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# Summer air quality over an artificial lake

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## Abstract

In the summer of 1998, the air quality (indicators: CO, NO, $NO_2$, $O_3$) above the water surface of the Lake Balderey (Essen, Ruhr area, North Rhine-Westphalia, Germany), an artificial lake used for recreation purposes, was measured using the Fourier transform infrared spectroscopy (FTIR) and differential optical absorption spectroscopy (DOAS) remote measurement methods. The lake, with an area of $3\,km^2$ was created by damming the Ruhr and is surrounded by higher ground. In calm, bright weather conditions, this location results in a low-exchange situation (formation of temperature inversions, cold air dynamics) with a sustained impact on pollutant concentrations over the lake. The results of trace substance measurements (1/2 h mean values) were compared with values from comparison stations (suburban, high traffic and forest) located outside the area of the lake. In general, it was found that mean CO and NO concentrations over the lake were very low (0.3 ppm and 7.5 ppb, respectively). $NO_2$ values ($\sim$15 ppb) were some 3.5 times higher than those recorded at the forest station and $O_3$ values, at 27 ppb, almost reached the same level as at the forest station (30 ppb). Mass flow densities as a function of wind direction, diurnal courses, differences between weekdays and weekends and comparisons with air quality standards are presented for the lake station.

*Keywords:* CO; NO; $NO_2$; $O_3$; $SF_6$ measurements (FTIR, DOAS); Leisure area

## 1. Introduction

The purpose of this study was to investigate air quality over an artificial lake near to a major conurbation which is widely used by the local population for leisure activities in the summer months.

In fine weather, both the lake shores and the lake are frequently used for leisure activities including sailing, surfing, rowing, paddling, etc. As these activities often continue for periods of several hours, air quality is an important factor from the human biometeorological point of view, in addition to the photoactinic and thermal complexes. To date, only isolated investigations have been made of the air quality over leisure areas in or near major cities. These have concerned city parks (e.g. Beckett et al., 1998; Kuttler and Straßburger, 1999; Mertens, 1999; Reitebuch et al., 2000) and woods near to cities (e.g. Mayer et al., 1994).

On the other hand, there are only few publications concerning air quality over small lakes in leisure areas. A similar investigation about the daytime photochemical pollutant transport had been realized in the lower Fraser Valley, Vancouver, B.C., over a lake where elevated concentrations of ozone ($O_3$) could be attributed to the advection of trace gases resulting from Vancouver metropolitan area and of reduced surface deposition (McKendry et al., 1998). Other studies deal with measurements of trace gases, mainly with ozone ($O_3$), in larger scales, such as the lake Michigan ozone study performed, e.g., by Luria et al. (1992) and Shafran et al. (2000). This article considers as a case study the aspect for a small artificial lake near to a major conurbation.

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## 2. Measuring site

The measurements were made on the shores and over the water surface of the Lake Balderey, an artificial lake about 6 km to the South of the city of Essen ($\rho = 51°27'\text{N}, \lambda = 7°00'\text{E}$) in the central Ruhr area (North Rhine-Westphalia, Germany) between 1 July and 30 September 1998. The lake is located in a recreation area characterized by woods and meadows (Fig. 1).

The artificial lake has a maximum width of 580 m, a depth of up to 4 m, a length of about 8 km (east–west direction), and a surface area of 3 km$^2$. It was created by damming the Ruhr. The surrounding terrain is about 50 m higher to the south of the lake and up to 140 m higher to the north.

On summer days, when the weather is fine, thousands of people visit the lake in search of recreation. As the use of motorboats on the lake is prohibited with the exception of a few excursion boats, there are scarcely any local air pollution sources. However, there is occasional pollution caused by visitors arriving and departing with their motor vehicles and as a result of the fact that the southern shore of the lake is a favourite meeting point for motorcyclists (between 100 and 200 motorcyclists may gather there in fine weather per day).

Certain major roads located especially to the east of the lake may also have a significant detrimental impact on air quality. In the immediate vicinity of the lake, the emission situation can be characterized as rural. As the centre of the Ruhr conurbation ($\sim$5 Mio. inhabitants) is located to the north of the lake and the edge of the main conurbation is about 3 km from the lake, pollution conveyed to the lake by the wind is to be expected in addition to local impairments of air quality with winds coming from these sectors.

## 3. Methods

### 3.1. Meteorological measurements

The meteorological values air temperature ($t_L$), relative humidity (rH) and three-dimensional wind

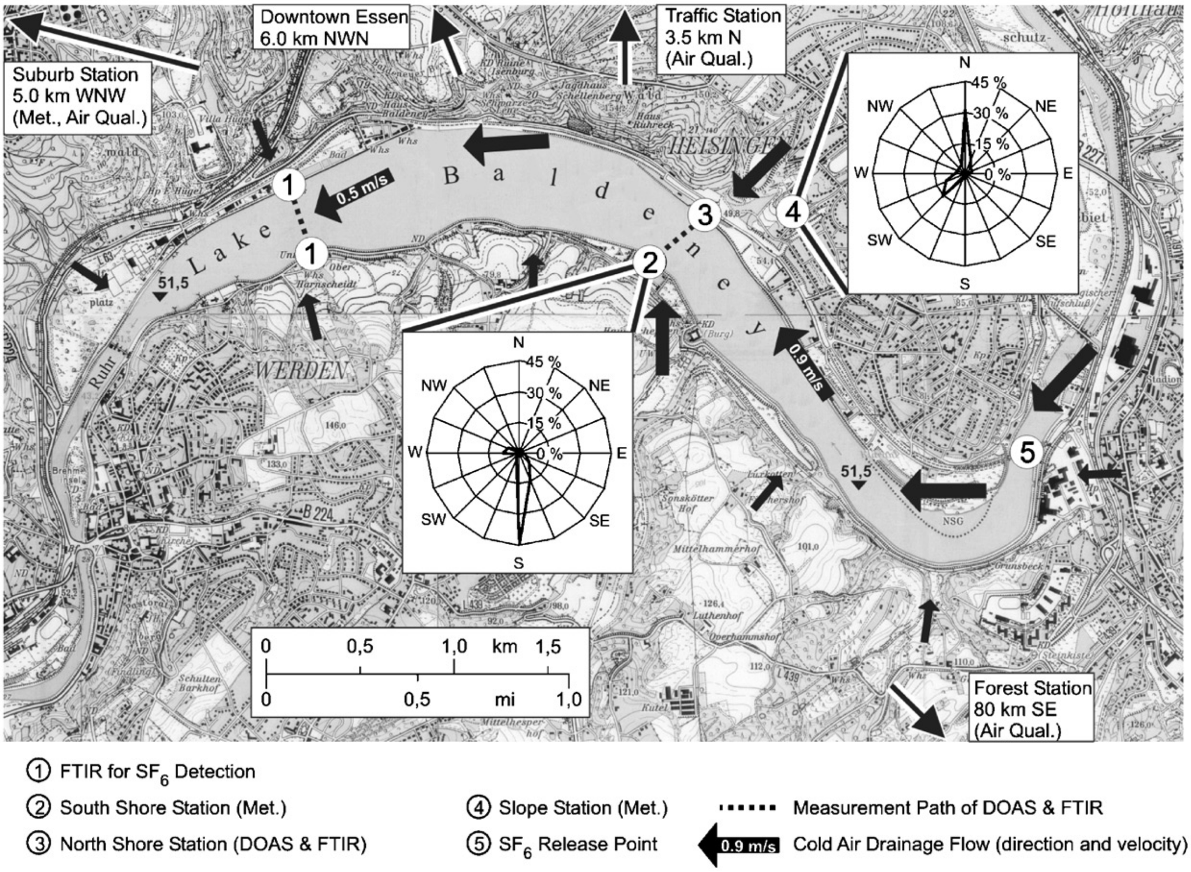

Fig. 1. Topographic situation, positions of measurement sites, surface wind over and around the Lake Baldeney, Essen, and mean wind directions during calm and clear nights ($n = 29$), July–September 1998.

vector $(u, v, w)$ were measured by hygrothermotransmitters, sonics and three-dimensional measuring propeller anemometers 2 and 10 m above ground level. The data sampling rate was 1 Hz with a reporting period of 1/2 h.

The main meteorological station was established on the southern shore of the lake (Fig. 1, point 2) and a tethersonde system was used for individual measurements on the northern shore (Fig. 1, point 3). Data from two further meteorological stations were also available, a station located on a slope (200 m to the north of the northern shore station, grassland, 94 m ASL), to measure cold air flow to the lake surface (Fig. 1, point 4), and a suburban station situated 5.0 km to the north-west (grassland, 135 m ASL). Data from the suburban station was used for calculating atmospheric lapse rates between the lake surface (50 m ASL) and the suburban station (135 m ASL).

### 3.2. Air pollution measurements

The air quality along a measurement distance of 390 m from the northern (Fig. 1, point 3) to the southern (Fig. 2, point 1) shore of the lake (elevation of both stations: 53 m ASL) was determined continuously by means of 1/2 h average values of CO, NO, $NO_2$ and $O_3$ trace gas concentration 3–5 m above the water surface utilizing the remote optical measurement methods Fourier transform infrared spectroscopy (FTIR) and differential optical absorption spectroscopy (DOAS).

These methods involve the measurement of the integral trace gas concentration along the traverse without contact. The attenuation of the electromagnetic radiation in the infrared or ultraviolet/visible (IR, UV/VIS) range as a result of the trace gases is determined by spectroscopy. For CO measurements, a FTIR long-path absorption method (ETG, liquid nitrogen, cooling MDL = 20 ppb) with a monostatic configuration was used (Weber, et al., 1998). The IR radiation source and the FTIR spectrometer required for the measurement were both positioned on the northern shore station of the lake. The ray emitted by the IR radiation source was transmitted back to the FTIR spectrometer by a reflector on the southern shore of the lake.

Table 1
Monthly mean averages of air temperature, $t_L$, relative humidity, rH, precipitation, $r$, and solar radiation, $R$, as well as quotient of the general weather situation (GWS) (July–September 1881–1997 and 1998)

| | Period | July | August | September |
|---|---|---|---|---|
| $t_L$ (°C) | 1931–60 | 17.5 | 17.3 | 14.6 |
| | 1998 | 16.1 | 17.1 | 14.5 |
| rH (%) | 1931–60 | 76 | 79 | 78 |
| | 1998 | 78 | 71 | 83 |
| $r$ (mm) | 1931–60 | 86 | 90 | 66 |
| | 1998 | 88 | 72 | 174 |
| $R$ (kWh) | 1931–60 | 152 | 136 | 91 |
| ($m^2$ Month) | 1998 | 118 | 125 | 71 |
| GWS | | | | |
| N | $\frac{1998}{1881-1997}$ | 0.6 | 1.0 | 1.5 |
| E | | (0.11) | 0.3 | 1.9 |
| S | | (0.07) | (0.09) | (0.08) |
| W | | 1.6 | 1.6 | 0.5 |
| Mixed | | 1.3 | 1.0 | 1.2 |

Values in parentheses concern 1881–1997.

A DOAS method (Opsis ER 130, AR 500) with a bistatic configuration (Platt, 1994) was used for NO, $NO_2$ and $O_3$ measurements (MDL = 1.5, 0.7 and 3 ppb). The radiation source (Opsis ER 110), which transmits UV/VIS radiation for the measurement of these trace gases, and the spectrometer were positioned on the northern and southern shores of the lake, respectively. A second FTIR station was installed temporarily about 2 km to the west (downstream) of this site to measure cold air dynamics over the water surface using $SF_6$ emitted at certain times from a bridge where the river enters the lake (Fig. 1, point 5). The FTIR technique was proven to continuously monitor $SF_6$ across the lake with a MDL of 0.1 ppb.

Comprehensive quality assurance procedures were developed and implemented for the validation of the measurement results (Weber et al., 1999; Lamp et al., 1999; Ropertz et al., 1999). It was proven by parallel measurements with standard point monitoring systems at the north shore station that FTIR and DOAS concentration data are comparable to the data of the conventional monitoring network since FTIR and DOAS determine the spatially averaged concentration value over a measurement path several hundred meters long, whereas the monitoring network measures only at the point of sampling. In general a better comparability with higher accumulation times was revealed. In this study the best fit is found using 1/2 h mean values ($R^2 = 0.84$, Lamp, 2002). Occasional concentration differences could be attributed to the sporadic passing of vehicles or cold air drainage flow with more influence on the point monitors.

In order to compare the data measured over the lake with corresponding data obtained outside the measurement area, data from selected stations of the air quality measurement network operated by the state of North Rhine-Westphalia were used.

The stations concerned were

- a suburban station located 5 km to the north-west, 153 m ASL,
- a high-traffic station located 3.5 km to the North (four-lane highway, Essen-Rellinghausen, Ruhrallee, traffic value: 60,000 vehicles per day, 112 m ASL), and

- a forest station located 80 km to the south-east (Rhenish Slate Mountains, Hilchenbach, 635 m ASL).

The measurements at these stations were made by non-dispersive infrared absorption (CO), chemiluminiscence (NO, $NO_2$) and UV absorption ($O_3$).

## 4. Representativeness of measurement period

The representativeness of the measurement period was checked by comparing the data collected with long-term meteorological values from a 20-year record. Apart from the large-scale situations, these data referred to the German Weather Service (DWD) meteorological station (6 km to the West of the lake). The data are shown in Table 1 and Fig. 2.

A comparison of air temperature (Table 1) shows that only July was more than 1 K cooler. rH was lower in August and higher in July and September. Precipitation was lower in August and almost 3 times higher in September. Global radiation flux densities were lower, in some cases significantly lower than the data from the comparison series in all 3 months considered. A comparison of large-scale meteorological situations shows that there were no southerly situations in the investigation period. Northerly situations occurred less frequently in July and more frequently in September. Easterly situations were not observed at all in July, occurred very rarely in August and were very frequent in September. Westerly conditions were severely over-represented in July and August and severely under-represented in September. A comparison of average wind directions (Fig. 2) shows that south-westerly (SW) wind directions were significantly more frequent in 1998 while NW-NE winds were observed rather less frequently. However, in overall terms, there is only a very slight discrepancy between the wind distribution in the measurement period from July to September 1998 and the long-term values (July to September 1980–1999).

As the lake is mainly used for recreation purposes in clear weather conditions (for definition, see Section 5.1) the results were evaluated with special reference to these conditions.

## 5. Results

### *5.1. Results of meteorological measurements*

The decisive factors which determine the air quality over the lake are emissions and chemistry, wind conditions and atmospheric stability. A comparison between the wind rose for the station on the southern shore and the suburban station shows that the wind direction on the lake is largely determined by its low position in relation to the surrounding terrain (Fig. 3). The prevailing wind direction at the suburban station is SW. This wind is channelled into a W direction by the higher land surrounding the lake. Apart from this main maximum, a secondary maximum in the SE sector is more clearly pronounced on the lake than for the

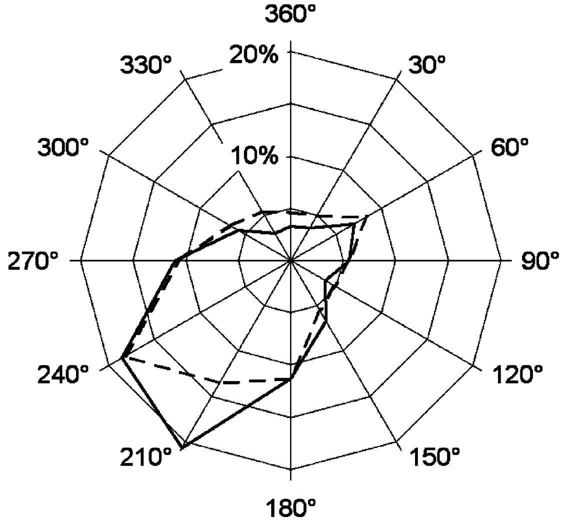

Fig. 2. Frequency distribution of wind directions (German Weather Service, Suburban Site) for July–September 1998 (—) and July–September 1980–1999 (----).

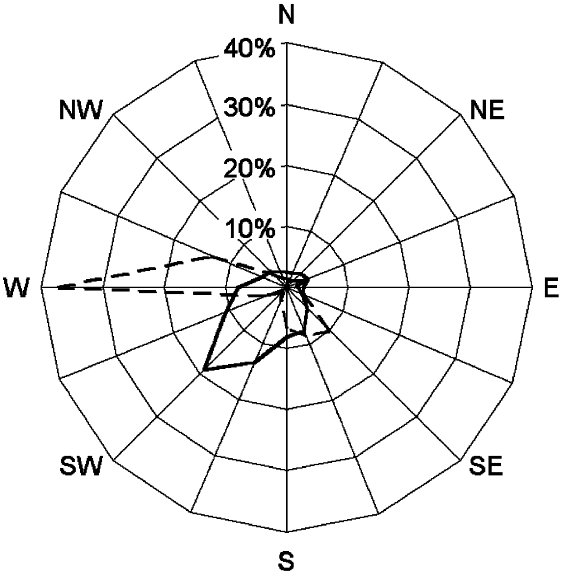

Fig. 3. Frequency distribution of wind directions at suburban site (—; calms = 0.5%; $n = 4416$) and Lake Baldeney site, Essen (---; calms = 9.2%; $n = 4274$) July–September 1998, 30-min averages.

suburban station. These south-easterly (SE) winds are caused by cold air inflow in clear weather conditions from a valley joining the lake on the southern shore. For this purpose, "clear and calm weather conditions" we used to refer to conductions with 50% unstable conditions during the day and 75% stable conditions at night. The term "allochtonous" is used to refer to windy weather conditions with at least 50% unstable stratification during the daytime and no more than 50% stable stratification at night.

The atmospheric stability class after Pasquill (1961) and Polster (1969) between the lake station (53 m ASL) and the suburban station (135 m ASL) was calculated for the duration of the measurement period on the basis of wind speeds and lapse rates. The stability classes determined are shown in Table 2. The share of calm conditions (windspeed, $u < 0.3\,\mathrm{m\,s^{-1}}$) in the lake area was some 20 times higher than at the suburban station.

Cold air inflow to the lake surface from the northern and southern hills and down the Ruhr was observed on 29 clear and calm days during the measurement period. Sample measurements of cold air flow down the Ruhr made using $SF_6$ as a tracer resulted in speeds between 0.6 and $0.9\,\mathrm{m\,s^{-1}}$ (see Fig. 1 and Lamp, 2002). The vertical profile recorded on 17th August 1998 during weather conditions of this type (Fig. 4) shows a relatively strong temperature inversion extending over the high ground to the north of the lake, coinciding with a relative humidity minimum at 175 m ASL. Near to the surface, the wind speed remains very low ($u < 1\,\mathrm{m\,s^{-1}}$). The change in the wind direction over the lake is mainly caused by the cold air flowing in from the surrounding high ground, at various elevations. Above the surrounding high ground, the wind turns to NNW and the wind speed increases.

Stable to highly stable conditions predominate between 8 p.m. and 7 a.m. during calm and clear weather conditions. During the daytime, stability conditions vary from neutral to slightly unstable (Fig. 5). On the other hand, high-exchange weather conditions are almost always characterized by unstable stratification.

### 5.2. Results of air quality measurements

#### 5.2.1. Averages

For the duration of the investigation period, the results of air quality measurements were calculated on

Table 2

Stability classes (3 = very stable, 0 = neutral and −3 = very unstable conditions) for Lake Baldeney site, Essen, July–September 1998 (after Pasquill, 1961; Polster, 1969)

| | $\Delta t = t_{\mathrm{lake}} - t_{\mathrm{sub}}$ (K/100 m) | | | | | | |
|---|---|---|---|---|---|---|---|
| $u_{10}$ m (m/s) | $\Delta t < -2.0$ | –2.0 to 0.1 | 0.0 to 0.6 | 0.7 to 0.8 | 0.9 to 1.1 | 1.2 to 1.4 | $\Delta t > 1.4$ |
| <1.0 | 3 | 3 | 0 | −1 | −2 | −3 | −3 |
| 1.1–2.0 | 3 | 3 | 0 | −1 | −2 | −2 | −3 |
| 2.1–3.3 | 2 | 1 | 0 | 0 | −1 | −2 | −3 |
| 3.4–5.4 | 1 | 0 | 0 | 0 | −1 | −2 | −2 |

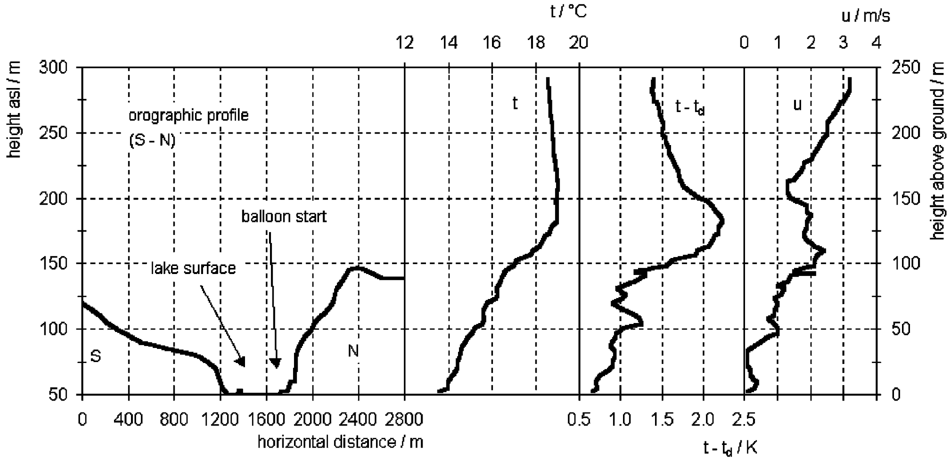

Fig. 4. Orographic profile (left side) and vertical distribution of air temperature ($t$), dew point temperature difference ($t - t_d$) and wind velocity ($u$) at the lake site during a typical calm and clear night from tethered balloon data on 17th August 1998, 23:25 to 23:37 CET.

the basis of 1/2 h (CO, NO, $NO_2$) or hourly ($O_3$) averages and, if applicable, then averaged for longer periods on this basis. The values measured on the lake were compared with those of the suburban, forest and traffic stations (Table 3). The standard deviation, as a percentage of the average ($\sigma$), taken as a measure of the variation in pollutant concentration, is slightly lower at the lake station (CO = 37%, NO = 94%, $NO_2$ = 38%) than at the suburban station (CO = 56%, NO = 119%, $NO_2$ = 52%). This indicates a relatively even pollution level at the lake, determined by more distant pollution sources. The lower value of the 98th percentile at the lake confirms the better air quality over the water surface, whereas this is not so clearly indicated by the average values for the lake and the suburban station. NO values at the lake are relatively close to the minimum detection limit (MDL, 6 ppb) for this trace gas. At the forest station, the NO values do not even exceed the MDL. The differences between lake, suburban and forest stations are clearer in the case of $NO_2$. The values measured at the lake station are 3.5 times higher and those measured at the suburban station are 4.2 times higher than those of the forest station. As expected, CO, NO and $NO_2$ levels at the traffic station are significantly higher.

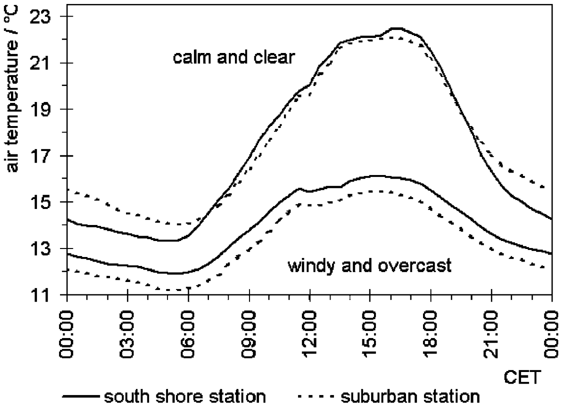

Fig. 5. Diurnal course of air temperatures at south shore station (50 m ASL) and suburban station (135 m ASL) Essen (July–September 1998) for calm and clear weather ($n = 29$) and windy and overcast weather ($n = 40$).

It is interesting to compare the $O_3$ values because high $O_3$ concentrations could have negative health effects especially in combination with sport activities. The average value for the lake is slightly lower than for the forest although the peak concentration (98th percentile) is the same. In other words, average ozone concentrations at the lake are comparable to those of the forest station which is located at a much greater distance from the nearest conurbation. Ozone values are considerably lower at the suburban station than at the lake or forest station.

### 5.2.2. Average diurnal cycles

As the lake is used for leisure purposes mainly in the late afternoon and early evening, at the end of a working day, the diurnal course of trace gas concentrations is also of some interest (Fig. 6). In comparison to the lake

Table 3
Mean values, standard deviation $\sigma$ and 98th percentile of CO, NO, $NO_2$ (1/2 h averages) and $O_3$ (hourly averages) concentrations for the lake, suburban, forest and high-traffic site (NRW, Germany) during the period from 1 July to 30 September 1998 for all weather conditions (number of values $1.947<n<4.140$) and for calm and clear days

| | CO (ppb) | | | NO (ppb) | | | $NO_2$ (ppb) | | | $O_3$ (ppb) | | | Ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | $\sigma$ | 98% | Mean | $\sigma$ | 98% | Mean | $\sigma$ | 98% | Mean | $\sigma$ | 98% | $NO_2$/NO |
| *All weather conditions* | | | | | | | | | | | | | |
| $C_{Lake}$ | 323 | 118 | 640 | 7.8 | 7.3 | 31.6 | 14.3 | 5.5 | 28.3 | 27.3 | 16.4 | 70.1 | 1.84 |
| $C_{Sub.}$ | 316 | 178 | 720 | 9.6 | 11.4 | 41.8 | 16.6 | 8.6 | 39.5 | 17.9 | 13.7 | 57.9 | 1.74 |
| $C_{Forest}$ | No values available | | | <6.0 | <6.0 | <6.0 | 4.0 | 2.7 | 11.2 | 30.0 | 13.7 | 71.0 | >0.67 |
| $C_{Traffic}$ | 808 | 518 | 2160 | 49.6 | 49.2 | 182.1 | 26.2 | 12.3 | 58.0 | No values available | | | 0.53 |
| *Calm and clear days* | | | | | | | | | | | | | |
| $C_{Lake}$ | 350 | 131 | 686 | 7.7 | 7.8 | 35.1 | 14.8 | 6.0 | 29.6 | 31.6 | 21.6 | 82.7 | 1.92 |
| $C_{Sub.}$ | 328 | 190 | 800 | 6.4 | 9.2 | 34.6 | 18.6 | 11.0 | 48.8 | 26.2 | 16.9 | 68.2 | 2.90 |
| $C_{Forest}$ | No values available | | | <6.0 | <6.0 | <6.0 | 3.9 | 2.7 | 12.2 | 41.3 | 16.5 | 83.6 | >0.65 |
| $C_{Traffic}$ | 841 | 551 | 2400 | 43.4 | 49.9 | 170.9 | 29.5 | 15.5 | 70.7 | No values available | | | 0.68 |
| *Ratio (calm and clear days/all weather conditions)* | | | | | | | | | | | | | |
| $C_{Lake}$ | 1.08 | 1.12 | 1.07 | 0.99 | 1.06 | 1.11 | 1.03 | 1.10 | 1.04 | 1.16 | 1.32 | 1.18 | 1.04 |
| $C_{Sub.}$ | 1.04 | 1.07 | 1.11 | 0.67 | 0.80 | 0.83 | 1.12 | 1.28 | 1.23 | 1.47 | 1.23 | 1.18 | 1.67 |
| $C_{Forest}$ | No values available | | | 1.00 | 1.00 | 1.00 | 1.05 | 1.00 | 0.92 | 1.37 | 1.21 | 1.18 | >1.05 |
| $C_{Traffic}$ | 1.04 | 1.06 | 1.11 | 0.87 | 1.02 | 0.94 | 1.13 | 1.26 | 1.22 | No values available | | | 1.29 |

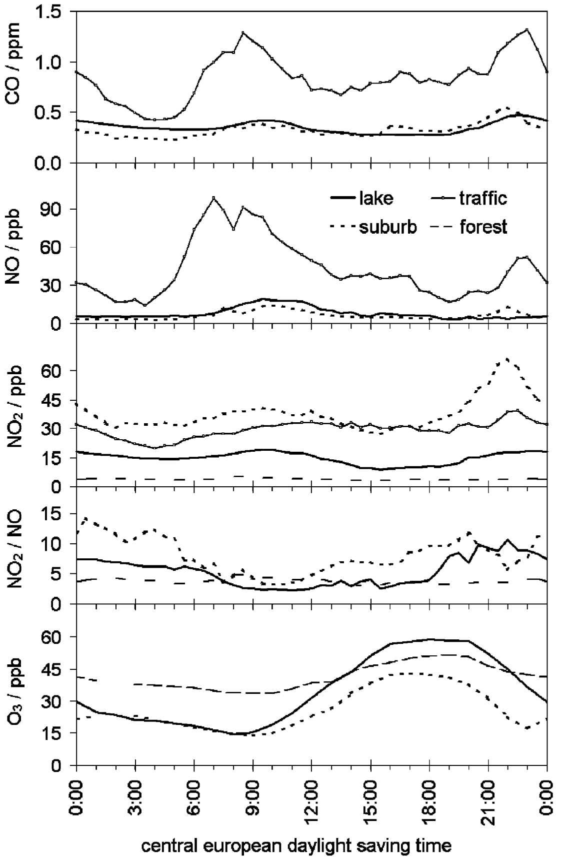

Fig. 6. Mean diurnal courses of trace gas concentrations at the suburban, forest, traffic and Lake Baldeney sites during calm and clear weather conditions ($n = 29$, 30-min averages), Essen, July–September 1998.

and suburban stations, the graph for the traffic station is characterized by two daily peak concentrations of primary trace gases (CO, NO) in the morning and evening (rush hour, establishment of stable conditions). Concentration levels at the lake and suburban stations are markedly lower and are characterized by a certain variation over the course of the day—however, this is much less pronounced. The morning maxima (CO, NO) also occur about 1 h later than at the traffic station, which is indicative of transfer processes.

$NO_2$ concentrations at the traffic station were also higher and the diurnal course was less pronounced than at the suburban and lake stations. The highest values were measured after 9 p.m. mainly due to increasing stability. On the other hand, the suburban and lake stations show a more pronounced diurnal course, with morning and evening maxima separated by a clear afternoon minimum. Evening values at the suburban station were considerably above those of the lake station, almost reaching the same level as at the traffic station. There was little daily variation in the values measured at the forest station, which were below 6 ppb.

Ozone concentrations at the forest site were relatively high, with little daily variation, and were therefore typical of a site at a considerable distance from pollutant sources. In contrast, the lake and suburban stations are characterized by pronounced diurnal ozone concentration courses. While the concentration plots between the second half of the night and the early morning were similar at the two stations, there were considerable differences during the daytime. From about 9 a.m., the mean concentration at the lake station rose more rapidly than at the suburban station reaching about 56 ppb, a much higher maximum than at the suburban station (37 ppb). Although the high $O_3$ concentrations at the lake station fell off again after 9 p.m., they only reached the concentration level of the suburban station after midnight.

The fact that the diurnal course of ozone concentrations is more structured over the lake than at the suburban station can be explained by the higher global radiation flux density (+10%) measured at the lake, the higher production of biogenic hydrocarbons (parallel indicated by isoprene concentrations of 0.2 ppb) and the more sheltered position of the lake. The fall in ozone concentrations at night could be due to the oxidation of primary air pollutants. In addition, secondary ozone maxima were measured at the lake during about 60% of nights between midnight and 4 o'clock. These were probably due to turbulent ozone transport from the reservoir layer above the inversion (Lamp et al., 1998; Reitebuch et al., 2000).

### 5.2.3. *Weekday vs. weekend concentrations*

In order to identify differences between weekday and weekend air quality, the concentration data of the trace gases studied measured on weekdays (Mondays–Fridays) and at weekends (Saturdays and Sundays) were compared for the lake and traffic stations (Fig. 7). At both stations, the concentrations measured for all trace gases were higher on weekdays than at weekends, with the exception of $O_3$ concentrations, where the opposite was the case. However, the differences between the two periods compared for all trace gases only reached maximum probability levels of $p_{\max} = 23\%$. As an example, the diurnal courses of CO concentrations were compared (Fig. 7). In general, the values measured at the traffic station were some 3–4 times higher than the lake station both on weekdays and at weekends.

The weekday concentration graphs for the two stations are characterized by morning and evening peaks caused by the rush hour, with significantly higher values at the traffic station. The morning maximum at the lake station occurs about 1 h later than at the traffic station, probably as a result of transfer processes and the stable conditions which start to collapse at about 7 a.m. The

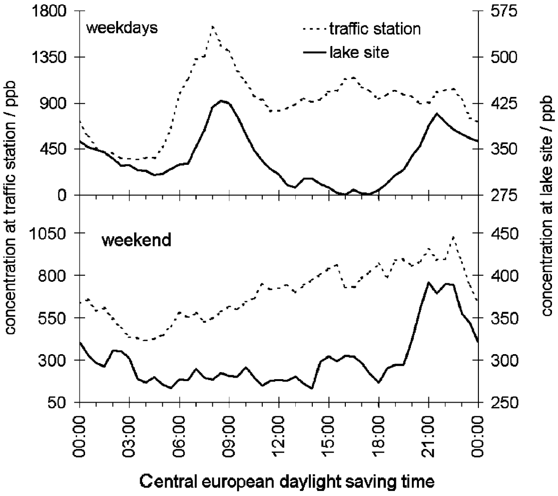

Fig. 7. Mean diurnal courses of CO concentration (30-min averages) at the traffic and Lake Baldeney sites, Essen, for weekdays (Mon–Fri) and weekends (Sat–Sun), July–September 1998.

pronounced evening rise in concentrations at the lake takes place at the same time as an increase in stability; this has less effect on the traffic station, which is located at a higher altitude.

At the weekend, there is no pronounced diurnal course at the traffic or the lake station. While the concentration at the traffic station rises steadily from the morning to the evening, peaking at about midnight CET, the lake values remain at a relatively low level until about 9 p.m. and then peak within about an hour. This abrupt rise in CO concentration over the lake from about 260 to almost 370 ppb is probably connected with the evening onset of low-exchange weather conditions over the lake. Detailed analyses showed that there were frequent gatherings of motorcyclists near to the station on the southern shore, especially at weekends. These might lead to considerable local pollution particularly in combination with the stable weather conditions in the Ruhr Valley.

### *5.2.4. Sources of trace gases*

The sources of CO and $O_3$ concentrations were investigated as examples of the primary and secondary air pollutants detected over the lake. The meteorological data measured at the southern shore station were used for an analysis as a function of wind sector. The average concentrations ($\bar{c}$), average mass flow densities ($M = \Sigma c_{\text{sector}} \cdot v_{\text{sector}}$) and the relative pollutant dose ($I_{\text{rel}}$; percentage of mass flow density per sector for whole measurement period), were calculated with reference to the measurement period for each wind sector.

Concentration wind roses were plotted for low- and high-exchange weather situations (Fig. 8). The results for low-exchange situations were analysed in more detail. Mean CO concentrations (Fig. 8.1) reached high values in the WSW-E wind sector, with a maximum (395 ppb) in the southerly direction. This maximum coincides with low wind speeds from the sector concerned, mainly caused by cold air drainage flow (see also Fig. 1). As these values do not give any indication of the level over the course of time and the total pollutant load, mass flow densities were calculated. This distribution indicates that the mean mass flow reaches peak values with an ENE air flow. The values are some 4 times higher than with air transported from the conurbation to the North.

However, if $I_{\text{rel}}$ is considered and distributed to the individual sectors as a percentage, roughly equal shares of the total pollutant load come from the sectors WSW-NW (45%), SSW-E and SE (32%) while the ENE-E sector only accounts for about 16%.

In comparison to CO, the concentration wind rose for ozone (Fig. 8.1) indicates maximum values for the W sector (69 ppb), while the lowest values (26 ppb) were measured with southerly winds.

The ozone concentration is—compared to CO—significantly higher in clear and calm weather conditions and is distributed more or less evenly over the wind rose, with the exception of a minimum in the SSW sector.

The mass flow densities reach peaks with winds from the W and SE. Westerly winds account for more than 65% of the mass flow over the entire measurement period. Secondary peaks of the type observed for CO do not occur in the case of ozone (Fig. 8.2).

### *5.2.5. Assessment of air quality*

In order to assess the air quality encountered by leisure-seekers at the lake, the results obtained were compared with German air quality standards. The values used for this purpose were the planning guidelines for leisure activities in the vicinity of cities (Kühling, 1980) and the maximum pollution values for the protection of human health (VDI 2310, 2000). During the measurement period, the maximum CO, NO and $NO_2$ values were not exceeded.

In the case of ozone, the planning guideline of 70 ppb (1/2 h average), was exceeded 75 times at the lake station and 12 times at the suburban station.

Table 4 shows the frequency of ozone concentrations in excess of limits at the lake, suburban and forest stations obtained by comparing the ozone concentrations measured with the maximum concentration values for the protection of human health (maximum air pollution concentration values 56 ppb as a 1/2 h average, 47 ppb as an 8 h average). The results show that values in excess of these limits were measured considerably more

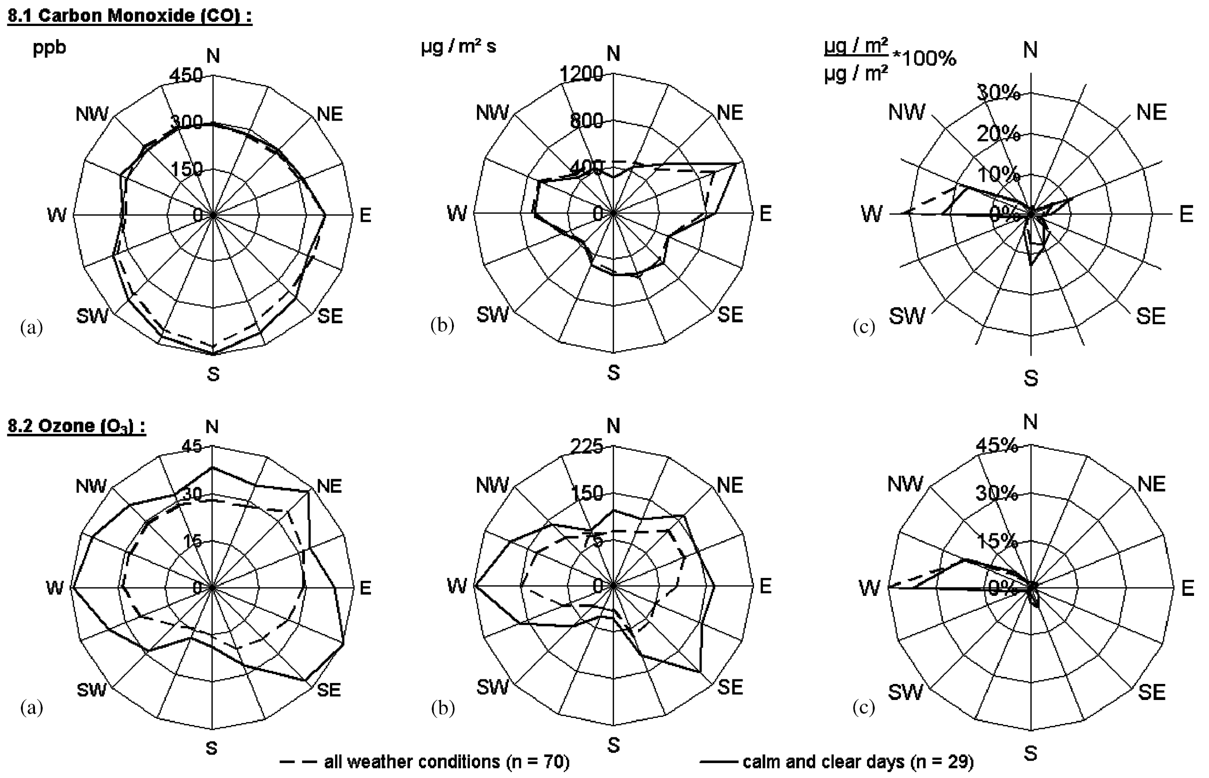

Fig. 8. Mean concentrations ($\mu g\,m^{-3}$), flux rates ($\mu g\,m^{-2}\,s^{-1}$) and relative dosis flux (%) for CO and $O_3$ at the Lake Baldeney site, Essen, July–September 1998.

Table 4
Exceedance of the maximum permissible ambient air concentration ($MIK_{1/2\,h} = 120\,\mu g\,m^{-3}$ (56 ppb); $MIK_{8\,h} = 100\,\mu g\,m^{-3}$ (47 ppb)) after VDI guideline 2310 (2000)

| | 1/2 h means | | 8 h means | |
|---|---|---|---|---|
| Lake Baldeney | 204 | (115) | 20 | (88) |
| Suburban | 80 | (87) | 7 | (78) |
| Forest | 22 | (111) | 15 | (93) |

In brackets absolute maximum concentration in ppb.

frequently at the lake station than at the other stations used for comparison purposes.

The highest ozone concentration measured in Germany at the stations of the Environment Protection Agency in 1998 was 131 ppb (UBA, 2000). This clearly indicates the high load at the lake station, where a maximum of 114 ppb was measured.

## 6. Conclusions

The topographic situation of the lake, surrounded by higher land, has a considerable influence on average wind speeds and directions (Fig. 3). In addition to the main prevailing wind direction (W), there is also a secondary prevailing direction (SE), caused by cold air inflow from the higher ground to the south at night. Especially with clear weather conditions resulting in the production of cold air, there is a pronounced diurnal course of atmospheric stability. At night, between 8 p.m. and 8 a.m., largely stable conditions are established; during the daytime, these are replaced by rather unstable exchange conditions. This is the factor which mainly determines the diurnal course of pollutant concentrations measured at the lake (Figs. 6 and 7).

As there are no continuous sources of air pollution in the immediate vicinity of the lake, the average concentrations of CO, NO and $NO_2$ (Table 3) are comparatively low. On the other hand, the mean ozone concentration and especially the 98th percentile of ozone concentration are higher, corresponding to those of the forest station. However, the clearly structured diurnal course of ozone concentration at the lake station with low nighttime and higher daytime values (Fig. 6) is typical of a site near to a conurbation and does not correspond to the less-pronounced diurnal course of a clean-air location. In terms of air quality, none of the CO, NO or $NO_2$ values measured were dramatic.

However, in the case of ozone, the limits defined (Table 4) are often exceeded in clear conditions. Analyses of pollutant origin carried out for CO and $O_3$ using wind sector specific mass flow densities showed that about 70% of the ozone reaching the lake came from remote sources. Apart from the large share of CO from remote sources (45%), a significant proportion (32%) came from local sources.

With respect to the trace substances CO, NO and $NO_2$, the investigations showed that the air quality in a recreation area near to a conurbation was surprisingly good. Only low concentration values were measured. However, relatively high ozone values were reached during the daytime, especially in calm, bright weather conditions. In some cases, these values were above the applicable air quality limits. In addition, the results demonstrate that the air quality monitoring network of the environmental state agency is not at a high enough spatial resolution for statements concerning air quality in areas near to conurbations which are frequently used for recreation purposes by local residents. Further investigations are planned in comparable recreation areas.

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