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Article

Air stress and air quality indices

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Abstract

Against the background of the growing demand for indices suited to assess the integral air quality that is not restricted to a single air pollutant, formulations for statistical air stress indices and an impact-related air quality index (DAQx) are presented. Their sensitivity depending on emission and air mass exchange conditions is investigated by test calculations based on air pollution data from three different sites in southwest Germany characterised by different air pollution levels and one site (Szeged) in southern Hungary with a comparatively high air pollution level. The results can be explained by methodical characteristics of the indices and the local emission situation.

Zusammenfassung

Vor dem Hintergrund der steigenden Nachfrage nach Indizes zur Bewertung der integralen Luftqualität, die über die standardmäßige Beurteilung einzelner Luftkomponenten hinausgeht, werden Ansätze für statistische Luftbelastungsindizes und einen wirkungsbezogenen Luftqualitätsindex (DAQx) vorgestellt. Ihre Sensitivität, die von den Emissionsbedingungen und den Austauschverhältnissen abhängt, wird über Testrechnungen für drei Standorte im Südwesten Deutschlands mit unterschiedlichem Emissionseinfluss und einen lufthygienisch belasteten Standort (Szeged) im Süden von Ungarn analysiert. Die Unterschiede in den Resultaten lassen sich über methodische Kennzeichen der berücksichtigten Indizes und die lokale Emissionssituation erklären.

1 Introduction

Many problems concerning environmental meteorology include the evaluation of ambient air pollutants. The normal case is the assessment of single air pollutants. It is based on standards, which exist for single air pollutants in almost every country of the world. However, these standards are insufficient in view of the persistent demands for the assessment of the air quality, which is not limited to a single air pollutant, because people is breathing in ambient air characterised by a mixture of different air pollutants and not by one alone. Examples for these demands are the consideration of air pollution in processes of urban or regional planning, for the environmental qualification of health and recreation resorts as well as the daily information of people in the Internet on the current integral air pollution level.

Therefore, indices for the assessment of the air pollution conditions were recently developed, which meet these demands and represent a supplementation to the normal case. These indices consider frequently monitored air pollutants at long-term stations within official air pollution control networks. They can be categorized into the two groups of air stress indices ASI and air quality indices AQI.

The objectives of this study are (1) the description of the methodology of both index groups, (2) an explanation of specific formulations for ASI and AQI, and (3) a comparative analysis of results from ASI and AQI test calculations for sites with different air pollution conditions.

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2 Methodology

2.1 Air stress indices

In general, air stress indices have the following structure (BAUMÜLLER and REUTER, 1995; FENGER, 1999; KASSOMENOS et al., 1999; SHARMA, 1999):

$$ASI = \sum_{i=1}^{n} \left[\frac{C}{R}\right]_i \tag{2.1}$$

or

$$ASI = \frac{1}{n} \cdot \sum_{i=1}^{n} \left[\frac{C}{R}\right]_i \tag{2.2}$$

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Table 1: Urban land cover related assessment of the air pollution conditions on the basis of ASI_1 and ASI_2 (according to MAYER et al., 2002b).

ASI_1: no single air pollutant exceeds the standard		
ASI_2: no single air pollutant shows a higher number of cases per year with air pollutant specific standards are exceeded than the permitted number		
level I	very low air stress	ASI_1, $ASI_2 < 0.2$
level II	low air stress	$0.2 \leq ASI_1$, $ASI_2 < 0.4$
level III	moderate air stress	$0.4 \leq ASI_1$, $ASI_2 < 0.6$
level IV	distinct air stress	$0.6 \leq ASI_1$, $ASI_2 < 0.8$
level V	strong air stress	ASI_1, $ASI_2 \geq 0.8$
ASI_1: at least one air pollutant exceeds the specific standard		
ASI_2: at least one air pollutant has a higher number of cases per year with air pollutant specific standards are exceeded than the permitted number		
level VI	extreme air stress	independent of ASI_1 and ASI_2

In the case of assessing an average air pollution stress, n is the number of air pollutants considered, C is the mean concentration (mostly over one year) and R is a reference value for the air pollutant i. In the second case of assessing a short-term air pollution stress, C is the annual number of actual exceedences of air pollutant specific standards and R is the corresponding annual number of exceedences permitted in directives or guideline, e.g. of the European Union (EU).

Examples for air stress indices of the type (2.2) are the planning-related air stress index ASI_1 for average air pollution stress and the planning-related air stress index ASI_2 for short-term air pollution stress both developed by the Office for Environmental Protection, Urban Climatology Section, City of Stuttgart, Germany (MAYER et al., 2002b):

$$ASI_1 = \frac{1}{4} \cdot \left(\frac{C(SO_2)}{20\mu g/m^3} + \frac{C(NO_2)}{40\mu g/m^3} + \frac{C(PM_{10})}{40\mu g/m^3} + \frac{C(benzene)}{5\mu g/m^3} \right) \quad (2.3)$$

$$ASI_2 = \frac{1}{4} \cdot \left(\frac{N(SO_2)}{24} + \frac{N(NO_2)}{18} + \frac{N(PM_{10})}{35} + \frac{N(CO)}{1} \right) \quad (2.4)$$

In Eq. (2.3) C values are the arithmetic annual means of the four air pollutants, while the long-term air pollutant specific standards of the EU serve as reference (denominator). In Eq. (2.4) N is the annual number of actual exceedences of air pollutant specific short-term EU standards and the denominator values are the corresponding annual number of exceedences permitted by the EU. As the secondary air pollutant ozone (O_3) can be hardly influenced by planning methods, it is not considered in Eqs. (2.3) and (2.4). Compared to Eq. (2.4), CO is not included in Eq. (2.3) because a corresponding EU standard is not available. Therefore, the approach for ASI_1 contains benzene. For the application of ASI_1 and ASI_2, a graded assessment scale was developed with respect to urban land covers (Table 1).

Compared to ASI_1 and ASI_2, the daily air stress index ASI_{BW} developed by the Federal State Institute for Environmental Protection Baden-Wuerttemberg (Karlsruhe, Germany) for the continuous information of people is of the type (2.1) and includes O_3 due to its changed purpose (MAYER et al., 2002b):

$$ASI_{BW} = \frac{C(SO_2)}{350\mu g/m^3} + \frac{C(CO)}{10mg/m^3} + \frac{C(NO_2)}{200\mu g/m^3} + \frac{C(O_3)}{180\mu g/m^3} + \frac{C(PM_{10})}{50\mu g/m^3} \quad (2.5)$$

In Eq. (2.5) $C(SO_2)$, $C(NO_2)$ and $C(O_3)$ are the air pollutant specific highest daily 1-h mean values ($\mu g/m^3$), C(CO) is the highest daily running 8-h mean value (mg/m^3) of CO and $C(PM_{10})$ is the daily mean value ($\mu g/m^3$) of PM_{10}. The reference values of Eq. (2.5) are temporally corresponding EU standards.

2.2 Air quality indices

Impact-related air quality indices are very rare, because it is difficult to quantify the impacts of a mixture of air pollutants, which is typical of the ambient air, on well-being and health of people in a graded way. Examples for such indices are the EPA air quality index AQI (EPA, 1999) and the daily air quality index DAQx, which was recently developed and tested by the Research and Advisory Institute for Hazardous Substances, Freiburg, Germany, and the Meteorological Institute, University of Freiburg, Germany (MAYER et al., 2002a, 2002b). The background for the development of DAQx has been the requirement for an impact-related index applicable for the information of people in the Internet on the daily integral air quality.

Table 2: Assignment of ranges of specific air pollutant concentrations to DAQx values and DAQx classes inclusive of classification names (according to MAYER et al., 2002a, b).

NO_2 ($\mu g/m^3$)	SO_2 ($\mu g/m^3$)	CO (mg/m^3)	O_3 ($\mu g/m^3$)	PM_{10} ($\mu g/m^3$)	DAQx value	DAQ class	classification
0–24	0–24	0.0–0.9	0– 32	0.0–9.9	≤1.4	1	very good
25–49	25–49	1.0–1.9	33–64	10.0–19.9	1.5–2.4	2	good
50–99	50–119	2.0–3.9	65–119	20.0–34.9	2.5–3.4	3	satisfying
100–199	120–349	4.0–9.9	120–179	35.0–49.9	3.5–4.4	4	sufficient
200–499	350–999	10.0–29.9	180–239	50.0–99.9	4.5–5.4	5	poor
≥ 500	≥ 1000	≥ 30.0	≥ 240	≥ 100	≥ 5.5	6	very poor

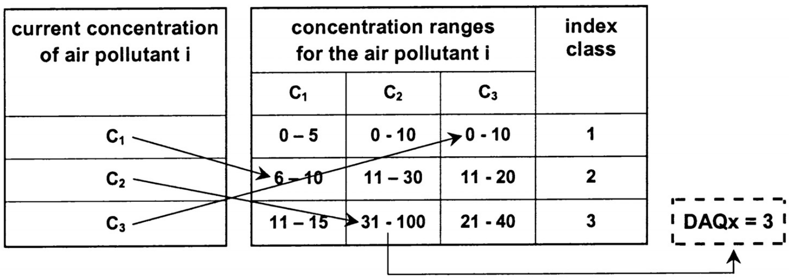

Figure 1: Schematic explanation of the method to determine DAQx.

The methodology of DAQx is to assign concentrations of ambient air pollutants to different pollutant specific ranges, which correspond to six index classes (Fig. 1). The highest single index class among the air pollutants considered represents DAQx itself. The relation to the impact on well-being and health of people is given by the differently classified ranges of air pollutant concentrations (Table 2), which were derived from numerous epidemiological and toxicological investigations. For practical purposes the second highest air pollutant specific index class can extend the information on the air pollutants, which affect people strongest.

DAQx considers the same air pollutants as ASI_{BW} (NO_2, SO_2, CO, O_3 and PM_{10}). To enable a linear interpolation between single index classes, DAQx is calculated for each air pollutant – according to the EPA index AQI – by:

$$DAQx = \left[\left(\frac{DAQx_{up} - DAQx_{low}}{C_{up} - C_{low}}\right) \cdot (C_{inst.} - C_{low})\right] + DAQx_{low} \quad (2.6)$$

where

$C_{inst.}$: daily maximum 1-h concentration of NO_2, SO_2, and O_3, daily highest 8-h running mean concentration of CO or daily mean concentration of PM_{10},

C_{up}: upper threshold of specific air pollutant concentration range (Table 2),

C_{low}: lower threshold of specific air pollutant concentration range,

$DAQx_{up}$: index value corresponding to C_{up},

$DAQx_{up}$: index value corresponding to C_{low}.

An example is given to explain the approach (2.6). A daily maximum 1-h O_3 concentration of 110 μg/m^3 leads to the following DAQx value:

$$DAQx = \left[\left(\frac{3.4 - 2.5}{119 - 65}\right) \cdot (110 - 65)\right] + 2.5 = 3.3 \quad (2.7)$$

The major distinctions between air stress indices in the form of Eqs. (2.3) to (2.5) and air quality indices in the form of Eq. (2.6) are: (i) The method of air stress indices is based on an arithmetic summation of relative concentrations of air pollutants resp. relative numbers of exceedences of air pollutant specific short-term standards. The only reference to human health is given by the air pollutant specific limit values, but there are no results in the field of environmental medicine, which give reasons for an arithmetic summation. (ii) Air quality indices contain a distinct relation to the impact of single air pollutants on people by the ranges of their concentrations, which differ significantly between single air pollutants. For the DAQx class 5, the values of $DAQx_{low}$ correspond to the air pollutant specific EU standards. (iii) Air quality indices have not the form of an arithmetic summation, as the highest DAQx class determined for a single air pollutant governs the resulting DAQx class.

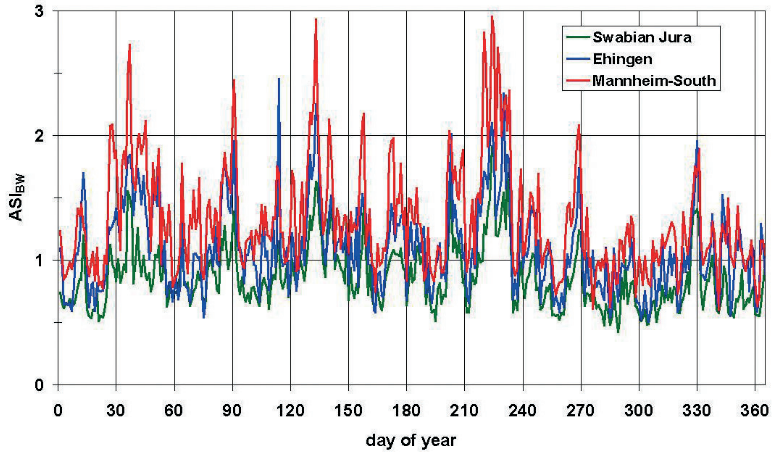

Figure 2: Daily ASI_{BW} values at three official air quality monitoring stations in southwest Germany in the year 1998.

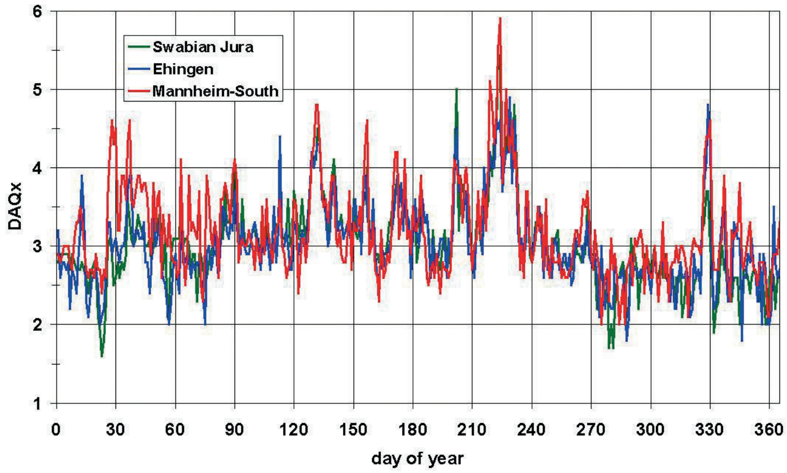

Figure 3: Daily DAQx values at three official air quality monitoring stations in southwest Germany in the year 1998.

Table 3: Assignment of ASI_{BW} ranges to ASI_{BW} classes.

ASI_{BW} class	*ASI_{BW} range*
I	$ASI_{BW} < 0.5$
II	$0.5 \leq ASI_{BW} < 1.1$
III	$1.1 \leq ASI_{BW} < 1.7$
IV	$1.7 \leq ASI_{BW} < 2.3$
V	$2.3 \leq ASI_{BW} < 2.9$
VI	$ASI_{BW} \geq 2.9$

3 Air pollution data

Test calculations were carried out to investigate the consequences on the assessment of the air pollution situation due to different methods for the determination of air stress and air quality indices. With respect to the last group, the behaviour of DAQx should be analysed because it was not systematically investigated before. Taking into consideration the timescale of DAQx, ASI_{BW} turned out to be the most suited air stress index of the formulations discussed before.

Air pollution data to calculate ASI_{BW} and DAQx originate from three official air quality monitoring stations in Baden-Wuerttemberg, a state in southwest Germany: Swabian Jura (799 m a.s.l., far from strong emissions on an agricultural plateau), Ehingen (530 m a.s.l., medium-sized city, 24.000 residents, with through traffic and industrial parks), and Mannheim-South (95 m a.s.l., larger city (325.000 residents) with high traffic and stronger industry emissions, which are typical of urban conurbations).

For comparison, air pollution data from Szeged, the largest city (79 m a.s.l., 155.000 residents) at the southeastern plain of Hungary, were used. The total urban

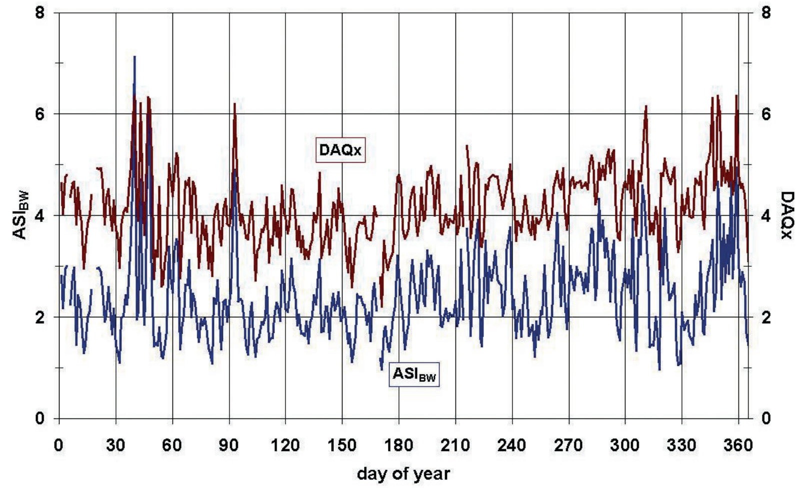

Figure 4: Daily ASI_{BW} and DAQx values at an official air quality monitoring station in Szeged, Hungary, in the year 2001.

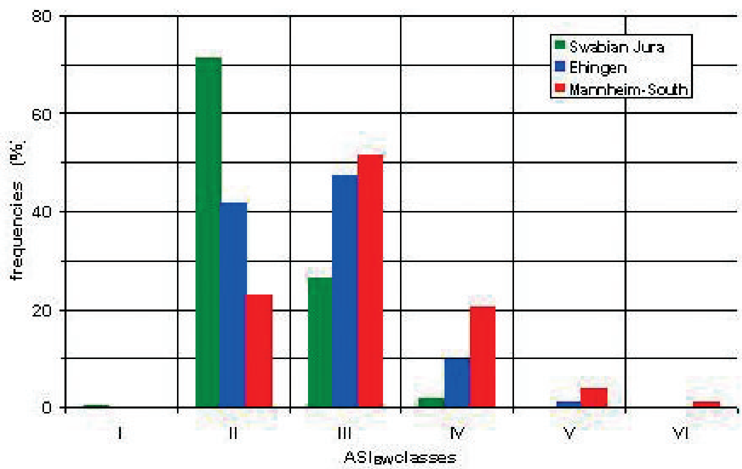

Figure 5: Frequencies of ASI_{BW} classes based on daily ASI_{BW} values at three official air quality monitoring stations in southwest Germany in the period 1996–1998.

spread extends well beyond the city limits and includes north of the town the largest oil field in Hungary with several oil torches. This oil field is a significant source of NO_x and SO_2. The power station, located in the western part of the town, and motor vehicle emissions have contributed to a comparatively high air pollution level in Szeged. The methods to monitor the air pollution at Szeged are approximately comparable with those at the selected air quality monitoring stations in Baden-Wuerttemberg.

4 Results

4.1 Annual courses of daily ASI_{BW} and DAQx values

Annual courses of daily ASI_{BW} and DAQx values calculated for the three official air quality monitoring stations in the state of Baden-Wuerttemberg in the year 1998 are analysed as examples of general annual cycles. The results for ASI_{BW} (Fig. 2) can be summarised as follows: (1) Different dispersion conditions caused by varying weather situations lead to a non-systematic variability of daily ASI_{BW} values. (2) Highest daily ASI_{BW} values occurr most frequently at the site with heaviest emissions (Mannheim-South), while lowest daily ASI_{BW} values are determined for the site far from emissions (Swabian Jura). Mean ASI_{BW} values amount to 0.86 at Swabian Jura, 1.09 at Ehingen and 1.32 at Mannheim-South. This behaviour corresponds to the customary expectations of people. (3) A distinct annual course of ASI_{BW} can not be found due to the annual behaviour of the specific air pollutants included in ASI_{BW}. (4) The annual variability of the daily ASI_{BW} values indicated by the standard deviation σ is highest at Mannheim-South (0.43) followed

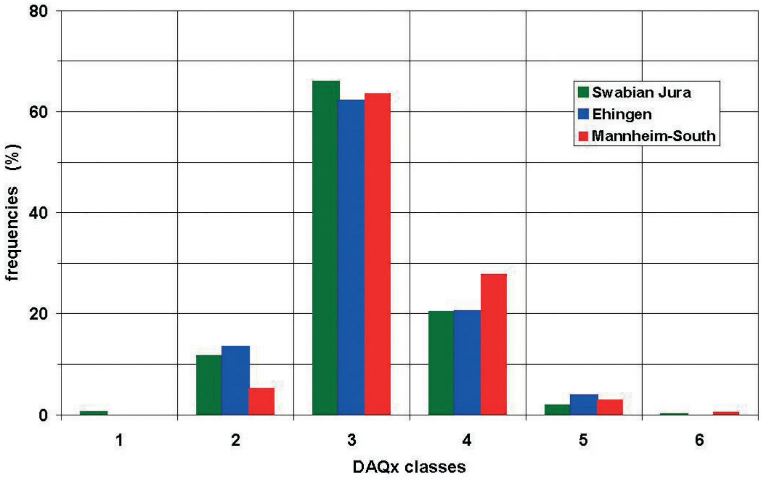

Figure 6: Frequencies of DAQx classes based on daily DAQx values at three official air quality monitoring stations in southwest Germany in the period 1996–1998.

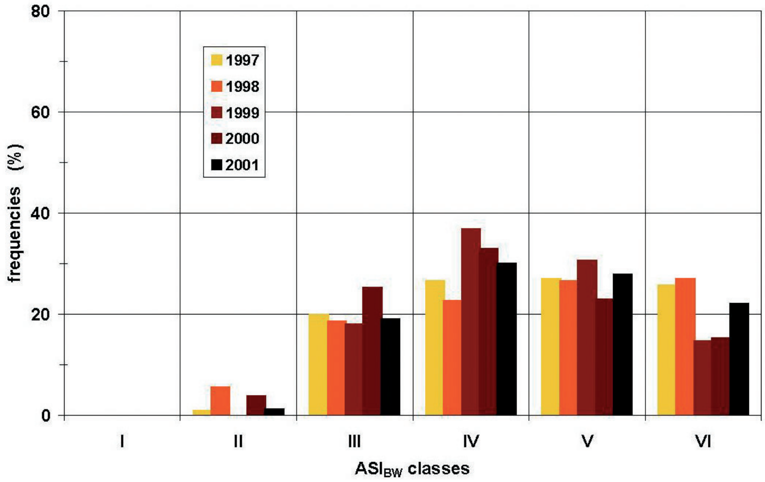

Figure 7: Frequencies of ASI_{BW} classes based on daily ASI_{BW} values at an official air quality monitoring station in Szeged, Hungary, in the period 1997–2001.

by Ehingen (0.35) and lowest at Swabian Jura (0.26).

The annual course of daily DAQx values in the year 1998 can be characterised by (Fig. 3): (1) A tendency of a slightly pronounced annual cycle can be detected with a maximum in August caused by high-pressure weather over several days. (2) Though the ranges of ASI_{BW} and DAQx are not comparable, the fluctuations of DAQx values from day to day become more evident. (3) The distinct increase of daily ASI_{BW} values from emission-related background to large cities conditions is not continuously reflected by the daily DAQx values. The main reason for this specific behaviour of both indices lies in their different methods, particularly in the air pollutant specific differentiation of DAQx. (4) Mean DAQx values amount to 3.02 at Ehingen, 3.03 at Swabian Jura and 3.19 at Mannheim-South. (5) The annual variability of the daily DAQx values determined by the standard deviation σ is highest at Mannheim (0.60) followed by Swabian Jura (0.55) and lowest at Ehingen (0.54)

Compared to the emission conditions at the three sites in Baden-Wuerttemberg, the elevated air pollution level at Szeged is reflected by relatively higher daily values of ASI_{BW} and DAQx (Fig. 4) as well as higher mean values of ASI_{BW} (2.41) and DAQx (4.19) in the year 2001, which has been used due to a better availability of air pollution data. As in Figs. 2 and 3, daily ASI_{BW} values at Szeged are lower than daily DAQx values but it must be taken into account that (1) the formulations of ASI_{BW} and DAQx are quite different and (2) a graded assessment scale for ASI_{BW} was not developed up to now. In contrast to the German sites, the σ value for ASI_{BW} (0.85) is higher than for DAQx (0.72) due to the more pronounced annual variability of the daily ASI_{BW} values at Szeged.

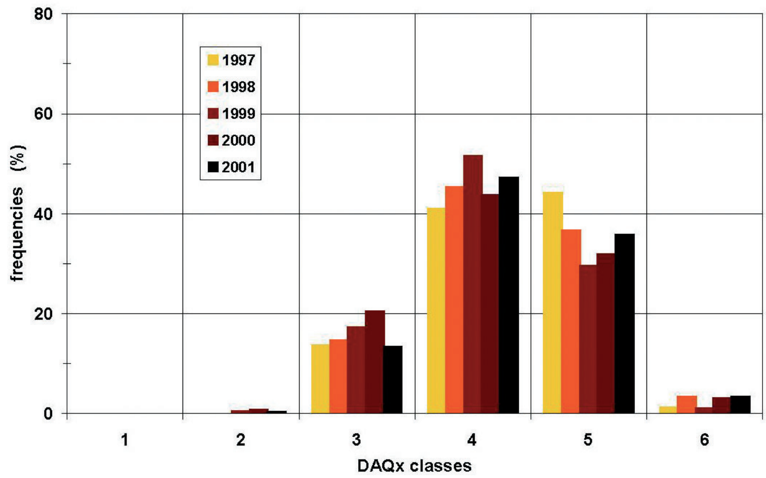

Figure 8: Frequencies of DAQx classes based on daily DAQx values at an official air quality monitoring station in Szeged, Hungary, in the period 1997–2001.

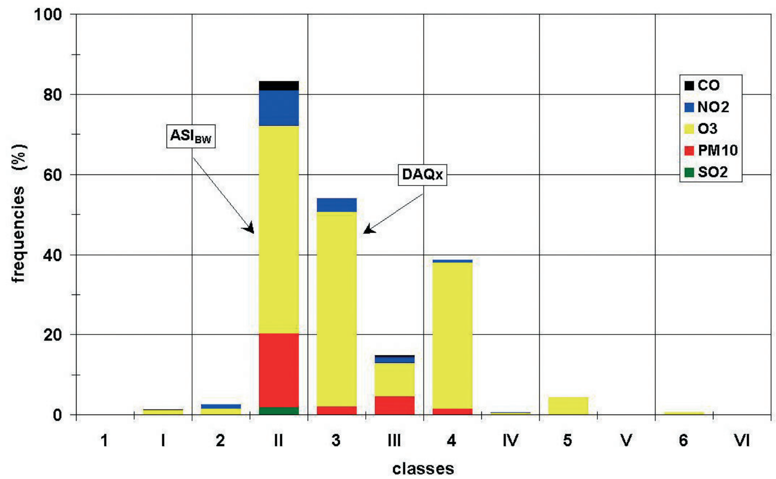

Figure 9: Comparative air pollutant related frequencies of DAQx (Arabic numerals) and ASI_{BW} (Roman numerals) classes based on daily DAQx and ASI_{BW} values at the official air quality monitoring station Swabian Jura, southwest Germany, in the year 1998.

4.2 Frequency distributions of daily ASI_{BW} and DAQx values

To get summarised information on differences in assessing the integral air pollution conditions, frequency distributions of daily ASI_{BW} and DAQx classes were determined for a longer period than one year. It covers the three years from 1996 to 1998 for the three sites in Baden-Wuerttemberg and the five years from 1997 to 2001 at Szeged. Since ASI_{BW} has an indirect relation to the impact on people at most, six ASI_{BW}-classes (no air pollution stress: class I, highest air pollution stress: class VI) were statistically defined on the basis of daily ASI_{BW} values calculated in this investigation (Table 3).

Comparing the results for ASI_{BW} (Fig. 5) and DAQx (Fig. 6) at the German sites, the forms of both frequency distributions differ at first sight. With respect to the daily ASI_{BW} values, it reflects the qualitative assessment of the air pollution conditions by people so far, i.e., air pollution decreases with increasing distance to emission sources. O_3, which exhibits generally higher values in areas with no direct anthropogenic emissions, is mainly responsible for the changed form of the frequency distributions of the DAQx classes. The dominating frequency maximum lies in the DAQx class 3 (satisfying) and does not show significant differences between the three sites of varying emission characteristic (Swabian Jura: 66 %, Mannheim-South: 64 %, Ehingen: 62 %). Based on air pollution data over the period 1995 to 2002, ROST and MAYER (2004) extended the sensitivity studies for DAQx to 12 air quality stations in Baden-Wuerttemberg. Their results confirmed the pro-

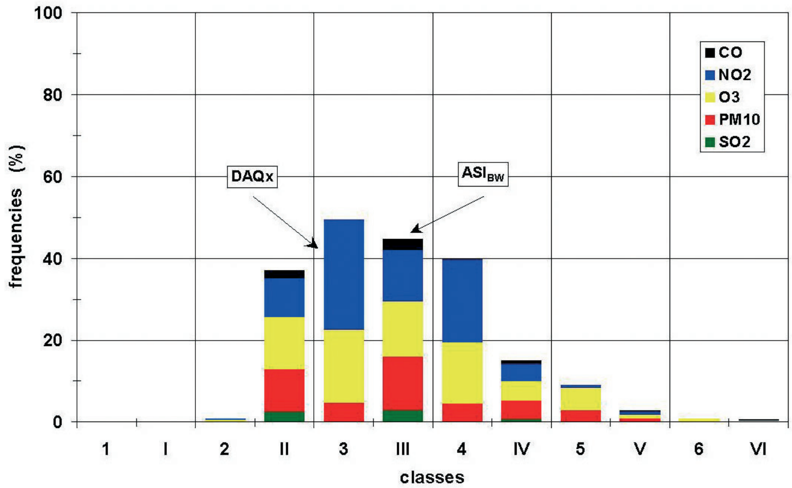

Figure 10: Comparative air pollutant related frequencies of DAQx (Arabic numerals) and ASI_{BW} (Roman numerals) classes based on daily DAQx and ASI_{BW} values at the official air quality monitoring station Mannheim-South, southwest Germany, in the year 1998.

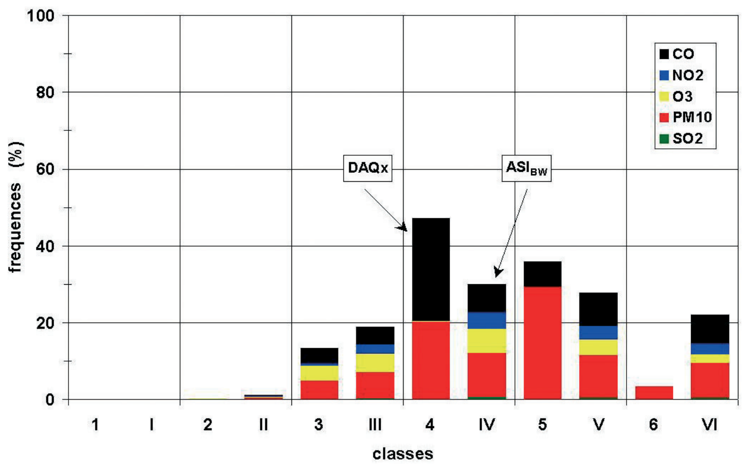

Figure 11: Comparative air pollutant related frequencies of DAQx (Arabic numerals) and ASI_{BW} classes (Roman numerals) based on daily DAQx and ASI_{BW} values at the official air quality monitoring station Szeged, Hungary, in the year 2001.

nounced frequency maximum of the daily DAQx values in class 3 as in Fig. 6.

The frequency distributions of ASI_{BW} (Fig. 7) and DAQx (Fig. 8) at Szeged exhibit a distinctly wider form than at the German sites, particularly with respect to ASI_{BW}. Therefore, the peak frequencies reach lower values. In addition, they shift to higher ASI_{BW} and DAQx classes due to the elevated air pollution level in Szeged. CO and PM_{10} are mainly responsible for the changed form of the frequencies of DAQx classes. Though the varying emission and air mass exchange conditions cause slightly different frequency distributions of ASI_{BW} and DAQx from year to year, a change of the ranking of the class specific frequency amounts can be hardly observed at Szeged during the investigation period. With the exception of the year 1997 where the peak frequency of 44 % lies in class 5 (poor), the highest frequencies of daily DAQx values (1998: 45 %, 1999: 52 %, 2000: 44 %, 2001: 47 %) are determined for class 4 (sufficient).

4.3 Significance of single air pollutants with respect to ASI_{BW} and DAQx

The results in Figs. 5 to 8 do not contain any information on the significance of single air pollutants in the class related frequencies of ASI_{BW} and DAQx. Therefore, further analyses were carried out for the sites Swabian Jura and Mannheim-South (year 1998) as well as Szeged (year 2001) to get an impression on the role of single air pollutants in dependence on site specific emission conditions. The results for the sites Swabian Jura (Fig. 9), Mannheim-South (Fig. 10) and Szeged (Fig. 11) can be summarised as follows: (1) At the site Swabian Jura, which is far from strong emissions, O_3 dominates within each ASI_{BW} resp. DAQx class prior to PM_{10}. (2) At the site Mannheim-South, characterised by traffic and industrial emissions typical of urban conurbations, O_3 has the highest portion in each ASI_{BW} class followed directly by PM_{10} and NO_2 with, however, only slight differences between both air pollutants. With respect to DAQx, NO_2 dominates the classes 3 and 4 prior to O_3 and PM_{10}, whereas O_3 is the dominant air pollutant in class 5 followed by PM_{10}. (3) At the site Szeged, with a comparatively more elevated air pollution ground level than at Mannheim-South, PM_{10} is the most significant air pollutant in all ASI_{BW} classes prior to CO in the ASI_{BW} classes IV, V and VI resp. O_3 in the ASI_{BW} class III. The DAQx classes 3, 5 and 6 are dominated by PM_{10} followed by CO, whereas this air pollutant is most relevant in the DAQx class 4 prior to PM_{10}. (4) Compared to both German sites in the year 1998, NO_2 plays a secondary role for the assessment of the air pollution conditions in Szeged in the year 2001.

5 Discussion and concluding remarks

In addition to the normal case of the evaluation of single air pollutants by standards, air stress and air quality indices enable an assessment of the integral air quality conditions, which are not restricted to single air pollutants and, therefore, reflect the ambient air consisting of a mixture of air pollutants more realistic (BAUMÜLLER and REUTER, 1995; EPA, 1999; MAYER et al., 2002b).

Test calculations, carried out for the air stress index ASI_{BW} and the air quality index DAQx, both based on the same air pollutants and time scale, exhibit partly different results in dependence on the site specific emission and air mass exchange conditions. The main reason is the varying way of taking into account the single air pollutants in the formulations for air stress and air quality indices presented in this study. The test calculations have additionally the character of a sensitivity study, because their results point out the ranges of daily ASI_{BW} and DAQx values as well as their annual variations, which are mainly influenced by the local emission and air mass exchange conditions. Indicated by σ values, annual fluctuations of daily DAQx values at the sites in southwest Germany are slightly more pronounced than for ASI_{BW}, while the annual variability of ASI_{BW} is larger at Szeged where the air pollution level is highest among the sites investigated.

The test calculations also give an overview on the air pollutant, which is most responsible for the integral assessment of the air quality situation. The dominating role of O_3 at the site far from strong emissions can lead to a modified estimation of the air pollution conditions at health and recreation resorts.

Due to enhanced requirements, further formulations for air stress and air quality indices are under discussion. They stay abreast of changes in environmental medicine and should serve as a basis for an international standardisation of methods to assess the integral air pollution conditions within different environments.

Acknowledgements

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