Pergamon

Atmospheric Environment Vol. 28, No. 7, pp. 1255–1266, 1994
Elsevier Science Ltd
Printed in Great Britain.
1352-2310/94 $6.00+0.00

1352-2310(94)E0009-9

ORIGIN OF OZONE IN VIENNA AND SURROUNDINGS, AUSTRIA

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(*First received* 12 *April* 1993 *and in final form* 20 *December* 1993)

Abstract—A statistical analysis of local scale ground-level trajectories during three summer half years was made to determine the influence of Vienna on the ozone concentrations in the surroundings. It was possible to show that on average, Vienna does not act as an ozone source for sites in the surroundings. Only on the hottest days of each year around noon is it a strong source of ozone. Therefore, long-range transport of ozone must be important for the average ozone concentrations. This was investigated by a statistical analysis of isobaric backward trajectories. In summer, high ozone concentrations in Vienna and surroundings are often associated with trajectories arriving from areas in Europe which agree reasonably well with those having high anthropogenic emissions of precursors. In winter, an important source of ozone in eastern Austria is transport from the Atlantic Ocean. Tropospheric background ozone concentrations in Vienna and surroundings were estimated from surface measurements during periods of high wind speed. A mean summertime tropospheric background concentration of 30–40 ppb ozone was found for air masses of maritime origin, while it was 70–75 ppb for continental air masses.

Key word index: Ozone, photochemical smog, urban plume, ozone transport, background ozone concentrations, statistical analysis of trajectories, Vienna.

1. INTRODUCTION

Ground-level concentrations of ozone in Europe have increased considerably since the pre-industrialized era, as has been shown by many authors (Bojkov, 1985; Feister and Warmbt, 1986; Kley *et al.*, 1988). Ozone concentrations in the free troposphere are also much higher now than 25 years ago (Staehelin and Schmid, 1991). Wege and Vandersee (1991) found that at the German site Hohenpeißenberg the ozone concentrations in the free troposphere increased by 2.2% per year between 1967 and 1989. Guicherit and van Dop (1977) were among the first to show that during photochemical episodes high ozone concentrations occur over large parts of Europe simultaneously.

Ozone and other photochemical pollutants are produced from a variety of precursors (Leighton, 1961), namely nitrogen oxides (NO_x), volatile organic compounds (VOC) and carbon monoxide (CO). In the initial steps of photochemical smog formation ozone is also being destroyed by the emitted species. Whether ozone concentrations at a given site are higher or lower than the background concentration (i.e. whether more ozone is produced or destroyed) depends on source strengths of primary pollutants, species of pollutants emitted, meteorological conditions and distance to the emitters.

A great number of studies investigating the urban influence on ground-level ozone exist. It has been shown by many authors that a plume of high ozone concentrations can form leewards of a large city during favourable meteorological conditions (e.g. Altshuller, 1988; Fricke, 1980; Kanbour *et al.*, 1987; Uno *et al.*, 1984; Varey *et al.*, 1988). Ober and Puxbaum (1990) and Wotawa *et al.* (1993) detected a similar effect leewards of Vienna. However, there have been discussions about the frequency of urban plume formation. Angle and Sandhu (1989) showed that Canadian cities act as sinks for ozone during most of the year and McKendry (1993) pointed out that ozone concentrations in Montreal are lower than in the surroundings during the whole year.

Therefore, the objective of this work was to investigate the frequency of local ozone formation or destruction in the plume of Vienna and to estimate the contribution of long-range transport to the observed ozone concentrations in Vienna.

2. DATABASE

The area under investigation is situated in the eastern part of Austria (Fig. 1), covering the city of Vienna (population 1.7 million) and its surroundings. The terrain is relatively flat at about 200 m above sea level (m.a.s.l.), but to the west and southwest of Vienna some peaks of the Alpine foothills (Wienerwald) rise up to 800 m.a.s.l. Vienna, at a latitude of 48°12′, generally has high temperatures in summer. The 1951–1980 mean temperatures of July and August at meteorological observatory Hohe Warte are 19.5 and 19.0°C, respectively (Auer *et al.*, 1989).

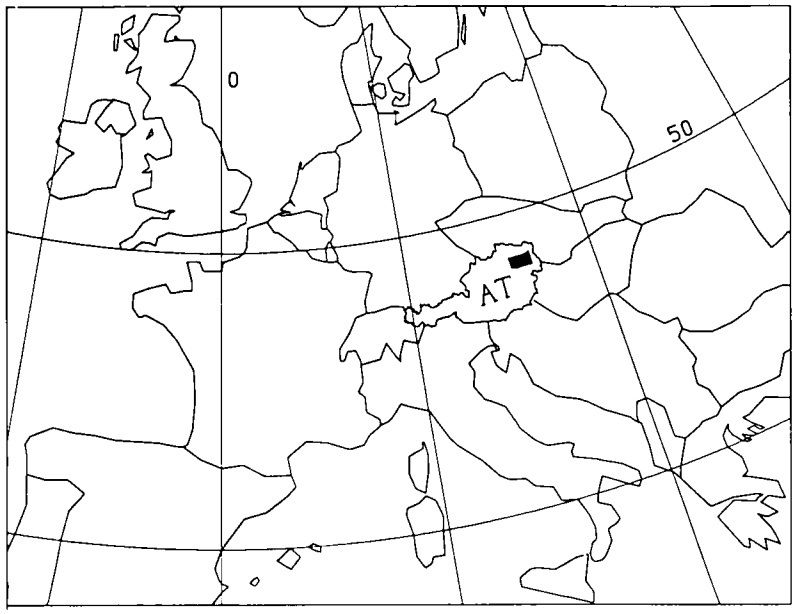

Fig. 1. Map showing the location of the investigation area (black rectangle) in eastern Austria.

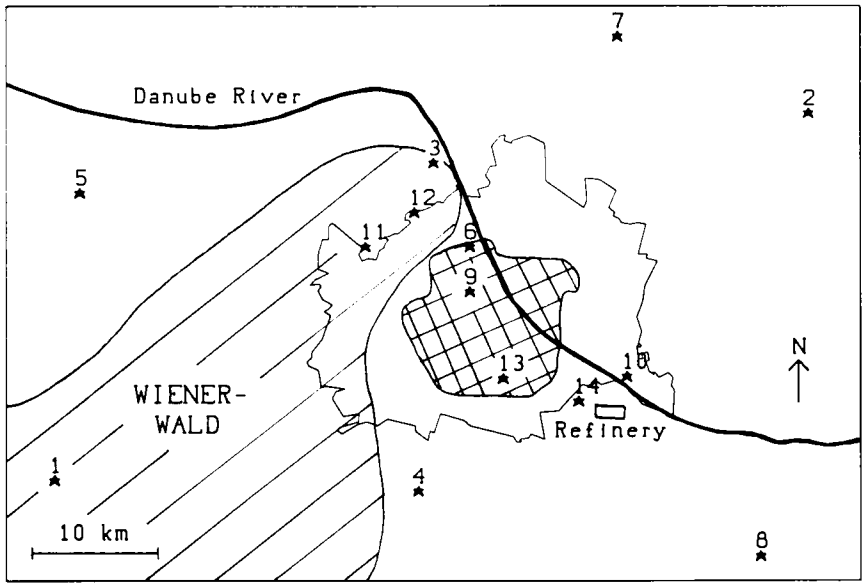

Fig. 2. Locations of the ozone monitoring stations. The sites mentioned in the text are: 6 Hohe Warte, 8 Stixneusiedl, 11 Exelberg. The thick solid line is the Danube and solid lines are city borders. The hatched area within the city borders is densely populated. The Wienerwald area has complex topography with peaks up to 800 m, the rest of the area is flat at about 200 m a.s.l.

Ozone data from the operational air pollution monitoring networks of the federal states of Lower Austria and Vienna, and the Austrian Federal Environmental Agency were analysed in this study. At most sites Monitor Labs 8810 devices with a detection threshold of 2 ppb were used.

The investigation covers the period from January 1989 to September 1992. Figure 2 shows the locations of the 14 ozone monitoring stations, which include three sites situated on top of hills in rural areas (stations number 1, 11, 12), six flat rural sites (2, 3, 5, 7, 8, 10), and five urban or suburban sites (4, 6, 9, 13, 14).

3. TRAJECTORY ANALYSIS

3.1. *Local scale*

The average of the half-hourly means of the 14 ozone measuring sites is considered to be an approximate measure of the spatial mean ozone concentration near the ground in the investigation area. It is only slightly influenced by local production or destruction, because only a few stations can be simultan-

eously situated in the plume of Vienna. The spatial mean concentration was subtracted from the actually measured concentration at one site to obtain "ozone surplus" values for this site. Using this method it is possible to reduce the influence of meteorological factors (such as temperature and global radiation) and regional scale transport on the results, as both the spatial mean and the concentration at a specific site should be influenced in the same way. Therefore, surplus values larger than zero indicate local production of ozone, e.g. in the plume of Vienna, whereas values lower than zero indicate local destruction of ozone. With the help of a statistical analysis of back trajectories the frequency of ozone production and destruction were examined.

Simple ground-level trajectories in Vienna and surroundings were computed using half hourly and hourly surface wind measurements of 25 observation sites. Figure 3 shows the wind roses of the sites used for this analysis. Winds are mostly from NW or from SE, but to the west of Vienna a clear influence of the hilly terrain of the Wienerwald can be seen, leading to frequent SW winds. Wind speed measurements were extrapolated to a reference height of 30 m using an exponential wind profile $u(z)=u(z_a)*(z/z_a)^m$, where z is 30 m, z_a is the anemometer height, u is the wind speed and m is an exponent, characterizing atmospheric stability. Wind direction was not modified. Greater accuracy of trajectories would have been obtained using a three-dimensional boundary layer model, but as no verified model exists for this region, this simple procedure was considered to be an acceptable approximation.

For the summer half-years 1990–1992 (April–September) every half-hour backward trajectories from the ozone measuring sites were calculated using the Petterssen scheme (Petterssen, 1940) with a time step of 15 min. The trajectories were computed until either a time limit of 15 h was exceeded or they left the investigation area.

A grid was laid over a map of Vienna and surroundings with a grid distance of 2 km. The residence time of each trajectory was calculated for each grid element it crossed and the subset of trajectories arriving at times when the 90th percentile of the "ozone surplus" was exceeded were compared with the complete set of trajectories. For the total residence time of all trajectories in one grid element the following relations are defined

$$T=\sum_{i=1}^{10}\sum_{j=1}^{n_i}\tau_{i,j}=\sum_{i=1}^{10}t_i$$

$$t_i=\sum_{j=1}^{n_i}\tau_{i,j}$$

$$n_i=N/4 \quad \forall i$$

where T is the total residence time of all trajectories, t_i is the residence time of trajectories in the ith subset, $\tau_{i,j}$ is the residence time of a single trajectory, N is the total number of trajectories and n_i is the number of trajectories of the ith subset.

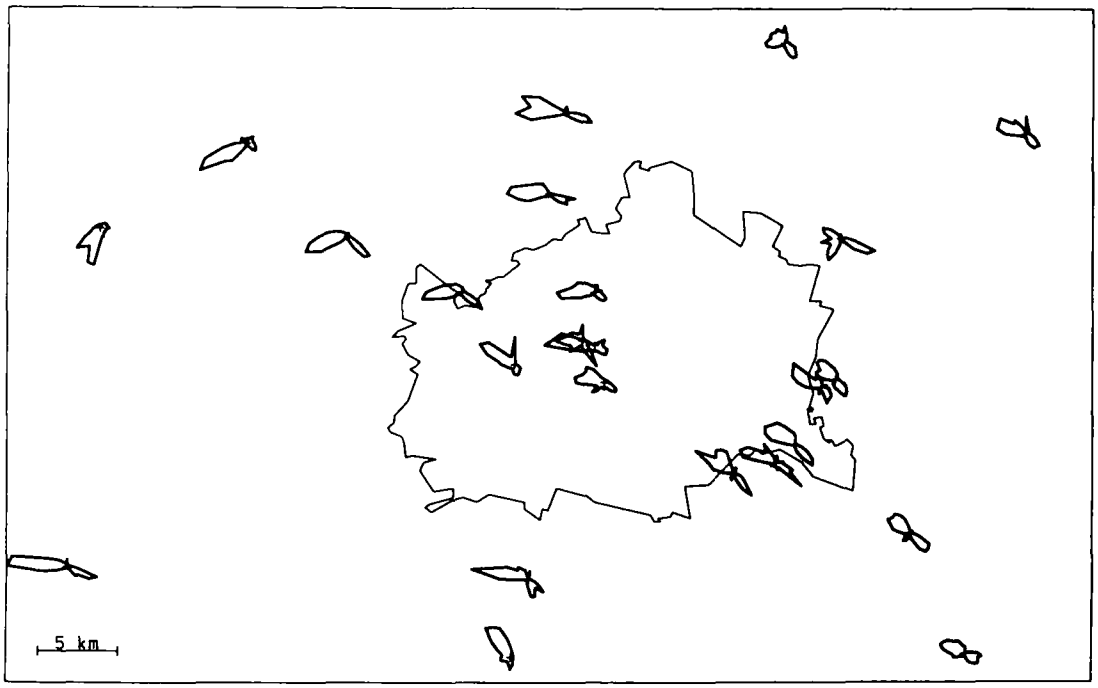

Fig. 3. Windroses of the 24 measuring sites used for trajectory calculation.

If the ozone concentrations were independent of the path of the trajectories, the expected value for the ratio t_i/T would be 1/10 for every grid element. However, since the path of an air parcel determines the ozone concentration in it to a considerable extent, deviations from this value can be found. No statistical test has yet been found to determine the significance of these deviations, since it is dependent on many factors such as persistence of weather patterns, number of trajectories crossing each grid element, speed of the air parcels, etc. Therefore, to eliminate obviously insignificant values, ratios of t_i/T were only calculated if T was larger than 3 h.

A ratio of $t_{10}/T > 0.1$ in a grid element indicates that an "ozone surplus" exceeding the 90th percentile occurs for more than 10% of all trajectories crossing over the area of this grid element, i.e. a higher frequency than expected from an independent distribution.

The figures presented are for the station Exelberg (wooded area, tower on top of a hill, 60 m above ground level), because it has the highest mean as well as the highest peak ozone concentrations in the investigation area and is therefore of special interest. However, the trajectory analysis yielded similar results for other stations. For the summer half years 1990–1992 the ratio t_{10}/T is slightly higher than 0.1 in the city centre (Fig. 4), but the highest values for t_{10}/T are found in the wooded area of the Wienerwald, where anthropogenic emissions are much lower than in the city. Thus, even for times with ozone surplus exceeding the 90th percentile, the city of Vienna is not an important source of ozone for Exelberg. Ratios of t_{10}/T below 0.1 are mostly found outside the area depicted in Fig. 4.

For a better estimation of the importance of plume formation leewards of Vienna the data set was restricted to daytime hours between 10 and 20 local time. t_{10}/T is approximately 0.2 in the city, but still no clear trajectory path leading most frequently to the highest ozone concentrations is discernible.

However, when reducing the data set to the noontime hours (11:30 a.m.–14:30 p.m.) of the 150 hottest days (highest mean daytime temperatures) of the years 1990–1992, a strong influence of the city of Vienna is visible (Fig. 5). There is a marked path of high values for t_{10}/T over the city of Vienna. More than 50% of all trajectories travelling along this path result in ozone surplus above the 90th percentile. Thus, the city of Vienna is a strong source of ozone at Exelberg during hot days around noon. The path does not exactly cross the city centre, which can be explained by the low level of the trajectories. It is probable that the corresponding trajectories at a higher level would lead over the centre, because of the vertical wind shear.

Nearly the same results can also be found for two other sites (3 and 12) immediately to the NW of Vienna. In Stixneusiedl (8), to the SE of Vienna, approximately 30% of the trajectories crossing the city centre are leading to ozone surplus exceeding the 90th percentile. For other sites this method is not applicable, either because they are too close to the city or because they are not in the main wind directions from Vienna.

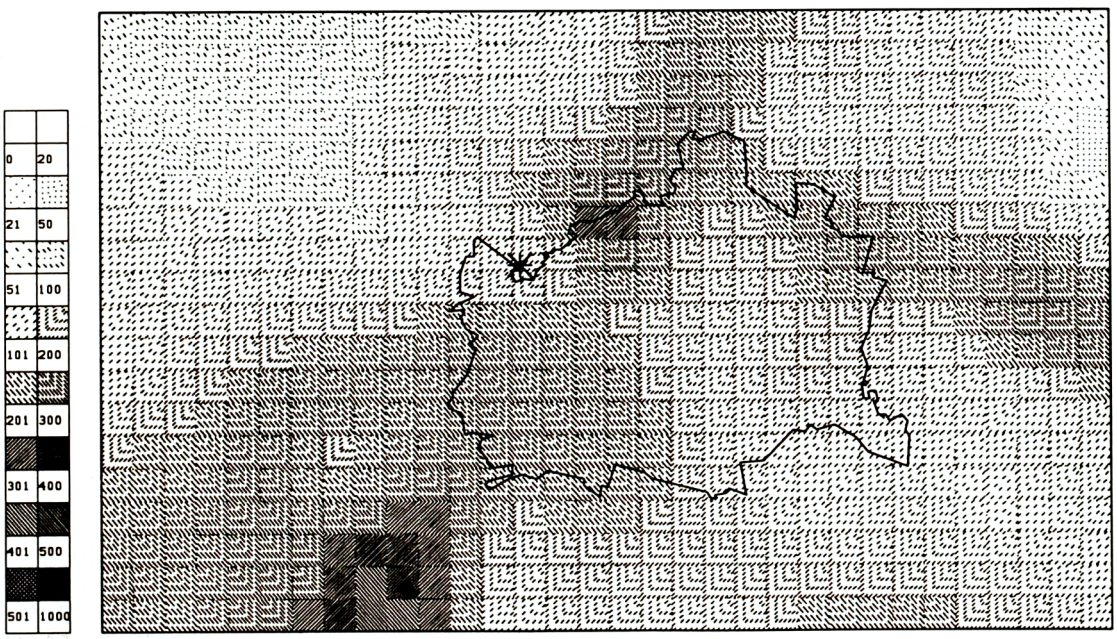

Fig. 4. Ratio t_{10}/T for the residence times of back trajectories arriving on Exelberg for the summer half-years 1990–1992. T is the residence time of all trajectories, t_{10} the residence time of trajectories leading to "ozone surplus" above the 90th percentile. The scale on the left side gives the shading code for t_{10}/T in per mille. The star marks the position of Exelberg.

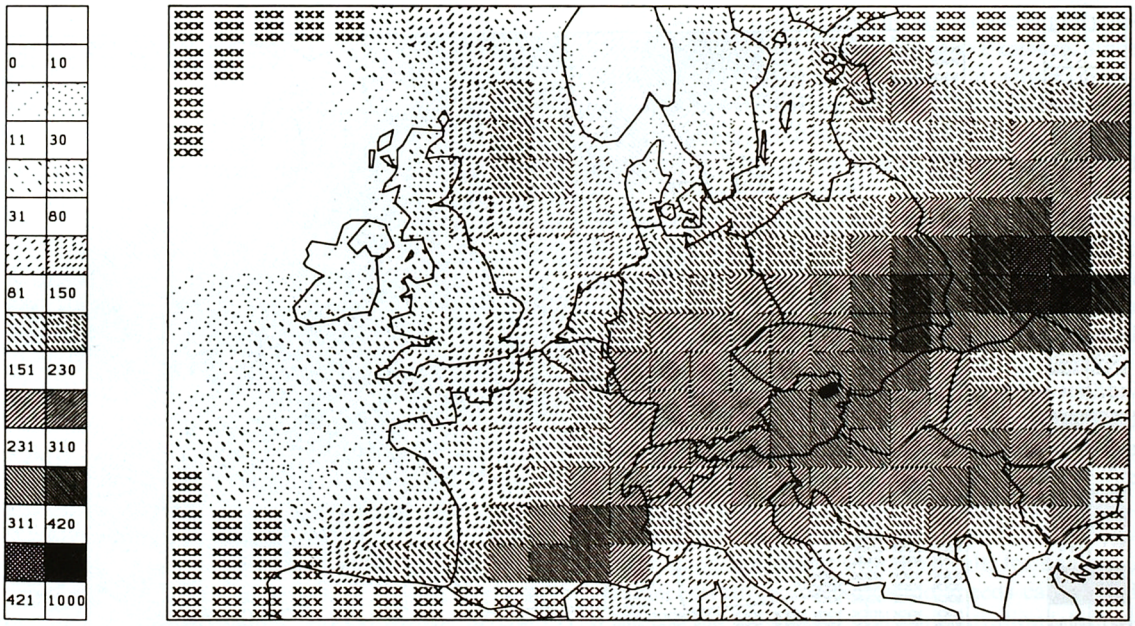

Fig. 5. Same as Fig. 4, but for the noontime hours (11.30–14.30) of the 150 hottest days of the years 1990–1992. Ratios t_{10}/T were not computed, when $T<3$ h to avoid obviously insignificant values. These grid elements were marked with "xxx".

Table 1. Average ozone surplus (ppb) on Exelberg for the whole summer half year (1), daytime hours (2) and hot days around noon (3). Values are given for all cases (A), times when trajectories came from the area to the west of Exelberg (B) and times when trajectories came from the city centre (C)

	A	B	C
1	12	12	10
2	19	18	20
3	5	−2	25

For a rough estimation of the contribution of the city of Vienna to the ozone budget on Exelberg another method was applied. The average ozone surplus values on Exelberg were computed for the whole data set, for times when the trajectories crossed the city centre (approximately the hatched area in Fig. 2) and for times when the trajectories came from the area to the west of Exelberg. The surplus values were weighted with the residence time of the trajectories in the respective areas. Results are given in Table 1. Because Exelberg has the highest mean ozone concentrations of all stations (which is partly due to the great height) ozone surplus is positive most of the time. Thus, conclusions on absolute values of ozone production or destruction in the urban plume can only be drawn by a comparison of the values for trajectories crossing the city centre with those which came from the west.

From Table 1 it can be seen that during the summer half years, Vienna acts as a weak net sink for ozone, although this result may not be significant. During daytime Vienna is a weak source of ozone, but for the hottest 150 days around noon (11.30–14.30) the additional ozone production in the plume of Vienna equals 20–25 ppb. These values may be an underestimation, because the spatial average, which is subtracted from the actual concentrations to give ozone surplus, is also influenced by the plume of Vienna to some extent.

For other stations the ozone production in the urban plume was smaller than at Exelberg. For the hottest days around noon, the average ozone production in Stixneusiedl, southeast of Vienna, was 15–20 ppb.

3.2. *Regional scale*

As has been shown above, local ozone production leads to the peak ozone concentrations, but the city of Vienna has little influence on the average ground-level ozone concentrations in the surroundings. Therefore, most of the ozone must be advected on a regional scale. For an investigation of these transport processes 48 h isobaric backward trajectories for 850 hPa (Mahringer, 1986) were analysed as described above for the period July 1990–September 1992. 850 hPa trajectories are thought to be most representative for the long-range transport of air pollutants, because this level approximately equals half the maximum mixing height in summer. The computation of the trajectories is based on 6-h updated analysed wind

fields of the ECMWF (European Centre for Medium-range Weather Forecasts). A computation scheme after Petterssen (1940) with a time step of 6 h is used. For each day at 12 and 0 UTC five trajectories with starting points in the corners and in the centre of the map shown in Fig. 2 were computed. The use of five trajectories instead of only one at a time gives somewhat smoother fields of residence times.

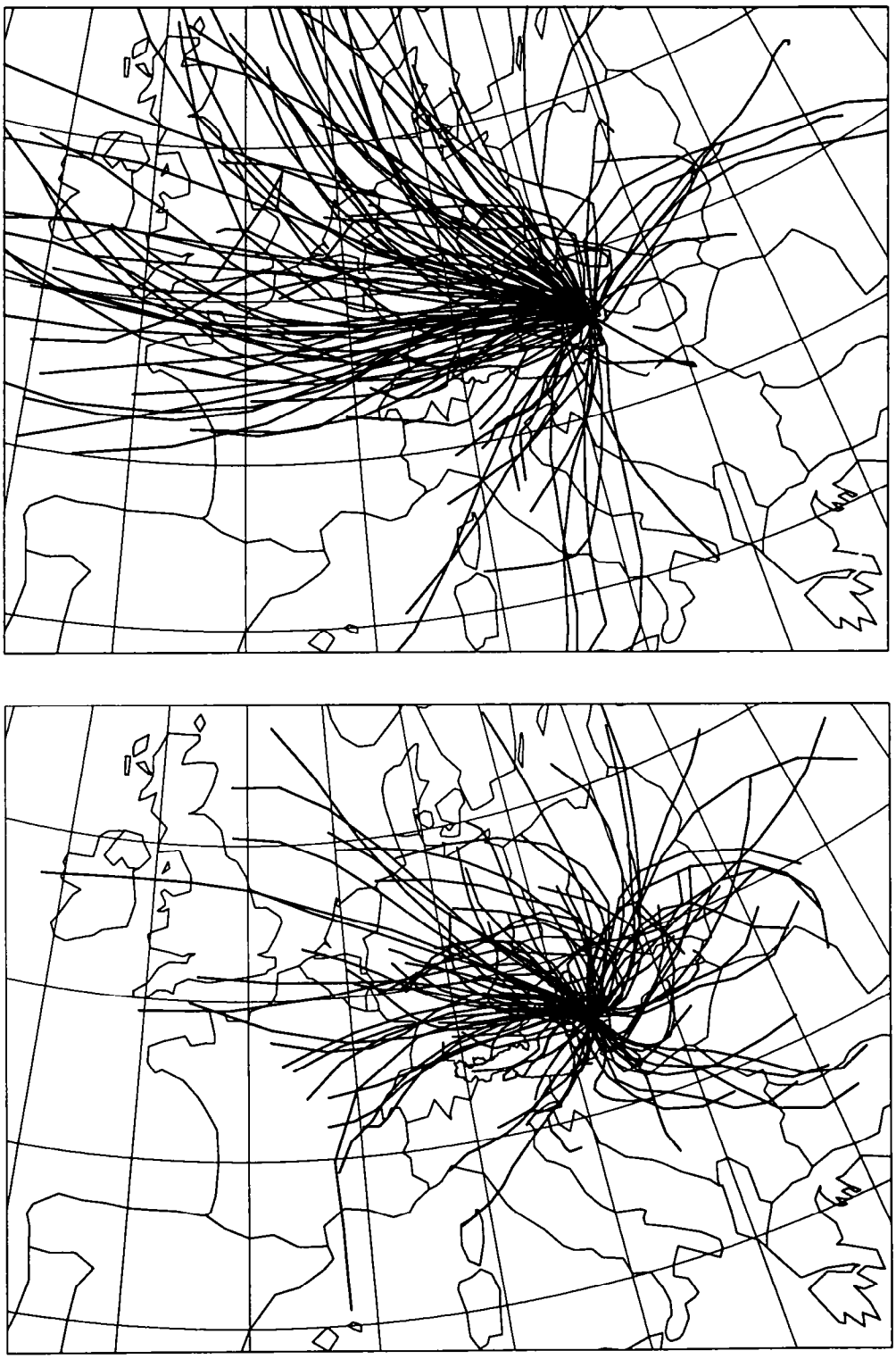

Fig. 6. Backward trajectories for the first (top) and the fourth (bottom) quartile of ozone concentrations.

To minimize the effect of any local influence on the ozone concentrations, the half-hourly means of the 14 measuring sites were averaged and the daily maximum was determined. Summer (April–September) and winter half-years (October–March) were analysed separately, because ozone shows a distinct behaviour in summer and winter.

As photochemical production of ozone is more likely to occur in June–July than April–May, the ozone concentrations are also higher in these months. To reduce this seasonal variation, each half year was divided into three 2-month periods. Each of these periods was divided into four subsets, representing the quartiles of ozone concentrations. The corresponding quartile subsets of the three 2-month periods were put together to yield only one subset for each quartile for the half year. Combining the highest quartiles of ozone concentrations for April–May, June–July and August–September is a sensible approach as the highest concentrations are expected to occur under similar conditions (even though the absolute values may be substantially different). Figure 6 shows the 12 UTC trajectories of the 1st and 4th quartiles, respectively. It can be seen that high ozone concentrations are frequently associated with anticyclonically bended trajectories (in many cases arriving from continental areas), while for low ozone concentrations trajectories have cyclonic curvatures and arrive from the Atlantic or the Mediterranean. This is in good agreement with the early findings of Guicherit and van Dop (1977).

For a more quantitative discussion the residence times of the trajectories of each ozone quartile were compared to the total residence times of all trajectories using the same method as in Section 3.1. A value of t_4/T for a given grid element for the 4th quartile does not necessarily indicate a frequent transport of high ozone concentrations from that area to the area of study. It might just mean that meteorological conditions favourable to those trajectories are also favourable to local ozone production in eastern Austria. Therefore, interpretation of the results has to be done carefully.

Figure 7 shows that in summer high ozone concentrations (values in the 4th quartile) are a phenomenon occurring mostly in continental air. A given trajectory is most likely to be connected with high ozone concentrations when it comes from the east, namely from Slovakia, Poland or Hungary or if it stays a long time in Austria. Approximately 40% of all trajectories from these areas lead to ozone concentrations in the 4th quartile. During high ozone concentrations practically no trajectories come from the Atlantic Ocean or Scandinavia (between 0 and 15% of all trajectories) and few from the Mediterranean.

For the 1st quartile the results for summer (not shown) are just the opposite. Over the Atlantic Ocean t_1/T is well above 0.4, while for eastern Europe t_1/T is below 0.1.

Temperature has a very important influence on ozone formation and resulting ozone concentrations (Wunderli and Gehrig, 1991). To reduce this influence (which does not give information on the influence of patterns of anthropogenic precursor emissions) a linear regression analysis for the summer half-year was

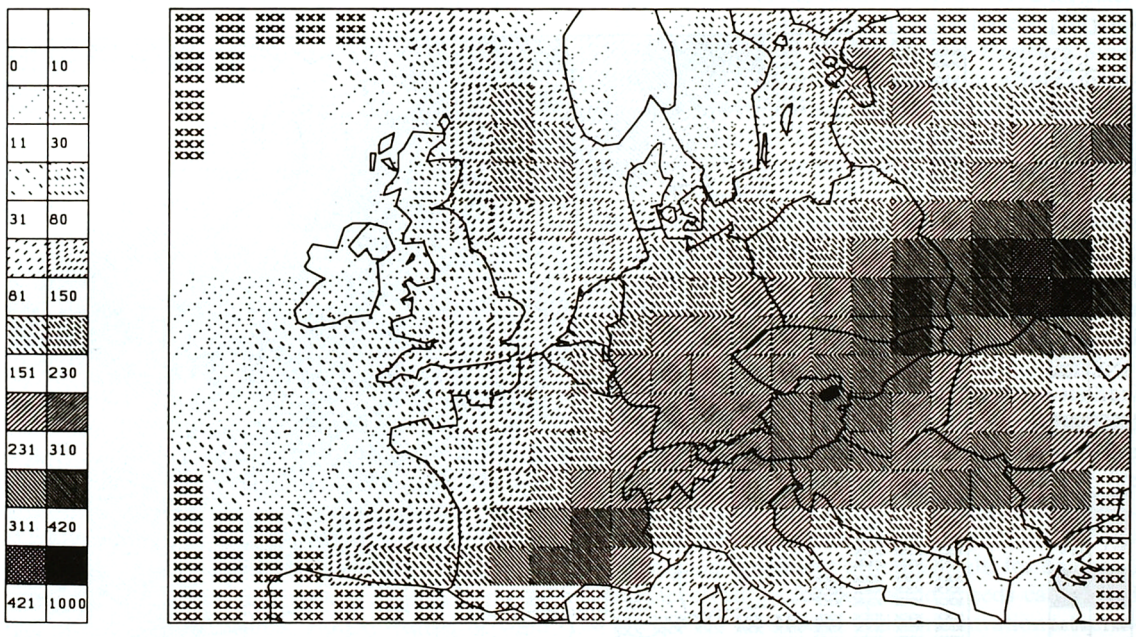

Fig. 7. Ratio t_4/T of trajectory residence times for the 14 station average ozone concentrations for the summer half-years. The scale on the left side gives the shading code for t_4/T in per mille. Ratios t_4/T were not computed, when $T<20$ h to avoid obviously insignificant values. These grid elements were marked with "xxx".

made. Correlation was found to be best ($r=0.74$) between daily maximum temperature at Vienna Hohe Warte and daily maximum ozone concentration of the 14-station average values: $[O_3]_{max}=1.7*T_{max}+11.4$ with $[O_3]$ given in ppb and T_{max} given in °C. Classification in 4 quartiles as before was applied to the residuals of the ozone concentrations, but without elimination of the yearly variation. High residual ozone concentrations occur also at meteorological conditions not so favourable for photochemical ozone production. Since meteorological conditions depend systematically on the direction of transport (in summer continental air is usually warmer than maritime air), residual ozone concentrations should better represent the influence of precursor emissions.

The result for the 4th quartile of ozone residuals in summer is shown in Fig. 8. Again the highest values of t_4/T (approximately 40%) occur over eastern central Europe, but in addition high values of t_4/T (30–40%) can also be found along a path from Sweden, Germany and the Czech Republic. Low values of t_4/T can be found over the Atlantic Ocean, France, the Mediterranean and Russia.

In general this pattern is in good agreement with the spatial distribution of VOC emissions in Europe (Stedman and Williams, 1992). The agreement with NO_x emissions (Iversen *et al.*, 1991; Lübkert and Tilly, 1989) is less marked. Especially the high NO_x and VOC emissions in Western Germany and the Netherlands do not frequently result in high ozone concentrations in eastern Austria. This may be due to unfavourable meteorological conditions during transport from those areas, which cannot be completely compensated by the regression with temperature.

In the winter half-year ozone concentrations are much lower than in summer. The patterns of t_4/T (Fig. 9) are also completely different from those in summer. t_4/T is highest over the Atlantic Ocean with a secondary maximum in former Yugoslavia. Nearly no high ozone concentrations are connected with continental air masses from the east and northeast.

While in summer most of the trajectories of the 4th quartile have an anticyclonic curvature, the opposite is true for winter. Weather conditions therefore in general will not be favourable to photochemical ozone production for the trajectories of the highest ozone concentrations, but vertical mixing is very effective. Therefore this ozone cannot be produced photochemically in the boundary layer, but is thought to be either photochemically produced in the higher troposphere (for example by oxidation of methane) (Fishman *et al.*, 1979) or of stratospheric origin. If it is of stratospheric origin, most of the ozone obviously does not reach the ground directly after a tropopause folding. In that case the trajectories should have an anticyclonic curvature near the ground (Danielsen, 1968; Vaughan, 1988).

Observations showed that in winter, ozone concentrations above the Atlantic Ocean are higher than over Europe (Winkler, 1988). Levy *et al.* (1985) found the same behavior in simulations with a General Circulation Model. The only source of ozone in the simulations was downward transport from the stratosphere. The modelled differences between concentrations over the ocean and over the continent are due to

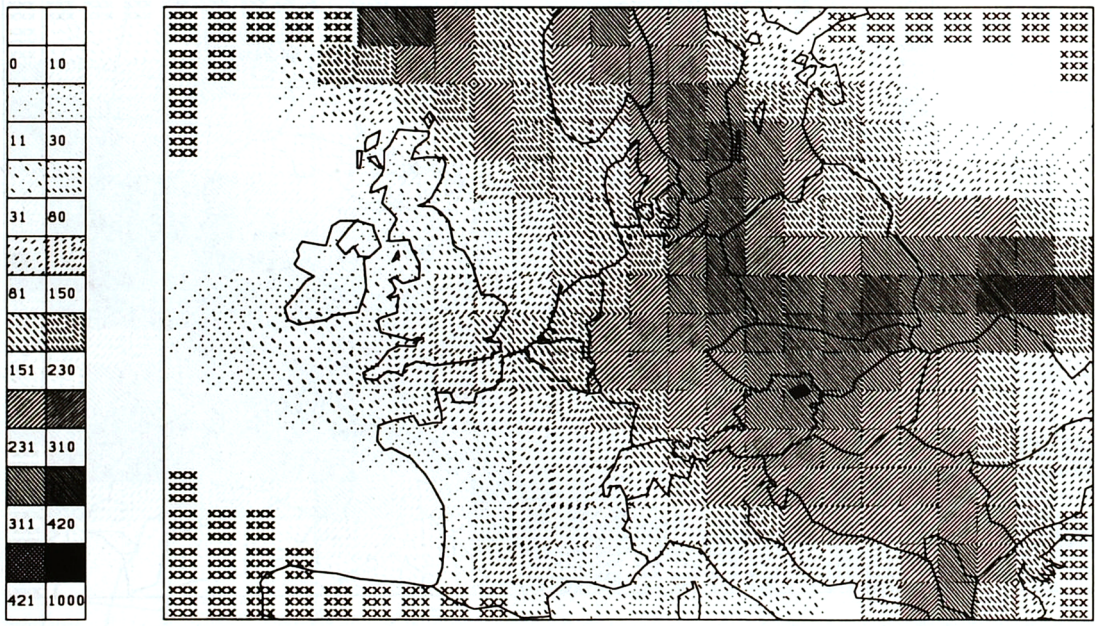

Fig. 8. Same as Fig. 7, but for the residuals of the 14 station average ozone concentrations with respect to linear regression with temperature.

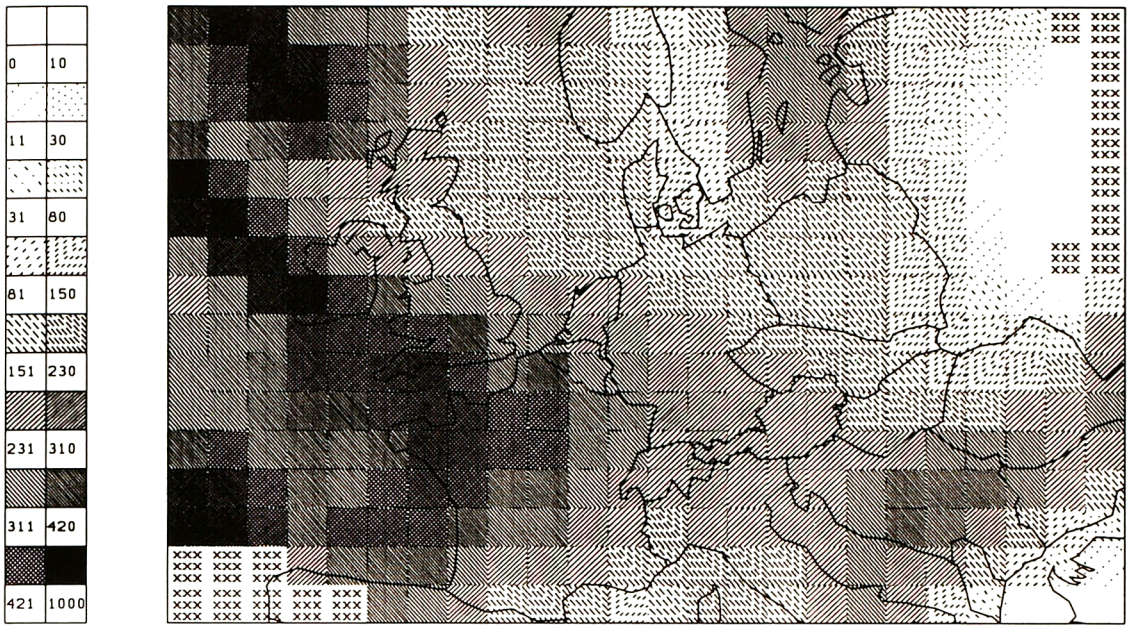

Fig. 9. Same as Fig. 7, but for the winter half-year (October–March).

the much slower dry deposition of ozone over the ocean. It appears that the lower troposphere over the ocean is a source of ozone for the continent in winter; when the air flow is directed from the ocean towards the continent, relatively higher ozone concentrations are advected to the continent. This matches the results of the trajectory analysis well and is a strong indication that indeed higher ozone concentrations in winter in Austria are due to transport. The troposphere above the Atlantic seems to be a main source of ozone in winter even for eastern Austria, more than 1000 km inland.

4. BACKGROUND O_3 CONCENTRATIONS DEDUCED FROM SURFACE MEASUREMENTS

Ozone production and destruction occurs on different spatial scales. It is assumed that a background ozone concentration exists which is not influenced by local ozone production or destruction, e.g. in cities.

Taking account of the very efficient vertical mixing during periods of high wind speed, Guicherit (1988) determined tropospheric background ozone concentrations in the Netherlands from surface measurements under such wind conditions. He derived background concentrations of 20 to somewhat above 40 ppb, depending on time of year. The maximum was observed in May.

The above-described method was applied to the 14 sites in and around Vienna. Hourly values of wind speed and direction from the meteorological station at Hohe Warte were used. The analysis was made separately for northwesterly (NW) and southeasterly (SE) winds, which represent the main wind directions in eastern Austria (Fig. 3). NW winds usually bring air from the Atlantic Ocean, while SE winds are associated with continental air masses or air masses from the Mediterranean Sea, as an analysis of 850 hPa backward trajectories showed. This is also confirmed by the good correlation between ground-level winds and radiosonde winds (Auer *et al.*, 1989).

Figure 10 shows the results for 1989–1992 for Exelberg. In winter, ozone concentrations are slightly increasing with increasing wind speed at Exelberg. Since this site is often above an inversion in winter, measured concentrations are thought to represent the background reasonably well during much of the time, regardless of the wind speed. A background of 25–30 ppb can be derived.

In summer, there is a clear concentration increase with increasing wind speed for SE winds (from 50 to approximately 75 ppb), whereas there is a decrease in concentrations for NW winds (from 50 to less than 40 ppb). This behaviour is essentially the same for all rural sites.

Urban sites in the vicinity of NO emissions show increasing ozone concentrations with increasing wind speed at low to medium wind speeds through all the year and for both wind directions. This is due to the more efficient dilution of NO at higher wind speeds. However, at wind speeds above 5 $m\,s^{-1}$, the behaviour is in good agreement with the results for Exelberg.

If concentrations for high wind speeds can indeed be interpreted as background concentrations, the results show that background concentrations in continental air are higher by a factor of almost 2 as compared with those in maritime air in summer. They

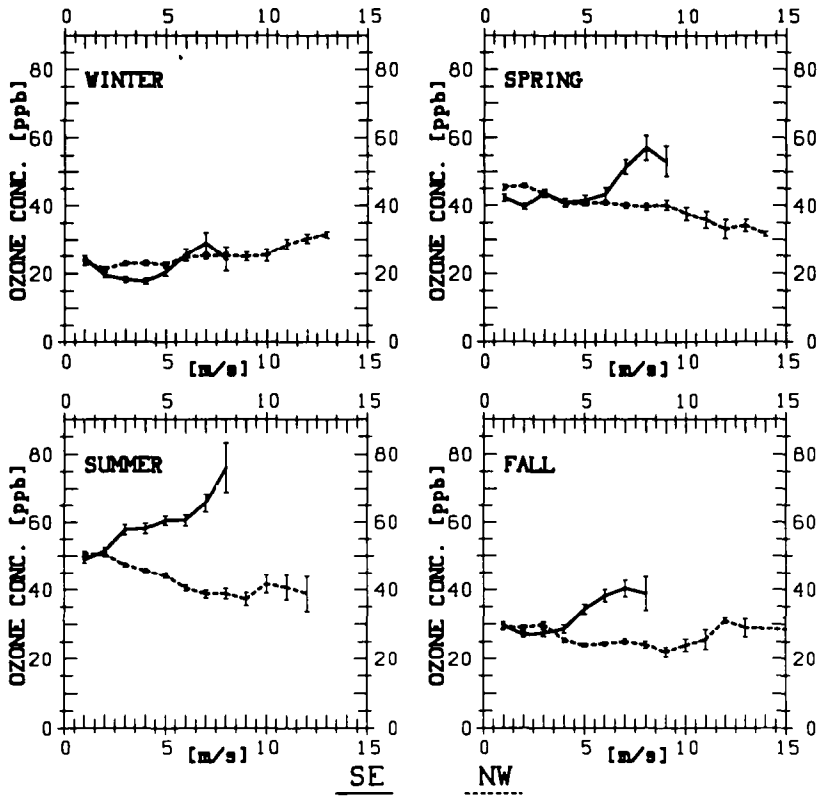

Fig. 10. Mean ozone concentrations at Exelberg (derived from half-hourly means) as a function of wind speed and wind direction at meteorological observatory Hohe Warte. Error bars give the 95% confidence interval of the mean.

are approximately 75 ppb in continental air and less than 40 ppb in maritime air.

It is not clear whether the derived background concentrations are typical for all weather patterns or just for those associated with high wind speeds. For NW winds high wind speeds are associated with frontal passages and low temperatures, whereas for SE winds high wind speeds are often associated with high temperatures. Therefore, the conditions for photochemical ozone formation are completely different. However, background concentrations should not change within a few days. Therefore, the derived background concentrations should be representative also for days with lower wind speeds.

While the resulting background concentrations for NW winds agree well with those measured by Guicherit (1988) in the Netherlands, those resulting for SE winds are considerably higher in summer. Mean tropospheric ozone concentrations, measured by balloon soundings in Payerne (Switzerland), agree reasonably well with those derived in this work. At the 700 hPa level mean summer ozone concentrations in Payerne were approximately 55 ppb from 1982 to 1988 (Staehelin and Schmid, 1991), which is only slightly more than what one would expect from the above derived background (NW winds are more frequent than SE winds). This is an indication that the measured ground concentrations during high wind speeds represent background concentrations reasonably well. The large difference between background concentrations in maritime and continental air in summer is due to photochemical ozone production over the continent, because of high anthropogenic emissions of precursors. It is enhanced by high temperatures and sunshine durations in continental air in summer.

The higher background ozone concentration in continental air also results in somewhat higher mean ground ozone concentrations in eastern Austria during transport of air from south and east as compared to north and west. Figure 11 shows the mean of the daily maximum half-hourly ozone concentrations for 13 sites during different flow patterns after Steinacker (1991) in summer. Steinacker (1991) classified 10 synoptic patterns: 8 flow patterns, corresponding to the flow directions N, NE, E, etc. in the 850 hPa level for the east Alpine area, and two classes for variable conditions and conditions with weak pressure gradient, which are not considered in Fig. 11. For the daily classification the weather chart Berliner Wetterkarte is recommended. It can be seen from Fig. 11 that mean summertime ozone concentrations are higher

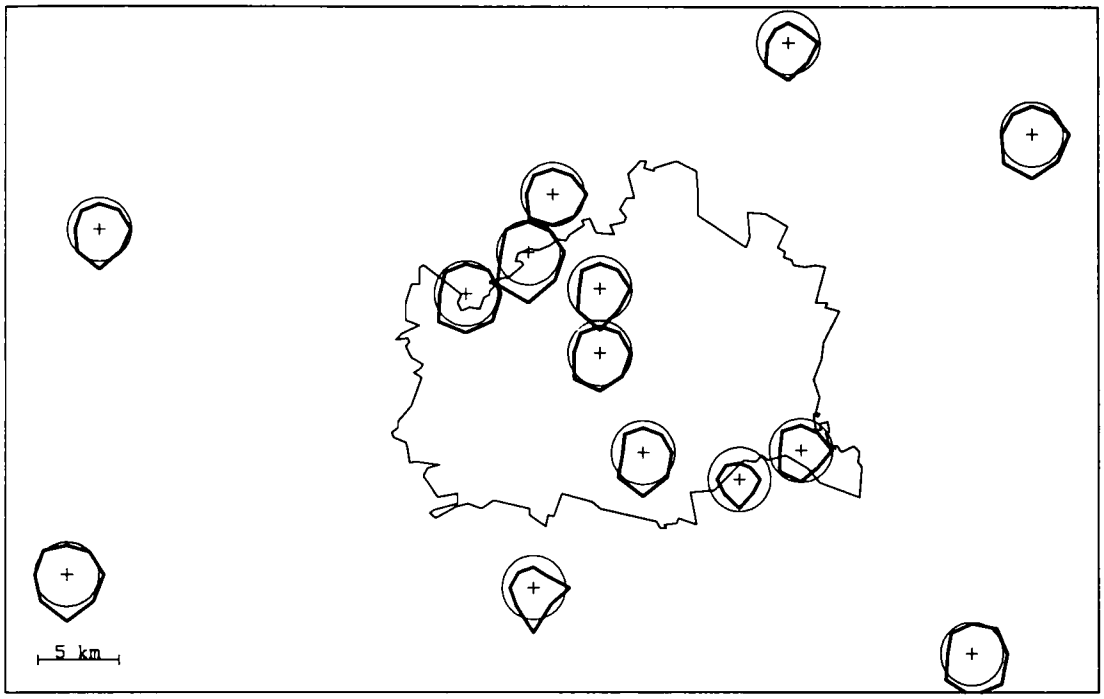

Fig. 11. Mean of the daily maximum half-hourly ozone concentrations for the eight different flow patterns after Steinacker (1991) and the 14 measuring sites; summer half-years 1989–1991. The circles correspond to ozone concentrations of 50 ppb.

for easterly and southerly flows as compared to northerly and westerly flows. This is in good agreement with the trajectory analysis.

5. CONCLUSIONS

The major findings are as follows:

(1) Photochemical episodes, during which a considerable portion of the ozone is produced locally in the plume of Vienna and the highest ozone concentrations are measured leewards of the city, are restricted to a few days per year and do not contribute a lot to mean concentrations.

(2) On average, Vienna does not act as a significant ozone source or sink for the immediate surroundings. Long-range transport processes are more important for mean ozone concentrations than local production or destruction.

(3) In summer, source areas of ozone as determined by statistical analysis of trajectories agree reasonably well with those areas in Europe, which have the highest anthropogenic precursor emissions. Therefore, the major part of ozone found in eastern Austria in summer is believed to be of photochemical origin.

(4) In winter, a major source of ozone in eastern Austria is transport from the Atlantic Ocean, where concentrations are higher than over the continent because of the small dry deposition velocity of ozone over water surfaces. This ozone is either of stratospheric origin or photochemically produced in the higher troposphere by oxidation of methane.

(5) In summer, background concentrations of ozone in eastern Austria are 30–40 ppb for air masses arriving from the Atlantic Ocean and 70–75 ppb for continental air masses. The difference is due to photochemical production over the continent, which is driven by anthropogenic emissions and favourable meteorological conditions.

(6) In winter, background concentrations of ozone in eastern Austria are approximately 30 ppb for maritime and 25–30 ppb for continental air masses.

Acknowledgements—Thanks are due to E. Scheicher from the Niederösterreichische Landesregierung, W. Spangl from the Umweltbundesamt and H. Schurz for providing the data, E. Petz for his support concerning data processing, H. Puxbaum, R. Knienider and P. Seibert for helpful discussions. Our special thanks go to referees for their valuable comments, which helped to improve the work considerably.

REFERENCES

Altshuller A. P. (1988) Some characteristics of ozone formation in the urban plume of St. Louis, MO. *Atmospheric Environment* **22**, 499–510.

Angle R. P. and Sandhu H. S. (1989) Urban and rural ozone concentrations in Alberta, Canada. *Atmospheric Environment* **23**, 215–221.

Auer I., Böhm R. and Mohnl H. (1989) *Klima von Wien*. Magistrat der Stadt Wien.

Bojkov R. D. (1985) Surface ozone during the second half of the nineteenth century. *J. Clim. appl. Met.* **25**, 343–352.

Danielsen E. F. (1968) Stratospheric–tropospheric exchange based on radioactivity, ozone and potential vorticity. *J. atmos. Sci.* **25,** 502–518.

Feister U. and Warmbt W. (1986) Long term measurements of surface ozone in the German Democratic Republic. *J. atmos. Chem.* **5,** 1–21.

Fishman J., Solomon S. and Crutzen P. J. (1979) Observational and theoretical evidence in support of a significant *in-situ* photochemical source of tropospheric ozone. *Tellus* **31,** 432–446.

Fricke W. (1980) Die Bildung und Verteilung von anthropogenem Ozon in der unteren Troposphäre. Ber. Inst. Met. Geophys. Univ. Frankfurt/Nr. 44.

Guicherit R. (1988) Ozone on an urban and regional scale. In *Tropospheric Ozone* (edited by Isaksen I. S. A.), pp. 49–62. D. Reidel Publishing Company, Dordrecht, Netherlands.

Guicherit R. and van Dop H. (1977) Photochemical production of ozone in Western Europe (1971–1975) and its relation to meteorology. *Atmospheric Environment* **11,** 145–155.

Iversen T., Halvorsen N. E., Mylona S. and Sandnes H. (1991) Calculated budgets for airborne acidifying components in Europe, 1985, 1987, 1988, 1989 and 1990. EMEP MSC-W Report 1/91 Technical Report No. 91, DNMI, Oslo, Norwegen.

Kanbour F. I., Faiq S. Y., Al-Taie F. A., Kitto A. M. N. and Bader N. (1987) Variation of ozone concentrations in the ambient air of Bagdhdad. *Atmospheric Environment* **21,** 2673–2679.

Kley D., Volz A. and Mülheims F. (1988) Ozone measurements in historic perspective. In *Tropospheric Ozone* (edited by Isaksen I. S. A.). D. Reidel, Dordrecht, Netherlands.

Leighton P. A. (1961) *Photochemistry of Air Pollution.* Academic Press, New York.

Levy H. II, Mahlman J. D., Moxim W. J. and Liu S. C. (1985) Tropospheric ozone: the role of transport. *J. geophys. Res.* **90,** 3753–3772.

Lübkert B. and De Tilly S. (1989) The OECD-map emission inventory for SO_2, NO_x and VOC in Western Europe. *Atmospheric Environment* **23,** 3–15.

Mahringer G. (1986) Trajektorien und ihre Anwendung in der Umweltmeteorologie mit besonderer Berücksichtigung der Trajektorienmodelle der Zentralanstalt für Meteorologie und Geodynamik. Diploma thesis, University of Vienna.

McKendry I. G. (1993) Ground-level ozone in Montreal, Canada. *Atmospheric Environment* **27B,** 93–103.

Ober E. and Puxbaum H. (1990) Sondermeßplatz Exelberg–Oxidantienmessungen im Großraum Wien. Umweltbundesamt, Wien.

Petterssen S. (1940) *Weather Analysis and Forecasting.* McGraw-Hill Book Company, New York.

Staehelin J. and Schmid W. (1991) Trend analysis of tropospheric ozone concentrations utilizing the 20-year data set of ozone balloon soundings over Payerne (Switzerland). *Atmospheric Environment* **25A,** 1739–1749.

Stedman J. R. and Williams M. L. (1992) A trajectory model of the relationship between ozone and precurser emissions. *Atmospheric Environment* **26A,** 1271–1281.

Steinacker R. (1991) Eine ostalpine Strömungslagenklassifikation. Unpublished manuscript of the Institute for Meteorology and Geophysics, University of Innsbruck, Austria.

Uno I., Wakamatsu S., Suzuki M. and Ogawa Y. (1984) Three-dimensional behaviour of photochemical pollutants covering the Tokyo metropolitan area. *Atmospheric Environment* **18,** 751–761.

Varey R. H., Ball D. J., Crane A. J., Laxen D. P. H. and Sandalls F. J. (1988) Ozone formation in the London plume. *Atmospheric Environment* **22,** 1335–1346.

Vaughan G. (1988) Stratosphere–troposphere exchange of ozone. In *Tropospheric Ozone* (edited by Isaksen I. S. A.), pp. 125–135. D. Reidel, Dordrecht, Netherlands.

Wege K. and Vandersee W. (1991) Ozonbeobachtungen am Nordrand der Alpen. *Meteorol. Rdsch.* **44,** 138–146.

Winkler P. (1988) Surface ozone over the Atlantic Ocean. *J. atmos. chem.* **7,** 73–91.

Wotawa G., Stohl A. and Kromp-Kolb H. (1993) Trajektorienanalyse für Wien und Niederösterreich während einer Ozonepisode am 31.7.1992–Bericht an das Umweltbundesamt. Institut für Meteorologie und Geophysik, Universität Wien.

Wunderli S. and Gehrig R. (1991) Influence of temperature on formation and stability of surface PAN and ozone. A two year field study in Switzerland. *Atmospheric Environment* **25A,** 1599–1608.