace (lower land values suggest resource intensive bluespace reclamation will be uncommon).
Surface roughness and resultant impact on convection efficiency	Reduced by inner-city greenspace loss. Dependent on other urban morphological features.	Greenspace loss at periphery leading to reductions in convection efficiency (drawing heat out of urban areas).
City-country impact on thermal energy gradient	Increased compaction (densification) may enhance the gradient leading to a stronger city-country breeze, which advects in cooling from the greenbelt.	Greater spread of the surface balance (urban sprawl) may lead to a reduced gradient and a resultant diminished city-country breeze.
Surface permeability reduction from greenspace loss	Further decreased from default low levels, thereby increasing runoff and reduce evaporative cooling of surface. One exception to this is green-roof based SuDS integral to any compaction project.	Greater loss of surface permeability at urban peripheries likely with urban dispersal than with compaction (Echenique et al., 2012).
Addition of features	Large ground level features unlikely in many new schemes. Smaller strategically spaced (wind direction) networks viable. Exception in the case of major green and blue infrastructure regeneration projects (e.g. Basel, Greenwich Peninsula London, Stratford East Village, London).	Smaller strategically spaced (wind direction) networks viable.
Synergetic arrangement	Potential to plan with regeneration schemes. Strategies can include enhancing greening at existing bluespaces with tree planting as a priority and planar greening as a secondary alternative, whether at ground level or on built form.	Greater potential to plan entire new urban extensions with optimal blue-green design from the outset (see e.g. 'Bluegreen Dream' project of Imperial College London)

Contributions of greenspace and bluespace to urban cooling should be considered in all urban development or redevelopment scenarios and assessed through a systematic modelling framework. In doing so, the magnitude and distribution of horizontal and vertical climate influence should be assessed to determine beneficial microscale processes that affect urban occupant comfort and health and the mesoscale processes that serve to mitigate the citywide UHI.

Compaction and dispersal arrangements of urban form modify the mesoscale UHI flow and heat flux (also referred to as city-country breezes) differently, the former potentially enhancing and the latter reducing the strength of such flux. There is little evidence however to suggest that this disparity is sufficient to conclude that one pattern of urban development is superior to the other in terms of thermal balance optimisation, as this mesoscale flow represents only one of several climate interactions that affect urban cooling. For example, the microscale effects of sheltering on transpiration from greenspace and the evaporation of water from bluespace implies that both need to be either sufficiently large or to have networks orientated such that wind sheltering is minimised. This is easier to achieve in a dispersed urban arrangement than in a compact urban form, where building height-to-width ratios are greater and sheltering is increased. As long as the evapotranspiration benefits are optimised in terms of such meso-to-microscale dynamics when designing green and blue infrastructural networks, both forms of urban arrangement remain capable in delivering healthy and comfortable urban environments.

Criticism of both compact and dispersed urban design for reducing UBL cooling requires reconsideration in light of the fact that evapotranspiration is not the primary driver of the boundary layer UHI. In humid temperate climates, where rural vegetation is typically dense due to ample precipitation, urban areas can be aerodynamically smoother than the surrounding rural areas. This is particularly true if the urban area under consideration follows a dispersed arrangement. In such cases, the urban area is less efficient at dissipating heat through convection, leading to a substantial daytime UBL UHI. Conversely, for dry arid climates, where rural vegetation is typically low lying, urban areas increase surface roughness and increase convective heat dissipation. A similar effect was noted for rural forests compared to adjacent rural shrub land. This suggests that for wetter climates where surrounding rural areas are aerodynamically rough, dispersed urban areas should be avoided in favour of aerodynamically rougher compact urban areas. However, for drier arid climates, the aerodynamic roughness needs to be balanced against height-to-width ratio of street canyons and increased storage of heat at street level in the UCL. In such cases, a more dispersed urban arrangement may produce a smaller citywide UHI. The night-time UHI is dominated by heat release from the urban fabric and as air moves across the cityscape it is warmed by heat from the UCL below. As such, the centre of a city and its downwind areas are likely to be comparatively warmer. By introducing greater inner-city roughness, turbulent flow that is more efficient in mass and heat transport is encouraged. This implies that measures to increase inner-city surface roughness could also introduce significant modification to UCL heat transport and the nocturnal UHI experienced.

For both greenspace and bluespace, thermal effects are influenced by scale, geometry, spread and interval of interventions, surface roughness, fetch length and morphology and materiality of the context; as well as the prevailing climate. These characteristics influence thermal exchange with the climate and horizontal and vertical transport. Greenspaces extend their microscale cooling effect greatest during conditions typical of high UHI intensity and heatwaves. Bluespaces however may provide a warming effect, particularly at night and towards the end of summer, when UHI intensity and risk from heat stress is greatest. This suggests that when considered in isolation, greenspace is of greater benefit to heat risk mitigation than bluespace. When employed together, both green and bluespace provide mutually dependent environmental capital, offering many benefits including synergistic cooling and other valued ecosystem services.

The addition of multiple smaller interventions/space (whether green or blue) 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 bluespace can be usefully introduced as infilling features even in high-density compaction and regeneration strategies. The addition of such green and blue infrastructural networks is in agreement with the public health objective of providing greater access to cooler environments in addressing urban heat stress. However, where groves of trees are placed next to bluespace, there is possibility for humid air becoming trapped beneath the canopy in the wind sheltered quiet zone, thereby reducing evapotranspiration from both the greenspace and bluespace, producing uncomfortable environmental conditions. In such cases, urban morphology needs to be arranged so that prevailing winds can be directed through these areas.

The study of green and blue-infrastructure in relation to urban growth models enables city-planners, policy makers, engineers and architects to determine the urban designs that are likely to protect and enhance the health and wellbeing of inhabitants by optimising ecosystem services. In particular, such study can help develop citywide strategies to mitigate the mesoscale UHI and provide greater climate resilience.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.01.158.

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