Seminar on

Monitoring and Modelling in the Mesoscale

Proceedings

Thessaloniki
September 27, 1991

edited by
N. Moussiopoulos, G. Kaiser
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German-Greek-Cooperation
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Welcome Address

It is a great pleasure for me to welcome distinguished members of the international scientific community to Thessaloniki, the historic capital of Macedonia. Founded in 315 B.C. by Cassandrus, the king of Macedonia, Thessaloniki was given the name of the founder's wife, a sister of Alexander the Great. Since then and thanks to a number of geographical advantages, our city prospered from every point of view and remained standing and inhabited over more than 23 centuries. Hence, Thessaloniki evolved to be an economic and cultural center on the entire Greece and on Balkan countries in general.

Air pollution, the main subject of your Seminar, is an unavoidable ingredient of our contemporary civilization. Dense traffic in modern cities and industrial activities in economically advanced countries result in elevated emissions of air pollutants, which inevitably threaten public health and already proved to be hazardous to ancient monuments.

The awareness of all authorities in Thessaloniki with regard to air pollution is reflected in their unanimous support for the International Measuring Campaign which is currently being held in our city. The Municipality of Thessaloniki participates actively at this campaign, as it recognizes the necessity to collect all data needed to optimize the air pollution abatement strategy for the Greater Thessaloniki Area.

In fact, the Municipality of Thessaloniki endeavours several years now to improve air pollution control in our city. Three fully equipped emission measuring stations and a ground-based meteorological station are being operated by the Municipality in the downtown area of Thessaloniki. These stations allow to monitor on a routine basis air quality in our city and to take proper measures so that pollutant concentrations remain below safe standards. Our monitoring network will be soon further expanded by the installation of two additional stations.

I am convinced that the discussions you will have during this Seminar will help you to improve your knowledge on various delicate issues related to air pollution. As we all will profit by progresses in atmospheric sciences, I wish to your Seminar the best possible success. Moreover, I wish to all of you a most enjoyable stay in our city and that you will have enough time to visit the monuments testifying Thessaloniki's unique role in history.

Ioannis Zournas
Vice-Mayor of Thessaloniki
Opening Address

The Greater Thessaloniki Area constitutes the second in size urban and industrial agglomeration pole in Greece. Its influence on the metropolitan area as well as on the Region of Central Macedonia and the Southern Balkan Penninsula is very significant.

The area experienced a rapid increase in the development rates of all sectors (primary, secondary and tertiary) following the World War era. It now has a population of about 1,000,000 inhabitants. In addition, it represents the largest exporting port of the country and carries almost 17% of the total industrial capacity of Greece.

The Thessaloniki Area is undergoing a considerable growth and development. The recent geopolitical events in the Balkans and the former Eastern European countries stress even more the importance of the role of the Thessaloniki Area while giving it new development perspectives and enhancing it furthermore. One should also mention the fact that due to the location of the area as well as its spatial considerations, it maintained its role throughout the 2,800 years of its history.

The Greater Thessaloniki Area faces increasing and rather alarming environmental quality problems like all contemporary metropolitan centers. The latter problems are even stressing due to the size and the poorly planned development of the area. Problems such as the pollution of Thermaikos Gulf and the degrading of the quality parameters of the atmosphere are characteristic examples. One should expect these problems to occur especially in the Greater Area. We can, for example, refer to a) the number of the vehicles used in the area: 200,000, and b) the 1 million tons of fuel that is daily consumed in the area. Facts and problems relating to the city and area development as the above need to be given the proper emphasis especially with regards to both the deterrence and mitigation efforts. It is well known that no real development can take place without taking - at the same time - measures with regard to the environmental protection.

The aforementioned thoughts were more intense in the decade of the '80s and have resulted, amongst other things, in the enactment of the Law concerning the Master Plan and Development of the Area: "Master Plan and Program for the Environmental Protection of Thessaloniki". As a conclusion, the Organization of Thessaloniki was made Law and initiated its functions aiming at the Master Plan implementation and continuous improvement in specific applications.

The Organization of Thessaloniki has placed special emphasis and priority on the thorough study and examination as well as the control and quality protection of the atmosphere since the very first weeks of its generation. This is because the above subjects are considered as the most crucial factors of the quality of living in a metropolitan area nowadays. The Athens lesson, of course, is considered important enough to prove evidence for the need to deter similar phenomena in Thessaloniki. As a matter of fact, the Organization of Thessaloniki has planned and is now carrying out a large program of studies regarding the atmospheric pollution. The program's
specific objectives are:

- The estimate of the current pollution levels.
- The survey of the pollution sources as well as the determination of the size of the pollution level.
- The proposal for short-term pollution mitigation measures in addition to measures for the development and incorporation of a global policy regarding the environmental protection.

In order to implement the program of the aerial pollution studies, the Organization of Thessaloniki mobilized the experts of the area and even the whole nation. As a result, the Aristotle University of Thessaloniki was assigned the "most challenging" tasks of the programs.

Specifically, the University is going to estimate a) the contribution of the vehicles to the area pollution levels, b) the mathematical forecast of the pollutants in the city's atmosphere through appropriate models of aerial diffusion (inertials and of photochemical substance), c) the examination and evaluation of the interrelationships between meteorological phenomena and pollution by the means of a well coordinated campaign that is currently under way. Referrals to those initiatives and activities will be made in the present Seminar.

We believe that, upon the finalization of the studies, the Organization of Thessaloniki as well as the Administration in general will be able to acquire valuable tools for the strategy formulation regarding the aerial pollution of Thessaloniki (both as a means of long-term planning and as a deterrence of impacts).

By doing the above, we believe that the collaboration of the University and the Administration along with the improvement of the modern technology are enhanced as they are the most important elements for overcoming complex problems such as the environmental management.

With these thoughts, in addition to the assurance that the conclusions and proposals of the Seminar will be used by the best possible way, I am now declaring this Seminar to be started.

Ioannis Sfendonis
Chairman of the Organization of Thessaloniki
Preface

The identification, analysis and, to the very end as ultimate goal, the solution of environmental problems is nowadays more than an interesting research task, it is a 'social must' because of the impact a polluted environment has to every human being.

However, the demands given by the complexity of the research subject are very high. Therefore, an interdisciplinary cooperation between chemists, physicists and engineers is not only mandatory, but a necessary pre-condition for any progress to be achieved.

Having this in mind and expecting synergistic effects by pooling the experience and know-how of scientists from different countries, two years ago the integrated project "Environmental Engineering" has been installed in the framework of the German/Greek cooperation programme. Today, this project comprises seven individual subprojects. It is sponsored by the Federal Republic of Germany with about one quarter of the total budget provided for the cooperation with Greece.

In an attempt to promote contacts among specialists in the field of Air Pollution, the Seminar "Monitoring and Modelling in the Mesoscale" was held at the Aristotle University Thessaloniki on September 27, 1991. This volume contains all contributions to the Seminar.

A number of the papers given at the Seminar deal with the "Thessaloniki '91" Measuring Campaign which was conducted September 15 - October 13, 1991. This campaign represents the biggest, most important and most expensive undertaking which was ever performed within the German/Greek cooperation programme.

It is hoped and may be expected that the data collected, processed and evaluated will be a sound basis for decisions to be made in the near future in order to improve the present situation in the Thessaloniki area with regard to air pollution. Therefore, the Seminar "Monitoring and Modelling in the Mesoscale" may be regarded as an integral part of the joint efforts of several institutions to contribute to the solution of a specific environmental problem in the Greater Thessaloniki Area.

Günter Kaiser
International Bureau, Research Center Jülich,
Federal Republic of Germany
Monitoring and Modelling in the Mesoscale

Air pollutant emissions may be hazardous for man, his living environment and materials. For any sensible action to prevent or to reduce environmental damage it is necessary to investigate the relationship between air pollutant emissions and immissions. This implies a thorough knowledge of the emissions as well as a detailed analysis of transport and transformation mechanisms in the atmosphere. The latter can be performed either on the basis of sufficient observational evidence (covering both meteorology and pollutant concentrations) or by the usage of suitable mathematical models or with a suitable combination of both.

A combination of monitoring and modelling is especially useful for studies of mesoscale dispersion over complex terrain: A detailed analysis based only on observations would require a dense monitoring network and hence extremely high operational costs. For this reason such a network could hardly be operated on a routine basis. Models, on the other hand, cannot be considered as reliable tools, unless they have been already successfully verified. Obviously, for verification purposes accurate and complete measured data are required. Relevant datasets may be conveniently collected in the course of intense measuring campaigns like the one organized in the Greater Thessaloniki Area September 16 - October 13, 1991.

This volume contains papers given in the Seminar "Monitoring and Modelling in the Mesoscale", which was held on the occasion of the Thessaloniki '91 Measuring Campaign September 27, 1991. The papers are divided into four sections. The first section contains an introduction to the environmental problems of Thessaloniki and a review of the so far activities to ameliorate the situation. The second section deals with the preparation and the organization of the Thessaloniki '91 Measuring Campaign. The third section consists of the invited lectures, which all deal with interesting aspects of dispersion modelling. The final section contains papers on emissions in Thessaloniki and on results of model application for the Greater Thessaloniki Area.

I would like to thank the authors of the papers for a job well done. I also wish to acknowledge the support provided by the International Bureau of the KFA Jülich for printing the proceedings. Finally, I would like to thank Dr. Günter Kaiser both for initiating the integrated project Environmental Engineering and for his continuous encouragement and support.

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SECTION 1: 
THESSALONIKI AND ITS ENVIRONMENT
Some Thoughts on Air Pollution

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Sixty years ago a seminar on air pollution problems would have attracted very few scientists. Those that did attend it would have felt that it was just an interesting subject as any other scientific one. Today when the term air pollution is mentioned almost everyone from the child in the primary school to the third age person realizes that we are dealing with a very significant problem affecting the modern society.

As with most sociological issues, it is difficult to separate fact from emotion. This is also the case with pollution. Pollution becomes a major subject for the political arena, further charging the emotional aspect and clouding the real facts. The air pollution problem cannot be solved solely through technology. The acceptance by the society of all or even part of the suggested measures is a primary factor for preventing the disastrous effects of air pollution.

Originally all these effects were attributed to the industry, but today the whole image has changed. The emissions from industry contribute only about 25 percent to the total air pollution effects. The internal combustion engines used in cars, buses, trucks, airplains and other means of transportation contribute about 50 percent and the rest is contributed by central heating, power stations and other units for the ultimate comfort of people.

So, now a seminar on air pollution provides valuable knowledge to the scientists who attend it and especially when a seminar is organized in a city or an area where the industrialization, the increase of population and consequently the heavy traffic have already created serious problems and measures must be taken to prevent a worse situation. This is the case of the city of Thessaloniki and the present seminar.

But what is actually air pollution? There are many definitions. In a general sense it is the addition to air atmosphere of any substance which may have a harmful effect to man, to animals, to plants and to materials used by man. Now, we can add that pollution is not only a substance, like a chemical compound, introduced to the atmosphere, but also an increased radiation produced by the depletion of the protective ozone layer. This increase is really harmful to life generally. People now know that not only the sun but a greater danger is also shining through the sky.
This effect was produced by using millions of tons of ozone depleting chemicals. It is estimated that more than 750 thousand metric tons of chlorofluorocarbons are used annually all over the world and these compounds react with ozone.

In the last years it has become increasingly evident that high levels of pollutants have caused the premature death of thousands of people. Meteorologists have shown that the unfavourable weather conditions that contributed several disasters in parts of our planet are likely to occur more often. On the other side, though acute effects of air pollution are alarming, the chronic effects are of more concern. Clinical and epidemiological surveys have related various air pollutants to almost all health factors from the common cold to some forms of cancer. These surveys correlated definitely air pollution and respiratory diseases. The number of possible air contaminants and their concentration levels is practically infinite. The means of testing and expressing pollutant concentrations is not so well defined. One of the most limiting factors in epidemiological studies is the relatively limited air quality data and the obvious effects of synergism.

Ozone is a typical secondary pollutant. It occurs naturally in the atmosphere and it is generated during electric storms. The primary source of high ozone concentrations in the lower atmosphere originates from the photochemical reaction of nitrogen oxides and hydrocarbons which are emitted by the transportation means and industries. Both of them are primary pollutants. Nitrogen dioxide reacts in the presence of sunlight to form nitrous oxide and atomic oxygen. This atomic oxygen combines with molecular oxygen, again in the sunlight, to form an ozone molecule. The rate formation of ozone depends upon the type of the hydrocarbons and their concentration in the air. Other factors are the concentration of nitrogen dioxide and the exposure time to sunlight.

Ozone bleaches plant cells and has adverse effects on dyed fabrics, synthetic fibers and other organic materials. It causes eye irritation at 0.1 ppm levels and this is one of the best known effects. Smelling is very sensitive to ozone, detecting its odor at as low as 0.02 ppm concentrations. Sensory fatigue may follow rapidly but nasal and throat irritation occurs at 0.3 ppm. At levels of 1 ppm, severe restriction of respiratory passages occurs and a number of persons cannot tolerate higher concentrations. Generally, a damage of the lung tissue occurs making it more susceptible to infections.

We stressed the ozone effects, as this is the pollutant which will be investigated now in the area of our city, Thessaloniki. Up to now the incidents of high ozone concentrations in the area of the city are very few according to the data of 1990. Anyway, the study of the phenomenon, the analytical procedures and the evaluation of the collected data will be very valuable for the future measures to be imposed by the state.

Much emphasis is placed today on monitoring potentiailly toxic materials in the air, particularly in cities close to industrial units, where people may encounter some of the emitted chemicals in their normal life.
There is always a need for new techniques to monitor these chemicals and to ensure that safe concentration limits are not exceeded. Although there are no legally enforceable standards for air quality in our city, informal "air quality objectives" are sometimes used. There are of course standards for car emissions and generally current EEC standards are accepted. If industrial units and vehicles use the best pollution control methods, they can reasonably afford the quality of air to remain within reasonable limits.

At present there are some monitoring stations in our city to assess the extent of air pollution and to decide when concentrations are too high requiring emission restrictions from industries, central heating and city traffic generally; at the same time, a working group is studying the feasible measures, accepting the concentration levels used in Athens to declare an air pollution episode.

By closing I wish to remind you of a "monster" which, every year, emits to the atmosphere about 30 kg of unburned hydrocarbons, 34 kg of nitrogen dioxide, 4000 kg of carbon dioxide, 400 kg of carbon monoxide, lead and suspended particles. Most probably you realized that this "monster" is a car. Take care!!
Distribution of Heavy Metals in the Area of Thessaloniki

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ABSTRACT

High concentrations of Air Particulate Matter have been found in the area of Thessaloniki. TSP samples, collected at two stations in the area of Thessaloniki during the period July 1987–June 1988 were analysed for heavy metals. Results obtained showed that Pb, Zn, and Cu are emitted from man-made sources (traffic, domestic heating, industry). V, Ni, and Co are derived partially from natural and man-made sources, while Cr is mainly soil-derived.

Heavy metals were also determined in roadside dust samples seasonally collected at 20 sampling points of the area of Thessaloniki during the same period. Results showed that roadside dust in the urban area of the city contained elevated concentrations of Pb, Zn, and Sb, whereas in the industrial area increased concentrations of As, Cd, Cr, and Pb have been found.

INTRODUCTION

Thessaloniki, the second largest city in Greece, with a population of 1,200,000, is one of the oldest cities in Europe. It stretches over twenty Kilometers in a bowl formed by low hills facing a bay that opens into Thermaikos Gulf.

The development of the city has followed the development of the country. Until 1960 the growth of the industry was relatively slow. But from that year there was a rapid increase of industrialization. Industries such as oil refinery steel processing, chlor-alkali, fertilizers and anticnock compounds plants were built up.

At the same time the building of new big houses and multifloor blocks was started, to satisfy the needs for housing. Because urbanization and industrialization had brought together large concentrations of people in relatively
small area. The lack of a plan to arrange and locate the new units resulted various environmental pollution problems.

Atmospheric pollution is one of the problems getting now increased attention. From meteorological point of view the area has a high frequency of calm weather and high humidity. Temperature inversions and the island effects are very common, thus there is only little dispersion of the pollutants.

Various research projects have been undertaken in order to study the atmospheric pollution in the area of Thessaloniki. It is well documented that one of the major air pollution problems in the area of Thessaloniki is the presence of high concentration of Air Particulate Matter (1,2).

Chemical analysis of the Air Particulates is always of great concern to people living in urban areas and, on the other hand, can assist in course identification.

From this point of view we analysed many Air Particulates samples collected from various sites of the area of Thessaloniki. Thus, Heavy metals and Toxic elements and Polynuclear Aromatic Hydrocarbons were measured in these samples. At the same time the mutagenicity of the hydrocarbons was examined with the Ames test.

The concentration of heavy metals in roadside dust can also provide valuable information about pollution levels in urban and industrial areas (10,19). Thus, from this point of view, we also examined many roadside dust samples for their metal content.

HEAVY METALS IN AIR PARTICULATES

EXPERIMENTAL (31)-2
One hundred and eighty-four samples of total suspended particulates (TSP) were collected during the period July 1987–June 1988 at two sampling stations in the area of Thessaloniki. St1 (91 samples), and St2 (93 samples). St1 was in the center of the city, while St2 at the northwestern border of the residential area, close to the oil refinery, and about 100 m from the main road. (Figure 1)

Airborne particulate matter was collected on glass fibre filters (General Metal Works, 203X254 mm) with 99% collection efficiency for particles of 0.3 μm by using high-volume samplers (General Metal Works, model 2000). Samples were collected at a height of about 4 m above ground level with an average sampling flow rate of 85 m³ h⁻¹. The duration of each sampling period was 24 h starting at midnight. Loaded and unloaded filter were weighted after conditioning in a desiccator in room temperature.
One quarter of each loaded filter was extracted with a mixture of HNO3 and HCL acid in an ultrasonic bath(3,4). Lead, copper, zinc and manganese were determined by flame, while chromium, cobalt, nickel and vanadium by electrothermal atomic absorption spectrophotometry. Quality control was assured by duplicate samples, blanks and the method of standard additions. The analytical variances of data obtained by instrumental measurements were <10% for each element.

![Map of studied area.](image)

**Figure 1** Map of studied area.

**RESULTS AND DISCUSSION**

A data summary obtained from the elemental analysis of air particulate matter is presented in Table 1.

As can be seen, quite large variations in TSP and heavy metal concentrations were observed. This can be attributed not only to the fluctuation of emission sources over the seasons (traffic, industries, domestic heating etc.), but also to weather conditions that strongly affect the dispersion of air dust.
Furthermore, Table 1 demonstrates that some metal concentrations fluctuate much more than the concentration of particles, indicating that these metals are likely to be emitted by specific sources.

In order to examine whether the mean values of TSP and heavy metal concentrations are significantly different for the two stations, the t-test was employed. No significant difference was found at the 99% confidence level.

TSP concentrations were found to be in very good agreement with that reported by other investigators for the atmosphere of the city (1,2). It is clear, however, that the annual average concentration of TSP is much higher than the EEC standard of 150 μg/m³. The frequency distribution of TSP concentrations is given in Figure 2. More than 30% of TSP concentrations are higher than 300 μg/m³, which is the limit of the 95th percentile of all mean daily values taken during the year. This indicates that the city of Thessaloniki is faced with a serious problem of atmospheric pollution caused by particulate matter. Heavy metal concentrations were found to be in the same order of magnitude with those reported for other cities (5-13).

The frequency distribution of Pb concentrations in the atmosphere is also given in Figure 2. Although these concentrations occasionally reached 3.3 and 7.1 μg/m³ at St1 and St2 respectively, the mean annual concentration did not surpass the limit of 2.0 μg/m³ of the EEC. Moreover, the decrease of Pb content in gasoline to 0.15 g/l since February 1988 will undoubtedly result in a further decrease of airborne Pb concentrations.
Temporal variations of TSP and metal mass proportions (µg of metal/g of air dust) are given in Figure 3. As can be seen, some metals have distinct emission patterns changing with the seasons. This means that metals with increasing mass proportions during winter are likely to be preferably emitted by sources that characterize this season. However, the influence of weather conditions, which during winter are more frequent by periods of atmospheric stability resulting in pollutant build-up, should not be discounted (14).

Figure 3 demonstrates that during winter air dust seems to be enriched with Fe, V, Ni, Co, Cr and partially Cu, while Mn and Zn showed more or less constant mass proportions throughout the year. Assuming no change in industrial activities over the seasons, the increased emissions of V and Ni (and partially of Cr, Cu and Co) during winter could be attributed to oil combustion in domestic and commercial heating facilities.

As far as Pb is concerned, higher concentrations in air dust were measured during winter at St1. Since gasoline combustion (the lead content in gasoline was 0.4g/l until February 1988) constitutes the primary source of Pb in this area, it may be that since Pb is emitted from a low height and is not dispersed effectively, due to the lack of strong atmospheric turbulence during this season. However, the emission pattern of Pb at St2 was somewhat different. In this case some contribution from industrial emissions is possible.

Ratios of Pb/Zn concentrations in air particulate matter were found to be much higher than the calculated for roadside dust from the same locations (15). This indicates that the measured airborne lead is derived from emission sources rather than wind blown roadside dust.
Figure 3 Temporal variation of TSP (μg/m²) and heavy metal concentrations (μg/g air dust) in the atmosphere of Thessaloniki.

Metal Enrichment in Air Dust
To evaluate the enrichment of heavy metals in air dust, the enrichment factors (EFs) were calculated with respect to their distribution in the earth's crust. (15, 17). Iron was used as the baseline element. This means that all iron determined in
Figure 4  Enrichment factors of heavy metals in air dust of the atmosphere of Thessaloniki (Fe was used as the baseline element).

<table>
<thead>
<tr>
<th>Metal</th>
<th>Entrainment</th>
<th>(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$S_{T1}$</td>
<td>$S_{T2}$</td>
</tr>
<tr>
<td>Pb</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Zn</td>
<td>14</td>
<td>8</td>
</tr>
<tr>
<td>Mn</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Cr</td>
<td>53</td>
<td>42</td>
</tr>
<tr>
<td>Co</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>
air dust is considered to be soil derived. The results are presented in Figure 4.

As can be seen, the mean EF values of Pb, Zn and Cu are much higher than unity. This means that these metals are released into the atmosphere almost exclusively by man-made sources. The EF values of Mn, Cr, Co, Ni and V are lower, (between 4 and 12) indicating significant contribution from natural sources (crustal materials) (18). It is worth noting that the EF of Cr in air dust is about the same as that found in roadside dust of the area of Thessaloniki (15). This means that the majority of atmospheric Cr is soil derived.

However, this distinction between natural and man-made sources is based on the total quantity of airborne particles collected by the high-volume sampler. Since EF values are strongly dependent on particle size, (7, 13) higher EFs for many metals (Pb, V, Ni, Cr etc) would be obtained if only fine particles were examined.

The contribution of historically-contaminated soils to the airborne metal concentrations was also considered. For this reason [M]/[Fe] ratios in suspended particulate matter were compared to the ratios found in local road-side dust (15). Assuming no change in elemental ratios upon entrainment by wind action, the contribution of entrained material was calculated from the relation:

\[
[M \text{ soil}] = \frac{[M \text{ entrained}] \times [\text{Fe atmos}]}{[\text{Fe soil}]}
\]

where [M] is the concentration of the metal being concerned (13). It must be pointed out that this calculation gives only an estimation of the entrainment contribution, which is overestimated if other sources of Fe are present. Results obtained are given in Table 2.

In this table Pb, Zn, Mn and Co appear to be derived from emission sources rather than wind-blown soil, while about 50% of Cr seems to be soil-derived.

HEAVY METALS IN ROADSIDE DUST

EXPERIMENTAL (15)

Dust samples from 20 sampling points were seasonally collected during the period Summer 1987-Summer 1988. The sampling points (Figure 5) were selected taking into account the possible emission sources and the traffic density. The characteristics of selected points are given in Table 3.

Dusts were collected from roadsides in clean polyethylene bottles by using a plastic spatula and dried to 110°C overnight. The fraction of particle sizes up to 1000 µm was
used for analysis.
All elements except Pb and Mn were determined by Instrumental Neutron Activation Analysis combined with high resolution γ-ray spectroscopy. The IAEA SOIL-7 Reference Material was used for the determination.

The activation of the samples were performed at 5 MW swimming pool-type research reactor of N.R.C.P.S. "Democritos" Athens. The duration of the irradiation was 30 min at a neutron flux of 2.10 n/cm² s. The counting was performed after a cooling time of 3 days at the Chemistry Department of the University of Thessaloniki by using an i-Ge-γ-ray detector (efficiency 20% compared to 1" X 1" NaI(Tl) detector, energy resolution 1.8 meV for the 1.332 MeV Co-line). The detector was connected with a 4K Multichannel Analyser (CANBERRA S-35 Plus). The counting times were optimized in order to get information about all possible elements of interest. Because of the long cooling and transport time, only elements producing long-lived nuclides (T1/2>15h) by activation could be determined.

For the determination of Pb and Mn, about 1 g of dried dust was digested with 8 ml of aqua regia and the final volume was adjusted to 50 ml with deionized water (20). The digests were subjected to A.A.S. analysis by employing the standard addition procedures.

RESULTS AND DISCUSSION
Results obtained from the analysis of roadside dust samples of the area of Thessaloniki showed a considerable variation for most of the elements. The seasonal elemental variation of two sampling points (6-CITY and 12-IND 1) are given in table 4. However individual elements found to have different seasonal dependency, probably due to differences in their release in the environment and their mobility.

The mean elemental concentrations are presented in Table 5. From these data it is seen that some elements are primarily dependent on industrial activities while others on traffic. Increased concentrations on As and Cd were found near and around the main industrial area (IND 1). Particularly high concentrations of As (up to 563 µg g⁻¹) were found at sampling points 12 and 13. These concentrations could be attributed to As emissions from the fertilizer plant located in this region, where about 80,000 ton y⁻¹ of FeS are burned for sulfuric acid production.

Relatively increased concentrations of As and Cr were also found at sampling point 19 (IND 2), next to the cement producing plant. The maximum concentrations of Cr, Co and Mn were observed south-east of the city (sampling points 1 and 2), where the main activities are agricultural and/ or light industrial. The high levels of Cr, Co and Mn are attributed to the fact that soil in this area is rich in chromites that
contain Co and Mn as minor elements. (21)

Figure 5 Map of the sampling area.

Pb was found to be strongly dependent on traffic density, since higher concentrations were determined along the main traffic roads, (sampling points 5, 6, 8, 13, 16, 18 and 19) or in front of bus stations (sampling point 7). The contribution of possible industrial emission sources to the Pb pollution level determined near and around the industrial area, could not be distinguished from the Pb emissions due to the traffic because this area is also characterized by high traffic density. Taking into account that the average Pb concentrations in the Greek sediments is 28 µg.g⁻², even the less frequented by traffic points (2 and 3) seem to be contaminated. (8)
Table 3 Characteristics of the sampling points

<table>
<thead>
<tr>
<th>Sampling point</th>
<th>Area's code (main activities)</th>
<th>Average traffic density (vehicles/h)</th>
</tr>
</thead>
</table>
| 10, 11, 12, 13, 14, 15 | IND 1  
Sulfuric acid production  
Fertilizer production  
Iron, steel manufacturing  
Oil products treating | 2500 |
| 4, 5, 6, 7, 8, 9, 10 | CITY  
Commercial-urban activities                                                                 | 2500 |
| 16, 17, 18, 19 | IND 1  
Cement production  
Various handicrafts  
Urban activities | 2225 |
| 1, 2, 3, 20 | RUR  
Agricultural activities  
Light industry | <1000 |

The mean Pb levels in roadside dust from the 20 sampling points (427 μg.g⁻¹) is in good agreement with that reported by other investigators for the city of Thessaloniki.(22,23) but they are higher than reported for Athens.(24) However, when compared with other cities of the world, Thessaloniki seems to be less contaminated by lead.(19,20,25,26) Of course, the selection of representative sampling points is, in this case of great importance.

Roadside dust in Thessaloniki was found to have a mean Zn level of 448 μg.g⁻¹ that is quite similar to those reported for other cities.(24,25) Zn concentrations seem to have a positive relation with the traffic conditions rather than the traffic density. Thus, they were higher in dust samples collected near the signs and corners (sampling points 5, 6 and 10), where the tyre wear is higher. However, some contribution of industrial sources to the overall Zn burden should not be excluded.

The ratios of Pb to Zn concentrations presented in Table 6 show a wide variation. Higher ratios were determined along main traffic roads, whereas smaller in less frequented by traffic sites. The mean ratio, compared to the natural background levels show a 5-fold enrichment factor.(24)

In order to evaluate the elemental enrichment in roadside dust, the enrichment factors (EFs) of all elements were calculated with respect to their distribution in the earth's crust.(16) The EF for an element X in dust was considered the same as for air particulate matter(17)

$$\text{EF}_{\text{dust}} = \frac{\text{[C}_x\text{]/C}_{F\text{e}}}{\text{[C}_x\text{]/C}_{F\text{e}}\text{ crust}}$$
Thus, elements originating from the earth's crust should have EF values close to unity, while those resulting from other sources higher than unity.

The results of EF calculations are given in Figure 2. It is seen that the mean EF values of Mn, Co and Cr are between 0.5 and 6.0. Sources of these elements are probably crustal materials. The mean EF values of the rest of the elements are much higher (10–70) indicating non-crustal sources.

The correlation matrix of the elements determined at the 20 sampling points is presented in Table 5. High correlation coefficients were found between elements mainly coming from crustal sources (Mn, Co, Cr).

Among the elements originating from man-made sources, Sb was found to be positively correlated with Pb and Zn. This could be attributed to the fact that antimony is widely used by the car industry in anti-friction alloys that contain Sb up to 13% (16).

High correlation coefficient was also found between Pb and Br, probably due to the use of leaded gasoline.

<table>
<thead>
<tr>
<th>Element</th>
<th>Sampling point 5 (CITY)</th>
<th>Sampling point 12 (IND I)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Su</td>
<td>Au</td>
</tr>
<tr>
<td>Fe (mg·g⁻¹)</td>
<td>31.4</td>
<td>28.5</td>
</tr>
<tr>
<td>Cr (µg·g⁻¹)</td>
<td>259</td>
<td>281</td>
</tr>
<tr>
<td>Cr (µg·g⁻¹)</td>
<td>14.2</td>
<td>7.6</td>
</tr>
<tr>
<td>Pb (µg·g⁻¹)</td>
<td>732</td>
<td>1343</td>
</tr>
<tr>
<td>Zn (µg·g⁻¹)</td>
<td>1975</td>
<td>789</td>
</tr>
<tr>
<td>Mn (µg·g⁻¹)</td>
<td>386</td>
<td>187</td>
</tr>
<tr>
<td>Cd (µg·g⁻¹)</td>
<td>1.10</td>
<td>n.d.</td>
</tr>
<tr>
<td>As (µg·g⁻¹)</td>
<td>78.1</td>
<td>24.7</td>
</tr>
<tr>
<td>Sb (µg·g⁻¹)</td>
<td>4.16</td>
<td>7.1</td>
</tr>
<tr>
<td>Se (µg·g⁻¹)</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>Br (µg·g⁻¹)</td>
<td>112.2</td>
<td>173.3</td>
</tr>
</tbody>
</table>

n.d.: Non-detected.
Table 5 Mean* elemental concentrations in roadside dust of the area of Thessaloniki

<table>
<thead>
<tr>
<th>Sampling area</th>
<th>Fe  (µg·g⁻¹)</th>
<th>Cr (µg·g⁻¹)</th>
<th>Co (µg·g⁻¹)</th>
<th>Pb (µg·g⁻¹)</th>
<th>Zn (µg·g⁻¹)</th>
<th>Mn (µg·g⁻¹)</th>
<th>Cd (µg·g⁻¹)</th>
<th>As (µg·g⁻¹)</th>
<th>Sb (µg·g⁻¹)</th>
<th>Se (µg·g⁻¹)</th>
<th>Br (µg·g⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RUR 1</td>
<td>38.8</td>
<td>1469</td>
<td>50.5</td>
<td>234</td>
<td>85</td>
<td>683</td>
<td>1.50</td>
<td>5.9</td>
<td>1.06</td>
<td>n.d.</td>
<td>1.1</td>
</tr>
<tr>
<td>2</td>
<td>23.0</td>
<td>1442</td>
<td>25.4</td>
<td>67</td>
<td>42</td>
<td>445</td>
<td>2.06</td>
<td>7.1</td>
<td>0.24</td>
<td>n.d.</td>
<td>1.8</td>
</tr>
<tr>
<td>3</td>
<td>22.9</td>
<td>338</td>
<td>10.4</td>
<td>60</td>
<td>208</td>
<td>281</td>
<td>1.80</td>
<td>10.0</td>
<td>0.97</td>
<td>0.15</td>
<td>5.8</td>
</tr>
<tr>
<td>20</td>
<td>13.0</td>
<td>46</td>
<td>5.6</td>
<td>102</td>
<td>98</td>
<td>152</td>
<td>n.d.</td>
<td>9.9</td>
<td>0.65</td>
<td>n.d.</td>
<td>9.1</td>
</tr>
<tr>
<td>CITY 4</td>
<td>20.1</td>
<td>90</td>
<td>8.9</td>
<td>454</td>
<td>431</td>
<td>256</td>
<td>1.68</td>
<td>10.3</td>
<td>1.69</td>
<td>0.28</td>
<td>110.4</td>
</tr>
<tr>
<td>5</td>
<td>26.9</td>
<td>201</td>
<td>10.5</td>
<td>1094</td>
<td>1086</td>
<td>249</td>
<td>1.30</td>
<td>31.5</td>
<td>5.89</td>
<td>0.01</td>
<td>139.6</td>
</tr>
<tr>
<td>6</td>
<td>23.7</td>
<td>139</td>
<td>8.9</td>
<td>771</td>
<td>807</td>
<td>349</td>
<td>0.90</td>
<td>16.7</td>
<td>7.09</td>
<td>0.07</td>
<td>113.8</td>
</tr>
<tr>
<td>7</td>
<td>26.4</td>
<td>210</td>
<td>10.5</td>
<td>936</td>
<td>214</td>
<td>253</td>
<td>1.47</td>
<td>14.2</td>
<td>4.18</td>
<td>0.73</td>
<td>153.9</td>
</tr>
<tr>
<td>8</td>
<td>25.4</td>
<td>102</td>
<td>8.0</td>
<td>589</td>
<td>583</td>
<td>353</td>
<td>1.01</td>
<td>24.1</td>
<td>4.78</td>
<td>0.46</td>
<td>36.9</td>
</tr>
<tr>
<td>9</td>
<td>31.9</td>
<td>166</td>
<td>8.7</td>
<td>575</td>
<td>517</td>
<td>347</td>
<td>0.62</td>
<td>179.2</td>
<td>6.65</td>
<td>n.d.</td>
<td>52.7</td>
</tr>
<tr>
<td>IND 1 10</td>
<td>29.2</td>
<td>170</td>
<td>9.3</td>
<td>431</td>
<td>1924</td>
<td>383</td>
<td>0.41</td>
<td>64.5</td>
<td>6.49</td>
<td>0.53</td>
<td>18.1</td>
</tr>
<tr>
<td>11</td>
<td>28.3</td>
<td>244</td>
<td>10.0</td>
<td>313</td>
<td>331</td>
<td>258</td>
<td>2.74</td>
<td>33.7</td>
<td>3.64</td>
<td>0.04</td>
<td>8.2</td>
</tr>
<tr>
<td>12</td>
<td>47.4</td>
<td>336</td>
<td>13.6</td>
<td>413</td>
<td>574</td>
<td>438</td>
<td>1.29</td>
<td>338.6</td>
<td>5.30</td>
<td>0.24</td>
<td>21.8</td>
</tr>
<tr>
<td>13</td>
<td>41.8</td>
<td>362</td>
<td>10.5</td>
<td>506</td>
<td>207</td>
<td>428</td>
<td>2.62</td>
<td>200.6</td>
<td>3.59</td>
<td>0.66</td>
<td>17.2</td>
</tr>
<tr>
<td>14</td>
<td>23.5</td>
<td>116</td>
<td>4.3</td>
<td>306</td>
<td>176</td>
<td>307</td>
<td>1.78</td>
<td>40.0</td>
<td>1.39</td>
<td>0.52</td>
<td>11.7</td>
</tr>
<tr>
<td>15</td>
<td>53.2</td>
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<td>8.4</td>
<td>255</td>
<td>217</td>
<td>352</td>
<td>2.64</td>
<td>67.2</td>
<td>2.87</td>
<td>0.29</td>
<td>14.0</td>
</tr>
<tr>
<td>IND 2 16</td>
<td>19.0</td>
<td>97</td>
<td>9.6</td>
<td>730</td>
<td>177</td>
<td>226</td>
<td>n.d.</td>
<td>23.5</td>
<td>1.79</td>
<td>0.97</td>
<td>66.2</td>
</tr>
<tr>
<td>17</td>
<td>23.5</td>
<td>161</td>
<td>8.3</td>
<td>420</td>
<td>567</td>
<td>260</td>
<td>0.36</td>
<td>29.9</td>
<td>1.72</td>
<td>0.31</td>
<td>47.1</td>
</tr>
<tr>
<td>18</td>
<td>30.0</td>
<td>371</td>
<td>8.9</td>
<td>611</td>
<td>474</td>
<td>493</td>
<td>0.22</td>
<td>65.8</td>
<td>3.30</td>
<td>0.03</td>
<td>47.2</td>
</tr>
<tr>
<td>19</td>
<td>50.3</td>
<td>1332</td>
<td>18.9</td>
<td>567</td>
<td>239</td>
<td>274</td>
<td>0.65</td>
<td>107.4</td>
<td>3.42</td>
<td>1.50</td>
<td>17.2</td>
</tr>
</tbody>
</table>

*Of four samplings (once a season) during the period Summer 1987-Spring 1988.

n.d.: Non-detected.
REFERENCES


23. A. Anagnostopoulos and J. P. Day, Chimica Chronica N.S. 49.
Brewer Spectrophotometer Measurements in the Industrial Area of Thessaloniki

A.G. Kelessis and N.M. Zoumakis
Laboratory of Atmospheric Physics, Technological Education Institute (T.E.I.), P.O.Box 14561, Thessaloniki 54101, Greece.

ABSTRACT

Total ozone, sulphur dioxide and nitrogen dioxide measurements have been made with the Brewer spectrophotometer #036, in the industrial area of Thessaloniki (40.4° N, 22.8° E), in Northern Greece. The Brewer spectrophotometer was operated reliably for more than two years of observations. The diurnal and seasonal variation of these pollutants can be used to characterize the air pollution situation of the greater Thessaloniki area.

INTRODUCTION

Today's concern about the quality of the earth's atmosphere increased the demand for high-precision measurements of primary atmospheric pollutants, such as sulphur dioxide, ozone, and nitrogen dioxide. Worldwide increasing trends of $SO_2$ and $NO_2$, their long-range transport and relation with acid rain problem\(^1\), and the partial destruction of the earth's ozone shield by anthropogenic pollution\(^2,3\) led to the necessity of continuous monitoring of these pollutants. Since early 1970's total burden of $SO_2$ has been included as an essential indicator of local and regional pollution. The increased $SO_2$ concentrations, in large urban centers and industrialized areas, that occur at both ground-level and aloft\(^4\), can be measured by ground based remote sensing instruments. The importance of $NO_2$ in controlling ozone layer\(^5,6\) has been extensively studied, but total ground based $NO_2$ columnar measurements are limited in estimating the amount and seasonal variability of $NO_2$ abundance\(^7,8,9\). The determination of global total ozone amount and trend needs a large number of accurate measurement stations, preferably distributed in a uniform pattern around the globe. Also, ground based total $O_3$ observations are used to validate satellite total ozone instruments performance.
An observational program was established to monitor (by measuring solar UV and visible radiation) total SO$_2$, O$_3$ and NO$_2$, in the industrial area of Sindos-Thessaloniki with Brewer #036 spectrophotometer$^{10,11,12}$. Urban Thessaloniki with 800,000 inhabitants, is located in Northern part of Greece (40.4°N, 22.8°E) covers an area of about 200km$^2$. Most industrial activities are located to the NW of the city, emitting 25000 tons of SO$_2$ and 10000 tons of NO$_2$ approximately per year$^{13,14}$.

INSTRUMENTATION

The total columnar SO$_2$, O$_3$ and NO$_2$ measurements presented here are direct sun observations, made with the Brewer spectrophotometer #036, in the Technological Education Institute of Thessaloniki, located near the industrial area of Thessaloniki.

Ozone and sulphur dioxide have strong absorption bands in the ultraviolet region of the solar spectrum. Brewer spectrophotometer #036 is a commercial monochromator capable in measuring the intensity of the UV-solar beam at six wavelengths 302.2, 306.3, 310, 313.5, 316.8 and 320nm with a 0.6nm resolution. The 302.2nm is reserved for calibration checks with a mercury lamp$^{12}$. Total columnar O$_3$ and SO$_2$ amounts are derived from measurements of solar intensities in the five remaining channels by applying a semi-empirical algorithm designed to reduce the effects of aerosol and molecular scattering and also random inhomogeneities in transmittance. Details on the instrument algorithms and performance may be found in Kerr et al.$^{11,12}$.

Nitrogen dioxide has strong absorption bands in the visible region (between 430-460nm) of the solar spectrum. Brewer spectrophotometer #036 is measuring light at five wavelengths simultaneously 431.4, 437.3, 442.3, 448.1 and 452.3nm with a 0.85nm resolution. The method used to estimate total NO$_2$ columnar amount is based on similar semi-empirical algorithm. Light intensities at the five visible wavelengths are linearly combined to reduce Rayleigh scattering, ozone absorption and other atmospheric parameters (cloud, haze, etc.)$^{7,15}$.

To ensure the stability of the Brewer instrument several tests were performed on a daily basis. The most important tests, the mercury calibration and standard lamp tests are performed several times during the day. The mercury lamp test ensures the proper measuring wavelength setting of the spectrophotometer while the standard lamp test gives informations on the spectral sensitivity and stability of the instrument$^{11,12,16}$. The spectrophotometer was found to be very stable throughout the two years of the measurements period$^{17}$.
RESULTS AND CONCLUSIONS

Measurements of stratospheric ozone concentrations exhibit a substantial variance which varies with location and season. Continuing concern about possible effects upon stratospheric O\textsubscript{3} by chemicals released into the atmosphere requires monitoring in a regular base, in determining any long-term changes in total ozone concentrations. Figures 1 and 2 show the monthly values of total columnar ozone in the industrial area of Thessaloniki. As it was expected the peak in the spring-time and the low values in autumn are clearly observed\textsuperscript{17}. The presented columnar values are also in accordance with those measured in the urban Thessaloniki area\textsuperscript{18}.

Columnar SO\textsubscript{2} and NO\textsubscript{2} measurements stress the importance of sources that discharge NO\textsubscript{2} and SO\textsubscript{2} in the mixing layer. Variation in concentrations reflect both variations of sources and intensity of mixing in urban and industrialized areas\textsuperscript{16,19}. The seasonal variability of the stratospheric NO\textsubscript{2} column also influences the total columnar NO\textsubscript{2} abundances\textsuperscript{17,20}. The diurnal variation of total NO\textsubscript{2} and SO\textsubscript{2} columnar hourly departures, \(C_{\mu} = 100[(C_{h} - C_{\mu})/C_{\mu}]\), are presented in Figures 3 and 4 for a winter (January) and a summer (July) month, respectively, (where \(C_{h}\) is the 24-hr averaged total concentration). The diurnal variation of NO\textsubscript{2} has maximum concentrations during the local-noon hours (Figure 3). The higher winter SO\textsubscript{2} columnar values during the morning hours (Figure 4) are due to the spatial and temporal variation of the SO\textsubscript{2} sources and horizontal and vertical dispersion parameters\textsuperscript{19,21,22}. In the early afternoon hours, columnar SO\textsubscript{2} is declining mostly due to the increasing ventilation and the decreasing of local sources. The diurnal variation during the summer period is due to the large mixing height diurnal variability and the prevailing sea-breeze and land-breeze wind patterns\textsuperscript{16,23}, which cause the evening peak on SO\textsubscript{2} industrial columnar values.

In conclusion, Brewer spectrophotometer was operated reliably in the industrial area of Thessaloniki, indicating the importance of long term seasonal and diurnal observations and the necessity of their continuation.

ACKNOWLEDGMENTS
The authors would like to thank Prof. C.S. Zerefos and Dr A.F. Bais for the intercomparison of the Brewer instruments.

REFERENCES
Figure 1. The seasonal variation of total ozone columnar values at the industrial area of Thessaloniki.

Figure 2. Monthly mean values of total ozone columnar amount at Thessaloniki area.
Figure 3. The diurnal variation of total NO$_2$ columnar hourly departures (%), in the industrial area of Thessaloniki.

Figure 4. The diurnal variation of total SO$_2$ columnar hourly departures (%), in the industrial area of Thessaloniki.
The Air Pollution Abatement Programme of Thessaloniki

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The Air Pollution Abatement Programme of Thessaloniki (APAPT) is a three-years coordinated consulting activity (1988-1991) which is administered by the Organization for Planning and Env. Protection of Thessaloniki and aims at:
a) the survey of emission sources in the Greater Thessaloniki Area (GTA)
b) the calculation of emitted pollutant loads
c) the proposal of immediate relief measures and an overall strategy for the continuous monitoring and control of Air Pollution in the GTA.

By means of consulting activities carried out by specialized offices and experts as well as university research teams (Annex I), the Programme, at an overall cost of 63 M Drs examines all major sources of air pollution such as vehicle traffic, industry and domestic heating regarding criteria pollutants (SO₂, NOₓ, VOC, CO, TSP, black smoke) and special pollutants and nuisances (smells etc) where appropriate. Separate activities are dedicated for the survey of meteorology and micrometeorology of the area, the assessment of existing air quality measurements and the construction of comprehensive dispersion models for the simulation of the existing situation as well as the testing of alternative scenarios of pollution control measures.

The source surveys include
a) a quantitative assessment of pollution loads emitted from each separate source
b) the proposal of alternative applicable solutions, based on international experience, for the reduction of existing emissions, accompanied with cost-efficiency data
c) an optimized selection of pollution reduction measures out of possible alternatives that present the best efficiency at a relatively low cost.

The final assessment of the feasibility and priority of alternative solutions (including the no intervention case) is done on the basis of a common cost-benefit criterion, where cost is defined as the direct application cost and the benefit as the efficiency in emission reduction (calculated as drs. per yearly tonne of pollutant removed) together with the ranked priority of the pollutant in concern. The latter depends on the "hazard" that the specific pollutant presents on the air quality of the area and is identified from the correlation of measured emission concentrations against EEC air quality standards applicable in GTA.
As expected traffic is responsible for practically all CO emitted in the area and for the major part of the NO\textsubscript{X} and VOC emissions. Industrial operations are responsible for a very significant part of SO\textsubscript{2} and TSP emissions and a considerable part of smoke, NO\textsubscript{X} and VOC emissions. Domestic heating, though not an overall critical polluter plays a decisive role in smoke and SO\textsubscript{2} pollution during winter periods. That is because of the timely concentrated emissions in the period November-March as well as their unfavourable dispersion characteristics (source concentration in the built area, low stack heights, emission concentrations in the unfavourable night hours). Computer simulations show that domestic heating, though responsible for 30% of SO\textsubscript{2} emissions during winter months attributes up to 85% of SO\textsubscript{2} immission concentrations in the city centre.

The emission densities are rather high and equal the densities calculated for Athens in 1985 for CO and VOC, while they exceed them for SO\textsubscript{2}, NO\textsubscript{X} and TSP/Smoke. That is due to the following reasons:

- very high residential densities in the built areas - lack of open spaces
- aged vehicle fleet (mean car age 12 years), badly maintained in conjunction with inefficient Public Transport
- bad maintenance of domestic and industrial boilers, inadequate air pollution control at industrial and commercial operations.

In 1989 following days with measurements above existing air quality limits have been recorded in the three continuous monitoring stations operated in Thessaloniki.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Monitoring Stations (1)</th>
<th>(2)</th>
<th>(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>0</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>TSP\textsuperscript{(4)}</td>
<td>20</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>Smoke\textsuperscript{(5)}</td>
<td>0</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>SO\textsubscript{2}</td>
<td>5</td>
<td>Ø</td>
<td>1</td>
</tr>
<tr>
<td>NO\textsubscript{2}</td>
<td>3</td>
<td>25</td>
<td>6</td>
</tr>
<tr>
<td>O\textsubscript{3}\textsuperscript{(5)}</td>
<td>1</td>
<td>-</td>
<td>6</td>
</tr>
</tbody>
</table>

(1) City Centre
(2) City Centre, heavy traffic location
(3) City Limits, boundary of industrial zone
(4) measurements in Stations I and III in the first 5 months only
(5) not measured in station II

Air Quality Standards:
- CO: 8 concussive hourly values mean: 10 mg/m\textsuperscript{3}
- (95 percentile) daily mean value: 300 µg/m\textsuperscript{3}
- Smoke: (98 percentile) hourly value: 250 µg/m\textsuperscript{3}
- SO\textsubscript{2}: (98 percentile) hourly value: 250-350 µg/m\textsuperscript{3}
- NO\textsubscript{2}: (98 percentile) hourly value: 200 µg/m\textsuperscript{3}
- O\textsubscript{3}: [W.H.O. limit] hourly value: 200 µg/m\textsuperscript{3}
GTA with an overall population of nearly 1 m. inhabitants is the second largest urban agglomeration in Greece comprising some 17% of the national industrial potential, heavy merchandise transport and a vehicle fleet of some 280.000 vehicles in 1989 (base inventory year of the Programme).

It is sited at the inmost part of Thermaikos Gulf on a smooth terrain which is extended wastwards to the Thessaloniki plain and is surrounded north and eastwards by hills of progressive height ending up at the mountain of Hortias (height 1200 m) at the east. Prevailing winds are of N - NW direction in winter and S-SE direction in summer, though very high (up to 45%) calmness has been recorded, especially during night-time (from 22.00 to 08.00 L.T.) throughout the year. The area shows relatively low rainfalls and cloudness and extremely low surface inversions during nights, especially during winter.

The built area of some 13,000 ha has a lengthy shape parallel to the coast and is surrounded by major industrial agglomerations to the N - NW and residential conurbations to the E - SE. Virtually all emissions take place in a stripe of 120 km² surface and a depth of 3 up to 7 km along the coast of Thermaikos Gulf. In the above area it is estimated that following fossil fuels were burned in 1989 for industrial, domestic and automotive use.

Table 1: Fossil Fuels burnt in GTA in 1989 (in tonnes)

<table>
<thead>
<tr>
<th>Fuels</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPG and gaseous fuels</td>
<td>80,000</td>
</tr>
<tr>
<td>Gasoline (automotive)</td>
<td>230,000</td>
</tr>
<tr>
<td>Distillate oil (automotive, domestic, commercial)</td>
<td>580,000</td>
</tr>
<tr>
<td>Residual oil (industrial)</td>
<td>220,000</td>
</tr>
<tr>
<td>Solid fuels (industrial)</td>
<td>130,000</td>
</tr>
</tbody>
</table>

Table II summarizes the emission inventory of 1989 in the GTA, as it has been constructed by the various techno-economic studies of the APAPT. (Annex I)

Table 2: Air Pollutant Emissions in the GTA (1989)

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>CO (KT)</th>
<th>TSP (%)</th>
<th>Smoke (KT)</th>
<th>SO₂ (KT)</th>
<th>NOₓ (%)</th>
<th>VOC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic</td>
<td>76.2</td>
<td>97.4</td>
<td>1.16</td>
<td>3.6</td>
<td>0.87</td>
<td>25.1</td>
</tr>
<tr>
<td>Dom. Heating</td>
<td>1.17</td>
<td>1.5</td>
<td>0.78</td>
<td>2.4</td>
<td>0.78</td>
<td>22.5</td>
</tr>
<tr>
<td>Industry</td>
<td>0.86</td>
<td>1.1</td>
<td>30.36</td>
<td>94</td>
<td>1.81</td>
<td>52.3</td>
</tr>
<tr>
<td>TOTAL</td>
<td>78.23</td>
<td>100</td>
<td>32.30</td>
<td>100</td>
<td>3.46</td>
<td>100</td>
</tr>
</tbody>
</table>

* Less than 0.5%
Table 5 summarizes the mean values of pollutant recorded in 1989 in stations I and III. [D.3]

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Station</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td></td>
</tr>
<tr>
<td>CO (mg/m³)</td>
<td>2.1</td>
<td>3.9 (01)</td>
<td>1.3 (04)</td>
<td>1.4</td>
<td>1.8 (10)</td>
</tr>
<tr>
<td>TSP (µg/m³)(4)</td>
<td>288</td>
<td>366 (01)</td>
<td>221 (05)</td>
<td>317</td>
<td>421 (01)</td>
</tr>
<tr>
<td>Smoke (µg/m³)</td>
<td>43</td>
<td>80 (01)</td>
<td>17 (07)</td>
<td>52</td>
<td>97 (01)</td>
</tr>
<tr>
<td>SO₂ (µg/m³)</td>
<td>142</td>
<td>290 (01)</td>
<td>71 (06)</td>
<td>150</td>
<td>188 (12)</td>
</tr>
<tr>
<td>NO₂ (µg/m³)</td>
<td>58</td>
<td>75 (08)</td>
<td>45 (01)</td>
<td>49</td>
<td>75 (01)</td>
</tr>
<tr>
<td>O₃ (µg/m³)</td>
<td>48</td>
<td>78 (09)</td>
<td>10 (06)</td>
<td>47</td>
<td>81 (06)</td>
</tr>
</tbody>
</table>

(1) Yearly average value
(2) maximum monthly average (month recorded)
(3) minimum monthly average (month recorded)
(4) data of the first 5 months only available

Though the existing air quality data are found to be insufficient, mainly for the years preceding 1989, following conclusions can be deduced:

a) TSP values are constantly in excess of the air quality limits.

b) Smoke values increase significantly during winter and, though not exceeding the set limits, present a threat to the air quality in GTA.

c) SO₂ values are well above limits mainly during winter and call for immediate action.

d) Sporadic incidents are recorded with an ever increasing frequency of high CO and NO₂ values especially in areas with heavy traffic.

e) There is an indication of considerable ozone formation in the city boundaries especially in the transient periods (spring, autumn) which show favourable conditions (high temperatures and solar radiation, calmness) for photochemical activity.

The collected air quality data indicate measures to be taken in the following main directions:

a) TSP control, mainly at industrial sources

b) Reduction in SO₂ emissions.

c) Smoke control in industry, domestic heating and diesel powered vehicles.

d) Control of emissions from gasoline powered vehicles.

Towards the end of 1989 two major SO₂ reduction measures have been taken in GTA, i.e. the installation of a sulfur scavenger plant in the existing crude oil refinery and the reduction of sulfur in the commercial distillate oil from 0.5% to 0.3%, reducing thus the overall SO₂ emissions from 43 KT/year in 23 KT/year. This proved to have a significant beneficial impact in SO₂ concentrations, as shown from measurements in the following years.
From the beginning of 1991 a beneficial taxation scheme is applicable in GTA (as well as all over Greece) for the withdrawal of old cars and the purchase of new ones equipped with catalytic converters.

This measure has a critical impact on the renewal of the aged car fleet in GTA, as during 1991 some 25,000 car owners in Thessaloniko took benefit of it and replaced their cars at an estimated cost of 62.5 B. drs. On the assumption that the new cars will drive the same mileage in GTA as the old ones a yearly emission reduction of 12.2 KT in CO (16% overall), 1.5 KT in VOC (10%) and 0.3 KT in NOX (3.6%) is expected. [A.24]

While assessing the impacts of these two major changes in pollutant emissions in GTA, the APAPT has formulated following pollution abatement programmes of immediate applicability:

I) Dust Abatement Programme at industrial and fugitive Sources

By introduction of up-to-date dust control technology in 11 major industrial branches operating in GTA (cement and concrete manufacturing, non metallic minerals, asphalt paving plants, brick and ceramic manufacturing, secondary steel and lead production, fertilizers, grain mills, tobacco manufacturing) an overall TSP emission reduction of 27 KT per year can be achieved at amortized annual costs ranging from 0.03 m. drs/yearly/tonne removed up to 5.2 m. drs/yearly/tonne removed and an estimated overall investment of 4.8 b. drs (1989 values). [A.2-A.23]

The Programme is complemented with following measures:
- control of bulk road transfer of dusty materials
- regular sweeping of major roads with heavy truck traffic
- relocation of limestone and gravel quarries outside GTA.

Its implementation is expected to have significant beneficial effects on the TSP emission levels in GTA.

II) Smoke Control Programme in domestic, commercial and industrial Boilers and diesel powered vehicles

Poor operation and maintenance standards in boilers and diesel powered vehicles is resulting in excessive amounts of fuel consumption and smoke emission. Thus, considerable reductions in fuel consumption and smoke emissions can be achieved by introducing periodical preventive Maintenance and Inspection Programmes. [A.14, A.24, A.25]

It is estimated that a seasonal maintenance and smoke and thermal efficiency control in the ca. 12,000 central heating boilers in GTA with an implementation cost of 240 m.Drs can result in smoke emission reductions of up to 25% from this source representing 0.2 KT annually (or 6% overall) and an efficiency improvement of 10% leading to annual fuel savings of 28 KT with a commercial value of 2.5 b. drs.
An analogous situation applies to commercial and industrial boilers, where half of the units operate below the acceptable efficiency standard of 80% and some 65% above the allowable smoke emission standard of Bacharach scale 1. A test control programme in 1989-1990 consisting of periodical controls performed by inspectors of the Organization of Thessaloniki showed considerable amelioration in the operation standards. [A.14]

Other proposals of the APAPT include:
- The staged implementation of a structural measurement stations network (extension of the existing one) to cover both meteorological and air quality measurements. [B.2]
- It is designed for the close monitoring of the main existing sources, the full coverage of photochemical precursors, and the quick retrieval and transfer of data to all interested parties through terminal telecommunication and has an incremental implementation cost of 400 m. drs.
- The back-up for the restructuring of the public transport system in GTA and the control of privat car use in the city, and for other planning interventions such as traffic avoidance in narrow streets presenting a "street canyon" effect etc.
- The environmental feasibility assessment and the orientation towards a quick penetration of LNG use for industrial, commercial and domestic purposes especially in the densely populated city areas.

Fine tunings and the buildup of an integrated strategy for the air pollution control of GTA, especially regarding photochemical pollution will be supplemented when the final data of a coordinated campaign of meteorological and photochemical precursors and indesces measurements, which is performed in autumn 1991 and reported elsewhere in the seminar will be available. This is expected in spring 1992.

On this basis the degree of intervention on NOx and VOC will be decided together with other factors influencing air pollution in GTA, such as stack heights, identification and preservation of clean air channels in the circumference of the built area, diurnal planning of intensity of traffic and city operations (shopping hours) etc.

It is expected that upon this integration, and provided that it will be frequently updated, the bulk of data and know-how, gathered by APAPT will provide a valuable tool for planning of development and environmental protection of GTA.
ANNEX I
Studies and Consulting activities of APAPT

A. Technoeconomical Source Oriented Studies.
2. Technoeconomical Study for emissions reduction from petrochemical plants in GTA, G. Stavropoulos et al., Organization of Thessaloniki, 1990.

B. Immission Oriented Studies
2. Study for the design of Network of Air Pollution Monitoring Stations in GTA, K. Nikolaou, Organization of Thessaloniki, 1990.

C. Dispersion Modelling - Meteorology
3. Survey of meteorological conditions in the atmosphere of GTA, N. Moussiopoulos - D. Assimakopoulos et al, Organization of Thessaloniki, 1991 (in conjunction with Thessaloniki '91 Measurements campaign carried out by the University of Thessaloniki, National Observatory of Athens, KFA Julich and Ruder Boskovitch Institute under the Coordination of Prof. N. Moussiopoulos).

D. Related Publications
SECTION 2:

THESSALONIKI '91 FIELD MEASUREMENT CAMPAIGN
Thessaloniki '91 Field Measurement Campaign Organization

N. Moussiopoulos
Laboratory of Heat Transfer and Environmental Engineering, Aristotle University Thessaloniki, 54006 Thessaloniki, Greece

ABSTRACT

The analysis of the dispersion characteristics and primarily the estimation of the photosmog formation potential were the aims of the field measurement campaign performed in the Greater Thessaloniki Area in the period 15 September - 13 October 1991. In this campaign wind and immersion data were monitored at twelve locations, mostly in the periphery of Thessaloniki. An acoustic sounder was operating downtown on the roof of a nine store building, where radiative fluxes were measured as well. Tethersonde ascends were performed at two locations to obtain vertical profiles of both meteorological quantities and the ozone concentration.

INTRODUCTION

The pollutant concentration levels in Thessaloniki certify the necessity for a rational strategy to abate air pollution. The experience from Athens shows that, as air pollution control is concerned, it is useless to pursue short-term results, as this misleads the authorities to improvised measures of doubtful effectiveness. At best, measures of this kind aim to minimize pollutant emissions and not, as they should, air pollution levels. The restriction to such measures not only prohibits an optimization of the air pollution abatement strategy, but it also runs the risk of unpleasant surprises, as for instance even an increase in secondary pollutant concentrations in spite of a decrease of primary pollutant emissions.

The pollutant concentrations resulting from given emission levels depend on the physico-chemical mechanisms governing atmospheric dispersion and transformation of air pollutants. These mechanisms, on the other hand, are deeply influenced by the meteorological conditions and the topography in the area of interest. So, it is of paramount importance to understand in each case prevailing local circulation systems (e.g. sea breeze circulation, mountain and valley winds, heat island phenomenon) and the diurnal variation of the mixing height.
From the above it follows that for a proper air pollution abatement in Thessaloniki it is essential to describe in detail the dispersion and transformation mechanisms of pollutants in the atmosphere of the Greater Thessaloniki Area (GTA). Such a description may ultimately lead to numerous important benefits. Examples are

- the calculation of how various polluters from different parts of the GTA contribute, depending on the meteorological conditions, to the occurrence of elevated concentrations of specific species at certain locations,
- the prediction of air pollution levels for the next future (e.g. the next day) on the basis of the synoptic weather forecast,
- the estimation of the long-term trend of the air pollution levels depending on supposed changes in infrastructure and/or physical planning and
- the verification of the effectiveness of certain pollution abatement measures for their reliable a-priori evaluation (i.e. a cost-to-benefit analysis).

WHY A FIELD MEASUREMENT CAMPAIGN?

Results of previous studies on air quality in the GTA\textsuperscript{1,2} as well as measured data from the permanent monitoring network reveal relatively high concentrations of suspended particles and of photochemical smog precursors (nitrogen oxides, hydrocarbons and, to a lesser extent, carbon monoxide). The available data do not suffice to safely estimate the photochemical smog levels, because the existing measuring stations do not allow representative measurements of ozone, the main indicator of photochemical smog.

A description of the photochemical smog levels in the GTA should be based on the application of contemporary mathematical models\textsuperscript{3} and the results of a field measurement campaign. The latter does not only allow an immediate investigation of physico-chemical phenomena, but it may also provide the basis for model verification. Field measurement campaigns are generally considered as the only method for reliable experimental analyses of dispersion and transformation phenomena in the atmosphere.

The aims of a temporary measuring network like the one installed during an intense campaign differ substantially from those of a permanent monitoring network: The purpose of the latter is to monitor continuously a few selected variables at a few selected locations. By this continuous monitoring the authorities may anytime detect exceedances from given air quality standards and, if indicated, take proper emergency measures. However, data from the permanent monitoring network are far too sparse to describe the three-dimensional distribution of the measured variables. Furthermore, a permanent monitoring network normally includes only stations operating at ground level. Correspondingly, practically no information on the vertical variation of the measured variables is available. This, however, is a major shortcoming, as many of the ground level measurements are decisively influenced by both pollution sources and the ground itself.

From the above it is evident that it would be wrong to consider a temporary measuring network as a substitute of the permanent network. On the contrary, the two networks are to a large extent complementary and only by taking profit of both it is possible to collect all data needed to optimize the air pollution abatement strategy. Of course, it is advisable to operate the temporary network during periods with high pollution levels in the area of interest, i.e. at times, when air pollution abatement is most urgently needed.
In summary, a complete field measurement campaign usually contains:

- Measurements of meteorological data and pollutant concentrations at ground level by the aid of stationary or mobile measuring units.
- Measurements of the vertical variation of selected meteorological data and pollutant concentrations as well as the diurnal variation of the mixing height. In addition to ground based methods (e.g. soundings, tethersondes, radars) it is possible, though rather expensive, to use properly equipped experimental aeroplanes, which may easily provide the detailed three-dimensional pattern of the different variables.
- In some cases, tracer experiments. By releasing inert gases which may be easily detected, even at very low concentrations, it is possible to investigate in detail specific dispersion phenomena of particular interest.

As the most striking feature of a field measurement campaign, all measurements are carried out simultaneously with the following obvious benefits:

- Intercomparisons of measured data lead to an increase in reliability and allow a detection of mistakes.
- Correlations among measured data usually result in additional useful conclusions.
- The composition of a complete dataset from available observations allows both to perform a comprehensive analysis of air pollution levels and to verify complex mathematical models.

CAMPAIGN ORGANIZATION

The first steps towards air pollution abatement in Thessaloniki were relevant studies by scientists of the Aristotle University Thessaloniki and actions by the responsible offices of both the Ministry of Macedonia and Thrace and the Municipality of Thessaloniki. These previous activities led to the installation of the permanent monitoring network in the urban area of Thessaloniki. In addition, valuable conclusions were drawn from the investigations sponsored by the Organization of Thessaloniki in the frame of its Air Pollution Study Programme.

The idea to organize a field measurement campaign in the GTA arose in the course of the research project "Adaptation and verification of mathematical models to describe dispersion and chemical transformation of atmospheric pollutants". Nested within the German/Greek scientific cooperation, this project is co-sponsored by the German Federal Ministry for Research and Technology and the Greek General Secretariat for Research and Technology. It is conducted by scientists of the Institute of Meteorology and Climatology of the Nuclear Research Centre Karlsruhe and the Laboratory of Heat Transfer and Environmental Engineering of the Aristotle University Thessaloniki.

The aim being to apply the mesoscale model system MEMO/MARS for the GTA, it was first decided to perform simultaneous ground level measurements of the ozone concentration at several locations in the GTA. In particular, ozone analysers were installed at Angelohori, Perea, Panorama, Vlatadon Monastery, Meteora, Langadas, Neohorouda, TEB Sindos and Gallicos (Fig. 1). At all these locations meteorological quantities were measured as well. As no electricity was available at Langadas (more precisely, close to the shore of the Lake Koronia), a photovoltaics system was installed for the energy supply of the instruments.
For the best possible preparation of the ozone measurements, the German scientists came twice within 1991 to Thessaloniki and inspected the pre-selected measuring sites very carefully. Ozone analysers, anemometers, data loggers and all other instruments needed for the measurements (total value: approximately 500 thousand DM) were sent as air freight to Greece. All analysers were calibrated in Thessaloniki just before the campaign commenced. It should be noted that scientists of the Ruder Boskovic Institute Zagreb came to Thessaloniki to participate at the ozone measurements in spite of the crisis in Yugoslavia in the second half of 1991.

Given that local circulation systems affect largely the dispersion characteristics and as the aim of the field measurement campaign was to obtain a more or less complete picture of the transport and transformation mechanisms in the GTA, it was decided to perform additional measurements, mainly of meteorological quantities. These additional measurements included:
The vertical variation of the wind velocity, the air temperature and the ozone concentration by the aid of tethersonde ascends at the Aristotle University Thessaloniki and at the Technological Educational Institute of Thessaloniki (TEI) Sindos. The ascends were performed at different times of the day up to a height of 700 m above ground level.

Diurnal variation of the structure of the atmospheric boundary layer and, more specifically, of the height of the mixing layer by operating an acoustic sounder on the roof of a nine-store building of the School of Engineering of the Aristotle University Thessaloniki.

Radiative fluxes also on the roof of the aforementioned nine-store building.

Concentrations of primary pollutants and ozone at Finikas (Fig. 1).

Wind velocity at the Aristotle University Thessaloniki and at the locations Finikas, Meteora and Phaedon (Fig. 1).

All additional measurements were sponsored by the Organization of Thessaloniki. Most of them were set up and performed by scientists of the University of Athens and the National Observatory of Athens.

After the successful completion of the campaign the tedious task of analysing its results started. A data pool was established to include all data measured during the campaign period by both the temporary and the permanent measuring network. It should be noted that all authorities involved with the latter willingly transmitted their data to the pool. These authorities were the responsible offices of the Ministry of Macedonia and Thrace and the Municipality of Thessaloniki, the Hellenic Meteorological Service, Laboratories of the School of Natural Sciences of the Aristotle University Thessaloniki and the Laboratory of Applied Physics of the TEI Sindos.

ACKNOWLEDGEMENT

The author wishes to thank the Minister of Macedonia and Thrace for accepting that the field measurement campaign be performed under his auspices. He also gratefully acknowledges the funds granted by the German Federal Ministry for Research and Technology, the Greek General Secretariat for Research and Technology and the Organization of Thessaloniki as well as the financial support by the Ministry of Macedonia and Thrace, the Municipality of Thessaloniki and the Aristotle University Thessaloniki. He is finally grateful to all those who contributed to the success of the campaign which turned to be a hard but also fascinating venture.

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Campaign of Photo-Oxidant Measurement in Greater Thessaloniki:
Preliminary Results

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ABSTRACT
In order to be able to assess the potential of photosmog formation and the transport of photo-oxidants in the Greater Thessaloniki area, ozone, as an indicator of photochemical smog, was measured together with meteorological parameters (wind velocity, wind direction, temperature) at nine stations. Each of the nine measuring stations spread over an area of about 30 x 30 km² is equipped with an ozone analyser, an anemometer, a thermocouple and a data logger.

First results show that the wind direction, especially in case of sea breeze events, exerts a strong influence on the ozone concentration in air at the various measuring sites. The local topographical and meteorological conditions give rise to higher ozone concentrations than expected during the night at those measuring sites (Panorama, Meteora), which are located above the level of the night-time inversion.

INTRODUCTION
The emissions from industrial facilities, power plants and traffic are responsible for the steady increase in air pollution and the formation of photochemical smog [1]. Photochemical smog is the result of photochemical reactions of primary pollutants (NOₓ, the oxides of nitrogen, and hydrocarbons) converted by sunlight to
secondary pollutants, like ozone, aldehydes, ketones, PAN etc. [1,2]. All the reaction products of photochemical smog formation are termed photo-oxidants. Ozone is the main reaction product and thus an indicator of the general level of photo-oxidants.

In coastal areas the meteorological phenomenon of sea breeze might be responsible for the accumulation of high concentrations of pollutants in spite of apparently good ventilation [3-6]. Differences in heating of land and sea surfaces often generate an inland flow of air during daytime. However, at night the land cools faster than the sea, and the wind may reverse its direction. The result is that within the sea breeze cell the air pollutants will be at least partially recirculated over the shore line and thus reach levels higher than would otherwise be expected. It has been shown that land-sea breeze systems influence air pollution transport and the local pollution level [3-6].

OBJECTIVES AND MEASURING SITES

The main objectives of the measurement campaign conducted in the Greater Thessaloniki area are

- to assess the potential of photosmog in this area, and
- to study the transport of photo-oxidants in this area, and
- to validate and verify the dispersion model developed by Moussiopoulos et al [7,8].

All measured wind data and ozone concentrations will be used in sensitivity studies of wind field reconstruction with a three-dimensional wind field model. In addition, vertical sounding of ozone concentration and meteorological parameters will result in information about the height of the vertical dispersion of ozone.

Figure 1 shows a map of Greater Thessaloniki with the locations of the measuring stations. The area selected for the measurement campaign is about 30 km x 30 km in size. We selected these places for the stations to take into account the main wind directions. The wind blows mostly along the major NE-SW axis. Stations were built
at Angelohori, Perea, Panorama, Moni Vlatadon, Meteora, Neohorouda, Gallicos, Sindos and at Langadas. Langadas lies behind the Hortiatis mountain range on the Lake of Koronia. The Greater Thessaloniki area is separated from the Lake of Koronia by this range of mountain of up to about 1200 m height. The lake which extends about 11 km from NW to SE and is 4-5 km wide is situated in a rural area and can act as a sink for air masses, especially during the night. This offers the possibility of studying transport phenomena and processes of air mass transfer over the mountain ridge. The stations Neohorouda, Meteora and Panorama are located on the western side of the mountain ridge, about 10 km distant from each other and at about 200 m altitude. The stations Angelohori, Perea and Gallicos surround the Bay of Thessaloniki and are located directly on the shoreline at about 10-20 m altitude. The site of the Angelohori station is a small cape separating the Bay of Thessaloniki from the Gulf of Thermaikos. All the nine measuring sites - with the exception of the one at Moni Vlatadon - are located outside of the City of Thessaloniki. There, the local stations of the Ministry of Northern Greece as well as those of the City of Thessaloniki will measure the concentrations of primary pollutants like NOx, CO, SO2, hydrocarbons, ozone and dust during the whole measurement campaign which is scheduled for mid-September to mid-October 1991.

ANALYTICAL INSTRUMENTATION

Generally, the ozone concentration, wind velocity and wind direction as well as the temperature are measured at every station. The temperature is measured with thermocouples made of copper-constantan. The wind direction and wind velocity are measured continuously with anemometers (Model 14512 I, Lambrecht, Göttingen) on a pole of 5 m height above the ozone sensor. The axis of rotation of the anemometer is connected to the slide of a ring potentiometer inside the housing. The wind direction can be calculated by means of resistance measurements made between the ends of the potentiometer and the position of the slide. A chopper
blade inside the housing rotates at the same speed as the cups of
the anemometers. Light reaches a photodiode through holes in the
chopper blade. The photodiode generates pulses whose frequency
is proportional to the velocity of the wind. Before the measurement
campaign all anemometers were calibrated in a wind tunnel in
Karlsruhe.

All ozone analysers operate on the principle of photometric
detection of the specific absorption of UV light by ozone [9]. The UV
absorption measurement technique is based on the capability of
ozone to absorb the wavelength of ultraviolet radiation at 254 nm.
The ozone analyser measures alternately ambient air with ozone
and ambient air without ozone. Ozone-free air is obtained by
passing ambient air over a scrubber which specifically removes
ozone. The valve for the two paths is actuated by a microprocessor.
The difference between the two responses is the absorption due to
ozone. The microprocessor solves the Lambert-Beer law and
calculates the ozone concentration expressed in volume fractions.
The temperature and pressure are measured permanently inside the
cuvette and the measured ozone concentration is automatically
corrected for these parameters. All ozone analysers (Model 1008-AH
Dasibi, Model O3 41M, Environment s.a.) were calibrated with an
ozone calibrator (Model 1008-PC, Dasibi) before the measurement
campaign.

To measure vertical profiles of ozone we have developed in
cooperation with our licensee GFAS (Gesellschaft für Angewandte
Systemtechnik, D-7997 Immenstaad) a small light-weight (< 1 kg)
and fast-response ozone sensor [10]. The advantage of this
instrument is its high sensitivity - detection limit 100 ppt - and its
fast response time of about 0.1 s. Together with small sensors for
temperature, pressure and humidity the instrument package,
payload of 2.5 kg including rechargeable batteries, is ideally suited
to measure vertical ozone profiles on a balloon. The balloon for
meteorological experiments will be provided by the Institute of
Meteorology of the University of Athens.
The measuring site on the Lake of Koronia is far away from main sources. Therefore, we installed a photovoltaic generator (Fig. 2) consisting of 5 m² of photovoltaic panels, 4 batteries of 12 V and 97 Ah and a regulator, type BCR 24 Sh 600 [11]. One ozonometer, Model 1008 AH, Dasibi was modified for use with 24 D.C. and directly powered via the regulator by the photovoltaic generator.

DATA RECORDING

All signals generated by the sensors are transmitted to a data logger, an instrument used to collect and process data. The analogue voltage of the ozone analyser is processed in the logger which, finally, yields the volume fraction of ozone, expressed in ppb. The temperature is measured in K. The calibration functions for the sensors can be selected by the software of the data logger (Model 21X, Campbell Scientific Ltd.).

The pulses from the anemometer are measured via a pulse counting input. The final output is the wind velocity in m/s, calibrated for the sensitivity of the instrument used. One of the excitation outputs of the logger provides the power for the resistance measurement allowing the components of the wind direction vector to be calculated. The wind direction is then determined by these components at the end of each measuring period. In our case, this was done after 15 minutes, the interval which is necessary to obtain mean values.

The data logger can store about 19,000 data points in its final memory. This means that we can store 15-minutes-mean values of ozone, wind velocity, wind direction and temperature for about four weeks. However, from time to time we collect the stored data by means of a small storage module which can be connected to the data logger. Without interruption of the measurement, the data are transferred to the storage module and, subsequently, to a computer for data recording on a floppy disk. A data logger next to an ozonometer is depicted in Fig. 3.
PRELIMINARY RESULTS

At this early stage of the measurement campaign in Greater Thessaloniki, we can report today, on September 27, only very preliminary results. For this “Monitoring and Modelling in the Mesoscale” seminar, organised within the framework of scientific cooperation between the Federal Republic of Germany and Greece, we present only a few results and vague conclusions on the data collected during the first week of this campaign.

The diurnal ozone concentrations at the various measuring sites in Greater Thessaloniki showed the typical pattern of photochemical smog formation: a steep rise in the ozone concentration in the early morning hours with a maximum in the early afternoon [1,2]. Ozone volume fractions up to 100 ppb were measured at the various stations. Even in the rural area of the Lake of Koronia fairly high ozone concentrations were recorded (Fig. 4). The average ozone volume fractions during the night were about 20 ppb. At several stations, above all at Perea and Panorama, interesting phenomena were observed during the night. After midnight, when the average volume fractions of ozone had reached values of about 10 to 20 ppb, sudden increases in the ozone volume fractions up to 50 ppb were observed for several hours until the next morning (Figs. 5 and 7).

Similar effects of unusually high night-time concentrations of ozone were observed at the measuring sites of Meteora, Vlatadon and Neohorouda. All these sites are located at the westerly slope of the Hortiatis mountain range.

Panorama is situated at 200-300 m altitude of the westerly slope of the Hortiatis mountain. Contrary to Perea, which is located on the south shore of the Bay of Thessaloniki, the average night volume fractions of ozone at Panorama are higher than 50 ppb (Figs. 5 and 7). At that site, the ozone concentration remains at the afternoon level until 6 o'clock in the morning (Fig. 5; 16 to 18 Sept.). At Perea on the sea side, about 15 km from Panorama, there is only a slight
increase in the ozone concentration during the night until 6 o'clock in the morning (Fig. 7). Since ozone is produced photochemically, higher ozone concentrations during the night than a background volume fraction of 30 ppb are an indication of transport phenomena. The high ozone concentrations at Panorama during the night can be explained by its situation at higher altitude compared to Perea.

The night-time inversion level in September might well be lower than that of the city of Panorama. Below the inversion layer, the ozone concentration decreases due to dry deposition on the ground and due to chemical reactions with other primary pollutants, like NO and olefins. Above the inversion layer, the high photochemical smog levels of the previous day are preserved in the well-stratified air masses. At Panorama, the decline of night-time ozone starts in the early morning hours at 5 to 6 o'clock. This is the time when the prevailing south-easterly wind direction suddenly turns to NW (see Figs. 6 and 8). The sudden turn of the wind direction is accompanied by an increase in wind velocity from 1 to 2 m/s up to 4 to 6 m/s of the northerly winds (Fig. 9). These northerly winds blow until noon. Again, at that time there is a sudden change back to south-easterly winds occurs (Fig. 8) and the daily cycle of the photochemical smog formation starts again (Figs. 5 and 7). The wind behaviour described is the classical picture of sea breeze events [3-5, 12].

A detailed calculation and reconstruction of the wind field in the Greater Thessaloniki area for the duration of the measurement campaign will give further insight into the flow of the air masses and the levels of pollution at the various measuring sites.

ACKNOWLEDGEMENT

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Figure 1: Map of Greater Thessaloniki with the measuring sites
Figure 2: Photovoltaic and ozone measurement station at Langadas (Lake of Koronia)
Figure 3: Data logger connected to ozonometer
Figure 4: Variation of ozone volume fraction on the lake of Koronia (September 12 to September 18, 1991).
Figure 5: Variation of ozone volume fraction at Panorama (September 13 to September 18, 1991).
Figure 6: Variation of wind direction at Panorama (September 13 to September 18, 1991).
Figure 7: Variation of ozone volume fraction at Perea (September 13 to September 18, 1991).
Figure 8: Variation of wind direction at Petau (September 13 to September 18, 1991).
Figure 9: Variation of wind velocity at Perea (September 13 to September 18, 1991).
A Combined Meteorological and Air Pollution Experiment over Thessaloniki

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ABSTRACT

A combined meteorological and air pollution experiment is thoroughly described giving details of the instrumentation used. The meteorological instrumentation includes Acoustic Radar (A.R.), tethered balloons and ground based wind stations, while the air pollutants were tracked by automatic continuous measuring systems. Thus combined data on the vertical and the horizontal structure of the Atmospheric Boundary Layer (ABL) and the basic air pollutants are monitored. Preliminary results of this experiment are also given examining selected cases of meteorological importance for the study of the Thessaloniki air shed.

1. INTRODUCTION

Thessaloniki is the second big city in Greece considering both population and industrial activity thus following the wellknown international pattern of polluted cities.

Several studies have already been performed by several research groups (e.g. Zerefos, Moussinopoulos and Flokas) in order to understand either the
micrometeorological pattern or to evaluate the air pollution levels within the Greater Thessaloniki Area, (GTA), (Zerefos et al., 1986; Zerefos and Zoumakis, 1984; Sahsamanoglou and Bloutsos, 1989; Sahsamanoglou et al., 1991).

However, questions like the detailed wind field or the horizontal and the vertical distribution of certain pollutants is not known thus leaving open the field for further investigation.

It is the purpose of this experimental effort, to study more extensively this field giving emphasis to ozone concentrations which are thoroughly investigated.

2. DESCRIPTION OF THE EXPERIMENT.

The city of Thessaloniki is located almost in the middle of the Thermaikos gulf in the northern part of Greece. The city is actually surrounded from the North and East by Kissos mountain, while on the West there is a flat and quite expanded area. Due to this arrangement the G.T.A. is subject to a rather complex microclimate. For example low wind conditions with clear skies, which are of particular importance for the air pollution concentrations over the city, will result to a complicated wind field.

The sea breeze circulation case which is associated with air pollution episodes, is again quite complex as it is applied on successively different directions with the time of day.

The G.T.A. and the location of the instrumentation used are given elsewhere by Moussiopoulos at the same edition. The stations were chosen in such a way to provide information on both meteorology and air pollution. Thus natural exits from the Thessaloniki valley as well as the central and the coastal area were covered and the profilometers were placed in the very central (urban) and the outskirts (rural) areas. The instrumentation used by the University of Athens research group for the experiments consisted of the meteorological and the air pollution monitors.

a) Meteorological:
- Ground based. The ground based instrumentation consisted of 3 wind stations which were mechanical
and were placed on 10m high poles on top of buildings or other suitable constructions.
- Profilmeters. The A.B.L. profile was monitored by two tethered balloon systems and a high frequency A.R. unit.

The first tethered balloon was combined with the A.R. in order to provide both qualitative and quantitative information on the A.B.L. thermal and wind structure which is of primary importance for the experiment and was placed on top of the Engineering building in the middle of the city. The second tethersonde was placed in a suburb area some 10km from the town city center in the western part which is quite open to all wind directions. Both balloons were equipped with a meteorological package which provided measurements on the wind speed and direction, temperature, humidity and pressure as well as with a wet chemical method of ozonesonde monitor. These were operated selectively during certain weather conditions. The high frequency acoustic sounder is a high resolution system and can provide detailed information on the wind and the thermal structure of the A.B.L. from about 8m up to about 300m. This instrument operated throughout the experiment on a continuous basis.

Details on all instruments are given elsewhere in this edition (Helmis et al., Soilemes et al.).

b) Air pollution Instrumentation:
Except from the ozonesonde all other instruments concerning ozone, carbon monoxide, sulfur dioxide, nitrogen oxides and hydrocarbons were ground-based. All instruments used were of the automatic type with continuous output on dedicated data loggers.

3. PRELIMINARY RESULTS AND CONCLUSIONS.

The day of 30/9/91 was selected as a typical case of sea-breeze circulation which is also associated with high air pollutant concentrations. In this paper however only the atmospheric physics part of the recorded data will be considered.

In particular Fig. 1 shows the development of sea-breeze as it was recorded by the A.R.. At the beginning (6.07-7.50 LST) a low thermal activity appears which is extended up to more than 100 m height. This activity has a patchy structure during
Fig. 1a. Acoustic radar records for the period 6.07-8.41
Fig. 1b. Acoustic radar records for the period 8.41-11.16
Fig. 1c. Acoustic radar records for the period
11.16-13.50
the transition period of the formation of the sea-breeze which became more solid afterwards (11.00 LST). By this time the thermal activity is present up to 200 m height. Later on (12.30 LST) this feature is changing due to the surface heating which produces an increased mixing in the lower atmospheric layer. It must be noticed that the solid thick line which appears in Figure 1 is due to the acoustic signal reflection, caused by the tethered balloon. Quantitatively this structure is also evident from the profiles of meteorological parameters (wind speed and direction, potential temperature and humidity) measured by the University of Athens profiler system. (Figures 2, 3 and 4). According to the first sounding (6.47-7.10 LST) it is shown that a stable layer extends up to 400 m height. This layer persists during the second sounding (7.49-8.09 LST) while during the third sounding (10.31-10.47 LST) the appearance of two distinct layers is evident. The lower layer which is developed due to the sea-breeze has a height of 120 m and is decoupled from the upper stable layer by a neutral layer. The next sounding gives the development of sea-breeze having the depth of more than 200 m. A neutral layer of about 120 m depth separates the two stable layers. The last sounding (14.16-14.44 LST) presents the full development of sea-breeze. In more detail, a super adiabatic layer is present at the surface layer while a stable layer is following above it up to more than 300 m.

All the above mentioned are confirmed with the corresponding profiles of relative humidity. In particular both the third and fourth profiles show two different layers concerning the water vapour content. While the last sounding (14.16-14.44 LST) gives a layer of almost constant humidity up to the height of 300 m.

Finally, the wind speed and direction profiles show the origination of wind. In the first sounding, wind of low intensity is blowing from the West throughout the whole stable layer which is followed by calm conditions according to the second sounding. At the sounding of 10.30 LST a 100 m layer of Southwesterly wind appears which increases in depth later on (11.46-12.07 LST). During the last sounding it is evident the increase of both the wind speed and depth of this layer.

It is also of importance the A.S. records for
Fig. 2. Vertical profiles of potential temperature.
Fig. 3. Vertical profiles of relative humidity.
Fig. 4. Vertical profiles of wind speed and direction.
Fig. 5. Acoustic radar records for the period 20.42-23.16
the same day, later in the night. Figure 5 gives the thermal structure of the Atmosphere where temperature inversion layer is present at the height of 170 m at the beginning. At the same time small thermal activity is present at the surface layer. Later on (at about 22.00 LST) this inversion merges with the ground based inversion which is produced due to the surface cooling. This procedure results in a more intense inversion layer at lower heights after 22.45 LST.

From the above preliminary data analysis can be summarized the following.

- The sea-breeze circulation is starting at about 8.00 LST while it is fully developed at around 14.00 LST and dies out after 19.00 LST.

- During the formation and establishment of the sea-breeze mechanism the wind speeds are low and the depth of the sea-breeze layer is relative small reaching less than 300 m height. This is probably due to the short distance of the measuring site from the coast (about 1 Km). For the same reason the sea-breeze circulation persists for a long period.

4. REFERENCES


The University of Athens profiler system

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ABSTRACT

A new approach to balloon sounding has been developed in the University of Athens, by using a tiny onboard microcomputer, instead of the well-known real-time data transmission technique. This system measures dry and wet bulb temperature, wind speed, wind direction and relative pressure, with very good accuracy up to 1000 m. More channels can be easily supported, due to the flexibility coming from the microcomputer used. Advantages and disadvantages of the system will be discussed, as well as the implementation of the whole sounding system.

SYSTEM DESCRIPTION

The system consists of:
1) a tethered balloon
2) a winch
3) an airborne package
4) a laptop P.C. and the associated software

The balloon is 5.2 m long, maximum diameter is 1.5 m and its volume is 4.25 m³. It has a lifting capability of about 2.8 kg at sea level. In calm weather, the package has been flown to heights of about 800 m.

The winch uses a 1/2 hp, 12 V D.C. motor attached to a rotating drum. A 1000 m nylon cord is wrapped around the drum and attached to the balloon. The rate of ascent (or descent) is continuously variable between 0 and 3 m/s.

The package, which measures 6.3x55x13 cm, con-
taining the necessary sensors, the appropriate electronic interfacing circuitry and the microcomputer, is shown in fig. 1. A rod is used to support the package on the balloon cables, about 2 m below the bottom of the balloon. It is powered by a 14 1.22 V/700 mAh Ni-Cad pack. Power consumption is 100 mA, so a worst case of 4 h of continuous operation is possible.

Figure 1. The airborne package

Because emphasis was given to system portability, a laptop P.C., was chosen as the ground station. Employment of a hard disk, greatly simplifies operation and data handling. The P.C. used is equipped with a 20 Mb hard disk and a 1.44 Mb floppy disk, a real-time clock and a serial port.
THE PACKAGE

The block diagram of the package is shown in fig. 2. As shown, the system was developed around the microcomputer. Details about the block diagram will be given in the corresponding paragraphs.

Figure 2. The block diagram of the package

Wet and dry bulb temperature
The classical psychrometric method is used to measure dry and wet bulb temperature, using two identical NTC thermistors placed along the axis of a plastic 16/20 mm tube, 85 mm long and placed horizontally, above and at right angle to the package supporting rod. The dry bulb thermistor is ahead of the wet bulb
thermistor in the flow and is spaced 30 mm from it, to prevent evaporation from affecting dry bulb temperature. An extension with a small fan in a 36/40 mm tube, 45 mm long, is added to the rear (with respect to the flow) to provide air flow in the order of 4 to 5 m/s in the 16/20 mm tube. The wet bulb thermistor is inside a wick, wetted by a small water reservoir, placed underneath the wet bulb element. To minimize thermal emission related problems, the psychrometer is placed inside the package, which is covered with 0.3 mm aluminum sheet.

Comparisons with Assmann psychrometers under steady-state conditions, have shown very good agreement.

Thermistors of 1 kΩ have been chosen for the application, to measure temperature in the range of 0 to 50°C. To compensate for spread of initial resistance, it was decided that 25°C would correspond to mid-scale, and span was decided to be about 500 bits, corresponding to a resolution of 0.1°C, to maintain interchangeability between different thermistors, without interfering with the electronics. Doubling the resolution would result to 1000 bits span, which, taking into account thermistors' spread of characteristics, would result to need of calibration for each individual thermistor to meet the 0-50°C scale accurately. It was decided not to use potentiometers for calibration, to avoid errors induced by mechanical or thermal disturbances, but calibrate the whole system (including the A/D) instead, so it was of no value to use precalibrated thermistors. To enhance accuracy, the circuit consists of a bridge excited by the voltage reference of the A/D, followed by an instrumentation amplifier. Overall voltage gain is about 80.
Overall noise is less than 1mVpp. The circuit configuration guarantees a ratiometric A/D conversion, eliminating any minor reference voltage stability related problem. The circuit diagram is shown in fig. 3. The thermal drift of the amplification circuitry is calculated to be less than ±0.2°C per 25°C. Actual performance was even better, because the operational amplifiers of the first stage were matched. Despite the low gain of the amplifier, care was taken in component selection and layout to avoid noise and drift induced by thermal gradients across the board.

**Pressure**

Pressure is measured relative with the surface pressure. The pressure transducer used is Sensym’s LX1601A. This is a piezoresistive transducer, it is fully signal conditioned, with temperature compensation and high output voltage. It operates from 10 to 20 psi and provides an output voltage of 2.5 to 12.5 Volts. A simple electronic circuit follows the transducer’s output. This can be divided into three parts. The first is a low-dropout regulator, the second is the signal conditioner to the A/D input and the third is a window comparator. The LX1601A has an internal voltage regulator, which operates for excitation voltages above 15 V. As already mentioned, a lowest battery voltage of 12 V is assumed, which calls for an extra voltage regulator. However, the sensor needs at least 10 V for normal operation, and at least 2 V above the highest output voltage to keep unsaturated. Assuming that the maximum pressure it will be operated, is to be 1100 mbars, it will produce 8.5 V, so applying 11.5 V is a very conser-
vative approach. To meet this specification, a low-
dropout voltage regulator is used. To retain the
dynamic range of the sensor output, a voltage sub-
tractor is used subtracting the voltage correspon-
ding to the surface pressure to keep from saturation
and allowing for a span of 170 mbars. Voltage sub-
traction is carried out by six jumpers, choosing
the appropriate voltage (and therefore pressure
range). Ranges differ 50 mbars from each other, al-
lowing for a minimum of 120 mbar differential pres-
sure range. The window comparator is used to provide
a visual display of the adjustment process. The
complete electronic circuit is shown in fig. 4. To ma-
ke the circuit insensitive to temperature variations
we use op-amps with low offset voltage temperature
coefficient and metal film resistors to avoid ther-
mocouple effects. Other techniques for reducing tem-
perature dependence, were not needed and therefore
not used. Span and offset adjustment potentiometers
were not used to avoid sensitivity to vibrations
and temperature variations. Also, the span stability
is typically 2.5 mbars/year, so it is a good practice
to calibrate it once a year.

Wind speed sensor
A commercially available Vector Instruments A101M
cup anemometer is used. Comparisons in the wind tun-
nel (using only the package) showed no appreciable
difference between data sheet specifications and
actual performance. The anemometer used, utilizes a
light chopper, to provide an output of 10 Hz per m/s
(±2%) and a threshold of 0.15 m/s. The anemometer's
output is lead to the counter input of the on-board
microcomputer, through a schmitt-trigger circuit.

Wind direction
The wind direction is measured by means of a magne-
tic compass. For this purpose an AANDERAA INSTRUMENTS
1248 compass was selected. Wind direction is given as
a potentiometer setting. When the compass is to be
read, a magnet assembly, normally free to swing, must
be clamped. Clamping is done electrically by the ef-
fect of a clamping current in an axially wound coil.
In the clamped condition, a contact wire on the mag-
et assembly, will make contact with a wirewound po-
tentiometer ring. Between readings, the clamping must
be interrupted for a few seconds (3.5 s for a 90°
step change in wind direction) to allow the magnet
assembly to swing towards North. Clamping current is
15 mA. Potentiometer resistance is 2000 Ω. Accuracy is
better than ±2%. Allowable tilt is 12°.

One I/O port of the microcomputer is used to
drive the circuit that locks the compass in position. The reference is applied to the potentiometer terminals of the compass, so that measurement is also ratiometric.

The On-Board microcomputer
A microcomputer was chosen over hardware implementation since collecting process can be easily modified. Extra instrumentation can be added with minimal circuitry and no changes on the main board are required (in fact, an ozone measuring device has already been added with success). Extra features such as power management can be added through the use of its I/O ports.

The microcomputer used is a TattleTale, model V. It is based on the 63A03Y CPU and contains an 11-channel, 10-bit A/D converter, 32 kBytes of RAM, 32 kBytes EPROM containing the operating system and a BASIC interpreter, 17 programmable I/O lines, one counter, on-board voltage regulator and two RS-232 communication ports. Its power consumption of 3 mA and its small dimensions (1.4" x 2.0" x 0.8"), make it ideal for the application. Another feature of this device is that a BASIC program of about 16 Kb can be stored in ROM and start running on power-up. RFI emission of the microcomputer is insignificant.

The microcomputer is used to collect the data, control the compass driving circuit and power manage the system.

When the sampling program is loaded, data collection begins. In the beginning of data collection, fan motor and power supplies are turned on. Time interval between stored values is 5 s. Data collection procedure is not the same for all channels. Pressure and temperature channels are acquired every 1 s. Data are averaged over 5 samples and stored. Wind direction is acquired every 5 s allowing 4 s for the compass to settle. The cup anemometer output is lead to a counter, internal to the microcomputer. Pulse counting lasts for 5 s, so an average of wind speed for this time interval is obtained. Data are stored in two bytes. The values obtained from sampling are stored in the datafile. This is a user defined memory area, supporting data storage. Because the BASIC program uses the same part of memory and the total memory available is 28 kBytes, the datafile size was set to 20 kBytes. A minor portion of the start of the datafile contains necessary data, like take off time, landing time, package number, sampling rate, etc. From
the above it can be calculated that data for 5 channels can be recorded for more than 2h and 45 min using two bits per sample and storing every 5 s. Upon data-collection completion, fan motor and analog power supplies are turned off and the compass stops being clamped.

![Graph showing pressure versus time for a typical balloon flight](image)

Figure 5. Pressure versus time for a typical balloon flight

THE GROUND STATION

Any P.C. compatible computer can be used as the ground station. In our case, the ground station is a common laptop P.C. as mentioned above. It is used before the flight, to onload the sampling program to the package through the serial port and after flight to collect and process the acquired data.
The processing programs used depend on the application. For profiling purposes, the common procedure is to take measurements at constant heights for a short period of time and produce mean, minimum and maximum values. The processing for this type of profiling is to be discussed.

Figure 6. A typical Td, Tw, WS, WD profile

As described above, all data are stored in memory during a flight. Surface pressure is subtracted
from all pressure values to remove the offset. To identify data taken at constant heights, the program seeks for successive pressure values that fall within a pressure range. This range varies linearly with pressure from 0.2 mbars at surface level, to 1 mbar at 100 mbars. This increase in range is necessary to compensate for increasing vertical movements of the balloon as height increases. Raw pressure data values versus time for a typical balloon flight, are shown in fig. 5, while in fig. 6, typical examples of vertical profiles of dry and wet bulb temperature, wind speed and wind direction are given. These measurements were taken during the Thessaloniki experimental campaign on 9-23-91 for the period 1152+1257 LST.

SOME CONCLUDING REMARKS

The present design has certain advantages and disadvantages in comparison with the well-known data transmission method (e.g. [1], [2], [3], [4]). These can be summarized as follows:

a) The proposed system is low-cost and easy to maintain.

b) It is independent of radio interference.

c) Can interrogate at high speed a large number of channels.

d) Can be easily modified to accommodate new instruments.

e) Its main disadvantage is that no data can be shown before the system is landed.

It is believed that future designs will be based in similar techniques.

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Digital interpretation of Sodar Observations
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ABSTRACT

An analysis of the procedure of a real-time digital display technique for minisodar echoes is presented. The estimation of the signal level from digitized data, using averaged values over more than one transmitted pulse and the suppression of environmental noise by statistical methods, are also given. An example of printer generated picture is given and discussed.

1. Introduction

Acoustic sounding has already proved its usefulness in the representation of the thermal structure of the Atmospheric Boundary Layer, the vertical mixing and the mixing layer behavior, e.g. Brown [2], Asimakopoulos [1], Helmis [3]. The traditional method for displaying the backscattered acoustic echo intensity as a function of time and height is the use of a facsimile recorder. The dynamic range of such a recorder is of the order of 10 dB, while the received signal has a dynamic range in the order of 40 dB. This results to a significant signal compression, giving in turn a loss of information about interesting phenomena of the atmospheric thermal structure. Also this type of recorder restricts the pulse repetition frequency of the system by the angular speed of its rotating drum, which can change only by changing the helix gears. Furthermore this method suffers from saturation at high level signals and no correction can be made to the returned signal, if it is necessary.
The use of a digital processing method and a display system is a solution to the above mentioned disadvantages. In this report a computer controlled system, which interprets automatically and on real time Acoustic Sounder echoes, by the use of a printer is presented. The estimation of the signal level and the suppression of the environmental noise are also given. Example of printer generated acoustic radar signals display is given and discussed.

2. System configuration and data display.

The system used is a monostatic sounder operating at a frequency of 4.3 kHz with an acoustic antenna of 5x5 elements array, using Motorola piezoelectric tweeters, with the corner elements removed. An IBM XT compatible computer is producing the transmitted frequency and control signals and processes the backscattered acoustic signals.

The signal which is processed by the system is the envelope amplitude of the backscattered echoes which are caused by atmospheric scatterers and has to be distinguished from the environmental noise, in order to make a decision about the level of the signal that can be displayed. An assumption is made that noise and signal statistics can be modeled by the Rayleigh distribution function, which holds for most cases. Because the Rayleigh distribution is fully defined by its mean value only, an estimation of the mean value of the environmental noise is made using the samples of the received signal which correspond to ranges where no signal is present and making an averaging of shots to get a more statistically reliable estimation of this value. Then a voltage threshold of noise level is calculated, with which every sample is compared and printed if it is greater than this value.

The noise voltage threshold is given by:

\[ V_n = (-4 \ln P_e/\pi)^{1/2} N \]  \hspace{1cm} (2)

where \( P_e \) is the noise error probability.

\[ (1-P_e=\int_0^{V_n} P(Z)dz) \]

and \( N \) is the mean value of the background noise. The \( P_e \) value is set to 0.2 and describes the probability
Fig. 1: Minisodar echo record displayed by a dot-matrix printer on 15 September 1991.

The echo record is a result of a survey conducted during the period 0425:0630.

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that a noise sample is interpreted as signal. According to the display device available, the sample is then quantized into one of the two available levels (for bilevel display devices) and is then displayed and stored in a hard disk to further enhance the easy management of data.

For the application described below a common black and white dot-matrix printer (EPSON RX-80) was used, interfaced to the computer via the Centronics parallel port. The signal intensity was displayed up to 400 m incorporating 480 dots, thus giving a space resolution of approximately 0.8 m/dot which is ideal for applications in minisodar systems utilizing short pulse lengths. The time resolution is 10 cm per hour.

Fig. 1 gives an example of minisodar echo digital display, which was recorded in Thessaloniki, Greece, for the period 0425:0630 LST of the 15th of September 1991. As seen from the figure at 0425h and for a period of about half an hour a strong-based inversion exists reaching a height of more than 200 m. Later on this inversion seems to be dissolved maintaining a ground-based inversion for the rest of the time within a height of 50 m and giving rise to inversion layering with patchy structure up to 300 m. All this activity seems to be concentrated after 0545 to a strong double layering at heights between 100 to 200 m and a wave like activity seems to be established. The increased display resolution of the system is evident compared with the traditional recording ones.

Concluding it is evident that the digital display systems have made the use of facsimile recorders obsolete, offering higher time and space resolution, adaptability to modifications of the operating parameters of the sodar and in conjunction with a computer system, easy management and reproduction of data.

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On the accuracy and precision of the Electrochemical ozonesondes in the lower troposphere

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1. Introduction

The chemical balloon-borne devices which have been developed for direct measurements of ozone in the atmosphere may be divided into two groups, the electrochemical and the chemi-luminescent one.

The operating principle of the electrochemical ozonesonde is based on the reaction of ozone with a potassium iodine solution. In the reaction, free iodine is released, which in turn is measured quantitatively by a coulometric method. These electrochemical instruments have been widely adopted for measuring atmospheric ozone and the data employed for various applications derive chiefly from two types of ozonesonde: the Brewer - Mast (BM) Bubbler (Brewer and Milford 1960) and the Electrochemical Concentration Cell (ECC) (Kohvnyr 1969).

This paper examines the accuracy and precision of most widespread wet-chemical ozonesondes (BM, ECC) in the lower troposphere.
2. Discussion

2.1. BM ozonesonde

BM has been used since 1963 by a large number of stations. Its sensor consists of a reaction chamber with a fine platinum gauze as cathode and a silver wire as anode immersed in a 2 ml of a phosphate buffered aqueous solution of 0.1% KI. In order to avoid a significant background current a polarizing potential of 410 mV is applied between the two electrodes. When atmospheric air is blown by a pump through the solution each ozone molecule releases two electrons. The current detected in this way is therefore proportional to the ozone reacted in the bubbler.

2.2. ECC ozonesonde

The sensing unit for the ECC is an iodine / iodide redox concentration cell composed of two platinum electrodes immersed in neutral buffered iodide solutions of different concentrations in the anode and cathode chambers. The sensor operates as a galvanic cell that causes a current to flow in an external circuit while it drives to equilibrium. In operation a continuous stream of ambient air is bubbled through the cathode compartment of the sensor by a constant volume pump. Ozone in the air oxidizes iodide in the cathode to iodine, unbalancing the equilibrium of the cell. As the cell returns to equilibrium, the resulting current in the external circuit gives a measure of the amount of the ozone in the sample air.

2.3. The accuracy of BM and ECC

The accuracy refers to the extent to which a given measurement agrees with the true but unknown value of the quantity being measured.

The BM and ECC ozonesondes suffer from several sources of inaccuracy. These do not provide absolute values for ozone concentration, and comparisons with ultraviolet spectrometers indicate differences of up to 30% in the troposphere (Hilsenrath et al. 1986).
The first source of error affecting the accuracy comes from errors in the primary calibration standards for the instruments in the flight simulator. The Ruska bourdon tube gauge, which served as the primary pressure reference for the experiments, has an absolute accuracy of 0.007 Torr with a calibration traceable to the National Bureau of Standards (NBS). The reference for the sonde current measurements in the flight simulator has a relative accuracy of 0.25% over all of its range and a calibration traceable to NBS.

Ozone wall losses in the sample tubing provide a second source of error. Based on results from Barnes et al. (1985) the calculations show the losses in the experimental system to amount to less than 0.5% of the ozone readings.

When the calculations are carried out, the worst case absolute errors amount to 4.0% of the ozone partial pressure readings for the major portion of the tropospheric profiles. If the r.m.s. values for the systematic errors are calculated, the relative errors in the measurement system are reduced to 2.6% over most of the range of the tropospheric profiles.

The failure of the bubbler to retain all the ozone entering it provides a third source of error. In a series of measurements with different bubblers it was found (Powell and Simmons, 1969) that the currents at 200 ml.min\(^{-1}\) varied up to 12% for one standard bubbler.

The variation of the volume of air delivered by the pump due to changes in the ambient pressure and the back pressure exerted by the bubbler provides a fourth source of error.

Finally, the departure of the reaction converting ozone to electric current from the assumed stoichiometricity provides a fifth source of error. This alone is sufficient to explain the difference of about 20% between the BM and ECC sensor.

2.4. The precision of BM and ECC

The precision refers to the extent to which a given set of measurements agrees with the mean of observations.

According to Barnes et al., (1985) the measurement
precision of the electrochemical ozonesondes is about 5-7 nb.

2.5. Chemical interferences in the BM and ECC

The coexistence of ozone and sulfur dioxide in the atmosphere, particularly around urban areas, creates many perplexing problems relating to the determination of these substances. The complication arises from the fact that, whereas liberation of iodine is the basis for instrumental analytical procedure for ozone, sulfur dioxide interferes in these procedures by reducing iodine. Therefore, sulfur dioxide provides a negative interference for the determination of ozone in potassium iodide solutions. Also, peroxyacetyl nitrate (PAN) and other oxidizing substances create iodine in a iodide solution. Thus, in an urban troposphere the chemical interferences might possibly add significant errors to the ozone measurements. However by proper choice of scrubbers no interferences were found for NO$_2$, SO$_2$, H$_2$S. PAN gave a response of 12% in mole equivalents of ozone.

References


SECTION 3:
ATMOSPHERIC DISPERSION MODELLING
Modelling Atmospheric Pollution in the Mediterranean – Possible Contributions from EURAD

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ABSTRACT

Simulations of photooxidant formation in the Mediterranean can be carried out on smaller scales focusing on air pollution effects in limited areas of the size of large cities and their surroundings. Another scale is that of larger regions which may be affected by air pollutants transported over larger distances. The latter aspect is a major focus of the EURAD model. Its potentials to treat transport of anthropogenic emissions and their chemical transformation for Mediterranean conditions are outlined. Special attention is given to the need of providing suitable emission data for realistic photooxidants calculations.

1 INTRODUCTION

The Mediterranean region poses specific problems for models aiming at the simulation of the transport of anthropogenic emissions and its chemical transformation. The major effect is photooxidant formation, i.e. production of ozone, PAN and other secondary pollutants hazardous to men and the biosphere. This formation depends on a larger number of meteorological processes influenced by the complex topography of the Mediterranean countries. A typical example is the land–sea breeze resulting from the diurnal variation of the thermal contrast between water and land surfaces. Such smaller scale processes are interacting with larger scale meteorological and pollutants fields. Understanding the complexity of such a situation can be enhanced by numerical simulations of the processes at both relevant scales.
The European Acid Deposition model (EURAD) which is described in this paper has been developed to study larger, i.e. regional, scale effects. It can support simulation studies on smaller scales by providing input data for the respective numerical models applied to Mediterranean areas. For this purpose the model has to be tested and improved where it is necessary. What is urgently needed are emission models of the Mediterranean which are required to generate input data for anthropogenic and biogenic tracers participating in the photochemical generation of ozone and other photooxidants.

Section 2 is an introduction into the model structure. Section 3 presents some model results. Here some examples from central Europe have been included since this area allows comparison with measurements to a certain degree. The emission problem is addressed in Section 4.

2 MODEL DESCRIPTION

EURAD is an episodic Eulerian transport model and consists of a meteorological and a chemical part. Meteorological initial and boundary conditions are obtained from ECMWF analyses. The combination of both parts which are often run at separate places by separate groups has considerably increased the flexibility of the EURAD model regarding its application and its development. A particular advantage is that it can easily be transferred to different regions of the globe. It is possible to increase the standard grid resolution and thus to concentrate on selected parts of the total model domain which is Europe. For instance, higher resolution studies have been conducted for East Germany and could be carried out for Greece, too.

The meteorological part of EURAD is the PennState/NCAR Meteorological Mesoscale Model MM4 (Anthes and Warner, 1978). It has been applied to a wide range of problems as outlined by Anthes (1990). The meteorological output of MM4 is used to drive the Chemical Transport Module (CTM) of EURAD. This module is based on the Regional Acid Deposition Model (RADM) as developed at the State University of New York at Albany. A comprehensive description of RADM has been given by Chang et al. (1987). The model system has been adapted to European conditions (EURAD, 1989).

Presently, a version containing 16 levels in the vertical between the surface and 100 hPa (about 16 km height) is used. The resolution decreases with altitude. Depending on the problem horizontal grids between 20 km x 20 km and 80 km x 80 km have been applied.

The CTM treats the temporal and spatial change of chemical species taking into account advection, diffusion, transport in clouds, dry and wet chemistry as well as dry and wet deposition. The RADM2 chemical meachanism
(Stockwell et al., 1990) is employed. The model has various options for the treatment of the boundary layer.

The complexity of atmospheric chemistry and transport and the limitations of the existing computers in handling these complex processes makes parameterizations unavoidable. Progress of computer performance, of numerical methods and of our scientific knowledge is leading to gradual improvements of such models. As regards EURAD special attention is given to testing and further developing the modules treating clouds, aerosols, the planetary boundary layer including deposition and the role of background and initial fields of pollutants.

3 EXAMPLES OF SIMULATIONS

The need of permanent adjustment of complex chemical transport models to the progress of environmental science and increasing computational performance brings about that model applications are also model tests to a high degree. The case studies carried out with EURAD have been planned in such a way that they allow to check the model from various points of view. Evaluation of calculations against observations is only one of them though the most important. Others concern the plausibility of effects and fields, for instance the behaviour of the boundary layer or the distribution of PAN as well as other species.

In this sense, the nuclear reactor accident which occurred at Chernobyl on 26 April 1986 and resulted in variable emissions over several days was simulated with the aim to study the ability of the model to handle the dispersion of polluted air originating from a single source. The results obtained with the forecast version of the meteorological mesoscale module MM4 have been described by Hass et al. (1990). They used a horizontal resolution of 80 x 80 km². Experiments with higher resolution yielded a reduction of numerical diffusion. It is also possible to run the CTM with observed meteorological data. Fig. 1 exhibits the structure of the Cesium cloud which is obtained about 55 days after the explosion if analyzed meteorological fields are employed. Such studies are carried out to explore the ability of the model regarding its application to emergency cases.
The period of the Chernobyl accident (25 April to 7 May 1986) has also been chosen to study chemical transport processes in the presence of convective clouds in larger areas (so-called wet case). Special attention is paid to the performance of the cloud module in EURAD as a critical element in the system of interactive processes. For this episode a simplified emission scenario as outlined in Section 4 has been used.

Only preliminary results are available till now for ozone as the principal tracer for model evaluation. Two examples of simulated time series for a hilly area (Schaunsland) and a pre-Alpine elevated location (Wank, Garmisch–Partenkirchen) are exhibited in Fig. 2. Though not every detail of the temporal variations is reproduced by the model, the magnitude and trend of ozone appears to be reasonably simulated despite the simplifications in the emission scenario. For eastern European locations where the \( NO_x \) emissions seem to be underestimated, the agreement between model and observations is less satisfying.
Figure 2: Ozone concentrations as measured (continuous line) and simulated (broken line) for the episode 25 April to 7 May 1986. Upper part: Schauinsland, 47.9 N, 7.9 E, 1205 masl. Lower part: Garmisch Partenkirchen, Wank, 47.7 N, 11.2 E, 1776 masl.

An impression how the model performs for larger areas including Greece can be obtained from diagnosing the large-scale distributions of secondary pollutants. For this purpose the period between May 3 and May 5 has been
selected. The synoptic situation shown in figure 3 over Europe is governed by an anticyclone over northern Europe and a developing cyclone moving from the atlantic coast of France towards Ireland.

Figure 3: Synoptic situation on May 3, 12 GMT (top) and May 5, 12 GMT (bottom). Shown is the geopotential height (gpm) at 850hPa together with the horizontal windfield.
Figure 4: Volume mixing ratio of ozone (ppbV) at the ground (top) and at 850hPa (bottom). The white areas are boxes containing high mountains.
Figure 5: Same as figure 4, but for PAN.
The air flows from the main emission regions in central Europe to the North Sea, the UK and Norway. The relevant ozone distribution is exhibited in Fig. 4.

It can be clearly seen that polluted air is transported over the North Sea, in particular at the higher level (850 hPa), and even became a part of the air which is moving around the center of the cyclone. Similar features are present in the volume mixing ratio of PAN. For the latter species also the volume mixing ratio at 500 hPa (ca. 5000 m) is shown (see Figs. 5 and 6). Due to the long lifetimes of these photo-oxidants one finds the highest amounts far from the main emission regions of the precursors. This is in particular the case for PAN due to its slow thermal decomposition at low temperatures. It is of special interest that even at 500 hPa the PAN mixing ratio over the Northern Atlantic Sea is about 0.8 ppbv and comparable to the values in heavily polluted areas in central Europe. Transport of polluted air masses from this area to the Mediterranean is clearly evident.

Figure 6: Volume mixing for PAN (ppbV) at 500 hPa.
4 EMISSION MODELLING

The problem of appropriate emission data for regional scale Eulerian models which are designed for the investigation of certain episodes of some days have been discussed by Memmesheimer et al. (1990). The chemical transport module of EURAD needs, as each Eulerian model of this type, a specific structure in space and time of emission data given by the model's grid and certain chemical species for the substances used in the chemical reaction scheme. EURAD is able to consider emissions of the anorganic species $SO_2, SO_4, NO, NO_2, NH_3$ and $CO$ and about twelve different classes for the volatile organic compounds (VOCs) (see Stockwell (1990)). If one starts as it is presently the case with annual values which are provided by the well known environmental project EMEP one has also to specify the emission rates with respect to the episode considered and the hourly values (daily variation). Therefore, the emission rates for all relevant species have to be given at a specific grid and for each hour of the episode. Usually existing emission data bases have to be transformed to meet the specific requirements of the model. As an example the transformation of the EMEP emission inventory for 1986 and other relevant emission data given at the EMEP grid to a spatial, temporal and chemical structure which can be used for EURAD applications will be shown.

The annual emission rates given at the EMEP grid have been used as starting-point for preliminary studies described in Section 3 for the episode April 25 till May 7, 1986. For $SO_2$ and $NO_x$ emissions the data are splitted by EMEP into low level sources (below 100 m) and high level sources (above 100 m). The emission rates for $NH_3$, also given as annual values at the EMEP grid, have been taken from the EMEP report 2/89 (Iversen et al., 1989), anthropogenic VOCs and $CO$ are coupled in a very first approach to the total $NO_x$ emissions. The $CO$ emission rate is assumed to be the $NO_x$ emission rate multiplied by five. For VOC emissions the values given by Selby (1987) are used as a basis to estimate the actual VOC emissions for 1986. The emission rates for total anthropogenic VOCs are calculated by

$$S_{VOC}^{anth} (1986) = S_{VOC}^{Selby} \cdot \frac{S_{NO_x} (1986)}{S_{NO_x}^{Selby}} \cdot 0.7$$

The weighting factor of 0.7 is estimated on the basis of recently published emission data for OECD countries (OECD, 1989) and accounts for a lower $NO_x/VOC$ ratio compared to that which has been assumed by Selby (1987). The VOC emissions estimated for the EMEP grid and published in a recent study by Simpson and Hov (1990) for 1985 are also available and may be used in future modeling studies. The model requires as input also emission rates for $NO_2$ and $SO_4$. It is assumed that 4% of the $NO_x$ emissions are
emitted as $NO_2$, $SO_4$ is assumed to be 3.9% of the $SO_2$ emissions, which is an average value from the TADAP/PHOXA inventory for area sources, which is used for a late winter smog episode in 1982 (Scherer and Stern, 1989).

EMEP emission data are given as annual values on a polarstereographic projection with a horizontal grid size of 150 km. For the JWC the EURAD modeling system is used with a horizontal gridsize of 80 km and a lambert conformal projection. Figure 7 shows the EMEP grid on a lambert conformal grid together with the EURAD area.

Figure 7: EMEP grid plotted on a Lambert Conformal projection. The EURAD area for the wet case is also shown.

In a first approach the emission rates given on the EMEP grid are transformed by an area weighting spatial transformation scheme to the EURAD grid. This procedure certainly overestimates the emissions in regions with low emissions and underestimates the emissions in regions with high emissions. Because the EMEP data are given on a grid size of about two times
the EURAD grid size there may arise an uncertainty of about one EURAD grid cell by applying the area weighting scheme without using additional information. A technique which partially may avoid such an error using as additional information population density is currently under development and will be used in future studies. Figure 8 shows the low level \( NO_x \) emissions after the application of the area weighting scheme for the EURAD modeling region. It should be mentioned that all sources on the ocean are eliminated within the framework of the transformation procedure. Consequently there is no EURAD grid box with emissions on the ocean that means that e.g. ship emissions are neglected in this approach. This neglect may cause problems for simulations in areas like the Aegean Sea and other parts of the Mediterranean Sea where intensive ship traffic is found.

![Figure 8: Low level \( NO_x \) emissions [Kt/year as \( NO_x \)] on the EURAD grid after the spatial transformation from the EMEP grid to the EURAD grid. Major cities are indicated by black dots.](image)

To specify values for certain episodes the seasonal variation for \( NO_x \) and VOCs given by Schmitt (1989) are used. This approach leads to a country based horizontal resolution of seasonal variations for anthropogenic VOCs and \( NO_x \).

The next step as far as temporal resolution is concerned is to define hourly values for the emission rates to be used in the model. For that purpose typical temporal variations for different daytypes (workday, saturday and sunday) have been defined for \( SO_2, NO_x, VOC's \) and \( NH_3 \). These daily variations are a combination of data published in the literature (Cocks and Fletcher, 1989; Müller et al., 1990; Asman, personal communication). The
total emissions for Sunday are 66% and for Saturday 75% of the total workday emissions for all constituents except $NH_3$, where it is assumed that there is no difference in total emissions and no difference in daily variations between different days of the week. For VOC the same temporal variation as far as $NO_x$ is assumed for the daily variation during the week.

In this study the same VOC profile is applied at each grid point and for each hour of the episode. The VOC profile following recommendations of W. Stockwell (personal communication) is shown in figure 9.

![Figure 9: VOC profile applied to each grid point and for each hour of the episode VOCs.](image)

Due to lack of information on source categories, it is not possible to improve this procedure at the moment using EMEP data. The situation may change because there is now a cooperation between EMEP and CORINAIR underway. This may improve the available database within the EMEP inventories for 1990 considerable on a European scale. The highlevel sources of EMEP are assumed to be constant throughout the episode. The above described temporal variations are only applied to the lowlevel sources, which are all assumed to be injected into the lowest layer of the EURAD model which is about 75 m thick. For the highlevel sources (only $NO_x$, $SO_x$) an estimated preliminary vertical distribution function (VDF) is applied.

Evidently, more work is needed to arrive at reliable anthropogenic emission data for episodic modelling. Inclusion of biogenic emissions can be based on a preliminary model by Lübker and Schöpp (1989). As regards Greece it
would certainly be benefitting to include more of the available information on emissions from this country in the emission model for EURAD.

5 CONCLUSION

The simulation of photooxidant formation in the Mediterranean forms a challenge to EURAD. Clearly, there is a great need to proceed with this task. This can profitably be done in cooperation with groups running models on smaller scales. Plans have been developed by the subproject EUMAC of EUROTRAC to carry out such joint studies.

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Pollutant Dispersion over the Coastal Zone of Northern Germany†

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Abstract

The high-resolution, nonhydrostatic mesoscale model GESIMA is used to estimate the transport and deposition of particulate matter over the coastal area of Northern Germany. Lead emitted from traffic, industrial emissions and household burning is used as a sample substance. It is found that during sea-breeze conditions in summer, the deposition rate in the wadden sea areas which are considered ecologically valuable amounts to about 1 \( \mu g/(m^2\cdot h) \). During a wintery inversion episode, \( Pb \) accumulates in the lower atmosphere. However, the deposition rate is about the same as in summer due to the strong surface inversion which prevents efficient deposition.

1. Introduction

Central Europe was one of the first areas to undergo fundamental changes due to the industrial revolution. Population growth and intensive landuse have diminished the natural countrysides to a few enclaves. The more it is necessary to protect and monitor these few remaining ecologically intact regions one of which is the coastal zone of Northern Germany with its wide Wadden Sea areas.

In this work the transport and deposition of atmospheric lead over Northern Germany is investigated with the use of the mesoscale model GESIMA (Geesthacht Simulation Model of the Atmosphere). Atmospheric lead which is emitted mostly by traffic is now considered of minor threat because legislation in the European Community is likely to have eliminated this main source of pollution within the next years, and focus has shifted to other hazardous materials such as mercury. However, as fairly safe knowledge on the long-range transport of lead, its emissions and atmospheric properties, has been accumulated during the last few years, it was taken as a sample trace metal to assess the effects of local sources in a confined area.

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Two typical episodes are simulated: a sea-breeze situation in summer and an inversion episode in winter. The main findings are:

a) the southern part of the solution domain which (extends from the region of Lüneburg in the south up to Odense in the north and from Emden in the west to a few km east of Lübeck) and the bigger settlement areas like Hamburg and Bremen show increased concentration and deposition, attributable to the higher traffic density in these regions,

b) though the summer and winter episodes are fundamentally different the deposition rates of lead into the Wadden Sea are about equal. Two effects counteracting each other seem to be responsible. In summer, deposition is favoured due to turbulence. However, less material is available at the ground due to the high mixing height. In winter, a stable surface layer seems to inhibit an effective deposition despite the concentration being held within the lowest three hundred meters of the atmosphere,

c) in winter the relative size of deposition in the Wadden Sea areas is bigger than in the other rural areas. This is likely to be the effect of the mixing of cold air coming from land when it is transported over the warmer Wadden areas.

2. Model Description

The basis of the dynamical part of the model is the anelastic equations as suggested by Ogura and Phillips, (1962) with the buoyancy term treated in Boussinesq approximation. In flux-form the equations for momentum, potential temperature and mass are:

\[
\begin{align*}
\frac{\partial}{\partial t} (\bar{\rho}u) + \nabla \cdot (\bar{\rho} u \otimes u) &= -\nabla p - 2\bar{\rho} \Omega \times u + \bar{\rho} \frac{\theta}{e_{air}^2} \nabla \cdot \bar{\rho} \tau \\
\frac{\partial}{\partial t} (\bar{\rho} \theta) + \nabla \cdot [u(\bar{\rho} \theta)] &= \nabla \cdot \bar{\rho} \sigma \\
\nabla \cdot (\bar{\rho} u) &= 0
\end{align*}
\] (2.1)

The nomenclature follows meteorological conventions. \( u \) is the mean velocity, \( \theta \) is the deviation of potential temperature from the temperature of an isentropic atmosphere defined by the profiles \( \bar{\rho}, \bar{\theta} \), and \( \bar{\rho} \). \( p \) is the nonhydrostatic perturbation pressure. \( \tau \) and \( \sigma \) are subgrid-scale fluxes due to turbulent averaging.

These equations are transformed into a terrain-following coordinate system while preserving the original flux-form. A staggered grid (Arakawa-C Grid) is chosen where fluxes are located on the grid-cell surfaces, and all other quantities in the grid-cell centers.

Time integration is performed by a second-order accurate predictor-corrector scheme. The Poisson Equation for pressure is solved by a preconditioned Conjugate-Gradient Scheme.
(Kapitza and Eppel, 1987). The Coriolis Force is treated time-centered, and for the vertical diffusion the Thomas Algorithm is used to solve the tri-diagonal equation system (for details see Kapitza, 1987). Scalars are advected with a variant of the Smolarkiewicz Scheme.

Surface fluxes and surface temperature are determined via an energy balance equation on the ground (Claussen, 1988). The cloud model used is a Kessler-type bulk formulation with cloud water, rain, and snow (Jacob, 1991, Levkov et al., 1989). For the parameterization of turbulent stresses the simple Blackadar, (1962) formulation is used, as no appreciable difference to the more involved turbulent energy parameterization could be found. Radiative transfer is calculated within the Two-Stream Approximation with eight optical windows in the infra-red.

3. The Summer Episode

The summer episode from 22. - 24. June 1981 is characterized by a strong persistent High, located over the North Sea; a frequent synoptic situation during summer in Northern Europe. The synoptic wind driving the model was obtained from Weather Map as 2 m/s from the east.

The solution domain (Fig. 1) was covered with a 51x51x23 grid with a vertical grid spacing increasing with height. Nineteen landuse categories (Fig.2) ranging from open sea, wadden areas, marshlands, sandy soil, forests, settlements, to downtown areas, were specified as input to the surface-energy-budget modul.

The model was initialized with 1-d profiles obtained by the 1-d version of GESIMA. The simulations start at 0:00 GMT, and results are presented from the second day on leaving one day for spin-up time.

In Figs. (3.a) to (3.f) a sequence of wind fields 20 m above ground is depicted at 6:00, 9:00, 12:00, 15:00 and 18:00. It is seen that Schleswig-Holstein is of too small an extent to support two separate sea-breeze systems for North- and Baltic Sea. The weak synoptic wind from the east is sufficient to prevent the appearance of the land-breeze during night, and to shift the sea-breeze front to the west coast.

An impression of the vertical structure of the wind field can be obtained from the wind distribution at 3:00 in the afternoon on a vertical x-z cut through the solution domain at grid plane J=14, through the centre of Hamburg (Fig. 4). On the abscissa, Hamburg is located between 150 and 175 km.
The transport of Pb was calculated with a source emission inventory on the GESIMA grid of 6x5 km² grid spacing (Fig. 5). The main emitter is traffic with more than 90% of the total emissions. It was assumed that the Pb particles have an average size of 1 μm zero sink velocity. In concordance with prior findings the deposition velocity was assumed to be 0.02 cm/s. Due to lack of information no daily variation in emission strengths were assumed. The calculations were performed with 20 ng/m³ as background concentration obtained in Graßl et al. (1989).

The concentration field in 20 m heigh above ground at 3:00 in the morning (Fig. 6.a) shows a considerable higher concentration field than the one at 3:00 in the afternoon (Fig. 6.b). The sea-breeze obviously has a ventilating effect. As already the slight synoptic wind used in this episode prevents a nightly returnflow it is likely that only little accumulation occurs during several daily cycles. The vertical mixing can be seen by comparing the concentration fields on x-z cuts (Figs. 7.a and 7.b) through the solution domain at J=14 for 3:00 in the night and 3:00 in the afternoon of the following day.

4. The Winter Episode

Similarly to the summer situation, the winter episode from 16. to 18. January 1987 is characterized by a persistent High over the North Sea. Even during day time ground temperatures do not rise above 273 K (Fig. 8) which is the assumed temperature of the sea. The whole land part of the solution domain is covered by snow rendering the surface more homogeneous than in summertime.

Due to the extreme stabiltiy of the atmosphere the wind field is more or less stationary. Figs. 9.a and 9.b show the wind distribution at night at 3:00 and at 3:00 in the following afternoon.

Similarly, the concentration fields in 20 m height above ground vary little with time as can be seen from Fig. 10.a (3:00 at night) and Fig. 10.b (3:00 in the afternoon). The mayor sources, town and cities, can easily be detected.

The vertical distribution of lead is depicted in Fig. 11.a (6:00 in the morning) and Fig. 11.b (12:00 noon).

The deposition pattern is depicted in the sequence Fig. 12.a to 12.d. Due to the higher temperature of the Wadden Sea areas and due to their larger roughness length than the ones for the snow-covered land, the cold air advected from land destabilizes the surface layer, and allows for an appreciable deposition. Closer inspection shows that the deposition
rate over the Wadden areas is around 1 $\mu g/(m^2s)$ which is about the value obtained for these regions during summer.

5. Conclusion

Simulations are presented for the transport of particulate lead resulting from mainly from traffic exhaust over the coastal zone of Northern Germany. Though the two episodes (sea-breeze flow in summer and inversion episode in winter) bear no meteorological similarity the resulting deposition rate of 1 $\mu g/(m^2s)$ into the Wadden Sea areas is about the same. Over land the deposition concentrated around the main settlements. There are only slight indications that Pb is accumulated in a sea-breeze during several daily cycles in the presence of a background synoptic wind.

Provision of plotting software by M. Resch is gratefully acknowledged.

6. Literature


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Deposition rate (mg/m²/h) 17.1.1987 36 h

42 h
Some Remarks on the k-ε Turbulence Model Applied to Sea Breeze Simulation: Buoyancy Effect on the $\varepsilon$-Equation and Horizontal Eddy Diffusivity

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ABSTRACT

Through the application of the k-ε turbulence model to sea breeze simulation, numerical experiments to investigate effects of and to quantify reasonable range of a model parameter, i.e. $c_{3\varepsilon}$, which controls buoyancy effect in the $\varepsilon$-equation, were performed. The results showed that the parameter $c_{3\varepsilon}$ should be varied in accordance with local thermal stratification for reasonable sea breeze formation: the preferred value of $c_{3\varepsilon}$ was 0 for unstable stratification and $\sim 1.0$ for stable stratification. In addition, influence of the formulation of horizontal eddy diffusivity on the computed sea breeze was also investigated.

INTRODUCTION

Prediction of vertical structure of the atmospheric boundary layer (ABL) has an increasing need for regional-scale air-pollution dispersion simulations. Particularly in coastal and mountainous region potential complexity of the ABL under the influence of thermally induced local flows such as sea/land breezes and mountain/valley winds need detailed description of the ABL structure for reliable air-pollution simulations.

In the situations described above, dynamical nature of the transport of turbulence should be predicted to better evaluate fields of turbulence and eddy diffusivity. Thus use of dynamic turbulence model which allows transport of turbulent quantities and length-scale of the turbulence is necessary.

The k-ε turbulence model has begun to be used in meso-scale meteorological flow calculations [e.g., 1, 2, 3, 4, 5], since the model is relatively simple and needs only two additional transport equations for estimating the dynamical nature of turbulence to some extent. However, the values of the model parameters have not necessarily been well-established in meteorological flow situations, because the k-ε model has been developed and applied mostly in various engineering-flows.
Especially, the parameter which controls buoyancy-effect on the
dissipation rate, $\varepsilon$, of the turbulent kinetic energy, $k$, has much
uncertainty in its value, and, moreover, the value should largely
affect the calculated flow and temperature. Thus we have tried to
quantify reasonable range of this parameter through sensitivity
test of the sea breeze over a hypothetical 3-D peninsula
topography. In the calculations we used the $\varepsilon$-equation given in
Hossain and Rodi(1982)[6] and Rodi(1985)[7] with the conventional
$k$-equation. The result obtained showed that the parameter is
better to be changed according to the local thermal
stratification rather than to be kept at its single value in the
whole domain through the simulation; i.e., the preferred values
are a positive number which is close to zero for unstable
situation and that close to one for stable situation. The use of
the single fixed value of 0.8, which was suggested in Rodi[7],
led to unrealistically large vertical eddy diffusivity in the
inland mixed layer where mean horizontal wind was very weak. In
the study we also examined the effects of horizontal eddy
diffusivity on the sea breeze.

**MODEL EQUATIONS**

Conservation equations for momentum with the hydrostatic
assumption for vertical component, and that for potential
temperature, $T$, and the mass-continuity equation are given as follows:

$$\frac{DU_i}{Dt} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} \left(-\overline{u_i u_i}\right) + f_1 (\delta_{ij} U_j - \delta_{ij} U_i) - \delta_{ij} U_j U_i \quad i=1,2$$ (1)

$$\frac{\partial P}{\partial x_i} = -\rho g$$ (2)

$$\frac{\partial U_j}{\partial x_i} = 0$$ (3)

$$\frac{D\Theta}{Dt} = \frac{\partial}{\partial x_i} \left(-\overline{u_i \Theta}\right)$$ (4)

where $D/Dt$ represents substantial derivative as $D/Dt = \partial/\partial t + \mathbf{U} \cdot \nabla$, $\delta_{ij}$ the Kronecker's delta, upper-case letters stand for
the mean quantities and lower-case letters for the turbulent or
fluctuating components: e.g., $U_i$ for the mean velocity and $u_i$ for
the velocity turbulence, and $f_1$ and $f_2$ are the Coriolis
parameters as $f_1 = 2\Omega \sin \Gamma$ and $f_2 = 2\Omega \cos \Gamma$ where $\Omega$ is the
angular velocity of the earth's rotation and $\Gamma$ is latitude, i.e., $\Gamma=35^\circ$N.

Equation for the averaged turbulent kinetic energy, $k = \overline{u^2}/2$.
can be written in its conventional form as follows:

$$\frac{Dk}{Dt} = \left(-\overline{u_i u_i} \frac{\partial U_i}{\partial x_i} + \frac{\partial \overline{u_i u_i}}{\partial x_i} \right) + \frac{\partial}{\partial x_i} \left[-(h_i + p) \overline{u_i u_i} \right] - \varepsilon$$ (5)

where $S$ denotes the production by wind shear, $G$ that by buoyancy,
and $T$ is for turbulent diffusion. The turbulent fluxes in
Eqs.(1), (4) and (5) can be given as follows:

$$-\overline{u_i u_i} = \nu_t \left(\frac{\partial U_i}{\partial x_i} + \frac{\partial U_j}{\partial x_j} - \frac{2}{3} \delta_{ij} U_j\right)$$ (6)

$$-\overline{u_i \Theta} = \nu_t \frac{\partial \Theta}{\partial x_i}$$ (7)
\[-(k' + \frac{P}{\rho})u_j = \nu_t \frac{\partial k}{\partial x_j}\]  
(8)

where \(k'\) denotes instantaneous turbulent-kinetic energy, i.e. \(k' = (1/2)u'^2\).

Equation for the viscous dissipation rate, of turbulent kinetic energy has still large uncertainty in its form. The conventional form of \(\varepsilon\) may be written as follows [6]:

\[\frac{D\varepsilon}{Dt} = \frac{\partial}{\partial x_j}(\nu_t \frac{\partial \varepsilon}{\partial x_j}) + c_{1e} \frac{\varepsilon}{\bar{k}} (S + G) - c_{2e} \frac{\varepsilon^2}{\bar{k}}\]  
(9)

where the second term on the right-hand side represents production of \(\varepsilon\) by wind-shear and buoyancy. In Eq. (9), the same coefficient of \(c_{1e}\) is used for both "shear-production" and "buoyancy-production" terms. However, according to experimental results, the coefficients for \(S\) and \(G\) terms tend to have different values depending on different flow situation [7]. Thus Rodi [7] tried to derive a generalized expression, which has "universal constant", for the second term on the right-hand side of Eq. (9) by rewriting it as:

\[c_{1e} \frac{\varepsilon}{\bar{k}} (S + G)(1 + c_{3e} R_{fr}^2)\]  
(10)

where \(R_{fr}^2\) is a modified flux Richardson number with its definition \(R_{fr}^2 = -G/(S + G)\) for horizontal buoyant shear layer. Substitution of this \(R_{fr}^2\) into Eq. (10) gives the following expression:

\[c_{1e} \frac{\varepsilon}{\bar{k}} (S + (1 + c_{3e}) G)\]  
(11)

We have started our numerical experiments on sea breeze by adopting this formulation for the \(\varepsilon\)-equation as:

\[\frac{D\varepsilon}{Dt} = \frac{\partial}{\partial x_j}(\nu_t \frac{\partial \varepsilon}{\partial x_j}) + c_{1e} \frac{\varepsilon}{\bar{k}} (S + (1 - c_{3e}) G) - c_{2e} \frac{\varepsilon^2}{\bar{k}}\]  
(12)

The formulation may be appropriate for sea/land breeze situation since land and sea surfaces work as heat source and sink, thus forming horizontal buoyant shear flow.

A set of equations (1) through (5) and (12) with the following relation for eddy diffusivity gives a mathematical model for thermally driven meso-scale flow:

\[\nu_t = c_w \frac{k^2}{\varepsilon}\]  
(13)

In principle, Eq. (13) represents eddy viscosity for both vertical and horizontal directions. However, by the two reasons that turbulence in the earth's atmosphere is not isotropic because of thermal stratification and the limited vertical extent due to existence of ground, and that in meso-scale flow simulation horizontal grid size usually has to be kept at much larger value than vertical grid size due to computational cost, we used Eq. (13) only for vertical direction, and adopted a constant value of 1000 m²/s for horizontal eddy diffusivity. Effect of the formulation of horizontal eddy diffusivity on computed sea breeze will be discussed in later section.
MODEL PARAMETERS

Since purpose of this paper is to investigate effect of the buoyancy production term in the $\varepsilon$-equation, model parameters expect for $c_3\varepsilon$ in Eq. (12) have been set at their conventional values [7], and they are listed in Table 1.

The parameter $c_3\varepsilon$ controls buoyancy-effect on the $\varepsilon$ production, and is thus potentially very important for simulations of thermally driven flows. Some of the values for parameter reported in literatures are shown in Table 2, with those tested in this paper; Table 2 also describes simulation cases. Rodi [7] used single value of $c_3\varepsilon = 0.8$ (case 1) for heated surface jets, while Bell and Haroutunian (1983) [8] used a little strange values for atmospheric surface layer, i.e., $c_3\varepsilon = 2$ and $-0.8$ for stable and unstable conditions, respectively (case 4). Bell and Haroutunian's choice implies that buoyancy always works as source mechanism of the dissipation rate regardless of thermal stratification. We used $c_3\varepsilon = 1$ and 0 for stable and unstable conditions, respectively (case 0) in our previous sea breeze study [2, 5]. Case 3 in Table 2 adopts $c_3\varepsilon = 0$, indicating use of the original form of the $\varepsilon$-equation, i.e., Eq. (9).

Table 1. Model parameters.

<table>
<thead>
<tr>
<th>$C_\mu$</th>
<th>$C_1\varepsilon$</th>
<th>$C_2\varepsilon$</th>
<th>$\sigma_z$</th>
<th>$\sigma_\Theta$</th>
<th>$\sigma_\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.09</td>
<td>1.44</td>
<td>1.92</td>
<td>1</td>
<td>1</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Table 2. Reported values of $c_3\varepsilon$ in Eq. (11) and simulation cases.

<table>
<thead>
<tr>
<th>Case No.</th>
<th>0+</th>
<th>1*</th>
<th>2</th>
<th>3$^\dagger$</th>
<th>4$^#$</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_3\varepsilon$ for Stable Stratification</td>
<td>1.0</td>
<td>0.8</td>
<td>0.5</td>
<td>0</td>
<td>2.0</td>
<td>0.8</td>
</tr>
<tr>
<td>$c_3\varepsilon$ for Unstable Stratification</td>
<td>0</td>
<td>0.8</td>
<td>0.5</td>
<td>0</td>
<td>-0.8</td>
<td>0</td>
</tr>
</tbody>
</table>

* Used for heated surface jets [6, 7].
$\#$ Used for atmospheric surface layer [8].
+ Used for sea breeze simulation [2, 4, 5]
$^\dagger$ This leads to the original form of the $\varepsilon$-equation, i.e., Eq. (9).

CALCULATION DOMAIN AND NUMERICAL METHOD

Figure 1 shows 3-D calculation domain where a peninsula is placed. Numerical method applied is that of the control volume [10] and is the same used in Kitada et al. [2, 5]. Temperature at sea surface has been kept at constant and that over land surface has been varied sinusoidally, reaching its peak value, which is 5°C higher than the sea surface temperature, at 1400 LST. All simulations were started at 0800 LST, when temperatures over both sea and land surfaces were the same. In the calculations, the
Fig. 1. 3-D calculation domain. Vertical profiles of dependent variables along lines A-A' at y = 14 km and B-B' at y = 26 km will be discussed in the text.

Fig. 2. Vertical cross sections of predicted eddy diffusivity, \( v_z \) (m\(^2\)/s), along A-A' in Fig. 1 at 1400LST in the cases of (a) 0, (b) 1, and (c) 4. See Table 1 for the cases.
lowest layer below 30 m high has been assumed as the constant flux layer, where the Monin-Obukhov similarity has been used [5].

EFFECTS OF BUOYANCY PARAMETER IN THE $\varepsilon$-EQUATION ON COMPUTED SEA BREEZE

To quantify an appropriate range of the parameter value ($c_{3\varepsilon}$), we have examined results of simulation cases listed in Table 2 in terms of wind, temperature, turbulent kinetic energy, dissipation rate and eddy diffusivity.

Figure 2 shows cross sections of computed eddy diffusivity and Fig. 3 of potential temperature along A-A' line in Fig 1 at 1400 LST for cases 0, 1 and 4. At the time, sea breeze is in its developed stage and the result of case 0 seems reasonable [5]. On the other hand, both cases 1 and 4 have produced unrealistic profiles as shown in Fig. 2 (b) and (c). In case 1, using the single value of $c_{3\varepsilon} = 0.8$, production of the dissipation due to buoyancy tends to be underestimated in unstable layer compared with case 0 (standard case), e.g., the instantaneous production rate by buoyancy in case 1 can be estimated as 20% of that in case 0. Thus the magnitude of eddy diffusivity has developed fast and reached its extremely large value especially in inland mixed layer where mean horizontal winds are very weak, e.g., maximum $u_*$ is 6200 m/s. In addition, because of this large eddy diffusivity, cool air mass originated from sea side has been mixed quickly with warm air over land and lost its identity, and the simulation thus shows no penetration of sea breeze.

In case 4 where $c_{3\varepsilon} = 2$ and - 0.8 are adopted for stably and unstably stratified layers, respectively, buoyancy force always works as much-enhanced source term in the $\varepsilon$-equation. Therefore, turbulent kinetic energy can not grow large enough to generate convective layer over land surface. Hence sea breeze has not developed at all as shown in Fig. 2(c) and 3(c).

Case 2 with $c_{3\varepsilon} = 0.5$ has showed eddy diffusivity profile similar to that of case 1, and thus gave similar shortcomings to the simulation, i.e., to produce very large eddy diffusivity. Results of case 5 were almost identical with those of case 0, showing realistic and reasonable sea breeze features.

In case 3 where $c_{3\varepsilon} = 0$ and thus the "standard" form of the $\varepsilon$-equation is applied, two production terms of the dissipation rate by wind shear and buoyancy have equal coefficient regardless of thermal stratification of the flow. Since this coefficient for the buoyancy term in stable condition in case 3 has the largest value among those in all cases, the dissipation rate in stable layer should decrease more rapidly than those in the other cases. Hence relatively large eddy diffusivity may appear in stable layer. This is shown in Fig. 4(c) which illustrates vertical cross section of eddy diffusivity along B-B' (Fig. 1) in case 3. Namely, Fig. 4(c) indicates relatively large eddy diffusivity over the sea surface between $x = 0$ and 16 km, where the flow is stably stratified and, furthermore, the turbulence produced over land surface is being transported in by the return flow of the sea breeze. In case 0, such a large eddy diffusivity has not appeared at similar locations, as shown in Fig. 4(a). Since air mass over the sea surface shows stable stratification, we judge the result shown in Fig. 4(c) is a little strange compared with that
Fig. 3. Same as in Fig. 2 but for potential temperature.

Fig. 4. Vertical cross sections of predicted eddy diffusivity, $\nu_\theta$ (m$^2$/s), along B-B' in Fig. 1 at 14:00 LST in the cases of (a) 0, (b) 1, and (c) 3. See Table 1 for the cases.
Fig. 4(a) for case 0. Figure 4(b) for case 1 presents again unusually large eddy diffusivity, as in Fig. 2(b).

HORIZONTAL EDDY DIFFUSIVITY

As mentioned in previous section, the k-ε model is for isotropic turbulence in principle. However, atmospheric turbulence is not necessarily isotropic. Furthermore, use of much larger grid size for horizontal direction compared with that for vertical direction may be inevitable in numerical simulation of meso-scale meteorological model, e.g., the grid sizes used in this study are $dx = dy = 2 \text{km}$, and $dz_{\text{min}} = 7 \text{m}$ and $dz_{\text{max}} = 200 \text{m}$. Therefore, use of different formulation for horizontal eddy diffusivity, with keeping relatively simple and desirable nature of the k-ε turbulence model as a tool providing vertical diffusivity, may be required.

Table 3. Simulation cases using different formulation for horizontal eddy diffusivity ($\text{m}^2/\text{s}$).

<table>
<thead>
<tr>
<th>Case No.</th>
<th>H1</th>
<th>H2</th>
<th>H3*</th>
<th>H4*</th>
</tr>
</thead>
</table>
| $\nu_{th}$ | 100 | 1000 | Eq. (14) with $\alpha = 0.72$ | Eq. (14) with $\alpha = 2$

# Used by Kikuchi et al. (1981) [12]

In this study we have tested four cases on the horizontal diffusivity, as listed in Table 3. In these simulations, vertical eddy diffusivity has been determined by the k-ε model with parameters listed in Table 1 and in case 0 of Table 2.

Cases H3 and H2 use constant horizontal diffusivity $\nu_{th} = 100$ and $1000 \text{m}^2/\text{s}$, respectively. The other two cases H3 and H4 apply the following formulation with different values of parameter $\alpha$:

$$\nu_{th} = \alpha ^2 \Delta x_1 \Delta x_2 \left( \frac{\partial U_x}{\partial x_1} \right)^2 + \left( \frac{\partial U_x}{\partial x_2} \right)^2 + \frac{1}{2} \left( \frac{\partial U_y}{\partial x_1} \right)^2 + \left( \frac{\partial U_y}{\partial x_2} \right)^2 \right)^{1/2} \tag{14}$$

Equation (14) is based on the idea of parameterizing effects of the sub-grid scale eddies [3], and was applied to meso-scale flow by Pielke (1974) [11].

Figures 5 and 6 show horizontal cross sections of vertical wind velocity and vertical cross sections along A-A' line in Fig 1, cases H1 through H4, respectively. Contour maps of vertical wind, i.e. $U_2$, in Fig 5 indicate the followings: (1) the constant $\nu_{th}$ of 100 $\text{m}^2/\text{s}$ (Fig. 5(a)) has produced many local maxima of the velocity $U_2$ over the peninsula, where horizontal winds have been strong, probably because of numerical instability; cell structures found in inland area, where mean horizontal winds have been very weak, seem to be reasonable since development of convective cells can be expected in this area; (2) the constant $\nu_{th}$ of 1000 $\text{m}^2/\text{s}$ (Fig. 5(b)) has generated reasonable $U_2$ profile over the peninsula, although convective cells in inland have been smoothed out; (3) the horizontal diffusivity by Eq. (14) with $\alpha =$
Fig. 5. Horizontal cross sections of predicted mean vertical wind velocity, $U_v$ (cm/s), at $z = 150$ m at 1400LST in the cases of (a) H1, (b) H2, (c) H3, and (d) H4. See Table 3 for the cases.
Fig. 6. Vertical cross sections of predicted turbulent kinetic energy, $k$ (m$^2$/s$^2$), along A-A' in Fig. 1 at 1400LST in the cases of (a) H1, (b) H2, (c) H3, and (d) H4. See Table 3 for the cases.
0.72 (Fig. 5(c)) has produced good $U_0$ profiles in general, which show desirable characteristics over the peninsula and the inland area; and (4) use of Eq. (14) with $\alpha = 2$ (Fig. 5(d)) has resulted in overly smoothed profile of $U_0$ over the peninsula; this can be seen also in the vertical profile of $k$ in Fig. 6(d), showing no local maxima over the peninsula, which is totally different from Fig. 6(b) (case H2) and 6(c) (case H3). Figure 7 presents temporal change of spatial distribution, along A-A' line in Fig. 1, of $\nu_{th}$ by Eq. (14) with $\alpha = 0.72$ (Fig. 7(a)) and 2.0 (Fig. 7(b)). Maximum value of $\nu_{th}$ in case H3 in Fig. 7(a) is about 1400 m$^2$/s. On the other hand, that in case H4 is 4500 m$^2$/s, as shown in Fig. 7(b), which seems too large. The values of $\nu_{th}$ over the inland area, where mean horizontal winds are weak, are small in both cases.

Fig. 7. Temporal variations of the spatial distribution of horizontal eddy diffusivity calculated with Eq. (14), $\nu_{th}$ (m$^2$/s), along A-A' at $y = 14$ km and $z = 30$ m in Fig. 1 in (a) case H3 and (b) case H4.

CONCLUSIONS

Numerical experiments on the $k$-$\varepsilon$ turbulence model applied to sea breeze simulation have been performed; the study has tried to quantify a reasonable range of a model parameter, $c_{3\varepsilon}$, which controls buoyancy effect in the $\varepsilon$-equation. In addition, effects of formulation for horizontal eddy diffusivity on sea breeze simulation have also been tested. Conclusions are as follows:
(1) In the application of the $k-\varepsilon$ model to stratified mesoscale flow, much attention should be paid to the buoyancy term in the $\varepsilon$-equation.

(2) The parameter $c_{3\varepsilon}$ is better to be changed according to local thermal stratification; the preferred value of $c_{3\varepsilon}$ for sea breeze simulation may be 0 for unsuitable layer and 1 for stable layer.

(3) For horizontal grid size of 2 km, Eq.(14) with $\alpha = 0.72$ may be a good choice for sea breeze simulation; to set minimum value as 100 m/s will be preferable for the stability of numerical solutions with keeping the model's ability to reproduce convective cell structure in inland mixed layer where mean horizontal winds are weak.

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REFERENCES


1 Introduction

The assessment of radiological consequences resulting from accidental releases of a nuclear installation is based on the calculation of atmospheric transport of radionuclides. An intercomparison of the calculation procedure in Germany and France shows differences characterized as follows:

- the relevant guideline in Germany recommends usage of the Gaussian-plume-model and dispersion parameters derived from the dispersion experiments at the research centers of Jülich and Karlsruhe /BMU, 1989/

- official guidelines to calculate the radiological consequences do not exist in France. At the Institut de Protection et de Surete Nucléaire (IPSN) radiological consequence assessment can be done by using three different types of Gaussian based models (nomograms, plume- or puff-model), each of them with the dispersion parameters based on Douy (1976).

Under the mandate of the German-French Commission for nuclear safety aspects (DFK), an intercomparison of these two methods has been carried out in 1987. Source distances up to 20km and a continuous release have been considered. The results revealed differences which could be attributed to the different parametrizations of the dispersion parameters. In view to an accident at a nuclear power plant located near the French-German border, the application of both methods could yield different emergency actions in both countries, a situation which is scientifically and politically unacceptable. Therefore the advisory board of the DFK gave another mandate to review and update the methodology for calculation of atmospheric transport of radionuclides to come up with a calculation scheme for emergency actions which should be used in both countries.
In the following chapters the activities of a working group are summarized, starting with a description of different turbulence parameterization methods for Gaussian puff models. The results of the proposed models have been compared to different dispersion experiments as well as to calculations with the methods used in the past.

2 Update of the Modelling concepts

In October 1987 a workshop of the DPK (1988) dealt with a discussion of appropriate methods for calculating atmospheric dispersion for emergency actions focussing on source distances up to 20 km. The French and German participants agreed on the fact that a Gaussian-puff-model should be used to calculate the atmospheric dispersion following a nuclear accident. Different ways to determine the diffusion parameters have been discussed. A spectral approach has been favoured by the French side, while a combined similarity and convective scaling approach has been given preference by the German participants.

2.1 French approach

The French approach is based on considerations upon the turbulence spectra and relations between the spectra and the standard-deviations. Assuming the emission of successive puffs that we observe after a travel time t and during a sampling time T, the standard-deviation of the distribution of a pollutant is a combination of two phenomena: the relative diffusion of the puffs around their centers of mass, noted $\sigma_b$, and the dispersion of the centers of mass of the puffs, noted $\sigma_c$. The total standard-deviation $\sigma$ is the result of these two phenomena which are assumed to be uncorrelated:

$$\sigma^2 = \sigma_b^2 + \sigma_c^2$$  \hspace{1cm} (1)

The relative diffusion has been studied by Smith and Hay (1961):

$$\frac{d\sigma_b}{dt} = 4/3 \int_{0}^{\infty} F_b(n) \cdot \text{sinc}(2\pi nt/\beta) \cdot (1 - \exp(-(2\pi n\sigma_b/u)^2)) \cdot dt \cdot dn$$  \hspace{1cm} (2)

$F_b(n)$: Eulerian turbulence spectrum in terms of frequency $n$

$\beta$: variable relating the Lagrangian values to the Eulerian values where $\text{sinc}(a) = \sin(a) / a$

$u$: characteristic velocity of the scale of turbulence considered

The second type of diffusion is based on Taylor's formulation (1921):

$$\sigma_c^2 = \frac{\tau}{3} \int_{0}^{\infty} F_c(n) \cdot \text{sinc}^2(\pi nt/\beta) \cdot (1 - \text{sinc}^2(\pi nT)) \cdot \exp(-(2\pi n\sigma_c/u)^2) \cdot dn$$  \hspace{1cm} (3)

In order to solve the equations of $\sigma_b$ and $\sigma_c$, it is necessary to choose $F_b(n)$ and $\beta$. The turbulence spectrum is considered as made of two parts /Crabol, 1979 and 1985/. One part is called "Small Scale Turbulence" corresponding to high frequencies, which are linked to the mechanical and thermal tur-
bulence generation in the lower part of the planetary boundary layer. The other one is called "Large Scale Turbulence" and corresponds to low frequencies being specific of the lower troposphere.

For the description of the high frequency region the empirical formulations of spectra found in the literature have been adopted /horizontal direction and stable stratification: Olesen et al., 1984, eq. 15-17; vertical direction and stable stratification: Busch and Panofsky, 1968, eq. 7 and 12; horizontal direction neutral and unstable stratification: Hojstrup, 1981 in Panofsky and Dutton, 1984, ch. 8.4, eq. 13; vertical direction neutral and unstable stratification: Hojstrup, 1981 in Panofsky and Dutton, 1984, ch. 8.4, eq. 8/: the energy spectra are functions of the friction velocity $u_z$, the boundary layer height $h$, the height $z$ in the atmosphere, the mean velocity of the wind $u(z)$, the roughness length $z_0$ and the Monin-Obukhov length $L$.

In the low frequency region and in the horizontal direction the van der Hoven spectrum /van der Hoven, 1957/ has been adopted up to now. The low frequency part of the spectrum is assumed to be independent of meteorological conditions. For travel times relevant in the dispersion experiments analysed in chapter 3, the low frequency part of the vertical turbulence spectrum has only little influence on the evolution of the dispersion parameters. Therefore no further characterization of the low frequency spectrum will be given here.

Because of the similarity between the Eulerian and Lagrangian velocity correlations $R_x$ and $R_y$, a connection between them may be expressed /Hay and Pasquill, 1959/ as:

$$R_y(t) = R_x(t) \quad \text{with} \quad \tau = \beta t \quad \text{or} \quad F_y(n) = \beta F_x(\beta n)$$

The value of the parameter $\beta$ is assumed to be a function of the frequency and of the atmospheric stability /Smith, 1968/ and is drawn from the literature /Solot and Darling, 1958, Kao, 1958/ (large scale of turbulence $\beta=0.5$; small scale of turbulence $\beta=2$ for unstable stratification, $\beta=4$ for neutral stratification and $\beta=6$ for stable stratification).

2.2 German approach

The German parameterization of the atmospheric turbulence is a hybrid approach of surface layer similarity and convective scaling. Within this approach the turbulent time scale and the turbulent fluctuations are only functions of the friction velocity $u_z$, the convective scaling velocity $w_0$, the boundary layer height $h$, and the height $z$ in the atmosphere:

$$T_u = g(u_z, w_0, z, h) \quad \text{characteristic time scale} \quad (4)$$

$$u^{12} = f(u_z, w_0, z, h) \quad \text{variance of wind speed component} \quad u \quad (5)$$

The characteristic time scales for neutral and unstable atmospheric stability can be determined using the formula:

$$T_{u,u,v} = u_{0.5} h / \sigma_{u,v} h_u(z/h) \quad (6)$$
with $a_u = a_v = a_w = 0.17$ following Hanna (1981),

where $h_v(z/h)$ expresses a height dependance for the vertical time scale /Janicke, 1987/. The corresponding standard deviations $\sigma$ of the velocity components $u, v,$ and $w$ can be expressed as:

$$\sigma_{u,v,w} = \left( \left(b_{u,v,w}u, \right)^n + \left(c_{u,v,w}w, \right)^n \right)^{1/n} h_v(z/h)$$

(7)

Based on /Janicke, 1987/ with $n=3$ one gets $b_u = 2.5$, $b_v = 2.0$, $b_w = 1.3$ and $c_u = 0.73$, $c_v = 0.58$, $c_w = 1.38(z/h)^{**1/3}$.

We have found a lot of different values for the coefficients $a_{u,v,w}$, $b_{u,v,w}$ and $c_{u,v,w}$ in the literature. However the differences are seldom larger than 10%.

In a stable atmosphere ($w$ equals zero) the variations of the coefficients among different authors are more pronounced than in a neutral or unstable atmosphere and all parameters show a height dependance. The same values for the coefficients $a_{u,v,w}$ and $b_{u,v,w}$ as for an unstable stratification have been applied.

Implementing such parameterizations in a Gaussian-puff-model (RIMPUFF /Mikkelsen et al., 1984/) the height dependance is neglected and $\sigma = \sigma_v$ has been assumed. The necessary horizontal ($h$) and vertical ($z$) dispersion parameters are calculated according to

$$\sigma_{h,z} = \sigma_{v,w} t / (1 + 0.5 t / T_{v,w})^{1/2}$$

(8)

with $t$ equal to the travel time of a puff. With the formulas (6) - (8) dispersion parameters for averaging times of the meteorological input data of 0.5 - 1 hour can be calculated. This averaging time limits their applicability to emission times of 0.5h and longer. Correction factors have to be applied for shorter emission durations.

The input parameters of this method can be calculated using a meteorological preprocessor and site specific data like roughness length, emission height and observed meteorological data.

3 Comparison of the parameterization schemes

The methods of turbulence parameterization described in the preceding chapter have been compared for typical meteorological conditions of French and German sites, averaging times of the meteorological parameters of $T = 0.5h$, and travel times $t$ up to some 1000 s. For source heights ranging from 10m to 180m above the ground and under unstable and neutral atmospheric stability both methods show similar results. Typical deviations between the dispersion parameters are in the order of some 10%. Under stable conditions, however, the horizontal dispersion parameters derived from the spectral approach are much larger than the dispersion parameters calculated by the similarity method. These differences can be attributed to the
large scale part of the turbulence spectrum (e.g. meandering of the windfield) which is not included in the similarity approach. Excluding the large scale part from the turbulence spectrum the spectral theory yields dispersion parameters comparable to the similarity approach.

The decision whether these updated modelling techniques are superior to those used in the past could be supported by a comparison with dispersion experiments. Some of the dispersion experiments carried out at the Karlsruhe Nuclear Research Center (KfK) and experiments under low wind speed conditions performed by the NOAA at Oak Ridge, Tennessee have been chosen for this purpose. For both experimental series the measured and calculated time integrated surface concentrations have been compared using different performance measures (Chi-square, relative Chi-square, scatterplot of measured and calculated concentrations, mean error factor, cumulated frequency distribution of the ratio of measured and calculated time integrated concentrations and a bootstrap method following Hanna (1989). For short only the intercomparison of the models with the data of the KfK-experiments will be reported in this paper. The results of the intercomparison of the spectral approach with NOAA-data will be published in a forthcoming report (Romeo, 1991).

Thomas and Nester (1985) have summarized the results of the tracer experiments at the Karlsruhe Nuclear Research Center. The test field consisted of open spaces and built-up as well as wooded areas. The dispersion experiments comprised source heights of 60, 100, 160, and 195m. Besides the measured concentrations and the emission data comprehensive information about the meteorological conditions up to a height of 200m has been available. During most of the experiments two tracers have been released from different heights in several time intervals. The sampling time has been 0.5h. For 39 sampling periods the old and new modelling approaches have been compared with the measurements.

Generally the application of the above mentioned performance measures result in a similar rating of the ability of a model to calculate tracer distributions specific for each dispersion experiment. Typical examples of the performance of the new parametrization techniques can be given by an intercomparison of measured and calculated time integrated tracer-concentrations for 60m emission height. The dispersion experiments have been grouped in 3 different stability regimes (unstable - diffusion categories A and B, neutral - diffusion categories C and D, stable - diffusion categories E and F). Only those receptor points have been retained in the datasets where the measured tracer concentrations exceed 1% of the maximum concentration detected during each experiment. The resulting datasets comprised 112 to 167 receptor points per stability regime. They have been evaluated using the bootstrap resampling method described (Hanna, 1989). As performance measures the fractional bias (FB) and the normalized mean square error (NMSE) have been used, the first giving an estimate of the models ability to describe high concentration values, the latter one as a global indicator for the scatter between observations and predictions. Means and confidence intervals of the two performance measures have been calculated. The results are summarized in fig. 1 and 2. The evaluation of the experiments
during stable stratification has been omitted due to large deviations between modelled and measured data.

\[ FB = \frac{2(C_o - C_p)}{(C_o + C_p)} \]

\( C_o \): observed concentration
\( C_p \): calculated concentration

![Fractional bias (FB) and confidence limits](image)

**Fig. 1:** Fractional bias (FB) and confidence limits (95%-percentile) between measured and calculated concentration data at Karlsruhe Nuclear Research Center for 60m emission height (Si = similarity approach, Sp = spectral approach, BMU = German Guideline /BMU 1989/)

\[ NMSE = \frac{(C_o - C_p)^2}{C_o \times C_p} \]

\( C_o \): observed concentration
\( C_p \): calculated concentration

![Normalized mean square error (NMSE) and confidence limits](image)

**Fig. 2:** Normalized mean square error (NMSE) and confidence limits (95%-percentile) between measured and calculated concentration data at Karlsruhe Nuclear Research Center for 60m emission height (Si = similarity approach, Sp = spectral approach, BMU = German guideline /BMU 1989/)

The evaluation of the experiments under unstable and neutral conditions shows that both new approaches give better results than the model of Doury. The similarity approach and the spectral approach implemented in a puff model give results of the same quality than the calculations with the Gaussian-plume-model /BMU, 1989/. In contrast to the plume model - using dispersion parameters which have partly been deduced from the KPK-experiments - the new approaches work on the basis of turbulence parametrizations which use only site specific topographical and meteorological information.

However for stable stratification both new techniques fail in the prediction of the concentrations. During most of the experiments under stable conditions broad distributions of tracer concentrations have been observed at ground level. This plume geometry could not be reproduced by similarity or spec-
tral approach. Additional calculations with the puff model using actual turbulence information in emission height (horizontal and vertical wind direction fluctuations as detected by vector wind vanes) or wind shear information using a Lagrangian particle model did not yield to better results. Mesoscale circulation systems like meander - attributable to the large scale turbulence - have often been reported as a mechanism for broadening of tracer plumes. They can be excluded as a reason for the resulting concentration field because time dependent wind direction data have been used for the dispersion calculations. No large scale periodicity could be detected in the time series of the wind direction in 60m height above the ground. We assume that under stable stratification local flows have developed near the ground (due to the inhomogeneity of the experimental area and the slightly uneven terrain) which are responsible for the detected broad concentration distributions.

4 Conclusions

It can be summarized that the simulations with the similarity approach and the spectral theory show a slightly better agreement to the measured concentration data than the schemes used in the past. Both approaches only use site specific meteorological data to calculate the necessary input parameters by conventional boundary layer theory. The mean advantage as compared to the older schemes is the independency from the experiments analysed. The dispersion parameters can easily be drawn from temperature gradient and wind speed measurements. They allow a continuous characterization of the atmospheric dispersion independent of diffusion categories.

The spectral approach incorporates the sampling time of the meteorological data as an adjustable parameter. This allows an adjustment of the dispersion model to different emission scenarios (short puff release, continuous plume release). Therefore this turbulence parameterization scheme will be foreseen as the basis for a joint French-German puff model.

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Influence of horizontal grid resolution on simulated wind and pollution concentration field in the Greater Athens Area

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ABSTRACT

In this paper the non–hydrostatic mesoscale model MEMO, which has been developed at the University of Karlsruhe, is applied to simulate the sea/land breeze circulation in the Greater Athens Area. In contrary to previous studies with the model for this area (Flasak and Moussiopoulos [1], Flasak [2]), the aim of this paper is to investigate the dependence of the numerical result on the horizontal grid resolution. Three different horizontal resolutions with a grid spacing of 4 km, 2 km and finally of 1 km are chosen which lead to 18×24, 36×48 and 72×96 horizontal grid points. In addition to wind field simulations, the dispersion of a pollutant, in this case of CO which is treated as non–reactive, is simulated at the three resolutions.

INTRODUCTION

For dispersion simulations of air pollutants the knowledge of the three–dimensional and time–dependent wind field is a prerequisite. To generate the wind field, in the last decade a lot of work has been done in the development and improvement of prognostic wind models which in principal solve the conservation equations for momentum, mass and energy numerically. Additionally, with the availability of extremely powerful supercomputers like the SIEMENS S 600/20 high resolution numerical wind field as well as dispersion simulations can be performed providing a more and more realistic view inside of the three–dimensional and time–dependent physical processes.

Aim of this paper is to investigate the dependence of simulated wind and concentration fields on the horizontal grid resolution. After a brief description of our prognostic wind model MEMO, simulated wind fields for the Greater Athens Area obtained from model runs with 4 km, 2 km and finally 1 km horizontal grid resolution are given. On the basis of those wind fields the dispersion of CO is computed with an Eulerian grid model. Results of those simulations are presented in the last section of this paper.
Figure 1. Topography in the Greater Athens Area. Altitude isopleths are contoured at 100 m, residential areas are stippled, industrial areas in the Athens basin and in the Thriassio plain are solid; the framed square corresponds to the domain shown in Fig. 3; in later sections results are given for the locations 'C' (sea adjacent to the coast), 'U' (urban) and 'S' (suburban).

MODEL DESCRIPTION

In this section only a brief description of our non-hydrostatic mesoscale model MEMO is given. More details can be found elsewhere (Flasak [2], Flasak and Moussiopoulos [3]). Within MEMO, the conservation equations in the atmosphere for momentum, mass and scalar quantities as potential temperature, turbulent kinetic energy and specific humidity are solved numerically. The presented results are obtained with the model version using the Boussinesq approximation. For the calculation of the turbulent diffusion K-theory is applied. The exchange coefficients for momentum and scalars are computed with an one-equation turbulence model (1 PDE for the turbulent kinetic energy, algebraic equation for the mixing length). At roughness height $z_0$ similarity theory is applied where $u^*$ and $\theta^*$ are calculated from the Businger equations.

The governing equations are solved in terrain-following coordinates. Non-equidistant grid spacing is allowed in the vertical and also in the two horizontal directions. Within the transformed coordinates, Cartesian momentum components are kept but derivatives are computed from the transformed coordinates (Clark [4]). Divergence operator and pressure gradient contain only pure differential quotients rather than products of metric coefficients and differential quotients. As a consequence, mass and momentum conservation is guaranteed within the discrete model equations.
The model MEMO includes an efficient numerical scheme for the calculation of the atmospheric radiative heating/cooling rates and of the radiative fluxes at ground level for both clear and polluted or cloudy atmosphere (Moussiopoulos [5]). The land surface temperature is computed from the surface heat budget equation. For the calculation of the soil temperature, an one-dimensional heat conduction equation for the soil is solved. Water temperature is kept constant during a simulation.

MODEL APPLICATION

The non-hydrostatic mesoscale model MEMO was applied to simulate the sea/land breeze circulation in the Greater Athens Area (GAA). Athens with a population of 3.5 million inhabitants is located in a basin of approximately 450 km² and is surrounded by mountains on three sides and the sea on the fourth.

The simulations were performed for a 48 hours period starting at midnight. The synoptic wind \((u_x=+0.5 \text{ m/s}, \ v_x=-1 \text{ m/s})\) was kept constant during the whole simulation and was used to initialize the velocity field with a mass consistent wind field model. At time zero, the atmosphere was considered to be neutrally stratified \((\theta = 297 \text{ K})\) up to 500 m. Above 500 m a stable stratification \((\partial \theta / \partial z = 3.5 \text{ K/km})\) was assumed.

For the calculation of the wind field a modeling domain of 72×96×6 km was chosen. Three different horizontal resolutions with a grid spacing of 1, 2 and 4 km lead to 72×96, 36×48 and 18×24 horizontal grid points. In the vertical direction the grid consists of 35 layers and is non-equidistant with a minimum grid spacing of 20 m near the ground. The timestep is given in Table 1. Calculations were performed on the vector processor SIEMENS S600/20 with 1GByte core memory and a peak performance of 5 GFlops. Memory demand and the ratio of simulation time to computer time are shown in Table 1.

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<th>(\Delta t)</th>
<th>(t_{\text{sim}}/t_{\text{com}})</th>
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RESULTS

In the following subsection we present surface wind fields at different times elucidating the sea/land breeze in the GAA. Subsequently, we
discuss how the numerical resolution affects the wind fields. The influence of the horizontal resolution on dispersion modeling is given in the last subsection.

**The sea/land breeze circulation in the GAA**

Figs 2a–d show the surface wind field (approximately 10 m AGL) of Run 3 (72×96×35 grid points) at 0600, 1200, 1800 and 2400 LST on the 2nd day of the simulation. For reasons of clearness, in these pictures only one fourth of the vectors are plotted and 16 km of the southern part of the computational domain are truncated.

![Diagram showing wind field at different times](image)

**Figure 2.** Computed horizontal wind field at high resolution (Run 3) in the lowermost computational layer (approximately 10 m AGL) at 0600, 1200, 1800 and 2400 LST on the 2nd day of the simulation (only one fourth of the wind vectors are shown; altitude isopleths are contoured at 200 m).
At night the temperature over land is lower than over the sea. This induces an off-shore flow near the ground, the land breeze. Over a sloped surface this circulation system is enhanced: The air temperature close to the ground is lower than the air temperature at the same elevation but away from the surface. This results in downslope mountain winds. The combined effect of downslope mountain wind and the land breeze is evident in the wind pattern at 0600 LST (cf Fig. 2a). During daytime the inverse situation occurs: As the temperature over land is higher than over water, a sea breeze develops. In addition, valley winds occur: Air adjacent to the mountain slopes is warmer than air at the same height in the atmosphere; this causes a pressure gradient toward the mountain slope near the ground. As shown in Fig. 2b, the combined sea breeze and valley wind system is fully developed at 1200 LST. Because of the strong vertical mixing during daytime the induced circulation system is much stronger than the inverse nighttime effect. At 1800 LST (Fig. 2c) the surface temperature has already exceeded its maximum value; consequently, the intensity of the sea breeze is decreasing. Between 1200 LST and 1800 LST the wind direction is nearly constant. As shown in Fig. 2d, at midnight the nighttime pattern is almost reestablished.

Influence of the horizontal resolution on the wind field
Simulations with a horizontal resolution of 1, 2 and 4 km have been performed (cf. Table 1). Surface wind fields for these three runs at 0600 and 1200 LST on the 2nd day of the simulation are shown in Fig. 3. In this figure only a subdomain is shown (cf. Fig. 1).

Comparing the flow pattern qualitatively, it could be stated that even the coarse grid simulation (Run 1, Δx = 4 km) resolves the main features of the sea/land breeze in Athens. However, the medium and high resolution runs additionally produce small scale structures which are not resolved at low and medium resolution, respectively. The differences mainly occur above the mountain slopes and their surroundings as can be seen for instance at 0600 LST above Mount Aegaleon, west of Athens. During daytime the flow converges above the summit of the mountains. At this location the upward velocity is strongly dependent on the numerical resolution, the highest values being calculated at high resolution.

Differences in the three runs occur because the model 'sees' at the three resolutions different topographies (e.g., steeper mountains with increasing resolution, a different coast line and also a different land use which causes differences in the surface temperature computed from the non-linear heat budget equation). Also a different numerical resolution affects the non-linear advection of momentum and the amount of numerical diffusion which is dependent on the grid spacing.

Dispersion modeling at different horizontal resolutions
To elucidate the influence of different resolutions in the wind field on dispersion modeling, transport and turbulent diffusion of a pollutant, in this case of CO, is calculated with an Eulerian grid model. In the GAA, CO is emitted almost only by motor vehicles. For this calculation, CO is considered as non-reactive. This assumption has been proofed by per-
Figure 3. Computed horizontal wind field at low, medium and high resolution (Run 1-3) in the lowermost computational layer (approximately 10 m AGL) at 0600 and 1200 LST (Altitude isopleths are contoured at 100 m).
forming calculations with a dispersion model for chemically active species (Moussiopoulos [6], cf. also Moussiopoulos et al. [7]): For these time and length scales, diurnal cycles of the CO—concentration treating CO as reactive differ only slightly from corresponding cycles, where CO was considered as inert.

For this simulation a yearly emission of 437.9 kt/a was assumed which is an estimate for 1990. Available emission data were used to compile an emission inventory with a horizontal resolution of 1 km. The normalized spatial distribution and the non—dimensional diurnal emission rate in Athens are shown in Figs 4 and 5. The runs with the dispersion model are performed with the same number of grid points as given in Table 1. Surface concentration fields calculated at low, medium and high resolution at 0600 and 2400 LST on the 2nd day of the simulation are shown in Fig. 6. Additionally, diurnal cycles of the surface CO—concentration at the locations 'C', 'U' and 'S' (cf. Fig. 1) are given in Fig. 7.

At 0600 LST the influence of the prevailing land breeze is dominant advecting emitted CO toward the sea in southern directions. At high resolution, parts of CO are advected to the north and south of Mount Hymettos toward the Mesogia Plain. At medium resolution, the advection process only occurs to the north of Mount Hymettos and at low resolution this transport paths are not resolved. At 2400 LST also differences in the surface concentration are evident: At high resolution, to the south of Mount Aegaleon, CO is advected rather to the west than to the southwest as in the two other runs. This results in a pronounced peak in the diurnal cycle of the high resolution run at the coast point 'C' around midnight (cf. Fig. 7c).
Figure 6. Computed CO-concentration field at low, medium and high resolution in the lowermost computational layer (approximately 10 m AGL) at 0600 and 2400 LST.
Figure 7. Diurnal cycle of the CO-concentration at location 'C', 'U' and 'S' in a height of 10 m AGL at (a) low, (b) medium and (c) high resolution.

In all three runs, at point 'U' the computed daily cycles of the surface CO-concentration show the typical peaks which normally can be detected on monitored daily cycles of the downtown surface CO-levels under sea breeze conditions. However, at low, medium and high resolution, differences in the CO-levels are evident which do not have a systematic trend (i.e. lowest peak value in the morning hours at medium resolution).

CONCLUSIONS

In this paper the wind field and subsequently the dispersion of CO (considered as non-reactive) in the Greater Athens Area (modeling domain: 72×96×6 km) were simulated at different horizontal resolutions (1, 2 and 4 km leading to 18×24, 36×48 and 72×96 horizontal grid points). Although the low resolution wind field simulation shows the major features of the sea/land breeze circulation, at medium and especially at high resolution additionally small scale wind pattern are resolved which cause not negligible differences in the concentration field and should be taken under consideration as an intrinsic error when comparing computed and measured concentration values. The obtained ratio of simulation time to computing time of the high resolution run reveals that, if the code is well structured and efficient algorithms are applied as it is done in the non-hydrostatic mesoscale model MEMO, meanwhile such simulations can be performed at a reasonable computing time.

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SECTION 4:
EMISSION CALCULATIONS AND IMMISSION PREDICTIONS FOR THESSALONIKI
Industrial Emissions of Air Pollutants in Thessaloniki

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ABSTRACT

Industrial activities and road traffic cause the vast majority of the pollutant emissions in the Greater Thessaloniki. The present paper deals with the industrial emissions. With the exception of three large emission sources, which are considered as point sources, industrial pollution sources are assumed to constitute area sources. In the case of the latter emission rates are calculated from fuel consumption data and suitable emission factors.

INTRODUCTION

Thessaloniki, the capital of Macedonia, is the second largest city in Greece with a population of about one million. As in many other Mediterranean urban areas, air quality in the Greater Thessaloniki Area (GTA, Fig. 1) is rather poor because of the high levels of anthropogenic air pollutant emissions.

In Greece emissions of air pollutants are traditionally classified into three main categories, heating, traffic and industry, the latter including major production plants as well as smaller units closely related to commercial consumption (e.g. bakeries, small factories, laundries, paint shops). In this sense, the vast majority of the emissions in the GTA are associated with the heavy traffic and with the manifold industrial activities in the area.

Figure 2 shows the annual emissions rates of major polluters in the GTA for all types of air pollution sources. As expected, industrial sources are characterized by high SO₂ emissions, while traffic leads to high emissions of the photosmog precursors (i.e., NOₓ, VOC and to a lesser extent CO).

Industrial activities are concentrated in the periphery of the GTA. The largest plants are located in the regions of Sindos, Kalohori, Diavata and Efkarpia. Smaller units operate also at Asvestohori, Thermi, Mihaniona and Vassilika (Fig. 1).
Figure 1. Map of the Greater Thessaloniki Area (GTA). The residential area is stippled, zones with industrial activities are marked. A, B and C represent the three major industrial air pollution sources in the GTA.

METHODOLOGY

In the following we present the emissions of NO\textsubscript{x}, VOC, CO, SO\textsubscript{2} and TSP (total suspended particles) from industrial activities in the GTA. Emission calculations are based on data valid for 1990 which were collected by the Organization of Thessaloniki\textsuperscript{1}. All data were elaborated on a 1 km x 1 km grid. In view of the different nature and precision of the original data, various diurnal variation functions were applied to achieve a temporal resolution of 1 hour.

With the exception of the three largest industrial air pollution sources, for which emission data are directly available, industrial pollution sources are considered in this study to constitute area sources, the emission of the latter being derived from fuel consumption data and suitable emission factors. The former may be related to usually available production data. An alternative treatment for the area sources, would be to estimate emissions
from yearly production data for entire branches and emission factors per unit of the goods produced. As no relevant information is available to estimate the latter, however, this approach is not followed in the present study.

EMISSION DATA

Fuel consumption
Figure 3 shows the geographical distribution of fuel consumption in the aforementioned industrial zones of the GTA. The consumption is given in tonnes per year and includes all types of fuel used in industry. The largest fuel consumption appears at the Western part of the Thessaloniki agglomeration, particularly at Diavata, Sindos and Kalohori. This agrees with the fact that the main industrial activities in the GTA take place just in this region.

The fuel consumption share into different industrial branches is given in Fig. 4. Apparently, large fuel quantities are consumed by the food and drink plants, followed by the fibres industry.

Point sources
As already mentioned, there are three major air pollution sources in the GTA: A refinery (A), a cement factory (B) and a large chemical plant (C). The location of these pollution sources is marked in Fig. 1. Their emission rates are presented in Fig. 5. A and C are characterized by high SO$_2$ emissions (up to 11 kt y$^{-1}$) and B from its NO$_x$ emission of 1.3 kt y$^{-1}$.

![Diagram](image_url)

Figure 2. Emissions of the major air pollutants from heating, traffic and industry in the GTA.
Figure 3. Fuel consumption in the industrial zones of Thessaloniki.

Figure 4. Share of the fuel consumption in the GTA.
Figure 5. Emissions of major air pollutants by the three largest industrial point sources in the GTA.

Figure 6. Emission factors used in the present study for the most common fuel types in the GTA.
Figure 7. Seasonal variation of the consumption of diesel oil and residual oil types in the GTA.

Figure 8. Emissions of major air pollutants by industrial point and area sources in the GTA.
Area sources
In the case of the industrial area sources in the GTA, emission rates are obtained by multiplying fuel consumption and suitable emission factors for all industrial branches and every type of fuel used. As the fuel consumption is concerned, information is required on its purpose (e.g. heating, production) and its diurnal variation for each category of industry. Emission factors, on the other hand, represent the average quantity of individual pollutants emitted from one specific source per unit mass of the fuel consumed. It should be noted that the emission factors depend on both the combustion procedure and the fuel type.

The most common types of fuels used by the industry in the GTA are residual oil 3500, residual oil 1500 and diesel. The code numbers 3500 and 1500 are related to the sulphur content of these types of fuel. Figure 6 shows the emission factors used in this study for these fuel types. These values were initially proposed by the U.S. Environmental Protection Agency. Diesel has the lowest emission factors for all pollutants except CO. Correspondingly, the use of diesel instead of residual oil may result in substantial reductions of the emission rates from industrial activities. The potential for a rigorous substitution of residual oil by diesel is considerable in view of the current consumption rates (diesel 11.1 kt/a, residual oil 1500 40.2 kt/a and residual oil 3500 56.2 kt/a).

Interestingly, the consumption of diesel and residual oil 3500 undergoes almost no changes during the year, while that of residual oil 1500 has its maximum in summer (more precisely, August and September, cf. Fig. 7). This behaviour is due to the high consumption of residual oil 1500 by the food industry.

DISCUSSION
The resulting emission rates of industrial area sources are shown in Fig. 8 compared with those of the three major point sources. Apparently, the latter cause a significant part of the overall industrial emissions in the GTA.

Contrary to the emission data from the three major industrial plants, the emission rates from the remaining industrial activities represent rather crude estimates in view of the uncertainties of the raw data used for their calculation. The systematic collection of more reliable raw data and, by their aid, the compilation of a complete emission inventory for the GTA are aims of our ongoing research work.

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REFERENCES
Traffic Conditions in the Urban Area of Thessaloniki as Input to Emission Models

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ABSTRACT

Traffic load data were available from 150 measuring stations, distributed over the city area and covering both main and secondary roads. The significance of each road was determined, based on these data. A road sample for speed recordings was selected, presenting an accumulative significance of 80%. Speed was recorded on real time basis over a total distance of 1500 km, travelled on the sample roads. Recordings were evaluated, using the least squares method, and the driving patterns of the individual roads as well as of the city as a whole were derived on one hour as well as on 24 hours basis. At this stage of the study, only the influence of the mean speed of the driving patterns is taken into account in determining the emission factors of the gasoline powered passenger cars.

INTRODUCTION

Emission modelling of urban areas requires an as accurate as possible knowledge of all input data. Among them traffic generated emissions are included, since traffic is one of the major contributors in atmospheric pollution of urban areas.

Traffic generated emissions are depended on the number of vehicles operating in the study area, on the emission factors of the vehicles and on the mean travelled distance in the unit of time.

Emission factors are strongly depended on the way the vehicles operate, i.e. on the driving pattern of the area or of the individual roads. In order to develop
the required driving patterns, real time speed recordings and proper evaluation is required.

This paper presents the methodology used to derive the driving patterns of Thessaloniki area both as an average over the year and as a function of the hour of the day.

ROAD SAMPLE FORMATION

Traffic load data were available from 150 measuring stations, distributed all over the city; evidently on the more loaded roads, both main and secondary. These data were provided by the relevant state agency and they were giving the number of vehicles passing the measuring station per hour. There were two to four measurements from each station per year.

It was assumed that the traffic load, as measured at each station, remains constant over a certain length of the road, the length depending on the number of the road crossings and the nature of the crossing roads (one or two way roads, main or secondary roads etc.)

The quantities "circulation of the road" and "significance of the road" were defined. Circulation was defined as the total traffic load of the road over the day times the length of the road for which the load was assumed to remain constant. Significance was defined as the circulation of the road divided by the sum of circulations of all the roads for which traffic load data were available. This implies the assumption that these roads handle the total traffic of the city area. The assumption is justified, since traffic load data were collected for the roads evidently most contributing to the total traffic of the city.

The most significant roads of the area formed the road sample for real time speed recording. Selection was based on the significance of each road. The cumulative significance of the sample was 80%.

The length of the recordings on each road was also based on the significance of the road. This allows to consider all recordings as equivalent. The total recording length on each road was distributed over the day, distribution based on the traffic load per hour as a percentage of the total load of the road.

63 roads or parts of roads formed the speed recording sample, as a result of the above described road sampling procedure. They covered more or less the entire city area, with an increased density in the city centre. This of course was expected, since the major part of the traffic is concentrated in this area.
SPEED RECORDING EQUIPMENT

The mean gasoline passenger car operating in Thessaloniki area was proved to be equipped with a 1224 cc engine (Pattas, Kyriakis [1]). In order to avoid significant differences in accelerations, imposed by significant differences in engine power, the vehicle chose for speed recordings was the SEAT Credos 1200 cc.

The travelling speed was measured, using an electronic speed sensor. The analog signal from the sensor was converted to digital, using an appropriate A/D converter, and stored (in km/h) on the 3 1/2" floppy disk of the on-board the vehicle computer (IBM XT compatible). Speed sampling frequency was 2 Hz, using the computer build-in clock for timing.

Figure 1 illustrates a part of a typical speed recording.

![SPEED RECORDING](image)

Figure 1: Part of a typical speed recording.

RECORDING EVALUATION

Evaluation of the recordings is based on the "motion module", which is defined as the time history of the speed between two successive stops of the vehicle, the initial idling included. Each motion module is linearised, using the least squares method. After linearisation the motion module can be described with five characteristic quantities: (a) the total duration of the module [s], (b) the idle duration of the module [s], (c) the constant acceleration [m/s²], (d) the constant speed [km/h] and (e) the constant deceleration [m/s²].

The linearisation was decided in order to produce driving patterns with the shape of the ECE 15, for comparison reasons.
Figure 2: The modules of the recording of Figure 1 after linearisation.

Figure 2 illustrates the two modules recognised in the recording of Figure 1 as they are linearised.

In order to take into account the parts of the recordings that started and/or ended with a speed different than zero, as the one of Figure 1, the recordings were extrapolated as needed, until zero speed.

**TRAFFIC LOAD TIME DEPENDENCE**

From the available traffic load data, mean values were calculated, Figure 3. It can be seen that during the hours 8 - 21 the mean traffic load of the city remains almost constant at a value of about 1200 vehicles per hour and lane. This time zone (Zone A) can be considered as the high traffic load zone of the city.

During the hours 1 - 5 the traffic load varies from 200 to 500 vehicles per hour and lane, with a mean value of about 350 vehicles. It can be assumed that this reduced load generally does not affect traffic conditions. This time zone can be considered as the low load zone (Zone B).

The rest hours of the day form the transient zone (Zone C), with intermediate traffic load.

Since traffic load can be considered as constant during time Zones A, B and C, it is reasonable to assume that traffic conditions, and consequently the driving patterns, remain relatively constant within each Zone as well.
Figure 3: Time dependence of the traffic load in Thessaloniki urban area.

DRIVING PATTERN DEVELOPMENT

In order to derive the mean driving pattern of the city as a whole all over the year, the total of the linearised modules were sorted, according to the value of the constant speed. They were then divided in three equally populated groups and average values for the five characteristic quantities of the modules were calculated. The city driving pattern consists of the modules formed by these average values.

The resulting THESS 89 driving pattern is shown in Figure 4, together with the ECE 15. It can be seen that even though constant speeds are more or less the same in the two driving patterns, THESS 89 has less idling, less total duration and steeper accelerations and decelerations. This results in an increased mean speed, as can be seen in Table 1, where the two driving patterns are compared.

Using the same procedure, but choosing only the linearised motion modules encountered on a specific road, the mean driving pattern of the road can be obtained. Table 2 presents a comparison between the two faster and the two slower roads of the sample.

By selecting the modules identified in the city during each of the time Zones A, B and C, it is possible, using the same algorithm, to develop the city driving
pattern for each Zone. Table 3 presents the basic characteristics of the three driving patterns, compared to those of the THESS 89.

![THESS 89 and ECE 15 Driving Patterns](image)

**Figure 4:** The THESS 89 and the ECE 15 driving patterns.

**Table 1:** Comparison between THESS 89 and ECE 15 driving patterns.

<table>
<thead>
<tr>
<th></th>
<th>Units</th>
<th>THESS 89</th>
<th>ECE 15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pattern distance</td>
<td>m</td>
<td>1209.0</td>
<td>1013.0</td>
</tr>
<tr>
<td>Pattern duration</td>
<td>s</td>
<td>177.0</td>
<td>195.0</td>
</tr>
<tr>
<td>Idle participation</td>
<td>%</td>
<td>24.1</td>
<td>30.8</td>
</tr>
<tr>
<td>Acceleration</td>
<td>%</td>
<td>13.7</td>
<td>22.6</td>
</tr>
<tr>
<td>Participation</td>
<td>%</td>
<td>11.6</td>
<td>17.4</td>
</tr>
<tr>
<td>Const. speed</td>
<td>%</td>
<td>50.7</td>
<td>29.2</td>
</tr>
<tr>
<td>MEAN PATTERN SPEED</td>
<td>km/h</td>
<td>24.6</td>
<td>18.7</td>
</tr>
</tbody>
</table>

**Table 2:** Main characteristics of the two faster and two slower roads of Thessaloniki area.

<table>
<thead>
<tr>
<th></th>
<th>Units</th>
<th>FAST 1</th>
<th>FAST 2</th>
<th>SLOW 1</th>
<th>SLOW 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>LENGTH</td>
<td>m</td>
<td>5508.00</td>
<td>4808.00</td>
<td>519.00</td>
<td>430.00</td>
</tr>
<tr>
<td>TOTAL DURATION</td>
<td>s</td>
<td>433.00</td>
<td>380.00</td>
<td>137.00</td>
<td>147.00</td>
</tr>
<tr>
<td>IDLE PARTICIPATION</td>
<td>%</td>
<td>11.50</td>
<td>17.10</td>
<td>32.10</td>
<td>51.70</td>
</tr>
<tr>
<td>MEAN SPEED</td>
<td>km/h</td>
<td>45.80</td>
<td>45.60</td>
<td>13.60</td>
<td>10.50</td>
</tr>
<tr>
<td>MAX. SPEED</td>
<td>km/h</td>
<td>71.10</td>
<td>75.10</td>
<td>30.80</td>
<td>37.50</td>
</tr>
<tr>
<td>MAX. ACCELERATION</td>
<td>m/s</td>
<td>1.21</td>
<td>0.95</td>
<td>1.25</td>
<td>1.37</td>
</tr>
<tr>
<td>MAX. DECELERATION</td>
<td>m/s</td>
<td>1.62</td>
<td>1.73</td>
<td>1.14</td>
<td>0.87</td>
</tr>
</tbody>
</table>

It is clear that traffic load significantly affects the mean speed of the pattern as well as the idle participation. But the factor of 6 observed between maximum...
and minimum traffic load is not repeated on the mean pattern speed or on the idle participation. Still, mean pattern speed is increased, while idle participation is reduced during the low traffic load Zone C as compared to those of the Zone A (high traffic load zone). This was expected since traffic load is not the only parameter affecting mean speed and idling. Traffic lights are still in operation even at night, imposing a number of stops and idling. Furthermore, even though the streets are relatively empty, maximum speeds achieved do not exceed certain limits, imposed by the nature of the roads (urban area with frequent road crossings).

Table 3: Characteristics of the driving patterns in different time Zones in Thessaloniki.

<table>
<thead>
<tr>
<th></th>
<th>Units</th>
<th>THESS 89</th>
<th>ZONE A</th>
<th>ZONE B</th>
<th>ZONE C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pattern distance</td>
<td>m</td>
<td>1209.0</td>
<td>1099.0</td>
<td>2200.0</td>
<td>1558.0</td>
</tr>
<tr>
<td>Pattern duration</td>
<td>s</td>
<td>177.0</td>
<td>170.0</td>
<td>220.0</td>
<td>200.0</td>
</tr>
<tr>
<td>Idle participation</td>
<td>%</td>
<td>24.1</td>
<td>25.3</td>
<td>16.1</td>
<td>21.0</td>
</tr>
<tr>
<td>Acceleration participation</td>
<td>%</td>
<td>13.7</td>
<td>13.3</td>
<td>16.8</td>
<td>14.6</td>
</tr>
<tr>
<td>Deceleration participation</td>
<td>%</td>
<td>11.6</td>
<td>11.7</td>
<td>11.2</td>
<td>11.3</td>
</tr>
<tr>
<td>Const. speed participation</td>
<td>%</td>
<td>50.7</td>
<td>49.8</td>
<td>55.9</td>
<td>53.0</td>
</tr>
<tr>
<td>MEAN PATTERN SPEED</td>
<td>km/h</td>
<td>24.6</td>
<td>23.2</td>
<td>35.7</td>
<td>28.1</td>
</tr>
</tbody>
</table>

By selecting the motion modules identified on each of the sample roads in each of the time Zones, and using again the same algorithm, it is possible to obtain the driving patterns of each road and time Zone. Figure 5 presents the ratio of the mean speeds of Zones A and B and A and C for some of the roads of the sample (the total number of roads was 28 but some of them are missing from Figure 5 because the available recordings were not sufficient to develop a reliable driving pattern, due to the reduced significance of the road). It can be seen that for the Zones A and B this ratio has a maximum value of 2.5, meaning that during the high traffic period the mean speed of the road is reduced by a factor of 2.5 as compared to that of the low traffic load period. The same ratio for Zones A and C is generally lower, due to the comparatively increased traffic load during the transient Zone C.

In Figure 5 is observed that some roads present similar B/A and C/A ratios. This is attributed to the fact that these are roads of areas highly populated with night clubs etc., with a different timing from the rest of the city.
MEAN SPEED INFLUENCE ON EMISSION FACTORS

As it was proved (Eggleston et al. [2]), mean speed significantly affects the hot start emission factors of CO, VOC and NOx of the gasoline powered passenger cars. Figure 6 presents this influence, as the ratio of the emission factor at a certain mean speed over the emission factor according to the ECE 15 driving pattern (mean speed = 18.7 km/h).

Figure 5: The time influence on the mean speed of the driving pattern for several roads of Thessaloniki area.

Figure 6: Hot start emission factor ratio (EFV/EF_ECE) for gasoline powered cars as a function of the mean speed of the driving pattern.
It is obvious that the mean speed strongly affects the hot start emission factors, especially in the case of CO and VOC.

The combination of this emission factor increase (decrease) with the increased (decreased) number of vehicles operating on the road during the high (low) traffic load zone makes essential for emission modelling of CO and VOC to take into account the time of the day. Time is also essential in the case of NOx emissions, although the picture, as far as emission factors are concerned, is inverted.

CONCLUSIONS

1. The THESS 89 driving pattern for Thessaloniki area was developed. It proved to be faster than the ECE 15, with same maximum speed but reduced idle participation.

2. In the area of Thessaloniki three time zones, with relatively constant mean traffic load, can be identified.

3. The maximum traffic load is observed at about 15.00 and the minimum at about 5.00. They are 1200 and 150 vehicles per hour per lane respectively.

4. The strong mean traffic load variation influences the corresponding mean speed of the city. During the high traffic load period, the mean speed of the city resulted to be 23.2 km/h, increasing to 35.7 km/h during the low traffic period.

5. The same influence of traffic load is observed on the individual roads, with a ratio of mean speeds up to 2.5, between low and high traffic load periods.

6. Since emission factors of gasoline passenger cars are strongly affected by the mean speed, and total emissions depend and on the number of vehicles operating on the roads, precise knowledge of traffic conditions as a function of time is essential for emission modeling.

REFERENCES


Road Traffic Emissions in Thessaloniki

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INTRODUCTION

It is since long recognised that road traffic constitutes the major air pollution source in urban areas, contributing substantially to the emissions of the precursors of photochemical oxidants VOC and NOx. This is particularly true for Athens (YPHODE 1989), case for which a number of studies were conducted in the recent past.

Aim of this paper is to provide an estimation of road traffic emissions in Thessaloniki. It summarizes the experience gained so far within a project sponsored by the organization of Thessaloniki (Pattas and Kyriakis 1991), combining it with developments on international level.

THE CHARACTER OF THE PASSENGER CAR FLEET

Among the EC countries Greece is the one with the lowest passenger car density. In 1985 Greece had a vehicle density of 127 vehicles per 1000 inhabitants, well below the Communities average of 303 veh./1000 inhabitants. The analysis of future trends (Samaras and Zierock 1991) shows that the number of passenger cars in Greece is expected to substantially increase in the coming decade. The forecast predicts a nearly doubling of the passenger car fleet between the years 1985 and 2000. However, even then the expected vehicle density (210 cars per 1000 inhabitants) will still be the lowest in the EC countries (estimated EC average for the year 2000: 386 cars / 1000 inhabitants). This need for motorisation of the country is reflected to the expected increase rate, which is estimated to be of the order of 64% between the years 1985 and 2000, and which is almost double of the EC average.

As specific socio-economic conditions impose the general character of the car market and car use in one country, it has to be stated already in the beginning that in Greece the private use passenger car was considered by the Greek authorities during the last 15 years as an important source of income. This was realized through a heavy taxation policy on the car upon its purchase.
(Special Consumption Tax). Moreover, it is also of importance to note that diesel as well as LPG powered engines are not allowed for use in private cars in Greece, their use being strictly limited on taxis.

The intense taxation of the cars led to the establishment of a characteristic of major importance: the "longevity" of the average car. This is clearly illustrated in Figure 1, which presents the age distribution of the passenger car fleet of Thessaloniki in 1988. The mean age of the fleet was about 10 years, i.e. by far greater than the BC average of 6 years, with 10% of the fleet exceeding 18 years.

As Special Consumption Tax on cars is calculated based on engine's swept volume, the tendency of the importers was to offer to the market cars with the lowest possible capacity. This resulted in a very low average cylinder capacity of the order of 1200 cm³, as Figure 2 displays. It is worth noting that almost 85% of the passenger cars are equipped with an engine of lower than 1.4l capacity, while only 1% is above 2l.

Here, a particular characteristic of the Greek car market behaviour has to be emphasized: a portion of the first registrations consists of second-hand cars, imported from other EC countries, and mainly from the Federal Republic of Germany. The contribution of these used cars was significant during the past decade: it even exceeded 30% of the total of firstly registered cars in the years 1986/87. The reason for the above market tendency is obvious: these used cars have lower prices than the new ones, being therefore attractive for a rather large portion of the potential buyers.

As private use passenger cars were heavily taxed, the light-duty gasoline powered truck became an alternative for those who were in the legal position to own such a vehicle, because of the lower prices (lower taxes) of this vehicle category. Therefore the market of light-duty trucks became important in Greece.
especially during the 80s. In general, all characteristics of the light-duty truck fleet are more or less identical to passenger cars.

With 1990 as reference year, Table I summarizes the vehicle fleet of Thessaloniki and presents an estimation of the total in-city annual mileage per vehicle category. This estimation is based on the balance of actual (statistical) fuel consumption in Thessaloniki (gasoline and Diesel separately) with the calculated one using experimentally determined fuel consumption factors, according to COPERT methodology (Samaras and Zierock 1989).

Based on these figures it is of interest to note the rather increased number of annual urban mileage driven by the passenger cars in the Greater Area of Thessaloniki: 6 900 km out of 13 000 km annually driven on average by each passenger car on all road classes (Samaras et al. 1991). As far as the diesel heavy duty trucks are concerned, fuel consumption balance produces the rather increased annual mileage of 15 000 km and 7 500 for trucks below and above 16t respectively.

<table>
<thead>
<tr>
<th>Vehicle Category</th>
<th>Vehicle Numbers</th>
<th>Vehicle km [10^6]</th>
</tr>
</thead>
<tbody>
<tr>
<td>VEHICLES &lt; 2.5t</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Private Use (Gasoline)</td>
<td>202396</td>
<td>1400</td>
</tr>
<tr>
<td>Taxis (Diesel &amp; LPG)</td>
<td>1850</td>
<td>185</td>
</tr>
<tr>
<td>Light Duty Vehicles</td>
<td>43124</td>
<td>300</td>
</tr>
<tr>
<td>TRUCKS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 16t</td>
<td>7100</td>
<td>110</td>
</tr>
<tr>
<td>&gt; 16t</td>
<td>3300</td>
<td>25</td>
</tr>
<tr>
<td>BUSES</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban Buses</td>
<td>490</td>
<td>35</td>
</tr>
<tr>
<td>Coaches</td>
<td>1160</td>
<td>15</td>
</tr>
<tr>
<td>TWO WHEELERS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 50 cm³</td>
<td>19000</td>
<td>115</td>
</tr>
<tr>
<td>&gt; 50 cm³</td>
<td>12000</td>
<td>70</td>
</tr>
</tbody>
</table>

The calculation of road traffic emissions in the Greater Area of Thessaloniki was conducted using the computer programme COPERT (Samaras and Zierock 1989). This programme was developed by the Lab of Applied Thermodynamics (LAT) of the University of Thessaloniki in collaboration with the German firm EnviCon on behalf of the Commission of European Communities (DG XI). It incorporates an appropriate methodology developed within the CORINAIR project (Eggleston et al. 1989), which makes use of a large amount of experimental data collected from almost all EC member states. In short, the programme enables the calculation of hot and cold-start emissions separately, with a split into urban, rural and highway driving conditions. It incorporates a detailed split of vehicle categories, according to their production period (specified in the case of passenger cars in the different ECE periods, i.e. according to the evolution of emission standards) and to their cylinder capacity. As an option, the programme offers the possibility to use
either the emission factors proposed by CORINAIR (and incorporated in the programme) or to introduce own (national) ones or to make a combination.

For this specific application, national emissions factors have been used, experimentally measured by LAT (Pattas et al. 1983, 1985, 1991). Figure 3 presents an example, referring to CO emission factors of passenger cars.

![Figure 3: CO emission factors expressed in g/km of Passenger Cars (LAT measured data) used for COPERT calculations](image)

RESULTS

Based on the results of the calculations, Figures 4 to 7 illustrate the contribution of the different vehicle categories to total traffic produced emissions, with regard to each pollutant separately. Thus the light gasoline vehicles (both passenger cars and light duty trucks) are the major CO emitter, contributing with 94% to total traffic CO emissions. The same holds true for VOC emissions (82% contribution of these vehicles), but here the contribution of two-wheeled vehicles becomes also of importance: 13% of VOC emissions is attributed to this category, mainly because of the two stroke engines.

![Figure 4: CO road traffic emissions in Thessaloniki (1990)](image)

![Figure 5: VOC road traffic emissions in Thessaloniki (1990)](image)
As far as NOx emissions are concerned, passenger cars contribute with more than 70% to the total, while trucks and buses share the remaining 30% (with 19% and 10% respectively). Finally, Total Particulate Matter (TPM) emissions are produced by trucks (54%), buses (31%) and the diesel powered taxis (15%). Nevertheless, as trucks are generally prohibited in the centre of the city, taxis and buses are recognised as the major smoke emitter in the central areas.

![NOx Emissions Road Traffic](image1)
![TPM Emissions Road Traffic](image2)

**Figure 6:** NOx road traffic emissions in Thessaloniki (1990)  
**Figure 7:** TPM road traffic emissions in Thessaloniki (1990)

Moreover, it is worth presenting the split of road traffic emissions into their hot, cold start and evaporative (only in the case of VOC) portions. It is of interest to note that about 25% of the total CO emissions is produced under cold-start driving conditions, while 27% of the total VOC emissions are evaporative losses, due to the favourable climatological conditions of Thessaloniki.

![Cold](image3)
![Evaporative](image4)

**Figure 8:** Hot and cold-start CO traffic emissions in Thessaloniki (1990)  
**Figure 9:** Hot, cold-start and evaporative VOC traffic emissions in Thessaloniki (1990)

The contribution of traffic to total atmospheric pollutant emissions is illustrated in Table II and in Figure 10 (source for other but traffic sources:
Organisation of Thessaloniki 1991). It is clearly seen that in the Greater Area of Thessaloniki traffic is the sole responsible of CO emissions, while its contribution to VOC emissions exceeds 95%. Nevertheless, the latter share is highly questionable, as no estimation of solvent emissions is included in these figures. Based on the international experience, it is expected that traffic contribution to total VOC emissions should exceed 60%, if all other VOC emission sources are properly taken into account.

With regard to NOx emissions, traffic is also found to contribute with more than 50%, with the industry in the second place (30%). Finally, Particulate emissions are mainly produced by the industrial activities, which contribute with almost 60% to the total; traffic and central heating equally share the rest.

Table II: Total Emissions in the Atmosphere of Greater Area of Thessaloniki - Reference Year 1990

<table>
<thead>
<tr>
<th>Pollutant [kt]</th>
<th>Traffic</th>
<th>Industry</th>
<th>Heating</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>76736</td>
<td>124.1</td>
<td>1285.5</td>
</tr>
<tr>
<td>VOC</td>
<td>11328</td>
<td>32.9</td>
<td>669.4</td>
</tr>
<tr>
<td>NOx</td>
<td>4628</td>
<td>2614.6</td>
<td>988.5</td>
</tr>
<tr>
<td>TPM</td>
<td>881</td>
<td>2383.3</td>
<td>761.1</td>
</tr>
</tbody>
</table>

REDUCTION PERSPECTIVES

In November 1990 a complete set of measures aimed at the drastic reduction of air pollution in Athens was proposed for public discussion by the Greek Ministry for the Environment, Physical Planning and Public Works (YPEHODE 1990). Core of the proposal formed measures referring to the drastic reduction of traffic produced air pollution. The proposal incorporates:

![Figure 10: Contribution of different sources to total emissions in Theassaloniki (1990)](image)
### Table III: Emission Standards for Clean Cars.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>EC Standards from 1.1.1993¹</th>
<th>Greek Incentives (Law 1882/90)²</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CC³ &gt; 2l</td>
<td>1.4l &lt; CC &lt; 2l</td>
</tr>
<tr>
<td>CO:</td>
<td>2.72</td>
<td>25(6.17)</td>
<td>30 (7.4)</td>
</tr>
<tr>
<td>VOC:</td>
<td>-</td>
<td>6.5(1.6)</td>
<td>-</td>
</tr>
<tr>
<td>NOx:</td>
<td>-</td>
<td>3.5(0.86)</td>
<td>-</td>
</tr>
<tr>
<td>VOC + NOx:</td>
<td>0.97</td>
<td>-</td>
<td>8(1.97)</td>
</tr>
<tr>
<td>Particulates</td>
<td>0.14</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Evaporative Losses</td>
<td>2.0 g/test</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

¹ In g/km. Type approval according to the new modified driving cycle.
² In g/test (in parentheses in g/km). Type approval according to the urban cycle.
³ CC: Cylinder Capacity

- **Subsidies for new clean passenger cars**
- **Subsidies for retrofitting in-use cars**
- **Traffic restrictions for polluting vehicles**
- **Establishment of the Exhaust Gas Control Card (EGCC)**

From the above, the first is of major importance and has already been implemented. Its outline is given below.

**Subsidies for new clean passenger cars** - i.e. gasoline powered vehicles equipped with closed-loop three-way catalysts and carbon canisters. To this aim a 50 - 60% reduction of the Special Consumption Tax is granted in case of a simultaneous scrapping of an old car, with an additional 5 year exception from the annual road tax. As clean are considered those cars complying with the emission standards presented in Table III. This subsidy adds to the one already enacted in April 1990, which foresaw a reduction of the Special Consumption Tax for the clean cars compared to the conventional ones. Thus, a new clean car has on average a 50% lower price than the equivalent conventional. Due to EC legislation, the above subsidies (granted since November 1990) will be in force until 31.12.1992 and they do not apply on vehicles of more than 2.0l.

A major change in the car market is already identified in 1990: the clean cars constitute 100% of the first registrations of new cars, while a tendency towards higher cylinder capacity vehicles is observed (upgrading the average to 1400 cm³).

Figure 11 presents an estimation of the expected reduction of traffic produced CO, VOC and NOx emissions, as function of the absolute number of scrapped cars. For these calculations, the emission factors for catalyst equipped cars have been used as presented by Samaras and Zierock (1991), while it was assumed that only older vehicles (i.e. vehicles older than 12 years) are scrapped and replaced by new catalyst equipped ones. Thus, it is estimated that the
"scrapping" potential of the car fleet in Thessaloniki is in the range of 50000 vehicles, this means approximately 25% of the actual fleet.

According to these Figures, traffic CO emissions may immediately be reduced by 30%, VOC by 25% and NOx by 14% if a total of 50000 passenger cars is withdrawn and replaced by new ones equipped with three way catalysts and evaporative control systems.

![Graphs showing reduction in emissions](image)

**Figure 11:** Estimated reduction of traffic emissions in Thessaloniki due to scrapping incentives
CONCLUSIONS

Based on the analysis presented so far, it is concluded that road traffic constitutes the major air pollution source in the Greater Area of Thessaloniki, as far as CO, VOC and NOx emissions are concerned. The recently enacted legislation, granting subsidies for the scrapping of older cars (with simultaneous replacement with new clean ones) will significantly lower the emission of pollutants from passenger cars.

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Preliminary Results of Mesoscale Model Simulations for Thessaloniki

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ABSTRACT

The nonhydrostatic prognostic mesoscale model MEMO and the Lagrangian model LAPMOD are used to simulate the wind flow and dispersion characteristics in the Greater Thessaloniki Area. The results reveal that the transport of air pollutants is largely influenced by the typical diurnal variation of the sea breeze circulation in Thessaloniki.

INTRODUCTION

For a complete understanding of atmospheric transport phenomena it is essential to combine monitoring activities and the application of appropriate models for simulations of pollutant dispersion under the influence of local scale wind flow patterns. The complementarity of monitoring and modelling is underlined by the fact that measured data are necessary to verify models, while models are required to interpret observations.

In the remainder of this paper we first briefly outline the structure of mesoscale models for simulations of wind flow and pollutant dispersion. Subsequently we present and discuss simulation results for the Greater Thessaloniki Area (GTA) originating from a first application of such models for this area.

MESOSCALE MODELS

Wind Flow
If pollutant transport is to be studied in the case of complex terrain, the spatial and temporal variations of the wind field have to be known. In principle, wind fields can be obtained either diagnostically or prognostically. As the starting point of diagnostic wind models, available wind measurements are interpolated to get a first estimate for the actual wind field. In a subsequent step, this wind field is adjusted to satisfy mass conservation
and to comply with the topography. There are several categories of diagnostic wind models, the most important category being that of models adopting the variational calculus method for the adjustment of the wind field. A representative for this category is the model of Moussiopoulos et al.\textsuperscript{1} which uses advanced algorithms and accounts for atmospheric stability in the adjustment step. Although only few wind data were available for the GTA before the 1991 Field Measurement Campaign was held, the calculation of wind fields with the aforementioned model was attempted. The results of these calculations reveal some of the characteristics of the sea and land breezes in the GTA (Kestenare\textsuperscript{2}). Being reasonable representations for the actual wind fields, diagnostic wind model results may be used for subsequent dispersion calculations.

Contrary to diagnostic models, prognostic models attempt a forecast of the wind pattern by simulating the dynamics of the planetary boundary layer. These so-called mesoscale meteorological models can be distinguished with respect to the parameterizations used and the assumptions made. One model of this category is the nonhydrostatic model MEMO\textsuperscript{3} \textsuperscript{4}. Taking into account the latest developments in this area, this fully vectorized model uses the anelastic approximation to filter sound waves. Second-order discretization is applied on a staggered grid ensuring the conservation of all fluxes. In particular, advective terms are treated with an explicit, monotonicity-preserving discretization scheme with only small implicit diffusion. The discrete pressure equation is solved with a direct elliptic solver in conjunction with a generalized conjugate gradient method\textsuperscript{5}. Turbulent diffusion is described in terms of the turbulent kinetic energy. At lateral boundaries generalized radiation conditions are implemented. The radiative heating/cooling rate in the atmosphere is calculated with an efficient scheme based on the emissivity method for longwave radiation and an implicit multilayer method for shortwave radiation\textsuperscript{6}.

Simulation results for the mesoscale circulations in the Greater Athens Area with the model MEMO allowed to identify all major features of the tidal air movements over Athens including onset, duration, vertical extension and intensity of the sea and land breezes in good agreement with available observations\textsuperscript{3} \textsuperscript{4}. Preliminary results of the model MEMO for the local flow characteristics in the GTA are presented in the next section.

**Pollutant dispersion**

A variety of model concepts is available for studies of atmospheric dispersion of air pollutants. Simpler models requiring a low computational demand (e.g. Gaussian models, box models) may easily be run on PC's. Unfortunately, such models do not qualify for dispersion and chemical transformation simulations in complex terrain, as for instance in the case of the GTA. For this application more sophisticated models have to be used, which take into account the inhomogeneity of both the topography and the wind flow as well as spatial and temporal variations of the emission rates. Models of the latter category can be applied efficiently only on powerful computers (large work stations or mainframes).

**Eulerian models** describing atmospheric dispersion usually cause considerable computational expenses and are not free of numerical diffusion. Nevertheless, they are very frequently preferred rather than Lagrangian models (see below), as they may provide full three-dimensional concentration fields and they can be readily extended to describe the coupled dispersion and chemical transformation of air pollutants\textsuperscript{3}. 


Lagrangian models are very well suited to describe the dispersion of individual plumes. By superposition of statistically fluctuating components to the mean wind field the individual motion of a large number of particles (or clusters of particles) is traced. This method has many obvious advantages: Firstly, it is free of numerical diffusion. Secondly, it allows to take into account gravitational effects on the particle motion. Thirdly, it is possible to identify the origin and the residence time of particles in the atmosphere and thus to describe the relationship between emission and immission in detail. Finally, precision (and, correspondingly, computational demand) may be controlled very efficiently by means of the number of the considered particles. The Lagrangian model LAPMOD has been successfully used to simulate the dispersion of inert pollutants in Athens\textsuperscript{8} \textsuperscript{9}. In the following section we describe the application of the same model for a preliminary description of the carbon monoxide dispersion in the GTA.

MODEL RESULTS

Wind field
For a realistic prediction of the local circulation system in the Greater Thessaloniki Area, the wind field was simulated for most of Central Macedonia. Fig. 1 shows the location of the 65×120 km\textsuperscript{2} computational domain.

![Figure 1. Location of the 65×120 km\textsuperscript{2} computational domain.](image-url)
Figure 2. Diurnal variation of the wind velocity and the CO concentration at ground level in Central Macedonia calculated with the nonhydrostatic mesoscale model MEMO and the Lagrangian dispersion model LAPMOD.
Figure 2. Continued
It should be noted that a considerable part of the domain is covered by water mass of the Theraic Gulf. For the calculation of the wind field a numerical grid of 26×48 grid points in the horizontal direction was used leading to a constant grid spacing of 2.5 km. In the vertical direction the grid consisted of 25 levels and was non-equidistant with a minimum spacing of 20 m. The upper boundary was set to a height of 6000 m above sea level. The simulation was performed for a weak synoptic wind from NNW.

Fig. 2 shows the computed diurnal variation of the wind field in the lowermost grid cell of the computational domain (approximately 10 m above ground level).

At night the temperature over land is lower than over the sea. This induces an off-shore flow near the ground, the land breeze, which appears to be enhanced in slopy terrain: Air over land cools off more rapidly than air at the same height in the atmosphere; the differential heating results in downslope mountain winds.

During daytime the situation changes. As the temperature over land gradually exceeds that over water, sea breeze cells develop. In the morning the corresponding pattern is rather complex, as the direction of the onshore air flow is more or less perpendicular to the coast. In addition, valley winds occur: Air adjacent to mountain slopes is warmer than air at the same height in the atmosphere; this causes a pressure gradient force toward the mountain slope near the ground.

Supported by the aforementioned upslope valley winds, in the afternoon an extended sea breeze develops, which leads to a large scale air motion to the North. Interestingly, the transition to this extended sea breeze implies a veering of the surface wind in the urban area of Thessaloniki from W-SW to S.

After 18.00 LST the surface temperatures over land have already exceeded their maximum values; consequently, the intensity of the sea breeze decreases. It should be noted, that in the afternoon the wind direction over the Theraic Gulf rotates slightly anti-clockwise. Besides, the strong vertical mixing during daytime causes that the induced circulation is much stronger than the inverse nighttime effect which is associated with stable conditions within the whole domain and a low vertical mixing.

**Pollutant dispersion**

The model LAPMOD was applied to simulate transport and dispersion of CO under sea breeze conditions in the GTA. The CO emissions were assumed to be caused solely by urban road traffic. The computational domain corresponds with that of the wind flow simulation (Fig. 1).

Fig. 2 shows the computed diurnal variation of the ground level CO concentration in Central Macedonia. In this figure particles are considered which reside up to a height of 100 m AGL.

At night air mass moves gradually to the South leading to an accumulation of air pollutants primarily over the Bay of Thessaloniki and the area of Mihaniona. After sunrise a large fraction of this polluted air mass is advected back to the urban area of Thessaloniki, where it joins pollutants emitted during peak hour traffic. In view of the rather low vertical mixing in the early morning, this mechanism leads to peak values of the CO concentration.

The gradual increase of vertical mixing around noon and the transition to the extended sea breeze result in an efficient dilution of CO in the GTA in the afternoon. After sunset transport phenomena weaken; consequently,
the downtown CO concentrations increase again. It should be noted that according to the model results in the evening pollutant transport occurs from the urban area of Thessaloniki to the area over the Lake Koronia and the town of Langadas.

SUMMARY AND CONCLUSIONS

The presented preliminary results of mesoscale model simulations for the GTA allow to identify some of the characteristics of wind flow and dispersion in this area:

- A weak land breeze during the night, resulting in an accumulation of air pollutants over the Bay of Thessaloniki and the area of Mihaniona.
- The setup of a rather complex sea breeze pattern in the early morning, leading to the re-advection of a large fraction of the above pollutants back to the urban area.
- A transition to an extended sea breeze in the afternoon, which is characterized by a large scale motion of air mass to the North. In conjunction with an intense vertical mixing, the extended sea breeze leads to an efficient decrease of air pollutant concentrations in the afternoon.
- After sunset transport phenomena weaken and pollutant concentrations increase. In the evening pollutant transport seems to take place from the GTA to the area over the Lake Koronia.

Most of the above features are confirmed by available previous observations. In the next future the simulation results will be compared in detail with the results of the Thessaloniki '91 Field Measurement Campaign.

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Multibox Model Simulations of Photochemical Smog Formation in Thessaloniki

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ABSTRACT

A multibox model is used to investigate the influence of emissions from industrial activities and from traffic on the photochemical oxidant levels in the GTA. The simulation results are very sensitive to several parameters including the assumed diurnal variation of the mixing height.

INTRODUCTION

Air pollution does not know any boundaries, neither those of a city nor those of the region where they originate from. Carried by the wind, air pollutants may be transported hundreds or even thousands of miles downstream before they are deposited. Chemically active air pollutants will at the same time take part in numerous chemical reactions of which some require intense solar radiation. Smog formation corresponds to one of the most severe forms of environmental deterioration. In particular, photochemical smog is known to be hazardous for man, his living environment and materials. Depending on the emission strength of its precursors, the intensity of photochemical smog, i.e. the magnitude of photochemical oxidant levels, is usually quantified in terms of the ozone concentration.

In this paper we apply our multibox model to simulate ozone formation caused by industrial and traffic emissions in the GTA. After discussing the underlying photochemical reaction system we describe the test case selected. Subsequently, we briefly present the model applied in this study and comment on the limitations of our approach. Based on sample results we discuss the influence of several parameters on ozone formation.

REACTION SYSTEM

The photochemical reaction system contains reactions leading to the formation of photochemical oxidants. The anorganic part of this system is relatively well understood. In daytime the most important anorganic reactions are the photolysis of NO₂, leading to the formation of ozone, and the
oxidation of NO to NO$_2$ by ozone. Obviously, these two reactions result in no net gain in ozone. Elevated ozone concentrations usually observed during photochemical smog episodes are caused by reaction paths where NO is converted to NO$_2$ without ozone being used up. The decisive role in such reaction paths play organic radicals which are formed in the course of the degradation of hydrocarbons. Typically, these reaction paths are initiated by reactions of hydrocarbons with ozone or with the OH radical. Even today, the organic part of the photochemical reaction system is rather poorly understood since there are several hundreds of reactants and even thousands of reactions occurring in a polluted airshed.

To allow for a mathematical description of these reactions, several reaction mechanisms were developed, differing in the way they simplify the organic part of the photochemical reaction system. An important criterion for the selection of a chemical reaction mechanism is the availability of necessary input data, i.e. the proper subdivision of the hydrocarbon emissions. In the absence of a detailed emission inventory, a less sophisticated reaction mechanism will compare favourably to much more refined ones because of the considerably higher computational demand of the latter at comparable accuracies. The simulations presented below are based on the condensed ERT reaction mechanism.

Figure 1. Layout of the domain. The residential area is stippled, the dots correspond to the major industrial point sources in the GTA.
Figure 2. Emission rates in individual boxes of the domain.

Figure 3. Assumed diurnal variation of the mixing height.
MODEL DESCRIPTION

Transport and photochemical transformations of pollutants were simulated with an one-dimensional multibox model including a self-adaptive implicit solution algorithm. The model is described in detail elsewhere. It should be noted that the boxes are assumed to have a variable height following a specified diurnal variation of the mixing layer.

Apparently, in a multibox model the pollutant concentrations are assumed to be constant within a box. The neglect of the vertical concentration variation is without any doubt the major shortcoming of multibox models. This shortcoming is, however, counterbalanced by the inherent simplicity and the broad applicability of these models.

TEST CASE DESCRIPTION

The below described simulations were carried out to describe qualitatively the interaction of industrial and urban emissions in the GTA with regard to the resulting photochemical oxidant levels. More precisely, the simulations aimed at a first estimate of how various parameters influence ozone formation.

Figure 1 illustrates the selected arrangement of the boxes, which were assumed to be 2.5 km long. The assumed emission scenario is shown in Fig. 2. In the "reference case", to which the discussion is restricted in the present paper, the wind comes from NNW. Hence, air mass is advected first above the main industrial zones of the GTA (where primarily NOx and VOC are emitted), reaches then the urban area with mainly traffic emissions (i.e. CO, NOx and HC) and continues its motion over emission free area. An appropriate diurnal variation was assumed for the urban traffic emissions, whereas industrial emissions were considered to be constant.

The meteorological input consisted of the wind speed and the diurnal variation of mixing height. The former was assumed to be constant, the latter was derived from preliminary results of the Thessaloniki '91 Field Measurement Campaign. For the concentrations of all chemical species initial and boundary conditions were specified to correspond to background concentration values, which were also depicted from preliminary campaign results.

RESULTS

Figures 4 and 5 show the calculated diurnal variation of the CO, NOx, NO2 and ozone concentrations at a constant NNW wind of 0.5 m/s in the urban area (cell #8) and in the rural area in the lee of the GTA. The corresponding spatial distribution of the same species on 8:00 and 18:00 LST is illustrated in Fig. 6.

For the interpretation of the results the following should be taken into account:

- The predicted emission levels correspond to average values which are representative for a rather large area. Apparently, this model cannot be expected to reproduce peak values for individual species. Therefore, there is no justification for comparing these predictions with actual measurements at individual receptor locations.
Figure 4. Diurnal variation of the CO, NO, NO₂ and ozone concentrations predicted for cell #8 (urban area) at a constant NNW wind of 0.5 m/s.

Figure 5. Same as Fig. 4 but for cell #13 (rural area).

- By the aid of additional simulations it could be proved that the model results are sensitive to several parameters and especially to the prescribed diurnal variation of the mixing height. Contrary to the nocturnal values for the mixing height, which could be derived from available observational evidence (see above), the daytime variation of the mixing height used in this study is merely a guess.
- If expressed per unit surface area of the boxes, the urban emission rates assumed for the GTA exceed those valid in Central European urban areas by as much as 100%.
- In view of the high emission rates and given that the domain considered is less than 40 km long, even at a wind velocity as low as 0.5 m/s the residence time of the air mass in the domain does not suffice for NO to be depleted. Consequently, very high ozone levels can hardly be expected in the area of interest.
Figure 6. Spatial distribution of the CO, NO, NO₂ and ozone concentration at a constant NNW wind of 0.5 m/s on 8:00 and 18:00 LST.
The predicted concentrations of all pollutants in the urban area reflects the combined influence of the assumed diurnal variations of the mixing height and the traffic emission rates. The latter are characterized by surprisingly high values in the late evening hours. Hence, CO reaches its peak value around midnight. As NO$_2$ is concerned, chemical production is not sufficient to counterbalance the combination of advective transport and dilution due to turbulent diffusion. Ozone only gradually increases to reach its maximum value of slightly more than the assumed background concentration (30 ppb) at about 18:00 LST.

Comparison of Figs 4 and 5 reveals that the particular case considered is governed by advection. The diurnal variations of both CO and NO$_2$ in cell #13 exhibit features already visible in cell #8 a few hours earlier. Of course, the NO values in the rural area are markedly lower than downtown, but still high enough to prevent an intense formation of ozone. The latter does not exceed the levels reached downtown, yet its daily mean concentration is higher than the corresponding value in the urban area.

Figure 6 largely confirms the already discussed interrelations. The behaviour of CO and NO$_2$ is rather similar: It exhibits a decrease from 8:00 to 18:00 LST, due to the increase of the mixing height, and a monotonic decline in the leeside of the city as a consequence of advection. In the case of NO, both the decrease from 8:00 to 18:00 LST and the decline in the leeside are significantly enhanced by photochemical oxidation processes. As expected, ozone behaves complementary to NO: It increases from 8:00 to 18:00 LST in spite of the increase of the mixing height; it exhibits a minimum, the location of which moves gradually in the course of the day from the city centre to the SSE; finally, it increases again up to the end of the day. Most probably, this increase would continue out of the domain.

CONCLUSIONS

The results of the present study prove that a multibox model may provide a reasonable impression of the photochemical processes occurring in an urban airshed. For more accurate results, however, a three-dimensional dispersion model for reactive pollutants should be applied.

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