Transactions on Ecology and the Environment vol 6, © 1995 WIT Press, www.witpress.com, ISSN 1743-3541

Transport and distribution of air pollutants in Athens (Greece): aircraft measurements during MEDCAPHOT - TRACE

O. Klemm
Fraunhofer-Institut für Atmosphärische Unweltforschung (IFU), Kreuzeckbahnstraße 19, D-82467 Garmisch-Partenkirchen, Germany

Abstract

A series of flights was conducted within the MEDCAPHOT - TRACE project between 06 and 15 September, 1994. The goals were to help understand the distribution, transport, and chemical reaction rates of pollutant gases emitted in the large urban agglomeration of the city of Athens. The flight routes covered the Greater Athens Area (about 60 × 60 km), including the inner basin, with low level (50 - 150 m above water or ground) flight legs. Additionally, vertical profiles were flown southwest and northeast of the city in order to characterize the physical and chemical structure of the boundary layer upwind and downwind of the city.

In some cases, a relatively strong northeasterly synoptic flow guaranteed good ventilation in most parts of the Athens basin and thus made an intense build-up of pollution impossible. In other cases, when a strong sea breeze developed during the day, the near-surface flow direction was into the basin from all sides. Therefore, pollutants could escape the basin only vertically, and high concentrations of primary and secondary pollutants built up in layers which were located NE of the city in altitudes of several 100's of meters. From these layers, pollutants were probably incorporated into long range transport towards S.

1 Introduction

The city of Athens, Greece, and its satellite communities add up to a large urban agglomeration of 4.5 million inhabitants. Most of the business and residential areas lay within a basin which is surrounded by mountains and ridges of various altitudes (Figure 1). Settlements of small industries are centered in the NW portion of the basin. Most of the air pollutant emissions originate from the very intense road traffic. Large crude oil refineries are located within the *Triassion* Plane, north of the *Aigaleo* Mountains.

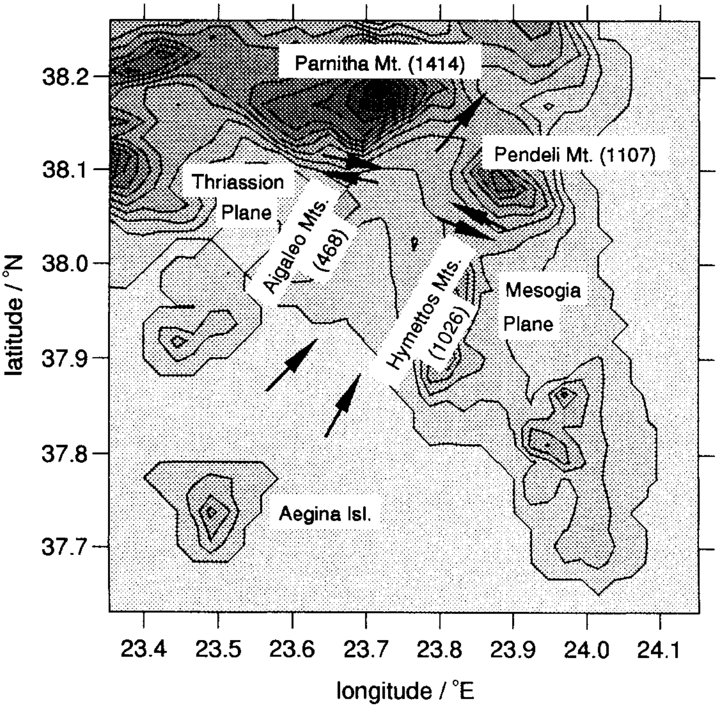


Figure 1: Map of the *Attica* Peninsula with topographic contour lines. Mountain peak altitudes (m above mean sea level) are given in parentheses. The Athens urban area lays between *Hymettos* and *Aigaleo* Mts., reaching up to the foothills of *Pendeli* Mt. Small industries are mostly located just SE of *Aigaleo* Mt. *Tatoi* airport lies in the valley between *Parnitha* and *Pendeli* Mts. Arrows indicate major routes of the sea breeze circulation.

During the summer months, the so-called *Etesians* winds, a persistent northerly flow, ventilate the basin most of the time [6]. When these winds become weaker in fall, a southwesterly sea breeze can develop during the day. While weak sea breezes are observed only locally near the coast, strong breezes can penetrate the entire Athens basin [9]. Such situations are associated with intense photochemical smog episodes [1, 2, 3, 4, 6].

Several photochemical episodes have been described under meteorological and chemical aspects on the basis of ground measurements. Only little vertical information [5] is available for chemical species, so that important questions are still unanswered. Some of these questions are: What is the chemical character of the sea breeze air masses, are they "clean" or "polluted"? What concentration levels are built up over the city? What is the typical composition of emissions? Where are the areas of highest pollution? How are the areas outside the basin affected during photochemical episodes? What is the ultimate fate of sea breeze air masses after being enriched with pollution over the city?

We studied the three - dimensional distribution of primary and secondary air pollutants in the Greater Athens Area (GAA) using a highly instrumented research aircraft. The measurements were conducted as part of the MEDCA-PHOT - TRACE (Mediterranean Campaign of Photochemical Tracers - Transport and Chemical Evolution) experiment in August / September 1994 and were supplemented by a variety of ground based measurements (meteorological, chemical, both *in situ* and remote sensing techniques). In this contribution, aircraft results of an intense sea breeze day (15 September 1994) will be presented. An overview of all aircraft measurements, a synthesis of aircraft with ground based measurements, and a comparison of experimental data with numerical model output datasets will be presented elsewhere.

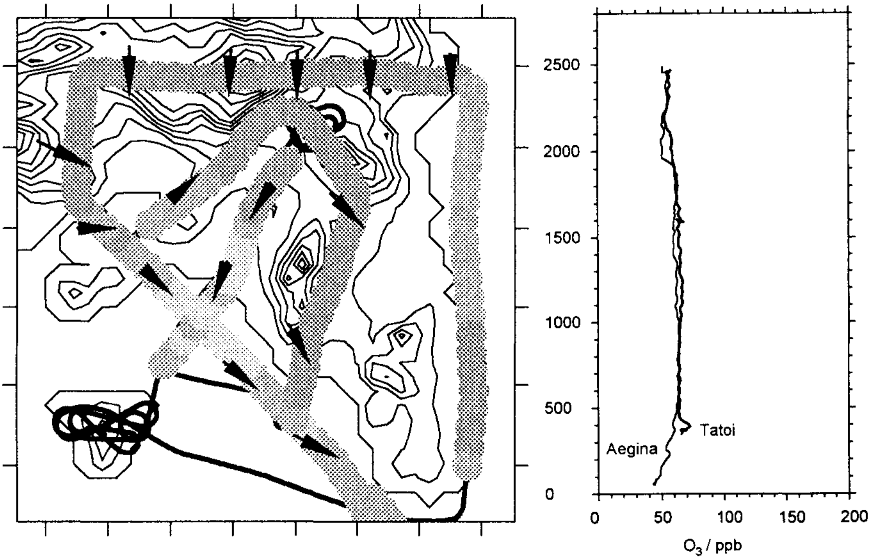
2 Aircraft Measurements

A *Dornier 228* twin - engine turboprop research aircraft was employed for the measurements. Payload, speed, and endurance of this aircraft proved to be ideal for the measurements within the GAA. The aircraft was equipped with instruments for the continuous (1 Hz) precision measurements of aircraft location (3-D), temperature, humidity, wind (2-D), O_3, NO, NO_2, NO_y, SO_2, CO, and CH_2O. Additionally, grab samples were collected for VOC analysis.

We conducted two flights on 15 September 1994, one starting before sunrise, and one around noon. The flight routes were virtually identical and covered overflights over the city at various altitudes, legs along the sea coasts around the *Attica* peninsula, low level legs in the plains and valleys around the Athens basin, and vertical profiles up to about 2800 m ASL over the island of *Aegina* and over *Tatoi* airport (see Figs. 1 and 2).

3 Results

The two research flights on 15 Sep 94 yielded very heterogeneous and complex datasets. Some of the results are summarized in Figures 2 and 3 and in Table 1. During the morning hours, the meteorological situation was characterized by a northerly flow across the whole domain. Within the Athens basin, low wind speeds and a stable boundary layer allowed the build-up of high pollutant levels over the city. Traffic emissions of NO were high enough to titrate O_3 completely in air masses reaching up to about 120 m above street level (see Fig. 2). Along the Athens seacoast, the concentration levels of primary pollutants were also high, resulting from nighttime emissions from the city. Over water, the polluted layer was about 150 m deep.



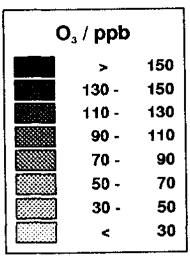


Figure 2: Results of the O_3 measurements during the morning flight of 15 Sep 94. In the left-hand graph, the flight route is plotted by a bold line with vertical profile spirals over *Aegina* Isl. and *Tatoi* airport. 30 s averages of the measured O_3 mixing ratio at low level (120 m above ground) legs are is plotted as grey-shaded dots. Contour lines and axis definitions are identical to Figure 1. Arrows indicate the wind direction as measured on board the airplane. Circles if the bold line indicate locations of vertical profiles. The right-hand graph shows O_3 profiles (vertical axis: m asl) as measued over and close to the island of *Aegina*, and over the airport of *Tatoi* (bold line).

Until the noon hours, a quite strong sea breeze developed. While the flow was still from a northerly direction in the northern part of the domain, the southwesterly sea breeze penetrated the whole basin from the Athens coast to *Pendeli* Mt. (Fig. 3). It was strong enough to exit the basin through the valley between *Pendeli* and *Hymettos* in easterly direction, while no significant flow

Transactions on Ecology and the Environment vol 6, © 1995 WIT Press, www.witpress.com, ISSN 1743-3541

was observed between *Parnitha* and *Aigaleo*. Apparently, there was a zone of convergence in the area between *Parnitha* and *Pendeli* Mts., with wind coming in both from southerly and northerly directions. Due to this convergence, and by support of the vertical slopes of the mountains, an intense upward flow must have developed in this zone. This becomes evident from the vertical profile data, of which an example is shown in Figure 3. Large enrichments of O_3 (Fig. 3) and other pollutants (see Table 1) were observed in a multi-layer PBL at altitudes up to 2300 m ASL. No such enrichments were observed in the *Aegina* profile, upwind of the city. Therefore, high concentrations of pollutants clearly resulted from emissions from the Athens basin, which were photochemically processed during their transport to NE and up to higher altitudes.

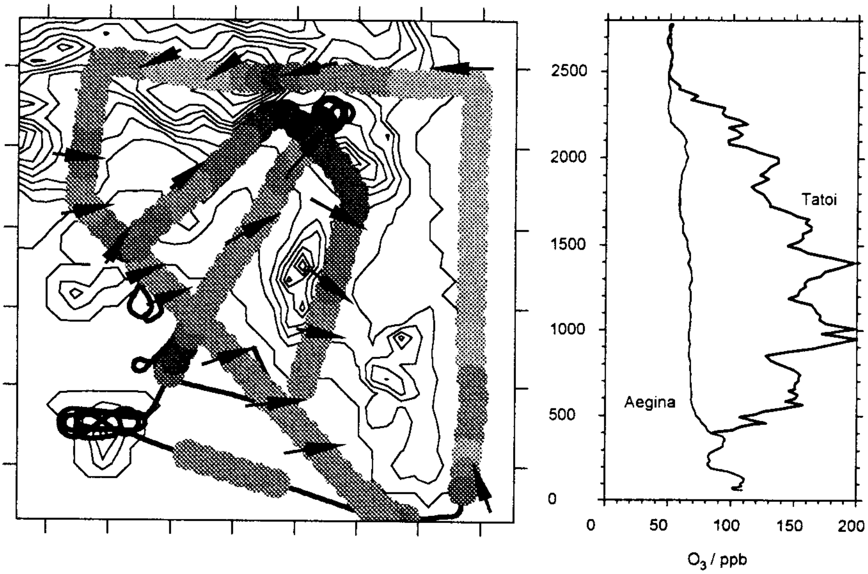


Figure 3: Same as Figure 2, but for the noon hours of 15 Sep 1994. Grey shades are also identical.

Several PBL air masses with typical characteristics were identified on 15 Sep 94 in the GAA. A "PBL background" air mass was encountered during the morning flight in the NW corner of the domain, during noon in the NE corner, and in the middle sections of the profiles, both morning and noon over *Aegina*, and morning over *Tatoi*. These air masses are well mixed (little structure in profile middle sections, Figures 2 and 3, low standard deviations, Tab. 1), and exhibit mixing ratios in the order of 62 - 69 ppb O_3, 1.3 - 4.2 ppb NO_y, 1.4 - 2.1 ppb CH_2O, and 190 - 270 ppb CO. Higher concentrations were generally observed during the noon hours. This type of air mass was not directly influenced by fresh emissions from the Athens area or other sources and can therefore be regarded as background PBL air for that particular day. Comparing its composition with those of free tropospheric air, enrichments of O_3, SO_2, NO_y, and CO were still large (Table 1).

Table 1: Averages and standard deviations of gaseous pollutant mixing ratios in various air masses as measured on 15 Sep 1994 in the Greater Athens Area

O_3	SO_2	NO	NO_2	NO_y	CH_2O	CO
"clean" boundary layer air influx from north						
morning						
62 ±2	**1.9** ±0.3	**0.02** ±0.01	**0.3** ±0.05	**1.6** ±0.1	**2.1** ±0.2	**214** ±5
noon						
69 ±1	**3.2** ±1	**0.25** ±0.04	**1.6** ±0.2	**4.2** ±0.3	(n.a.)	**267** ±11
lower free troposphere						
morning						
52 ±2	**0.5** ±0.2	**0.05** ±0.01	**0.05** ±0.07	**0.61** ±0.09	(n.a.)	**85** ±14
noon						
50 ±2	**0.3** ±0.2	**0.05** ±0.01	**0.03** ±0.01	**0.81** ±0.04	(n.a.)	**98** ±5
profile middle sections						
morning Aegina (500 - 1900 m ASL)						
63 ±2	**2.0** ±0.7	**0.04** ±0.02	**0.43** ±0.4	**1.5** ±0.4	**1.4** ±0.5	**209** ±13
morning Tatoi (500 - 2100 m ASL)						
64 ±3	**1.7** ±0.7	**0.05** ±0.01	**0.30** ±0.2	**1.3** ±0.4	**1.4** ±0.6	**238** ±44
noon Aegina (600 - 2000 m ASL)						
66 ±3	**1.3** ±0.4	**0.06** ±0.01	**0.19** ±0.09	**1.5** ±0.4	**1.5**±0.8	**192** ±36
noon Tatoi (500 - 2300 m ASL)						
144 ±28	**7.8** ±2	**0.53** ±0.2	**6.4** ±3	**19** ±6	**2.3** ±1.4	**964** ± 02
sea breeze						
noon						
84 ±10	**12** ±4	**0.9** ±0.9	**4.3** ±3.7	**11** ±7	**5.8** ±1.6	**303**±85

Air masses entering the basin from SW with the sea breeze were very heterogenous in composition. It is evident from the *Aegina* profile in Figure 3 that pollutants were enriched in a surface layer over water which was about 150 m deep. Extensive measurements were conducted in that layer during the SE -

NW flight leg along the Athens sea coast. Here, elements of fresh pollution (O_3 decreasing with increasing NO_y, indicating titration by NO) as well as aged pollution (O_3 parallel to NO_y due to photochemical O_3 production, like in the middle section of the Tatoi profile) were found. Apparently, air parcels of various origin entered the Athens basin with the sea breeze. Although there is no proof of the origin of these air masses, it is hypothesized that at least some of them were enriched with pollutants by the city itself a few hours earlier, transported to the sea and recirculated by the sea breeze. Especially the secondary pollutants O_3 and CH_2O were enhanced over background PBL air (84 versus 65 ppb for O_3, 5.8 versus 1.5 ppb for CH_2O).

4 Conclusions

In this contribution, first results of 3-D measurements of meteorological and air chemistry parameters in the Greater Athens Area (GAA) were presented. We found that PBL air masses entering the Athens basin in the morning of 15 Sep 94 were not affected by fresh emissions, however exhibited a considerable level of O_3 (62 ppb). Nitrogen oxide emissions resulted in intense O_3 depletion over and downwind of the city. Until the noon hours, a strong sea breeze developed. Sea breeze air masses were polluted compared to the levels of background PBL air. The SW sea breeze penetrated the entire Athens basin. Between *Parnitha* and *Pendeli* Mts., however, it converged with the northeasterly flow from the east coast of the *Attica* peninsula. Due to this convergence, and supported by the mountain slopes, the polluted air masses were transported upward, resulting in a highly polluted PBL of layered structure, as measured during the profile over Tatoi airport. High levels of pollution were found at altitudes up to 2400 m ASL. We hypothesize that from this zone, highly polluted air masses (up to 200 ppb O_3, 30 ppb NO_y, 1.5 ppm CO, and 4 ppb CH_2O) are incorporated into long range transport towards the south.

The general pattern of our results is in good agreement with model results [*e.g.*, 7, 8,] for sea breeze situations the Athens area. Our data from 15 Sep 94 and other flight days will be compared in detail with models which will be initialized with the actual meteorological conditions.

Acknowledgements. The measurements could be a success only through the strong support by our Greek collegues from the *University of Thessaloniki* (I. Ziomas and many others), by the Athens air traffic controllers, by the *DLR* pilots (R. Henrici and others), and by the never-tired *IFU* ground crew.

References

1. Cvitas, T., Güsten, H., Heinrich, G., Klasinc, L., Lalas, D.P. & Petrakis, M. Characteristics of Air Pollution During the Summer in Athens, Greece. *Staub - Reinhaltung der Luft,* 1985, **45,** 297 - 301.

2. Güsten, H., Heinrich, G., Cvitas, T., Klasinc, L., Ruscic, B. & Lalas, M. Photochemical Formation and Transport of Ozone in Athens, Greece. *Atmospheric Environment,* 1988, **22,** 1855 - 1861.

3. Kallos, G., Kassomenos, P. & Pielke, R.A. Synoptic and Mesoscale Weather Conditions During Air Pollution Episodes in Athens, Greece. *Boundary Layer Meteorology,* 1993, **6,** 163 - 184.

4. Lalas, D.P., Asimakopoulos, D.N., Deligiorgi, D.G. & Helmis, C.G. Sea-Breeze Circulation and Photochemical Pollution in Athens, Greece. *Atmospheric Environment,* 1983, **17,** 1621 - 1632.

5. Lalas, D.P., Tombrou-Tsella, M., Petrakis, M., Asimakopoulos, D.N. & Helmis, C. An Experimental Study of the Horizontal and Vertical Distribution of Ozone over Athens. *Atmospheric Environment,* 1987, **21,** 2681 - 1693.

6. Mantis, H.T., Repapis, C.C., Zerefos, C.S. & Ziomas, J. Assessment of the Potential for the Photochemical Air Pollution in Athens: A Comparison of Emissions and Air-Pollutant Levels in Athens with Those in Los Angeles. *Journal of Applied Meteorology,* 1992, **31,** 1467 - 1476.

7. Moussiopoulos, N. A Numerical Simulation of the Sea-Breeze in Athens, *Pageoph,* 1985, **123,** 314 - 327.

8. Pilinis, C., Kassomenos, P. & Kallos, G. Modeling of Photochemical Pollution in Athens, Greece. Application of the RAMS-CALGRID Modeling System. *Atmospheric Environment,* 1993, **27B,** 353 - 370.

9. Prezerakos, N.G. Characteristics of the Sea Breeze in Attica, Greece. *Boundary Layer Meteorology,* 1986, **36,** 245 - 266.