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Urban bioclimatology

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Abstract. This article deals with the part of urban climatology which is of particular relevance to human beings. Presented first is a summary of all human biometeorologically effective complexes, as well as other factors which are relevant to urban planning and which depend on atmospheric conditions in urban structures in a direct or indirect manner. Later, methods for human biometeorologically significant assessment of thermal and air pollution components of the urban climate are discussed in detail, because these components can be strongly influenced by urban planning. The application of these methods is illustrated by some results of appropriate investigations in urban areas.
Key words. Urban climate; urban air pollution; human biometeorologically relevant assessment.

Introduction

For many purposes in urban climatology, especially for urban planning, information about single meteorological parameters such as air temperature or air pollutants such as ozone concentration is not sufficient if properties of urban microclimates are to be characterized or climatic effects of planned changes in land use of urban spaces are to be estimated[23]. Urban planning and urban redevelopment should take into account the health and well-being of human beings living and working in different urban areas. Therefore, urban climate has to be assessed in a physiologically significant manner. This task is an essential part of urban human biometeorology, which deals with the effect of weather, climate and air pollution on the human organism. The physiologically relevant assessment of urban climate, and especially different urban microclimates, requires the use of methods including threshold values and guide numbers developed in human biometeorology. These methods are at present standardized in Germany in the VDI-guideline *Human Biometeorological Assessment of Climate and Air Quality for Urban and Landscape Planning*[25].
The following effective complexes of human biometeorology are important in urban planning: thermal complex, air pollution complex, actinic complex, odors, noise, and wind comfort[2,9,19]. This article deals mainly with the thermal and the air pollution components of the urban climate, because generally they are most relevant to urban planning.

Ideal urban climate

One task of applied urban climatology is the recommendation of planning measures in order to approach local climate conditions which are ideal for human beings, especially in the urban canopy layer. The committee of experts in biometeorology of the German Meteorological Society has defined the expression 'ideal urban climatology' as follows[24]:

"'Ideal urban climate' is a spatially and temporally variable state of the atmosphere within urban structures containing as little air pollutants produced anthropogeneously as possible. In addition, a great spatial variety of urban microclimates should be offered to urban population (characteristic length of urban spaces with different climates related to cities in mid-latitudes: about 150 m) by avoidance of extreme conditions."

Such an 'ideal urban climate' cannot realistically be achieved. Therefore, applied urban climatology has to indicate how this ideal situation can be approached by planning measures in order to minimize climatic stress for human beings. The final objective is to get a 'tolerable urban climate'.

Methods for human biometeorologically relevant assessment of urban climate

Thermal component of urban climate

Predicted Mean Vote. The thermal component of the urban climate includes all energy fluxes occurring in the urban area[19]. In modern human biometeorology, assessing the thermal component of urban climate, in particular the thermal comfort of humans in a thermo-physiologically significant manner, means the interpretation of the human energy balance equation with its energy fluxes and physiological parameters. Nowadays, one of the most popular models is Fanger's 'comfort equation' for indoor climate[4], which allows the calculation of the so-called 'Predicted Mean Vote' (PMV). PMV predicts the mean assessment of the thermal environment for a large sample of human beings by a value according to the seven-step Ashrae comfort scale (table 1).

Table 1. Classification of PMV values for assessment of the thermal environment by a collective of human beings according to the seven-step ASHRAE psychophysical voting scale[4]

PMV values	Human sensations
−3	Cold
−2	Cool
−1	Slightly cool
0	Comfortable (neutral)
+1	Slightly warm
+2	Warm
+3	Hot

Table 2. Classification of thermal stress on human beings according to ranges of PMV values[14]

Ranges of absolute PMV values	Thermal stress levels
0	No stress
0.1–0.5	Resting range
0.6–1.2	Slight stress
1.3–2.0	Moderate stress
2.1–3.0	Strong stress
3.0	Very strong stress

Jendritzky et al.[14] have extended the comfort equation for application in outdoor conditions by parameterizing short- and long-wave radiative fluxes using readily available meteorological data (so-called 'Klima-Michel-Model', KMM). Based on KMM the derived PMV values enable the assessment of the thermal component of urban climate by a single thermophysiologically significant index. In addition, Jendritzky et al.[14] developed a human biometeorological classification for thermal stress on human beings using PMV values (table 2).

Physiologically equivalent temperature. Mayer and Höppe[26] have shown that it might be useful for urban planners and other people who have less contact with the field of thermophysiology to describe the thermal bioclimate by a measure that can be more easily used than PMV. One of these measures is the physiologically equivalent temperature (PET).

PET is a human biometeorological index which can be calculated from the human energy balance model MEMI (= Munich Energy Balance Model for Individuals) by Höppe[8]. The fundamental idea in the establishment of PET is the transfer of the actual thermal bioclimate to an equivalent fictitious indoor environment in which the same thermal sensation can be expected. PET now can be calculated as the air temperature at which the energy balance for the assumed indoor conditions is balanced by the same mean skin temperature and sweat rate as calculated for the actual outdoor conditions. Thus, for example, almost everybody can characterize indoor thermal conditions with an air temperature of 30 °C, while only experts can interpret as a thermophysiological parameter what a mean skin temperature of 35.7 °C means for somebody walking in a sunny street canyon.

According to its definition and to general experience of thermophysiology, PET values around 20 °C can be characterized as comfortable. Higher PET values indicate increasing probability of heat stress, whereas lower values indicate atmospheric conditions too cool for comfort[26].

Examples. The physiologically relevant assessment of the thermal component of urban climate requires the spatial and temporal analysis of the thermal complex in different urban structures. Some examples are discussed here. Jendritzky and Nübler[15] have analysed the thermal environment in the whole of Freiburg, a small city in the south-west of Germany, by presenting the spatial distribution of PMV values for a daytime and a nighttime situation. Jendritzky and Sievers[16] investigated the thermal conditions in a street canyon by coupling a meteorological boundary-layer model with KMM and calculating the two-dimensional distribution of PMV values for different heights of marginal buildings but at a fixed width of the street. On the basis of KMM, Jendritzky[12] also provided bioclimate charts of different parts of Germany, which are an essential resource for landscape planning. Jendritzky[13] as well as Grätz et al.[6] presented bioclimate charts (heat load) at high resolution (10 m) for the town Waldkirch at the western border of the southern Black Forest. Such information is of great importance for urban planning. In addition, Grätz[5] has investigated a specified area in Waldkirch to show how some aspects of urban planning (table 3) influence wind velocity, air temperature, mean radiation temperature and PMV as measures of heat stress. Compared to the original land use as 'grassland', the results show (fig. 1) higher PMV values for each of the four variants because the wind velocity is always lower. Variant 4 is most beneficial for human beings. Interdispersed treestock causes a comparatively low value of mean radiation temperature, which leads to a low PMV value.

Höppe and Mayer[11] as well as Mayer and Höppe[26] have assessed the thermal conditions during daytime in

Table 3. Data for the investigation on human biometeorological effects of planning alternatives related to a specified area in Waldkirch[5]

Original land use:	Grassland
Variant 1:	Total built-up area: 50% Area of houses: 32% Height of houses: 18 m House density: 0.000413 houses/m^2
Variant 2:	Total built-up area: 36% Area of houses: 28% Height of houses: 15 m House density: 0.000221 houses/m^2
Variant 3:	Like variant 2 but with facade greenery
Variant 4:	Like variant 2 but with interdispersed treestock

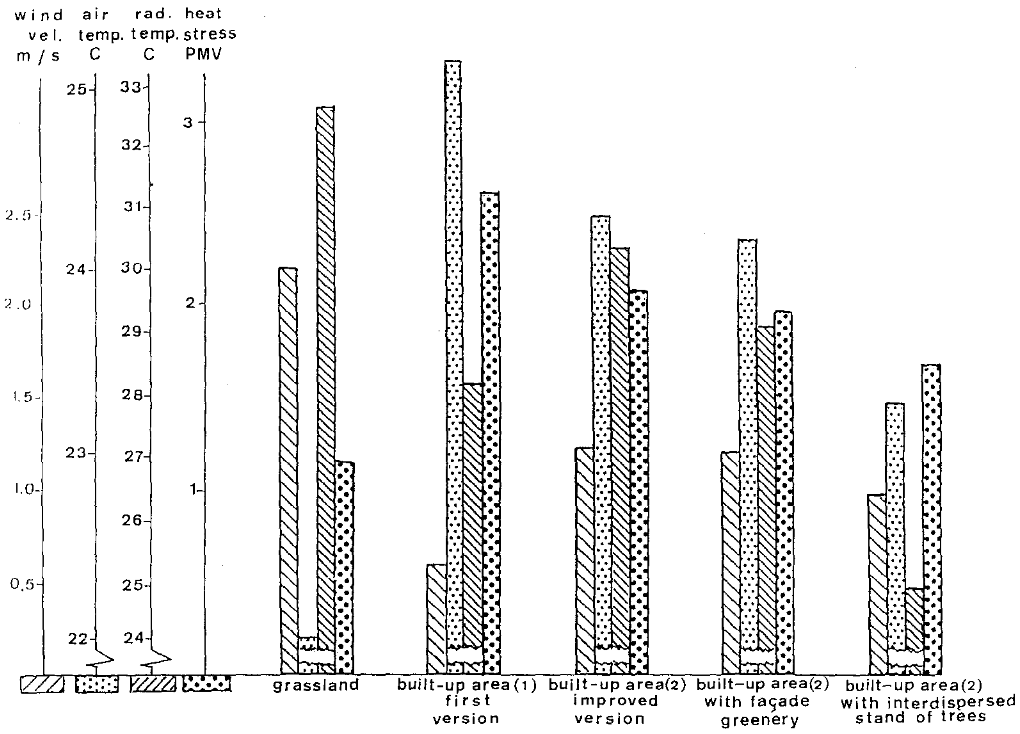

Figure 1. Human biometeorological effects of planning variants, illustrated by the example of Waldkirch[5].

different urban structures in Munich using PMV and PET values. Matzarakis and Mayer[22] calculated PMV and PET values in order to analyse the very high thermal stress on human beings during an extreme heat wave in Athens in July 1987. In this period, the highest daily maxima of air temperature were between 35.0 °C and 43.6 °C. At these times PMV ranged between 5.4 and 7.2, while PET was between 49.0 °C and 57.8 °C. Koch et al.[18] have discussed long-term variations in different stages of thermal comfort in Vienna since 1873. They applied the Human Energy Balance Model (EBM) which hardly differs from MEMI and used a homogeneous set of meteorological data from Vienna. As an example of the diurnal variations of PMV and PET on a hot summer day in different urban structures, some results of Höppe and Mayer[11] shall be presented more comprehensively. On August 13th, 1985 they performed appropriate meteorological measurements simultaneously at three different sites in Munich, and, in comparison, in the trunk space of a nearby tall spruce forest. The three measuring sites within Munich are situated close to each other. The direction of both streets is N-S, the width of their asphalt roadways is 22.5 m, the width of their granite sidewalks is 7.5 m. The height of the marginal buildings is about 25 m on the east side and about 19 m on the west side. One of the streets is lined on both sides with poplar trees (*Populus nigra 'Italica'*) which are about 18 m in height. Meteorological measurements were taken at the eastern sidewalk. The open space is circular in form with a diameter of 124 m. It lies about 200 m north of the site 'street without trees' and about 200 m south of the site 'street with trees'. The large street between these sites crosses the centre of the open space. The meteorological measurements were performed on the sidewalk of granite at the eastern centre of the open space. The tall spruce forest has a stand height of about 35 m, and a trunk space up to 17 m above the forest floor. The stem density is about 500 per ha. The measuring height was always 1.1 m above ground, which corresponds to the average height of the centre of gravity for adults.

The diurnal courses of air temperature T_a (fig. 2) at the four sites characterize the hot weather during the measuring day. The smallest values of T_a were recorded during the day in the trunk space of the spruce forest (abbreviated SP). The highest values of T_a were measured in the afternoon in the street without trees (SOT). In the late afternoon, the values of T_a in the street with trees (SWT) were smaller than in SOT. Apart from that no marked differences in the behaviour of T_a between the three urban sites can be determined. The results of the equivalent temperature T_{eq}, which has been used in earlier works as a bioclimatic index for thermal comfort of human beings, lead to the assumption that the thermal comfort conditions are nearly the same at the four sites (fig. 3). Based on KMM and MEMI, however, the investigations show clear differences in thermal comfort between the four sites (figs. 4–6). Therefore, an analysis of thermal comfort by use of T_{eq} is inadequate because T_{eq} is not a thermophysiologically significant index.

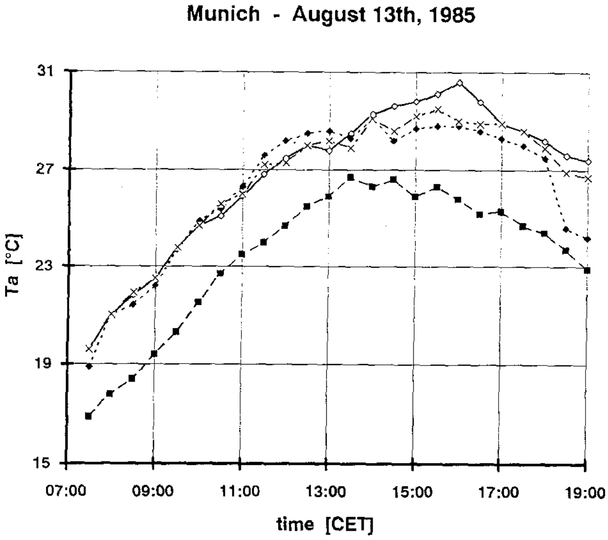

Figure 2. Air temperature T_a at three urban structures in Munich and in the trunk space of a nearby tall spruce forest on a hot summer day (modified according to Höppe and Mayer[11]). —◇— street (N-S) without trees, ---◆--- street (N-S) with trees, —×— open space, --■-- tall spruce forest.

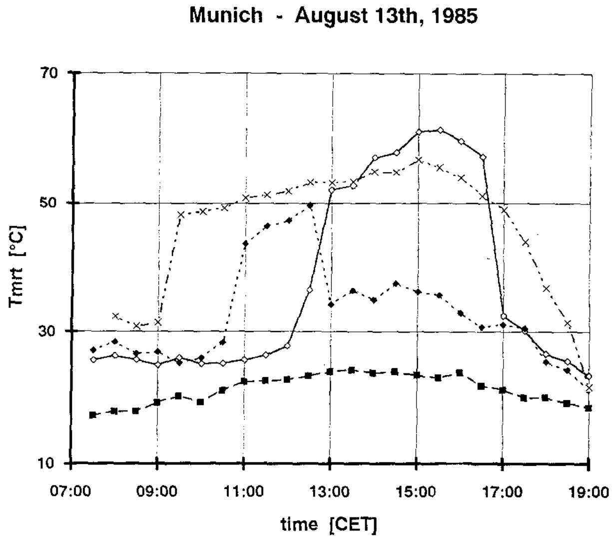

Figure 4. Mean radiation temperature T_{mrt} at three urban structures in Munich and in the trunk space of a nearby tall spruce forest on a hot summer day (modified according to Höppe and Mayer[11]). —◇— street (N-S) without trees, ---◆--- street (N-S) with trees, —×— open space, --■-- tall spruce forest.

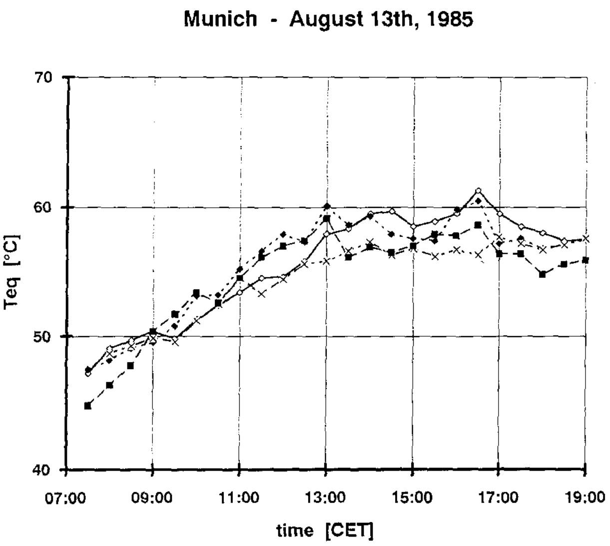

Figure 3. Equivalent temperature T_{eq} at three urban structures in Munich and in the trunk space of a nearby tall spruce forest on a hot summer day (modified according to Höppe and Mayer[11]). —◇— street (N-S) without trees, ---◆--- street (N-S) with trees, —×— open space, --■-- tall spruce forest.

The diurnal course of the mean radiation temperature T_{mrt} is presented in figure 4. T_{mrt} is a suitable measure for the heat stress on the human organism due to the effect of the radiation from the whole surrounding sphere. Estimation of T_{mrt} for outdoor conditions is explained in detail by Höppe[10] and Jendritzky et al.[14]. Related to a standing human being the results for T_{mrt} show some special features. The smallest values of T_{mrt} have been calculated for SP. T_{mrt} clearly increased or decreased at the three urban sites, when the sun appeared beyond or disappeared behind the horizon which was influenced differently by local buildings. SOT has the highest values of T_{mrt} occurring in the late afternoon because the measuring site on the eastern sidewalk receives comparatively large amounts of short-wave radiation reflected and long-wave radiation emitted by the marginal building. The diurnal course of T_{mrt} at SWT is of great interest at noon, as it shows the remarkable decrease of T_{mrt} due to the shading effect of the poplars' crowns on the direct solar radiation. The measuring site at the open space (OS) shows almost a steady diurnal course at T_{mrt} with higher T_{mrt} values than at SWT but lower T_{mrt} values in the afternoon than at SOT.

The results for the thermophysiologically significant terms PMV and PET are shown in figures 5 and 6. The diurnal courses of PMV and PET on that hot day are very similar to the diurnal course of T_{mrt}. Therefore, they reveal near thermal comfort for human beings in SP, whereas different heat loads are characterized for the investigated urban sites. It can also be seen for SWT in contrast to SOT that the shading of direct solar radiation markedly reduces heat load for human beings. There are some practical possibilities for the shading of direct solar radiation. From the point of view of human biometeorology, the best is vital deciduous trees with crowns as large as possible.

Air pollution component of urban climate

General aspects. In some climate regions, e.g. parts of Central Europe, the air quality component of the urban climate is of greater importance than the thermal component, because

- stress on human beings due to air pollution occurs during the whole year, even if the significance of

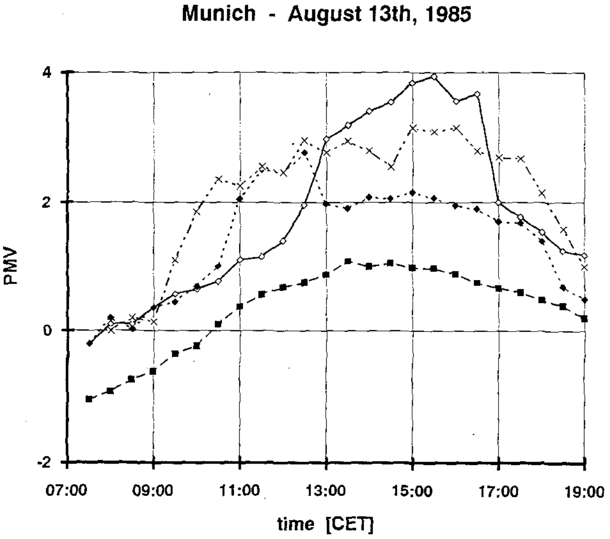

Figure 5. Predicted Mean Vote (PMV) at three urban structures in Munich and in the trunk space of a nearby tall spruce forest on a hot summer day (modified according to Höppe and Mayer[11]). —◇— street (N-S) without trees, ---◆--- street (N-S) with trees, —×— open space, —■— tall spruce forest.

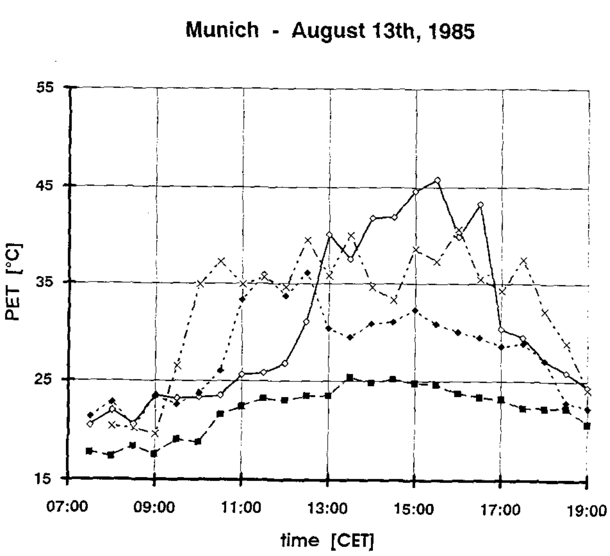

Figure 6. Physiologically equivalent temperature (PET) at three urban structures in Munich and in the trunk space of a nearby tall spruce forest on a hot summer day (modified according to Höppe and Mayer[11]). —◇— street (N-S) without trees, ---◆--- street (N-S) with trees, —×— open space, —■— tall spruce forest.

individual air pollutants is variable over a year (e.g. NO_2 in winter, O_3 as key substance of photooxidants in summer) and

- air pollutants can be found everywhere, so no individual protective measure is possible for human beings (whereas a decrease in thermal load can be achieved by going from a sunny to a shaded sidewalk or reducing the heat resistance of clothing).

The assessment of air pollution in urban structures is focused on the question of how intensely the urban microclimates are loaded with air pollutants[27]. For urban planning, a measure of air quality of the atmosphere must be found which can be evaluated by guide numbers or standards. Air pollutants recorded at air quality monitoring stations, which are typical of the source groups 'motor-traffic', 'industry', 'power stations', 'trade' and 'domestic fuel', provide baseline data. The components sulphur dioxide (SO_2), nitrogen monoxide (NO), nitrogen dioxide (NO_2), carbon monoxide (CO), ozone (O_3) and total suspended dust (TSD) are mostly measured at well-equipped air quality stations. It is possible that some other air pollutants such as hydrocarbons may become more significant[20] resulting in their routine recording in air quality monitoring networks.

The atmospheric concentration of primary air pollutants, e.g. NO or CO, will be directly proportional to the rate of emission but, of course, will also be dependent on the atmospheric processes of transport, dilution, and removal. A comparison of emission and pollution by primary air pollutants thus provides a means for establishing the relative importance of these atmospheric processes in the different urban microclimates that modify the local concentrations.

Besides primary air pollutants, an equal or greater health hazard is presented by the photochemical pollutants, e.g. O_3, which, as their name implies, are compounds formed by chemical reactions stimulated by short-wave radiation, the reacting compounds being the primary or precursor pollutants[21]. While an increase in emission of precursor compounds can be expected to result in an eventual increase in photochemical air pollutants, chemical reactions take time, and reaction rates are sensitive to air temperature and the relative concentration of reactants. Thus, the relation between emission rates and photochemical levels is much less direct than for primary air pollutants.

Standards for the assessment of air pollution. For the effects of air pollutants, their concentration and dose as well as the individual disposition of human beings are the determining factors. The human biometeorological evaluation of air pollution conditions in urban structures is complex, because

- it is not one single air pollutant but a great number of air pollutants that have an effect on human beings at the same time[31],
- human beings are mobile,
- air pollutants from motor traffic and their photochemical reaction products reveal a great spatial variation within urban structures due to different traffic densities[7].

Values for the assessment of air pollution conditions are based on results of epidemiological investigations, experience in the field of working medicine, and findings from animal experiments. One has to bear in mind that

Table 4. Standards for concentrations of O_3 in the air given by the European Community[3]

- Standard for health protection (long-term exposure): 110 μg/m³ as mean value during 8 h
- Standards for protection of vegetation: 200 μg/m³ as mean value during 1 h; 65 μg/m³ as mean value during 24 h
- Standard for activation of warnng system for health protection (short exposition time): 180 μg/m³ as mean value during 1 h

Table 5. Yearly assessment value I1 (in μg/m³) and short-term assessment value I2 (in μg/m³) for concentrations of the air pollutants SO_2, NO_2 and total suspended dust (=TSD) used in Germany (according to the standards of the '*TA Luft*' and the *Guidelines of the European Community*)

Air pollutant	TA Luft		European Community	
	I1	I2	I1	I2
SO_2	140	400	50	125
NO_2	80	200	50	135
TSD	150	300	50	120

these guide numbers ensure only a collective protection, not protection for a single human being. That means a residual risk cannot be excluded, due to the great variability of human responses.

Nearly every country has standards for the assessment of air quality conditions (see Kallaste[17]). The European Community[3] has laid down guidelines including long-term provisions for sulphur dioxide and total suspended dust, lead content, nitrogen dioxide and ozone (see table 4 for ozone), which are important for the protection of human health.

Furthermore, other standards exist for estimating the levels of air pollution[29]. These standards are related, for example, to periods of smog in winter, forests, health resorts or to the general health of people.

Human biometeorological assessment of air pollution in urban areas. In principle, the human biometeorological assessment of air quality should take into consideration carcinogenic and non-carcinogenic substances in the atmosphere. In relation to urban planning it is often sufficient to determine the load of the atmosphere due to air pollution from non-carcinogenic substances only[29]. Independent of the evaluation of individual air pollutants, it is appropriate to apply an air quality stress index (AQSI), which considers some air pollutants and their standards[1]. AQSI combines measured concentrations of air pollutants with assessment criteria.

The calculation of AQSI should include the components SO_2, NO_2, and total suspended dust, which are representative for different source groups of air pollution, and therefore reflect the different kinds of air pollutants in the urban atmosphere. In general, these components are also recorded at air quality monitoring stations. Their summing up is consistent with the real effect of these components on human beings.

AQSI can be calculated for the assessment of average and short-term loads by air pollution. $AQSI_a$ is given for average air quality conditions by:

$$AQSI_a = 1/3 * \sum_{i=1}^{3} \frac{Ia(i)}{I1(i)} \qquad (1)$$

with Ia(i): yearly average of concentration of air pollutant i

I1(i): yearly standard of air pollutant i

$AQSI_s$ is given for short-term air quality conditions by

$$AQSI_s = 1/3 * \sum_{i=1}^{3} \frac{I98(i)}{I2(i)} \qquad (2)$$

with I98(i): 98%-value of the sum frequency of concentrations of air pollutant i

I2(i): short-term standard of air pollutant i

The standards in (1) and (2) can be related to the conditions in the urban structure analysed. As an example, table 5 contains assessment criteria which are applied in Germany. For the human biometeorologically significant assessment of air quality conditions, Reuter[28] suggests the gradation in table 6, which is part of the VDI-guideline *Human Biometeorological Assessment of Climate and Air Quality for Urban and Landscape Planning* in Germany.

Illustrative results. There are only a few previous studies assessing air quality conditions in urban structures by the use of AQSI. Baumüller et al.[1] as well as Reuter et al.[29] describe the grid-wise mapping of AQSI in Stuttgart. Matzarakis and Mayer[22] have calculated daily average values of AQSI for the period of the extreme heat wave in Athens in July 1987. They have extended the determination of AQSI by a fourth air pollutant and considered NO_2, O_3, CO and TSD, because these air pollution data are typical of the air conditions in summer in Athens. As assessment criteria of air pollution they used appropriate VDI standards (VDI, 1987). The results for AQSI related to one site in the centre of Athens ranged between 0.5 and 1.3 in the investigation period compared to 0.7 as average value for the whole year of 1987.

On the basis of concentrations of SO_2, CO, NO_2 and TSD, table 7 contains values for $AQSI_a$ and $AQSI_s$, which have been calculated for the sites 'Stachus' (central area) and 'Effnerplatz' (suburban area with comparatively high traffic density) in Munich for the years

Table 6. Human biometeorological assessment of air pollution in urban areas by use of the air quality stress index AQSI[28]

AQSI	Assessment
0.0–0.4	Slightly stressed
0.5–0.8	Moderately stressed
>0.8	Heavily stressed

Table 7. Values of $AQSI_a$ and $AQSI_s$ at the sites 'Stachus' and 'Effnerplatz' in Munich from 1980 to 1988

Year	'Stachus' $AQSI_a$	$AQSI_s$	'Effnerplatz' $AQSI_a$	$AQSI_s$
1980	0.43	0.38	0.35	0.35
1981	0.53	0.43	0.38	0.33
1982	0.60	0.45	0.40	0.38
1983	0.50	0.38	0.40	0.35
1984	0.60	0.40	0.40	0.35
1985	0.33	0.38	0.28	0.43
1986	0.33	0.33	0.25	0.38
1987	0.40	0.38	0.30	0.40
1988	0.35	0.38	0.33	0.35

of 1980 to 1988. Besides year to year variations due to yearly weather variations and changes in emission conditions, the results show higher values of $AQSI_a$ in the central area, whereas $AQSI_s$ has sometimes been higher in the suburban area due to the dense motor traffic.

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