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Nocturnal secondary ozone concentration maxima analysed by sodar observations and surface measurements

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Abstract

The occurrence of nocturnal secondary ozone maxima was investigated by ground-level meteorological and air quality measurements in an urban park in Essen, Germany, during 29 individual summer measurement campaigns between May 1995 and September 1997. In addition, during an intensive measurement campaign in May 1997, SODAR measurements of wind and turbulence were made. The spatial and temporal distribution of nocturnal ozone maxima within the measurement network of the Environmental Protection Office of North Rhine–Westphalia was also analysed. Two case studies of nocturnal secondary ozone maxima are discussed in more detail. They represent two different types of this phenomenon, associated with a nocturnal low-level jet (LLJ) and the passage of a front, respectively. In both cases, the nocturnal increase in ozone concentration was accompanied by a significant increase in the standard deviation of the vertical wind speed σ_w across the lower stable boundary layer, indicating enhanced vertical mixing. During the LLJ case, ozone maxima were observed at 33% of the stations of the Environmental Protection Office network at approximately the same time. In the case of the front, the time of the ozone concentration rise could be allocated to the time of the passage of the front, moving from northwest to southeast across the study area. For the first time, the measurements presented here document turbulent mixing induced by shear forces in the whole layer between the core of the LLJ and the ground surface during secondary nocturnal ozone maxima.

Keywords: Tropospheric ozone; Nocturnal ozone maxima; SODAR; LLJ; turbulence

1. Introduction

Tropospheric ozone concentrations are determined by air chemistry, turbulent diffusion, and deposition to the Earth's surface (Haagen-Smit, 1952; Seinfeld, 1989). Measurements of the diurnal courses of ozone concentration show the results of the interaction of these different mechanisms. Chemical reactions, mainly photolysis of NO_2, induce a daytime maximum of the tropospheric ozone content (Emeis et al., 1997), air chemistry leads to a destruction of ozone (most effectively by titration with NO at night), deposition removes ozone from near-surface atmospheric layers, mean winds result in considerable horizontal transport of ozone in the upper part of the boundary layer and in the free troposphere, and turbulent mixing leads to a vertical exchange of ozone between the surface layer and the layers above. In this way, ozone concentrations measured over a certain time may show a large variety of features.

On warm spring and especially summer days with few clouds and low wind speeds away from strong emission sources, the daily variation of surface layer ozone concentration usually shows a distinct maximum during the

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afternoon hours and an equally distinct minimum in the early morning before sunrise. A few hundred metres above ground level in the so-called residual layer, the concentrations are much more homogeneous because deposition and titration by NO during the night are missing here. But this simple temporal and spatial distribution is quite often disturbed by various horizontal and vertical transport processes, and sometimes secondary nocturnal ozone maxima occur.

2. Previous studies

Nocturnal secondary ozone maxima have been established during calm weather conditions over plains (Teichert, 1955; Winkler, 1980; Corsmeier et al., 1997; Strassburger and Kuttler, 1998), in valleys (Löffler-Mang et al., 1997), and on mountain tops (Samson, 1978). Nighttime secondary ozone maxima may also occur during the passage of fronts (Schneider and Georgii, 1993; Löffler-Mang et al., 1996). The principal explanation for the increase in the ozone concentration in all cases is enhanced vertical mixing. However, there are various reasons for enhanced vertical mixing.

In valleys, diurnal wind systems may be responsible for enhanced vertical mixing. In the daytime, polluted air is advected from the forelands (Grell et al., 2000). During the night, ozone-rich air from the residual layer above may be brought down by mountain and downslope winds. Mountain tops are often directly exposed to the conditions in the residual layer at night. No stable surface layer exists here because cold air which is formed by outgoing long-wave radiation immediately flows downhill and is replaced by ozone-rich air from above. In the case of a frontal passage, vertical mixing is linked to the secondary frontal circulation and the turbulence which usually accompanies the front.

None of these explanations applies over the plains during calm weather conditions. Here, the wind shear below nocturnal low-level jets (LLJ) which form over large areas in the stable boundary layer (Blackadar, 1957; Roth et al., 1979; Malcher and Kraus, 1983; Stull, 1988) is responsible for episodes of enhanced vertical mixing during the night. Corsmeier et al. (1997) support this explanation of secondary ozone maxima by radiosonde and tethered balloon data of mean wind speed, ozone concentrations, and potential temperature as well as supplementary surface measurements of the vertical turbulent ozone flux.

Hanna and Chang (1992) modelled the nocturnal increase in pollutant concentrations with a dispersion model. They found that an increase in the standard deviation of the vertical wind speed σ_w by a factor of 4 to 5 could explain the magnitude of downward mixing during LLJ events and derived a simple parameterization for σ_w.

SODAR backscatter intensities showing the typical evolution of the height of the stable boundary layer at nights with and without LLJs are analysed in Beyrich (1994). Parallel observations of ozone profiles and SODAR data for nights in which no LLJ appeared although a shallow stable boundary layer had formed are presented in Beyrich et al. (1996). They found good correlation between the ozone concentration decrease in the first half of the night and the formation of shallow stably stratified nocturnal boundary layers close to the ground.

The effects of nocturnal vertical mixing on ozone concentrations have also been investigated by Neu (1995) using routine SODAR data from Payerne (Switzerland). He did not consider the ozone increase close to the ground but rather the corresponding ozone decrease in the residual layer, concluding that vertical turbulent mixing towards the ground could be the only reason for the fall in ozone concentration in the residual layer during the night. The O_3 reduction due to mixing is stronger than the O_3 increase due to entrainment of ozone from the free troposphere into the residual layer from above. However, Teichmann et al. (1997) were unable to confirm Neu's findings from data taken at Melpitz (East Germany). They speculated that this could be the result of differences in the meteorological situation and to site-dependent characteristics.

However, the shear-induced turbulent mixing itself (especially σ_w) in the whole layer between the surface and the LLJ has not been documented. We intend to fill this gap by presenting SODAR data from nights with secondary ozone maxima. We will present one case with a low-level jet and one case with a frontal passage.

3. Investigation area and experimental set-up

Near-surface meteorological and air quality measurements were carried out in the Grugapark, an urban park with an area of 70 ha in Essen (590,000 inhabitants (1999), North Rhine–Westphalia, Germany) in low-wind, mainly summer, daytime high-radiation meteorological situations (Kuttler and Strassburger, 1997; Strassburger and Kuttler, 1998). Both the concentrations of trace substances O_3, NO, NO_x and CO and meteorological parameters such as wind speed and direction, air temperature and net radiation balance, UV and global radiation, which are relevant to the distribution and photochemical formation of trace substances were measured. Individual measurement campaigns with a total duration of 725 h were conducted between May 1995 and September 1997. In addition, SODAR observations were carried out in an intensive measurement campaign at the same site to record the vertical wind and turbulence structure. These measurements were made continuously from 24 May 1997 19:00 CET to 30 May 1997 10:00 CET.

3.1. *Surface measurements*

Surface measurements of meteorological and air quality parameters were made with a time resolution of 1 and 30 min averages, each based on 10 s values. The measurements were made using the mobile laboratory of the Institute of Ecology, University of Essen, which is equipped for continuous analyses of O_3 (UV absorption, Horiba APOA-350E), NO, NO_x (chemiluminescence, Horiba APNA-350E) and CO (IR absorption, Horiba APMA-350E) 4 m above ground level. In addition, wind speed and wind direction (10 m above ground level), air temperature and relative humidity (1 and 10 m above ground level), global radiation, UV radiation (3.5 m above ground level) and radiation balance (2 m above ground level) were measured.

3.2. *SODAR measurements*

The measurements of wind and turbulence profiles were made with the METEK DSDR3 × 7 Doppler SODAR (Reitebuch and Emeis, 1998) of the Fraunhofer Institute of Atmospheric Environmental Research (IFU), Garmisch-Partenkirchen. The SODAR consists of three antennas mounted on a trailer. This instrument measures the acoustic backscatter intensity, and the three components of the mean wind and the standard deviation of the vertical wind speed σ_w can be determined from the Doppler shift of the returned signal. For this purpose, one antenna is oriented vertically and two antennas are titled about 20° from the vertical in two directions perpendicular to each other. For this experiment, data were obtained from 60 to 700 m with a vertical resolution of 20 m. The accuracy of the instrument is about 0.1 m s^{-1} with reference to the vertical component and about 10% with reference to the horizontal wind speed. Accuracy has been evaluated by comparison with data from a meteorological mast equipped with sonic anemometers (Reitebuch and Vogt, 1998).

4. Results

4.1. *Characteristics of nocturnal secondary ozone maxima*

In order to identify possible reasons for the occurrence of nocturnal secondary ozone maxima, the characteristics of the nocturnal ozone maxima concerned were initially derived from the data obtained during the measurement period from May 1995 to September 1997. 17 nocturnal ozone maxima were recorded during the 29 summer nights investigated. These maxima showed the following characteristics.

1. In all 17 cases, the ozone concentration increase during the night was in excess of 10 ppb, with *maximum concentrations* ranging from 13 to 91 ppb. The nocturnal maxima corresponded to between 20% and 80% of the preceding daytime maximum (Fig. 1a). In 10 cases, the nocturnal maximum was between 40% and 60% of the preceding daytime maximum.
2. The *distribution over time* shows that the maximum concentrations were reached between 23:30 and 05:00 CET. Two-thirds of the maxima were measured between 0:30 and 3:00 CET (Fig. 1b).

Furthermore, 11 of the 17 nocturnal maxima observed were accompanied by almost simultaneous CO, NO_x and NO_2 concentration minima and by a rise in the air temperature measured 2 m above ground level.

The 17 nocturnal ozone concentration courses can be allocated to two main types (Fig. 2):

Type I: (LLJ, 8 cases) This type of nocturnal ozone maximum mostly occurred in nights with LLJ events (verified by radiosonde data of the German Weather Service, Essen). The nocturnal ozone maximum is reached shortly after midnight, 4.5 to 8.5 h after sunset. Following the peak, there is a significant fall in concentration, often as low

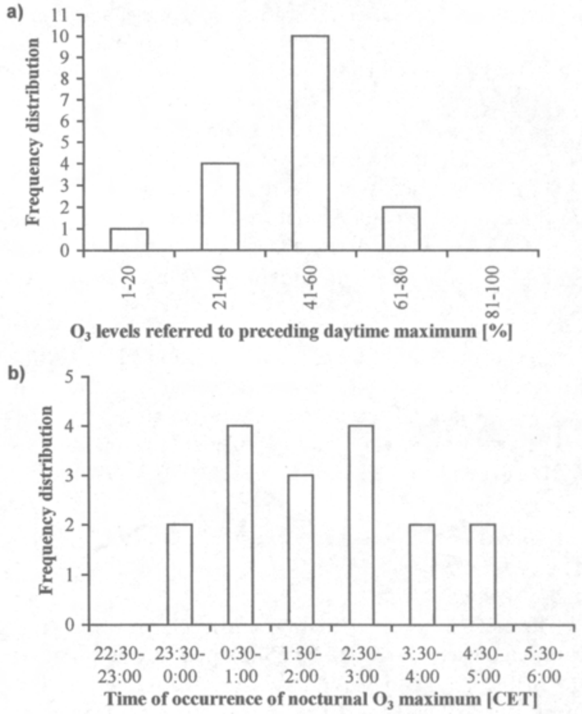

Fig. 1. Characteristics of 17 nocturnal ozone maxima in an urban park: frequency distribution (a) of ozone levels referred to preceding daytime maximum, (b) of time of occurrence of nocturnal maximum, 30 min averages (based on 10 s values), measurement period 5 May 1995 to 16 September 1997 (selected measurement days in summer half-years), Grugapark Essen.

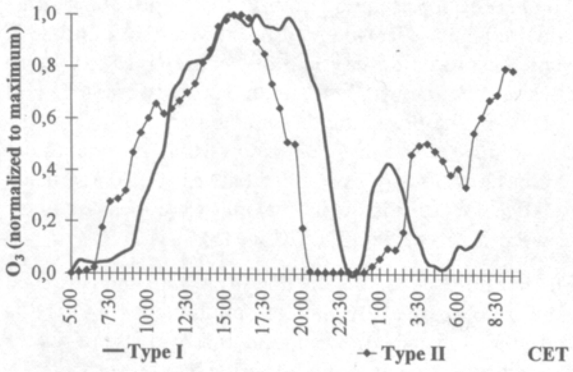

Fig. 2. Examples of diurnal course types with nocturnal secondary ozone maxima, Type I: 26/27 May 1995, Type II: 8/9 August 1996, 30 min averages (based on 10 s values), Grugapark Essen.

as the detection threshold of 0.4 ppb. During the secondary maximum, air temperature and wind speed increase. Following the maximum, the wind speed normally falls below 0.1 m s^{-1} (30 min average).

Type II: (front passage, 9 cases)! Type II was observed during front passages. The nocturnal ozone maximum is reached before or after midnight. In contrast to type I, the concentration remains virtually constant or only falls slightly. Wind speed, which increases as the maximum is reached, does not fall off significantly afterwards. In addition, following the main nocturnal maximum, O_3 concentration falls slowly and further secondary maxima with lower concentration levels may be observed.

As the vertical structure of the lower troposphere during low-wind meteorological conditions is one of the main causes of secondary nocturnal ozone maxima, the vertical distribution of wind and turbulence was analysed by SODAR measurements from 24 to 30 May 1997.

4.2. Intensive measurement campaign, 24–30 May 1997

4.2.1. Synoptic pattern

The meteorological situation during this measurement campaign was dominated by a high pressure system over the British Isles and Scandinavia which advected cool air from the northeast towards Central Europe. Ozone concentrations in this cool air were relatively low, with maximum daily concentrations of 62 ppb. Two cold fronts passed the measurement site, one at about midnight of 26/27 May, the other on the morning of May 30. Neither of the fronts caused precipitation in Essen. The first front was fully covered by the SODAR measurements and is presented below. The second front occurred at the end of the campaign.

LLJs developed in the nights of 25/26 and 28/29 May; these were verified by radiosonde data of the German Weather Service, Essen. The latter case is presented in more detail in this paper because it was accompanied by a secondary nocturnal peak in surface ozone concentration, which was larger in both relative and absolute terms. The first event was also coupled with a nocturnal peak in surface ozone concentration and an increase in vertical turbulent mixing but the synoptic situation was not completely undisturbed.

4.2.2. LLJ event, 28/29 May 1997 (ozone concentration maximum type I)

4.2.2.1. Surface measurements. Fig. 3 shows the diurnal course of near-surface air quality and meteorological parameters on 28/29 May 1998. The nocturnal secondary ozone concentration maximum, between 23:00 and 03:30 CET (maximum concentration: 4 h after sunset), reached 60% of the maximum daytime concentration and was combined with a significant reduction in NO_2 and CO levels. NO_2 and CO minima may have been caused by downmixing of low concentrations in NO_2 and CO from the residual layer. No reduction was measured in the NO concentration, which was already low at 5 ppb; the available NO had probably already been oxidized to NO_2 before the increase in ozone concentration.

At the same time as the peak ozone concentration, an increase of 2 K in near-surface (1 m above ground level) air temperature was measured, resulting in a reduction in the near-surface temperature gradient (between 1 and 10 m above ground level) from 0.25 K m^{-1} to 0.09 K m^{-1} with continued but reduced stable stratification. An increase in horizontal wind speed to 1.2 m s^{-1} was also recorded. This ozone maximum is an instance of type I, characterized by a significant fall in ozone concentration following the peak value.

4.2.2.2. Vertical soundings. The SODAR backscatter measurements (not shown) reveal that the top of the nocturnal PBL (planetary boundary layer) sinks from 330 m at 18:00 CET to about 150 m at 22:00 CET. Then it increases again to about 250 m at midnight before sinking again to about 150 m before sunrise.

The reason for this wave-like structure in the altitude of the nocturnal boundary layer can be found in Fig. 4 which shows the horizontal wind speed from the SODAR data. In Fig. 4 (as in the following Figs. 6 and 10) each little coloured box represents the true resolution of the measurements: an average over 30 min and 20 m in the vertical. The evening starts with low wind velocities of about 1 m s^{-1} at all observed heights. At 22:00 CET, the wind speed begins to increase aloft (400 m above ground level). At midnight we find a well-developed LLJ with

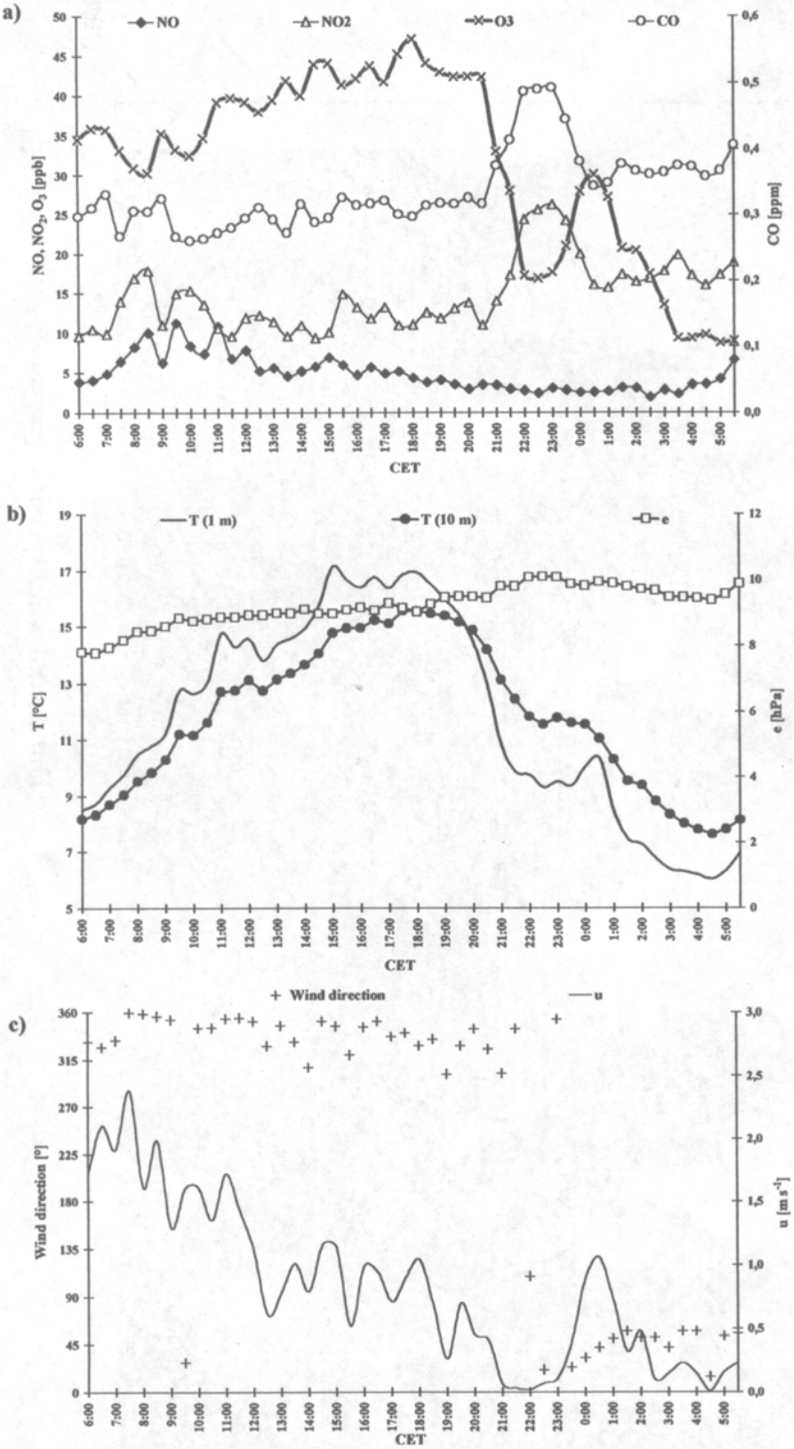

Fig. 3. Surface measurements during LLJ event: diurnal courses of (a) NO, NO_2, O_3 and CO concentrations, (b) air temperature (1 and 10 m above ground level) and water vapour pressure, (c) wind direction and speed, 30 min averages (based on 10 s values), 28/29 May 1997, Grugapark Essen.

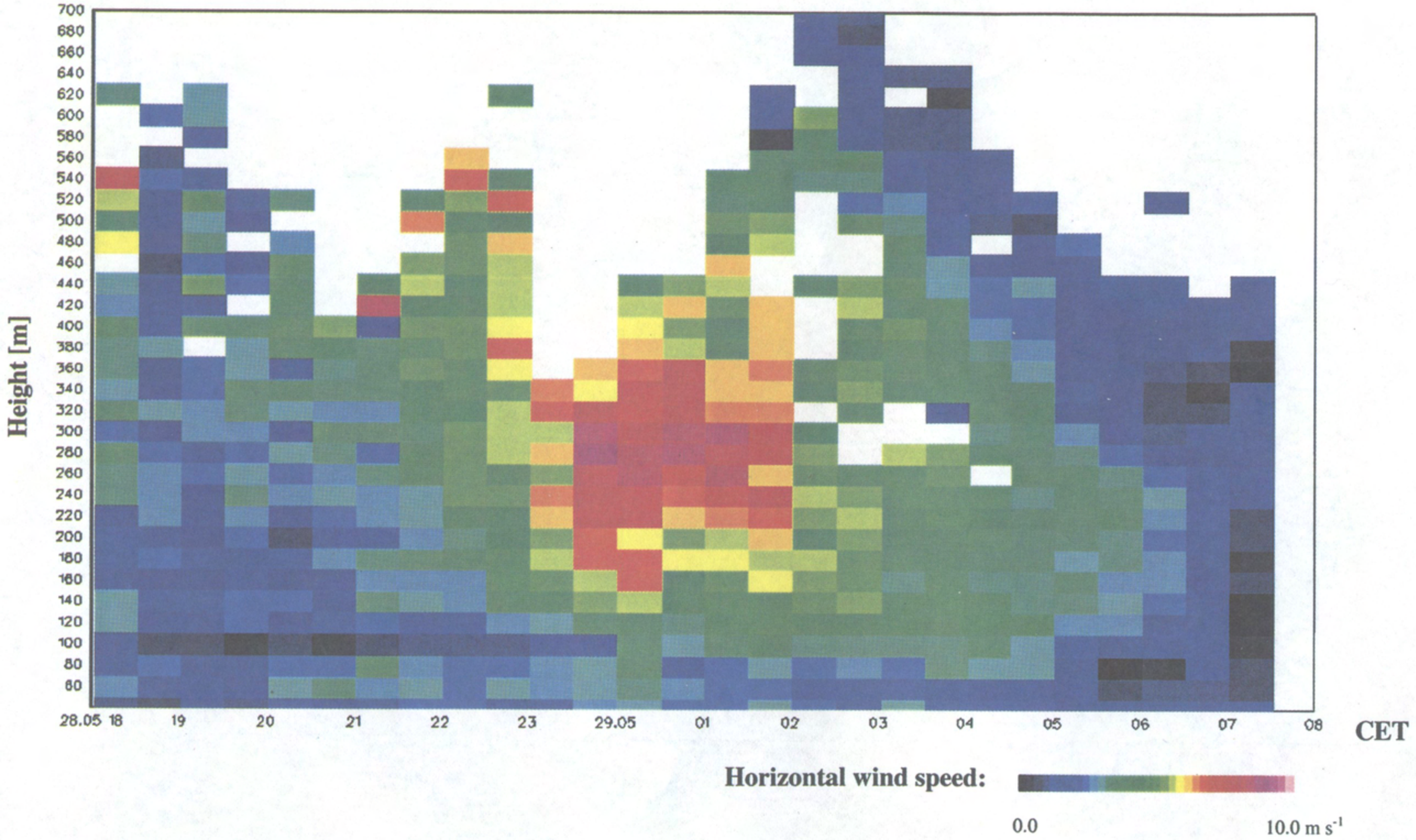

Fig. 4. Vertical soundings during a LLJ event with SODAR: horizontal wind speed from 60 to 700 m above ground, 20 m height resolution, 30 min averages, 28/29 May 1997, Grugapark Essen.

a peak speed of almost 10 m s^{-1} above ground level. This is just above the top of the nocturnal PBL at about 250 m. The fall in wind speed with increasing height above the core of the LLJ is also partly documented by the SODAR data. At 500 m we find a wind speed of 4 to 5 m s^{-1}.

Fig. 5, which shows the direction of the horizontal wind during that night from 18:00 CET to 07:30 CET the next morning, clearly confirms that this wind maximum is a LLJ. Here we find a 90° clockwise turn in the wind direction between 22:00 CET and 03:00 CET. An estimated 360° turn would take about 20 h, only slightly longer than the duration of the inertial oscillation which characterizes a LLJ at this latitude.

The most important parameter connected with the nocturnal ozone peak is the atmospheric turbulence. Fig. 6 shows the standard deviation of the vertical wind speed σ_w, which was about 0.6 m s^{-1} in the early evening. With the stabilization of the air, σ_w fell to about 0.2 m s^{-1} at 22:00 CET. AT 23:00 CET it started to rise again from above. In the first half hour after midnight values of 0.5 m s^{-1} and higher can be found in the whole column between the surface and the LLJ core. This is an increase by a factor of about 3. Later in the night, the air stabilizes again.

The increase in σ_w coincides perfectly in time with the increase in the surface ozone concentration. This finding therefore proves that the increase in the surface ozone concentration at midnight is due to enhanced vertical mixing. This vertical mixing is caused mechanically by the wind shear below the core of the LLJ.

4.2.2.3. Spatial distribution of O_3 maxima in North Rhine–Westphalia. The spatial distribution of ozone maxima was analysed using data obtained from the measurement network of the State Environmental Protection Office of North Rhine–Westphalia (area of North Rhine–Westphalia: approx. 34,000 km^2). This network consists of 33 ozone measurement stations located at the positions shown in Fig. 7.

On 28/29 May 1997, pronounced ozone maxima (Type I) were recorded at 11 of the stations in the centre in the Rhine/Ruhr area (shown as black circles in Fig. 7). To the east and south, very low ozone maxima were measured. The increase in concentration was less than 10 ppb – these stations are shown as grey circles. At the other stations (shown as white circles) in the far eastern and southern parts of North Rhine–Westphalia, there was no ozone maximum.

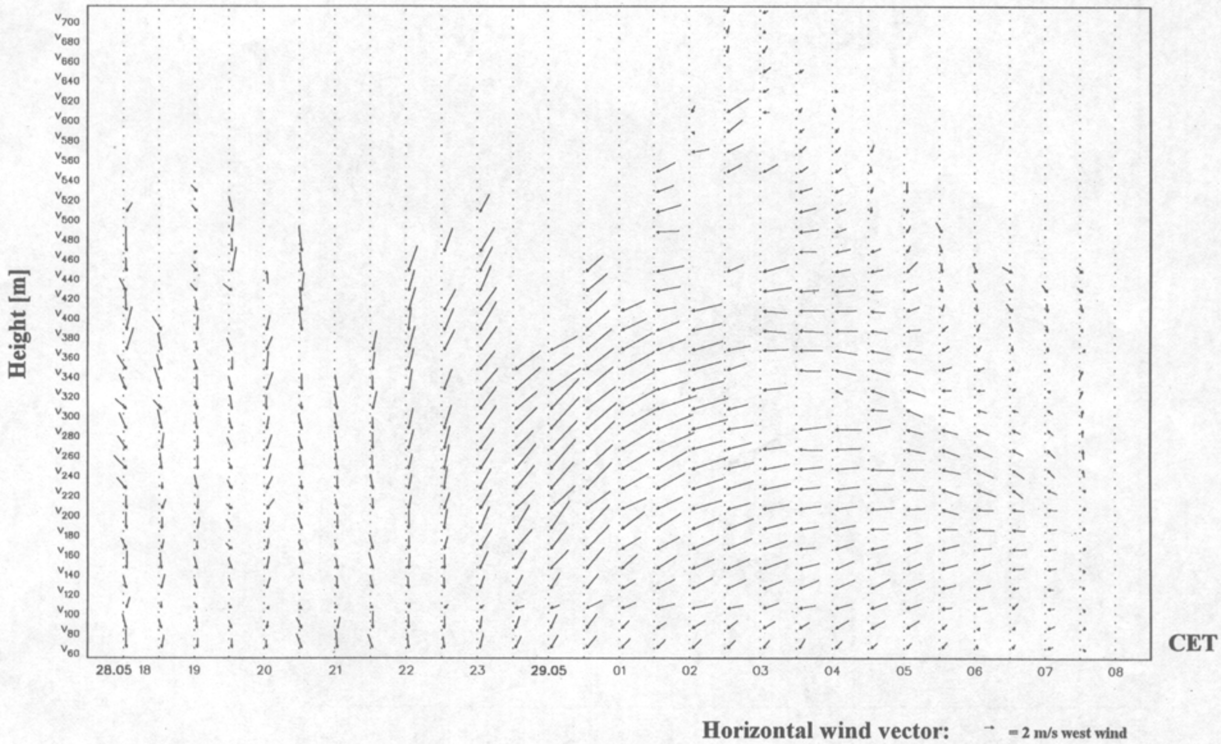

Fig. 5. Vertical soundings during a LLJ event with SODAR: horizontal wind vector from 60 to 700 m above ground, 20 m height resolution, 30 min averages, 28/29 May 1997, Grugapark Essen.

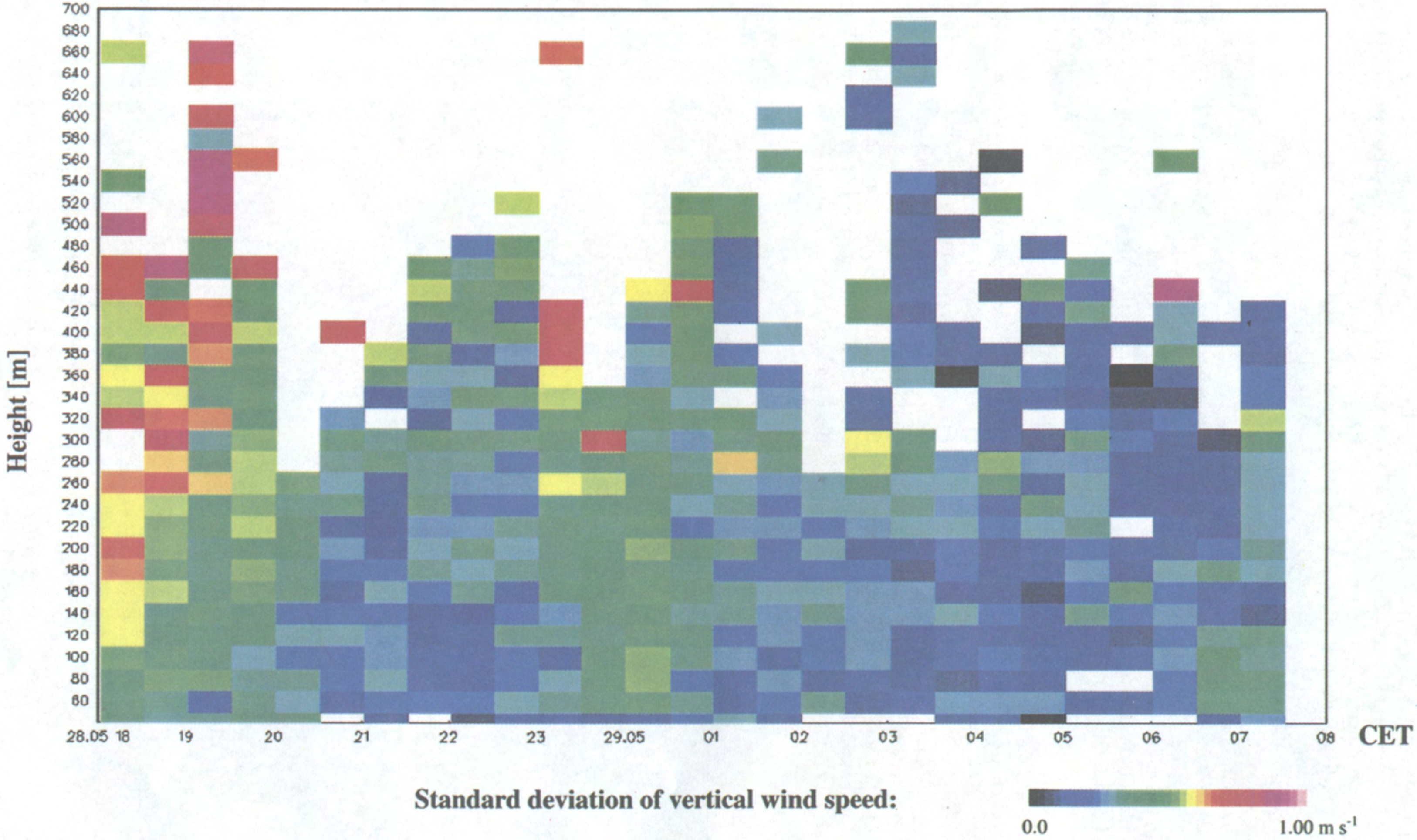

Fig. 6. Vertical soundings during a LLJ event with SODAR: standard deviation of vertical wind speed σ_w from 60 to 700 m above ground, 20 m height resolution, 30 min averages, 28/29 May 1997, Grugapark Essen.

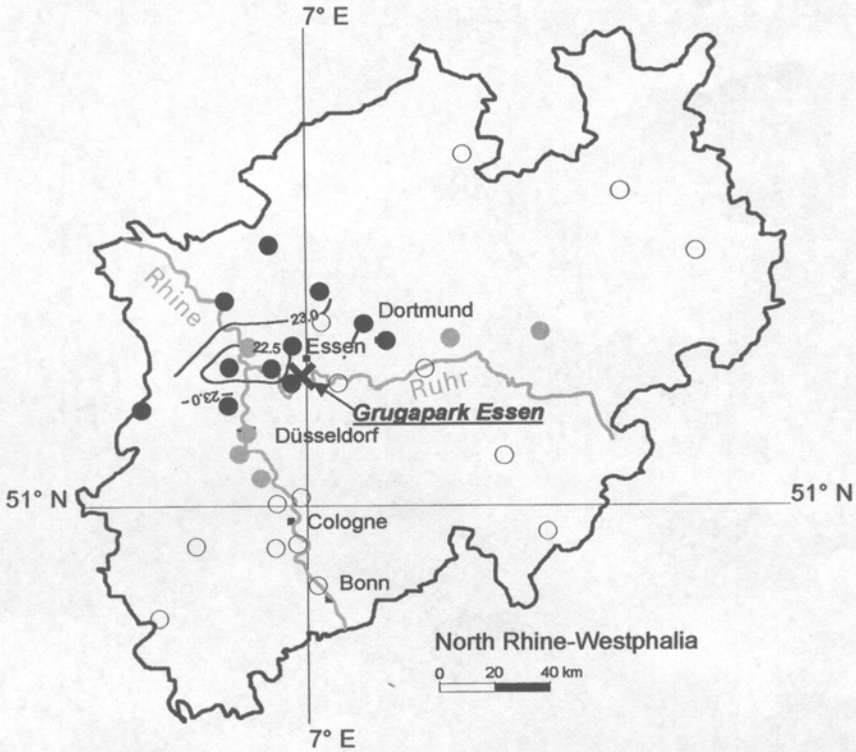

Fig. 7. Spatial and temporal distribution of ozone maxima with isochrones of the start time of ozone increase within the measurement network of the State Environmental Protection Office of North Rhine–Westphalia, 28/29 May 1997 (ozone maxima ⩾ 10 ppb – black circles, ozone maxima < 10 ppb – grey circles; no ozone maximum – white circles).

The time of occurrence of the maximum[2] is shown by the isochrones in Fig. 7. All the ozone maxima recorded during this night were Type I maxima and occurred at about the same time (22:00 and 23:30 CET). The ozone maximum in the Grugapark started at about 23:00 CET. These temporal and spatial conditions can be taken as an indication that the reason for the ozone concentration measured at all stations was the turbulence generated by the LLJ event. In the case of the Grugapark, this was confirmed by the SODAR measurements.

4.2.3. Passage of cold front, 26/27 May 1997 (ozone concentration maximum Type II)

4.2.3.1. Surface measurements. The event of 26/27 May 1997 is an example of an ozone maximum induced by a cold front. Fig. 8 shows the near-surface air quality and meteorological data. This cold front, which was not very strong, had a twofold structure. A first wind speed maximum and a small wind turn occurred around midnight (Fig. 8c); a second wind speed maximum and a somewhat larger wind turn took place at about 4:00 CET. Surface temperature and moisture recordings show that this event was accompanied by an air mass change. The air became cooler (most pronounced after 4:00 CET) and more humid between the two wind speed maxima (Fig. 8b). After the passage of the rear part of the front, dryer air arrived; this is a normal phenomenon following cold fronts.

The nocturnal ozone maximum occurred at about 0:30 CET, followed by a further maximum at a lower concentration level at 04:30 CET (Fig. 8a). Furthermore, wind speeds between 1.0 and 1.5 $m\,s^{-1}$ were recorded during the entire night. This nocturnal ozone maximum can be classified as Type II as there was no significant fall in ozone concentration following the peak value.

4.2.3.2. Vertical soundings. The synoptic analysis (not shown) and the analysis of the wind direction from the SODAR data (Fig. 9) also show that the front passed the measurement site during the night of 26 to 27 May 1997. A first very slight turn in the wind direction was observed

[2] In this case the time is the beginning of the O_3 increase because data at most stations during the peak concentration are not available due to monitor calibration.

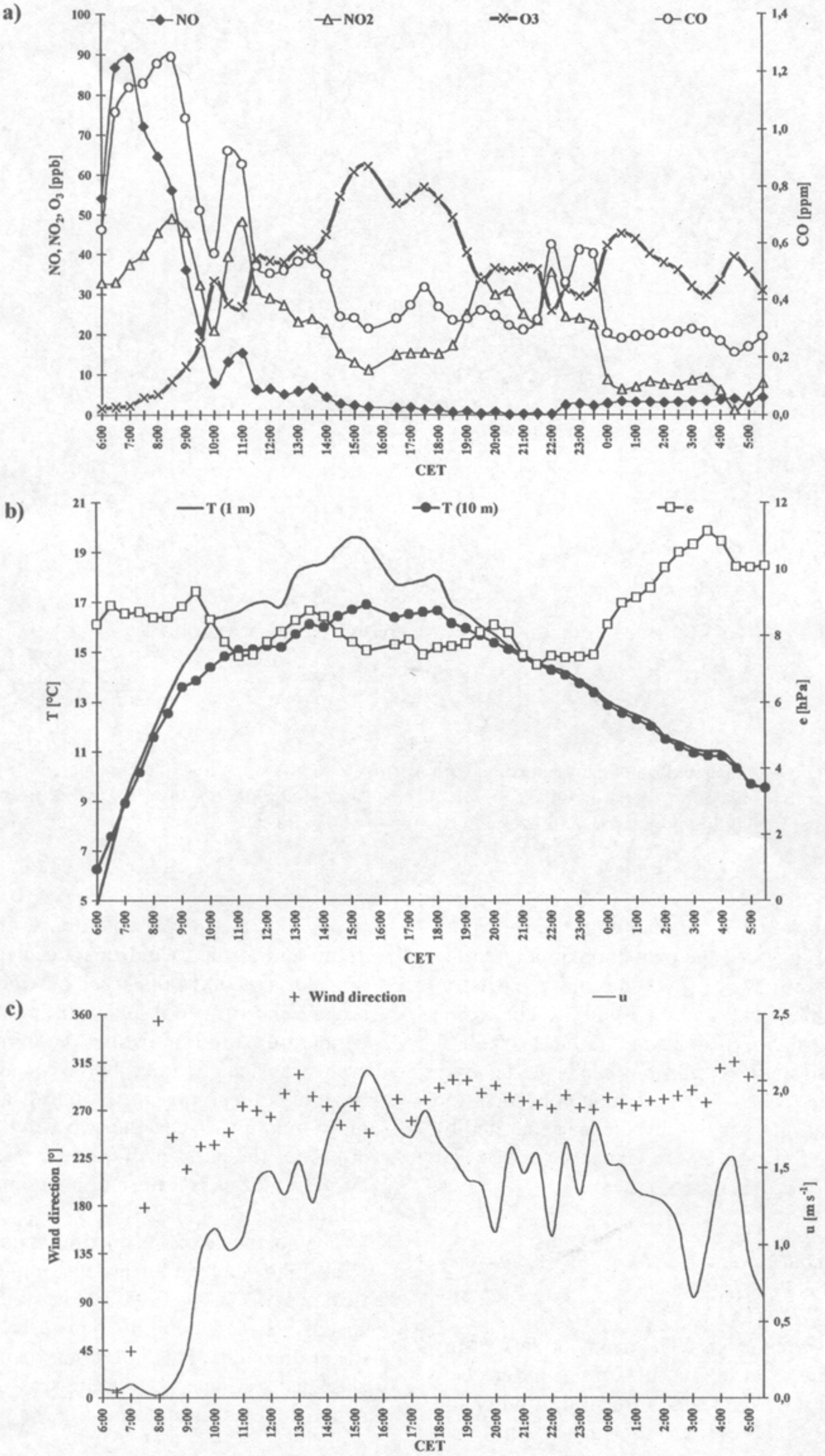

Fig. 8. Surface measurements during a cold front passage: diurnal courses (a) NO, NO_2, O_3 and CO concentrations, (b) air temperature (1 and 10 m above ground level) and water vapour pressure, (c) wind direction and speed, 30 min averages (based on 10 s values), 26/27 May 1997, Grugapark Essen.

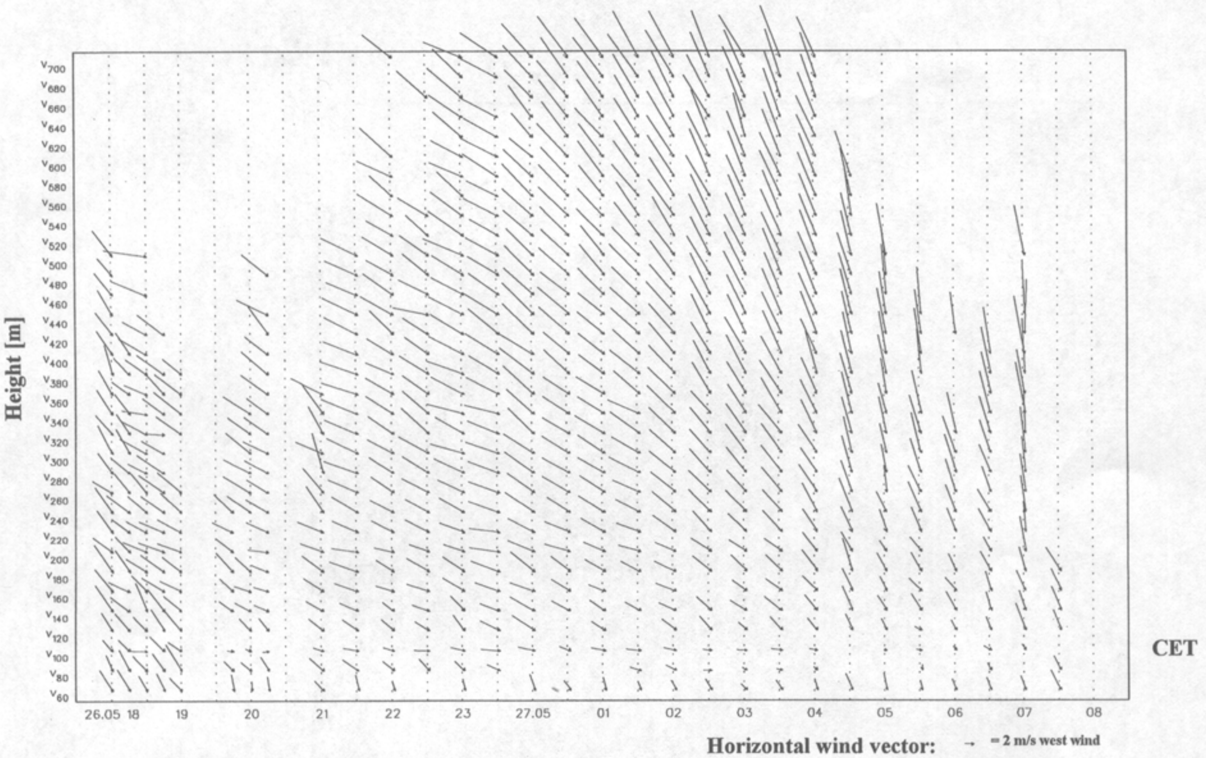

Fig. 9. Vertical soundings during a cold front passage with SODAR: horizontal wind vector from 60 to 700 m above ground, 20 m height resolution, 30 min averages, 26/27 May 1997, Grugapark Essen.

at about midnight. A second, somewhat stronger turn in the wind direction was detected about 4 h after midnight. It can be seen that the wind speed close to the ground remained low through the whole night. High wind speeds between 7 and 12 $m s^{-1}$ can be found at heights above 300 m. However, secondary wind speed maxima were also apparent at heights between 150 and 300 m at midnight and 04:00 CET.

Fig. 10 presents the standard deviation of the vertical wind speed σ_w during this night. This parameter reaches a maximum of 1.0 $m s^{-1}$ at 23:00 CET at a height of 280 m above ground level. Until midnight, σ_w increases with increasing height between ground level and 200 m. One hour after midnight, σ_w falls off again. A secondary maximum in σ_w at all heights can be detected at about 04:00 CET. The two σ_w maxima coincide with the twofold structure of the cold front and with the two ozone peaks during the night, at 00:30 CET and at 04:00 CET. Just as the increase in σ_w at about midnight was more pronounced than that observed at 4:00 CET, the increase in ozone concentration at midnight was larger than at 4:00 CET. This case is an example of increased nocturnal ozone concentrations caused by enhanced vertical mixing as the result of the passage of a front.

4.2.3.3. Spatial distribution of O_3 maxima in North Rhine–Westphalia. In North Rhine–Westphalia as a whole, secondary ozone maxima were measured at 26 of the 33 ozone measurement stations of the State Environmental Protection Office. In contrast to the maxima caused by LLJ on 28/29 May 1997, the maxima were measured in a clear temporal sequence between the different stations on 26/27 May 1997. Fig. 11 shows the stations with concentration maxima (black circles) together with isochrones of the start time of concentration increase. This clearly shows that the front passed through the investigation area from northwest to southeast following the prevailing wind direction (NW). In accordance with this pattern, ozone maxima were recorded at about 21:00 CET in the northwest of the investigation area and at about 00:00 CET in the south and southeast.

5. Discussion

On the basis of the surface and SODAR measurements made in Grugapark in Essen, it is possible to discern two different types of secondary ozone maxima. Type I is

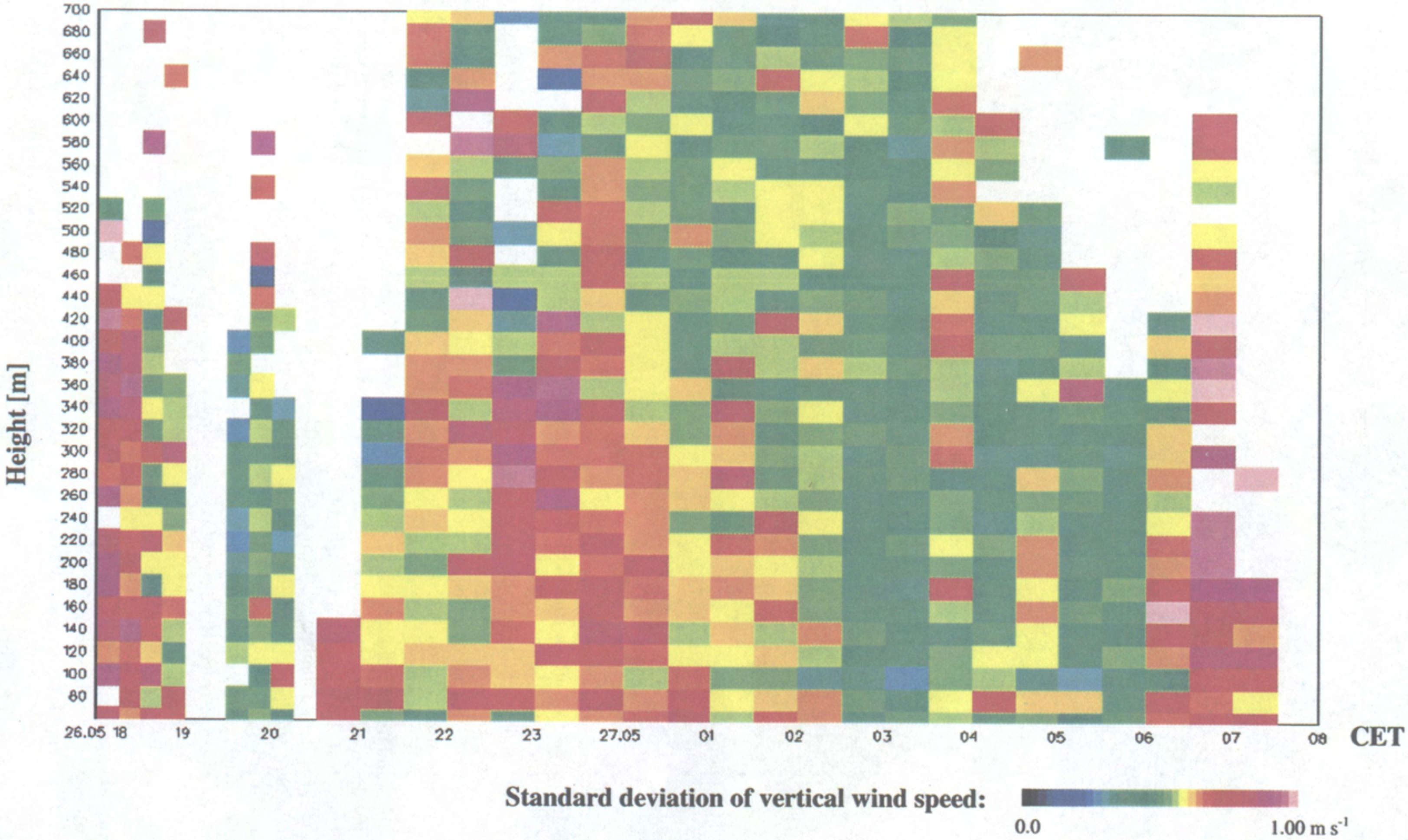

Fig. 10. Vertical soundings during a cold front passage with SODAR: standard deviation of vertical wind speed σ_w from 60 to 700 m above ground, 20 m height resolution, 30 min averages, 26/27 May 1997, Grugapark Essen.

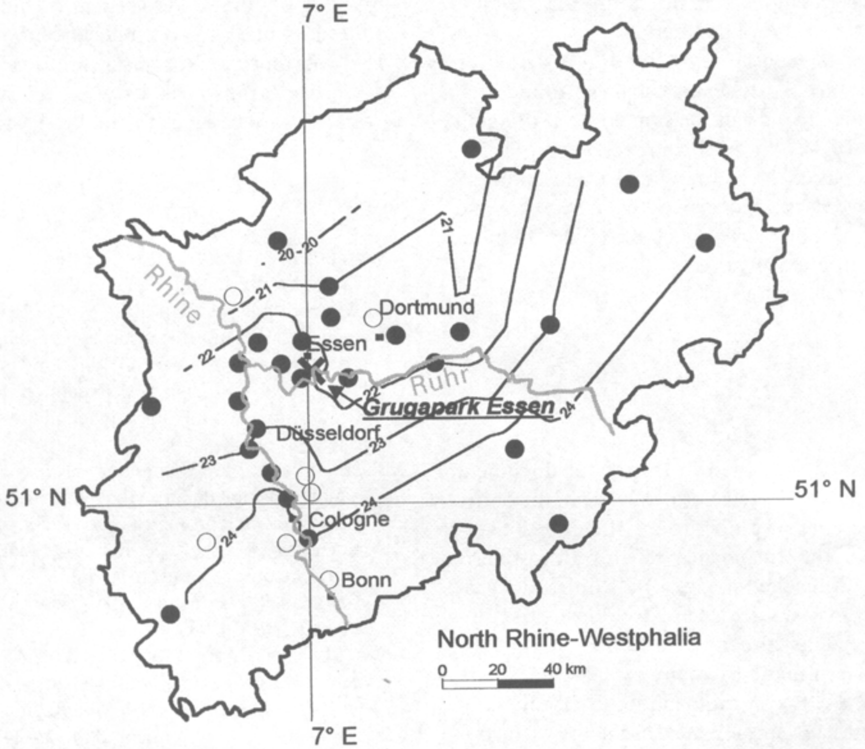

Fig. 11. Spatial and temporal distribution of ozone maxima with isochrones of the start time of ozone increase within the measurement network of the State Environmental Protection Office of North Rhine–Westphalia, 26/27 May 1997 (ozone maxima ⩾ 10 ppb – black circles, no ozone maximum – white circles).

mainly caused by turbulence induced by a nocturnal LLJ. Type II is mainly caused by turbulence linked to the passage of a front. The occurrence of this turbulence in the whole layer between the surface and 400–600 m above ground level is documented by the results from the SODAR measurements. Similar classifications of nocturnal ozone maxima have already been attempted. For example, Corsmeier et al. (1997) define two different types for a rural site. They also assume turbulence generated by a LLJ in one case on the basis of vertical temperature and humidity fluxes near the surface.

With regard to the occurrence of secondary ozone maxima, our results are in accordance with those of other authors as Zurita and Castro (1983), who measured nocturnal ozone concentration increases in Madrid between 01:00 and 06:00 CET. Spectral analyses showed peaks at intervals of 12 and 24 h. The 12 h peaks correspond to diurnal courses with one peak during the daytime and one nocturnal maximum. In Hamburg, Winkler (1980) showed that ozone maxima occurred during about 30% of summer nights and that the maximum occurred after at least six hours of negative radiation balance in 90% of the cases. These observations are also confirmed by the Grugapark data where nocturnal ozone maxima occurred at least at 5.5 h after negative radiation balance. Winkler (1980) suspected that secondary ozone peaks were connected with a disturbance of the nocturnal boundary layer which could have two causes. The first cause suggested was turbulence generated by a boundary layer jet stream. With inertial fluctuation with a period of 16 h on the North German plains, maximum wind shear is expected after 4–8 h. The second cause proposed is density-induced waves at the inversion limit, occurring at about 04:00 CET, 1–2 h later than the nocturnal ozone maximum. Other authors also attempt to explain nocturnal ozone concentration increases and vertical transfer of heat and momentum by breakdown of stability (Nappo, 1991). For example, in the rural Central Piedmont region of North Carolina, Das and Aneja (1994) recorded an increase in H_2O_2 concentration and air temperature at the same time as a rise in ozone concentration. In accordance with our investigation, an increase in air temperature and wind speed is also observed by other authors during nocturnal breakdown of stability, e.g. Garland and Derwent (1979) or Jacobi and Roth (1995). However, Steinberger and Ganor (1980) investigated the frequency of nocturnal ozone concentration increases in excess of 30 ppb in Jerusalem and Tel Aviv. They did not find any correlation between wind, air temperature and relative humidity of the type determined here.

With respect to the spatial and temporal distribution of secondary nocturnal ozone maxima, we found that ozone peaks occurred at about the same time at different stations during a LLJ event. According to Freytag (1978), for example, the spatial extension of nocturnal boundary layer jet stream events may reach lengths of 2000 km and widths of 400 km. Löffler-Mang et al. (1996) demonstrated the sequential occurrence of ozone maxima with the passage of a cold front, similar to the results presented here.

6. Conclusions

The measurements presented in this paper document for the first time the shear-driven turbulence in the entire layer between the core of a nocturnal LLJ and the surface. In addition, the turbulence in the atmospheric boundary layer during the passage of a front is demonstrated. The SODAR data presented confirm assumptions which have – as already mentioned in the discussion above – been made by many researchers. These data close the gap between radiosonde observations of the LLJ itself and near-surface measurements of turbulent vertical fluxes. Hitherto, the existence of the shear-driven turbulence in the layer below a nocturnal jet could only be inferred indirectly from the radiosonde and surface data. Further, the classification of the temporal pattern of the surface ozone concentrations during the night proposed in this paper allows the frequency of such nocturnal turbulent vertical fluxes to be estimated from surface observations.

The direct measurement of this shear-driven turbulence is a first important step towards the quantification of vertical turbulent fluxes of energy and atmospheric admixtures. These turbulent vertical fluxes establish a link between the surface layer and the residual layer above, and thus influence the pollutant budgets in the residual layer and especially in the rather shallow nocturnal boundary layer.

The knowledge of these fluxes is important for the assessment of the air quality in the nocturnal boundary layer. Pollutants such as nitric oxides and CO from anthropogenic emissions which have accumulated in the shallow nocturnal boundary layer may be transported away into the residual layer. This has a positive effect on the air quality in the surface layer. On the other hand, other pollutants such as ozone which have been advected by long-distance transport in the residual layer may be transported downward into the surface layer, with a negative impact on the air quality in the surface layer.

If the parallel remote sensing techniques with vertical and temporal resolution, comparable to the SODAR data become available for rapid fluctuations in atmospheric pollutants, the vertical turbulent fluxes of these pollutants may be computed from such measurements. This will represent an important link in the whole chain of vertical transports between all atmospheric layers from the surface layer to the lower stratosphere.

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