Variability of tropospheric ozone concentrations: comparison of ground-level data with aircraft measurements during the “O₃ Reg” campaign (19–21 July 2000)

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The aim of the campaign presented here is to compare data networks' measurements of atmospheric pollutants (mainly tropospheric ozone) with airborne measurements in the atmospheric boundary layer. It is designed to determine whether ozone fields are homogeneous on a regional scale and to show the modulation, on a local scale, of ozone concentrations due to local emissions of anthropogenic and industrial primary pollutants, and/or meteorological thermal processes such as sea/land breeze.

The study bears on ozone concentration variability within an anticyclonic air mass on a scale of about 500 km. The contribution of large-scale phenomena in the formation of ozone episodes is shown. Daily maximum ozone values are relatively well representative of tropospheric ozone aircraft measurements. Zooming in on southeastern France establishes that in this area, ozone concentrations arise from multiscale phenomena.

Keywords: Regional-scale air quality; Ozone pollution; Boundary layer structure; Land/sea breeze

1. Introduction

Monitoring networks enable the assessment of primary and secondary pollutant fields on a local (about 10 km), or even regional (about a few hundred kilometres) scale.

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Modelling results allow the estimation of pollutant fields on larger scales. The “O₃ Reg” campaign was carried out so that pollutant fields could be studied on a large scale in an experimental way. Previous results led to the measurement of pollutant fields on this scale. Indeed, by analysing the data from the French ground networks, Pont and Fontan (2000a) showed that, in the boundary layer, ozone contents were related to the air mass continental characteristic. Their conclusions supported the hypothesis of a transport of ozone and its precursors on the scale of the air mass. The influence of the long-range transport of ozone and related pollutants has been well documented for both North America and much of Europe (Solomon et al., 2000). The regional component of the ozone concentration is locally modulated by primary pollutant emissions that participate in the ozone formation cycle.

To quantify the range of this local modulation, a comparative study of variations in daily ozone maxima between Fridays and Sundays in big French cities over the summer periods of 1994, 1995, and 1996 was conducted. Results indicated a difference, at the most, of 20% between the highest values of ozone concentrations measured on Fridays and Sundays, whereas traffic levels (important local sources of primary pollutants) vary by more than 40% (Pont and Fontan, 2001). Bruckmann and Wichmann-Fiebig (1997) also found comparative results for the day-to-day of the week ozone trend in Europe. It revealed the chemical non-linearity of ozone (Liu et al., 1987; Lopez et al., 1987; Brönniman and Neu, 1997) due to the complex dependence on the VOC to NO_x ratio (Dodge, 1984). It mainly showed the advection of an important background level of ozone over these urbanised areas, to which, limited local production is added.

As Clarke and Ching (1983) did, Pont and Fontan (2000b) underlined the influence of regional-scale phenomena on the formation of ozone episodes, and also the influence of smaller scale phenomena such as the land/sea breeze effect. Thanks to the statistical analysis of data from French southern networks.

High ozone concentrations mainly occur under anticyclonic continental air masses, which brings high ozone contents on a regional scale, as described above, modulated by a limited local formation depending on local emissions and local meteorology and orography.

In the western edge of France, the Porspoder station data enabled to show the contrast in the chemical composition of the air masses coming, on the one hand, from the Atlantic Ocean, and on the other hand, from the European continent. The continental photo-production had reached 20 ppb during 1992 and 1993 (Hov, 1997). Highest summer concentrations develop in the southeastern part of central Europe. The ozone mean levels for these central/southeastern European regions are around 56 ppb in summer, 21 ppb in winter and around 46 ppb during the transition. For western France, the ozone concentrations in the boundary layer are around 27 ppb in winter and around 40 ppb in summer (Beck and Grennfelt, 1994).

The “O₃ Reg” campaign was established to study horizontal fields of pollutants on the scale of the country within a continental air mass. At first, aircraft measurements led to a horizontal field of various pollutants (O₃, CO and NO_x) in the atmospheric boundary layer. Secondly, these flights were considered as a spatial integration between the different French ground networks so that these measurements in the atmospheric boundary layer could be compared with pollutant concentrations from the overflowed ground networks.

2. Experimental

2.1. Aircraft measurements during the “O₃ Reg” campaign

The “O₃ Reg” aircraft campaign occurred on 19–21 July 2000 over France. The aircraft used was the Merlin, from Météo-France, equipped with different implements that acquire mean dynamical, thermodynamic and chemical parameters.

Ozone is measured by an Environment 41 M UV absorption analyser. Measurements of CO are made with a Thermo-Environment 48 CTL infrared absorption analyser. Concentrations of NO_x are measured by a Thermo-Environment 42 S analyser. NO_x and NO contents are acquired that enables to know the NO₂ contents by difference between these two concentrations. Every concentration is expressed in ppbv.

Meteorological parameters such as temperature, water vapour mixing ratio (g/kg), pressure, radiation, and wind are also measured.

During the 3 days of the campaign, the synoptic meteorological situation was not as continental as expected. Indeed, the anticyclone, as shown in Fig. 1, was not largely spread over the European continent. On the first day of the campaign (19 July 2000), the anticyclone came over northwestern France that generated a northern moist flux over the northeastern regions of France. On the second day (20 July 2000), the anticyclonic cell was centered on the British Islands and went on spreading over the continent. On the third day (21 July 2000), France was under a continental anticyclonic influence.

Six flights were made during this period; the map shows the trajectories of these flights (cf. Fig. 2). Flights were planned so that the measurements should be carried out in the atmospheric boundary layer.

On the first day, in the morning (07:58–10:57 (UT)), aircraft measurements were made across northern France (Paris–Rouen–Strasbourg–Paris; flight no. 1); in the afternoon (13:03–14:40 (UT)), the Merlin took off from Paris and reached Toulouse (flight no. 2). On the second day, in the morning (07:56–10:07 (UT)), measurements were carried out between Toulouse, Nice, and Marseilles (flight no. 3); in the afternoon (13:09–14:06 (UT)), the Merlin made the sea breeze flight, crosswise to the Marseilles coast (flight no. 4). On the third day, in the morning (07:27–08:17 (UT)), the plane made the land breeze flight along the same trajectory as that of the previous day (flight no. 5); in the afternoon (11:58–14:13 (UT)), the plane took off from Marseilles towards Paris, flying over the Rhone Valley up to Lyon (flight no. 6).

The airborne measurements were completed by the French network of ground stations measuring the daily variations of ozone concentrations.

2.2. Network measurements

Ozone data are obtained from various monitoring networks such as Airparif, Airlor, Aspa, Oramip, Airmarais, located, respectively, in and around the following cities: Paris, Nancy, Strasbourg, Toulouse and Marseilles. The data in ppbv (1 ppbv = 1.96 µg/m³) represent the hourly mean value. Ozone concentrations are measured by Environnement UV absorption analysers. The uncertainty in the hourly concentration measurements is about 10% (Vecchi and Valli, 1999). Types of measurement sites differ according to their

location, indeed, sites may be of urban (U), rural (R), street (S), or mountain (M) type. Only R types are considered in this study, as street and urban sites can show a high variability of the ozone concentration daily variation due to neighbouring emissions of nitrogen monoxide.

Daily variations in ozone concentration depend on the stability of surface and boundary layers, thus on the altitude of samplings, as well as on photochemical production, destruction and transport. As the daily ozone maximum occurs when the atmospheric boundary layer is well-mixed, it can be considered as the most representative value of the well-mixed atmospheric boundary layer (Lopez et al., 1993). Sampling altitude is no longer restrictive so maximum values from different sites can easily be compared together (Pont and Fontan, 2000b) and compared with ozone concentration measurements found during flights in the atmospheric boundary layer.

2.3. Ancillary data

Three-dimensional back trajectories were calculated with the NOAA Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLOT). The model uses a $1 \times 1^\circ$ resolution and the FNL (final) meteorological database (HYSPLOT4 Model, 1997). The six-hourly FNL archive data are generated by the NCEP's GDAS wind field reanalysis (NCEP=National Centers for Environmental Prediction; GDAS=Global Data Assimilation System). Basic fields such as u- and v-wind components, temperature, and humidity at

Fig. 1. Meteorological surface analysis on 19, 20, and 21 July 2000.

Fig. 1 (continued).

Fig. 2. Flight trajectories during the 3 days of the campaign.

13 vertical levels, from surface to 20 mbar, are stored in the FNL database. More information about this meteorological database can be found at <http://www.arl.noaa.gov/ss/transport/archives.html>. The model's performance has been found to be sensitive to the low-level wind profile for backward trajectories (Draxler and Hess, 1998).

3. Data analysis and discussion

These large-scale flights enable to know the behaviour of primary and secondary pollutants along with the change of air masses.

3.1. Flight 1 'Paris–Rouen–Strasbourg–Paris'

Actually, the first flight, made over northern France on 19 July 2000 in the morning, while the anticyclone began spreading over northwestern France, shows a large difference in levels of ozone concentrations, indeed, Fig. 3 shows two striking levels: a first ozone level around 70 ppbv, standing for the western part of the flight from Paris, and a second

Fig. 3. Variations of dynamical and chemical parameters along the Paris–Strasbourg–Paris flight on 19 July 2000, in the morning. Upper graph: MR = mixing ratio, alt = flight height; arrows show intensity (min = 0.01 m/s, max = 12.54 m/s) and wind direction; black stars stand for daily maximum ozone values from the considered ground networks.

level, around 30 ppbv, standing for the ozone concentration over cloudy northeastern France. In spite of this change in ozone levels during the flight, the ozone concentrations stand quite homogeneous within each air mass crossed. During the part of the flight between Strasbourg and Paris, the ozone concentration went on increasing as the aircraft went back in the anticyclonic air mass; the return flight to Paris was made at lower latitudes. By considering back trajectories (cf. Fig. 4), it can be noted that the difference in ozone concentrations can be linked to the nature of the air mass (cyclonic or not), and overall to the continental character of the air mass and the residence time of the particle within this air mass over the continent. These two 96-h backward trajectories do not show the same residence time of the particle over land, indeed, the particle along the first backward trajectory (cf. Fig. 4a) moved slower than along the second one (Fig. 4b), moreover, the slowest air mass, which flew over Great Britain, enabled the air mass to weigh with pollutants. The backward trajectory of the second particle had a more oceanic characteristic that could explain the low ozone concentrations within this air mass. Relative to continental air masses, high wind speeds and low photochemistry within oceanic cloudy air masses prevent them from weighing with primary pollutants and consequently with secondary pollutants.

If NO_x concentrations are considered, Fig. 3 shows that they vary along the flight depending on the plume of the urban areas flown over. Outward these areas, primary pollutant concentrations are low and near the detection threshold of the analyser. This trend is found along every flight of the campaign; in the atmospheric boundary layer, NO and NO_2 concentrations vary, spatially speaking, in an inhomogeneous way; these variations depend on the source location.

3.2. Flight 2 ‘Paris–Toulouse’

On 19 July 2000 in the afternoon, the anticyclone covered the western part of France. During the second flight, between Paris and Toulouse, the ozone concentration did not vary strongly (between 55 and 60 ppbv) whatever the flight altitude considered (500, 800 and 1100 m). While the atmospheric boundary layer was well mixed, ozone concentrations stood relatively homogeneous within the continental air mass, on a spatial scale of about 700 km (cf. Fig. 5). Only landing and takeoff stages showed variations in pollutant concentrations. These stages of measurements cannot be considered reliable because of the fast variations of pressure and humidity during measurements (Lopez et al., 1993).

3.3. Flight 3 ‘Toulouse–Nice–Marseilles’

On the following day, this flight enabled us to show a higher level of ozone concentrations over southeastern France, indeed, the mean ozone level over this area was 20 ppbv higher than the one during the first part of the flight (cf. Fig. 6). This difference has already been emphasised by Pont and Fontan (2000b) with ozone data from the ground networks. This trend was also found with ozone data from ground networks as shown by the stars in Fig. 6. Variability of ozone concentrations was higher during this flight than during the previous afternoon as measurements were made while the atmospheric boundary layer went on developing, moreover, this flight was not realised at a constant

(a)

(b)

Fig. 4. Ninety-six-hour backward trajectories run with HYSPLIT model, initialised from aircraft observations, representing two different cases: (a) high ozone levels around Paris; (b) low ozone levels in eastern France.

Fig. 5. Variations of dynamical and chemical parameters along the Paris–Toulouse flight on 19 July 2000, in the afternoon. Upper graph: MR=mixing ratio; arrows show intensity (min=0.03 m/s, max=7.95 m/s) and wind direction; black stars stand for daily maximum ozone values from the considered ground networks.

Fig. 6. Variations of dynamical and chemical parameters along the Toulouse–Nice–Marseilles flight on 20 July 2000, in the morning. Upper graph: MR = mixing ratio; arrows show intensity (min = 2.41 m/s, max = 13.16 m/s) and wind direction; black stars stand for daily maximum ozone values from the considered ground networks.

altitude level because of the overflow relief. Ozone concentrations decreased each time a high NO_x -concentrated urban plume or a NO_x -concentrated convective movement was met. Urbanised areas are ozone sinks (Mc Kendry, 1993). Wind directions and intensity were unsettled all along the flight. Winds were higher during the first part of the flight (until 13.16 m/s), whereas they reached the mean value of 3.53 m/s all along the final part of the flight between Nîmes and Marseilles. Fig. 7 enables the comparison of two 96-h backward trajectories, respectively, initialised in southwestern France near Toulouse and in southeastern France near Marseilles. Difference between ozone levels from these two regions could be explained by the fact that the southeastern particle moved over more industrialised areas than the southwestern one. Western France is less industrialised; sources of anthropogenic emissions are less numerous than in the areas over which the southeastern particle moved. The southeastern air mass might be more weighed with primary pollutants along the trajectory that enables a greater production of ozone on a large temporal scale. To estimate the ozone formation along the Rhone valley, ozone measurements from a device that belongs to the Clermont-Ferrand (see Fig. 2) measurements network (ATMO Auvergne) are considered; this site is situated on the top of the Puy-de-Dôme and gives ozone concentration within the free atmospheric boundary layer. At this site, the daily maximum of ozone on 19 July 2000 was 52 ppbv. If the 96-h backward trajectory that begins in southeastern France is followed (see Fig. 7), we can note that the air parcel covered the distance between the Puy-de-Dôme and Marseilles in 24 h. By making the difference between both ozone concentrations, the ozone formation in 24 h along the Rhone valley can be estimated around 23 ppbv. Thus, the ozone formation rate is 1.92 ppbv per daily hour along a path of 400 km.

During the final part of this flight, the plane flew overland between Marseilles and Nice, and made its way back over sea. Whatever kind of surface was flown over, ozone concentrations did not vary in a striking way from one to another. The mean ozone concentration over sea was about 66 ppbv, whereas the one overland was about 73 ppbv.

3.4. Flight 6 ‘Marseilles–Paris’

On the third day of the experiment (21 July 2000), in the afternoon, two levels of ozone concentrations were also found: a level around 85 ppbv in southeastern France and another level around 65 ppbv during the rest of the flight. High ozone concentrations were measured about 150 km from the takeoff location. The highest value was about 115 ppbv and was located where the wind direction was changing (cf. Fig. 8). The wind was southerly during the first part of the flight (mean wind speed = 6.44 m/s) and turned to a northern–northeastern direction (mean wind speed = 6.20 m/s). On 21 July 2000, southeastern France experienced a strong sea breeze effect in the afternoon (cf. Fig. 9). Thus, it may be thought that the sea breeze flow came inland up to about 150 km from the coast. The wind was southerly and the mean wind speed was about 6 m/s; we could suppose that it blew pollutants up to where they stood stuck in the area where the wind direction was reversing. The Rhone valley directs this flow of pollutants when the breeze wind is southern. Breeze conditions on this day were particular. Indeed, the incoming breeze flow was influenced by the southern flow of the cyclonic system spread over the Mediterranean

Fig. 7. Ninety-six-hour backward trajectories run with HYSPLIT model, initialised from aircraft observations, representing two different cases: (a) initialisation around Toulouse; (b) initialisation around Marseilles.

Fig. 8. Variations of dynamical and chemical parameters along the Marseille–Paris flight on 21 July 2000, in the afternoon. Upper graph: MR=mixing ratio, alt=flight height; arrows show intensity (min=0.11 m/s, max=10.22 m/s) and wind direction; black stars stand for daily maximum ozone values from the considered ground networks.

Fig. 9. Intensity (square points) and wind direction (arrows as wind socks) on 21 July 2000 at the “Martigues-Gatasse” site located 122 m of altitude, south of the Berre pond, near the shoreline, and northwest of Marseilles. This figure, given by Météo-France, shows the sea breeze effect over the southeastern region.

sea and centered near the coast that enabled the southern composed flow to reach sites far inland (cf. Fig. 10—wind fields at the 500 m level on 21 July 2001).

If concentrations of daily ozone maxima measured by ground networks during the studied period mentioned above are now considered (see Table 1), it is possible to note that

Fig. 10. Wind fields at the 500 m level on 21 July 2000 (12:00 UT) over France; this map was delivered by the ARPEGE model from Météo-France. We can note that the anticyclonic circulation over a large part of France and the cyclonic circulation over southeastern France due to a low pressure center spread over the Mediterranean sea.

they are close to the values of the aircraft measurements. Ozone concentrations measured within the air mass, in the atmospheric boundary layer, are found again in the ground network as the maximum value of the daily variation of ozone concentration. This means

Table 1

Comparative table between maximum daily ozone concentrations (ppbv) measured by ground measurement networks (N max O₃) and ozone aircraft measurements over considered areas (Aircraft O₃)

Networks	19 July 2000		20 July 2000		21 July 2000	
	N max O ₃	Aircraft O ₃	N max O ₃	Aircraft O ₃	N max O ₃	Aircraft O ₃
Airparif (Paris)	4038	72	80	*	63	56.8 ± 5.3
	4142	53.5	71.5		48.5	
	4158	69.5	76.5		57	
	4322	61.5	73.5		53.5	
	4324	42	82.5		59.5	
Aspa (Strasbourg)	16,031	29.5	59	*	50	*
	16,032	42.5	50.5		54	
	16,201	40	55		60	
Airlor (Nancy)	30,028	43	52	*	62.5	*
Oramip (Toulouse)	12,029	65.5	66	48.0 ± 12.5	70.5	*
	12,031	60	64.5		67.5	
Airmaraix (Marseilles)	3027	67.5	90	64.3 ± 13.5	84	87.1 ± 11.1
	3031	53.5	72		101	

that, even if rural-type sites are often downwind of large cities, ozone concentrations are not much influenced by the small-scale or local production and depend largely on the development of the boundary layer, as well as on the continental character of the air mass.

4. Zoom in southeastern France (flights 4 and 5)

The southeastern region stands apart from the rest of France by its higher levels of ozone (Pont and Fontan, 2000b). On a regional scale, this coastal region knows particular circulations of air masses due to a complex orography and land/sea breeze effect. During the campaign, two flights transverse to the coast were made: the first one on 20 July 2000, in the afternoon, and the second one on 21 July 2000, in the morning. The first flight was not made in breeze conditions. Throughout the flight, the ozone concentration stood homogeneous around 65 ppbv, whatever the flight level considered.

In the following part, only the second flight made in the early morning (between 07:00 and 09:00 (UT)), will be considered. All along this flight, the wind was low and its direction unsettled (cf. Fig. 11), as it was the time when the breeze was turning from land to sea breeze (cf. Fig. 9). Thanks to this figure (Fig. 9), established with Météo-France measurements at the Martigues-Gatasse site, we can consider the 21 July 2000 as a breezy day. This flight consisted of a way from the takeoff location up to the sea, of a climbing probe over sea, of a way back up to 60 km inland at a 2300 m altitude level, of a descending probe overland and finally of a way to the airport. Fig. 11 shows that the plane was out of the atmospheric boundary layer at the 2300 m altitude level, as the water vapour mixing ratio was lower (about 2 g/kg) than during low altitude levels. At the 2300 m level, primary pollutant concentrations are low and ozone concentrations vary homogeneously around 55 ppbv. During the descending probe, only CO and O₃ concentrations varied highly; other primary pollutants reached concentrations near the detection threshold of the analyser. During the rest of the flight, primary pollutants showed a high variability that enables to explain the variability of the ozone concentrations at this low altitude level.

By analysing the descending and climbing probes, it can be noted that the atmospheric boundary layer is highly stratified in ozone concentrations (cf. Figs. 12 and 13). Over land (cf. Fig. 13), temperature inversions can be noted until 800 and above 1200 m. Ozone concentration reached its maximum value around 1200 m (95 ppbv). This ozone value was measured while the plane was just coming into a layer whose H₂O mixing ratio increased highly, moreover, this high level of ozone was found at the top of a near-adiabatic layer, 400 m thick, swept by eastern–southeastern winds. This layer was relatively moist, as its mean mixing ratio was about 7.6 g/kg. The ozone profile shows the existence of different layers of ozone concentration, mostly linked to the stability of the layer and to the wind direction. It can be thought that this highly concentrated layer is a nocturnal residual layer, the result of the content in ozone of the atmospheric boundary layer of the previous day plus advection or local production. CO concentration also increased simultaneously. This high quantity of ozone is likely to supply lower layers with ozone when temperature inversion erodes. Moreover, this quantity of ozone is likely to be photodissociated from sunrise and to generate hydroxyl radicals that set off oxidising reactions generating ozone. High O₃ concentrations in the nighttime residual layer may contribute to the next day's O₃

Fig. 11. Variations of dynamical and chemical parameters along the breeze flight on 21 July 2000, in the morning. Upper graph: MR=mixing ratio, alt=flight height; arrows show intensity (min=0.45m/s, max=9.41 m/s) and wind direction.

Fig. 12. Wind direction, wind intensity (max=7.69 m/s, min=0.15 m/s), vertical profiles of potential temperature, H₂O mixing ratio (MR), and ozone concentrations over the sea during the climbing probe on 21 July 2000 in the morning (at about 07:35 (UT)).

maximum (Berkowitz et al, 1998; Ryan et al., 1998; Zhang et al., 1998). This analysis strengthens results overviewed in Solomon et al.'s (2000) paper, indeed, it was showed that undercutting of marine air under surface air inland as part of sea breeze conditions could force polluted air aloft, remaining as a nocturnal stable air layer until deeper mixing develops later in the day (Mc Kendry et al., 1997).

Below 800 m, along the temperature inversion, ozone concentrations decreased down to the ground, which reveals the chemical and deposition sinks for ozone. Above 1900 m, the aircraft measurements were made in the free atmosphere as values of the water vapour mixing ratio represented a dry air mass. Ozone concentrations in the free atmosphere were around 50 ppbv.

It can be noted that wind directions were not established along this probe and did not show reverse directions specific of the breeze cell. This probe, realised overland at a 60-km distance from the shoreline, showed that the breeze cell was not yet completely developed. This profile does not enable to show the land/sea breeze cell as aircraft measurements were made at the time when neither land breeze nor sea breeze was established. At the time when measurements were performed along this probe, the incoming sea flux did not reach the overflown spot. Indeed, near the shoreline in Marseilles, the breeze incoming flux begins to be measured generally at 08:00 (UT)

Fig. 13. Wind direction, wind intensity (max = 7.15 m/s, min = 0.86 m/s) vertical profiles of potential temperature, H₂O mixing ratio and ozone concentrations over the land during the descending probe on 21 July 2000 in the morning (at about 08:00 (UT)).

and the maximum of the breeze cell development occurs at 14:00 (UT) (Puygrenier et al., 2002). The spot where the probe was performed in the morning was overflowed in the afternoon; it was reached by the breeze cell in the afternoon as measured winds were southerly (cf. Fig. 8).

If the climbing probe performed over the sea is now considered, it is possible to note that the ozone concentration profile (cf. Fig. 12) shows a low deposition flux (Affre et al., 1999), as ozone concentrations did not decrease while going down to sea level. Ozone concentration reached its maximum value (about 82 ppbv at 500 m) at the top of a near-adiabatic layer. Above this layer, the potential temperature profile increased in a constant way between 500 and 1300 m, which conferred a stable character to the crossed layer. Ozone concentrations decreased with altitude in a homogenous way within this moist air mass. Above 1300 m, the H₂O mixing ratio strongly decreased; the wind changed from southeastern near sea level to northwestern in altitude. Thus, it can be thought that the height where the reverse flow of the breeze cell occurred was around 1300 m, although it was mixing with the synoptic flux. Ozone concentration strongly decreased above 1300 m and reached a constant value of about 52 ppbv within this dry air mass. The same values as the ones measured in the free atmosphere over land were found again. The land/sea breeze cell over the sea was well developed at about 08:00 (UT). The reverse flow of the cell was so dry that this flow could be thought to be combined with the synoptic flow in altitude.

These profiles enable to show the important stratification of ozone concentrations over the ground and a lower one over the sea. Most layers crossed were stable, which gave limited vertical exchanges. Advection and complex local circulations made vertical fields of ozone inhomogeneous. Contrary to what had been found during other flights, thermodynamical characteristics and ozone fields varied in an important way along distances from some tens to a hundred kilometres.

5. Conclusion

This aircraft measurement campaign was performed on a regional spatial scale during 3 days when an anticyclonic air mass stagnated over western Europe. The front part of the anticyclonic air mass was continental. During its continental course, the air mass was weighed with pollutants. The residence time of the particle in the system over the continent is larger for remote areas than for regions near the anticyclonic center (Vukovich et al., 1977). Consequently, the air mass should have been weighed with secondary pollutants like ozone. The processing of aircraft measurements enabled to show the homogeneity of ozone concentrations within the air mass, which confers a regional origin to the ozone formation. Local ozone production could have been measured in urban plumes, but its intensity seemed to be limited. On the other hand, these aircraft measurements over France reveal the inhomogeneity of the primary pollutant fields on a regional scale, depending on the emission sources' location.

By comparing aircraft measurements of ozone with daily maxima of ozone values from the ground networks, it was shown that the daily maximum of ozone is close to the ozone measurement made in the atmospheric boundary layer. The daily maximum of the ozone concentration variation mainly depends upon the atmospheric boundary layer development. In the case of coastal breeze conditions, the aircraft probe enabled to show the strong ozone values in the nighttime residual layer that might confer a high potential of oxidation to the boundary layer that goes on developing and might contribute to the daily O_3 maximum. Moreover, soundings enabled to show the high variability of thermodynamical parameters and ozone concentrations versus altitude. The high vertical variability was due to thermal stratification, high temperature inversions, and wind rotations.

The O_3 Reg experiment allowed to reinforce results obtained from statistical analysis with ground network data. These results are in agreement with the overview of scientific findings from major ozone field studies in Europe and North America as shown in Solomon et al. (2000). Indeed, the O_3 Reg campaign strengthened the premise that ozone accumulation and production are regional phenomena that affect both urban and rural environments. The ozone concentration limited variability is due to the local formation (or loss) depending on local primary emissions. Ozone reduction strategies considered only on a local scale are not sufficient to fight against the regional photochemical pollution.

6. Uncited reference

Sillman, 1999

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