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Climate of the 21st Century: Changes and Risks

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Urban Climate and Global Climate Change

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Abstract: *The article investigates the consequences for urban climates of an assumed increase of 2 °C in the temperature of the Earth s atmosphere by the end of the 21st century. Following a discussion of the properties and main features of urban climates, the expected changes in terms of thermal conditions and air hygiene are presented. With reference to conditions in central Europe, it is expected, on the basis of model calculations, that the number of days with heat load in the summer will increase, while there will be a decrease in the number of cold load days in the winter. In cities where the winter is the determining factor, power consumption will probably fall. There will be an increase in ozone pollution.*

Urbanisation is a process that is evident throughout the world, characterised by urban population growth rates which are high and still growing, especially in developing countries. In the 21st century, it is expected that more than 60% of the world's population will live in towns or cities, including 27 megacities with populations of more than ten million.

Urbanisation causes massive ecological change within the human environment, especially as regards climate and air hygiene.

This article considers the extent to which the global warming of the Earth's surface and lower atmosphere may affect urban climates and air hygiene conditions in cities. Against this backdrop, some of the modifications which are generally to be expected are discussed as examples.

Characteristics of the urban climate

Urban climate embodies anthropogenic climate change and is in evidence in industrialised conurbations throughout the world. There are of course differences between the urban climates of cities in different parts of the world connected with the different macroclimatic conditions which apply to them. However, as a result of the emission of low-lived atmospheric trace gases in conurbations, which may then be transported over considerable distances, urban climates have an impact on global climate change.

There are mainly three causes which lead to the establishment of an urban climate (KUTTLER 1997). Firstly, areas with vegetation are reduced. Secondly, these surfaces, which previously represented natural soil, are converted into highly structured surfaces sealed mainly by synthetic materials. Thirdly, industrial plants produce thermal and pollutant emissions. These factors affect the radiation and heat balance and the processes of advection and diffusion, changing the climate of the city in comparison to the surrounding countryside. The characteristic properties of the urban climates of large cities in the temperate latitudes are indicated in *Table 3.35-1.*

The feature of an urban climate which is most striking and has received most attention is overheating with reference to the surrounding open countryside. This heat island is the result of different weighting of various elements in the radiation and heat balance in town and country and the release of additional anthropogenic heat by domestic heating, industrial plants and vehicles. Expressed as an annual average, the temperature in the city may be some 1 to 2 °C higher than in the surrounding area. For some exceptional episodes, values as high as 10 °C may even be reached. This overheating phenomenon is generally restricted to the built-up area of the city. However, local air movements caused by the temperature difference between city and country may carry cold air from the surrounding countryside into the urban area via air channels, modifying the heat island effect. A wind system of this type, which may become established during overall low wind conditions and therefore may occur only occasionally, is referred to as country breeze (BARLAG and KUTTLER 1990/91, KUTTLER et al. 1998). In bioclimatic terms, country breezes may help to alleviate the heat load and improve air quality under certain conditions. Apart from anthropogenic heat output, the degree of overheating in the city depends on a number of factors related to the type of building development (horizontal restrictions, proportion of sealed areas) and to meteorological conditions (cloud cover, wind speed). The heat surplus can be derived from the size of the city, expressed in terms of population figures. Normally, heat surplus is positively correlated with the number of inhabitants (KUTTLER 2000).

Another characteristic feature of urban climate is air pollution. On this basis, it is possible to define two broad categories: cities with air quality determined mainly by domestic and industrial emissions such as dust, soot and sulphur dioxide (SO_2) and those where road vehicle emissions such as carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOC) and their successors peroxyacetyl nitrate (PAN) and ozone (O_3) are the determining factor. Currently, urban climates in eastern Europe and many conurbations in Asia and Africa

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Table 3.35-1: Characteristics of the urban climate of a large city in the temperate zone (Based on LANDBERG 1981, KUTTLER 1998).

Factor	***Change with reference to surrounding open countryside***
Radiation	
• global radiation (horizontal surface)	-20 %
• Atmospheric counterradiation	10 to 40%
•UV radiation winter	-70% to -90%
summer	-10% to-30%
Sunshine duration	
• winter	-10%
• summer	-8 %
Sensible heat flux	50%
Air temperature	
• annual average	approx. 1 °C
• winter minimum	1 to 3 °C
• in individual cases	up to 10 °C
Duration of frost period	-30 %
Wind	
• speed	-25 %
• direction	severe variations
Absolute humidity	
• daytime	lower
• night-time	higher
Fog	
• large city	less
• smalltown	more
Precipitation	
• rain	10% (lee side)
• snow	less
• dew	-65%
Bioclimate	
• human heat load	*up to 40% more frequent*
• vegetation period	*up to 10 days longer*
• heating days"	*up to 10% fewer*
Air pollution	
• CO, NO , AVOC[2], PAN[3]	more
•0,	less

heating day = day with average temperature <15°C
A VOC = anthropogenic volatile hydrocarbons
PAN = peroxyacetyl nitrate

are largely of the first type, while those of cities in western industrialised countries are mainly dominated by road vehicle emissions. *Table 3.35-2* includes some selected cities from different continents as examples. The table shows that it is mainly NO, that represents a global pollution problem with frequent infringements of limits. In addition, high particulate matter and dust concentrations and in some cases ozone and SO, are problems of regional importance.

Potential effects of global climate change on conurbations

As the concentration of CO_2 in the atmosphere will probably double in the course of the 21st century, it is expected that average temperatures in Europe will increase by some 2 °C compared with figures for 1985 (IPCC 1996a). This prediction is based on numeric simulations which lead to different results depending on the scenario selected (see Chapter 3.4). It would be beyond the scope of this article to discuss the validity of the input data used or the uncertainty of the results. For the following analysis, this prediction is assumed to be correct. As a general principle, it is also assumed that there will be no change in the main factors which directly or indirectly affect urban development during the period under consideration. In other words, the current situation is frozen: the only variable considered is the global temperature increase as it affects urban climate.

Thermal environment and near-surface exchange conditions

As already stated, 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. Taking the city of Berlin as an example, *Table 3.35-3* indicates the thermal changes expected for days with different meteorological events. Whereas the winter will become less severe and there will be 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 aspect 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 repetition 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, bright colours should be used for facades, vegetation should be planted on buildings and adequate ventilation channels should be provided to allow the transportation of cooler air from the surrounding countryside as far as possible into the city centre (e.g. country breeze).

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 exchange is restricted by low-wind conditions and extremely stable

Table 3.35-2: Annual average concentrations of atmospheric trace substances for selected cities in different continents (all figures in ug/nf; except CO in mg/m'; SST = total suspended solids. PM_{MI} = respirable particulate matter < 10 urn; - = value not available; bold type indicates values in excess of WHO guidelines (1997) for SO, = 50 ug/m\ NO, = 40 ug/m').

Continent/city	SO_2	NO_2		*CO*	*SST*		*Soot*	*Year*
EUROPE								
Athens	44	95	25	5,1	-	-	99	1995
Brüssel	22	50	43	-	68	20	-	1995
Edinburgh	29	49	29	0,7	-	-	9	1995
Geneva	13	58	28	1,2	29	-	-	1995
Helsinki	4	42	38	1,0	92	31	-	1995
Copenhagen	11	69	24	1.7	78	-	35	1994
London	26	88	20	2.1	-	28	-	1995
Madrid	13	25a	-	-	-	-	85	1996a/97
Sofia	39	208	-	-	308	-	-	1996
Vienna	11	33	41	0.9	-	36	-	1996
AFRICA								
Durban	30	-	-	-	-	-	-	1995
Johannesburg	22	40	54	1.8a	106	-	61	1994a/95
Cape Town	21a	72	41	-	-	27	-	1994a/95
ASIA								
Bangkok	17a	32a	-	-	138	-	-	1993a/95
Calcutta	31	35	-	-	542	378	-	1996
Manila	55	-	-	-	164	-	-	1993
New Delhi	24	77	-	-	459	246	-	1996
Osaka	19	62	57	1.6	40	-	-	1994
Beijing	90	-	-	-	343	-	-	1994
Pusan	66	55	34	1,3	93	-	-	1995
Seoul	35	67	24	L5	-	78	-	1996
Shanghai	79	-	-	-	289	-	-	1994
Tokyo	18	70	31	0,9	-	48	-	1995
NORTH AMERICA								
Los Angeles	3	92	39	2,3	-	43	-	1995
Montreal	10	41	-	0,8	39	-	-	1993
Vancouver	21	55	10	1,5	39	-	-	1993
CENTRAL AMERICA								
Mexico City	53	81	69	3,2	180	61	-	1996
SOUTH AMERICA								
Caracas	35a	79	-	-	63	-	-	1994a/95
Mendoza	6	76	-	-	61	-	94	1997
Quito	22	-	-	-	154	57	120	1995
Santiago de Chile	23	86	12	2,8	91	-	-	1995
Sao Paulo	34	88a	65a	5,9	116	89	-	199 la/95
A USTRALIA/NEW ZEALAND								
Sydney	-	33	18	5,0	70	31	-	1995
Auckland	7	20	-	-	33	25	9	1996

Source: Healthy Cities - Air Quality Management Information System - AMIS 2.0, 1998, Copyright 1997/98 World Health Organisation, Geneva, compiled and kindly made available by Dr. Mücke, WHO, Berlin

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 high temperature inversions (> 300 m) would occur 20% more frequently under the conditions mentioned than in 1985. On the other hand, flat or low temperature inversions will probably occur less frequently under the same conditions. The reason for these developments is a change in the characterisation of the air masses. As thicker inversions are more stable than thinner ones, the problem of air pollution is likely to be vitiated during such episodes as they will probably be of longer duration.

Table 3.35-3: 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 (ECHAM1, 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

Power consumption

As power consumption is determined largely by climatic conditions, the geographical location of a city is a major factor. The city of Essen, Germany (590,000 inh., temperate zone) and the larger city of Los Angeles, USA (3.5 million inh., subtropical zone) may be taken as examples. In the case of Essen, the figures confirm, as expected, that power consumption is inversely proportional to temperature (*Fig. 3.35-1*). At temperatures below 0 °C, a temperature change of 1 °C results in additional or reduced power consumption of the order of 400 MWh/°C, or twice as much as the change in power consumption at summer temperatures around 25 °C (about 200 MWh/°C). *Table 3.35-4* indicates the portions of the months in annual power consumption. If the annual average temperature rises by 2 °C, there will be a fall of about 8% in overall power consumption, entirely as a result of higher winter temperatures. There will be no difference in power consumption in the summer. As already indicated, this assumes that there will be no change in consumer behaviour (= business as usual) as a result of higher temperatures, i.e. there will not be an increased tendency to use air conditioning systems in hot periods in the summer. The predicted reduction in power consumption should also lead to reduced emissions, especially of carbon dioxide, by power stations.

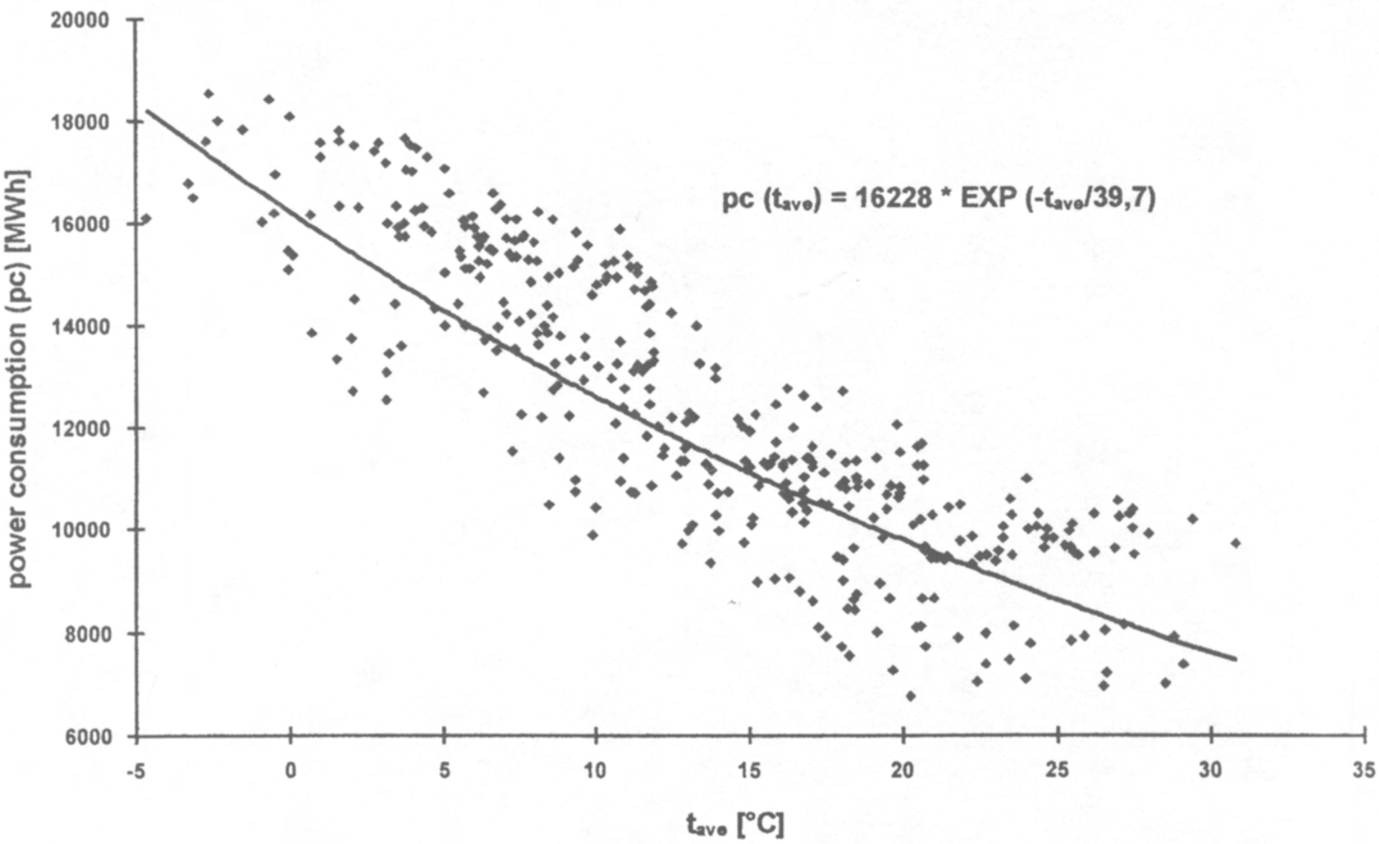

Fig. 3.35-1: Correlation of mean average daily temperatures (t_{ave}) with average daily power consumption (pc) for the supply area of Essen municipal utility (city areas of Essen, Mülheim an der Ruhr and Heiligenhaus and the Hösel and Breitscheid districts of Ratingen) (Based on RWE, Essen, pers. comm. 1997).

Table 3.35-4: Relative portion of monthly power consumption in annual power consumption of the city of Essen [1] under current (1995, (a)) and changed (b) climatic conditions [1995: 4,523 GWh [2] = 100 % [3]].

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 municipal utility (city areas of Essen, Mülheim an der Ruhr, Heiligenhaus, the Hösel and Breitscheid districts of Ratingen) (Based on RWE, Essen, pers. comm. 1997), [2] GWh = gigawatt-hours, [3] rounded.

In contrast to the situation in the temperate zone, it is expected that higher temperatures will lead to increased power consumption in western subtropical cities. As winter power consumption is only of secondary importance in such areas, 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 a third of the initial value between 20 °C and 25 °C. Apart from intensifying the urban overheating effect, the higher power consumption results in more severe air pollution and the increased depletion of the resources needed for power generation.

Air quality

As chemical reactions are normally accelerated by rising temperatures, 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 emissions of certain anthropogenic and biogenic volatile hydrocarbons (AVOC and BVOC) which play a major role in the formation of tropospheric ozone, will be intensified. The most widespread AVOC in urban areas are the BTX compounds (benzene, toluene and xylene) which are mainly produced by road vehicles. Apart from exhaust emissions, the benzene emissions caused by evaporation losses, refinery leakages,

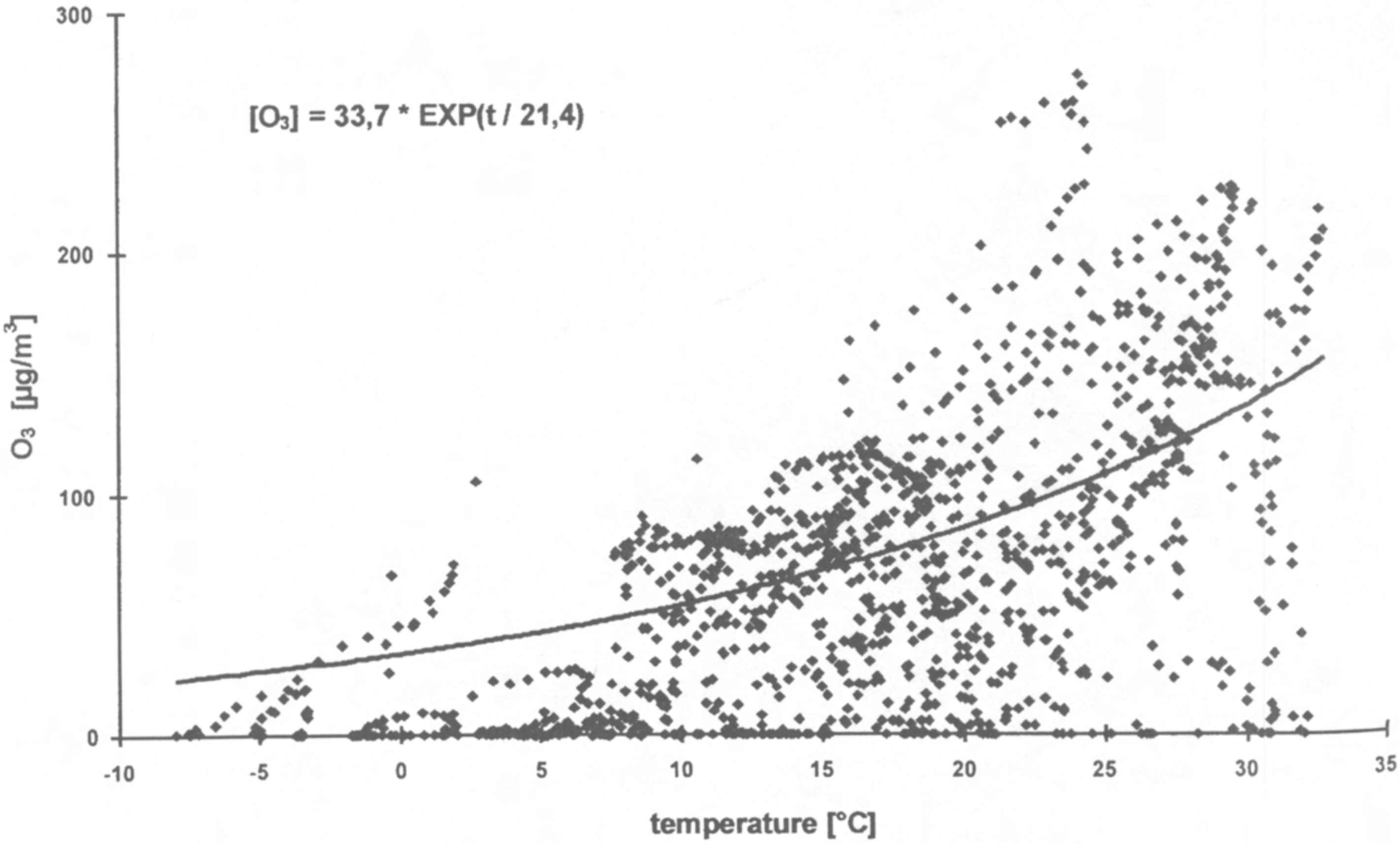

Fig. 3.35-2: Ozone concentration $[O_3]$ as a function of air temperature [t] for clear days in a 70-hectare urban park in Essen (data basis: 1,231 30-minute averages recorded from May 1995 to September 1997).

fuel production, refuelling, tank breather and parking losses are a major factor in air pollution. In addition, motor industry projections indicate that both the number of vehicles and the distances 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 use of catalytic converters.

Biogenic volatile hydrocarbon emissions (mainly including isoprene and the monoterpene group) 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. 3.35-2* indicates the relationship between ozone concentration and air temperature on the basis of measurements made in a large urban park in Essen (KUTTLER and STRASSBURGER 1999). On this basis, ozone concentration increases by 5%/ K between 25 and 30 °C. However, it must be noted that air temperature is largely a function of insolation and that this is therefore only an apparent correlation.

Conclusion

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

As already demonstrated on the basis of examples, it is to be assumed 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 where this type of air pollution does not occur today. In terms of preventive environmental protection, we must ask what action can be taken to alleviate the predicted development. Where technically feasible, action to improve air quality should of course preferably be taken at the various pollution sources. In addition, the design of new buildings should be adapted to climatic conditions (BARLAG 1997).

It will be the task of town and country planners to ensure that ventilation channels allowing fresh air from the surrounding areas to penetrate as far as possible into the city centre are systematically developed. In addition, it would be beneficial to increase the size of urban parks and gardens by planting both horizontal surfaces and suitable facades and roofs. Plants which have proved their resistance to urban environmental stress over the decades should preferably be used. Further information is given by WITTIG (1991). According to TAHA (1996), the positive effects to be expected as a result of more vegetation in cities are basically as follows:

- Reduced radiation and air temperatures at ground level would not only alleviate thermal discomfort but also save energy as a result of shading and wind protection effects. Forestry authorities in the USA assume that cost reductions of the order of US $ 4 billion per year through energy savings could be achieved if 100 Mill, additional trees were planted in North America (IPCC 1996). In addition, there would be a positive effect 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. Otherwise, high vegetation density could have a counter-productive effect, even accelerating ozone formation. As a general indication, plants with isoprene emission rates of less than 2 ug/(g-h) and monoterpene emission rates of less than 1 ug/(g-h) are recommended.
- An increase in exposed plant area and deposition rates, which are a function of surface roughness, favours the deposition of air pollutants (KUTTLER 1991).
- The concentration of CO_2 falls as this greenhouse gas is absorbed by plants for the photosynthesis process.

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, work in this field needs to be initiated or intensified as a matter of urgency"

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