A Review of Climate Change Impacts on the Built Environment

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There is growing consensus that the populations, infrastructure and ecology of cities are at risk from the impacts of climate change. This review collates evidence of effects in four main areas: urban ventilation and cooling, urban drainage and flood risk, water resources, and outdoor spaces (including air quality and biodiversity). It is shown that built areas exert considerable influence over their local climate and environment, and that urban populations are already facing a range of weather-related risks such as heat waves, air pollution episodes and flooding. Although climate change is expected to compound these problems, building designers and spatial planners are responding through improved building design and layout of cities. For example, green roofs and spaces provide multiple benefits for air quality, mitigating excessive heat and enhancing biodiversity. Hard engineering solutions will continue to play a role in adapting to climate change, but so too will improved forecasting and preparedness, along with risk avoidance through planning controls. There is also an over-arching need for higher-resolution weather data for testing future performance of buildings, urban drainage and water supply systems at city scales.

Introduction

Increasing attention is being paid to the potential impacts of climate change on urban environments. At present, roughly 50 per cent of the world's population live in cities, but this figure is expected to rise to more than 60 per cent over the next 30 years. Most of the future growth of the urban population is anticipated in the developing world (figure 1*a*). The vulnerable populations of many low-income countries are already exposed to shortages of clean drinking water and poor sanitation, and often occupy high-risk areas such as floodplains and coastal zones (Haines *et al*., 2006). As the concentration of urban populations and their assets is increasingly juxtaposed with growing risks of extreme events, so the re-insurance industry is suffering rising costs of weather-related losses (figure 1*b*) (Berz, 1997).

The scientific community is responding to these serious human health and welfare issues via a resurgence of interest in the fundamental processes governing urban atmospheres, as well as by research to improve operational weather and air quality forecasts for urban areas (Souch and Grimmond, 2006). There has also been a growing desire by planners and architects to develop settlements and construct houses that are more energy and water efficient, and simultaneously reduce risks to human and environmental health (Mills, 2006). Others have pointed to the significant contribution made by the world's major cities to global climate change, and the urgent need for energy efficient infrastructure and changed patterns of resource consumption (Hunt, 2004). With such a range of issues to tackle, it is not surprising that there have been calls for wider participation and more effective interaction

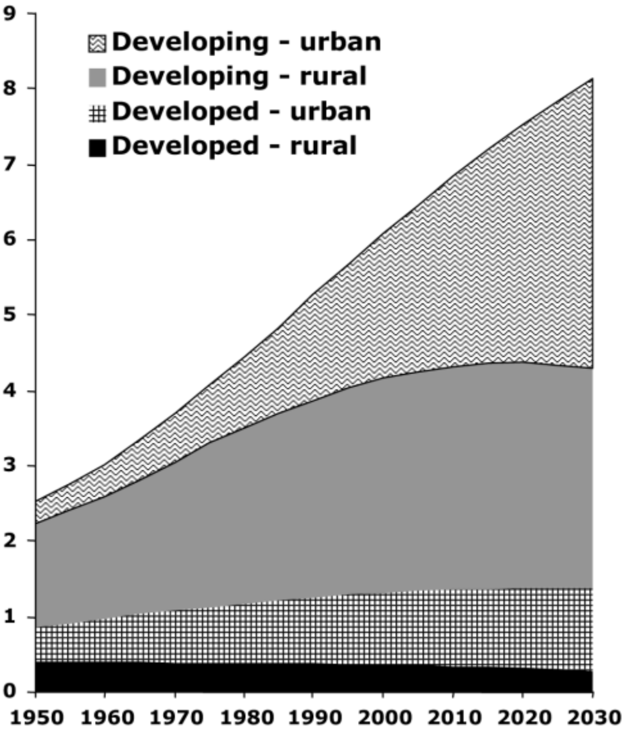

Figure 1*a*. An increasingly urbanized global population. (*Source*: United Nations Population Division, 2004)

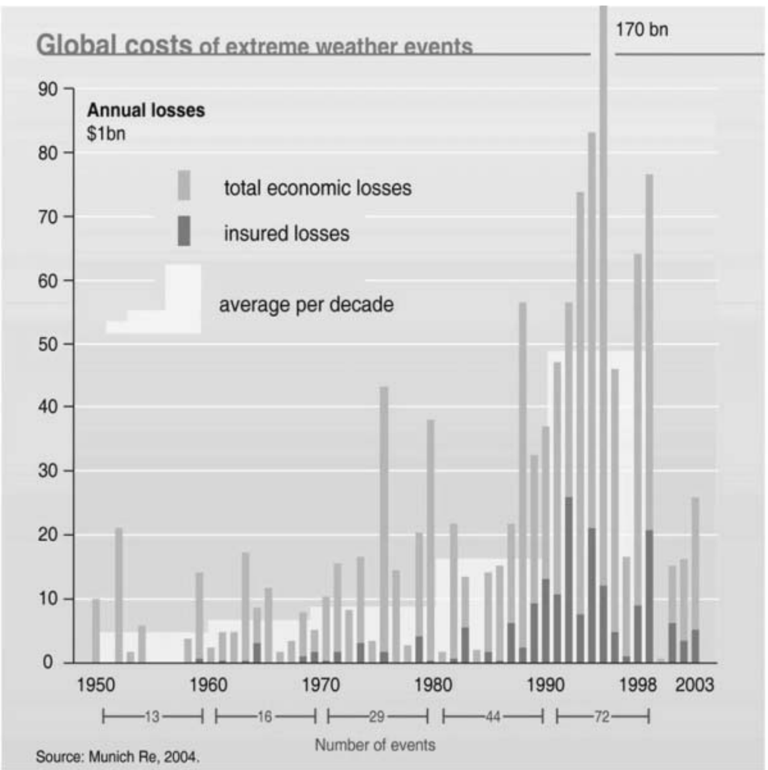

Figure 1*b*. Rising costs of weather-related losses. (*Source*: Munich Re, 2004)

between complementary disciplines (Oke, 2006). Thus, it is recognized that urban areas are both subject to, and an important component of, regional climate change.

Changing Global Climate

The Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) sets out a strong case linking human emissions of greenhouse gases to climate change. Amongst the bold statements were the assertions that most of the global warming over the last 50 years is attributable to human activities; that human activities will continue to change the composition of the atmosphere; and that global mean temperatures and sea levels will continue to rise for many centuries to come (IPCC, 2001).

Climatologists are already beginning to detect and attribute changes in extreme events to human influences on the global climate system (Zwiers and Zhang, 2003). For example, the risk of a heat wave like that experienced across Europe in 2003 is thought to have doubled due to historic greenhouse gas emissions (Stott *et al*., 2004). The risk of other extremes such as intense precipitation (Groisman *et al*., 1999), destructive tropical cyclones (Emanuel, 2005) and flooding (Milly *et al*., 2002) is also expected to increase. Not surprisingly, managing existing weather-related risks has become a key activity as evidenced by, for example, the growing number of urban heat health warning systems, or measures for countering excessive temperatures in urban centres through improved planning and building design (e.g., Shimoda, 2003).

However, the range of potential impacts is expected to go beyond heat waves. Other anticipated consequences of climate change for cities include fewer periods of extreme winter cold; increased frequency of air and water pollution episodes; rising sea levels and increased risk of storm surge; and changes in the timing, frequency and severity of urban flooding associated with more intense precipitation events (IPCC, 2001). These changes will, in turn, have both direct and indirect impacts on the ecological resources of urban communities (Wilby and Perry, 2006).

Changing Urban Climate

Detection of climate driven trends at the scale of individual cities is problematic due to the high inter-annual variability of local weather and confounding factors such as land-use change or urbanization effects. It has long been recognized that built areas can have urban heat islands (UHI) that may be up to 5–6°C warmer than surrounding countryside (Oke, 1982). Compared with vegetated surfaces, building materials retain more solar energy during the day, and have lower rates of radiant cooling during the night. Urban areas also have lower wind speeds, less convective heat losses and evapotranspiration, yielding more energy for surface warming. Artificial space heating, air conditioning, transportation, cooking and industrial processes introduce additional sources of heat into the urban environment causing distinct weekly cycles in UHI intensity (Wilby, 2003*a*). For recent reviews of urban climate research see Arnfield (2003) or Souch and Grimmond (2006).

The physical constituents of built areas and human activities within urban centres also interact with other climate drivers. For example, runoff from impervious surfaces can have dramatic effects on downstream risks of flooding and erosion (Hollis, 1988), as well as modifying river temperatures and water quality via uncontrolled discharges of storm water (Paul and Meyer, 2001). Urban air pollution concentrations may also increase during heatwaves with significant consequences for mortality as in the summer of 2003 (Stedman, 2004). This is because high temperatures and solar radiation stimulate the production of photochemical smog as well as ozone precursor biogenic volatile organic compounds (VOCs) by some plants.

Conversely, urban vegetation can deliver lower energy demands for air conditioning and help reduce health hazards by removal of air pollutants (Solecki *et al.*, 2005).

Climate Change Impacts on Built Environments

One of the earliest climate change impact studies for a major city was commissioned by the London Climate Change Partnership (LCCP, 2002). Table 1 summarizes the main findings of the report and gives examples of how climate change could increasingly affect the integrity of the built environment. More recently the partnership has issued guidance on designing developments for a changing climate (GLA, 2005). The overall aims of the document are to assist developers and their design teams to future-

Table 1. Potential climate change impacts on London. (*Source*: London Climate Change Partnership, 2002)

Issue	*Key impacts*
Higher Temperatures	• Intensified urban heat island, especially during summer nights • Increased demand for cooling (and thus electricity) in summer • Reduced demand for space heating in winter
Flooding	• More frequent and intense winter rainfalls leading to riverine flooding and overwhelming of urban drainage systems • Rising sea levels, storminess and tidal surges require more closures of the Thames Barrier
Water Resources	• Heightened water demand in hot, dry summers • Reduced soil moisture and groundwater replenishment • River flows higher in winter and lower in summer • Water quality problems in summer associated with increased water temperatures and discharges from storm water outflows
Health	• Poorer air quality affects asthmatics and causes damage to plants and buildings • Higher mortality rates in summer due to heat stress • Lower mortality rates in winter due to reduction in cold spells
Biodiversity	• Increased competition from exotic species, spread of disease and pests, affecting both fauna and flora • Rare saltmarsh habitats threatened by sea level rise • Increased summer droughts cause stress to wetlands and beech woodlands • Earlier springs and longer frost-free season affect dates of bird egg-laying, leaf emergence and flowering of plants
Built Environment	• Increased likelihood of building subsidence on clay soils • Increased ground movement in winter affecting underground pipes and cables • Reduced comfort and productivity of workers
Transport	• Increased disruption to transport systems by extreme weather • Higher temperatures and reduced passenger comfort on the London Underground • Damage to infrastructure through buckled rails and rutted roads • Reduction in cold weather-related disruption
Business and Finance	• Increased exposure of insurance industry to extreme weather claims • Increased cost and difficulty for households and business of obtaining flood insurance cover • Risk management may provide significant business opportunity
Tourism and Lifestyle	• Increased temperatures could attract more visitors to London • High temperatures encourage residents to leave London for more frequent holidays or breaks • Outdoor living, dining and entertainment may be more favoured • Green and open spaces will be used more intensively

proof developments at the design stage, to incorporate resilience to climate change impacts within existing communities, and to help planners scrutinizing planning applications. The resulting checklist provides a useful framework for reviewing climate change impacts on urban ventilation and cooling, urban drainage and flood risk, water resources, and outdoor spaces. This structure is applied here and will form the bulk of this review. The focus will be mainly on climate change impacts, as adaptation responses are dealt with elsewhere in this issue. The final section sets out some priorities for future research.

Ventilation and Cooling

As noted above, city centres can be several degrees warmer than surrounding rural areas due to the UHI effect. Detailed temperature monitoring in London has established that the heat island is most pronounced at night, that it weakens with increasing wind speed and distance from the city centre, and that the location of the thermal maximum shifts with changes in wind direction (Graves *et al.*, 2001). The heat island is also highly changeable from one day to the next as a consequence of variable weather patterns. During some nights temperature differences can be up to 7ºC between St James's Park (central London) and Wisley (a rural location 32 km south-west of London) (Wilby, 2003*b*). The annual number of nights with intense heat islands stronger than 4ºC has climbed at a rate of over four days per decade since the late 1950s, whilst the average nocturnal heat island intensity increased by ~0.1ºC per decade over the same period. In contrast, the

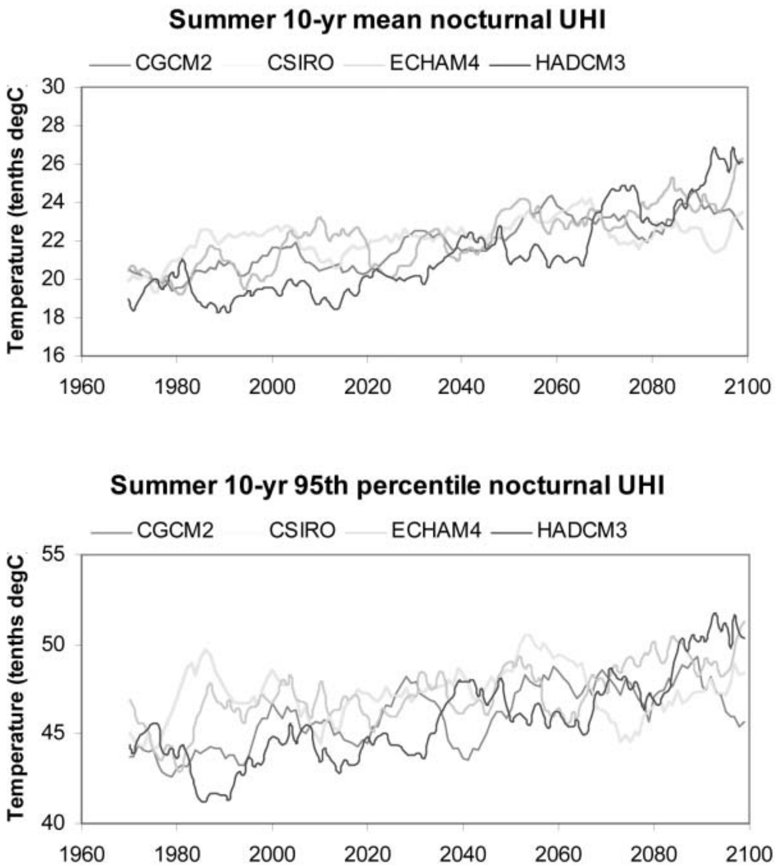

Figure 2. Project trends in London's nocturnal UHI in summer under medium-high (SRES A2) emissions. The scenarios were downscaled from four climate models: the Canadian Centre for Climate Modelling and Analysis model (CGCM2); the Mk2 Commonwealth Scientific and Industrial Research Organization model (CSIRO); the Max-Planck-Institut for Meteorology model (ECHAM4); and the UK Met Office Hadley Centre's coupled ocean/ atmosphere climate model (HadCM3).

number of intense daytime heat-islands has declined to about one event per year since the mid 1980s.

Heat waves are expected to increase in frequency and severity in a warmer world (Meehl and Tebaldi, 2004). Urban heat islands will exacerbate the effects of regional warming by increasing summer temperatures relative to outlying rural districts. Furthermore, UHIs could even intensify with projected increases in solar radiation, and lower wind speeds (under anticyclonic conditions). Recent results from both dynamical and statistical models point to further intensification of the mean nocturnal heat island (Betts and Best, 2004; Wilby, 2003*b*). For example, using a statistical downscaling method, Wilby (2006) showed that London's nocturnal UHI could intensify by a further 0.5°C in August by the 2050s. This translates into a 40 per cent increase in the number of nights with intense UHI episodes. Although the rate of intensification differs between climate models the results are qualitatively similar (figure 2) and all should be regarded as conservative estimates since additional heat sources (from air conditioning, transportation etc.) were not included in the analysis.

If realized, these projected trends could have significant consequences. The cooling potential of natural ventilation falls with rising outdoor temperatures, so the demand for summer cooling could grow as internal temperatures rise during heat waves. For example, a study of energy demand in Athens showed a 30 per cent increase in energy demand by the 2080s during July and August (Giannakopoulos and Psiloglou, 2006). Mortality is also known to increase in hot weather especially amongst the elderly (Haines *et al*., 2006). As witnessed during the major European heat wave of 2003, urban centres such as Paris were particularly affected due to extreme day-time temperatures and by lack of relief from high nocturnal temperatures (Vandentorren *et al*., 2004). Thus, even in the absence of climate change, summer heatwaves combined with the UHI effect can trigger major public-health crises in largely urbanized populations (see table 2). Using present-day relationships between extreme heat and summer excess mortality for the Los Angeles metropolitan area, heat-related deaths were found to increase by up to seven times by the 2090s even with acclimatization (Hayhoe *et al*., 2004).

Urban Drainage and Flood Risk

Long-term observations support the view that the frequency and intensity of heavy rainfall increased in many regions during the twentieth century (Groisman *et al*., 1999), and regional climate models suggest that intensities will continue to increase over coming decades (Ekström *et al*., 2005). Although the general implications for the

Table 2. Excess mortality attributed to the 2003 heat wave in Europe. (Adapted from Haines *et al*., 2006)

Location	*Date*	*Excess mortality*	*% increase*
England and Wales	Aug 4–13	2091	17
France	Aug 1–20	14802	60
Germany	Aug 1–24	1410	–
Italy	Jun 1–Aug 15	3134	15
Netherlands	Jun–Sep	1400–2200	–
Portugal	Aug	1854	40
Spain	Jul–Aug	4151	11
Switzerland	Jun–Sep	975	7

urban hydrological cycle are understood (figure 3), there have been relatively few credible studies of changing flood risk for *whole* urban areas. This reflects the challenge of adequately modelling high-intensity precipitation (or snowmelt) events at city-scales (Schreider *et al.*, 2000), and of representing land-surface controls of storm runoff generation (Bronstert *et al.*, 2002). Assessing urban flood risk is further complicated by the performance of the urban drainage system, which responds to highly localized effects such as blocked culverts or overwhelming of the hydraulic capacity of sewers (Ashley *et al.*, 2005). Urban drainage in cold regions dominated by snowmelt may be especially vulnerable to climate change (Semadeni-Davis, 2004). There is also a wide variety of tangible and non-tangible secondary impacts associated with flooding in urban areas (table 3).

The UK Government's Foresight Report (OST, 2004) estimates that 80,000 urban properties are presently at risk from flooding caused by heavy downpours, yielding average annual damages of £270 million. The number of properties at high risk from intra-urban flooding could quadruple and annual damages rise to £15 billion by the 2080s. However, the authors concede that considerable uncertainty surrounds the incidence of flooding because of the complex interplay between the amount of precipitation change in relation to the excess capacity of sewer and drainage pipes. It is also difficult to quantify other costs associated with foul

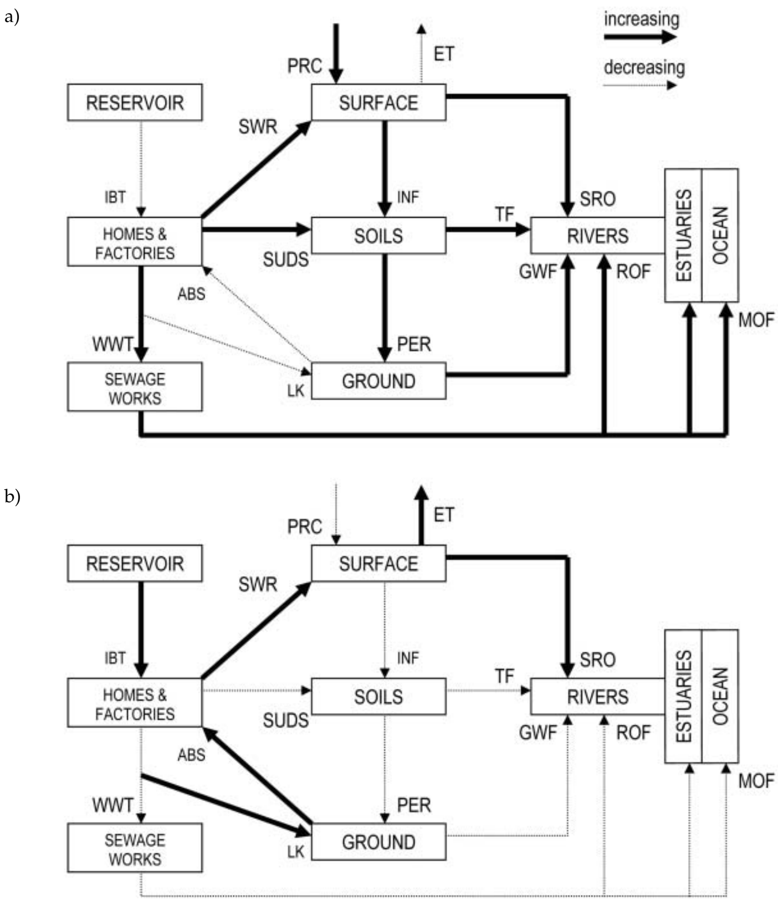

Figure 3. Implications of climate change for the urban hydrological cycle in a) winter and b) summer. Key: PRC = Precipitation; ET = Evapotranspiration; IBT = Inter-basin transfer; WWT = Waste-water treatment; SUDS = Sustainable urban drainage system; ABS = Groundwater abstraction; INF = Infiltration; PER = Percolation; LK = Leakage; SWRO = Surface water runoff; SRO = Surface runoff; GWF = Groundwater flow; TF = Through flow; ROF = River outfalls; MOF = Marine outfalls. (*Sources*: Wilby and Perry, 2006 and Handley, 2004)

Table 3. Potential consequences of sea level rise and increased fluvial flood risk in London identified by stakeholders. (Adapted from LCCP, 2002)

- Loss of freshwater/riparian habitats (see below)
- Saline intrusion further up estuary and into adjacent freshwater marshland
- Greater demands placed upon emergency services
- Disrupted operations in floodplain landfill sites or loss of potential landfill sites
- Higher costs of flood protection for new developments
- Mortgage and insurance difficulties leading to blighting of some communities
- Flooding of the London Underground (already being pumped)
- Greater threat to riverside developments and inundation of major assets such as sewage treatment works
- Access and aesthetics impaired by raised flood defences
- More foul water flooding
- Severe disruption to utilities and transport systems
- Disruption to river-based activities such as navigation
- Stress to flood victims

water flooding, or risks to human health such as diarrhoeal and respiratory diseases (Ahern *et al*., 2005). There could also be significant disruption to system-wide performance of transportation networks as in the case of the Boston Metro Area (Suarez *et al*., 2005).

Many of the world's major cities are located on low-lying areas near coasts and estuaries and are threatened by long-term sea level rise (Nicholls, 2004). Assessments of future flood risk for these cities bring the added complexity of interactions between sea level rise, tidal surges and storminess combined with fluvial flooding and coastal erosion (Lowe *et al*., 2001; Svensson and Jones, 2002; Woth, 2005). Given such large and multiple uncertainties, some flood risk managers are turning to the use of precautionary allowances and sensitivity testing as a means of factoring climate change into urban development control or engineering designs. For example, in the UK a 20 per cent sensitivity allowance is applied to daily rainfall, peak river flow volumes and urban drainage volumes to account for climate change by 2050 (Hawkes *et al*., 2003). Contingency allowances are also provided for sea level rise, offshore wind speeds and wave heights. All the guidance was recently reviewed within Planning Policy Statement (PPS25) and extended to periods beyond 2050.

'Climate change factors' have also been derived for design floods of given recurrence interval for several regions in south-west Germany (Ihringer, 2004). For example, figure 4 shows that the magnitude of the 50-year flood flow in Region 3 should be increased by a factor of 1.25 to accommodate climate changes projected up to 2050. The factors are applied only to new developments and are based on precipitation changes from a single climate model (ECHAM4) under a low emissions scenario. Nonetheless, this is regarded as a significant step forward because climate change is now explicitly factored into engineering design (Caspary and Katzenberger, 2006.). Detailed cost analysis has also shown that adaptation of existent flood protection measures is much more expensive than incorporating climate change effects at the planning stage.

Water Resources

Water resources planning has traditionally viewed climate as stationary, a position that is increasingly untenable given that

T[a]	Region 1	Region 2	Region 3	Region 4	Region 5
2	1.25	1.50	1.75	1.50	1.75
5	1.24	1.45	1.65	1.45	1.67
10	1.23	1.40	1.55	1.43	1.60
20	1.21	1.33	1.42	1.40	1.50
50	1.18	1.23	1.25	1.31	1.35
100	1.15	1.15	1.15	1.25	1.25
200	1.12	1.08	1.07	1.18	1.15
500	1.06	1.03	1.00	1.08	1.05
1000	1.00	1.00	1.00	1.00	1.00

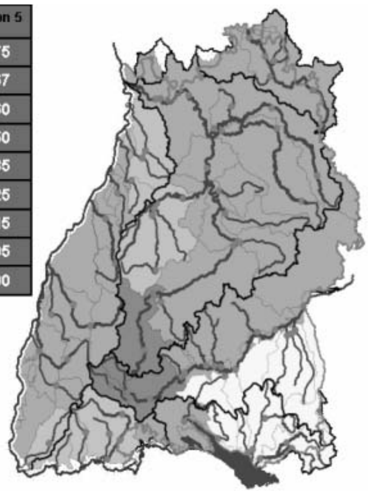

Figure 4. Climate change factors as a function of recurrence interval T[a] for different regions of south-west Germany. The figures show the amount by which a flood of given return period (*T* years) should be scaled to reflect projected climate change between 1971–2000 and 2021–2050. (*Source*: Caspary and Katzenberger, 2006)

infrastructure can be in place for many decades, even centuries. The latest macro-scale models driven by future rainfall scenarios show increasing water scarcity around the Mediterranean, parts of Europe, central and southern America, and southern Africa (Arnell, 2004; Milly *et al.*, 2005). Long-term planning taking into account climate variability and change must also accommodate the various, and often conflicting, demands for water as well as the need to protect the wider environment. In developing countries, failure of water supplies and irrigation systems can lead to poor sanitation in urban areas, as well as food shortage and reduced power generation (Magadza, 2000). Reduced reliability of surface water supplies could shift reliance to groundwater resources that are already over-exploited as in the case of many agricultural areas of California (Hayhoe *et al.*, 2004).

Numerous studies have been undertaken worldwide to assess impacts of climate change on water resources. Conventional approaches involve generating scenarios for daily or monthly hydroclimatic variables using climate model output, then applying these to water balance models to investigate consequences at river catchment scales (e.g., Diaz-Nieto and Wilby, 2005). Using continuous simulation models it is then possible to extract required flow statistics, such as the annual minimum 30-day flow (figure 5). These procedures are now being adapted to accommodate uncertainties in the emission scenario, climate model output, downscaling scheme, impact model structure and parameterization (Wilby and Harris, 2006). For example, figure 6 shows the conditional probability of low-flows in the River Thames by the 2020s, 2050s and 2080s reflecting the weight attached to these uncertainties. Overall, there is little change in the likelihood of below average minimum flows, but the probability of larger reductions in minimum flows (>–20 per cent change) does increase with time.

Urban water supplies can be disrupted through deteriorating quality, and climate change has the potential to affect water quality in several ways. For example, lower summer flows in impermeable catchments will reduce the volume available for dilution of treated effluent or uncontrolled discharges from sewers, and increase the potential for saline intrusion in estuaries. Urban river water temperatures are expected to increase with higher air temperatures and lower volumes of flow (Webb *et al.*, 2003). Higher nutrient concentrations and river water

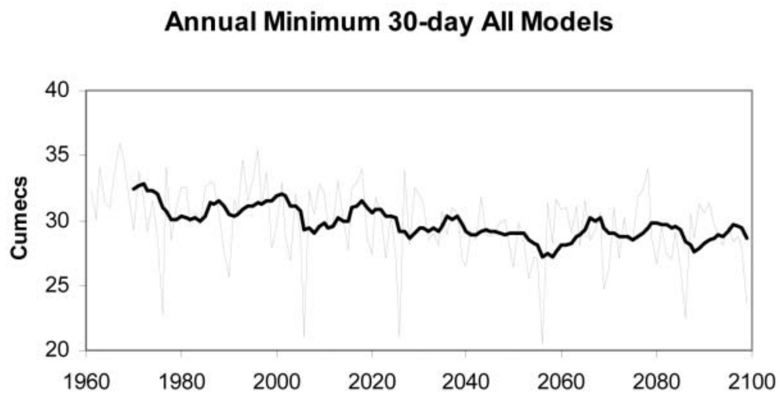

Figure 5. Transient simulation of annual minimum 30-day flow in the River Thames 1961–2100.

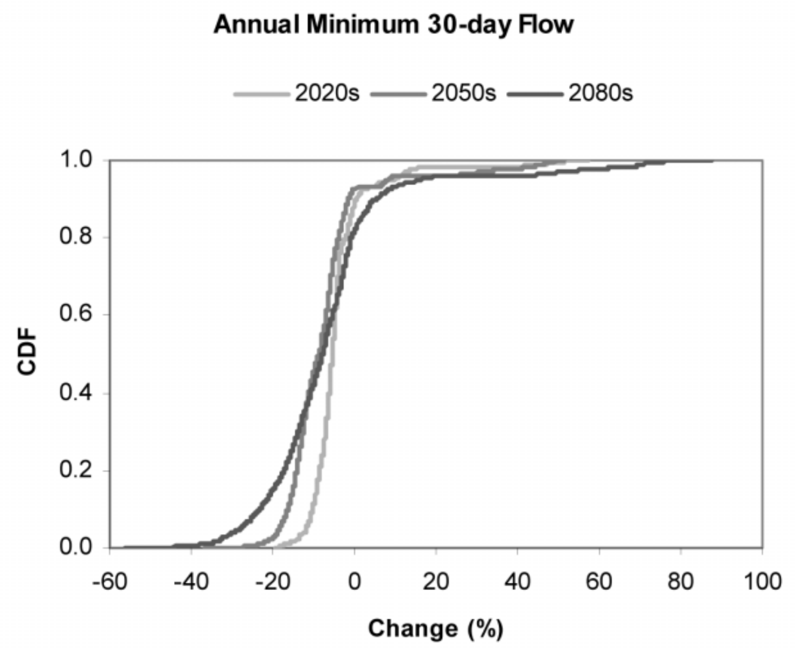

Figure 6. Conditional probabilities of changes in the annual minimum 30-day flow of the River Thames by the 2020s, 2050s and 2080s.

temperatures could, in turn, encourage the growth of algal blooms and other plants that deoxygenate water bodies (Wade *et al*., 2002). Conversely, higher ambient temperatures could improve the performance of water treatment works.

In addition to water availability and impact on the natural environment, climate change also affects water resource planning through changing patterns of water consumption (Herrington, 1996) and patterns of seniority in water rights (Hayhoe *et al*., 2004). Domestic water use is expected to increase as a result of hotter summers leading to increased garden watering and personal washing. The impact of climate change on industrial water use could be felt most keenly where consumer demand for products is temperature dependent (e.g., the food and drinks industry), or where industrial processes are less efficient at higher temperatures (e.g., water cooling for power generators) (LCCP, 2002).

Outdoor Spaces (Air Quality and Biodiversity)

Green space is regarded by many as a crucial component of urban landscapes, not least for countering the UHI, reducing flood risk, improving air quality and promoting habitat availability/connectivity (Defra, 2005; Solecki *et al*., 2005; Wilby and Perry, 2006). Gardens can cover a significant proportion of urban areas and their conservation value should not be underestimated (Rudd *et al*., 2002). But like other habitats, gardens are also susceptible to climate change (Bisgrove and Hadley, 2002).

Developers and design teams are already encouraged to incorporate green space in their plans, and to make good use of shading and green roofs to help reduce the UHI (GLA, 2005). This provision is also made on the understanding that urban populations will want more access to outdoor natural spaces as temperatures increase. Care must still be taken to ensure that vegetation does not lead to local drying of soils, clay shrinkage, and hence induce subsidence and leakage from water mains (Doornkamp, 1993). Green roofs are regarded as a Sustainable Drainage System (SUDS) technique, and can help attenuate surface runoff, as well as trap pollutants and promote groundwater recharge (GLA, 2005).

Although urban vegetation can be beneficial for some aspects of air quality, Defra's (2006) Air Quality Expert Group cautions that some species may exacerbate existing problems of summer photochemical smog episodes by releasing ozone precursor biogenic volatile organic compounds (VOCs). The production of VOCs is linked to temperature and solar radiation so future climate conditions could provide more favourable conditions for their release. According to Stewart *et al*. (2003) Sitka spruce and poplar are the dominant emitting species for the British Isles as a whole, but willow and oak can be locally significant sources of isoprene.

Atmospheric circulation patterns are a major factor affecting ambient air quality and pollution episodes, and hence the health of urban populations as witnessed during the 2003 heat wave (Stedman, 2004). Several studies have indicated that weather patterns favouring air stagnation, heat waves, lower rainfall and ventilation could become more frequent in the future leading to deteriorating air quality (e.g., Langner *et al*., 2005; Leung and Gustafson, 2005; Wilby, 2006) (figure 7). Under existing air pollution abatement policies 311,000 premature deaths are projected in 2030 due to ground-level ozone and fine particles (EEA, 2006). Full implementation of measures to achieve the EU's long-term climate objective of limiting global mean temperature increases to 2°C would reduce premature deaths by over 20,000 by 2030. Other ancillary benefits of this 'climate action scenario' include lower costs of controlling air pollutant emissions as well as improved health of ecosystems impacted by acidification and eutrophication.

Despite the benefits associated with green spaces, urban wildlife could still suffer serious threats from degradation and/or loss

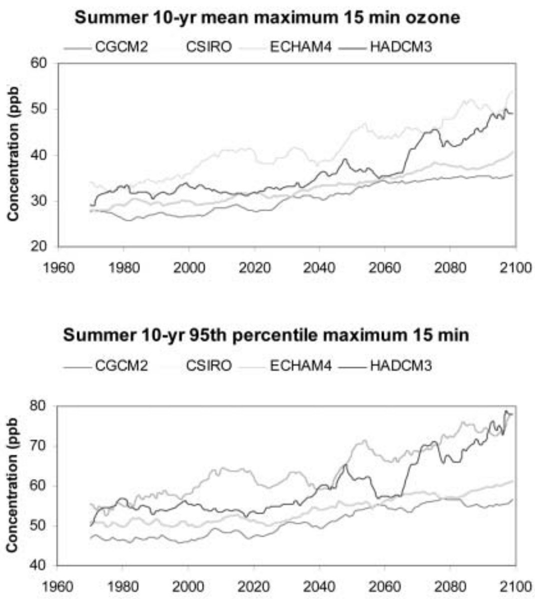

Figure 7. As in figure 2 but for maximum 15-minute ozone concentrations in summer at Russell Square, London. (*Source*: Wilby, 2006)

of habitats, the introduction and spread of problem species, water pollution, unsympathetic management, and the encroachment of inappropriate development (Wilby and Perry, 2006). Climate change could add to these problems through competition from exotic species, the spread of disease and pests, increased summer drought stress for wetlands and woodland, and sea level rise threatening rare coastal habitats. Earlier springs, longer frost-free seasons, or reduced snowfall could further affect species phenology (such as the dates of egg-laying, emergence, first flowering or leafing of plants). Conversely, some small birds and naturalized species could benefit from warmer winters associated with the combined effect of regional climate change and enhanced UHI (LCCP, 2002).

Concluding Remarks

There is no doubt that the populations, infrastructure and ecology of cities are at risk from the impacts of climate change. However, tools are becoming available for addressing some of the worst effects. For example, appropriate building design and climate sensitive planning, avoidance of high-risk areas through more stringent development control, incorporation of climate change allowances in engineering standards applied to flood defences and water supply systems, or allocating green space for urban cooling and flood attenuation. Some of these adaptation measures will be explored in further detail by other authors in this issue. Citizens also have a responsibility to mitigate their collective impact on the local and global environment through reduced resource consumption and changed behaviour (Hunt, 2004). Under some circumstances both adaptation and mitigation must be addressed within a broader developmental context (du Plessis, 2003).

This review has described the most significant climate change impacts expected to shape the future character and functioning of urban systems. Several important knowledge gaps have emerged. First, there is an ongoing need to improve preparedness and forecasting of climatic hazards, such as intense heat island or air pollution episodes, to safeguard human comfort and health. Long-term projections of the UHI will require better characterization of anthropogenic heat sources and land-surface feedbacks on boundary layer climates (as in Fan and Sailor, 2005).

Second, there is clearly a need for improved representation of intra-urban flooding, at local, city and catchment scales. Also for a move away from hard engineering solutions to urban drainage problems. More research is needed on future changes in the joint occurrence of tidal surge, storminess and fluvial flooding in estuaries (as in Svensson and Jones, 2005).

Part of the answer to these concerns will be the wider-availability of high-resolution (space and time) scenarios for precipitation, wind speeds and heat waves. For example, building designers are beginning to use high-resolution weather data to design climatically-sensitive buildings that maximize human comfort yet minimize energy requirements (see Hacker *et al.*, 2006). New modelling techniques will also be needed to exploit fully emergent probabilistic climate change information. But there could be new cost implications arising from the use of such data, dependent on the level of risk and uncertainty that is acceptable in the resultant engineering design (for example, reflected by the height of a flood defence asset, or reservoir capacity).

Above all, there is an urgent need to translate awareness of climate change impacts into tangible adaptation measures at all levels of governance. The *Primer for Municipal Water Providers* (Miller and Yates, 2005) and the *Checklist for Development* (GLA, 2005) provide good examples of how the latest scientific understanding of sectoral impacts and adaptation responses can be shared with practitioners. The next challenge is to integrate measures *across* sectors so that such responses are implemented in a co-ordinated and cost-effective way.

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