Urban Ecology

An International Perspective on the Interaction Between Humans and Nature

John M. Marzluff · Eric Shulenberger
University of Washington, Seattle, WA USA

Wilfried Endlicher
Humboldt University, Berlin Germany

Marina Alberti · Gordon Bradley · Clare Ryan
Craig ZumBrunnen
University of Washington, Seattle, WA USA

Ute Simon
Humboldt University, Berlin, Germany

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The Urban Climate – Basic and Applied Aspects

Wilhelm Kuttler

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Introduction, Definition and Features of Urban Climate

Towns and cities are the most densely populated areas on Earth and will continue to be the artificial landscapes most widely used by the greater part of the Earth's population in the future. In 2030 more than 60% of humans will live in cities. Changes in urban conditions have often caused deterioration in environmental quality and may result in damage to the health of city-dwellers. The differences between the climate of a city and the climate of its surroundings are referred to as the "urban climate". The most important features of urban climate include higher air and surface temperatures, changes in radiation balances, lower humidity, and restricted atmospheric exchange that causes accumulations of pollutants from a variety of sources. Although these changes mainly affect local or regional conditions, persistent substances released into the atmosphere may also affect larger areas or even the global climate.

Causes of Urban Climate

The four main causes of urban climate, which result from different uses of built-up areas, are:

1. replacement of natural soil by sealed surfaces, mostly artificial and having a strong 3-D structure;
2. reduction of the surface area covered by vegetation;
3. reduction of long-wave emission of the surface by street canyons and
4. release of gaseous, solid and liquid atmospheric pollutants, and waste heat.

These factors all have severe impacts on radiation and thermal properties such as evapotranspiration, water storage, and atmospheric exchange in near-surface layers. Properties of urban climates throughout the world are generally comparable. However, the regional and local situation of an urban area, the infrastructure available and local economic structures all modify the local anthropogenic climate (Wienert 2002). Here, we will discuss only the most important characteristics of urban climate, and only for mid-latitude settlements.

W. Kuttler
Department of Applied Climatology and Landscape Ecology, University of Duisburg-Essen (Campus Essen), Essen, Germany
e-mail: wiku@uni-due.de

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Table 1 Thermal properties of typical "urban surfaces" (asphalt) and "natural bare surfaces" (loamy soil) (after Zmarsly et al. 2002)

Material	Density ρ/kg m^{-3}	Specific heat c/J kg^{-1} K^{-1}	Heat capacity $c\rho$/J m^{-3} K^{-1}	Thermal conductivity λ/W m^{-1} K^{-1}	Thermal diffusivity a/m^2 s^{-1}	Thermal admittance b/J $s^{-0.5}$ m^{-2} K^{-1}
Asphalt	2,100	920	$2.0 \cdot 10^6$	0.75	$0.4 \cdot 10^6$	1,200
Loamy soil (40 % pore space; dry)	1,600	900	$1.4 \cdot 10^6$	0.25	$0.2 \cdot 10^6$	600
Ratio Asphalt/ Loamy soil	1.3	1.02	1.4	3.0	2.0	2.0

Thermal and Hydrological Properties of Urban Surfaces

The thermal behaviour of sealed surfaces is largely determined by the density, heat capacity, thermal conductivity, thermal diffusivity and thermal admittance coefficients of the materials used (see Wesolek, this volume and a summary in Table 1).

The behaviour of sealed surfaces with respect to water drainage and seepage is highly heterogeneous, because porosity and water-bearing properties may fluctuate severely as a function of capillarity and pore volume. The large-scale use of impermeable materials for the almost complete sealing of urban surfaces normally means that precipitation is drained rapidly through underground sewers which are protected against evaporation, and that exposed surfaces are only wetted for a very short time. As a result of reduced evaporation, more energy is available for long-wave emission, sensible heat flux and conduction to the subsurface, and latent heat flux of evaporation is severely reduced.

Structure of Urban Atmosphere and Wind Conditions

The 3-D relief of cities multiplies effective surface area. The aerodynamic properties of surfaces can be characterized by the roughness length (z_0) and the zero plane displacement (d_0), which together measure the unevenness of a surface with respect to the surface's effects on the horizontal and vertical wind vectors. Although disturbances of the near-surface boundary layer can be measured at up to 500 m above ground in densely built-up areas, a largely undisturbed wind field is usually found at 400 m in suburbs and at 300 m in the surrounding areas, both of which are less intensively developed.

The structure of the urban atmosphere depends on the type, size and arrangement of obstacles to air flow and the resulting mechanical and thermal turbulence. As air flows from the countryside to the city it encounters a new and very different set of boundary conditions. That is why during calm and clear weather conditions an internal boundary layer develops downwind from the leading-edge of the city. The *urban boundary layer* is a local to meso-scale phenomenon whose characteristics are governed by the nature of the general urban 'surface'. Beneath roof-level is the *urban canopy layer*, which is produced by micro-scale processes operating in the streets ('canyons') between the buildings (Fig. 1). Its climate is an amalgam of microclimates each of which is dominated by the characteristics of its immediate surroundings. In the case of severe convection in the daytime, the total thickness of the urban boundary layer may reach several hundred metres. During the night,

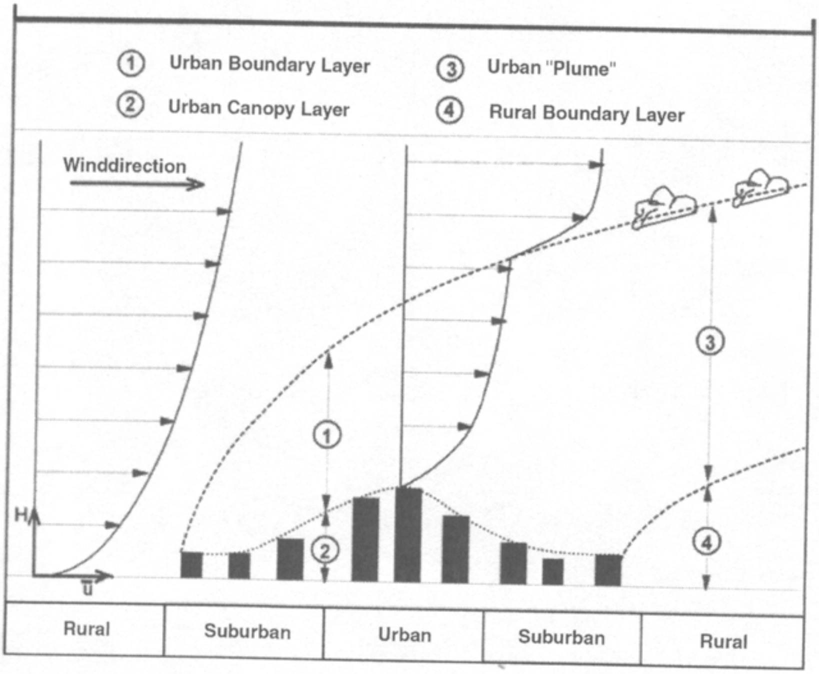

Fig. 1 Features of the urban boundary layer (adapted from Kuttler 1997, after Helbig 1987)

the layer is only a few decametres thick. In these weather conditions, radiation inversions may form; in the surrounding area, these inversions may be more intensive because of severe cooling and the lack of heat emitted by the urban fabric. On the lee side of a city, the urban plume may extend several km downwind, resulting in conditions similar to the urban climate, but less pronounced.

Normally, urban windspeed is lower than that of the countryside. But the surface-level windspeed may be significantly higher in built-up areas than in surrounding areas during calm and cloudless weather conditions (especially at night and in the early morning) when Urban Heat Island ("UHI") values are high and the overall airflow is in transition. The transitional speed depends on the size and structure of the city. Such thermally-generated airflows are called country breeze systems, and are characterized by a relatively low-speed (and normally intermittent) air flow in a layer of a few metres above the surface. In ideal conditions, this country breeze flows radially into the city, supplying cold air to the urban area (Barlag & Kuttler 1990, 1991). The pressure gradient required for air flow between the surrounding area and the city is created by differences in heating between city and surrounding areas. These wind systems can be relevant for urban planning if they improve the air quality in the city, for example by eliminating thermal stress and facilitating renewal or exchange of the urban atmosphere (Weber & Kuttler 2003). However, this is only possible if cold air from the surrounding area can flow freely into the city centre (Weber & Kuttler 2004). General features of such urban air paths (UAP) are (after Matzarakis & Mayer 1992):

- $\mathbf{z_0} < 0.5\,\mathrm{m}$
- $\mathbf{d_0}$: negligible
- length $\geq 1.000\,\mathrm{m}$
- width $\geq 50\,\mathrm{m}$ (depends on lateral obstacles)
- width of obstacles within UAP is 2 – 4 times the height of the lateral obstacles (min. 50 m)
- height of obstacles within UAP $\leq 10\,\mathrm{m}$

- orientation of largest width of obstacles within UAP should be parallel to axis of UAP
- single obstacles within UAP should have a ratio of height of obstacle to horizontal distance between two successive obstacles of 0.1 to 0.2

Urban air paths can be classified into ventilation paths (having different thermal regimes and air pollution levels), clean air paths (differing thermal levels, and without air pollution), cold air paths (differing air pollution levels, without thermal differences) and bioclimatic clean and cold air paths (without thermal differences and without air pollution). Examples of urban air paths (after Kuttler 2000) include:

MAIN TRAFFIC ROUTES

- low z_0 – values
- relatively warm surfaces
- possible high shearing stress
- potential air pollution by cars and domestic heating
  - Evaluation: only ventilation paths because of potential air pollution

RAILWAY TRACKS

- low z_0 – values
- relatively cool surface
- small shearing stress
- air pollution if Diesel-engines operate in goods depots
  - Evaluation: Clean air paths/Bioclimatic clean and cold air paths if Diesel-engines don't operate in goods depots

VEGETATED AREAS/PUBLIC PARKS

- z_0-, d_0 – values depend on vegetation height and density
- relatively cool surface, stable atm. conditions near the ground
- no release of anthropogenic air pollutants, but possibly of
  - biogenic emissions (VOC)
- filtering aerosols and gases
  - Evaluation: Bioclimatic clean and cold air paths with regard to prevailing low vegetation height

RIVERS and URBAN WATERS

- very low z_0-values
- relatively warm surface
- no release of anthropogenic emissions
- absorber of atm. aerosols and gases
  - Evaluation: Clean air paths; thermal effects can be reduced because of relatively warm waterbody

Radiation and Heat Balance

Compared with the surrounding countryside, the radiation and heat balances of an urban area are subject to a wide variety of effects. These are caused by gaseous, particulate and liquid air pollutants, which reflect, scatter and absorb radiation, and the type, structure, use and exposure of urban surfaces. The short and long-wave albedo long wave emission, effective radiation and thermal behaviour of the surface are determined by the composition of the urban atmosphere and the city's surface conditions. During low advection conditions without precipitation, the radiation and heat balance of the ground/air boundary layer is:

$$Q^* + q_m + q_a + q_g + q_l + q_s = 0 \quad (\text{all in W m}^{-2})$$

wherein:
Q^* = radiation balance /W m^{-2}
q_m = metabolic heat flux density / W m^{-2}
q_a = artificial heat flux density /W m^{-2}
q_g = heat flux density in the ground /W m^{-2}
q_l = turbulent latent heat flux density /W m^{-2}
q_s = turbulent sensible heat flux density /W m^{-2}

Conservation of energy demands that the total of the individual components of the radiation *and* heat balance must be zero. The radiation balance (Q^*) is:

$$Q^* = (I + D)(1 - \rho_s) - A(1 - \rho_l) + E/\text{W m}^{-2}$$

wherein:
I= direct solar radiation / W m^{-2}
D= diffuse solar radiation / W m^{-2}
ρ_s = short-wave reflectivity coefficient of surface / -
ρ_l = long-wave reflectivity of surface / -
E= long-wave counter radiation / W m^{-2} , and
$E = \sigma \cdot \varepsilon \cdot T_0$
A= long-wave radiation from the ground / W m^{-2}
σ = Stefan-Boltzmann constant ($5.67 \cdot 10^{-8}$ W m^{-2} K^{-4})
ε = emissivity / -
T_0 = surface temperature / K

By convention, radiation and energy flux densities are positive if they are directed towards the surface being considered. Because the urban atmosphere is normally polluted, the ratio of direct (I) to indirect solar radiation (D) is low. The reflected short-wave radiation intensity is a function of sun elevation angle (γ) and the characteristics and exposure of city surfaces. For European and North American cities, the usual value of short-wave reflectivity is ~10 %. Long-wave reflectivity (ρ_l) reaches ~5 % and is normally not taken into consideration, given the error in determining the other factors. The long-wave *radiation flux densities* expressed in the second part of the above equation are largely determined by surface and air temperatures, air humidity and CO_2 content and the corresponding emissivity values (ε). The long-wave counter-radiation (E) is affected by the atmosphere and very strongly by the raising of the horizon (i.e., the artificial "horizon" seen from within the city – that is, building roof-lines), which can be expressed in terms of the relationship between the width of roads and the height of road-edge buildings. In the case of high ratios, i.e. wide roads and low buildings, about 90 % of the energy input is still available in suitable weather conditions. With low ratios (e.g. 0.5) < 30 % of the energy is emitted. As regards long-wave radiation flux densities, cities have higher counter-radiation values (more intense greenhouse effects) and greater emission from the ground.

The *urban energy balance* includes the factors q_m, q_a, q_g, q_l and q_s. Metabolic heat production (q_m) comes from living organisms (in cities, mostly humans). Since q_m is quite small relative to the other flux densities, it is normally not taken into consideration (although it is about 100 watts/person).

Artificial heat production (q_a), from vehicles, power stations, industrial plants, domestic heating systems, air conditioning systems, and the like can reach widely variable, and sometimes significant, values depending on the city's geographical location and topographical situation. For easier handling, the ratio proposed by Bowen (Bo) is often used to characterize the main factors q_s and q_l which describe the climate of a city in thermal terms:

$$\mathrm{Bo} = \frac{q_s}{q_l}$$

Surfaces with less evaporation emit energy mainly via q_s and have Bo-values > 1, whereas values <1 are reached where turbulent latent heat flux predominates. The Bowen ratio allows a detailed classification of areas that have different land uses with respect to the predominant heat transfer mechanism. On this basis, negative values are only found over green spaces, early in the morning, in the evening and especially at night. During the daytime, both the sensible and latent heat fluxes are mainly directed away from the surface. During temperature inversions, heat transfer direction may be reversed, giving negative Bo-values. Because of the heat island effect, inversions are relatively rare in urban areas, hence the Bo-ratio may fall below 1 but normally does not become negative. Negative values may happen in the surrounding area if the q_s-transfer towards the surface is combined with the q_l-transfer away from the surface to the atmosphere.

A major factor in the urban energy balance is the heat-flux density in the ground q_g. In view of the high thermal conductivity and heat capacity values of construction materials, the ground and the buildings store significant heat. In dry conditions, q_g accounts for up to 50 % of the urban heat balance. During the night, the energy reserve formed in this way fuels the heat island effect (Parlow 2003).

To summarize, the components D, E, A, q_a, q_g and q_s of the radiation and energy balance normally play a more important role in the city, whereas I and q_l are less important.

Urban Moisture Environment, Precipitation Amount, Fog Density

The urban atmospheric moisture environment depends on the water balance of the urban area:

$$p + J + F = E + \Delta r + \Delta S + \Delta A \quad \text{(all units in mm time}^{-1}\text{)}$$

wherein:
- p = precipitation
- J = water supply from rivers and reservoirs
- F = water released to air by combustion (cars, industry, domestic heating)
- E = evapotranspiration
- Δr = net runoff
- ΔS = moisture storage
- ΔA = net moisture advection

Precipitation patterns are odd in urban areas - most rain falls on the lee side of the city (see Fig. 2), due to the urban heat island effect, the urban emission of particles which become condensation nuclei and, the higher roughness length which causes rain not to fall vertically (Schütz 1996).

Relative humidity is affected by the pattern of rainfall. During the day it will be lower in the city than in the surroundings because of higher runoff, sealed surfaces and loss of vegetation. But

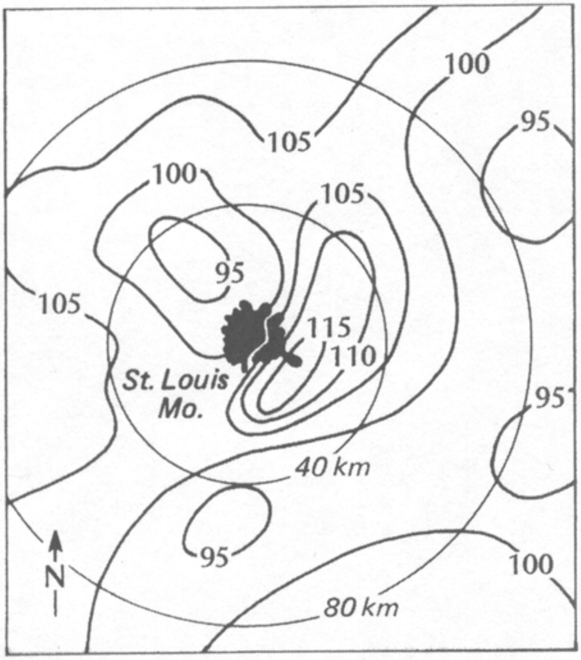

Fig. 2 Average rural/urban ratios of summer rainfall near St. Louis, 1949–1968 (after Changnon et al. 1971). The Rural/Urban ratio is the ratio of the precipitation recorded at any station to that at two stations near the urban center

at night the city can be more humid because of higher temperatures and less dew-fall than in the countryside (Fig. 3). In former days towns and conurbations in industrialized countries had more fog days than did their surroundings. But the number of foggy days is decreasing, due to cleaner air and a stronger urban heat island effect caused by a decrease in the percentage of natural surfaces within the cities.

Urban Heat Island Effect

Air and surface temperatures in cities are normally higher than in the surrounding areas. Urban excess heating is the result of the different importance of the various factors in the energy balance and air movement in cities and surrounding areas. The severity of excess heating, known as the Urban Heat Island Intensity (UHII), is normally expressed in terms of the horizontal temperature difference (Δt_{u-r}) between the city (u) and the surrounding area (r). Mechanisms producing the Urban Heat Island Effect include (after Oke 1979):

Urban Boundary Layer

- Anthropogenic heat from roofs and stacks
- Entrainment of heat from warmer canopy layer
- Entrainment of heat from overlying stable air by the process of penetrative convection
- Shortwave radiative flux convergence within polluted air

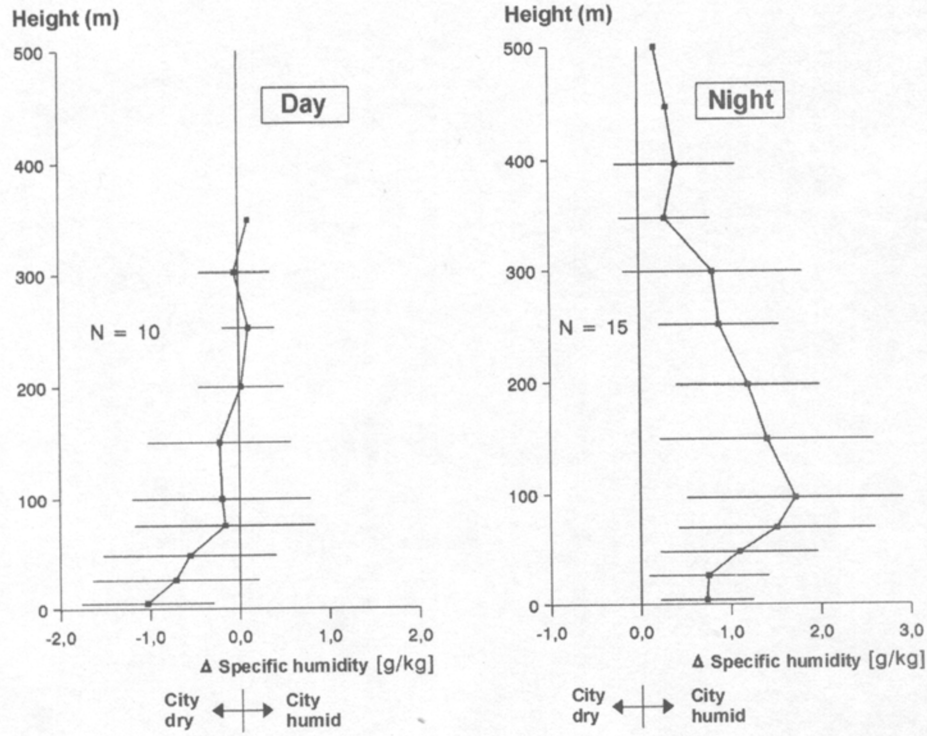

Fig. 3 Variations of mean nocturnal urban excess humidity with height over Christchurch during clear, calm weather (after Tapper 1990)

Urban Canopy Layer

- Anthropogenic heat from building sides
- Greater shortwave absorption due to canyon geometry
- Decreased net long-wave loss due to reduction of sky view factor by canyon geometry (sky-view factor is the ratio of the amount of the sky "seen" from a given point on a surface to that potentially available)
- Greater daytime heat storage (and nocturnal release) due to thermal properties of building materials
- Greater sensible heat flux due to decreased evaporation resulting from removal of vegetation and surface waterproofing
- Convergence of sensible heat due to reduction of wind speed in canopy

Several types of heat islands may occur at different times and cover different areas.

Surface heat islands are affected by the ground and caused by high surface temperatures. They mainly occur in built-up areas and therefore have clearly defined boundaries. They can be demonstrated on the basis of surface temperatures measured directly or by infrared photographs.

The *heat islands of the urban canopy layer* affect the atmosphere between the surface and mean roof height. *Urban boundary layer heat islands* form above the canopy layer as a result of heat transfer (q_s, q_l), artificial heat input (q_a), and increased absorption of radiation by atmospheric pollutants with resulting thermal re-emission. This type of heat island already extends so far upwards into the atmosphere above a city that it is propagated downwind by the overall wind patterns and gives the well-known "urban plume".

Factors Affecting Urban Heat Islands

Thermal conditions in conurbations are determined by land use, the structure of buildings and the size of the city. Especially severe urban excess heating occurs during calm and cloudless weather. During about 80% of the hours in a year, central European cities differ from their surroundings by $\overline{\Delta}t_{u\text{-}r} \geq 1$ K. The UHII is affected especially strongly by wind speed, and less by cloud cover.

There are also relationships between the maximum intensity of heat islands and the size and functioning of a city. For assessing UHII, a city's population is often used as a surrogate for city size, because it is relatively easy to measure. The sealing of surfaces and the geometry of street canyons also affect UHI intensity. For example, the sky view factor (SVF) is the ratio of the actual visible area of sky to the potentially visible area. Low values (SVF ~0,1 – 0,4) indicate higher UHII (Blankenstein & Kuttler 2004).

UHII not only depends on these local factors but also on the city's geographic and regional location. For example, coastal cities have much less severe UHII than cities located in valleys and depressions or inland (Park 1987) and the more northern a city is located the higher the UHI.

In the case of human-bio-meteorological problems, city dwellers are exposed to greater thermal stress in the summer (due to higher air and radiation temperatures and reduced near-surface air exchange) than are the inhabitants of surrounding areas. This is confirmed by the higher incidence of heart and circulation problems in conurbations during hot spells (Kalkstein et al. 1996). But there are also positive effects of the urban heat island, e.g a reduction in the energy required for space heating.

It would be beyond the scope of this chapter to discuss the other changes caused by urban excess heating. These include an increase in the length of the growing season, a shift in vegetation growth-phases and larger numbers of immigrant or imported plant species, and animals from warmer areas. And of course, apart from a reduction in the number of frosty and icy days, a reduction in the number of snowy days reduces costs for snow and ice clearance.

Urban Air Pollution

Urban air quality is mainly determined by road traffic, industry, power and heating plants and households. The most important pollutants in urban atmospheres include NO, NO_2, CO, NMVOC (Non-Methane Volatile Organic Compounds), O_3, SO_2, dust and soot. The urban CO_2 (which is not pollution but is an important determinant of the atmosphere's infra-red behavior) concentrations are enhanced in sealed areas (Henniger & Kuttler 2004). Depending on the degree of industrialization, economic conditions and the geographic location of conurbations, different pollutants predominate, resulting in varying air quality problems. For example, NO_x, CO und O_3 tend to predominate in areas with high traffic density, whereas SO_2, dust and soot are the main pollutants associated with coal and oil heating, power generation systems, and lower traffic densities. An analysis for central Europe shows that road traffic accounts for ~50% of NO_x, 60% of CO and > 30% of NMVOC emissions. Among other things, these pollutants are ozone precursors and may result in high urban ozone concentrations during sunny summer conditions. In some countries, the air quality of conurbations is also affected by emissions from biomass combustion or dust carried in by the wind from deserts and elsewhere.

Table 2 shows the general situation of air pollution in individual cities. The various individual species of pollutants include:

SO_2: Over the past few decades, SO_2 concentrations especially in Middle Europe and North America have generally been reduced some cities, by installation of filters and flue gas scrubbers on industrial plants and power stations, use of low-sulphur fuels, and changes in consumer behaviour (use of gas instead of coal and oil). However, relatively high concentrations still severely impair air quality in some cities, especially where coal or peat are common fuels ([e.g. Beijing (90 $\mu g\ m^{-3}$), Shanghai (79 $\mu g\ m^{-3}$), Manila (55 $\mu g\ m^{-3}$)].

NO_2: Worldwide, the main source of NO_2 pollution is internal-combustion vehicles. Areas where catalytic converters are not widely used or traffic densities are high often have severe NO_2 concentrations, e.g., Sofia, Athens, Los Angeles, London and São Paulo, where concentrations are sometimes $> 75\ \mu g\ m^{-3}$.

O_3: Ozone concentrations in the cities listed in Table 2 range from 10 $\mu g\ m^{-3}$ (Vancouver BC Canada) up to 69 $\mu g\ m^{-3}$ (Mexico City). In Los Angeles, where high values were still measured a few years ago, pollution control action has reduced the concentration of precursor substances and now limits ozone concentrations.

CO: In most conurbations, CO concentrations are 1 – 2 $mg\ m^{-3}$. Significantly higher values sometime occur, e.g. São Paulo (5.9 $mg\ m^{-3}$), Athens (5.1 $mg\ m^{-3}$) and Sydney (5.0 $mg\ m^{-3}$).

SST and PM 10: Particulate sources not only include industry, domestic heating systems and road traffic but also the deflation (aerial erosion) of soil material, which is a main reason for the high values recorded in several cities of Asia (e. g. Calcutta, New Delhi, Beijing).

Soot: Only limited data are available on soot concentrations. Soot comes mostly from diesel engines and the combustion of coal and oil. These are probably the main reasons for the high concentrations in Quito (120 $\mu g\ m^{-3}$), Athens (99 $\mu g\ m^{-3}$) and Mendoza (94 $\mu g\ m^{-3}$).

Most air quality problems are caused by SO_2, NO_2 and SST/PM 10. In western industrialised countries 'classical' air pollutants such as SO_2 are no longer a serious problem in most areas.

Urban Climate and Global Climate Change: the Future, as Best we can Guess it Today

Because the concentration of CO_2 in the atmosphere will probably double in the next 100 years, global average temperatures will likely increase ~2 K over those of 1985 (Houghton et al. 2001). This prediction is based on numeric simulations which lead to different results depending on the scenario selected. It is beyond the scope of this article to discuss the validity of the input data used or the uncertainty of the results. Here, this prediction is assumed to be correct: we also assume there will be no change in the main factors which directly or indirectly affect urban development. In other words, the current situation is assumed to be frozen: the only variable considered is the global temperature increase as it affects urban climate.

Table 2 Annual average concentrations of atmospheric trace substances for selected cities in different continents (all figures in μg m-3; except CO in mg m-3; SST = total suspended solids, PM10 = respireable particulate matter ≤ 10 μm; – = value not available; bold type indicates values in excess of WHO guidelines (1997) for SO2 = 50 μg m-3, NO2 = 40 μg m-3; a relates to the year of measurement period) (after Kuttler 2000 and Healthy Cities – Air Quality Management Information System – AMIS 2.0, 1998, WHO, Geneva (from Dr. Mücke, WHO, Berlin)

Continent/city	SO_2	NO_2	O_3	CO	SST	PM_{10}	Soot	Year
EUROPE								
Athens	44	**95**	25	5.1	–	–	99	95
Brussel	22	**50**	43	–	68	20	–	95
Edinburgh	29	**49**	29	0.7	–	–	9	95
Geneva	13	**58**	28	1.2	29	–	–	95
Helsinki	4	**42**	38	1.0	92	31	–	95
Copenhagen	11	**69**	24	1.7	78	–	35	94
London	26	**88**	20	2.1	–	28	–	95
Madrid 1	3	25*a*	–	–	–	–	85	96*a*/97
Sofia	39	**208**	–	–	308	–	–	96
Vienna	11	33	41	0.9	–	36	–	96
AFRICA								
Durban	30	–	–	–	–	–	–	95
Johannesburg	22	40	54	1.8*a*	106	–	61	94*a*/95
Cape Town	21*a*	**72**	41	–	–	27	–	94*a*/95
ASIA								
Bangkok	17*a*	32*a*	–	–	138	–	–	93*a*/95
Calcutta	31	35	–	–	542	378	–	96
Manila	**55**	–	–	–	164	–	–	93
New Delhi	24	**77**	–	–	459	246	–	96
Osaka	19	**62**	57	1.6	40	–	–	94
Beijing	**90**	–	–	–	343	–	–	94
Pusan	**66**	**55**	34	1.3	93	–	–	95
Seoul	35	**67**	24	1.5	–	78	–	96
Shanghai	**79**	–	–	–	289	–	–	94
Tokyo	18	**70**	31	0.9	–	48	–	95
NORTH AMERICA								
Los Angeles	3	**92**	39	2.3	–	43	–	95
Montreal	10	**41**	–	0.8	39	–	–	93
Vancouver	21	**55**	10	1.5	39	–	–	93
CENTRAL AMERICA								
Mexico City	**53**	**81**	69	3.2	180	61	–	96
SOUTH AMERICA								
Caracas	35*a*	**79**	–	–	63	–	–	94*a*/95
Mendoza	6	**76**	–	–	61	–	94	97
Quito	22	–	–	–	154	57	120	95
Santiago	23	**86**	12	2.8	91	–	–	95
Sao Paulo	34	**88***a*	65*a*	5.9	116	89	–	91*a*/95
AUSTRALIA/NEW ZEALAND								
Sydney	–	33	18	5.0	70	31	–	95
Auckland	7	20	–	–	33	25	9	96

Table 3 Climatological event days for the greater Berlin area with present and changed climatological conditions (according to Wagner 1994 and Hupfer 1996, with some changes)

Event	Present [Number]	Modelling, scenario A, for end of 21st century (ECHAM I, T21) [Number]	Change [Number]
Extremely hot days, $t_{max} > 39\,°C$	0.01	0.04	+0.03
Hot days, $t_{max} > 30\,°C$	5.4	11.7	+6.3
Summer days, $t_{max} > 25\,°C$	27.2	41.8	+14.0
Frosty days, $t_{min} > 0\,°C$	56.6	38.6	−18.0
Ice days, $t_{max} > 0\,°C$	22.0	8.8	−13.2
Extremely cold days, $t_{max} > -10\,°C$	0.7	0.11	−0.59

Thermal Environment and Near-Surface Exchange Conditions

The climate in a city is largely determined by thermal conditions and changes in the wind field. These factors affect not only the human bioclimate but also energy consumption, emissions of anthropogenic and biogenic hydrocarbons, and the formation of secondary pollutants. For Berlin, as an example, Table 3 indicates the thermal changes expected for days with different weather. Whereas the winter will become less severe (18 fewer frosty days and 13 fewer icy days), there will be 14 additional summer days and 6 additional hot days per year. Less severe winter weather will probably lead to a reduction in energy consumption for heating (this will be dealt with later). On the other hand, an increase in the number of summer days could lead to rising energy consumption for air conditioning. The temperature thresholds mentioned confirm a reduction in the recurrence cycle for hot days and the less frequent occurrence of frosty, icy and extremely cold days. Town and country planners should take action at an early stage to counteract the increased thermal discomfort occurring during the summer. For example, highly reflective colours should be used for facades, vegetation should be planted on the roofs of buildings, and adequate ventilation channels should be provided to allow of the flow of cooler air from the surrounding countryside as far as possible into the city centre.

As a result of the surface roughness caused by buildings, wind speeds in urban areas are normally lower than in the surrounding countryside. If near-surface air-exchange is restricted by low-wind conditions and extremely stable atmospheric stratification (temperature inversion), there may be an increase in atmospheric pollutant levels. The question therefore arises as to whether global warming leads to changes in ventilation conditions in cities. For Berlin, Gross (1996) predicted that thick temperature inversion layers (> 300 m) would occur 20 % more frequently under the conditions mentioned than in 1985. On the other hand, less severe (thinner) temperature inversions will probably occur less frequently under the same conditions. This is because of a change in the characteristics of the air masses. Thicker inversions are more stable than thinner ones, therefore air pollution is likely to be worse during such episodes as they will probably last longer.

Power Consumption

Because power consumption is determined largely by climatic conditions, the location of a city is a major factor in its energy use. Essen, Germany (pop = 590,000; temperate zone) and Los Angeles, USA (3.5 M pop, subtropical zone) are good examples. For Essen, as expected, power consumption

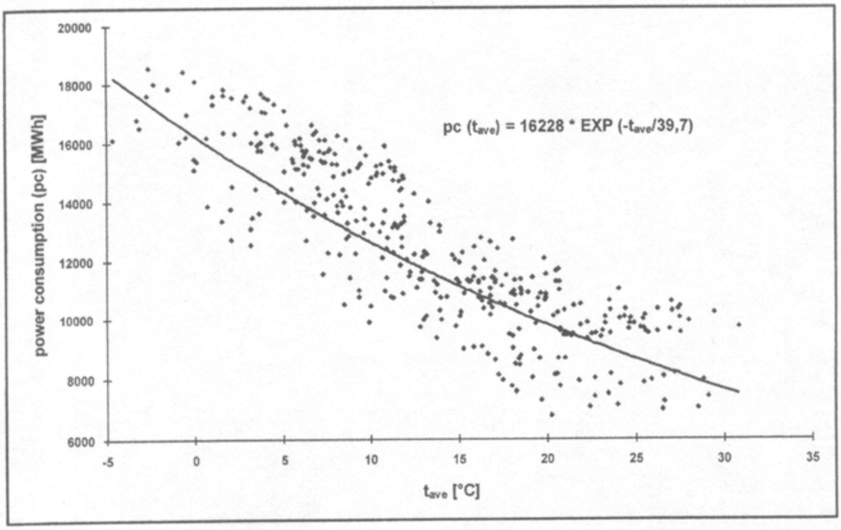

Fig. 4 Dependence of average daily power consumption (pc) on mean daily temperatures (t_{ave}) for the supply areas of Essen and adjacent cities; (after Kuttler 2001)

is inversely proportional to temperature (Fig. 4). At temperatures <0 °C, a temperature change of 1 K results in a change in power consumption of ~400 MWh/K, or twice as much as the change in power consumption at summer temperatures around 25 °C (~200 MWh/K) – people are more sensitive to cold than they are to excess warmth. Table 4 indicates the monthly percentage of annual total power consumption. If the annual average temperature rises by 2 K, there will be a fall of about 8 % in overall power consumption, entirely as a result of higher winter temperatures and the reduced demand for heating. There will be no difference in power consumption in the summer. Of course, this assumes that there will be no change in consumer behaviour (= business as usual) as a result of higher temperatures, i. e. there will no increase in use of air conditioning in the summer. The predicted reduction in power consumption should also lead to reduced emissions, especially of carbon dioxide, by power stations.

In contrast to the situation in the temperate zone, higher temperatures are predicted to cause increased power consumption in western subtropical cities. Winter power consumption is only of secondary importance in such areas, so the increase in power demand for air conditioning will be the major parameter. Taking weekday power consumption in Los Angeles as an example, Oke (1994) demonstrated that power consumption remains roughly constant at temperatures between 15°C and 20°C, but then rises by about 33% between 20°C and 25°C. Apart from intensifying the urban overheating effect, the higher power consumption results in more severe air pollution and increased use of all resources needed for power generation.

Table 4 Relative portions of monthly power consumption in annual power consumption of the city of Essen[1)] under present (1995, (a)) and changed (b) climatic conditions [1995: 4,523 GWh[2)] = 100%[3)]] (after Kuttler 2001)

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
(a)	11	9	10	8	7	7	6	6	7	8	10	11	100
(b)	9	8	9	8	7	7	6	6	7	7	8	10	92
(b)-(a)	−2	−1	−1	0	0	0	0	0	0	−1	−2	−1	−8

[1)] supply area of Essen and adjacent cities, 2) GWh = gigawatt-hours, 3) rounded.

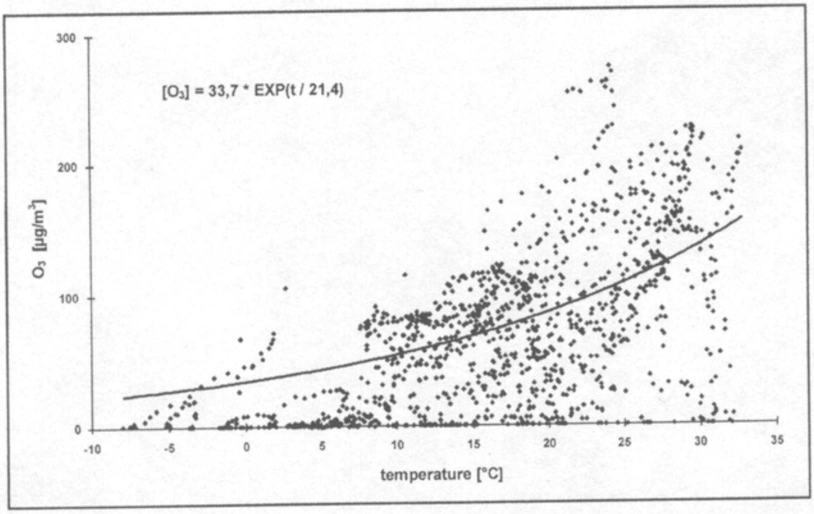

Fig. 5 Dependence of ozone concentrations $[O_3]$ on air temperature [t] for clear days in a 70-hectare urban park in Essen (data basis: 1,231 30-minute-averages recorded from May 1995 to September 1997; after Kuttler 2001)

Air quality

Most chemical reactions are accelerated by rising temperatures, so global warming will affect the emission, transmission and concentration behaviour of atmospheric trace substances and therefore also urban air quality. For example, it is expected that there will be more emissions of certain anthropogenic and biogenic volatile organic compounds (AVOC and BVOC) which play a major role in the formation of tropospheric ozone. The most widespread urban AVOCs areas are BTX compounds (benzene, toluene and xylene) which are mainly produced by road vehicles. Apart from exhaust emissions, the collective benzene emissions caused by evaporation losses, refinery leakages, fuel production, refuelling, tank-breather and parking losses are also major factor in air pollution. In addition, motor industry projections indicate that both the number of vehicles and the distance travelled by each vehicle per year are likely to grow. As a result, further increases in pollutant output, especially in developing countries, must be expected despite the increase in use of catalytic converters. Biogenic volatile hydrocarbon emissions (mainly isoprene and monoterpenes from conifers) are positively correlated with air temperature and, in the case of isoprene, with solar radiation flux density. BVOC compounds are highly reactive and therefore represent considerable ozone formation potential even in low concentrations. In addition, it is assumed that the portion of BVOC in total global hydrocarbon emissions is of the order of 90% (Guenther et al. 1993). Although concentrations of biogenic hydrocarbons in urban areas are normally low, various studies made in urban parks and gardens confirm that they may play a considerable role in ozone formation (Benjamin et al. 1996). The expected climate changes will lead to an increase in the chemical reaction rate of ozone precursors. As a result, in combination with the rise in NO_x and carbon dioxide concentrations, ozone concentrations will reach higher levels than at present. Fig. 5 indicates the relationship between ozone concentration and air temperature in a large urban park in Essen (Kuttler & Strassburger 1999). There, ozone concentration increases by 5%/ K between 25 and 30 °C. However, air temperature is largely a function of insolation and therefore this correlation does not necessarily indicate causation.

Conclusions

The air quality in a city is chiefly determined by the thermal and air hygiene components of the bioclimatic complex.

As data from example cities show, it is likely that the number of days with high summer temperatures will increase in the temperate and subtropical zones, and that areas with thermal discomfort will become larger. On the other hand, the climatic situation in cool temperate cities may be expected to improve.

The concentration of ozone, the key component of summer smog, will increase and summer smog will spread to areas presently unaffected.

In terms of preventive or protective environmental actions, we must ask what might be done to alleviate the predicted developments. Wherever technically feasible, actions to improve air quality should be taken at the pollution sources. In addition, new buildings should be designed specifically for local climates (Barlag 1997).

Town and country planners must ensure systematic development of ventilation channels allowing fresh air from the surrounding areas to penetrate as far as possible into the city centre. In addition, it would help to increase the size of urban parks and gardens, and to increase total green area by planting both horizontal surfaces and suitable facades and roofs, using plants which have proved their resistance to urban environmental stress. More information is given by Wittig (1991). Taha (1996) says the positive effects of more vegetation in cities include:

- Reduced surface and air temperatures at ground level – This would not only alleviate thermal discomfort but also save energy as a result of shading and wind protection. Forestry authorities in the USA assume that cost reductions of the order of US $\$ 4 \times 10^9$ per year through energy savings could be achieved if 100 million additional trees were correctly situated in North America. In addition, there would be positive effects on chemical reaction behaviour, in the form of reduced reaction rates.
- A reduction in biogenic hydrocarbon emissions caused by high temperatures and radiation also leads to lower ozone formation potential. However, when planting urban areas, it is important to select species with low isoprene and monoterpene emissions (no pine trees!). Otherwise, high vegetation density could be counter-productive, and might even accelerate ozone formation. In general, plants with isoprene emission rates of less than $2\,\mu g/(g \cdot h)$ and monoterpene emission rates of less than $1\,\mu g/(g \cdot h)$ are recommended. (A combined listing of 377 species found in the California South Coast Basin is ranked according to total [isoprene and monoterpenes] biogenic emission rate on hourly basis in Benjamin et al. 1996).
- An increase in exposed plant area also increases surface roughness and that in turn raises the rates at which particulate air pollutants settle out of the atmosphere (Kuttler 1991).
- The concentration of CO_2 falls because the gas is consumed by plants during photosynthesis.

Research into the potential effects of atmospheric warming on existing climatic and air hygiene conditions in conurbations is still at a very early stage. Systematic analysis is difficult because of the high complexity of urban ecosystems and the dependence of these ecosystems on the climate zone in which they are located. From the point of view of urban climatology, such work must be urgently expanded.

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