Executive Summary

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1 Prologue

The main aim of SATURN has been to reach a better understanding of urban air pollution as a prerequisite for finding effective solutions to air quality problems and for sustainable development in the urban environment. To this end, the main scientific objective of SATURN has been to improve substantially our ability to establish source-receptor relationships on the urban scale. Ensuring the validity of such relationships may also facilitate the assessment of the impact of urban areas on regional and global scale problems of the atmospheric environment.

The following methodology was adopted to meet the above objective:

- Development of an appropriate model hierarchy, covering also the local scale (down to street canyon geometries) to the extent necessary to establish source-receptor relationships.
- Evaluation of individual models with suitable procedures.
- In support of such procedures, the creation of appropriate validation data sets from observations and experimental results originating from laboratory studies and field campaigns.

The structure of SATURN was based on three different clusters. The *Local Cluster* dealt with microscale and local scale phenomena investigated in the field, but also with wind tunnel experiments and numerical simulations. The *Urban Cluster* addressed urban-to-regional scale phenomena (without resolving individual obstacles) with field experimental campaigns and numerical models. Modelling work in both clusters included the development and validation of models with emphasis on the formulation of multi-scale concepts. The *Integration Cluster* concentrated on the integration of models in Air Quality Management Systems to be used for various applications including exposure estimates, and the testing/validation of such systems with collected data.

One of the major aims of SATURN was to contribute to the formulation of improved tools for urban air quality assessments. For instance, SATURN developed and improved methods to allocate the contributions of various sources to increased air pollution levels in conurbations. Such methods are very valuable for urban authorities wishing to have insight into the causes of air pollution and in the possibilities to reduce air pollution levels or to control anticipated increases of such levels. Also, methods to simulate the effect of long-term emission changes were improved as a basis for formulating and evaluating reasonable air pollution abatement strategies. On the same basis, novel systems for the prediction of air pollution episodes were among SATURN's deliverables. The modelling systems developed were validated with appropriate quality assurance techniques and together with the available technology, i.e. satellite information and telematics can be used for public information on air quality.

2 Characteristics of air pollution in European cities

A vast majority of the urban and suburban population in Europe is exposed to conditions that exceed air quality standards set by the World Health Organisation (WHO). For exposure estimates it is necessary to investigate the spatial and temporal features of air pollution, especially under conditions that lead to the most severe air quality problems in different European regions.

Urban air pollution phenomena encompass a wide range of spatial and temporal scales: from a few metres (street canyon pollution) to hundreds of kilometres (secondary pollutant formation in city plumes). Within SATURN, special interest has been focused on stable, low wind conditions which lead to high pollutant concentrations. The effects of these meteorological conditions have been investigated in a local/street canyon scale as well as in the larger mesoscale and regional scales. The microscale effects of low wind conditions have been investigated to determine the behaviour of pollutant dispersion in the vicinity of large ground-level sources. This is an important issue as an increasing number of roads in urban areas are constructed as cut and cover tunnels. Ground-level sources can be large parking areas, garages, small industries, etc.

Other microscale phenomena that need special attention are those related to the heat fluxes in the vicinity of the buildings. Mesoscale wind circulations, e.g., mountain-valley wind systems, greatly affect the pollution dispersion in several industrialised and densely populated areas located in basins (e.g., in the area of the Alps). In addition, atmospheric circulations created by the city itself, notably the so-called urban heat island, directly influence the dispersion of pollutants. On the other hand, the local concentration levels are in many cases also influenced by regional scale processes such as the atmospheric transport of pollutants emitted in surrounding cities and industrialised areas as well as from neighbouring countries as in the case of ozone and particles.

The combined microscale, mesoscale and regional scale effects on urban air quality can be investigated with adequate multi-scale model cascades. The formulation of such cascades was among the main scientific objectives of SATURN. Several methods for coupling individual models were proposed in SATURN. This coupling allows consideration of the interactions between the various scales and assessment of the effect of such interactions on urban air quality.

An experimental campaign that helped to provide insight on the parameters affecting the airflow in a street canyon under low wind conditions was performed at the centre of Nantes, France, in June 1999. In particular, the effect of the thermal convection induced by the differential heating of the street surfaces due to variable solar heating on the airflow within the street and consequently on the pollution dispersion was investigated. The analysis of the air and wall temperatures showed the presence of a steep temperature gradient within the first few centimetres of the wall receiving direct solar radiation. This led to a strong convection which directly affected the transport of pollutants from the canyon to the layer aloft. The examination of the flow field indicated a main re-circulation during the whole day for wind perpendicular to the street. The thermal effects on the flow within a canopy were also investigated with wind tunnel experiments.

Investigation of dispersion under low wind conditions has been performed using a combination of mesoscale and Lagrangian particle models. In particular these models were applied for the Graz region in the lee-side of the Alps and used in conjunction with sonic anemometer observations. The results of the analyses made in a suburban area South of the city of Graz reveal peculiarities of the turbulent transport under low wind conditions influenced by the mixed land use and the low building density.

New modules of the French model SUBMESO were developed for simulating the mean flow and turbulence, the physics and microphysics, and the transport-diffusion-transformations of reactive pollutants within an urban area. The models include modules for dynamics, microphysics, terrain and soils, chemistry (transport-diffusion-transformation) fed by the tropospheric chemistry model MOCA, and a grid generator designed for complex terrain. The stable atmospheric boundary layer as well as urban canopy processes (radiative trapping, heat storage by the walls, mutual shadowing and vegetation over artificial surfaces) were investigated. Development and refinement of existing modelling tools were performed for the triangle Antwerp-Brussels-Gent, a highly urbanised area in northern Belgium, and integrated in the model system AURORA. The sensitivity to a set of variable input parameters (temperature, solar angle, etc.) was found to be high.

3 Methodology for specifying urban emissions

Emission inventories are important tools to describe the emission situation and eventually to manage air quality. They provide comprehensive information on emission sources and emission fluxes in the area under consideration. When looking at pollutant dispersion and air quality modelling, it is necessary to have an accurate and high quality description of the emission sources in terms of quantity and dynamic behaviour. This requires an emission inventory with a high resolution in space and time.

Consistency among urban emission inventories is a prerequisite for the sensible comparison of the air quality situation in various European cities. Within SATURN, guidelines were developed for setting up urban emission inventories to minimum requirements. The aim of these guidelines was to:

- present a harmonised method for the compilation of urban emission data,
- provide sources for suitable emission factors,
- provide tools for producing emission inventories.

For the generation of emission data, guidelines were designed for methodologies, models, pollutants, resolution in time and space, emission factors and quality assurance. In addition, a protocol for the comparison of urban emission inventories on qualitative and quantitative bases was established, and comparisons concerning pollutants treated and methodology used were performed.

The comparative analysis of several urban emission inventories suggests that it is not easy to find a common basis for intercomparison purposes. A first comparison was based on total emissions. The local emission situation differs strongly and is a function of the heating characteristics and the industrial activities in the domains under consideration. Special emphasis was put on the emissions from the industrial sector. In this sector the emission inventory is especially complicated as it is sometimes difficult to obtain information about the specific process activities in each industrial branch. Moreover, this kind of data accepts little aggregation.

A much higher potential for successful comparisons among various urban emission inventories was found for the road traffic emissions. The basis for the comparison is now the vehicle kilometres travelled, so that the result is a fleet averaged emission factor in grams per kilometre.

4 Contribution of urban emissions to the ozone budget

Photochemical pollution refers to the complex formation of ozone and other photochemical oxidants resulting from the interaction of high solar irradiation levels with the precursor substances of nitrogen oxides (NO_x) and hydrocarbons (VOCs). NO_x is produced by combustion processes and is emitted by vehicles and industries mostly as NO with the balance being NO_2. VOCs originate from both anthropogenic and biogenic sources.

Ozone is a major environmental concern because of its adverse impacts on human health. Since the 1970s health standards for ozone have been often violated in major metropolitan areas in Europe, especially in southern Europe (e.g., Athens). The relative importance of ozone and its precursors transported into an area distinguishes the characteristics of an episode. Therefore, the needs to characterise the ozone episodes accurately and to identify the potential role of transport are closely related. As ozone is highly associated with the presence of NO_x and VOCs, it is necessary to understand how ozone depends on these substances in order to develop an effective policy response.

Within SATURN, the OFIS (Ozone Fine Structure) model was applied to the investigation of the characteristics of photochemical pollution in an urban environment over periods of several months. The OFIS model belongs to the European Zooming Model system, a comprehensive model system for simulations of wind flow and pollutant transport and transformation. OFIS can provide a realistic statistical estimation of urban scale ozone levels and is therefore suitable for assessing ozone exposure at the urban scale for the optimisation of control strategies. The model was used for studying ozone formation in about 60 European cities in geographically different regions. The analysis of combinations of additional NO_x vs. VOC emission reductions at the local scale has provided information on how to achieve maximum reductions of ozone levels in the conglomeration around each city or cluster of cities. In addition, an analysis was made as to how exposure to ozone is affected by regional and local measures associated with NO_x and VOC emission reductions. One of the major results was that regional emission controls may have a significant influence on urban ozone concentration. Ozone exceedance statistics proved that the highest ozone values are present mainly in urban Mediterranean areas, while exceedances of the WHO guideline value for the protection of human health are also found in central and northern Europe, but only for shorter periods.

Two integrated modelling systems for photochemical pollution control were designed and applied to the Lombardia area in Italy. The modelling system STEM-FCM (Flexible Chemical Mechanism) was upgraded to describe the influence of different chemical mechanisms for ozone predictions and emission control strategies. The simulations made with the GAMES modelling system pointed out that, because of the main influence of the regional ozone production dynamics, the road network strategy has a modest influence on the concentration field. As for recent EU directives concerning vehicle technology, simulations show how pollution abatement measures addressing road traffic alone may prove inadequate. It must be stressed that the area studied is characterised by a VOC-limited atmospheric chemistry regime.

In addition, the experimental investigation of the chemical composition and aerodynamic distribution of the urban aerosol, performed over the Milan urban area in July 2000 during a typical summer high pollution episode, helped to understand which chemical multi-phase modelling schemes have to be implemented in the mesoscale models. Results mainly concerned the urban aerosol mass closure determination and the relation between secondary aerosol formation and photochemical properties of the atmosphere. Aerosol analysis was combined with a complete characterisation of the primary and photochemical pollutants, both at ground level and vertical structure.

Numerical modelling work concerning ozone formation dependent on NO_x-O_3 chemistry was also performed at the street canyon scale with microscale modelling tools complemented by a module describing fast chemical reactions.

5 Particulate matter in European cities

Particulate matter (PM) is a suspension of solid and liquid particles in the air. PM is associated with adverse effects on health, climate and ecosystems. These effects are highly dependent on the size distribution and chemical composition of PM. Particulate matter may be either of primary or secondary origin. Those of primary origin are directly emitted by anthropogenic or biogenic sources, while those of secondary origin (the so-called secondary aerosols) are associated with long-range transboundary transport and are formed by atmospheric reactions arising from, e.g., emissions of SO_2, NO_x, NH_3 and organic compounds. SATURN aimed to investigate the chemical composition of size-fractionated aerosol in order to draw some general inferences about the sources and processes generating this class of pollutants in different European areas.

Several field experiments were conducted within SATURN in order to develop sufficiently detailed databases to enable source apportionment studies and characterisation of particles, including fine as well as ultra-fine particles. These experiments were performed in Stockholm, Toulon, Marseille, Nantes, Helsinki, Copenhagen, Budapest and in a semi-rural site in the UK at Hatfield.

Traffic is considered to be one of the most important sources of fine particles. Determination of emission factors of fine particles from the actual car fleet for different types of vehicles is essential for reliable model calculations of the directly emitted particles from the traffic. Measurements of fine and ultra-fine particles were carried out during winter/spring 1999-2000 in Denmark, at street and roof levels in central Copenhagen, and at street level in the city of Odense. The major goal of the study was to provide tools for determination of traffic generated air pollution, and the collection of data for the development and validation of urban and local scale air quality models. Significant correlation at street level was observed between the CO, NO_x, and ultra-fine particles, indicating that the traffic is the major source of ultra-fine particles in the air. Time series of the number and mass size distributions were analysed over the period of several months using statistical methods. Factor analysis was used for identifying important sources, and a constrained physical receptor model was used for source apportionment and for determination of source size distributions of ultra-fine particles from diesel and petrol fuelled vehicles. Other pollutants related to traffic (e.g., benzene and toluene) were also monitored.

The physical characterisation of aerosol particles at ground and roof levels in the urban zone and their dynamic behaviour within the street were investigated with different experiments conducted in Toulon, Marseille and Nantes. The measurements showed that the mass size distribution of fine particles corresponded closely to the distribution of traffic emissions at the field sites. Measurements of the coarse particle size distribution at several heights within the streets led to similar distributions characterised by a mode of approximately 2 μm. The fact that the concentrations were, on average, higher at the highest measuring level within the street than at street level suggests that the phenomenon of suspension of PM from the road dust deposit, which is believed to be the main process of coarse particle generation at street level, is not really dominant. On the other hand, the fact that the concentrations during rainy days were higher suggests that coarse particles are more commonly transported over the urban canopy and introduced into the road at roof level rather than generated at street level.

Gaseous pollutants and several quantities characterising PM were measured in an urban area and in a road tunnel in Stockholm. In detail, the measurements included aerosol size distribution, $PM_{2.5}$ and PM_{10} mass (i.e. concentration of particles with size up to 2.5 μm and 10 μm, respectively), coarse and fine fraction elemental composition, organic and elemental carbon, CO, NO, NO_2, light hydrocarbons, semi-volatile hydrocarbons, polycyclic aromatic hydrocarbons, benzene, toluene, xylene and ethyl-benzene as well as filter samples. The hourly averaged total particle concentration reached its maximum in the road tunnel during morning rush hours. Most of the particles had aerodynamic diameters in the range 10 to 60 nm. The number of particles was lower in the street and the size distribution was shifted towards smaller particles. At rooftops the number of particles was found to be significantly lower. Some indication of formation of secondary particles was observed.

Between April 1996 and June 1997 concentrations of atmospheric particles and gases were monitored and size-segregated aerosol sampling and detailed chemical analysis combined with measurements of local weather conditions were performed at an urban and at a rural site in the Helsinki area. One of the aims was to estimate gas-particle interactions and particle deposition. More than 60 chemical components were determined and correlations between them were calculated. In the fine particle range four groups of correlating components were observed at both measuring sites. Average chemical composition of fine particles was fairly similar at the urban and rural sites.

The particle concentration was also investigated with field experiments in the UK. The results suggested that particle mass resides predominantly in the fine fraction ranges (PM_1) indicating their anthropogenic association. The results also indicate a low concentration of lead that might have resulted from the complete phasing out of leaded petrol in the UK. Generally the trend in size distribution exhibited by the analysed species is explainable in terms of their possible source origins. The size-distributed concentration results also suggest that most of the species have very high occurrence in the fraction of aerosols with diameter less than 1μm. These may have serious implications for human health and also indicate the extent of the influence of anthropogenic activities on the ambient aerosol.

Particle size distribution was also measured in the eastern Mediterranean area (in Crete and on a scientific boat located between the Greek mainland and the island of Crete). The first data analysis from this intensive measurement campaign indicates periods with elevated levels of number concentration and enhanced aerosol scattering.

6 Source apportionment and other modelling techniques

The chemical composition of atmospheric pollutants is influenced significantly by the nature of human activities leading to their emission. Therefore, the study of the source origin of the different elements is of crucial importance for environmental management on urban scale. Various studies within SATURN aimed at evaluating the characteristics of several trace elements of natural and anthropogenic origin under different conditions.

During a three year project (1998–2000) data were obtained in order to establish source-receptor relationships for hydrocarbons and particulate matter in the urban area of Stockholm, to evaluate the relative contribution of individual sources for the distribution of these compounds, and finally to evaluate emission inventories using a combination of measurements, source-receptor models and dispersion models. The project included both emission and air quality measurement campaigns and provided chemical and physical characterisation of the aerosol. The experimental results show that the particle number size distribution varies considerably with distance from traffic sources going from a road tunnel via streets with high traffic and urban roof-top locations to a background site far from the city.

Particle interactions with local emissions and background air pollution may be characterised with suitable numerical methods. The assessment of existing and new methods of this kind proved this characterisation to be computationally non-trivial.

Receptor modelling was applied to provide quantitative estimates of the impacts of various sources on ambient air quality. Source profiles for waste incineration, traffic, oil and coal burning were established and used in model calculations. Aerosol sampling for fine size range aerosol particles was also carried out at the sources and at two receptor points, in the downtown area of Budapest during November-December 1999. Source signatures for coal and oil burning were adopted from the fine size range aerosol measurements carried out in the plume of power plants operating in the Czech Republic. It was found that high amount of zinc, lead and copper are emitted from a waste incinerator. Regarding the traffic profile, the most important element is still lead; however its relative contribution decreased rapidly during the past five years.

Mathematical models have also been developed, evaluated and applied in order to predict aerosol processes and the number and mass concentrations, such as $PM_{2.5}$ and PM_{10}, in urban areas. An aerosol dynamical model MONO32 has been applied both in Stockholm and Helsinki. The model takes into account gas-phase chemistry and aerosol dynamics (nucleation, coagulation, condensation/evaporation and deposition). In Stockholm, the model was tested by comparison with measurements in a road traffic tunnel; in Helsinki, the influence on aerosol evolution of various chemistry and aerosol processes was quantitatively evaluated.

Roadside emission and dispersion models for PM were developed and evaluated in the United Kingdom and Finland. The predictions of the CALINE4 and the CAR-FMI models were compared with field data. A simple model was developed for predicting the concentrations of $PM_{2.5}$ in urban areas, including the influence of both primary and non-exhaust vehicular emissions, and the regionally and long-range transported contributions.

Based on the observations that local vehicular traffic is responsible for a large fraction of the street level concentrations of both PM_{10} and NO_x, either due to primary or secondary emissions (suspension from street surfaces), a semi-empirical modelling system for PM_{10} was developed and evaluated against the data collected from the air quality monitoring network in the Helsinki Metropolitan Area.

7 Air pollution exposure – emphasis on particulates

It is unquestionable that air pollution has severe impacts on human health. In recent years increasing interest has been focused on aerosols, especially the particles of small diameter that are associated with epidemiological effects and respiratory diseases. In particular, a large number of health effects of traffic-generated air pollution are suspected. However, quantitative estimates that are required for risk assessment and management are extremely difficult due to the lack of data and/or difficulties with extrapolating data from other geographical areas and time periods with large differences in composition of air pollution. Moreover, very few and mainly small studies have so far attempted to assess individual exposures. The aspect of human exposure to ambient air pollution in urban areas has been extensively studied within SATURN. In particular, the relationships between particulate air pollution emissions and human/population exposure leading to potential effects on health have been investigated.

The complex concentration patterns in cities, particularly near hotspots such as roads, is a major reason why the relation between concentration and population exposure is far from trivial. Work was done on the assessment of road-user exposure to fine particulate air pollution in London using measurements and atmospheric dispersion modelling, specifically a comparison between the two. The road-user exposure with $PM_{2.5}$ was measured from the breathing zone for car, bus and bicycle users and compared with model results. Various human exposure studies were also carried out in Denmark and serve as the basis for model development and validation. Personal exposure to particles ($PM_{2.5}$) and nitrogen dioxide was monitored in Copenhagen, outdoors as well as indoors. Preliminary results indicate that a strong correlation exists between indoor and personal-monitored $PM_{2.5}$ concentrations indicating that indoor concentrations play a significant role for the personal exposure. The correlation between indoor and outdoor $PM_{2.5}$ concentrations seems less pronounced than expected, but more detailed analysis is required before conclusions may be drawn. The same study was aimed at extracting relationships between particle exposure and the response in biomarkers.

Mathematical transport-chemistry models are strong tools for the evaluation of emission reduction strategies, for providing information to the public, and as the central part of models for human exposure to air pollution. For instance, in Denmark, Finland, Norway and the United Kingdom, existing modelling systems have been extended to allow for the exposure of the population to air pollution. In Helsinki, the main objective was to evaluate the exposure of the population with a reasonable accuracy, instead of the personal exposures of specific individuals. Combination of the predicted concentrations, the location of the population and the time spent at home, at the workplace and at other places of activity was carried out. This modelling system has been designed to be utilised by municipal authorities in urban planning, e.g., for evaluating impacts of future traffic planning and land use scenarios.

Future scenarios of population exposure above the EU directive limits have also been investigated applying integrated software packages with operational functionalities suitable for use also by non-specialists. Several European cities have a PM_{10} problem mainly due to the use of studded tyres on cars, and subsequent suspension of PM from the road dust deposit of worn away road surface. Applications included assessing various abatement strategies towards 2010 to reduce or eliminate the problem, as well as forecasting future NO_2 pollution levels.

8 Obstruction of local wind flow by buildings

Urban emissions occur mainly within or shortly above the urban canopy layer, i.e., within a zone where the atmospheric flow is largely disturbed by buildings and other obstacles. It is well known that, in comparison to unobstructed terrain, building effects can change local concentrations by more than an order of magnitude. In the street canyon scale, airflow and turbulent fields depend largely on the strongly non-linear interactions between street geometry and micrometeorology. As a consequence, the pollutant concentration fields within the streets and at roof level are poorly assessed. For this reason, the significance of sensors measuring proximity pollution levels within streets, e.g., for health impact assessment, is unknown, especially since vehicle pollutants transform rapidly during their dispersion within the streets themselves. In addition, the accurate representation of the airflow caused by the building obstruction is essential in order to adequately predict air quality in the micro and local scales.

Wind tunnel and full-scale experiments have been conducted by SATURN groups in order to give a better insight into the airflow characteristics generated by obstacles, and to provide detailed databases for the evaluation of numerical model results. The effects of streamwise aspect ratio on the flow within a nominally two-dimensional street canyon whose axis is normal to the oncoming wind were studied in the wind tunnel of the University of Surrey. In particular, the width/depth ratios studied were 0.3, 0.5, 0.7, 1.0 and 2.0. The flow regimes have been studied experimentally using a range of instrumentation for wind velocity and turbulence measurements. The experiment showed that the flow regimes change from a single main re-circulation for aspect ratios 1.0 and 2.0, and a two-vortex flow for aspect ratios 0.5 and 0.7 to a very weak flow within the street canyon that is difficult to be measured by the instruments, indicating the importance of geometry on street ventilation.

The effects of building geometry on the flow become more complex when treating an urban quarter in three dimensions. The experiments conducted in the wind tunnel of the Hamburg University showed that even small changes in street canyon geometry can change the flow pattern within the canopy layer quite significantly. This was demonstrated in the example of the Goettinger Strasse in Hanover, Germany, for which field data was also available. Three different obstacle configurations were replicated in the wind tunnel. It was found that geometrical variations can fundamentally change the flow behaviour within street canyons. Adding geometrical detail or further buildings to the wind tunnel model modifies not only the flow inside the street canyon but also in the side streets. The flow in the streets perpendicular to the canyon can even change direction which results in a completely different ventilation pattern and thus large differences in local pollutant concentrations within the canyon. The airflow and pollution dispersion in this complex urban configuration have been simulated with the prognostic numerical model MITRAS. It was shown that the flow pattern is influenced by local obstacles or openings which should be considered when simulating pollutant transport at a local scale.

The collected data sets from all wind tunnel experiments were used to validate several computational fluid dynamics (CFD) codes, all applying the standard k-ε model. This exercise showed that the implementation of the wall function by the codes is mainly responsible for the differences between experiment and predictions that appear close to solid boundaries for the simple two-dimensional cavities. The results of a complex three-dimensional case showed discrepancies in distinct features of the flow patterns. On the other hand, comparison of model results with the field data illustrated that the agreement or disagreement found is not necessarily a quality indicator for the model when the measurements are taken at only one position within a street canyon close to building irregularities (as is usually the case). Due to the large variations in local concentrations, agreement and disagreement is likely to be random. Special attention should be paid to this result when decisions for the selection of positions for urban monitoring stations are taken. In the frame of SATURN it could be demonstrated that data collected under carefully controlled conditions in wind tunnels are useful for the proper validation of microscale numerical models developed for the simulation of dispersion processes within the urban canopy layer.

The Nantes ’99 experimental campaign offered a detailed database concerning the turbulent characteristics of the flow arising from the presence of vehicles within the street. The analysis of the turbulence produced by the vehicle motion and its effect on pollution dispersion showed the influence of turbulent kinetic energy (TKE) produced by traffic. In low wind conditions, TKE increases up to a threshold value of vehicles density per lane, while above this number the vehicles act rather as a “moving wall”, leading to a TKE reduction. The TKE was found to be correlated with the CO concentration within the canyon and, consequently, it was demonstrated that turbulence induced by traffic does influence pollution dispersion within the street. A method accounting for the influence of moving vehicles in specific urban situations, such as the area around road tunnel openings, street canyons and intersections has been established in CFD modelling, in order to predict the effects of traffic on the local scale pollutant dispersion.

The three-dimensional structure of the turbulent flow in the roughness sublayer over an urban-type surface comprising regular arrays of roughness elements was also investigated within SATURN. Experimental study in the University of Surrey wind tunnel determined the growth of the depths of the inertial and roughness sub-layers over a flat surface covered with a regular array of 3D roughness elements. Spatial averaging was used to remove the variability of the flow due to the individual obstacles. This showed that the spatially averaged mean velocity in both sub-layers could be described by a standard logarithmic law, with mean zero-plane displacement, using the true roughness length and surface friction velocity.

9 Remote sensing and urban air quality management

In recent years remote sensing techniques have gained much importance in the context of air quality management. At the urban scale such techniques range from new monitoring approaches to the use of satellite information.

In the frame of SATURN, the Differential Optical Absorption Spectroscopy (DOAS) technique was applied for the analysis of air pollution in St. Petersburg. In addition, Fourier spectrometers were utilised to assess air pollution in Kiev. Furthermore, an interferometric method was applied for deriving roughness length information from satellite data. The knowledge of the appropriate roughness length is a prerequisite for the reliable description of transport velocity and deposition rates of atmospheric pollutants. This parameter is, therefore, required for environmental pollutant transport and deposition models. Until now roughness lengths were mapped on the basis of land use data from optical remote sensing systems. The disadvantage of this method is the uncertainty in the image classification and the high cost of data processing.

A mapping procedure for roughness length from synthetic ERS interferometry data has been developed within SATURN. Several tests with the real mode airborne Synthetic Aperture Radar (SAR) interferometry data were performed for an area near Bonn and the surroundings of Oberpfaffenhofen, Germany. The major aim of the tests, performed for different areas with different land use types, was to investigate if the typical scattering of the relative phase measurement found in the synthetic interferometry is also present in the real mode interferometry. The results show a high correlation between the standard deviation of the relative phase and the roughness for all major land use categories with the exception of waters.

10 Model Quality Assurance

In order for urban air quality assessments to be reliable, the models used should be quality assured. Model quality assurance (QA) procedures are designed to ensure that the appropriate methods and data are used, that errors in calculations and measurements are minimised and that documentation is adequate to meet the project objectives. As one of the subproject's main objectives, activities were performed within SATURN aiming at the evaluation of local and urban scale models with adequate data sets.

Urban air pollution model evaluation has to be based on an appropriate evaluation procedure and requires the availability of appropriate quality assured data from field studies and/or laboratory experiments. Detailed specifications are normally formulated for all data involved in evaluation procedures in order to avoid model evaluation attempts failing because of missing or inadequate data.

Within SATURN a new methodology was established for the validation of local scale models. This methodology is based on the utilisation of high quality data from wind tunnel measurements. A CFD model evaluation was performed through an intercomparison exercise leading to the conclusion that the implementation of the wall function plays an important role for the simulated flow in the vicinity of solid boundaries.

New knowledge regarding quality assurance of urban scale models resulted from intercomparison activities and sensitivity studies. Model intercomparison is very useful for identifying inconsistencies and for estimating model uncertainties. In particular, the MESOCOM exercise was conducted as a pilot study aiming to improve the transparency of urban scale models. The model results collected were analysed and published on the Internet. A major finding was that large differences exist among the various models, which were found to be primarily due to the surface layer parameterisation and the boundary condition treatment.

Six research groups participated in ESCOMPTE_INT. This model validation exercise aimed at assessing to what extent current models are capable of describing airflow and dispersion phenomena in the atmosphere above a coastal urban area. The exercise elucidated the strengths and weaknesses of the approaches adopted in the models and led to interesting conclusions regarding future research needs.

The use of experimental data in the model validation process makes the implementation of QA measures for data collection necessary, the principal objective being to quantify and to reduce the uncertainties of measurements. For this reason, Data Quality Indicators and Data Quality Objectives were used for the determination of the completeness and the range of acceptability of the data sets.

11 Urban Air Quality Management Systems

The European Air Quality Framework Directive and associated Daughter Directives require projections of air quality in urban areas for assessment against air quality objectives. In addition, air quality strategies necessitate the development of plans to reduce pollution in specific areas. The principal aim of the ongoing development is a practical management system, which can be used to undertake these tasks. This requires an advanced operational air quality model such that a range of air quality management scenarios may easily be assessed. These can include traffic management options such as low emission zones, clear zones or multiple occupancy vehicles etc. and other emission reduction options for other sources. Such analysis also requires that input parameters such as emission factors may easily be modified.

Products of policy relevance that resulted from SATURN work are related to the development and application of integrated systems for supporting urban air quality management as well as reliable tools for forecasting the frequency and severity of air quality limit value exceedances in cities. Therefore, the main common target of the SATURN groups working on such integrated systems was to extrapolate the present air quality into the future for various abatement scenarios. First attempts were performed towards linking Urban Air Quality Management Systems with the optimisation of abatement action packages (e.g., according to cost benefit calculations), using the AIRQUIS integrated air quality management system. The URBIS system was developed as a comprehensive tool for the assessment of air quality in conformity with the new EU air quality directives. The need for comprehensive assessment, both in space (full city) and in time (full year) in combination with high resolution in space (hotspot quantification) and time (hourly concentrations) renders it impossible to rely solely on full-scale 3D grid models. The ADMS-Urban system has undergone significant progress and testing with the development of the Atmospheric Emissions Toolkit, while the system was further used for many local authorities and several major applications regarding air quality review and assessment. The multi-scale model ZEUS was the basis for the development of OPUS-AIR, which is a policy-oriented system for the integrated assessment of technical and non-technical measures that are put forward in order to reduce urban air pollution levels. Several experiments have been performed with OPANA, a tool that may be used by city environmental offices in Europe to "validate" the air quality modelling tools they are using or are intending to use in the future.

Gradually, the tools developed within Urban Air Quality Management Systems for modelling and predicting air pollution are improving in quality and efficiency. At the same time more provisions have been built that link to elements that are at or even beyond the borderline of air pollution research: to the behaviour of the population and the related exposure and health risks; to the costs and the benefits of technical and non-technical measures; to other environmental topics that have strong relations with air pollution (noise, external safety).

12 Public information on air quality

One of the main objectives of SATURN was to investigate the key points in urban environment decision and policy making that interact with the environmental information produced and with relevant integrated environmental surveillance, information and management systems. In order to meet these aspects, activities focused on the requirements for the design and development of such systems, the development of air pollution forecasting tools and the scientific support of multimedia presentation and guidance related to environmental impact assessment related information.

Urban Air Quality Management and Information Systems are systems produced for sophisticated, integrated applications that are city-tailored. Therefore, there are no standards for their development and construction. The development process (life cycle) of such systems results mostly from experience. Also their content may vary significantly from one application to the other. Within SATURN, air quality forecasting tools were developed and tested against hourly mean values of air pollution data in different European urban areas. They were based on time-series models that may be applied for short-term predictions of urban air pollutants such as ozone and SO_2. Moreover, statistical techniques were used as a tool in the development and implementation of a warning system for personal exposure that is designed to support the air quality management of local authorities. A statistical tool based on the Classification and Regression Tree analysis was also used, in particular for ozone forecasting.

Another important application within SATURN was the use of multimedia for an effective interpretation of environmental information. A CD-ROM application was developed with the aim to instruct those wishing to learn more on methods and procedures regarding the compilation of an Environmental Impact Assessment study. The application also includes a general introduction on the basis of a carefully planned presentation scenario.

13 Epilogue

SATURN combined 40 individual contributions from 19 European countries and the European Commission. The total costs of the research conducted is of the order of € 50 million. The results of all contributions were integrated in order to be used for air quality management. The most important prerequisite for bridging the gap between environmental research and management are regular interactions between environmental scientists and decision makers. For this reason, SATURN developed a common structure for the scientific results (data, models, methods) providing an application-oriented framework to be used by the researchers as well as allowing for monitoring the performance of the contributions taken together and analysing the results in terms of applicability. As a result, novel modelling systems were developed comprising models and tools that are properly validated by specially developed techniques. These systems are already being used by local authorities for air quality management and population information.

The advances in the science of urban air pollution achieved within SATURN may be summarised as follows:

- Contributions of field studies to a better insight into the characteristics of polluted urban air
- Significant refinement of urban scale models and methods used therein; valuable new knowledge regarding quality assurance of these models resulting from intercomparison activities and sensitivity studies
- Substantial progress in the development and application of local scale models and establishment of a methodology for their validation
- Development of versatile Urban Air Quality Management Systems and their installation for use by city authorities; successful integration of urban air pollution research into the areas of information and communication technology

Despite the scientific progress achieved in SATURN, several issues related to urban air pollution have not yet been fully explored. More knowledge is needed on the pollutant emissions due to the real traffic behaviour and the sources of PM_{10} and $PM_{2.5}$ affecting the urban atmosphere. Further research is also needed on the chemical and physical properties of particles with emphasis on the formation and regional transport of secondary aerosol. Novel multi-scale model systems based on nested domains with different models will be needed for assessing the impact of urban sources vs. long-range transport with regard to air quality. Also, more effort will be required for the accurate prediction of pollutant concentrations at hot-spot locations. From today's perspective, this aim can only be accomplished with sophisticated local scale models. These, however, will have to be better adapted to regulatory needs. In this context, the combined and fully integrated use of measuring and modelling for air quality assessments is still to be promoted. Finally, the further development of standardised Quality Assurance procedures will result in an increased quantitative level of confidence of model predictions. More and higher quality data from field campaigns and laboratory experiments will be required to meet the needs of complete model evaluation procedures.