Socio-economic Impacts—Urban Climate

15

K. Heinke Schlünzen and Sylvia I. Bohnenstengel

Abstract

About 80 % of the population within the North Sea countries currently lives in an urban area and this percentage is projected to continue to rise. Urban areas are not only impacted by changes in regional climate but are themselves responsible for causing local modifications in regional climate resulting in the so-called 'urban climate'. The urban climate in North Sea cities has several common features: higher temperatures relative to the surrounding regions (especially at night), greater temperature variability, deeper but less stable boundary layers at night, lower average wind speeds but stronger gusts, reduced evapotranspiration, and greater air pollution (local exceedances of limit values for nitrogen oxides, nitrogen dioxide and particulate matter, with ship emissions a relevant contributor in harbour cities). Indications of climate change are now apparent and include hinterland flooding, more intense precipitation, and drier and warmer summers. Cities contribute to greenhouse gas emissions and measures are needed to reduce these. Cities also need to adapt to climate change. Despite broad similarities between urban areas, in terms of mitigation and adaptation to climate change there are large location-specific differences with regard to city planning needs. Hamburg and London are used as examples. Adaptation measures include better insulation of buildings to reduce energy use and anthropogenic heat emissions, higher dykes to protect against increased water levels, and rain water drainage to avoid hinterland flooding. Scenarios are outlined for urban development with greened roofs, higher albedo values and lower sealing of surfaces.

15.1 Introduction

Worldwide every second person lives in a town; in the North Sea region the percentage is even higher. About 80 % of the population within the North Sea countries currently lives in an urban area and this percentage is projected to continue to rise (Fig. 15.1). Nine out of ten citizens are predicted to be living in an urban area by the middle of this century. This level of urbanisation is higher than in Europe as a whole or worldwide, but is similar to that of the United States. The megacity of London (~ 14 million people) is located on the periphery of the southern North Sea, as are several metropolitan areas with at least 1 million inhabitants (Rotterdam, Hamburg, Amsterdam, Antwerp). Because so many people live in urban areas it is important to understand the interrelations between regional and urban climate and how both will develop over time.

The urban climate is affected by the regional climate and specific local characteristics such as closeness to the ocean or nearby mountains. Most urban areas in the North Sea region (e.g. Amsterdam, Antwerp, Hamburg, London, Rotterdam) experience a warm temperate climate, which is fully

---

K.H. Schlünzen (✉)
Institute of Meteorology, CEN, University of Hamburg, Hamburg, Germany
e-mail: heinke.schluenzen@uni-hamburg.de

S.I. Bohnenstengel
Department of Meteorology, University of Reading, Reading, UK
e-mail: s.i.l.d.bohnenstengel@reading.ac.uk

Present Address:
S.I. Bohnenstengel
MetOffice@Reading, University of Reading, Reading, UK
e-mail: sylvia.bohnenstengel@metoffice.gov.uk

M. Quante and F. Colijn (eds.), *North Sea Region Climate Change Assessment*,
Regional Climate Studies, DOI 10.1007/978-3-319-39745-0_15

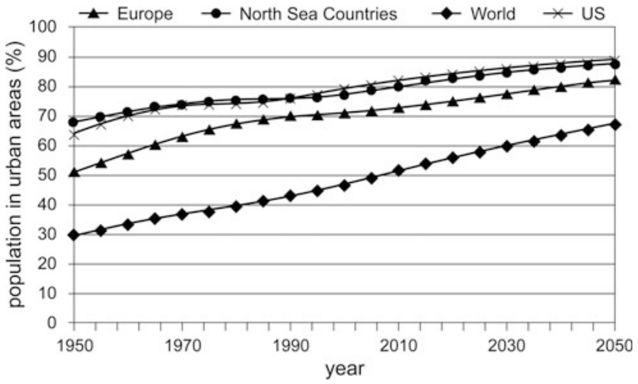


Fig. 15.1 Development of urbanisation in countries bordering the North Sea and other regions of the world (based on UN 2014)

humid with a warm summer (Class Cfb following the Köppen-Geiger climate classification as given by Kottek et al. 2006). Only in the northernmost part of the North Sea region is snow a regular winter feature, which means cities such as Oslo or Bergen are on the margin of the Dfb Köppen-Geiger climate class. More details of the North Sea climate can be found in Chaps. 1 and 2.

The proximity of the large metropolitan areas to the North Sea implies they are generally located in low altitude areas; some parts are even partly situated below sea level (see Annex 5, Fig. A5.1). This is especially true for the urban areas of the Netherlands (Amsterdam, Rotterdam, The Hague and Utrecht), but also for Antwerp, London or Hamburg. Although for the latter at least some parts of the metropolitan area are 10 m or more above sea level. As a result, adaptation to climate change in a coastal urban area means it is important to consider potential changes in sea level, river level, storm surge and connected groundwater level (Schlünzen and Linde 2014). However, while for city planners the rise in sea level (Chaps. 3 and 6) and river level are extremely important, they have little impact on urban climate and so fall outside the scope of this chapter (see Chap. 18 for discussion on this topic). Soil water is relevant, however, since its availability could affect evapotranspiraration and thus temperature and humidity in an urban area (Sect. 15.4.2).

15.2 Urban Climate in the North Sea Region

Any changes in the natural conditions of an area will modify the regional climate such that it is locally altered, resulting in a so-called ‘urban climate’ in the case of urban areas. Local modifications to regional climate in urban areas largely depend on the urban fabric (e.g. building height, percentage of sealed surfaces, building materials, atmospheric emissions), and for North Sea cities result in several common features:

- *Higher temperatures.* These result from changes in the surface energy budget due to urban fabric having greater heat storage than vegetation in rural areas. In urban areas, heat is stored during the day and then emitted during the evening and at night, supplemented by anthropogenic heat emissions; this increase in air temperature is termed the ‘urban heat island’ effect (UHI, Sect. 15.4.2). The UHI shows both a diurnal and an annual cycle. The intensity of the night-time warming is even more intense at the surfaces (surface urban heat island).
- *Greater temperature variability.* This results from shading and reflection of short-wave radiation by buildings, radiative trapping, heat storage by buildings, and increased energy use and emission of waste energy (Sect. 15.4.2).
- *Deeper boundary layers and more frequent unstably stratified boundary layers at night.* This is due to the UHI effect and could affect turbulent mixing of pollutants (Chemel and Sokhi 2012) which could in turn increase ozone (O_3) concentrations near the surface at night and reduce nitrogen dioxide (NO_2) concentrations (Zhang and Rao 1999; Sect. 15.4.2).
- *Lower average wind speed and greater gustiness.* The presence of buildings in urban areas causes lower average wind speeds, but local maxima can occur especially within street canyons facing the coastline or river bank. The buildings also trigger an overall increase in gustiness; wind comfort is thus much lower in coastal urban areas of the North Sea region than in inland urban areas (Sect. 15.4.3).
- *Reduced evapotranspiration.* Owing to less vegetation, less water storage capacity and often lower groundwater levels in urban areas, evapotranspiration is smaller. For North Sea cities, even the areas with high groundwater levels have reduced evapotranspiration, if the surfaces are sealed (Sect. 15.4.2).
- *Changed precipitation fields.* The urban fabric and UHI effect lead to convergences and more updrafts in the flow field, often resulting in more downwind precipitation (Shepherd et al. 2002) if anthropogenic pollutant emissions are neglected. In an urban area with high pollutant emissions (e.g. sulphur dioxide, SO_2) the urban area might reduce precipitation; however, aerosol impacts are still uncertain (Pielke et al. 2007). Whether downwind precipitation is higher or lower depends among other things on aerosol composition, meteorological situation, and urban surroundings (Han et al. 2014). Urban precipitation impacts are visible through changes in downwind precipitation (Sect. 15.4.3).
- *More air pollution.* Owing to higher emissions from a range of anthropogenic sources (traffic, households, industry) there are higher levels of primary pollutants. Also, most of the cities mentioned above are harbour cities, with Rotterdam, Hamburg and Antwerp the largest

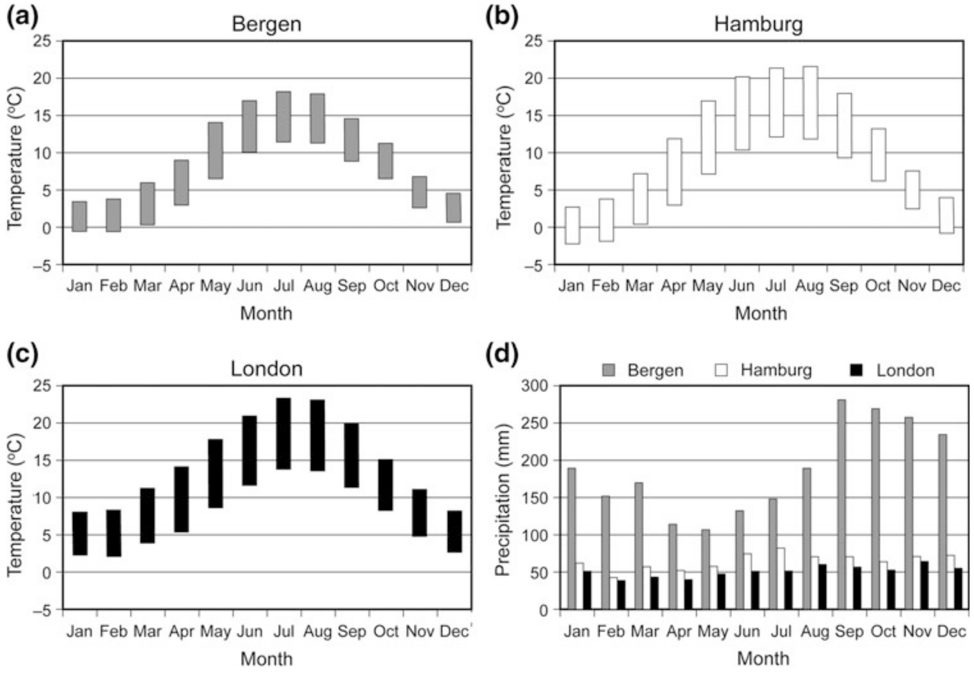


Fig. 15.2 Monthly average minimum and maximum temperatures for Bergen, Hamburg and London, and monthly average precipitation for the three cities. *Data sources* Bergen (http://wetter.welt.de/klimadaten.asp, accessed 16 February 2014), Hamburg (temperature http://wetter.welt.de/klimadaten.asp accessed 16 February 2014; precipitation averaging period 1981–2010, www.dwd.de accessed 3 April 2015), London (averaging period 1981–2010, www.metoffice.gov.uk accessed 3 April 2015)

in Europe. For these cities, emissions from ships add to the air pollution load (Sect. 15.4.1).

The effects of urban areas are referred to collectively in this chapter as the 'urban footprint'.

The following sections examine urban climate in the past (Sect. 15.3) and present (Sect. 15.4), as impacted by climate change (Sect. 15.5) and adaptation measures (Sect. 15.6), using two cities as examples: the megacity of London with an extensive metropolitan area (14.3 million inhabitants[1]) but no international harbour and the comparatively small metropolitan area of Hamburg (2.7 million inhabitants[2]) with one of the largest harbours in Europe. The two cities are about 700 km apart, with Hamburg having a slightly more continental climate, visible in lower winter temperatures, a greater minimum to maximum temperature range and a more pronounced summer precipitation maximum (Fig. 15.2). The busy North Sea harbour cities of Rotterdam and Antwerp have a climate similar to that of London or Hamburg, which implies the external climate drivers interacting with urban-induced changes are similar. In contrast, one of the northernmost North Sea cities, Bergen (Norway), has a lower temperature range in each month and throughout the year, and thus little problem with excessive summer temperatures. However, due to the nearby mountain ranges Bergen experiences much higher precipitation (roughly three-fold higher) and this must be considered in urban planning.

London and Hamburg have experienced urban climate problems, especially regarding heavy air pollution (Sect. 15.3). Only in the past few decades, especially since the very warm summer of 2003, have other parameters characterising the urban climate come into focus (Sects. 15.4–15.6). With a similar climate in both cities, the challenges mainly concern their differences in size and thus urban footprint on regional climate.

15.3 Historical Problems in Urban Climate

Historically, air pollution drove studies on urban climate. A severe pollution event was followed by action to understand and improve air quality (Table 15.1). Elevated sources were found to create widespread pollutant plumes as well as high pollutant concentrations, in urban areas as well as in rural areas. Standards for air quality were initiated by the European Communities Programme for Action on Environment from 1973. This led to the first directive (Council Directive 80/779/EEC, see EC 1980) on levels of SO_2 among EU member states. More EU-wide directives on limit values for pollutant concentrations followed (e.g. Council Directive 96/62/EC, and its later updates given in EC 2008). This initiated national and local strategies to reduce pollutant concentrations. For instance, in London the Clean Air Act of 1993 was followed by the Greater London Authority Act in 1999. With a focus on London, GLA (2002) gives a detailed overview of air pollution control and air quality strategies

---

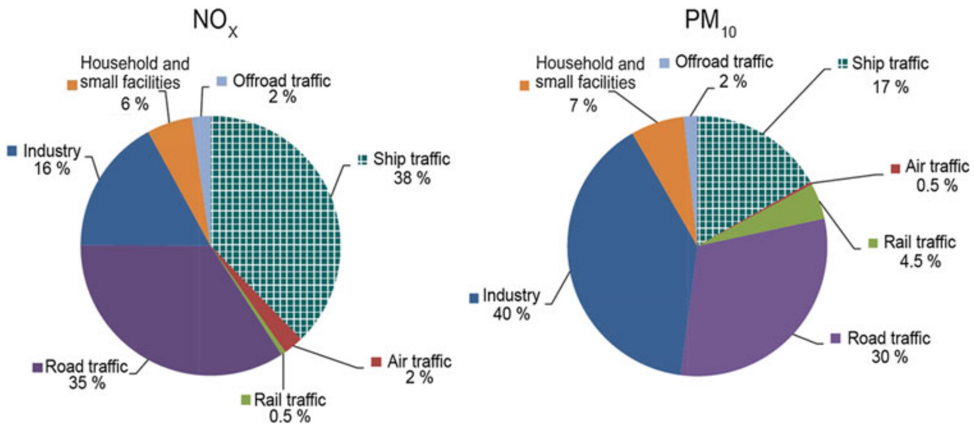
[1] www.citypopulation.de/world/Agglomerations.html accessed 11 December 2015.

[2] www.citypopulation.de/world/Agglomerations.html.

Table 15.1 Occurrences related to air pollution

Date	Event
1952	About 4000 people died within five days during a winter smog episode in London (GLA 2002)
1957	Field experiments were performed in the UK to study the dispersion of pollutants (Hay and Pasquill 1957)
1957	Commission on clear air was founded in Germany
1967	First air quality measurement sites established in Germany (financed by the German Research Foundation, DFG); later becoming an operational network
~1970	Dispersion field experiments took place in several countries to better understand dispersion (heavy gases, elevated stack emissions)

Fig. 15.3 Sector contributions to total emissions of nitrogen oxides (NO_X) and particulate matter (of 10 µm or less in diameter; PM_{10}) in Hamburg (based on data from Böhm and Wahler 2012)



over the last 150 years starting from the control of air pollutants by industry to reduce smoke, to ambient air quality standards.

Heat is an additional health threat. The 2003 heat wave caused around 70,000 excess deaths in Europe, with about 20–38 % attributed to air pollution (Jalkanen 2011). There was an overall 17 % increase in death rates for England and Wales with the excess mortality most pronounced in London, with a 33 % increase in the over 75-year old age group (Kovats et al. 2006). Since regional heat waves and the strongest UHIs are both observed in summer during stationary anti-cyclonic conditions with calm winds, the UHI is even more relevant during heat waves. After summer 2003 it was clear that the additional temperature enhancement in urban areas can lead to unbearable and health-threatening temperatures during a heat wave, even in cities of the North Sea region. This led to the start of several research projects and experimental campaigns to better understand the current urban climate and to develop urban footprint reduction and adaptation measures.

15.4 Current Urban Climate

15.4.1 Air Quality

The contribution of high-stack emissions to the total emissions of primary pollutants and high concentrations recorded in urban areas today is small compared to those of the past (see Sect. 15.3). For example, in 2005 only 25 % of the total nitrogen oxide (NO_X) emissions in Germany were from high stacks. Local traffic and—for harbour cities—ship traffic are now the main sources of several primary pollutants). For Hamburg, 78 % of NO_X emissions and 53 % of PM_{10} (particulate matter of 10 µm or less in diameter) emissions result from traffic, with ship emissions contributing 38 % of the total NO_X emissions (Fig. 15.3). Traffic emissions (except air traffic) are ground-based and so directly increase concentrations within the urban area. Therefore, measurements mainly show exceedances of the NO_2 annual average limit value of 40 µg m^{-3} at traffic-impacted sites, where air masses are confined and so less mixed than in less built-up areas. This is true for Hamburg (Böhm and Wahler 2012) and London (Fuller and Mittal 2012).

However, Fuller and Mittal (2012) found that the limit values are even exceeded at urban background stations in locations such as inner London, close to Heathrow or near the M4 motorway, probably due to the huge commuter belt around London. This is not the case for Hamburg and even in the harbour the NO_2 values are currently below the annual average limit values of 40 µg m^{-3}, but above the values measured at urban background stations (Böhm and Wahler 2012). With the development of new residential areas on the banks of the River Elbe, air masses will be more confined and ship emissions might lead to higher air concentrations that could affect the health of the residents. As a consequence, plans for reducing air pollution concentrations now include ship emissions (Böhm and Wahler 2012).

For NO_X concentrations in London, Fuller and Mittal (2012) found a seasonal cycle with higher concentrations in winter and an overall decline since 1998. The decrease is greatest close to roadsides. Carslaw et al. (2011) reported an increase in the ratio of NO_2/NO_X over the last decade at roadsides and the increase has been more marked in London than at other UK sites. The increase is probably due to higher NO_2 emissions for vehicles conforming to newer emission standards (e.g. through oxidation catalysts and particle filters in light-duty diesel vehicles) (Carslaw et al. 2011). The changes are similar for Hamburg and in Europe as a whole, and so a similar change can be assumed across the whole of the North Sea region.

Annual average PM_{10} concentrations show more or less a decrease for Hamburg between 2001 and 2011, although values are still up to 80 % of the EU annual average limit value of 40 $\mu g\ m^{-3}$ (Böhm and Wahler 2012). The interactive map developed by the European Environment Agency[3] gives an annual mean for PM_{10} of the same order (31–40 $\mu g\ m^{-3}$) for London in 2012. This is the highest value in the UK, but comparable to Leiden (Netherlands), Bremen (Germany) and Antwerp (Belgium). According to Fuller and Mittal (2012), monthly mean PM_{10} concentrations vary between 25 and 38 $\mu g\ m^{-3}$ depending on location in London (roadside, background, city centre, fringes). They found that several monitoring stations at roadsides in London exceed the 50 $\mu g\ m^{-3}$ daily mean limit value on more than 35 days in 2011. However, according to Jones et al. (2012) a large decrease in particle number has occurred in London since 2007 possibly due to the introduction of ultra-low sulphur diesel. Sources of PM_{10} in London depend on the weather pattern and comprise local sources and advection from within the UK and Europe. First results by the ClearfLo campaign measuring the composition of particulate matter in 2011 and 2012 in London at an urban background site suggest that organic aerosol is the most abundant (35 % of the total) followed by secondary inorganic aerosols such as nitrate (18 %), sulphate (11 %) and ammonium (9 %), and smaller contributions from marine aerosol components such as chloride (7 %) and sodium (4 %), and combustion emissions such as elemental carbon (Bohnenstengel et al. 2015). Early analysis indicates that local London emissions have a bigger impact in winter when the lower boundary layer enables a build-up of primary pollutants. See www.londonair.org for a summary of air quality measurements in London from several stations and information on exceedances.

North Sea urban regions have undertaken active measures to reduce pollutant exceedances: The Air Quality Strategy for London (GLA 2010) details some of the measures taken in London to further reduce PM_{10} concentrations. These include low emission zones, cleaner vehicle transport, cycle superhighways, best practice guidance for construction and demolition, and biomass boilers. Measures have also been taken in Hamburg and a reduction in exceedances is expected due to future emission reductions from traffic (including bus-lanes, car-sharing, and land-based energy supply for ships; Böhm and Wahler 2012). However, wood is increasingly used for heating (owing to its CO_2-neutral emissions); without regulatory measures PM_{10} emissions from households and thereby PM load might increase again, especially in winter.

15.4.2 Temperature and Humidity

The UHI is the most well-known feature of urban climate, and describes the temperature difference between urban and rural areas (Oke 1982). It is most pronounced during calm nights with clear skies (e.g. Schlünzen et al. 2010; Richter et al. 2013). This is important because higher night-time temperatures can cause discomfort and increase mortality rates during prolonged hot summer periods, as found for example for London (Armstrong et al. 2011).

In these situations the UHI at night for North Sea cities can be up to 7 K (London: Watkins et al. 2002), 10.5 K (Hamburg: Hoffmann et al. 2012) or 7 K (Rotterdam: Heusinkveld et al. 2014). However, the monthly average values for night-time temperature enhancements are lower. For Hamburg, analyses show monthly average minimum temperature differences between the urban and surrounding rural area of 1 (suburbs) to 2.7 K (inner city) for April through October (Schlünzen et al. 2010). Similar monthly average night-time temperature enhancements were found by Heusinkveld et al. (2014) for Rotterdam (June, July, August: median 0.7–2.26 K depending on location) and Jones and Lister (2009) for London (enhancement of minimum temperatures of 1.6 K for St James Park based on four 30-year averages 1901–1930, 1931–1960, 1951–1980, 1981–2006, and 2.8 K for the central London weather station for 1981–2006). Unpublished long-term simulations with the UK Met Office Unified model at 1-km horizontal resolution show the spatial pattern of positive temperature anomalies in the order of 2–3 K around 1 UTC (Universal Time Coordinated) (Fig. 15.4) and 1–2 K around 4 UTC, averaged for June to August 2006. Using the same model, Bohnenstengel et al. (2011) showed the temperature enhancement to remain constant throughout the night for the London city centre from the evening transition to the morning transition for a case study in May 2008 with moderate winds speeds.

---

[3] www.eea.europa.eu/themes/air/interactive/pm10.

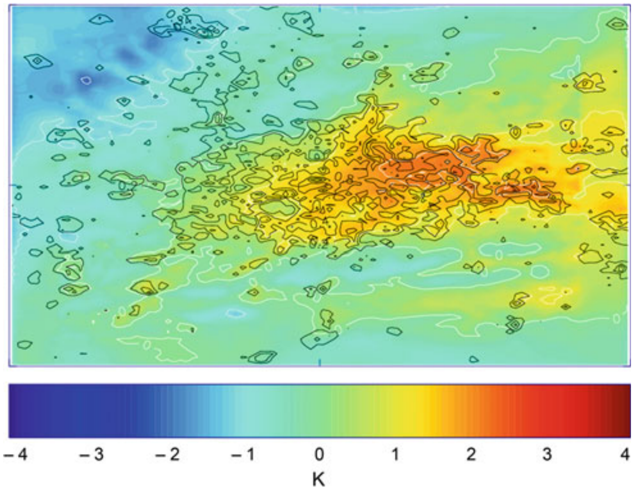


Fig. 15.4 Urban temperature enhancement for London at 1UTC averaged over the period 1 June to 15 August 2006. Values are derived from long-term model simulations with the UK Met Office Unified Model employing the MORUSES urban parameterisation (model setup described by Bohnenstengel et al. 2011). *Black lines* indicate sub-grid scale urban land-use fraction per grid box ranging from 0 (no urban land use) to 1 (grid box entirely covered by urban land use) and *colours* represent the urban temperature anomaly in *K*. A grid box is roughly 1 km^2

As in other regions of the world, urban land-use is the biggest driver of UHI in the North Sea cities (Schlünzen et al. 2010; Bohnenstengel et al. 2011; Hoffmann 2012; Heusinkveld et al. 2014). The effect of greening reduces the enhanced temperatures on a clear night with low wind speeds by 2–3 K (model results by Bohnenstengel et al. 2011 and Grawe et al. 2012, both for London). Similar effects were found for Hamburg and Rotterdam based on measured data, where the heat island is smaller in green areas than in areas with sealed surfaces (Schlünzen et al. 2010; Heusinkveld et al. 2014). Detailed model studies show the significant effect of building height and urban fabric on perceived temperatures (Schoetter et al. 2013). Perceived temperature is a measure of thermal comfort and is based on a heat budget model for the human body; it takes into account temperature, short- and long-wave radiation and wind speed effects on the human body (Kim et al. 2009; Staiger et al. 2011).

Air mass history and the evolution of the urban boundary layer with distance from the rural/urban transition also affect urban air temperature. On a night with moderate wind speeds, air temperature can be around 2 K lower over the upwind fringes of a city such as London than over the city centre and areas downwind of the city centre (Bohnenstengel et al. 2011).

Coastal form and meteorological situation (Crosman and Horel 2010) affect the inland penetration of sea breeze fronts and the front moves further inland the later the afternoon (Simpson et al. 1977). Thus, depending on distance from the coast, sea breezes and marine air intrusions can reduce the intensity of the UHI in the evening or at night for a couple of hours in North Sea cities in spring and early summer. This is especially the case during high pressure situations with calm winds (e.g. Chemel and Sokhi 2012). However, for an inland city like Hamburg (about 100 km inland of the North Sea, 80 km from the Baltic Sea) the impact of sea breezes is rare, since sea breeze fronts typically travel inland by up to 40 km only (Schlünzen 1990), rarely further.

Lane (2014) determined a mean temperature enhancement of 1.9 K for summer (JJA) and 1.6 K for winter (DJF) based on hourly temperature measurements from a roof top site 18 m above ground level in central London and a spatial average of 10 rural stations mostly to the east and west of London. As for other cities, the enhancement of the maximum temperatures is quite small compared to the rural surroundings and most pronounced in winter months (determined for Hamburg; Schlünzen et al. 2010), when anthropogenic heat emissions play a larger role. Schlünzen et al. (2010) found a range of 0.2 (suburb) to 0.7 K (inner city) for Hamburg’s monthly average winter maximum temperature enhancements. The maximum temperature enhancement for London is of a similar order at 0.6 K (St James Park; 1901–2006) and 0.9 K (London weather centre; 1981–2006) according to Jones and Lister (2009). They stated that maximum temperature enhancements in St James Park differ marginally between seasons, while minimum temperature enhancements are slightly higher in spring and summer. They found no evidence for climate-related enhanced warming trends in central London compared to the trends found for rural stations around London.

As summarised by Mavrogianni et al. (2011), the excess heat in urban areas affects energy use, comfort and health. Their simulations show that the number of hours with indoor temperatures exceeding 28 °C increases towards the city centre of London for a building without air conditioning. However, building form and urban land-use also play a role in comfort temperatures in London and need to be taken into account when designing strategies that reduce overheating. Iamarino et al. (2011) showed for a resolution of 200 m × 200 m that anthropogenic heat fluxes for the Greater London area are of the order of 10 Wm^{-2}, while the city centre is associated with anthropogenic emissions of the order of 200 Wm^{-2} and, according to Hamilton et al. (2009) and Bohnenstengel et al. (2014), of 400 Wm^{-2} at peak times. Petrik et al. (in prep) determined the anthropogenic heat at 250 m resolution for Hamburg, finding values of 10 Wm^{-2} in suburbs and up to 100 Wm^{-2} at some industrial sites and in harbour areas. These lower values agree well with the findings of Allen et al. (2011) who determined anthropogenic heat fluxes globally on a 2.5 arc minute grid. For North Sea cites, they found higher values for London,

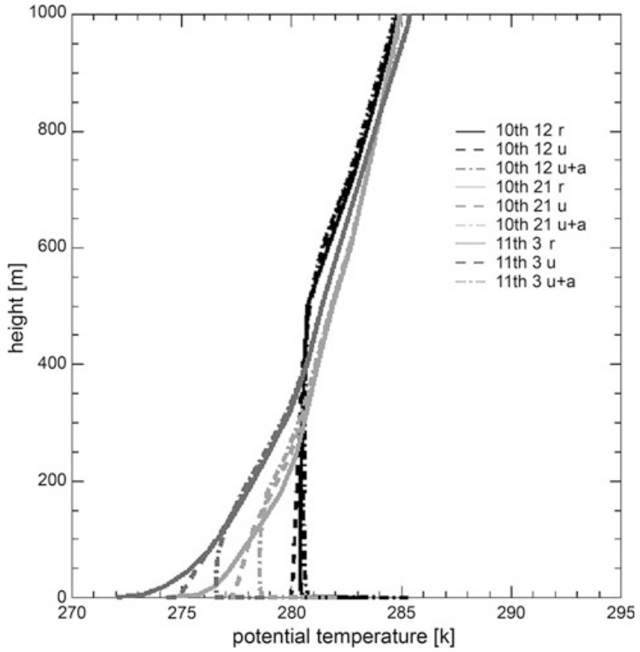


Fig. 15.5 Vertical potential temperature profiles over the London city centre for 9–12 December 2009. *Dark grey lines* depict profiles at noon, *light grey lines* depict profiles at 21UTC and *black lines* depict profiles at 3UTC. *Solid lines* depict the rural simulation, *dashed lines* the urban simulations and *dash-dotted lines* urban simulations with anthropogenic heat fluxes included (Bohnenstengel et al. 2014)

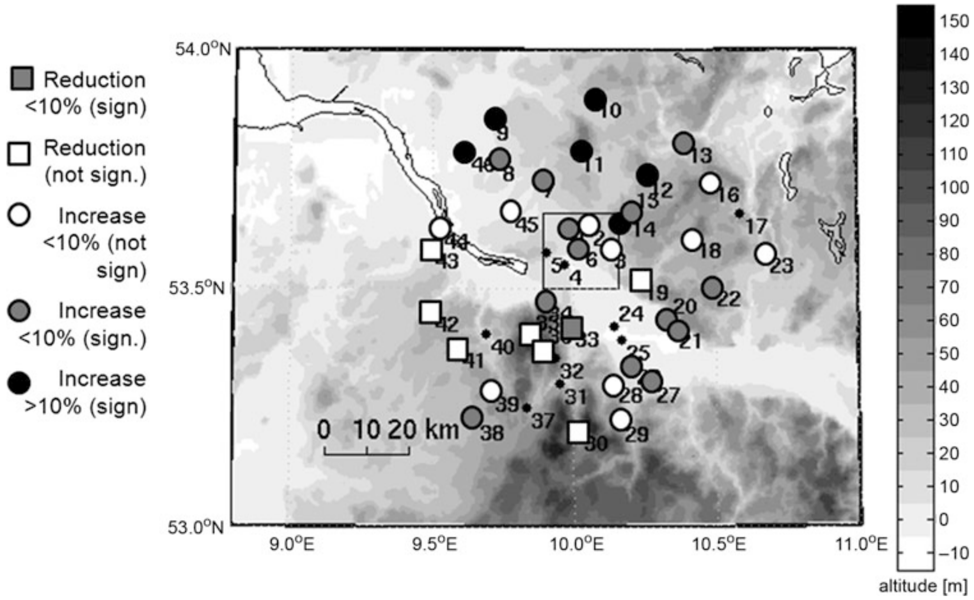
Brussels, Rotterdam and Amsterdam (> 30 Wm^{-2} annual average) and lower values for smaller cities and the Ruhr area, Hamburg or Bremen. Based on their 250-m resolution model studies with the mesoscale model METRAS, Petrik et al. (in prep) found the highest impacts on temperature at night, when the anthropogenic heat is mixed into a shallow boundary layer. Thus, night temperatures are more affected than day temperatures resulting in a summer average night-time temperature increase of up to 0.5 K in those parts of Hamburg with the highest waste heat emissions.

Bohnenstengel et al. (2014) examined the impact of anthropogenic heat emissions on London's UHI using 1-km resolution simulations with the UK Met Office Unified Model for a winter case study with calm winds over the period 9–12 December 2009. They compared three simulations covering London: a 'rural' control run, where London was replaced by grass, and two simulations including the urban surface energy balance—one with and one without high-resolution time-varying anthropogenic heat emissions. During calm and clear winter nights, anthropogenic emissions were found to increase the UHI by up to 1 K. In fact, anthropogenic emissions can tip the balance and maintain a well-mixed boundary layer (Fig. 15.5). This is based on a case study for winter, when the urban boundary layer was shallow and anthropogenic heat emissions affected a very small volume of air. In such cases, anthropogenic heat could affect the mixing properties of the urban boundary layer and thereby pollutant concentrations (Sect. 15.4.1). In spring or summer, when the daytime urban boundary layers are much deeper, the impact of anthropogenic emissions on temperatures (and thus vertical mixing) is within the measurement uncertainty.

Most North Sea cities have a considerable fraction of water surfaces within the urban area. For example, more than 3 % of Hamburg has water surfaces (channels, ponds, small lakes, rivers; Teichert 2013). In summer, the suburbs close to the inner-city water bodies experience advective cooling during the day and warming at night, since the water bodies dampen the diurnal cycle. This results in UHI-like effects at night due to the advection of warm air from the adjacent water bodies (Schlünzen et al. 2010). The water- and urban-fabric-induced reduced night-time cooling are additive and also affect the occurrence of plant species (Bechtel and Schmidt 2011). For large water bodies, such as the River Elbe downstream of Hamburg's harbour the water bodies might cause a river breeze that affects temperatures a few 1000 m off the river, as Teichert (2013) found for a calm meteorological situation in summer simulated with METRAS. It should be noted that daytime cooling by water bodies only occurs if the water temperature is lower than that of the land surfaces. Water temperatures are affected by water use: among others, water is abstracted for drinking water, industrial production or power plant cooling; and discharged in part as waste water, clean but often at higher temperatures than the abstracted water. This can increase river temperature throughout the year, especially if the river is tidal and the same water is used several times. For example, the River Weser regulations aim to prevent river water temperatures of more than 28 °C (www.fgg-weser.de). A river used to discharge the warm waste water might act as an all-year central heating system, especially at night. This can be advantageous in winter, similar to the warm North Atlantic current that acts as a central heating system for all North Sea cities.

To summarise, for industrial cities such as Hamburg or London, waste heat emissions can add to the rise in night-time temperature caused by the urban fabric. In addition, water bodies within built-up areas hinder cooling at night especially in summer when cooling is most needed, for instance during heat waves. Rivers help to cool a city in summer, if their temperature is kept low enough and waste water-related warming is also kept low. Coastal water bodies may cool cities in spring and summer, as observed in Rotterdam or Bergen compared to a city setting more inland and without sea breeze impacts. However, it should be noted that all water bodies reduce urban cooling in autumn and winter and so could help save energy during the cold season. Since urban fabric, heat emissions and water bodies are all very locally structured, a pattern of high temperatures is also

Fig. 15.6 Average percentage increase in precipitation per event, if a site is downwind of the city centre (marked by a *square*) (based on results by Schlünzen et al. 2010). *Black* and *grey filled circles* depict significant increases, the *grey filled rectangle* depicts a significant decrease, and *white filled rectangles* and *circles* depict no significant change



locally structured, with higher night-time temperatures in harbour and industrialised sealed areas, if these are not directly next to a cool river or ocean.

15.4.3 Precipitation

The urban precipitation impact can lead to precipitation enhancement downwind of an urban area. Measured data show this to be the case for Hamburg (Schlünzen et al. 2010), with increases of 5–10 % per precipitation event and found for many (but not all) downwind sites (Fig. 15.6). Assuming only one wind direction throughout the entire year (an extreme and unrealistic assumption), the difference could be 80 mm y^{-1}, which is still less than half of the 200 mm climatological difference with its decrease from the north towards the south-east (Hoffmann and Schlünzen 2010). Thus, despite urban impacts the regional effects might actually be of greater significance.

Schlünzen et al. (2010) also studied long-term changes in precipitation. They found a greater increase in precipitation upwind of Hamburg than downwind of the urban area (trend 1947–2007), which might suggest an overall decline in urban impact. However, these results are speculative, since detailed model studies with METRAS by Schoetter (2013) showed the urban impact of Hamburg is only observable under some meteorological conditions, which agrees with findings by Han et al. (2014). The effects are very local (as can also be inferred from Fig. 15.6) and dependent on the actual meteorological situation. Overall, the impact of Hamburg's urban fabric is not significant for the summer. However, the urban impact might differ in winter or for other urban areas in the North Sea region. Han et al. (2014) pointed out that orography plays an additional role. This was also found for Hamburg, where the highest elevations are only 100–200 m and the urban buildings are low. METRAS model simulations without orography show that orographic effects drive a statistically robust change in the precipitation pattern (Schoetter 2013).

15.5 Scenarios for Future Developments

Adaptation to climate change is of utmost importance for cities to maintain the wellbeing of their inhabitants. Several studies have investigated climate change impacts on urban climate, with some very detailed studies undertaken in Hamburg and London. The ARCC network[4] provides an overview of UK-focussed projects involved with adaptation to 'technological, social and environmental change, including climate change, in the built environment and infrastructure sectors'. Of these the ARCADIA project gives an overview of adaptation and resilience in cities, presenting city-scale climate change scenarios consistent with the UKCP09 scenarios. The Lucid project[5] brought together meteorologists and building engineers to assess the impact of local climate on energy use, comfort and health, while the SCORCHIO project[6] used climate projections to determine adaptation measures focussing on Manchester. Similar multidisciplinary research studies on climate change adaptation were performed for several German cities under the framework of the KLIMZUG program[7] (Climate change in

---

[4] www.arcc-network.org.uk.

[5] www.homepages.ucl.ac.uk/～ucftiha/index.html.

[6] www.sed.manchester.ac.uk/research/cure/research/scorchio.

[7] www.klimzug.de.

regions): The North Sea region was investigated in northwest 2050[8] (area Bremen/Oldenburg with a focus on the development of roadmaps of climate adaption for three economic sectors: food industry, energy production and distribution, and port management and logistics) and KLIMZUG-Nord[9] (metropolitan area of Hamburg, with a focus on the development of an adaptation master plan that continues until 2050 using the thematic focal points Elbe estuary management, integrated spatial development, nature conservation and governance).

15.5.1 Climate Change Impacts on Urban Climate

Urban areas are a major source of carbon dioxide (CO_2) and anthropogenic heat. While the former drives changes in global climate, the latter has a potentially strong impact on city-scale climate. McCarthy et al. (2011) used an urban land surface scheme (Best et al. 2006) with the Hadley Centre Global Climate Model (HadAM3) and compared the impacts of doubling CO_2 emissions against effects due to urbanisation and anthropogenic heat release in urban areas. They found that urban and rural areas react differently to climate change. While their climate change scenarios (transient SRES A1B scenarios, urbanisation and anthropogenic heat release in urban areas) increased the number of hot days in both areas to the same extent, they found that London has a bigger increase in the number of hot nights (>18.2 °C) than rural areas. The reasons for this difference are local forcing such as anthropogenic heat release and urbanisation leading to the UHI. In fact, local changes such as urbanisation and anthropogenic heat release also increased the frequency of hot days, as did doubling CO_2 emissions. It should be noted that as the UHI is not caused by local CO_2 emissions, it cannot be reduced by lowering them. Oleson (2012) confirmed the results of McCarthy et al. (2011) concerning more frequent hot nights in urban areas compared to rural areas for Europe. Thus, heat risk for the urban population will increase more than for their rural counterparts due to local urban forcing.

Hamdi et al. (2014) studied present (1981–1990) and future climate (2071–2100) for Brussels. On average, the observed nocturnal UHI is of the order of 1.32 K, which agrees well with the simulated average of 1.31 K. Under an A1B scenario, night-time UHIs vary between 0 and 7 K with the frequency of UHIs above 3 K decreasing due to soil dryness in summer. For the city centre the number of heat days will rise by 62.

For Hamburg, Hoffmann et al. (2012) and Grawe et al. (2013) found small changes in the pattern and amplitude of the UHI for climate change scenarios, if the urban fabric remains unchanged. If threshold values are used (such as 18.2 °C for night-time temperatures), these are more frequently exceeded under the future climate due to the higher overall temperatures. The number of exceedances is also higher within urban areas compared to rural areas, because the additional temperature enhancement of urban areas also contributes. However, non-linear effects that contribute to a greater temperature enhancement in urban areas compared to rural areas were not apparent by mid-century under the A1B climate change scenario.

Large precipitation amounts challenge urban infrastructure and could cause streets and houses to flood, or even the total breakdown of some urban infrastructure. Summer precipitation from convective cloud systems may lead to local flooding as was observed in Rostock (Germany) when nearly twice the average monthly rainfall fell within a day (22/23 July 2011; Miegel et al. 2014). A projected increase in winter precipitation of 12–38 % in the climatological mean towards the end of this century (Rechid et al. 2014) poses additional challenges to city planners. Especially in winter, when the already low evapotranspiration in urban areas is even lower and statured soils cannot take up any excess water, this so-called ‘hinterland flooding’ needs to be addressed in adaptation measures for cities (KLIMZUG-NORD 2014).

15.5.2 City Development Impacts on Urban Climate

As already described (Sect. 15.4), urban areas affect the regional climate through their urban footprint. This relationship provides an opportunity to reduce the regional climate change impact on urban areas—or to enhance it if the wrong mitigation and adaptation measures are applied. Several recent research projects have investigated the impact of planned changes in urban structure on the urban footprint.

The nationally-funded research projects KLIMZUG-NORD (final results in KLIMZUG-NORD 2014) and Cli-SAP (Schlünzen et al. 2009) investigated different aspects of Hamburg’s development on the urban summer climate. In all development scenarios, Hamburg’s growth is confined mostly to the current regional area and is restricted vertically. In fact, Hamburg has a ban on high-rise buildings. This means that surface cover changes are relatively small, follow a compact city approach and include aspects of adaptation to the changing climate. More greening (especially of roofs) and higher albedo values on roofs and other sealed surfaces that cannot be greened (e.g. roads) were assumed. Other assumptions include some rebuilding of

---

[8] www.nordwest2050.de.

[9] www.klimzug-nord.de.

single houses into duplex or terraced houses, replacing terraced houses by blocks, and adding another story to multi-story buildings. All these changes were assumed to be accompanied by a larger greening fraction and more reflective (higher albedo) material. Several simulations were performed with the mesoscale model METRAS to reproduce (at 250-m resolution) a climatological-average summer situation. According to the adaptation measures selected, the average summer temperature could be reduced by 0.2 K with the greatest decreases in those areas where the sealing is very high (KLIMZUG-NORD 2014). Anthropogenic heat emission was prescribed unchanged in these model studies. However, energy use will be more efficient in the future due to retrofitting of houses with better insulation. However, the impacts of better insulation on the surface energy budget are still unclear. Nevertheless, anthropogenic heat emissions will be lower and this will lead to a reduction in the UHI throughout the year.

Impacts on heavy precipitation events were examined for the same scenarios of urban development. As already mentioned (Sect. 15.4.3), the urban fabric has little impact on precipitation, at least for Hamburg, and this was confirmed by the model simulations. Nevertheless, more sealed surfaces pose a challenge for city planners, as these surfaces cannot take up the water and the water must to be drained to avoid hinterland flooding (see Sect. 15.5.1).

Changes in the wind field are expected to be local and possibly very large close to building structures (Schlünzen and Linde 2014). The effects of new buildings on the wind climate of a growing suburb of Hamburg (situated on the large island of Wilhelmsburg) were investigated using the obstacle-resolving model MITRAS (Schlünzen et al. 2003) at a resolution of 5 m. Impacts over a distance of 1000 m from the new buildings were found not just close to the surface but also at higher levels thus affecting ventilation of the buildings in the upper floors (Schlünzen and Linde 2014). Some streets or even balconies on upper stories could become less usable, owing to excessively high wind speeds around the new buildings, while formerly well flushed places could become very calm; this can increase heat stress on sunny days. Furthermore, pollutant dispersion can change due to changes in the wind and temperature fields and this can lead to high concentrations in different sites to before and could change the human exposure pattern.

Studies indicate that changes in temperature and precipitation resulting from urban development scenarios that aim at mitigation and adaptation measures can only slightly reduce the projected climate-driven rise in temperature and change in precipitation patterns. However, although small these local reductions might become more relevant during hot periods by keeping urban temperatures at night at values that reduce health risk. To ensure the cooling effect of urban greening, the watering needs of the vegetation must be ensured (such as by storing water during the wet periods). If the urban vegetation dries out its cooling effect is lost.

15.6 Adaptation and Urban Footprint Reduction Measures

Many North Sea cities are close to the coast or to a river and so must prepare for storm tides. This can be achieved using dykes, as for example in the Netherlands or along the river Elbe for Hamburg, or the Thames Barrier for London. Such measures are expensive, but vital to protect valuable infrastructure and save lives. Hinterland flooding has become an increasing challenge in recent years and similar preparedness needs to be developed here as for storm tides. While upriver dykes help prevent river flooding, and are constantly being improved and strengthened, coastal cities appear to lack focus in terms of rain events that can be equally challenging. Measures are needed to remove rain water following heavy precipitation events. Methods already exist, for example a city like Bergen handles at least twice the precipitation amounts observed in the southern North Sea region every month (Fig. 15.2d). Hamburg has introduced a separate rain water drainage system in recent years and introduced financial penalties, if rain water is not locally drained by home owners. To cope with intense precipitation events (Schlünzen et al. 2010) and increased amounts of winter precipitation, it is essential that urban areas can store water. Storing precipitation in winter would help to cope with future drier summers. Cities will need larger amounts of water in future for two reasons: warmer air can take up more water and so evapotranspiration will be higher, and increased urban greening to help reduce high urban night-time temperatures needs enough water to prevent the vegetation drying out.

Any increase in sealed surfaces should be kept to a minimum (they are sometimes introduced for flood protection, such as new dykes or walls with bitumen or stone cover), since they increase the amount of heat-storing surfaces and thus night-time temperatures. The current replacement of green spaces and gardens in urban and suburban areas by buildings and sealed surfaces should also be limited as this will also cause an increase in urban night-time temperatures. Plus, there is a tendency for urban spread into surrounding rural areas which extends the UHI in space. Hamburg has already begun implementing measures to keep UHI effects within reasonable limits, possibly even causing a reduction. In contrast, London can only grow vertically in the city centre, leading to more heat storage capacity, presumably greater anthropogenic heat release and warmer nights. Any increase in the spatial extent of London, and thus an increase in sealed surface, would also increase the spread of the UHI. Higher temperatures in urban areas would lead to several stress factors. Heat in itself is a recognised health factor. Planners in all North Sea cities should ensure that existing green areas are kept and that new ones are added. In addition, all waste heat emissions (to the atmosphere and to water bodies) should be reduced especially in summer to reduce night-time heat exposure within urban areas. Projections by Iamarino et al. (2011) suggested an increase of 16 % in anthropogenic heat emission due to a larger working population in the city of London by 2025 compared to 2005. Without measures to reduce the urban footprint, this would lead to even higher temperatures within the city of London. This shows a clear synergy between adaptation, mitigation and urban footprint reduction measures: less energy-consuming computers, factories, and vehicles, not only reduce CO_2 emissions (or equivalent) and thus global temperature increase in the long term, but also directly and quickly reduce the amount of waste heat emitted into the urban area and thus night-time temperatures. The same is true for well-insulated buildings: using less energy for heating in winter and cooling in summer means lower CO_2 emission (for energy production). Lower CO_2 emissions implies less global warming, while better insulation reduces UHI at night.

The projected increase in global temperatures could lead to higher biogenic volatile organic compound (VOC) emissions from vegetation, which could in turn increase O_3 levels if NO_X emissions are not considerably reduced (e.g. Meyer and Schlünzen 2011). To avoid additional VOC emissions, new urban vegetation needs to be selected with low VOC emission potential (Kuttler 2013: 281).

Drier summers would mean more particles eroded from dry surfaces and an increase in the already high particle load in urban areas. This supports the argument for increasing the amount of vegetated surface in urban areas and for providing these areas with water during dry periods. An immediate measure used in London to reduce the atmospheric particle load has been to spray adhesives onto roads in some of the most polluted areas, although this does not reduce the source of the particulate matter.

15.7 Conclusions

Urban areas are not only impacted by changes in regional climate, but themselves contribute to climate change through their large greenhouse gas emissions. Urban areas also modify the regional climate through their urban footprint. This is mainly visible in terms of concentration levels above EU limit values for NO_X (daily average value), NO_2 (annual average value) and particulate matter (PM_{10} daily average values). Higher temperatures, especially at night, result from changes in the surface energy budget due to the urban fabric and additional emission of anthropogenic heat. The temperature difference can be in the range of a few degrees in the monthly average. It may be up to ~7 K under favourable conditions (clear skies, high radiative impact, low large-scale pressure gradients).

Despite broad similarities between many urban areas, there are also large location-specific differences with regard to city planning needs (such as poorly insulated Victorian housing stock in the UK wasting large amounts of energy). While some cities are growing, others show little change with respect to the number of inhabitants and some are even shrinking. Whatever the future, it will involve change. Changes in climate will become increasingly apparent, especially towards the end of the century, with the first indications of what is to come already apparent (hinterland flooding, more intense precipitation, and drier and warmer summers). Because even in a 'non-changing' city, inhabitants will renovate buildings and young people will adopt new infrastructures and new technologies that will one day be standard for all, there is an opportunity for cities to change for simultaneously adapting to and mitigating climate change such that the worst impacts of climate change can be avoided by mitigation measures, and the unavoidable impacts of climate change can be met by adaptation measures, while the urban footprint becomes ever smaller.

References

Allen L, Lindberg F, Grimmon CSB (2011) Global to city scale urban anthropogenic heat flux: model and variability. Int J Climatol 31:1990–2005

Armstrong BG, Chalabi Z, Fenn B, Hajat S, Kovats S, Milojevic A, Wilkinson P (2011) Association of mortality with high temperatures in a temperature climate: England and Wales. J Epidemiol Commun H 65:340–345

Bechtel B, Schmidt KJ (2011) Floristic mapping data as a proxy for the mean urban heat island. Clim Res 49:45–58

Best MJ, Grimmond CSB, Villani MG (2006) Evaluation of the urban tile in MOSES using surface energy balance observations. Bound-Lay Meteorol 118503–525

Böhm J, Wahler G (2012) Luftreinhalteplan für Hamburg: 1. Fortschreibung 2012. Behörde für Stadtentwicklung und Umwelt. www.hamburg.de/contentblob/3744850/data/fortschreibung-luftreinhalteplan.pdf

Bohnenstengel SI, Evans S, Clark PA, Belcher SE (2011) Simulations of the London urban heat island. Q J Roy Meteor Soc 137: 1625–1640

Bohnenstengel SI, Hamilton I, Davies M, Belcher SE (2014) Impact of anthropogenic heat emissions on London's temperatures. Q J Roy Meteor Soc 140:687–698

Bohnenstengel SI, Belcher SE, Aiken A, Allan JD, Allen G, Bacak A, Bannan TJ, Barlow JF, Beddows DCS, Bloss WJ, Booth AM, Chemel C, Coceal O, Di Marco CF, Dubey MK, Faloon KH, Fleming Z, Furger M, Geitl JK, Graves RR, Green DC, Grimmond CSB, Halios C, Hamilton JF, Harrison RM, Heal MR, Heard DE, Helfter C, Herndon SC, Holmes RE, Hopkins JR, Jones AM, Kelly FJ, Kotthaus S, Langford B, Lee JD, Leigh RJ, Lewis AC, Lidster RT, Lopez-Hilfiker FD, McQuaid JB, Mohr C, Monks PS, Nemitz E, Ng NL, Percival CJ, Prévôt ASH, Ricketts HMA, Sokhi R, Stone D, Thornton JA, Tremper A, Valach AC, Visser S, Whalley LK, Williams LR, Xu L, Young DE, Zotter P (2015) Meteorology, air quality, and health in London: The ClearfLo project. B Am Meteorol Soc 96:779–804

Carslaw DC, Beevers SD, Westmoreland E, Williams ML, Tate JE, Murrells T, Stedman J, Li Y, Grice S, Kent A, Tsagatakis I (2011) Trends in NO_X and NO_2 emissions and ambient measurements in the UK. Version: July 2011

Chemel C, Sokhi RS (2012) Response of London's urban heat island to a marine air intrusion in an easterly wind regime. Bound-Lay Meteorol 144:65–81

Crosman ET, Horel JD (2010) Sea and lake breezes: A review of 527 numerical studies. Bound-Lay Meteorol 137:1–29

EC (1980) Council Directive 80/779/EEC of 15 July 1980 on air quality limit values and guide values for sulphur dioxide and suspended particulates. European Commission (EC)

EC (2008) Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe (OJL 152, 11.6.2008). European Commission (EC)

Fuller G, Mittal L (2012) Air quality in London – Briefing note to GLA Environment and Health Committee. Environmental Research Group, Kings College London

GLA (2002) 50 years on: The struggle for air quality in London since the great smog of December 1952. Mayor of London, Greater London Authority (GLA)

GLA (2010) Clearing the air: The Mayor's Air Quality Strategy, Mayor of London, Greater London Authority (GLA)

Grawe D, Thompson HL, Salmond JA, Cai X-M, Schlünzen KH (2012) Modelling the impact of urbanisation on regional climate in the Greater London Area. Int J Climatol 32:2388–2401

Grawe D, Flagg DD, Daneke C, Schlünzen KH (2013) The urban climate of Hamburg for a 2K warming scenario considering urban development. Present EMS 2013 Reading, 13.09.2013

Hamdi R, Van de Vyver H, De Troch R, Termonia P (2014) Assessment of three dynamical urban climate downscalling methods: Brussels' future heat island under an A1B emission scenario. Int J Climatol 34:378–399

Hamilton IG, Davies M, Steadman P, Stone A, Ridley I, Evans S (2009) The significance of the anthropogenic heat emissions of London's buildings: a comparison against captured shortwave solar radiation. Build Environ 44:807–817

Han JY, Baik JJ, Lee H (2014) Review: Urban impacts on precipitation. Asia-Pac J Atmos Sci 50:17–30

Hay JS, Pasquill F (1957) Diffusion from a fixed source at a height of a few hundred feet in the atmosphere. J Fluid Mech 2:299–310

Heusinkveld BG, Steeneveld GJ, van Hove LWA, Jacobs CMJ, Holtslag AAM (2014) Spatial variability of the Rotterdam urban heat island as influenced by urban land use. J Geophys Res-Atmos 119:1–14

Hoffmann P (2012) Quantifying the influence of climate change on the urban heat island of Hamburg using different downscaling methods. Dissertation, Univ Hamburg, Germany

Hoffmann P, Schlünzen KH (2010) Das Hamburger Klima. In: Poppendieck HH, Bertram H, Brandt I, Engelschall B, von Prondzinski J (eds) Der Hamburger Pflanzenatlas von a bis z. Dölling und Galitz Verlag GmbH, Hamburg, p28–31

Hoffmann P, Krueger O, Schlünzen KH (2012) A statistical model for the urban heat island and its application to a climate change scenario. Int J Climatol 32:1238–1248

Iamarino M, Beevers S, Grimmond CSB (2011) High-resolution (space, time) anthropogenic heat emissions: London 1970-2025. Int J Climatol 32:1754–1767

Jalkanen L (2011) WMO addressing climate and air quality. Technical Workshop on Science and Policy of Short-lived Climate Forcers, September 9-10, 2011, Mexico City. http://mce2.org/SLCFWorkshop/docs/%28Jalkanen%29%20SLCF%20Mexico%20WMO.pdf

Jones PD, Lister DH (2009) The urban heat island in Central London and urban-related warming trends in Central London since 1900. Weather 64:323–327

Jones AM, Harrison RM, Barratt B, Fuller G (2012) A large reduction in airborne particle number concentrations at the time of the introduction of "sulphur free" diesel and the London Low Emission Zone. Atmos Environ 50:129–138

Kim J, Kim KR, Choi BC, Lee DG, Kim JS (2009) Regional distribution of perceived temperatures estimated by the Human Heat Budget Model (the Klima-Michel Model) in South Korea. Adv Atmos Sci 26:275–282

KLIMZUG-NORD Verbund (ed) (2014) Kursbuch Klimaanpassung. Handlungsoptionen für die Metropolregion Hamburg, TuTech Verlag, Hamburg. www.klimzug-nord.de

Kottek M, Grieser J, Beck C, Rudolf B, Rubel F (2006) World map of the Köppen-Geiger climate classification updated. Meteorol Z 15:259–263

Kovats RS, Johnson H, Griffiths C (2006) Mortality in southern England during the 2003 heat wave by place of death. Health Statist Quart 29:6–8

Kuttler W (2013) Klimatologie. 2. aktualisierte u. ergänzte Ausgabe, Schöningh, Paderborn (UTB 3099)

Lane S (2014) Assessing the validity and impact of urban-scale numerical weather prediction. PhD thesis. University of Reading

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

McCarthy MP, Harpham C, Goodess CM, Jones PD (2011) Simulating climate change in UK cities using a regional climate model, HadRM3. Int J Climatol 32:1875–1888

Meyer EMI, Schlünzen KH (2011) The influence of emission changes on ozone concentrations and nitrogen deposition into the southern North Sea. Meteorol Z 20:75–84

Miegel K, Mehl D, Malitz G, Ertel H (2014) Ungewöhnliche Niederschlagsereignisse im Sommer 2011 in Mecklenburg-Vorpommern und ihre hydrologischen Folgen. Teil 1: Hydrometeorologische Bewertung. Hydrologie und Wasserbewirtschaftung 58:18–28

Oke TR (1982) The energetic basis of the urban heat island. Q J Roy Meteor Soc 108:1–24

Oleson K (2012) Contrasts between urban and rural climate in CCSM4 CMIP5 climate change scenarios. J Climate 25:1390–1412

Petrik R, Grawe D, Bungert U, Schlünzen KH (in prep) Quantifying the impact of anthropogenic heat on the urban climate of Hamburg in the summer season. J Urb Clim (in internal review)

Pielke RA, Adegoke J, Beltran-Przekurat A, Hiemstra CA., Lin J, Nair, US, Niyogi D, Nobis TE (2007) An overview of regional land-use and land-cover impacts on rainfall. Tellus B, 59:587–601

Rechid D, Petersen J, Schoetter R, Jacob D (2014) Klimaprojektionen für die Metropolregion Hamburg. Berichte aus den KLIMZUG-NORD Modellgebieten 1. TuTech Verlag, Hamburg. www.klimzug-nord.de

Richter M, Deppisch S, von Storch H (2013) Observed changes in long-term climatic conditions and inner-regional differences in urban regions of the Baltic Sea coast. Atmos Climate Sci 3:165–176

Schlünzen KH (1990) Numerical studies on the inland penetration of sea breeze fronts at a coastline with tidally flooded mudflats. Beitr Phys Atmos 63:243–256

Schlünzen KH, Linde M (2014) Wilhelmsburg im Klimawandel. Ist-Situation und mögliche Veränderungen. Berichte aus den KLIMZUG-NORD Modellgebieten 4. TuTech Verlag, Hamburg. www.klimzug-nord.de

Schlünzen KH, Hinneburg D, Knoth O, Lambrecht M, Leitl B, Lopez S, Lüpkes C, Panskus H, Renner E, Schatzmann M, Schoenemeyer T, Trepte S, Wolke R (2003) Flow and transport in the obstacle layer - First results of the microscale model MITRAS. J Atmos Chem 44:113–130

Schlünzen KH, Ament F, Bechtel B, Böhner J, Eschenbach A, Fock B, Hoffmann P, Kirschner P, Leitl B, Oßenbrügge J, Rosenhagen G, Schatzmann M (2009) Development of mitigation measures for the metropolitan region of Hamburg (Germany). Conference Contribution to Climate Change: Global Risks, Challenges and Decisions. IOP Conf Ser: Earth Env Sci 6 332034, doi:10.1088/1755-1307/6/33/332034

Schlünzen KH, Hoffmann P, Rosenhagen G, Riecke W (2010) Long-term changes and regional differences in temperature and precipitation in the metropolitan area of Hamburg. Int J Climatol, 30:1121–1136

Schoetter R (2013) Can local adaptation measures compensate for regional climate change in Hamburg Metropolitan Region. PhD thesis in Meteorology, Univ Hamburg, Germany

Schoetter R, Grawe D, Hoffmann P, Kirschner P, Grätz A, Schlünzen KH (2013) Impact of local adaptation measures and regional climate change on perceived temperature. Meteorol Z 22:117–130

Shepherd JM, Pierce H, Nergi AJ (2002) Rainfall modification by major urban areas: Observations from spaceborne rain radar on the TRMM satellite. J Appl Meteorol 41:689–701

Simpson JE, Mansfield DA, Milford JR (1977) Inland penetration of sea-breeze fronts. Q J Roy Meteor Soc 103:47–76

Staiger H, Laschewski G, Grätz A (2011) The perceived temperature – a versatile index for the assessment of the human thermal environment. Part A: scientific basics. Int J Biometeorol 56:165–176

Teichert N (2013) Analyse von Oberflächeneinflüssen auf die sommerlichen Temperaturen in der Metropolregion Hamburg unter Anwendung eines GIS. Diploma Thesis Meteorology, Fachber Geowiss, Univ Hamburg, Germany

UN (2014) World Urbanization Prospects: The 2014 Revision. CD-ROM Edition UN, Department of Economic and Social Affairs, Population Division. http://esa.un.org/unpd/wup/CD-ROM Accessed 11 December 2015

Watkins R, Palmer J, Kolokotroni M, Littlefair P (2002) The London heat island: results from summertime monitoring. Build Serv Eng Res T 23:97–106

Zhang J, Rao ST (1999) The role of vertical mixing in the temporal evolution of the ground-level ozone concentrations. J Appl Meteorol 38:1674–1691