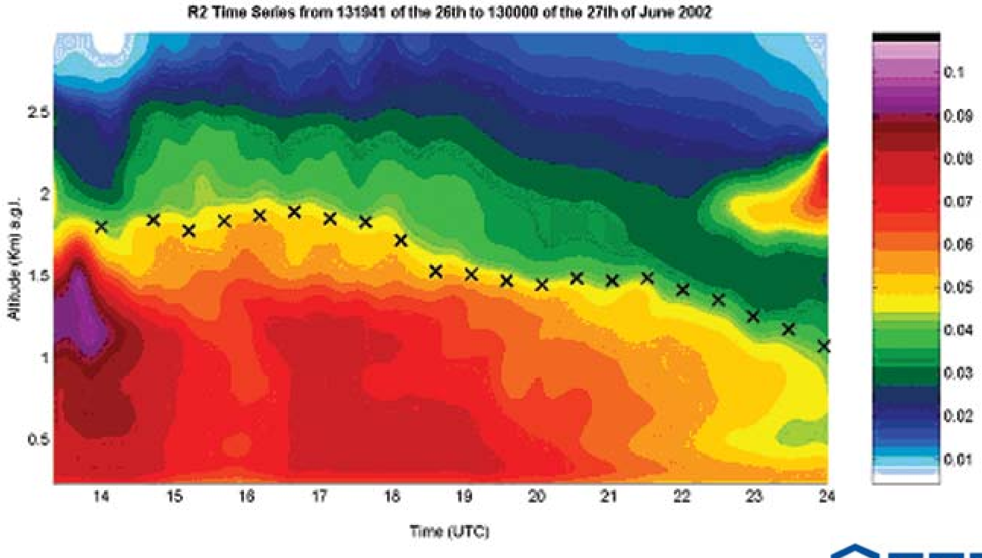
METEOROLOGY APPLIED TO URBAN AIR POLLUTION PROBLEMS

Final Report COST Action 715

Editors: Bernard Fisher, Sylvain Joffre, Jaakko Kukkonen,
Martin Piringer, Mathias Rotach, Michael Schatzmann



COST – the acronym for European **CO**operation in the field of **S**cientific and **T**echnical Research – is the oldest and widest European intergovernmental network for cooperation in research. Established by the Ministerial Conference in November 1971, COST is presently used by the scientific communities of 35 European countries to cooperate in common research projects supported by national funds. The funds provided by COST – less than 1% of the total value of the projects – support the COST cooperation networks (COST Actions) through which, with only around € 20 million per year, more than 30.000 European scientists are involved in research having a total value which exceeds € 2 billion per year. This is the financial worth of the European added value which COST achieves. A "bottom up approach" (the initiative of launching a COST Action comes from the European scientists themselves), "à la carte participation" (only countries interested in the Action participate), "equality of access" (participation is open also to the scientific communities of countries not belonging to the European Union) and "flexible structure" (easy implementation and light management of the research initiatives) are the main characteristics of COST. As precursor of advanced multidisciplinary research COST has a very important role for the realisation of the European Research Area (ERA) anticipating and complementing the activities of the Framework Programmes, constituting a "bridge" towards the scientific communities of emerging countries, increasing the mobility of researchers across Europe and fostering the establishment of "Networks of Excellence" in many key scientific domains such as: Physics, Chemistry, Telecommunications and Information Science, Nanotechnologies, Meteorology, Environment, Medicine and Health, Forests, Agriculture and Social Sciences. It covers basic and more applied research and also addresses issues of pre-normative nature or of societal importance.

COST Action 715
Final Report

Front cover:
LIDAR scans of the backscatter from the atmosphere on 26 June 2002. The measurements are performed in Basel during the BUBBLE experiment. The mixing heights as determined from the derivative of the range-corrected signal are indicated by crosses. *Courtesy of V. Mitev, R. Matthey and G. Martucci, Observatory of Neuchatel, Switzerland.*

Back cover:
Schematics of the boundary layer over an urban area. Red represents the urban internal boundary layers where advection processes are important. Green shows the inertial layers that are in equilibrium with the underlying surface and where Monin-Obukhov scaling applies. The blue region is the roughness layer that is highly inhomogeneous both in its vertical and horizontal structure. The yellow region represents adjustment between neighbourhoods with large accelerations and shear in the flow near the top of the canopy. After Batchvarova and Gryning, 2005 (In *Theoretical and Applied Climatolofy, 2005*). *Courtesy of Morten Gryning for the drawing.*

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Generally the worst air pollution occurs in cities. This report describes the conclusions of the COST 715 programme, a European activity which supports scientific exchange and networks, on 'meteorology applied to urban air pollution problems'. One of the key aims of European environmental policy is to improve air quality in European cities and urban areas. Given a certain level of emission and that adverse air quality conditions are mainly driven by specific meteorological conditions, one should be concerned whether urban meteorology is being treated properly in regulatory air quality assessments. This concern introduces real practical problems for the meteorological community. For example, some of the meteorological variables in regulatory air quality models are quantities that are not routinely measured, such as the surface flux parameters, or the mixing layer depth. COST 715 has tackled these problems. It has developed and reviewed the latest scientific approaches to describing the urban boundary layer, which has a complex structure involving wide variations in time and space.

Participants in COST 715 are listed in Appendix G.

Work within four Working Group has concentrated on measurements and models to understand:

1. The dynamics of the urban boundary layer: Working Group 1, Chairman Mathias Rotach, Swiss Federal Office for Meteorology and Climatology,

MeteoSwiss, mathias.rotach@meteoswiss.ch, and members: Ekaterina Batchvarova, Ruwim Berkowicz, Josef Brechler, Zbynek Janour, Ewa Krajny, Emilia Georgieva, Douglas Middleton, Leszek Osrodka, Victor Prior and Cecilia Soriano.

2. The thermal structure of the urban surface and boundary layer: Working Group 2, Chairman Martin Piringer, Central Institute for Meteorology and Geodynamics, Vienna, Martin.Piringer@zamg.ac.at, and members: Sylvain Joffre, Alexander Baklanov, Koen De Ridder, Marco Deserti, Ari Karppinen, Patrice Mestayer, Douglas Middleton, Maria Tombrou, Part-time: Jerzy Burzynski, Andreas Christen, Roland Vogt, Joao Ferreira.

3. Air pollution episodes: Working Group 3, Chairman Jaakko Kukkonen, Finnish Meteorological Institute, jaakko.kukkonen@fmi.fi, and members: Ranjeet Sokhi, Douglas Middleton, Sandro Finardi, Luisa Volta, László Bozó, Tamás Präger, Alix Rasmussen, Barbara Fay, Rosa Salvador, Millán Millán, Erik Berge, Leiv Håvard Slørdal, Renato Carvalho, Victor Prior, Antonio Viseu, Francois Bompay, Alexis Coppalle, Christine Lac, Guy Schayes, Petroula Louka.

4. Preparation of meteorological input data for urban air pollution models: Working Group 4, Chairman Michael Schatzmann, University of Hamburg, Meteorological Institute, schatzmann@dkrz.de, and members: Arno Graff, Wolfgang Müller, Giovanni Leuzzi, Nicolas Moussiopoulos, Daniel Martin, Alexis Copalle, Raimund Almbauer, Marco Deserti.

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Executive summary

One should be genuinely worried whether urban meteorology is being treated properly in air quality assessments used in regulatory applications. European requirements for air quality management come under the EC Framework Directive 96/62/EEC on Ambient Air Quality Assessment and Management. This Directive defines the policy framework within which limit values for air pollutants are set. Limit values for the specific pollutants have progressively been set through a series of Daughter Directives. For many of these pollutants highest concentrations arise in urban areas. Urban air quality is a high priority as it is directly linked to concerns about human exposure and health. The Framework Directive imposes monitoring conditions on cities and as well as the duty to prepare action plans to deal with poor air quality. Since this requires tackling future situations it is only through modelling, which depends on a good understanding of urban meteorology, that proper assessments can be made and the appropriate decisions made.

The technical implementation of the Framework Directive is being undertaken through the Clean Air for Europe (CAFE) programme of technical analysis and policy development. Its aim is to develop a strategy to protect against significant negative effects of air pollution on human health and the environment. Its requirements include developing information relating to the effects of outdoor air pollution, and air quality assessment and projections, leading to the identification of the measures required to reduce emissions. Urban meteorology plays an important role in this and has been a neglected area, with meteorological conditions often applied with little regard to whether urban factors are important.

The urban area can be considered as a special case of a non-homogeneous terrain. Simple methods relying on the assumption of homogeneous surface conditions to describe the meteorology affecting atmospheric dispersion do not necessarily work. Sometimes the inhomogeneity can be described in a numerical weather prediction model, but if the urban area comprises a few grid cells or less in the model, the prediction is likely to be inaccurate. The hope is that by suitable aggregation, surface variations will be smoothed, and methods which treat inhomogeneity in an approximate way will be sufficient. This is the problem of the aggregation of surface variations. Exact guidance on how to treat this situation is hard to obtain. It is a problem of dealing with complexity because of the nature of urban surfaces, and the extent to which large scale variations can be treated without dealing with small scale variability. Even with the availability of advanced computing, it is not possible to apply the direct approach and describe detailed factors over every scale. Simplifications adopted in some other areas of science cannot be applied because the development and structure of urban regions are dependent on local factors, which are not easily generalised. Urban meteorology can thus be seen as one example of the problem of treating variations over a broad range of scales. The benefits of COST 715 are wider than urban meteorology. Ideas discussed within COST 715 can be used in other applications.

To tackle this complex problem COST 715 has encouraged the development of a number of new data sets and the testing of a range of approximating procedures. COST 715 has considered most of the available methods. All methods require measurements for testing, but as these need to be made above roof level such data is not routinely available, except from a few specific measurement programmes and these will be reviewed. There is an ongoing debate on where to site meteorological instruments in urban areas, as measurements would not be representative of a larger area (another way of stating the averaging problem). Nevertheless regulators need to make decisions about industrial processes in or near an urban area. COST 715 has concluded that regulators in many European countries are applying methods to urban dispersion problems which may be suspect, because of the way urban meteorological data is handled.

An inventory of European urban meteorological sites has been prepared and COST 715 has made recommendations on the siting of urban meteorological instruments so that pollution calculations are more reliable. Notable results are the need to describe properly the roughness sublayer of the atmosphere, containing and in the vicinity of large urban roughness elements, to treat the urban surface heat exchange at night, and to interpret extensive urban field measurement programmes and urban air pollution episodes. In addition COST 715 provides advice on where urban meteorological data may be obtained. It proposes a 'reference height' for urban meteorological wind speed measurements.

As no single solution to the averaging problem has emerged, computer models are seen as the way of tackling this complex issue as well as improving the forecasting of air pollution episodes. The sensitivity and accuracy of air quality predictions to assumptions regarding urban meteorological parameterisations in computer models is discussed. A broader view of environmental decision making should be taken, especially with regard to the inclusion of uncertainty. The new COST actions on meso-scale and micro-scale models should be noted. Finally the future role of remote sensing and physical modelling should be stressed.

1. General Introduction

Bernard Fisher

1.1. COST 715 within the scientific and legislative context

One of the key aims of European environmental policy is to improve air quality in European cities and urban areas. The framework Directive on air quality assessment and management was adopted by the Council of Ministers of the European Union in September 1996. It has led to daughter Directives on several air pollutants (NOx, ozone, CO, PM_{10} etc) for which assessments of air quality in certain areas (mainly large urban areas with high populations) will be required. Remedial plans may need to be drawn up in areas of poor air quality. To undertake these tasks, reliable air pollution models are necessary to supplement, and sometimes replace, measurements and also to investigate future emission scenarios. These models will need accurate meteorological input variables consistently applied within EU Member States.

These requirements introduce real practical problems for the meteorological community. For example, some of the meteorological variables are quantities that are not routinely measured, such as the surface flux parameters or the mixing layer depth. Usually the number of full meteorological stations in urban areas is limited to a few sites, often just at airports, thus not really representing urban conditions.

One reason for this discrepancy is that the resolution of atmospheric/meteorological models has previously been too coarse (a few tens of kilometres) to be able to encompass small-scale features typical of urban areas. However following huge advances in computational power as well as improved understanding of small-scale processes, the meteorological community has recently started to shift to so-called γ-mesoscale models (1–10 km, 0.5–3 hours), whereby many local features can be described and/or modelled. On the other hand, this has induced new requirements for observational arrangements in terms of parameters, resolution and frequency.

Most major European cities have an air pollution monitoring network and are interested in predicting air pollution episodes one day or more in advance. The intention of city administrators is to issue warnings about forthcoming episodes and encourage a change in the urban population's behaviour. Emergency plans have been designed for several European cities which involve city authorities taking air quality management measures to reduce the adverse health impacts on the population. Such measures could include (1) to encourage a decrease in car use, (2) to provide free public transport (or to promote its use), or (3) to persuade sensitive individuals to take precautionary action. Any such measures require accurate predictions of the meteorological variables which determine air quality. However the meteorological description of pollution episodes requires parameters that are not normally directly available, and therefore significant processing of routinely measured data has to be undertaken.

Another related requirement of pollution protection agencies in European countries is to be able to explain and interpret why high pollution levels have occurred on a specific day. High pollution levels may be recorded by a monitoring network, or could coincide with an increase in hospital attendances. The causes of air pollution episodes are complex and depend on various factors including emissions, meteorology, topography, atmospheric chemical processes and solar radiation. Commonly the meteorological description of the episode is crucial to the interpretation. Long-term monitoring data can be used to raise awareness of decision-makers and to define and assess protection measures (e.g. legislative, technical and social).

Characterising and predicting air quality in urban areas is a tremendous task that cannot be accomplished solely by monitoring chemical and meteorological descriptors at a few sites. The complexity of the urban environment sets special requirements for siting the observation equipment to provide representative values of a given urban zone, which are not much affected by nearby buildings or pollution sources. The interpretation of atmospheric conditions and pollution levels between measuring sites, and the forecasting of meteorological and air quality conditions require models. Models able to accurately calculate meteorological and pollution conditions in the layers close to the surface, require data inputs and/or parameterisations (i.e. pre-processors) of urban wind, turbulence profiles, surface heat flux and mixing height.

Models for urban wind, turbulence profiles, surface heat flux and mixing height
Models for simulating air quality pollution transport include both simple dispersion models and more complex, numerical simulation models. Meteorological pre-processing models are needed to provide the boundary conditions, or parameter values, profiles etc, needed by the pollution transport models. Such boundary conditions and parameter values and profiles are commonly provided for rural areas. The underpinning purpose of COST 715 Action, Meteorology

Applied to Urban Air Pollution Problems, was to review, assess and contribute to the development of methods for providing this meteorological information specifically for urban pollution transport models. The urban situation is important, as pollution levels are generally highest in urban areas and this is where the vast majority of European citizens live (ca. 70%). The meteorological pre-processing methods and models should be tested against detailed measurements.

This report should be considered a working document of a newly stimulated field of research. Hence it represents work in progress and contains some repetition. This repetition has been retained as new ideas and concepts sometimes need to be expressed in different ways. The breadth of issues is considerable. To focus ideas attention has been paid to the practical questions of making air quality predictions or assessments in urban areas. There has been in parallel to the work reported, much progress and development elsewhere, such as in North America. (See, for example, the technical programme at the American Meteorological Society Meeting in Seattle, January 2004, Symposium on Planning, Nowcasting and Forecasting in the Urban Zone, `http://ams.confex.com/ams/84annual`.) No attempt has been made to incorporate such work in this volume as it represents research not directly associated with COST 715.

1.2. Urbanising pollution transport models

The preparation of meteorological data for urban air pollution models takes various forms and is an important part of an air quality prediction, much like the preparation of emission data. The preparation depends on the type of assessment to be performed. In COST 715 a large number of methods have been reviewed (see COST 715 reports Appendix D) ranging from the simple to the complex. A 'simple' assessment would represent an air quality dispersion model in which the meteorological description is simple (one-dimensional in the vertical), with dispersion not varying with the location of the source in the urban area, except with source height. Simple models may be contrasted with 'complex' integrated, grid-based models, in which the description of the meteorology is three-dimensional, and the flow and dispersion varies in space and time. The term 'simple' may appear to be a contradiction when applied to an urban area, but it is often very difficult to specify an accurate three-dimensional flow field over an urban area. The choice of approach depends on the observational data available and on the accuracy of the assessment intended.

Clearly if the emission data is uncertain there is no point in applying a detailed model.

In each case the meteorology should be 'urbanised' if it is to be appropriate to urban areas. The starting point for a dispersion calculation is one or more sets of meteorological data within the urban area. The data set typically consists of hourly measurements of wind speed, direction, temperature, cloud cover, or more sophisticated radiation observations, and these data will be processed to produce an urban set of dispersion categories (e.g. the Monin-Obukhov length) and wind speeds. The COST 715 Inventory of Urban Meteorological Stations may be consulted (see Chapter 9).

The alternative approach, which permits time and space varying meteorological fields to be used, is the meteorological meso-scale model. In this case no specifically urban data is required, but one faces issues relating to scales.

The general features of a meso-scale model need to be considered in relation to the urban area's location e.g. does surrounding topography, or background sources affect the choice? The user of a three-dimensional transport model needs to decide on the input data sets needed to make the calculation. Features of the meso-scale model depend on the pollutant under consideration and the spatial variability in concentration fields. Questions arise about the extent of the area to be modelled to avoid boundary effects and under what situations is the extra calculation worthwhile.

A numerical model has a finite resolution. Methods for aggregating fluxes which vary over lengths scales shorter than the grid length need to be agreed. In particular, the treatment of fluxes near the surface is critical for an adequate representation of the key processes at play. These fluxes need to be parameterised. Some meso-scale models do not take account explicitly of the urban area because of their limited spatial resolution. Most of them, even if they have good enough spatial resolution, parameterise the near-surface fluxes by means which do not take into account the dominating roughness elements in urban areas. Therefore the lowest level in the model should be set somewhere near the so-called blending height, at which surface variability merges into a more homogeneous structure. Alternatively, a specific urban parameterisation must be invoked.

For the model to be useful at street level, methods for downscaling the model from grid squares to local features are needed. Local scale models can be nested within meso-scale models. These issues have been discussed within COST 715 and reported in various COST 715 publications.

One of the main benefits of meso-scale air pollution models is that they enable predictions of air pollution episodes to be made. Urban meso-scale models also enable observational data to be interpreted. Concepts applied in the simpler models can be tested in more detailed numerical or physical experiments, to determine whether the concept is useful, or has generalised application.

1.3. Purpose of the COST 715 Action

The COST 715 Action was launched when the scientific communities from two previous Actions, COST 710 and COST 615, joined together to address the specific issues concerned with measuring, describing and modelling meteorological and atmospheric characteristics in the urban environment, in order to improve air pollution models aimed at diagnosing or predicting air quality in cities or conurbations.

There has been a suite of COST Actions dealing with these specific issues, as COST is very suitable for European co-ordination and harmonisation in the exploration of developments in new and emerging problems. COST (European Co-operation in the field of Scientific and Technical research) is the oldest (founded in 1971) and widest European intergovernmental network (see `http://ue.eu.int/cost/default.asp` or `http://cost.cordis.lu/src/home.cfm`). It includes 35 member states.

The Action COST 710 (Harmonisation in the pre-processing of meteorological data for dispersion models, 1994-1997, involving 16 countries) addressed the issues of intercomparability of sub-modules for dispersion models (Fisher *et al.*, 1998). It identified schemes in current use for obtaining the key meteorological variables associated with pollution. However COST 710 could not pay much attention to urban meteorological situations due to the lack of suitable data and of a satisfactory conceptual framework.

The COST Action 615 (Database, Monitoring and Modelling of Urban Air Pollution, 1993-1998, involving 18 countries) was one of four parts of the COST programme CITAIR Science and Research for Better Air in European Cities.

The intention of the programme was to launch a major European concerted effort in the field of urban environmental protection. New infrastructure projects or land-use alteration requires environmental impact studies before they can be accepted, while information on air quality has to be provided to the public. Moreover local meteorology and topography vary considerably throughout Europe as do the emission fingerprints from traffic, domestic heating or industrial activities. This has led to the fragmentation of efforts with little exchange of information and experience between local decision makers.

COST 615 promoted an overview of existing databases for urban air quality and considered a framework for a European database and the use of databases and comprehensive air quality indices. Secondly it addressed the European-wide harmonisation of urban monitoring activities including current techniques, siting criteria, inter-calibration and the development of methods for determining real human exposure to pollutants. Thirdly it reviewed models used for urban air pollution studies by considering the types of models used, the use of models, the quality of models and the harmonisation of model requirements, descriptions and limitations (Schatzmann, 2000). However this was only a preliminary step, mainly addressing the very small scale (up to a few streets) and COST 615 did not make any assessments of these data and methods.

The purpose of COST Action 715 involving 19 countries (1998-2004, `http://www.dmu.dk/atmosphericenvironment/cost715.htm`) was thus specifically to focus on the key topic of urban meteorology at all scales, and on the aspects of meteorology which determine pollution levels. The joint endeavour leading to COST 715 was timely as current atmospheric numerical models are in the phase of refining their spatial resolution, through the increase in computing capacity, to a few kilometres, whereby urban features (and their feedbacks) can be included.

The objective of COST 715 was to increase knowledge of, and the accessibility to, the main meteorological parameters which determine urban pollution levels, by comparing and contrasting methods in use in European countries, leading to recommendations of the best way of using routine meteorological information in air pollution assessments. Specifically this included the intention to:

- to review relevant theoretical concepts of the structure of the urban boundary layer with available field measurements for calculation of relevant parameters.

- to review and assess pre-processors, schemes and models for determining the mixing height, the surface energy budget and the stability. Cases of strong stability and/or light wind conditions are of special interest.
- to identify and review suitable data sets within and outside the group of COST 715 participants which that could be used to test and validate the pre-processors and models.
- to carry out inter-comparisons and to summarise comparisons of different schemes against each other and against data under specific conditions.
- to assess the suitability of remote sensing tools to estimate canopy characteristics and surface fluxes.
- to provide recommendations for the improvement of existing pre-processors and models and for the development of new schemes.
- to provide recommendations for planning and conducting field campaigns in order to fill existing gaps in empirical data relating to urban air pollution.
- to provide recommendations for developing representative meteorological monitoring able to describe various fields and processes under urban conditions.
- to promote co-ordination of related activities in Europe of presently scattered research, objectives, and responsibilities.

1.4. Outline and structure of COST 715 final report

The theme of models, observables and concepts to aid understanding, runs throughout this volume. COST 715 shows examples of trying to build integrated models from their parts. There is a need to have understanding of the individual processes and how they relate to one another. Even in a detailed model, averaging over grid squares must occur and this requires simplifying concepts. The starting point is an understanding of the urban boundary layer.

Chapter 2 introduces the structure of the urban boundary layer. In Chapter 3 the dynamics of urban areas are reviewed (essentially the role of Working Group 1). In Chapter 4 the surface energy balance in urban areas is considered, followed by the related topic in Chapter 5 of the mixing height and inversions in urban areas (Working Group 2's areas of interest). Chapter 6 shows how pollution episodes can be analysed and evaluated, and how advanced models can be applied to predicting episodes. This is closely related to the description of the broad features causing air pollution episodes in southern European cities described in Chapter 7. Chapters 6 and 7 are outcomes of Working Group 3's work.

Chapter 8 gives practical advice on the shape of wind profile in urban areas (one outcome of Working Group 1's work), while Chapter 9 shows how meteorological input for urban air pollution assessments may be obtained in European cities (the area of interest of Working Group 4). Chapter 10 explains how the concepts have been tested in a large field programme, while Chapter 11 illustrates their use at a single city location. In Chapter 12 an EU funded research programme promoted by the COST 715 community to test and improve forecasting methods is described. A wide range of European cities have been involved, either in the testing or the application of air pollution models.

Chapter 13 addresses the specific issue of the interactions and the untangling of the various intervening scales in urban meteorology and diffusion problems. Chapter 14 summarises the various results of the Action, while Chapter 15 assesses the remaining gaps in our knowledge and formulates some recommendations and conclusions. Appendix A aims at explaining, in simple words, the main concepts developed and used in this Report. Finally the other Appendices list the details of publications, workshops and field experiments generated or stimulated by and through COST 715.

1.5. Chapter references

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2. Structure of the urban boundary layer

Mathias W. Rotach

2.1. Broad features of the urban boundary layer

The urban boundary layer has a complicated three-dimensional structure making it difficult to comprehensively describe (Rotach *et al.*, 2002). In Fig. 2.1 this (idealised) structure is sketched. Its major modification as compared to the traditional 'text book' boundary layer is largely determined by the fact that exceptionally large roughness elements, such as buildings and trees, are present. Moreover for city centres the majority of the roughness elements are buildings that have distinctly different aerodynamic properties (e.g. stiffness) than more commonly investigated trees, bushes or grass.

In the horizontal, an urban environment is characterised by a distinct, and sometimes a less distinct, change in the roughness and thermal surface properties (heat capacity, albedo) of the surface at the city's edge. This is thought to lead to the formation of an internal boundary layer (Fig. 2.1a), although its rate of growth and characteristics has not yet been investigated in detail for real cities. As a suitable model for its growth, therefore, the standard internal boundary layer growth (e.g. Kaimal and Finnigan, 1994) is often used. Clearly in a large conurbation with different suburbs (e.g. 'downtown', 'suburban' 'industrial') further internal boundary layers may evolve according to the differences in the surface properties of each suburb or quarter.

In the vertical, the lowest distinct layer is the urban canopy layer that ranges from the ground up to roughly the average height of roughness elements (buildings and trees), z_H (Fig. 2.1c). Within the urban canopy layer, the best-investigated entity is a street canyon, ideally straight and with buildings of equal height on either side. In Figure 2.1c a circulation flow ('vortex') is sketched, which ideally develops for ambient flow normal to the canyon axis. This vortex can be simulated using high-resolution numerical modelling (e.g. Sini *et al.*, 1996) and has also been observed (e.g. DePaul, 1984). Given the fact that pollutant sources in a street canyon mainly originate from traffic, such a vortex can induce substantial pollutant gradients between the windward and leeward sides of the street. The thermal conditions in a street canyon are determined through the sky view factor (Fig. 2.1c) and hence the width-to-height ratio. In real street canyons the varying orientation, intersections and areas of buildings of variable height pose the largest problem when attempting to apply idealised concepts.

The urban canopy layer is part of the roughness sublayer, which encompasses the height range in which the flow is directly influenced by the roughness elements and hence is essentially three-dimensional (Raupach *et al.*, 1991). Its height, z^*, is dependent on the height and density of roughness elements, but for simplicity is often expressed as $z^* = az_H$ where a is found to range between 2 and 5 for plant canopies (Raupach *et al.*, 1991). Recent studies indicate that for the relatively regular structure of the urban fabric, as it is typical for many European cities in their central parts, a may lie closer to the lower end of this range i.e. $a \cong 2$ or even slightly smaller (Rotach 2001, Kastner-Klein and Rotach, 2004). These findings arise from defining $z*$ based on the profile of Reynolds stress (see Section 3) and may have to be changed if other variables are considered. Although the roughness sublayer is, through its definition, three-dimensional in its flow and turbulence structure, it is often found useful to devise spatially averaged profiles for these quantities, at least if urban-scale pollutant dispersion is concerned.

Above the roughness sublayer there is an inertial sublayer (see Fig. 2.1b) that corresponds to the true matching layer over ideal surfaces (Tennekes and Lumley, 1972). Hence under ideal circumstances (stationary conditions and a large enough distance to the smooth-rough transition and the city boundary etc.) we may expect Monin-Obukhov Similarity Theory (MOST) to apply within the inertial sublayer. However for typical conditions the inertial sublayer may often be squeezed between the roughness sublayer and the layers above (Fig. 2.2). This diagram further shows that the crucial layer to know within an urban environment is the roughness sublayer simply due to its usually dominant vertical extension.

Note that the lowest atmospheric layer over less rough and ideal surfaces is often called the surface layer (e.g. Kaimal and Finnigan, 1994) and hence Monin-Obukhov Similarity Theory is referred to as surface layer scaling. (This simply means that in such cases the roughness sublayer is too thin to be relevant). We are therefore left with the choice between a name for this layer that corresponds to the scaling regime, but has a misleading meaning (surface layer, but not the lowest layer next to the surface) and a name that refers to its dynamical origin, inertial sublayer. In this volume this layer is referred to as the inertial sublayer, so that the two sublayers (roughness and inertial sublayer) make up the equivalent to the surface layer over smoother surfaces. However this entire

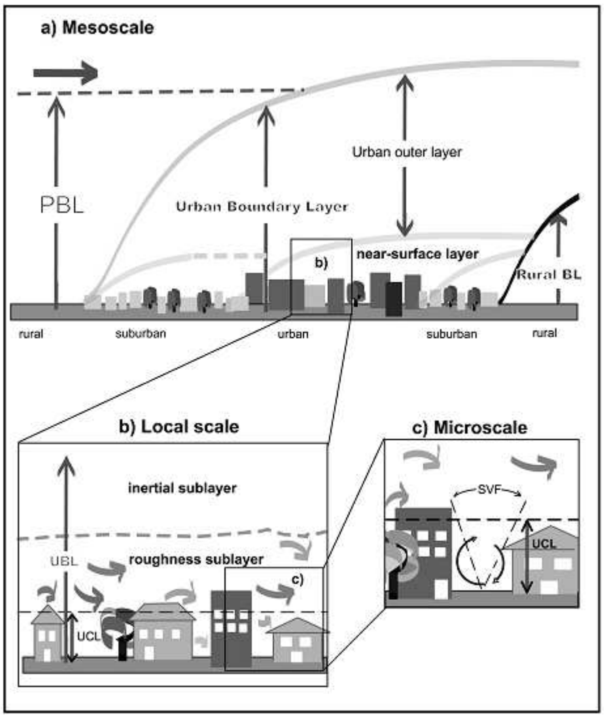

Fig. 2.1: Sketch of the urban boundary layer structure indicating the various (sub)layers and their names (from Rotach et al., 2004, modified after Oke, 1987). An unstable daytime urban boundary layer is shown. For a stable layer of height $h \cong 200$ m, $h/z_H \cong 10$ and $z^*/h \cong 0.1$ to 0.3.

layer next to the surface does not obey conditions found in other papers when referring to surface layer scaling.

Above the inertial sublayer, the urban boundary layer is, except for exceptionally extensively homogeneous city structures, to a large extent determined through advective processes (illustrated in Fig. 2.1a). Little is known, at present, as to whether or not this outer part of the urban boundary layer exhibits the characteristics of mixed layer scaling under convective conditions or local scaling under stable stratification (see Sections 4 and 5 for a discussion on stability over urban surfaces). One should therefore refer to this layer as to the outer urban boundary layer without making a distinction according to stability.

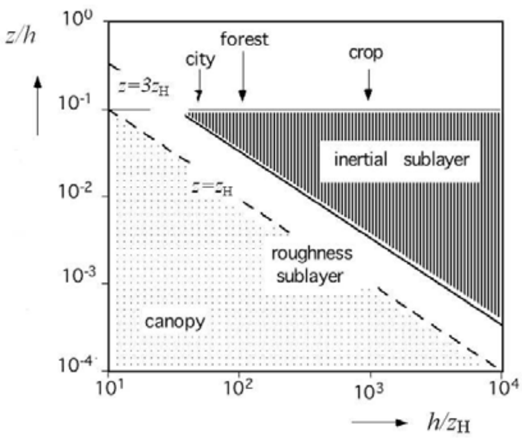

Fig. 2.2: Sketch of the vertical extension of the various layers over rough surfaces and their variation with the non-dimensional quantities z/h and h/z_H, where h denotes the boundary layer height and z_H stands for the canopy height. The height of the roughness sublayer z^* is assumed to equal $3z_H$. The arrows 'city', 'forest' and 'crop', are drawn using $h = 1000$ m together with $z_H = 20$ m (city), $z_H = 10$ m (forest) and $z_H = 1$ m (crop), respectively. From Rotach (1999).

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3. Modification of flow and turbulence structure over urban areas

Mathias W. Rotach and Working Group 1[1]

3.1. Issues

The flow and turbulence characteristics in the boundary layer over an urban surface are largely determined by the surface's very rough character and the typical 'surface' materials, that are predominantly impervious and characterised by a relatively large thermal conductivity. These two factors determine the general features of the urban boundary layer structure as they were outlined in Chapter 2. In this chapter we are mainly concerned with the dynamical characteristics of the flow (increased roughness), while the thermodynamical properties are summarised in Chapter 4. Key to the understanding of the flow structure over an urban surface is therefore the fact that a roughness sublayer of non-negligible vertical extension is present (see Fig. 2.2 in Chapter 2) and must be taken into account when describing it. Typically when the roughness elements reach an average height of 20–40 m in a European city, the top of the roughness sublayer z^* is at some 50–100m. Observations are generally made within this layer (ideally at its upper end) and models of air pollution transport and dispersion depend on its characteristics.

From a meso-scale perspective, that is when the individual roughness elements cannot be resolved, the bulk characteristics of the rough surface determine the exchange of momentum, heat and atmospheric constituents (such as pollutants). This exchange, due to the presence of the roughness sublayer, is different from that over a reasonably smooth surface. Noting that in a high-resolution meso-scale model (1 km horizontal grid spacing, say, or meso-γ) at least the lowest model level is within the roughness sublayer and that traditional surface exchange schemes use surface layer scaling,this raises a question:

1. To what extent is surface layer scaling appropriate for the conditions within an urban roughness sublayer?

From a micro-scale perspective we may note that street canyons or intersections are often 'hot spots' in terms of pollutant concentrations, and modelling efforts

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are needed to address possible abatement strategies. Hence depending on the application, either the details of every single roughness element need to be modelled, using a physical model (wind tunnel) or a very highly resolved (of the order of one metre) numerical model, or the street canyon under examination is investigated using an idealised and simplified model. In the latter case, some information on the overall flow situation must be provided. Then the relevant question becomes:

2. Is there a suitably well-defined 'above roof wind', from which the flow and turbulence state within the canyon can be inferred?

To attempt to answer this the following key issues were addressed within COST 715:

1. A need to understand the physical processes driving the turbulent exchange in the urban roughness sublayer and to parameterise the typical vertical profiles for variables of interest therein.
2. A need for having appropriate means to assess the spatial variability within the urban roughness sublayer. This will help to judge the representativeness of an observation used as input to any type of numerical model. Also local information may be aggregated for use in a model at a larger scale.
3. A need for assessing the extent to which existing parameterisations of boundary layer profiles (mean wind speed, turbulence statistics) are appropriate for use in the urban context, and especially how the 'surface' fluxes of momentum and sensible heat need to be defined in order to obtain suitable scaling variables (e.g. friction velocity, convective velocity scale etc).

Associated with 1 to 3, there is a need to give advice on how to treat the 'surface exchange' in meso-scale models and how to use remote information (e.g. from the nearest airport) to estimate input data in an urban application.

3.2. Approaches

Concerning the flow and turbulence characteristics in urban areas the following approaches were adopted within COST 715[2].

Expert knowledge
By assembling a number of experts on urban boundary layer meteorology and observations, working group meetings provide an excellent opportunity to obtain a literature review of existing physical approaches and collect information on existing data sets to be used in order to test these.

Organisation of workshops
Based on a literature review and the identification of specific topics of interest, a workshop on Urban Boundary Layer Parameterisations was organised in April 2001 in Zürich, Switzerland (Rotach *et al.*, 2002). Apart from members of the COST 715 community, a number of experts from Europe and the USA contributed significantly to this workshop, which yielded an up-to-date overview of the topics and possible approaches to the questions outlined above (Rotach *et al.*, 2002).

Triggering of specific research initiatives
The work within COST 715[2] triggered a number of research activities at the institutions of the participants:

1. The Basel UrBan Boundary Layer Experiment (BUBBLE) was a major urban boundary layer research activity, directly made possible through special funding conditions for COST Actions in Switzerland. BUBBLE directly responded to questions and needs as raised within COST 715. An overview on BUBBLE is given in Chapter 10 of this report.

2. An institutional partnership was launched between the Swiss Federal Institute of Technology, the National Institute for Meteorology and Hydrology, Bulgaria, and partners from Macedonia in the framework of the SCOPES programme and again responded to a number of the questions brought forward by COST 715. Progress is outlined in Chapter 11.

3. Three urban experiments were conducted in Birmingham, U.K., as described in Ellis and Middleton (2000a, b, c). Instruments were operated

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on 15, 30 and 45m masts for 4-week periods in 1998, 1999 and 2000 at a factory site within the city. Synoptic observations were taken from a station outside the city. During the 2000 campaign, following discussions in COST 715, a sonic anemometer was also placed on the 15m mast beside the rural station, to measure turbulence statistics simultaneously at both sites. Just adding this one instrument to an existing standard observing station provides valuable measurements of variables that strongly influence dispersion near the ground, the friction velocity and the Monin-Obukhov length. Traditionally these are not often routinely observed. The experiment was reviewed in Middleton *et al.* (2002) and some results are introduced in Chapters 4 and 5 of this report.

Development of specific tools
In the course of COST 715 a number of approaches were developed concerning the estimation of the 'urban' wind speed from nearby rural observations and the specification for the wind profile throughout the urban boundary layer. They are briefly outlined in the next section.

3.3. Achievements

Flow and turbulence structure of the urban roughness sublayer
From the above activities a clear picture of the flow and turbulence structure within an urban roughness sublayer emerged (Kastner-Klein, 2002). The two main characteristics are identified as follows.

Turbulent fluxes are not constant with height. Although different from city to city and site to site, parameterisations can be found which use the height of the maximum Reynolds stress and a zero plane displacement height, as length scales, and the magnitude of the maximum Reynolds stress, as the basis for a velocity scale (Rotach 2001, Kastner-Klein and Rotach 2004). Figure 3.1 shows an example. Similarly results from BUBBLE (Chapter 10) show for the first time that turbulent fluxes of sensible heat are also not constant with height within the urban roughness sublayer (Fig. 3.2).

As an answer to the first question in Section 3.1 and as a consequence of the above result, it is clear that surface layer scaling cannot be employed within the urban roughness sublayer. Instead local scaling has been found to apply at least in the upper part of the roughness sublayer. Roth (2000) gives a comprehensive overview of available data sets and results.

The height where the turbulent fluxes exhibit their maximum magnitude is thus an important quantity to estimate. It ranges between 1.5 and 5 times the average building height and is clearly also dependent on the variability of building heights around the mean. For very uniform building arrangements it is closer to the lower limit of the above range, while in cases of large variability it is closer to the upper limit. No functional description has been established so far, which would relate this height to the commonly used descriptors of urban morphology.

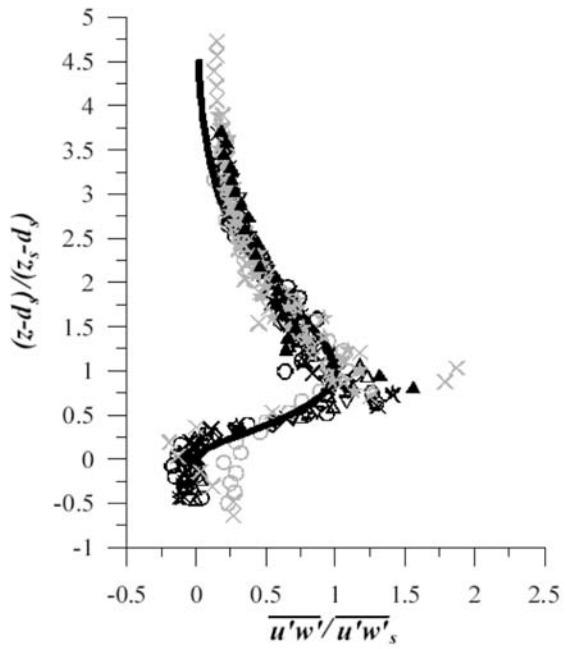

Fig. 3.1: Profiles of suitably scaled momentum flux at 11 different urban sites. Data from a wind tunnel study using a model of the city of Nantes (Kastner-Klein and Rotach, 2004).

The magnitude of the maximum Reynolds stress can be interpreted as the result of the total drag the surface exerts on the flow aloft. It therefore determines the 'surface friction' from a bird's view and can be used to derive a friction velocity for use above the roughness sublayer. A description of the profile of Reynolds stress within the roughness sublayer is also required (Kastner-Klein and Rotach 2004). The local Reynolds stress, at the level of interest, can be used to derive a local friction velocity u_* at this level, which may be used for scaling purposes within the roughness sublayer.

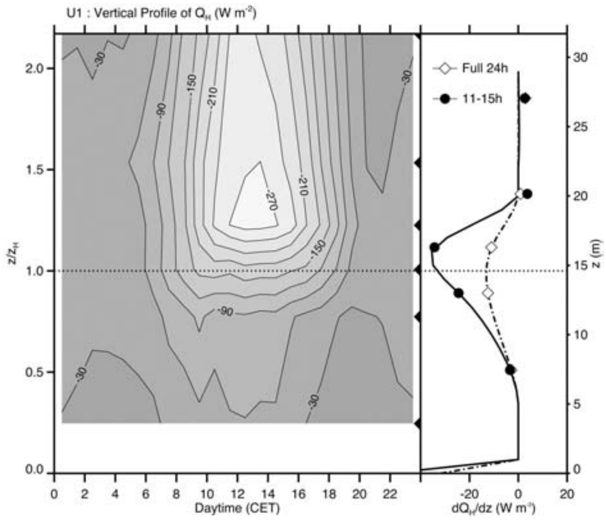

Fig. 3.2: Vertical profile of sensible turbulent heat flux (Q_H) within and above the street canyon at the BUBBLE site Ue1 (see Fig. 10.1) during the diurnal cycle. The mean building height z_H is indicated by the horizontal dotted line. The black triangles at the middle axis indicate the six measurement heights with eddy correlation instrumentation. The left plot shows the average diurnal course during the summertime intensive observation period from June 10 to July 10, 2002. The right plot shows vertical flux density divergence dQ_H/dz in Wm^{-3} derived from the difference of Q_H between the six heights, for the whole day (white diamonds) and only during mid-day hours (11–15h, filled circles). Lines show the suggested fits through the urban canopy (from Christen and Vogt, 2004).

Note that below the zero plane displacement height (for the flux, see Kastner-Klein and Rotach, 2004), the Reynolds stress usually vanishes, and the above approach using local scaling are no longer useful. For the lower part of the roughness sublayer, namely the canopy, only very crude empirical relations for turbulence variables, or prototype profiles are available (Kastner-Klein *et al.*, 2001).

Consequences for pollutant dispersion modelling

1. If the roughness sublayer is not explicitly taken into account in a meso-scale model, the lowest model level should be at a height greater than z^*.

2. If the roughness sublayer is resolved in a meso-scale model (but still treated in a statistical manner), the additional drag due to the roughness elements has to be modelled somehow. Examples of approaches and corresponding parameterisations can be found in Martilli *et al.* (2002), Belcher and Coceal (2002), Coceal *et al.* (2003).

3. For micro-scale (street canyon) dispersion modelling studies, often a wind speed above roof level is required. As the profile of mean wind speed exhibits its largest vertical variation exactly in this region (see below), extreme care must be taken in the application of empirical relationships that are based on observations from one site alone.

4. Some studies have attempted to compare the impact of using, or neglecting, the turbulence structure of the roughness sublayer on surface pollutant concentrations (De Haan *et al.*, 2001, Rotach 2001, Leone *et al.*, 2003). Clearly this impact is dependent on source height and atmospheric stability and may be as large as a factor of two or more. For a mix of stabilities and source heights, De Haan *et al.* (2001) obtained approximately 30% larger annual average surface concentrations from taking into account the roughness sublayer flow and turbulence structure. Since in this study annual average concentrations were determined at more than 20 sites in Zürich, Switzerland, this result yields a rough estimate of the overall impact of the roughness sublayer flow and turbulence. In other words if one adopts the simplistic 'modified roughness length' approach (Craig and Bornstein, 2002, call it the 'flat sandbox' approach), surface concentrations are underestimated by roughly 30%.

Spatial variability
The most important contribution from COST 715 to the problems of spatial inhomogeneity has been the BUBBLE project (see Chapter 10) and its experimental layout. At full scale (Fig. 10.1) and in wind tunnel measurements, various different sites (or many different sites in case of the wind tunnel) were investigated with similar surface characteristics (urban, suburban, rural etc.). Fig 3.3 gives an example of the spatial variability of profile information between

different sites and varying upwind conditions. There is quite a pronounced site-to-site variability, but the characteristics of the profiles, once properly scaled, are similar and justify an attempt to build spatially averaged, characteristic urban profiles (compare with data presented in Fig. 3.1).

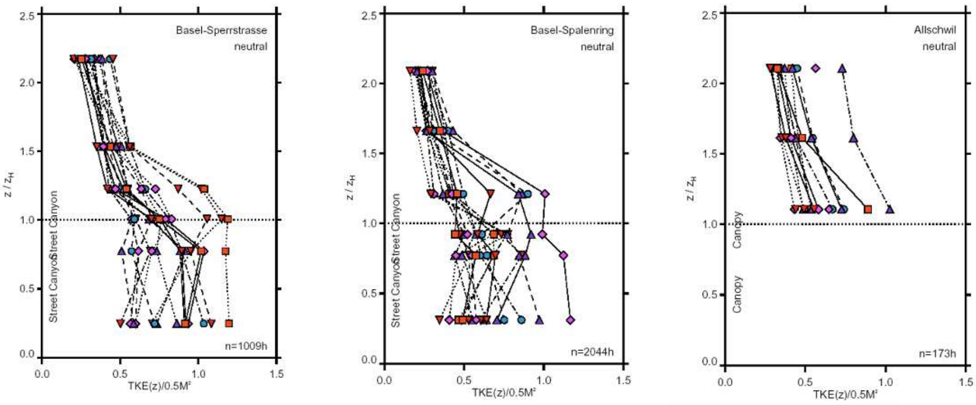

Fig. 3.3: Examples of spatial variability in an urban area of the mean profiles of the scaled turbulent kinetic energy at two urban sites from BUBBLE (Sperrstrasse, left, and Spalenring, middle) and a suburban site (Allschwil, right), for near-neutral conditions. Each profile represents a wind direction section (16 at each site), thus showing the influence of different, upwind, urban surface conditions on the profiles (courtesy of Andreas Christen, University of Basel.)

An overview on methods to determine urban roughness parameters (roughness length, zero plane displacement), based on morphological surface parameters was prepared by Mestayer and Bottema (2002, and references therein). Results from BUBBLE on this topic can be found in Chapter 10. The spatial variability of urban meteorological information on a larger scale was discussed within COST 715 based on the example of the urban network established in a number of cities in Portugal.

Urban boundary layer profile of mean wind speed
The literature review within COST 715 did not reveal any published work on theoretical or parameterised formulations for the wind speed profile throughout the entire urban boundary layer (the same is true for profiles of other variables). Therefore an attempt was made to extend a theoretical approach based on Rossby Number similarity to very rough surfaces. The approach is outlined in Janour and Benes (2002) and Bezpalcova *et al.* (2002, 2004). This approach is clearly quite idealised, as it is based on the assumptions of station-

arity and horizontal homogeneity of the urban boundary layer and only covers neutral stratification. However it can be used to obtain important insight in the characteristics of the urban boundary layer.

An attempt was made to use the approach of Bezpalcova *et al.* (2004) to estimate the so-called blending height i.e. the height above which the wind profile becomes universal and hence independent of surface characteristics. Using some characteristic values (boundary layer height of 1000m and urban roughness length > 1 m), it is found that the blending height is of the order of twice the height of the surface layer, or a height near to the depth of the inertial sublayer (Bezpalcova *et al.*, 2004).

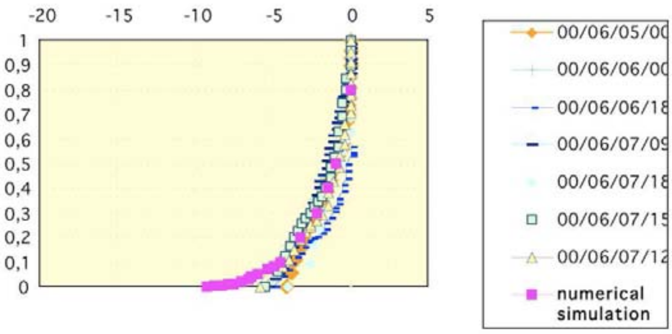

Fig. 3.4: Comparison of the velocity defect profiles inside the urban boundary layer simulation with radio soundings launched from the Portugal Hydrometeorological Institute in Lisbon. The date and time of the observation are given as yy/mm/dd/hh, north east wind direction at the top of the urban boundary layer (from Bezpalcova et al. (2004).) The non-dimensional velocity defect $(U - U_g)/u_*$ is plotted along the horizontal axis, where U is the wind speed in the urban boundary layer, u_* is the friction velocity and U_g is the geostrophic wind speed at the top of the urban boundary layer. The non-dimensional height relative to the depth of the urban boundary layer is plotted along the vertical axis.

Within COST 715 it was possible to use some available observations from radio soundings in Lisbon (Fig. 3.4) and Barcelona (Fig. 3.5) to compare the Rossby Number approach with field data. For carefully selected periods (in Figs. 3.4 and 3.5), of near-neutral and quasi-stationary conditions in the most homogeneous wind direction sectors, the agreement is very good, demonstrating the validity of the approach under ideal conditions. Also from Fig. 3.5, it is evident that a relatively deep layer near the surface exists (below the blending

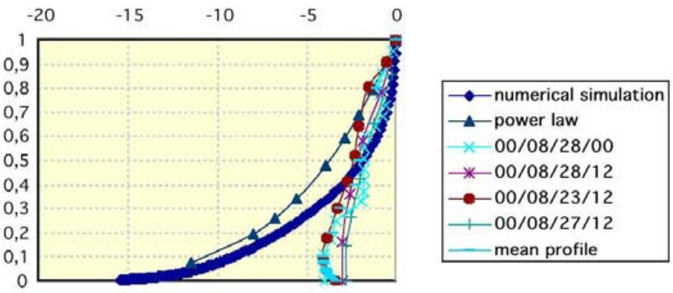

Fig. 3.5: Comparison of the velocity defect profiles inside the urban boundary layer simulation with radio soundings launched in Barcelona. The date and time of the observation are given as yy/mm/dd/hh, south east wind direction (from Bezpalcova et al. (2004).) The non-dimensional velocity defect $(U - U_g)/u_*$ *is plotted along the horizontal axis, where* U *is the wind speed in the urban boundary layer,* u_* *is the friction velocity and* U_g *is the geostrophic wind speed at the top of the urban boundary layer. The non-dimensional height relative to the depth of the urban boundary layer is plotted along the vertical axis.*

height), where the Rossby Number similarity approach does not comply with the observations because it is outside the range of its applicability.

As mentioned above, no parameterised profiles for wind speed or turbulence statistics in the entire urban boundary layer are available from the literature. While BUBBLE data (full scale and wind tunnel) are still being analysed in this respect at the time of writing, some indirect evidence for the choice of such parameterisations could be obtained from analysing the tracer data of BUBBLE (Section 10). In simulations using a Lagrangian particle dispersion model with parameterised profiles of mean wind and turbulence statistics, Rotach *et al.* (2004) found very good agreement with the observed tracer concentrations. The turbulence parameterisation used was based on the following principles:

1. applying the approach outlined in Section 3.3.1 for the roughness sublayer
2. for higher levels using normal boundary layer parameterisations.
3. Interpreting the maxima of the turbulent fluxes (see Section 3.3.1) as ‘surface fluxes’ to derive a friction velocity and a convective velocity scale for use in the boundary layer parameterisations (but not in the roughness sublayer).

The success with using this approach in terms of simulated concentrations may be viewed as indirect evidence that the approach is useful. Similar success with this approach was reported by Rotach (2001) when analysing tracer release experiments in other cities (Copenhagen, Indianapolis) and De Haan *et al.* (2001) for Zürich.

Comparison of urban and rural wind speeds
Often when urban wind speed or momentum flux information is required for an urban pollutant dispersion study, only measurements from a nearby rural station (such as an airport) are available. COST 715[3] has therefore attempted to investigate the relation between urban and rural wind speed. Two approaches were adopted: (a) a direct, statistical comparison, and (b) the development of a physically based procedure to estimate urban wind speed from rural observations.

(a) Statistical comparison of urban versus rural wind speed
From a number of urban-rural pairs made available by COST 715 participants and from various cities, linear regression plots were constructed. An example for Copenhagen is given in Fig. 3.6. In a preliminary study, Soriano *et al.* (2002) have summarised the following general observations.

1. The urban wind speed is usually smaller than the rural reference (due to the increased roughness) as indicated by the slope coefficients smaller than 1 in Fig. 3.6.

2. From all pairs, it is evident that for 'no wind' conditions at the rural site, measurable wind speeds (of the order of $1 \mathrm{ms}^{-1}$) are still observable at the urban site (as indicated by the positive values of the zero intercept). This is attributed to thermally driven flows generated by the urban heat island.

3. The exact ratio of urban-to-rural wind speed is site specific, dependent on the wind direction sector (upwind urban surface characteristics, see Fig. 3.6) and most likely dependent on atmospheric stability. This requires more investigation.

4. The most important determinant of this ratio is the height at which the urban observation is taken. Unlike the rural reference, where the WMO recommendations specify a measurement height of 10m, no such urban

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reference height is yet established. Consequently the urban observations stem from a variety of different levels within the urban roughness sublayer and hence are difficult to compare.

From this last finding, it follows that there is a need for an urban reference level z_{refu} for wind speed. As a working hypothesis, $z_{refu} = d + 10$ m, where d is the zero plane displacement, was adopted by COST 715[4]. Although this has the advantage of being similar to the rural definition, it bears the risk that the urban reference level might be below[5] or too close to mean roof level. Therefore a reference level that is clearly above the mean building height would seem preferable. Based on the considerations of Section 3.3 an ideal candidate would be the height of the roughness sublayer, z^*. Since this is at a level 2 to 5 times the mean building height (Raupach *et al.*, 1991), such a height is not useful for practical applications. However this is not such a serious limitation if one is able to estimate wind speed at a given height from observations at any level within the urban roughness sublayer. This is the subject of the second approach.

(b) Physically based approach to estimate urban roughness sublayer wind speed
Based on the literature review and the results concerning the general structure of flow and turbulence within the urban roughness sublayer (Section 3.3) a procedure was devised by COST 715 to estimate the urban wind speed from observations at other locations. This approach is explained at length as a kind of 'recipe' in Chapter 8. In summary, the procedure gives practical advice on how to estimate wind speed at an urban site and at a given level, if

1. the wind speed and turbulent fluxes are available from the same site, but a different level,
2. the wind speed and turbulent fluxes are available from another related site, namely a rural reference station,
3. the wind speed only is available from a rural reference station.

The physical background of this procedure is based on a number of relatively recent studies in the urban context (see references in Chapter 8) and is thus

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[5] Using the rule of thumb that $d = 0.7z_H$, this is the case for a mean building height of about 30 m.

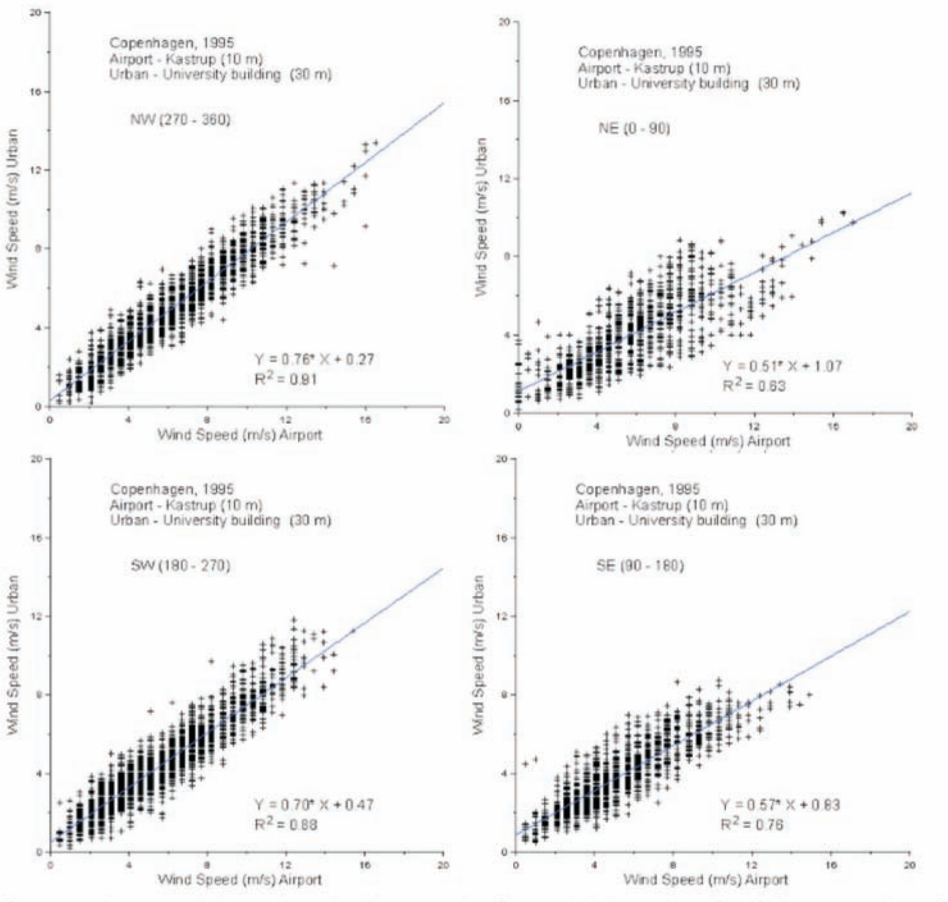

Fig. 3.6: Comparison of hourly wind speeds from the University building station (y-axis) in Copenhagen, Denmark and the nearby Kastrup Airport station (x-axis), according to wind sector. Top left: 270 to 360 degree wind direction; top-right: 0 to 90 degree wind direction; bottom-left: 180 to 270 degree wind direction and bottom-right: 90 to 180 degree wind direction. From Soriano et al. (2002).

validated to a certain extent. An independent test that is a validation of the approach based on data, which were not employed to derive the physical concepts on which it is based, was one of the goals of COST 715. However no suitable, existing data sets could be made available for this task. Only with the BUBBLE data set did an opportunity arise to undertake this test. A point by point evaluation of this procedure is given in Chapter 8 using BUBBLE data. In this chapter only some of the most salient aspects of this evaluation are presented. Figure 3.7 shows a comparison of measured and estimated wind speed at one of the urban BUBBLE sites. It can be seen that in general there is a very good correspondence between measured and estimated wind speed if the reference level is close to the observation level (middle panel). A slight underestimation is obtained for a data level close to mean roof height (left panel) and is even more pronounced if the observations are made within the street canyon (see Chapter 8). For the highest level near $z*$ (right panel) the correspondence is also good, except for a number of cases with a local maximum of Reynolds stress near roof level (see Chapter 8).

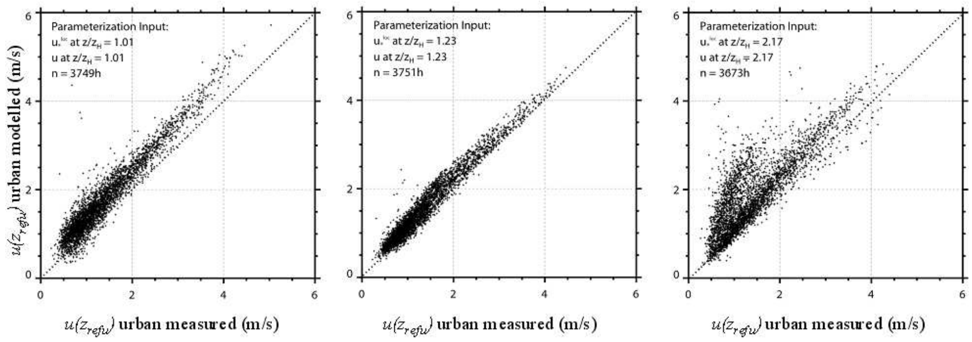

Fig. 3.7: Comparison of measured (x-axis) and estimated wind speed at an assumed reference level $z_{refu} = d + 10$ m at the site Ue1 (see Fig. 10.1) of the BUBBLE network. The inputs used for the estimation are the mean wind speed and turbulence (1) near roof level (left), (2) near that the reference level (centre) and (3) close to the estimated roughness sublayer height (right). Data are from the BUBBLE project with all stability conditions included (see Chapter 8).

For situations when no local turbulence observations are available, Figure 3.8 shows a comparison of local friction velocity, observed at an urban site, with that estimated according to the procedure in Chapter 8 from rural measurements. Clearly the urban friction velocity is larger than the rural (as expected, due to increased roughness) and the local friction velocity at the urban site is underestimated when following the recommendations of the procedure in Chap-

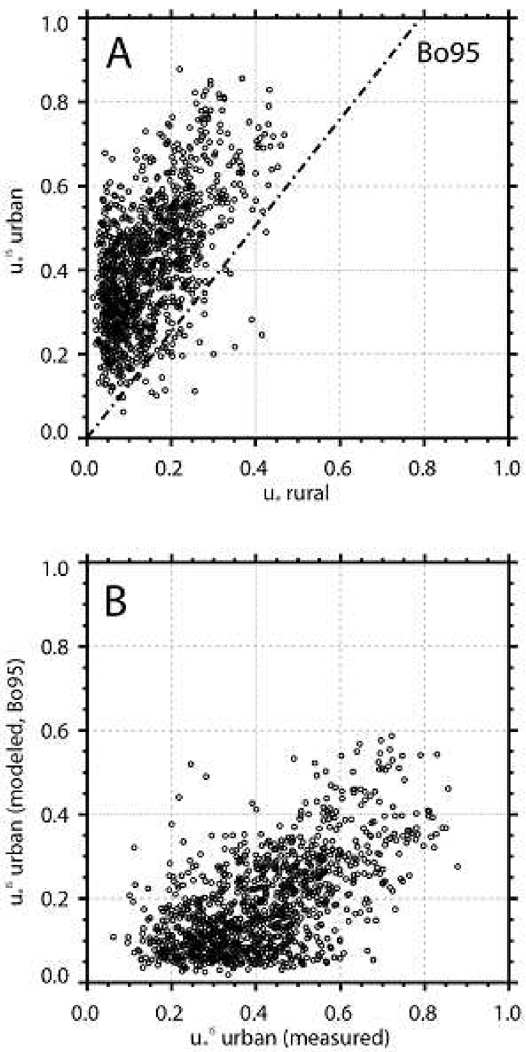

Fig. 3.8: Turbulent momentum fluxes (expressed as friction velocity) from the BUBBLE data set. A: Comparison of the measured rural u_* at site Re2 (see Fig. 10.1) with the measured urban u_{*IS}, that is the value for the inertial sublayer at site Ue1. B: Comparison of measured urban u_{*IS} at site Ue1 and that estimated according to the procedure in Chapter 8. The line labelled Bo95 in panel A refers to the expected relationship according to Bottema (1995), see equation (8.4) in Chapter 8.

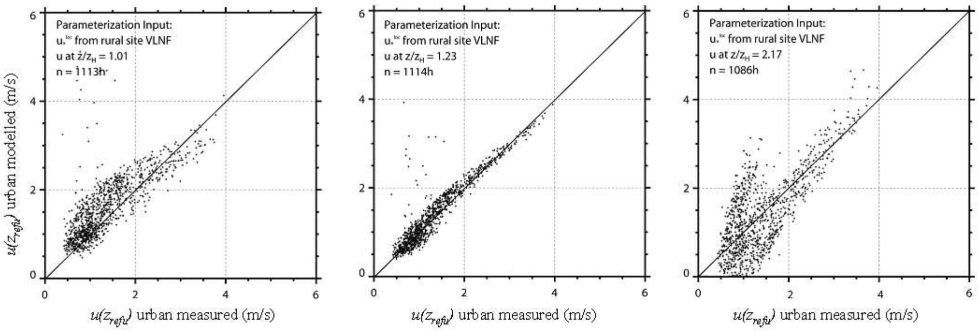

Fig. 3.9: As Fig. 3.7 but only measured 'rural' wind speeds are used as input to derive the estimated ('modelled' in the label) urban wind speed. The text in the caption 'u_*^{loc} from rural site' is meant to indicate that this value is estimated from mean variables observed at the rural site Village Neuf.

ter 8 (lower panel in Fig. 3.8). This points to the need to revise some of the parameters suggested in Chapter 8. However even if the estimated urban friction velocity is too small, the effect on the resulting estimated wind speed is less dramatic. Figure 3.9 shows a comparison of measured wind speed to that estimated under the assumption that only a rural wind speed measurement is available.

Nevertheless quite a good correspondence can be expected between observed and estimated urban wind speed if the procedure as recommended by COST 715 is employed. Clearly more detailed data sets will be needed in order to fully evaluate the proposed procedure, and especially some of the recommended parameter values.

3.4. Open Questions

A number of issues with respect to urban flow and turbulence characteristics remain to be addressed. Most of them are related to either the extraordinarily large depths of the urban roughness sublayer (see Fig. 2.2), or to the difficulty of observing turbulence variables using remote sensing instrumentation. The open questions can be summarised as follows.

1. Profiles of turbulence statistics, such as velocity variances, throughout the entire urban boundary layer are essential for pollutant dispersion mod-

elling. As outlined in Section 3.3 no attempts were made within COST 715 to systematically evaluate characteristics of these variables. This is mainly due to the lack of corresponding observations. Consequently no parameterisations which are specifically designed for urban applications are available. If suitable observations were available, a starting point would be to investigate whether traditional boundary layer parameterisations (with no urban-specific parameters) are suitable, with the 'surface fluxes' to derive scaling variables determined according to the recommendations in Section 3.3. Note that some single tower observations would be available for such a task (e.g. Pascheke *et al.*, 2002), but they suffer the problem of being subject to different footprints (see below) at different levels and hence spatial variability.

2. Estimating the upwind influence region (footprint) for an observation at a given point is essential to assessing its representativeness for a specified purpose. Footprint modelling has become the approach of choice for this task in recent years (Schmid, 2002). However even if some models allow for large roughness lengths as an input (e.g. Kljun *et al.*, 2004), this does not necessarily mean that they are suitable for urban application. The crux is that these models usually use surface layer turbulence characteristics close to the ground and hence neglect the roughness sublayer. Especially in urban environments, this cannot be justified (see Fig. 2.2). While footprint models for vegetation canopies are starting to emerge from the scientific literature, no such attempt seems to be available yet for urban surfaces.

3. The internal boundary layer, that is built up due to the change in surface roughness and thermal surface properties at the 'edge' of a city (see Fig. 2.1) or between different city districts, is a concept that is well known from theoretical arguments (including numerical modelling) and from observations on much smaller scale than urban. It is very difficult however to thoroughly observe and hence to investigate this concept at full-scale.

4. The rate of dissipation of turbulent kinetic energy, ε, is an important variable for many aspects of pollutant dispersion modelling (e.g. for $k-\varepsilon$ closure in turbulence models, or Lagrangian particle dispersion models). Standard observational practice is to use the high-frequency (inertial subrange) part of the power spectra together with Kolmogorov's theory for the inertial subrange to derive ε. However there is no reason to assume that this approach is applicable within the roughness sublayer. Indeed when analysing roughness sublayer data, inertial subrange characteristics

are often found to be violated, thus rendering the approach to derive ε uncertain (to say the least). Turbulent kinetic energy budgets from very detailed data sets may be used to assess this problem in more detail.

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4. The surface energy balance in urban areas

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4.1. Introduction

The surface energy budget with the surface temperature and heat fluxes determine the stability conditions in the lower atmosphere, which regulate the mixing of pollutants. The turbulent kinetic energy is essential, both as input and boundary condition, in advanced air pollution dispersion models. Using measurements performed well above the roofs to adequately represent urban conditions (see Chapters 2 and 3), the urban surface energy budget (in W m^{-2}) may be expressed in directly measured terms, each one of which automatically includes part of the energy released by combustion:

$$Q^* = K\downarrow - K\uparrow + L\downarrow - L\uparrow = Q_H + Q_E + \Delta Q_S$$

where Q^* is the net all-wave radiation; $K\downarrow$ is the incoming short-wave radiation; $K\uparrow = \alpha_0 K\downarrow$ is the outgoing, reflected short-wave radiation, where α_0 is the surface albedo; $L\downarrow$ is the incoming long-wave radiation from the sky and surrounding environment 'seen' from the point; $L\uparrow = \varepsilon_0 \sigma T_0^4 + (1-\varepsilon_0)L\downarrow$ is the outgoing long-wave radiation including both that emitted from the surface consistent with its emissivity ε_0 and absolute surface temperature T_0, and the reflected incoming long-wave radiation; Q_H is the turbulent sensible heat flux, Q_E is the turbulent latent heat flux and ΔQ_S is the canopy storage heat flux, i.e. the heat stored in the air layer, in the ground and in building materials. However usually the surface energy balance or its components are not directly measured at monitoring stations.

Building and ground-covering materials have radiative properties, such as albedo (fraction reflected) and emissivity, different from natural grounds and vegetation, while the vertical structure of spaces between buildings provides shade and radiation trapping. In addition, buildings have not only horizontal but also vertical and/or slanted orientations, which strongly alter the radiative transfers and energy budget. The heat flux to or from the ground changes with surface materials (concrete, tarmac, soil etc.) The anthropogenic energy use can be a significant fraction of the annual solar input and thus influences the local stability of the air.

Piringer *et al.* (2002) summarised previous knowledge available to COST 715, focusing on experimental results from North America (Table 4.1) and model results, mainly the Town Energy Balance (TEB) scheme of Masson (2000), the surface exchange parameterisation in the Finite Volume Model (FVM) of Martilli *et al.* (2002), new parameterisations for urban soil-atmosphere interactions in the French SUBMESO model (Guilloteau and Dupont, 2002) and the Local-scale Urban Meteorological Pre-processing Scheme LUMPS (Grimmond and Oke, 2002). In the following, new developments and results initiated by or accessible to COST 715 members are briefly summarised. A more complete review of the problem together with analyses of recent experimental data can be found in a separate report by Piringer and Joffre (2004).

4.2 Empirical evidence

Dedicated experiments together with recently developed detailed surface exchange parameterisations and other approaches have provided new insight in the partitioning of the surface energy budget into sensible, latent, and storage heat fluxes. Table 4.1 displays some typical ranges for the various terms of the surface energy budget for North American cities. One salient feature of urban sites is that the storage heat flux is as significant as the sensible heat flux, which is different from typical rural sites where it is much less. (Positive values denote heat is absorbed).

During the major Basel Urban Boundary Layer Experiment BUBBLE (Rotach *et al.*, 2004; see also Chapter 10), three urban sites provided turbulent flux densities and radiation data over dense urban surfaces. Together with a suburban site and three rural reference sites, this network allowed the simultaneous comparison of the urban, suburban, and rural energy balance partitioning in a Central European city during a summertime period of one month (Figure 4.1). The curves represent the average diurnal variation including all weather conditions from clear skies to completely overcast days. The increasing importance of the storage heat flux as one goes towards the city centre is thus also a typical feature of a European city.

Table 4.1: Ranges of average daily maximum values of net radiation and fluxes in North American cities (after Grimmond and Oke, in Piringer et al., 2002)

Parameter	Range (W m^{-2})
Net all-wave radiation Q^*	$< 400 - 650$
Latent heat flux Q_E	$10 - 235$
Sensible heat flux Q_H	$120 - 310$
Storage heat flux ΔQ_S	$150 - 280$
Average daytime Bowen ratios Q_H/Q_E:	(dimensionless)
residential sites	$1.2 - 2$
during irrigation ban Vancouver	~ 2.8
light industrial site	~ 4.4
city centre	~ 9.8

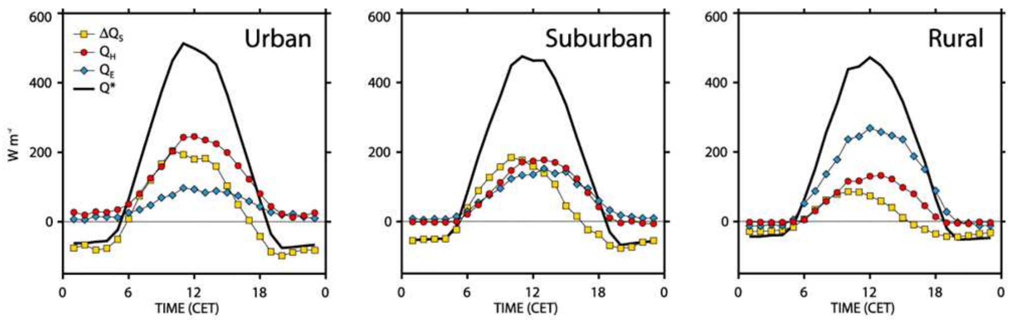

Figure 4.1: Ensemble diurnal variation of the energy balance at three sites during BUBBLE: average days for the intensive observation period from June 10 to July 10, 2002 (including all sky conditions) at an urban site (Sperrstrasse, Basel), a suburban site (Allschwil), and a rural site (Village Neuf) (modified after Christen et al., 2003).

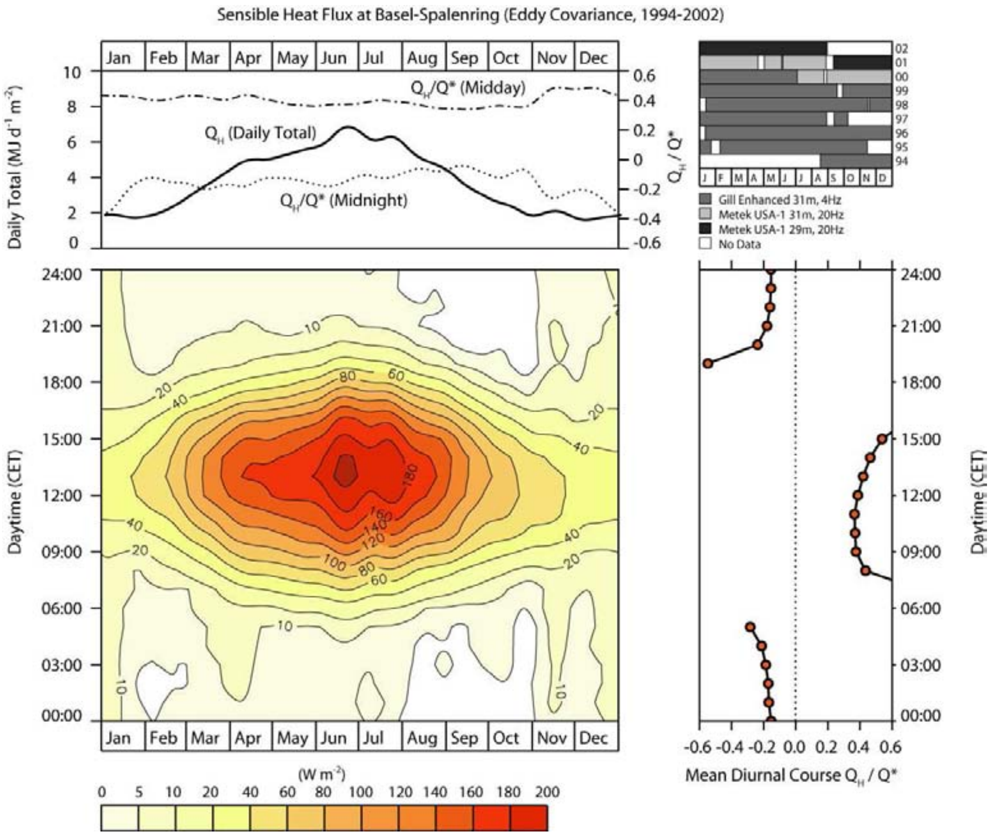

Figure 4.2: Measured sensible heat flux Q_H between 1994 and 2002 over the urban surface at the long-term Spalenring tower, Basel, using different eddy-covariance systems. Main plot: the isoflux diagram illustrates the climatologically averaged values of the sensible heat flux (Wm^{-2}) as a function of the hour and the day of the year. This shows that during the night positive heat fluxes (i.e. away from the surface) are measured throughout the year. Right plot: mean diurnal course of the fraction Q_H /Q^* as a function of the hour of the day for the period 1994–2002. Upper left plot: annual variation in the daily total values (full line) and fraction $Q_H/Q*$ at midday and midnight. Upper right: documentation about the different eddy covariance systems that were operated at this site Ue2 and contributed to the climatologically averaged values (modified after Christen et al., 2003).

In contrast to rural surfaces, where the nocturnal sensible heat flux Q_H is directed towards the surface, both the turbulent fluxes Q_H and Q_E transfer energy away from the surface over urban areas in the city centre of Basel. Long-term measurements between 1994 and 2002 at the Spalenring tower in an urban environment show the observed nocturnal turbulent sensible heat flux to be directed upwards throughout the year (Fig. 4.2, from Christen and Vogt, 2004).

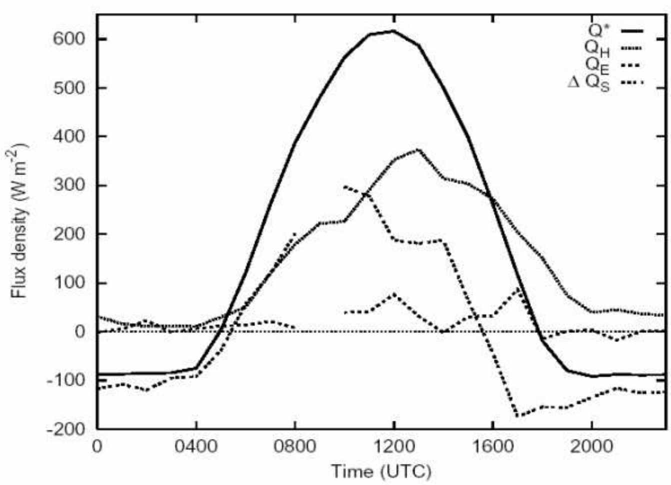

Figure 4.3: Observed surface energy balance fluxes for the six days of the intensive observation periods 2a and b (days 172-178, June 21-26 2001) at the Marseilles city centre site. Data are ensemble means for the period including the storage heat flux determined as the residual of the observed terms. $Q*$ is the net all-wave radiation, Q_H is the turbulent sensible heat flux, Q_E is the turbulent latent heat flux and ΔQ_S is the canopy storage heat flux.

Another recent major urban campaign is the UBL-ESCOMPTE campaign in and around Marseilles. Surface energy budget fluxes were measured for a total of 28 days (June 16 to July 14, 2001) at the city centre site. Preliminary results show that the turbulent sensible heat flux is the dominant mode of heat transfer away from the surface during the middle of the day. As found at other densely developed urban sites in other cities, the convective sensible heat flux remains positive throughout the night, sustained by large releases of heat stored in the urban fabric during the day (Oke, 1988, Grimmond and Oke, 1999, 2002). As expected, given the absence of vegetation cover at this site and the dry conditions during the measurement period, the latent heat fluxes are small (Figure 4.3). As found in other urban areas (Grimmond and Oke, 1999),

ΔQ_S peaks before solar noon and the flux turns negative about 2 hours before the net all-wave radiation (Q^*). Heat storage at this site has been investigated in detail by Roberts *et al.* (2003).

The sensible heat fluxes were estimated using also large aperture scintillometers. Line-averaged Q_H from the large aperture scintillometers were computed over 15-minute periods using two methods (McAneney *et al.*, 1995, De Bruin *et al.*, 1995). The very good agreement found between both methods and the eddy covariance measurements on the CAA central mast (see Fig. 4.9) illustrates the promising potential of scintillometry for urban areas where spatial heterogeneity is large (from Lagouarde *et al.*, 2002).

An experiment was performed in 2001 and 2002 within and around Bologna, Italy, located in the south-eastern border of the Po Valley basin, near the Apennines mountain chain. The aim of the experiment was to investigate the surface fluxes and evaluate the surface energy budget and the mixing height, during typical summer and winter weather conditions. During the experiment, the heat island effect was also mapped by deploying 21 thermometers in the town, the suburbs and rural surroundings. All the data were compared with data from 9 ground meteorological stations located inside the experimental area. The data cover periods of 20-30 days during winter (January–February 2001) and summer (May–June 2001). Analysing the interpolated temperature distributions revealed the heat island effect of the urban area by subtracting from the temperature based on all data the temperature field made up of rural data only (Bonafè *et al.*, 2003). An example is shown in Fig. 4.4 with a clear distinctive urban heat island feature that is particularly strong (with mean differences of 5 °C between urban and rural sites) during winter nights and periods of synoptic calm and clear sky conditions. The heat island effect depends on cloud cover and the heat island intensity was observed to be almost linearly correlated with the mean nocturnal cloud cover, as observed at the city airport (Fig. 4.5).

Three urban field trials were carried out in 1998, 1999 and 2000 in Birmingham, U.K., to measure the sensible heat flux and the Monin-Obukhov length L, in order to improve air quality forecasting (Ellis and Middleton, 2000a, b, c). Instruments were operated on 15m, 30m, 45m masts for 4-week periods in 1998, 1999 and 2000 at the Dunlop tyre factory site within the city. Synoptic observations were taken from a rural station outside the city at Coleshill, and were complemented in 2000 by a sonic anemometer placed on a 15m mast beside the Coleshill station, to measure Q_H, u_* and L simultaneously at both sites. Figure 4.6 shows a clear difference in the hourly average heat fluxes over the

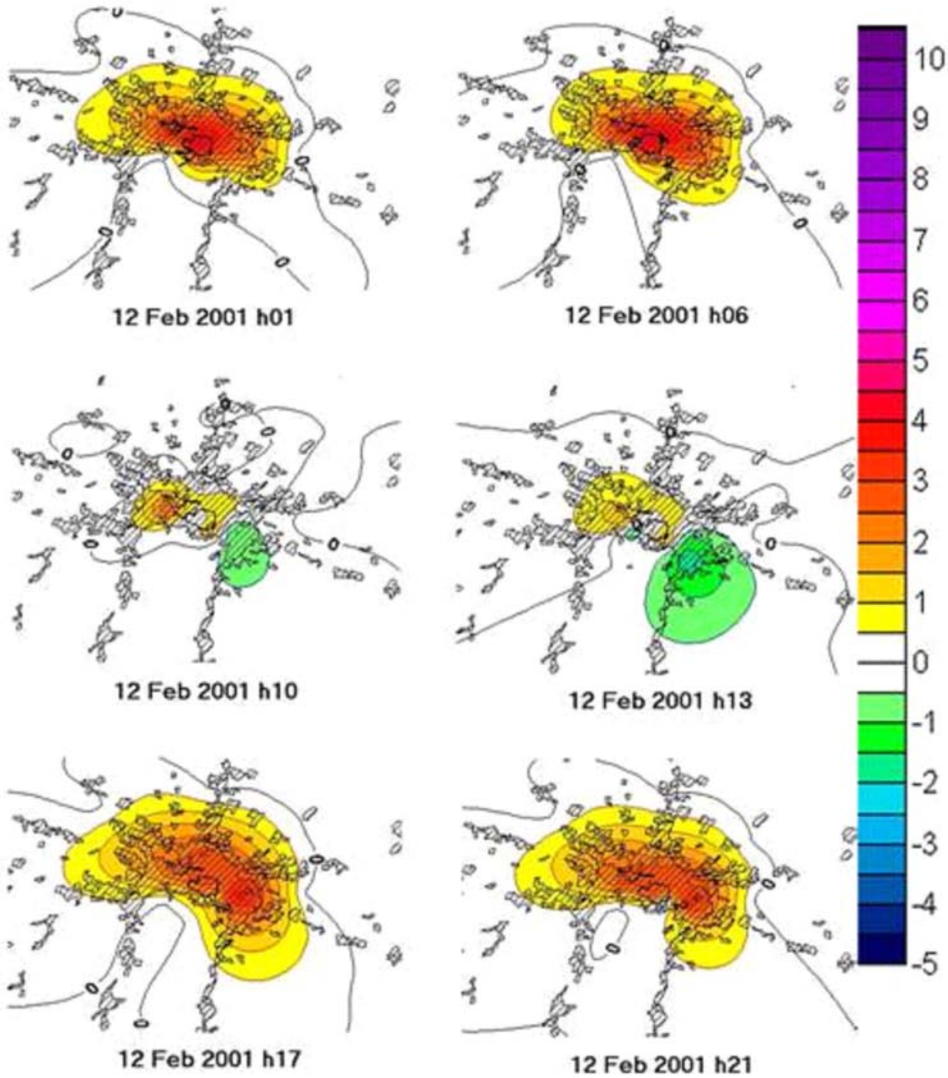

Figure 4.4: Evolution of the hourly heat island in Bologna on 12 February 2001 under clear sky conditions. The map represents the difference between rural and urban temperatures. The colour scale is in $^\circ C$.

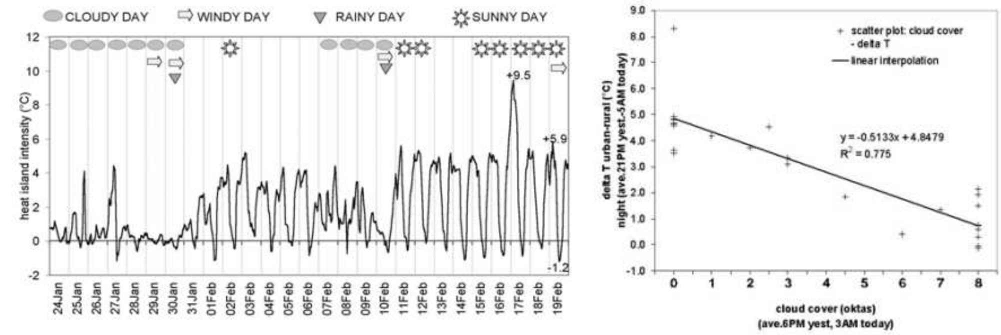

Figure 4.5: *Left hand side: meteorological conditions during the winter phase of the temperature mapping experiment in Bologna. Right hand side: relationship between the heat island and the mean nocturnal cloud cover, as observed at the city airport. (Heat island intensity =* T_{average} *of urban sites –* T_{average} *of rural sites.)*

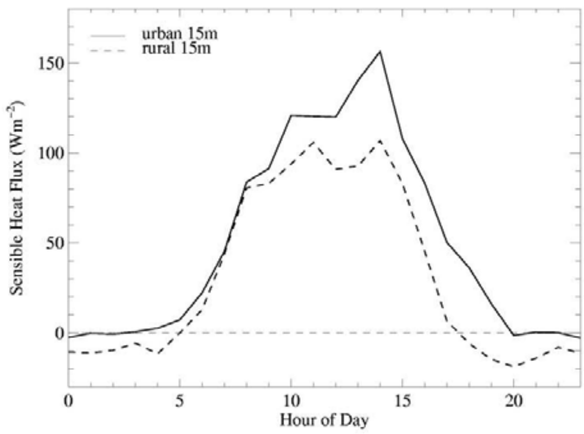

Figure 4.6: *Comparison of sensible heat flux measured using sonic anemometers on 15 m masts at Coleshill synoptic station and at the Dunlop Tyres Ltd factory site plotted by Nikki Ellis (personal communication). Results are averages by hour of day. The period covered was from 10.00 UTC on 7 July 2000 to 17.00 UTC on 28 July 2000. The urban heat flux at the Dunlop site was on average larger during the day. At night the average remained practically zero (neutral), whilst the rural synoptic site had a negative average heat flux (stable) reaching a minimum of* -30 *W* m^{-2} *at 20.00 UTC. The difference may be due to both the urban heat storage effect and energy generated by man-made activities*

21 day period at the two sites (Middleton *et al.*, 2002). The factory data (solid line) at Dunlop showed a larger heat flux than at Coleshill (broken line). At the factory site, during the night, the hourly averaged heat fluxes remained very close to zero. Meanwhile the rural site showed a negative hourly averaged heat flux. Thus night-time conditions were near neutral at the factory, but stable at the rural site. A long period of observations at a rural and an urban site would be needed to see what happens in other seasons of the year.

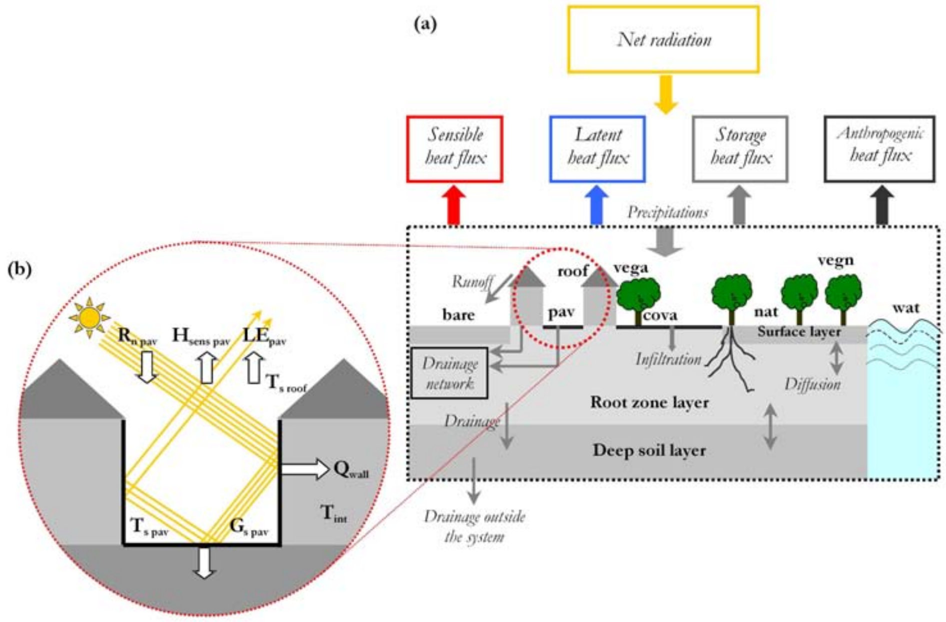

Figure 4.7: (a) Schematic representation of the SM2-U energy and water budget models with 8 surface types (pav, cova, bare, nat, roof, vega, vegn, wat, see text for explanation) and 3 soil layers, (b) Energy budget of paved surfaces.

4.3 Parameterisation and modelling

Though parameterisation schemes have been developed to estimate net radiation, sensible heat flux and other boundary layer parameters on a routine basis from hourly standard meteorological data (e.g. van Ulden and Holtslag, 1985, Berkowicz and Prahm, 1982), most of these models were developed and validated using data from flat, grass-covered environments and were limited to horizontally quasi-homogeneous conditions (see a review in Fisher *et al.*, 1999). As shown in Section 4.2, in urban areas there are marked differences in energy partitioning compared to rural conditions and there is still considerable uncertainty concerning the role of surface cover (e.g. the fractions of built-up areas/green space), city surroundings and prevailing meteorological conditions. Nevertheless, very recently, some substantial improvements have been achieved in including urban features specifically into pre-processors or parameterisation schemes. They range from simple parameterisations requiring standard meteorological observations (e.g. the LUMPS scheme of Grimmond and Oke, 2000, 2002), to numerical models with detailed surface exchange parameterisation schemes, such as the Town Energy Balance (TEB) of Masson (2000) or the Finite Volume Model (FVM) of Martilli *et al.* (in COST 715, 2002).

The SUBMESO model has been further developed into the SM2-U soil model. SM2-U keeps the principal characteristics of the force-restore model of Noilhan and Planton (1989). SM2-U separates 8 types of surfaces (Figure 4.7a), namely: bare soil without vegetation (denoted "*bare*"), bare soil located between sparse vegetation elements (*nat*), vegetation over bare soil (*vegn*), vegetation over paved surfaces (e.g. trees on the road side: *vega*), paved surfaces located between the sparse vegetation elements (*pav*), paved surfaces located under the vegetation (*cova*), building roofs (*roof*) and water surfaces (*wat*). The surface dynamic influence is represented through specific roughness lengths and displacement heights usually computed with morphometric methods (see summary of Mestayer and Bottema, 2001). Horizontal exchanges inside the urban canopy are not considered except radiation reflections and water runoff from saturated surfaces. SM2-U accounts for horizontal processes of the urban canopy by means of the fine resolution of the computational grid, and in the vertical dimension by parameterising their influence (Figure 4.7b). Examples of the simulations obtained for four typical European districts are shown in Figure 4.8 (Dupont *et al.*, 2003). This figure demonstrates the influence of building density and district structure not only on the magnitude of the heat fluxes, but also on the phase lag between the energy budget components, which is a key factor in the urban heat island process. In the first half of the day a large amount of heat is diverted from the budget and temporarily stored in the artificial ground and building materials, at the expense of the sensible heat, while in the evening and night these materials, warmer than air, release the stored heat to provide the nocturnal positive sensible heat flux.

The TEB scheme of Masson (2000) was evaluated off-line using observations of local scale fluxes and surface temperatures made during the UBL-ESCOMPTE campaign. In this study, the TEB scheme is used for built areas and the ISBA scheme (Interaction Soil-Biosphere-Atmosphere, Noilhan and Planton, 1989)

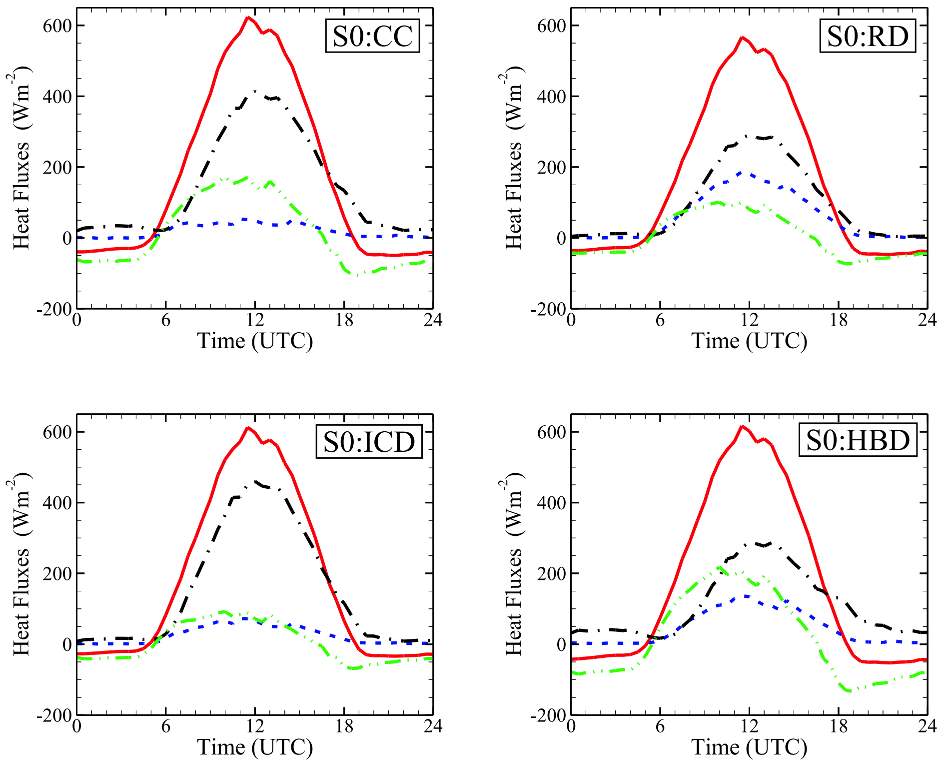

Figure 4.8: Energy budgets of four typical European urban districts (from Dupont et al., 2004): CC, city centre; RD, residential district; ICD, industrial-commercial district; HBD, high building district. The simulation corresponds to an average diurnal cycle in July. ——, net radiation flux; —-, latent heat flux; –·–·–, sensible heat flux; –··–··–, storage heatflux.

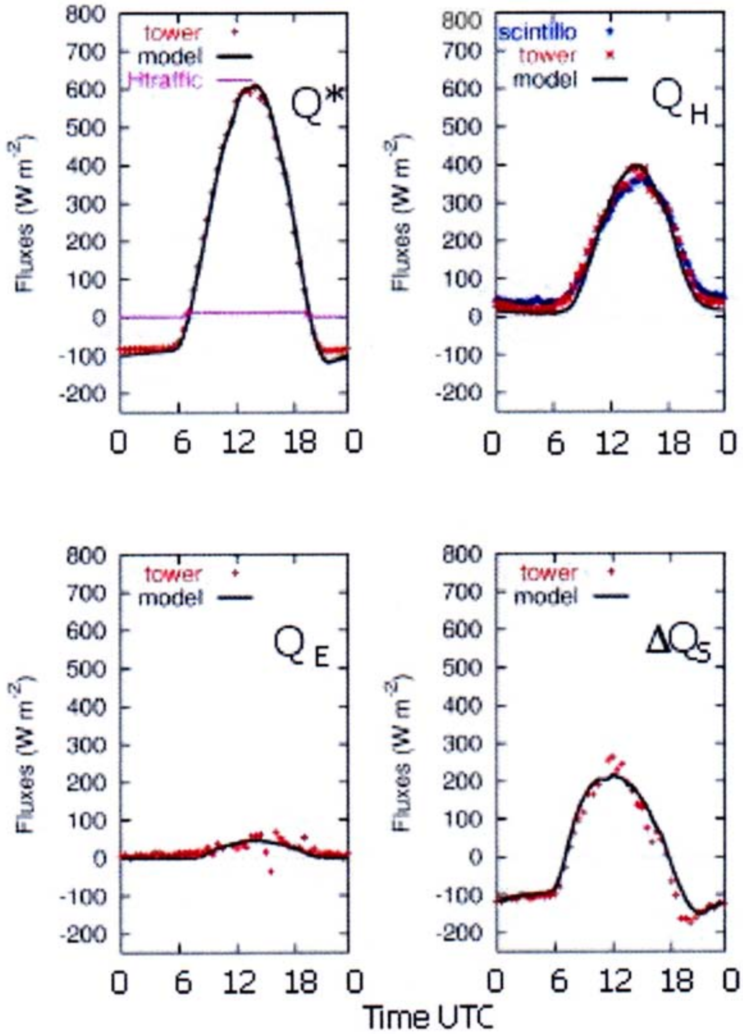

Figure 4.9 Comparison between observed and simulated surface energy balance fluxes in the city centre of Marseilles, averaged over 21 days. Red crosses: observed eddy covariance fluxes; continuous line: simulated fluxes using the TEB scheme (averages of the fluxes from roads, walls, roofs and natural surface cover). Blue stars in the turbulent sensible heat flux graph are calculated from the scintillometer data using the free-convection method (after Lemonsu et al., 2004).

for vegetated areas. The two models are combined using the plan areas of built and vegetated surfaces with their respective weighting. For Marseilles, TEB-ISBA is being evaluated using the measurements of air temperature from within the street canyons, the surface temperatures of roads, roofs and walls, and fluxes from the city centre tower (eddy co-variances) and the large aperture scintillometers. It is assumed that the amount of energy leaving the top of the canopy does not change with height, as in a classical 'constant flux' atmospheric surface layer, which can be true only for a horizontal spatial average, since vertical and horizontal flux divergence prevails in the roughness sublayer (see Fig. 3.2). Figure 4.9 shows a comparison of the measured and simulated fluxes, on average. Heat flux measurements at the mast and from the scintillometers show excellent agreement, while the energy fluxes appear well simulated. The model succeeds in producing a positive turbulent sensible heat flux at night, and the correct daily cycle of heat storage.

The Advanced Regional Prediction System (ARPS) is a non-hydrostatic mesoscale meteorological model developed at the Center for Analysis and Prediction of Storms at the University of Oklahoma (Xue *et al.*, 2000, 2001). An advanced land surface scheme (De Ridder and Schayes, 1997) was incorporated into ARPS to study the impact of land use changes on atmospheric circulations and pollutant dispersion (Lefebre *et al.*, 2004). The surface scheme calculates the interactions between the land surface and the atmosphere, including the effects of vegetation (represented using the big-leaf approach) and soils on the partitioning of incident radiant energy between the turbulent fluxes of sensible and latent heat, and the storage heat flux. Terrain heterogeneity within a model grid cell is accounted for by calculating energy fluxes separately for bare surfaces (soil or urban substrate) and vegetation, obtaining the grid-average flux as a weighted mean, using the fractional occurrence of each as weights. Recently the scheme was modified to better represent urban surface types, the most significant modification being the inclusion of Brutsaert's (1975) temperature roughness parameterisation. This parameterisation yields extremely high values of the ratio z_0/z_{0t} over cities, where z_0 andz_{0t} are the surface and temperature roughness parameters respectively, eventually resulting in higher ratios of the canopy storage heat flux to sensible heat flux $\Delta Q_S/Q_H$ which are able to reproduce observed values.

Figure 4.10 shows the simulated components of the surface energy balance with the Advanced Regional Prediction System ARPS model, together with values produced by the Objective Hysteresis Model OHM (Grimmond *et al.*, 1991). The most striking feature of the energy balance is the magnitude of the stor-

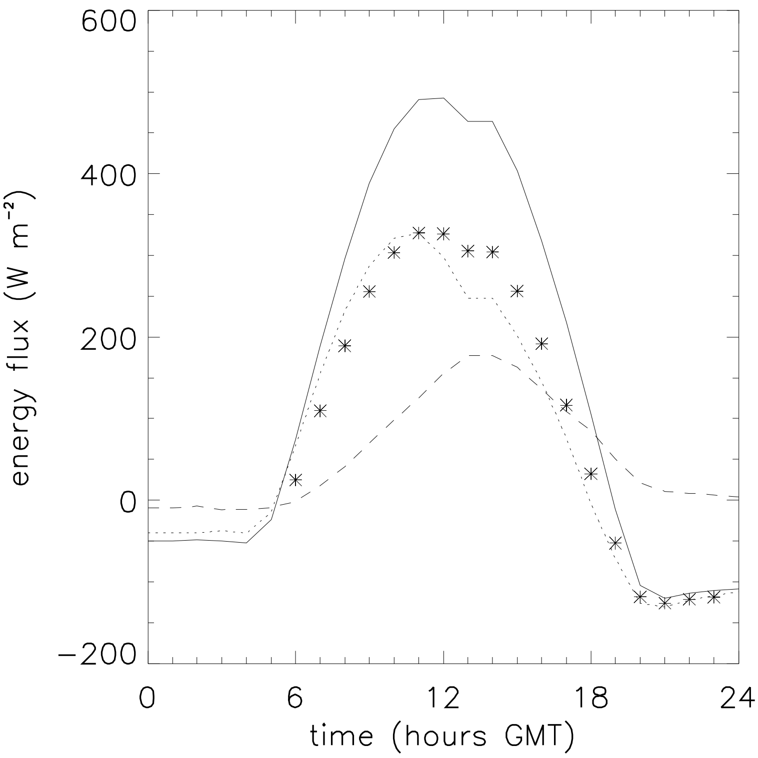

Figure 4.10: Simulated surface energy balance for the central part of Paris: net radiation flux (solid line), storage heat flux (dotted line), and sensible heat flux (dashed line). The asterisks represent the values calculated by the Advanced Regional Prediction System model together with the Objective Hysteresis Model for the storage heat flux term (De Ridder and Lefebre, 2003).

age heat flux, both during the day (positive) and at night (negative). The consequences of this behaviour of the urban surface energy budget are rather significant. Since the storage heat flux takes such a large share of the available radiant energy, relatively little is left during daytime for the sensible heat flux to the atmosphere (dashed line in Figure 4.10). This leads to the apparently paradoxical conclusion that even though urban surface temperatures are about 10 to 15 degrees warmer at noon than their surroundings, the heat they inject into the atmosphere is in fact only marginally higher. Practically, this means that the impact of vegetation changes on urban daytime atmospheric circulation patterns may be less important than anticipated. The situation is quite different though during the night, because after sunset the city starts liberating this large amount of heat stored during the day. Therefore heat flux values remain positive throughout the night over the city, whereas rural sensible heat flux values plunge towards negative values of a few tens of Wm^{-2}.This confirms earlier findings that the main effect of cities on atmospheric structure and circulations is more prominent during the night than during the day.

In the context of urban air quality modelling, a significant improvement in models can be achieved through better specific representation of urban features in the land surface model i.e. with appropriate values for albedo, thermal admittance and roughness, as well as an adequate representation of water flow after rainfall. It appears that the most fundamental change lies in the parameterisation of the temperature roughness. A subsequent issue concerns the averaging/aggregation techniques to represent the patchwork of various types of surfaces with their intrinsic characteristics at each model cell.

Modern nested numerical weather prediction (NWP) models utilise land-use databases down to hundred metres resolution or finer, and are approaching the necessary horizontal and vertical resolution to provide weather forecasts for the urban scale. In combination with recent scientific developments in the field of urban sublayer atmospheric physics (see above) and the enhanced availability of high-resolution urban surface characteristics, the capability of NWP models to provide high quality urban meteorological data will therefore increase once they have been 'urbanised', i.e. modified to include representative and critical urban features. Before that however, since NWP models have not primarily been developed for air pollution modelling, their results need to be designed as input to urban and mesoscale air quality models. Therefore a revision of the conventional concept of urban air pollution forecasting in Urban Air Quality Information and Forecasting Systems (UAQIFS) is required. This has been initiated by the current European project FUMAPEX 'Integrated Systems for Forecasting Urban Meteorology, Air Pollution and Population Exposure' (see Chapter 11, and Baklanov and Joffre, 2003). The forthcoming Action COST 728 (Enhancing Meso-scale Meteorological Modelling Capabilities for Air Pollution and Dispersion Applications) will also provide a suitable forum for such developments.

The improvement of urban meteorological forecasts will also provide new information to city managers, regarding additional hazardous effects or about other compounds and/or urban climate stress (e.g. urban runoff and flooding, icing and snow accumulation, high urban winds or gusts, heat or cold stress) in growing cities and/or factors in a warming climate. Moreover the availability of reliable urban scale weather forecasts could be a significant support for the emergency management of fires, accidental toxic emissions and potential terrorist action etc.

4.4 Conclusions and recommendations

Air quality management is mainly concerned with identifying pollution 'hot-spots' or areas of exceedence, and modelling of concentration maxima in these areas is very sensitive to our capacity to diagnose stably stratified conditions. Modelling of the urban surface energy balance and stability is largely absent from current dispersion models. Across Europe, different cities can be expected to influence local stability to differing extents, but little is known about this. A promising approach to obtain the surface fluxes needed in urban air pollution assessments is the use of nested numerical weather prediction and meso-scale meteorological models. Such models will approach the necessary resolution for the urban scale, but parameterisations of urban effects in most of the existing operational models are absent or too greatly simplified for this purpose (Baklanov *et al.*, 2001). Research, such as the work presented here, is able to identify sensible constraints on stability diagnosis, and to improve parameterisations. The experimental and numerical studies undertaken by COST 715[1] leads to the following conclusions and recommendations.

1. Validated siting criteria for urban stations are urgently needed (see also Chapter 3 and Chapter 8). Sites should be characterised with the help of aerial photographs, satellite observations, local surveys, maps, building dimensions, GIS and urban databases.

2. Measurement of surface fluxes at meteorological stations is desirable, but so far such measurements have only been undertaken in research programmes of limited duration. Urban meteorological measurements should be performed above the roughness sublayer, in the inertial sublayer. The height of this level varies with conditions and fetch (in general it is 2 to 5 times the building height, see Chapters 2 and 3). For central urban areas with relatively tall buildings, the above requirements may be unrealistic for practical purposes. Therefore the urban roughness sublayer should be investigated in more detail, specifically with regard to testing the recommended guidelines (see Chapter 3) for the siting of meteorological instruments in urban areas.

[1]Working Group 2

3. Available observations of urban heat fluxes demonstrate significant perturbation of the surface energy balance partitioning compared to the rural surroundings. In particular the convective sensible heat flux remains positive throughout the night, sustained by large releases of heat stored in the urban fabric from the previous day. As expected, given the lack of vegetation cover at most urban sites, the latent heat fluxes are small, and the Bowen ratio is therefore larger than 1 (Table 4.1).

4. The behaviour of turbulent flux profiles in the roughness sublayer, due to high roughness elements requires more study, both in the field and with models.

5. The state of the rural soil moisture, and therefore soil thermal admittance is a very important determinant of city heat island effects. The state of the surrounding countryside therefore must be considered in any such studies.

6. Horizontal inhomogeneity of the canopy means that the diffusivities for heat and water vapour differ (i.e. $K_E \neq K_H$). This is because while all surfaces are sources of sensible heat, not all urban surfaces are sources of water vapour (Roth and Oke, 1995).

7. A number of European groups run meso-scale models with sub-models of fluxes for urban areas. These models are not operational yet, but advances are very encouraging. Preliminary simulations indicate that the influence of the urban canopy, building energy flows and thermal properties, along with effective albedo reduction by radiative trapping between canyon walls are important and need to be properly described in models.

8. When one is only interested in the overall effect of cities on the overlying atmosphere, in the context of atmospheric dispersion studies, a non-explicit approach is sufficient in as far as one uses correct values for the main parameters such as albedo, thermal admittance, roughness (momentum and heat or other scalars), moisture availability etc. However modelling of the urban heat storage must be introduced to simulate correctly the heat flux diurnal cycle. Explicit modelling is needed only if one wants to look in detail at the processes that occur in the canyons, or to couple detailed traffic emission models with meteorology, in which case knowing the vertical profiles of turbulence characteristics in the street canyons is required.

9. The importance of the ratio z_0/z_{0t} , where z_0 andz_{0t} are the surface and temperature roughness parameters respectively, should be emphasised, as it exhibits the most significant differences of behaviour between urban and rural types of surface. Current knowledge regarding this ratio is insufficient, with different alternative formulations in the literature (e.g. Brutsaert, 1975; Joffre, 1988; Cahill *et al.*, 1997; Hasager *et al.*, 2003) and more research on this topic is required.

10. For applications in connection with dispersion modelling, no detailed surface exchange parameterisation can (computationally) be afforded. As an alternative, a meteorological pre-processor that has been modified for urban surfaces (LUMPS) is available. Turbulent fluxes (and hence stability) obtained from this scheme apply to heights sufficiently far from the urban fabric. A detailed validation, especially using data from European cities, would complement already existing North American studies and is much to be encouraged.

11. Satellite instruments can in principle be used to measure the urban surface energy balance, but there are significant issues concerning their ability to estimate the appropriate interface temperature. Furthermore satellite-based methods applied to cities are particularly sensitive to errors in this interface temperature and to surface-atmosphere exchange coefficients. In the future, better results are to be expected from methods based on the change of surface temperature with time from geostationary platforms, combined with spatial disaggregation techniques to obtain the high horizontal resolution required for urban studies.

12. More work is needed on developing techniques for the aggregation of terms (surface characteristics, fluxes) in models together with adequate validation exercises. This necessitates a new approach for collecting, analysing and integrating adequate microscale information on surface characteristics (using GIS) in co-operation with city authorities and other data providers.

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5. The mixing height and inversions in urban areas

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5.1. Introduction

The atmospheric boundary layer is the layer near the surface in which heat, momentum and moisture are exchanged between the Earth and the atmosphere. The turbulent properties of this layer (diffusivity, mixing, transport) will determine whether pollutants are dispersed and diluted or whether they build up and lead to pollution episodes. Thus the atmospheric boundary layer height, or the mixing height, which will determine the volume available for pollutant dispersion, depends on basic meteorological parameters, surface turbulent fluxes and physical parameters, and follows a diurnal cycle. The mixing height cannot be observed directly by standard measurements, so that it must be parameterised or indirectly estimated from profile measurements or simulations.

The mixing height depends on the vertical variation of temperature in the atmosphere. A particular type of situation is the temperature inversion, which can have a significant influence on air quality, including ground-based inversions and elevated inversions above the atmospheric boundary layer. Inversions can be caused by several atmospheric mechanisms, such as subsidence, fronts, radiation and advection. The radiation and advective inversions occur most frequently in the course of air quality episodes. The interdependence of mixing heights and temperature inversions was discussed during a Workshop organised by COST 715[1] (COST 715, 2002b).

COST 710 (Seibert *et al.*, 1999) performed a comprehensive review of different definitions and practical determinations of the mixing height from measurements, modelling and parameterisation, and from outputs from numerical weather prediction models, but only involved rural sites. During the last decades, however, several experimental studies of the atmospheric boundary layer have been performed for urban areas (Baklanov, 2002). COST 715 has analysed the properties of the urban mixing height and verified different methods for estimating the mixing height against measurements (remote sensing

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devices and diagnostic evaluation methods for radiosonde profiles) for several types of urban areas. COST 715 organised a Workshop to assess various parameterisation schemes to determine the urban mixing height (COST 715, 2002a, Rotach *et al.*, 2002). Additionally statistical surveys of the urban atmospheric boundary layer were performed, focusing on its basic characteristics (e.g. height, inversion strength) and behaviour (e.g. growth and extent). More extended discussions of COST 715 results concerning the mixing height can be found in Baklanov *et al.* (2004) and Piringer and Joffre (2004).

5.2. Evidence and complexities of the urban boundary layer

The urban boundary layer, in comparison with rural atmospheric boundary layers, is characterised by greatly enhanced mixing, resulting from both the large surface roughness and increased surface heating, and by enhanced horizontal inhomogeneity of the mixing height and other meteorological fields due to differences in surface roughness and heating between rural and central city areas. So it is reasonable to consider the urban boundary layer as a special case of the atmospheric boundary layer over a very non-homogenous terrain with specific characteristics, primarily the abrupt changes of the surface roughness and the urban surface heat fluxes at the micro-scale.

Figure 5.1 illustrates an example of the daily cycle of the aerosol concentration over Basel during the Basel Urban Boundary Layer Experiment BUBBLE (Chapter 10 and Rotach *et al.*, 2004) together with the diagnosed aerosol mixed layer height, showing the typical development and decay of the convective boundary layer through the day. While the situation presented yields clear results concerning the aerosol mixed layer height, a more complicated aerosol structure can sometimes be observed. During the night, elevated layers of high aerosol concentrations may be present in the residual layer and sometimes up to three local minima in the derivative of the concentration profile are observed. Interestingly, quite often there is a pronounced local minimum in the derivative of the lidar signal at about 2.5 to 3 km (see also Fig. 5.1), most of the time well above the readily determined aerosol mixed layer height.

The mixing height is often higher in urban areas than in the rural case. This has been illustrated for Athens (Figs. 5.2 and 5.3), using two versions of the Penn State/NCAR Mesoscale Model MM5 (Anthes *et al.*, 1978). The MM5 model was applied in its original version with the high resolution non-local

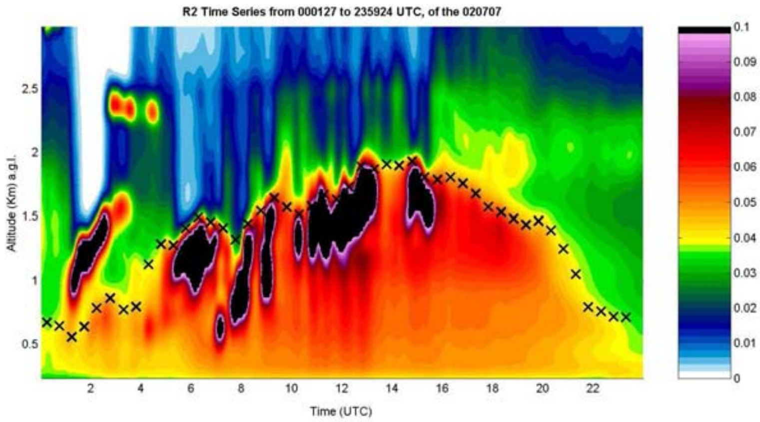


Figure 5.1 Lidar scans of the backscatter from the atmosphere on 7 July 2002 at a site in central Basel, Switzerland. The colour coding is proportional to the aerosol concentration (black=clouds). Crosses indicate the diagnosed aerosol mixed layer height from the derivative of the logarithm of the range-corrected signal. (Data courtesy of Valentin Mitev and Giovanni Martucci, Neuchâtel Observatory.)

NCEP MRF (National Center for Environmental Prediction Medium Range Forecast Model) atmospheric boundary layer scheme. This scheme is based on Troen and Mahrt's (1986) representation of counter-gradients and K-profiles in the well-mixed convective boundary layer (Hong *et al.*, 1996). In this version, urban areas are represented as bare soil with specific surface characteristics and physical parameters, such as roughness length, albedo etc. In order to examine topographic influences on air motions in the city basin, another simulation was performed with the original version, but one in which Athens was replaced by dry cropland and pasture surface as in the surrounding areas. A third simulation uses a modified (urbanised) version of MM5, in which urban features were introduced both in the thermal and the dynamical part (Dandou *et al.*, 2004). In particular, the urban heat storage was incorporated into the model following the Objective Hysterisis Model (OHM) of Grimmond *et al.* (1991) and anthropogenic heat effects for Athens were considered following Taha (1998).

Figure 5.2 illustrates the diurnal variation of the mixing height at the National Observatory of Athens station in the city centre and for the rural station Spata, produced by the original MM5/MRF model with the urban area replaced by a dry cropland and pasture area and by the modified MM5/MRF model on 14 September 1994 (during the MEDCAPHOT experimental campaign). The modified version of MM5, which includes some urban effects, increases the mixing height for nocturnal conditions (due to anthropogenic heat and storage heat terms). During daytime, the values are a little smaller than those calculated by the original version and there is a delay of two hours before the maximum value is reached. On the other hand, the changes do not affect the mixing heights for the non-urban site. For the case when the urban area of Athens is replaced by a dry cropland and pasture area, mixing heights are much lower (300 m) compared to the ones from the original version. Nevertheless the maximum mixing heights in the area are still formed in the Athens basin due to the surrounding topographical features. This unrealistic run illustrates, as in the case of Marseilles, that in a complex situation, urban influences co-exist with other mechanisms. Figure 5.3 shows the night-time spatial distribution of the mixing height for the original case and the modified one. The increase of the mixing height in the Athens area compared to the surroundings is clearly visible.

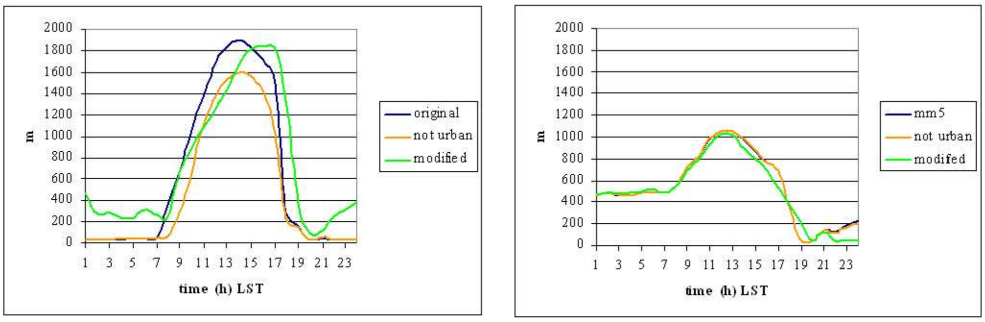


Figure 5.2: The diurnal variation of the mixing height (m) at the National Observatory of Athens station in the city centre of Athens (left) and the rural station of Spata (right), produced by the original MM5/MRF model (dark blue line), the urban area replaced by a dry cropland and pasture area (orange line) and the modified 'urbanised' MM5/MRF model (green line) on 14 September 1994.

Another example of complex interactions is evident from the atmospheric boundary layer vertical structure during the ESCOMPTE campaign (Mestayer *et al.*, 2004) using data from 7 sodars, 7 radars and 5 lidars, of which 3, 1 and 2 (sometimes 3) respectively were located within the Marseilles urban area. Additionally aeroplane data complemented the surface energy balance measurements within and outside the city. Preliminary results show sometimes the counteracting influences of several different factors: the synoptic flow regime (especially the northerly Mistral wind), the sea breeze systems at the local scale and regional scale, the topography, as well as the urban canopy and surface. In

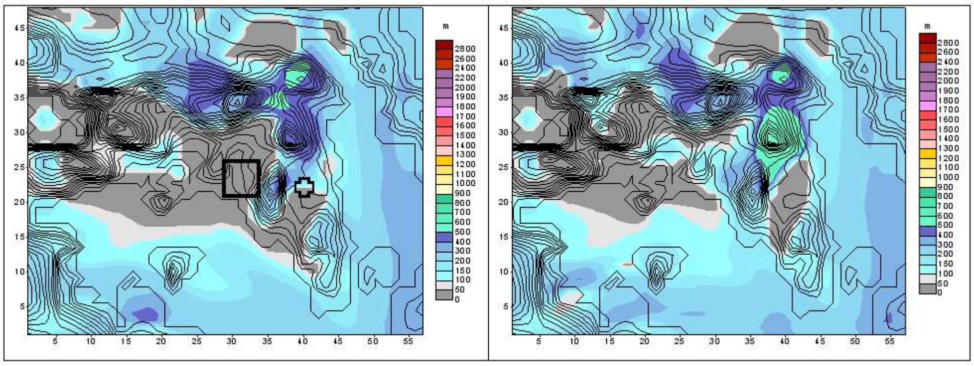


Figure 5.3: Spatial distribution of the mixing height calculated by the original (left) and modified (right) MM5/MRF model, at 23:00 LST on 14 September 1994. The axes represent number of grid cells of 2 km each. Central Athens is indicated by a box in the middle of the left figure, the rural Spata station is indicated by a cross. The urban National Observatory of Athens station is inside the box.

such a complex situation urban influences are never observed in isolation.

These complex patterns are illustrated in Fig. 5.4 derived from a UHF profiler at the site Observatoire, close to the city centre, and a RASS sodar measuring wind and temperature vertical profiles at the Vallon Dol site, located at the border of the city and overlooking most of the urban area. These graphs also show that different devices and different parameters respond to different signals or features, thus emphasising the need to use sets of composite data for an integrated view of complex atmospheric processes.

Direct comparison of the sea breeze systems over the urban and non-urban areas in Marseilles shows that: (i) the local city breeze is easily smeared out by a larger scale breeze system that develops on a daytime scale, and (ii) the complex influence of the city on the mixing height, with sometimes some periodic urban boundary layer growth and destruction cycles within one day, with a period of about 1.5 hours. This phenomenon is probably linked to both the large urban sensible heat flux and also the large contribution of the energy balance that is diverted to the canopy heat storage during the first half of the day. During some of the nights, the persistence of elevated stratified layers was observed over the urban area. Also the observation of relatively homogeneous ozone concentrations at night in the lowest layer may indicate a weak low-level stable stratification, or even an unstable layer due to the weak, but positive, nocturnal sensible heat flux in the city.

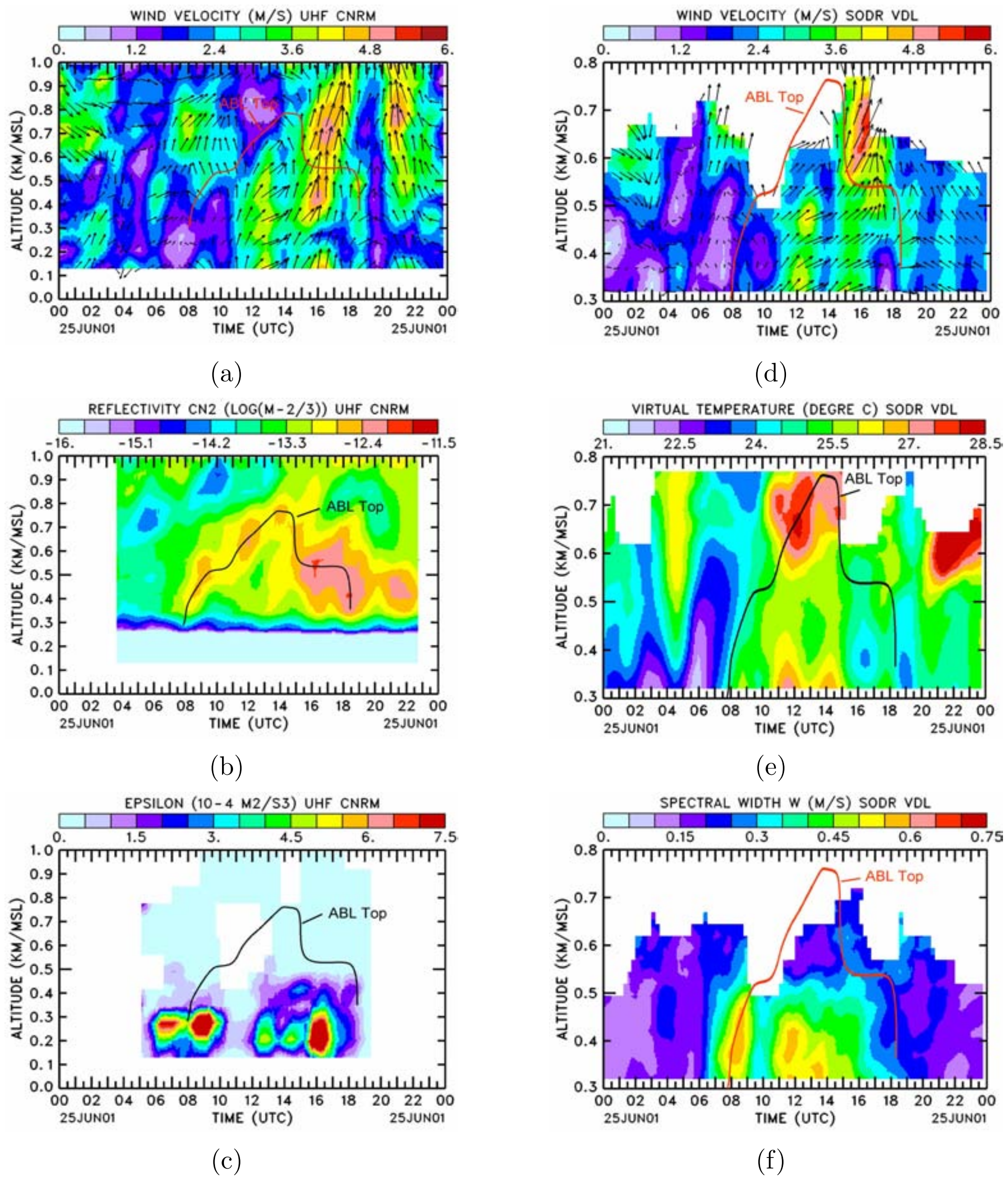
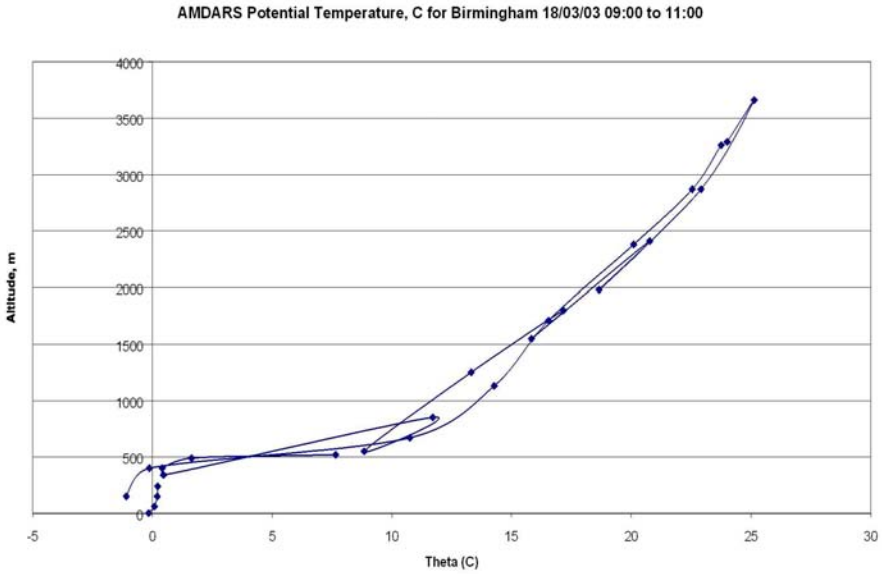


Figure 5.4: Time-height sections of UHF profiler at the Observatoire (left) and sodar-RASS at Vallon Dol (right): (a), (d) Horizontal wind velocity, (b) C_n^2 reflectivity (e) virtual temperature (c) sodar Doppler spectral width, and (f) dissipation rate of turbulent kinetic energy ε. The superimposed line is the top of the atmospheric boundary layer deduced from the maximum UHF reflectivity.



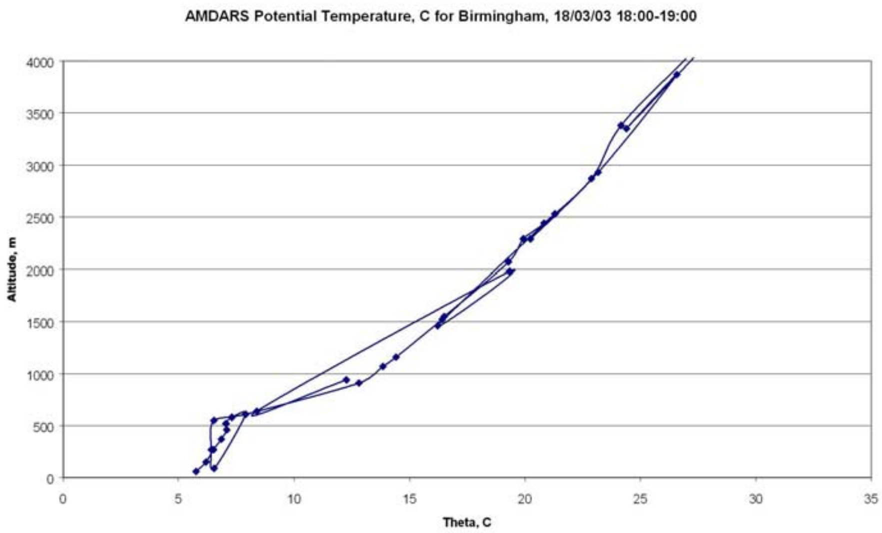


Figure 5.5 AMDAR profiles of potential temperature θ versus altitude z for aircraft at Birmingham Airport for the morning (left) and afternoon (right) of 18 March 2003 (from Davies et al., 2003).

New opportunities for estimating the mixing height and profiles of potential interest to the air pollution meteorologist, have recently arisen from a joint European project (AMDAR, 2002) looking at the use of data from civil aircraft, to complement existing radiosoundings. This EUMETNET AMDAR (Aircraft Meteorological Data Reporting) system uses the aircraft sensors for measuring wind speed and direction, air temperature, altitude, a measure of turbulence and the aircraft position. Data are archived by meteorological services along with more traditional synoptic observations and provide profiles of temperature and wind near airports close to most of the European large cities.

In Figure 5.5 the AMDAR profiles of potential temperature versus altitude for the morning and afternoon of 18 March 2003 for aircraft near Birmingham Airport are plotted. They show clearly a mixed region up to 450 m in the morning, and 600 m in the evening. Some issues need further consideration, including improvements in processing and evaluation of AMDAR data relative to other observations/model products, and the usefulness (or otherwise) of the AMDAR information for air quality studies. Their use and validity for use with dispersion studies is still under study, and there may be further refinements and developments to the AMDAR data processing programme. Thus in the absence of radiosonde ascents over cities or at experimental sites, the AMDAR data offer useful substitute profiles in the lower atmosphere. Standard objective methods for the determination of the mixing height from profiles (e.g. parcel ascent, Richardson Number) may then be applicable to the AMDAR data.

5.3. Statistical characteristics of the urban boundary layer

The different geographical environments of cities (e.g. flat terrain versus mountain valleys, coastal area versus continental cities, northern versus southern cities) can strongly affect the formation of the urban boundary layer and thus the corresponding mixing height. For example the nocturnal stably stratified boundary layer is not common for cities in the USA (Bornstein, 2001), or middle and southern European cities, where frequently elevated nocturnal inversion layers and thus higher night-time mixing heights are found. However especially in central and northern Europe, the nocturnal stable boundary layer is fairly common (e.g. in Helsinki, Karppinen *et al.*, 2001, 2002; Railo, 1997), and additionally can persist for an extensive period (even during daytime) in wintertime, resulting in frequent very low night-time mixing heights that are liable to exacerbate pollution episodes.

Table 5.1: Average mixing height for Munich diagnosed from radiosoundings downwind of the city using the Heffter (He), bulk Richardson Number (Ri), Parcel (Pa); Advanced parcel (Apa) and Humidity jump (Hu) methods for determining the mixing height.

a) daytime

winter rural

	He	Ri	Pa	APa	Hu
number of cases	142	138	91	91	74
mean	482	421	381	496	868
standard deviation	524	445	389	452	651
difference to APa	105	132	-115	0	358
number of data pairs	90	86	91		61

summer rural

	He	Ri	Pa	APa	Hu
number of cases	54	51	52	51	34
mean	1134	1290	857	1039	1109
standard deviation	681	826	568	561	706
difference to APa	204	464	-203	0	31
number of data pairs	48	44	51		32

winter urban

	He	Ri	Pa	APa	Hu
number of cases	116	117	88	88	61
mean	962	728	531	727	1347
standard deviation	635	606	358	433	766
difference to APa	385	255	-196	0	518
number of data pairs	81	82	88		52

summer urban

	He	Ri	Pa	APa	Hu
number of cases	210	203	230	230	132
mean	1506	1431	1021	1207	1516
standard deviation	550	623	482	469	637
difference to APa	333	324	-186	0	258
number of data pairs	206	199	230		132

b) night-time

winter rural

	He	Ri
number of cases	161	161
mean	120	181
standard deviation	184	83
difference to Ri	-60	0
number of data pairs	161	

summer rural

	He	Ri
number of cases	186	187
mean	78	177
standard deviation	76	106
difference to Ri	-99	0
number of data pairs	286	

winter urban

	He	Ri
number of cases	123	124
mean	564	241
standard deviation	572	148
difference to Ri	322	0
number of data pairs	123	

summer urban

	He	Ri
number of cases	192	195
mean	392	213
standard deviation	503	101
difference to Ri	182	0
number of data pairs	192	

Differentiating the urban boundary layer from the usual rural atmospheric boundary layer is also apparent using the approach of Baumann–Stanzer and Groehn (2004), who based on the quality controlled, comprehensive Alpine radiosonde data set CALRAS, created as a result of MAP (Mesoscale Alpine Programme, http://www.map.ethz.ch/), investigated the ability of routine radiosoundings to 'see' urban effects on the mixing height when they were launched downwind of the city of Munich (Table 5.1). In comparison to profiles from predominantly rural sectors arriving at the radiosonde site, an increase in the average mixing height for the urban sectors is expected, and is indeed observed in all the different mixing height estimation methods applied (the Parcel Method was used as a reference in daytime conditions, see Section 5.5). An extended discussion of these results and an explanation of these methods are available in Baklanov *et al.* (2004) and Piringer and Joffre (2004).

A study in Copenhagen by Baklanov and Kuchin (2003) gave similar results, in which the urban mixing height is considerably higher for (nocturnal) stable boundary layer cases in comparison with the 'non-urban' mixing height. On the other hand, daytime (usually convective boundary layer) mixing heights do not differ very much in urban and 'non-urban' sectors. For convective conditions, the anthropogenic heat flux does not play a dominating role and the roughness features play the major effect. Therefore an interaction between the sea breeze and urban effects, together with a combination of internal boundary layers, determine the mixing height under convective boundary layer conditions over Copenhagen. This also supports the conclusions of Seibert *et al.* (1999) that it is more acceptable to apply standard methods for estimating the daytime mixing height than for the nocturnal mixing height. To minimise uncertainties, it is recommended that a combination of the Richardson Number and Parcel Methods is used for diagnosing the mixing height from radiosounding profiles for both urban and non-urban convective boundary layer conditions.

5.4. Surface inversions and pollution episodes

Temperature inversions can result in peak pollution episodes, especially when they are intense, shallow and last for an extended period. They can occur in weak synoptic scale meteorological flows (low wind speed and meandering wind direction), although this is not always the case. It is generally a challenging meteorological task to predict and forecast such cases. Regularly during the night, most ground-based inversions are generated by surface cooling through upward radiative and turbulent heat transfer. This inversion can develop with time to reach a few hundred metres, involving the dampening of turbulence and mixing. Though the turbulent atmospheric boundary layer can be only a fraction of the inversion layer, no obvious practical relationship between the two depths can be established, as they depend on a unsteady wind profile (low level jet) resulting in intermittent bursts of turbulence.

Chapter 6 of this report presents an analysis and evaluation of air pollution episodes in several European cities (especially in relation to particulate matter, NO_2 and ozone), and examines their causes in relation to local emissions and meteorological conditions. For both particulate matter and nitrogen oxides, low-level inversions and local low wind speeds are key factors in many European regions with respect to the formation of air pollution episodes. In the case of PM_{10} episodes, suspended particulate matter originating from street surfaces can also be an important contributor, especially in northern and central European cities.

COST 715 has initiated work on the dependency of episodes on temperature inversions in both northern and southern European countries. The Action has evaluated the performance of both numerical weather prediction models and air quality forecasting models regarding their ability to predict relevant meteorological parameters and air quality. One of the main challenges for the future is to improve the performance of such models in order to forecast the evolution of urban temperature inversions during pollution episodes.

Numerical weather prediction (NWP) modelling has been used to try to simulate strong wintertime inversions in northern Europe by Berge *et al.* (2002) using two NWP models (HIRLAM, High Resolution Limited Area Model, and ECMWF, European Centre for Medium-range Weather Forecasts), combined with the utilisation of the non-hydrostatic MM5 model. The numerical runs for Oslo, using 10, 3 and 1 km nesting, revealed the need for high resolution to resolve patterns induced by topographical features. An episode in Helsinki that involved an extremely strong ground-based temperature inversion (15 °C over the lowest 30 m, on the 27-28 December 1995) was also simulated and compared with observations from the Kivenlahti radio tower located in a semi-urban area 15 km to the west of the Helsinki city centre. The NWP models could not completely reproduce the strong inversion. The structure of the inversion was realistically simulated, but the magnitude was somewhat underestimated (Pohjola *et al.*, 2004; Rantamäki *et al.*, 2004).

Nine years (1989-1998) of 1-hour averaged temperature and wind data from the Kivenlahti mast measured at the heights of 26 and 91 metres were analysed by Karppinen *et al.* (2001). The frequency distribution of the vertical temperature differences for all the studied stable cases are depicted in Figure 5.6. The temperature gradient is scaled to represent a temperature difference over 100 metres using the actual measured temperature differences between the measurement levels. The vast majority of stable cases are in the inversion category with a temperature gradient less than 6 °K/100 m. Numerical integration of the distribution function shows that about 20% (10 000 cases) of the studied temperature inversions are larger than 4 °K/100 m, and only 6% (2 500 cases) of the temperature gradients are larger than 6 °K/100 m.

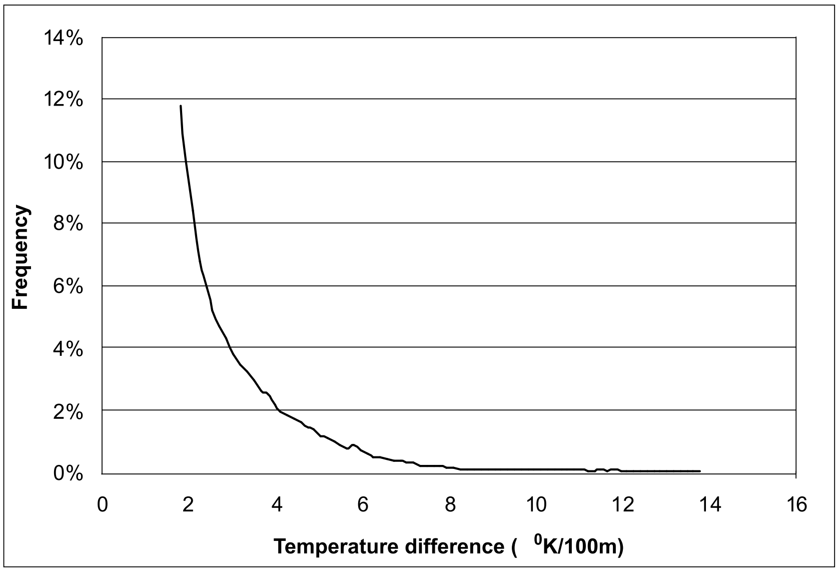


Figure 5.6: The frequency distribution of the potential temperature differences (°K/100 m) for cases with a stable atmospheric stratification, evaluation based on mast measurements at the heights of 26 m and 91 m at the station Kivenlahti located in the Helsinki suburban area, during 1989–1998 (Karppinen et al., 2001).

Three different episodes that occurred in northern Italian cities were analysed based on synoptic meteorological information, local vertical profiles from soundings, and meteorological and chemical measurements from an air quality network (Finardi *et al.*, 2002). It was shown that Milan is a city where topography plays an important role in the development of inversions in winter. Whilst high pressure may build the inversion, meso- and microscale processes determine the local wind field near the ground. The low level circulation may be decoupled from the synoptic scale, being driven by local and mesoscale effects.

A set of meteorological criteria with their temporal evolution can be specified for predicting the potential formation and occurrence of air quality episodes. Such criteria can include limit values in terms of wind velocity, inversion strength or gradient, atmospheric stability and Richardson Number. However any single meteorological parameter, or just one criterion, cannot be sufficient.

5.5. Empirical determination/monitoring of the urban boundary layer

Radiosoundings are in principle relevant for estimating the mixing height (including operational modelling), but sounding stations are usually located outside urban areas. However in many European countries, they are getting closer to or sometimes inside growing urban agglomerations, and therefore for many cities it is becoming reasonable to analyse radiosonde data for urban mixing height estimation by selecting wind direction sectors downwind of the city (see Section 5.3).

Under unstable conditions the mixing height is often identified as the base of an elevated inversion or stable layer. Heffter (1980) formulates a criterion to analyse potential temperature profiles for such ‘critical’ inversion heights, in which the mixing height is the level within the lowest layer with a potential temperature lapse rate equal to or larger than 5 °K km^{-1}, where the temperature is 2 °K higher than at the inversion base. Seibert *et al.* (1999) found the Parcel Method (e.g. Holzworth, 1967) to be the most reliable in convective situations. It is based on following the dry adiabat from the measured surface temperature (or an expected maximum temperature) to its intersection with the temperature profile of the associated radiosounding. Thus the mixing height is taken as the equilibrium level of an air parcel with this temperature, but depends on the surface temperature and the existence of a pronounced inversion at the top of the convective boundary layer. This method was refined by Garrett (1981), Stull (1991) and Wotawa *et al.* (1996) by adding an excess temperature at the surface (Advanced Parcel Method). In the convective boundary layer, the mixing height is sometimes identified as the height of a significant reduction of air moisture, often accompanied with wind shear (e.g. Lyra *et al.*, 1992). A decrease of the water vapour mixing ratio of more than 0.01 g kg^{-1} m^{-1} with height is interpreted as a signal for the top of the mixing layer from daytime profile data only. This method is called the Humidity Jump method.

A standard generic method for estimating the mixing height is based on the Richardson Number approach. This approach includes several variants differing in the choice of levels over which the gradients are determined and in the value of the critical Richardson number, Ri_c. Following Zilitinkevich and Baklanov (2002), we can distinguish four different Richardson Number methods and examples of its application can be found in Maryon and Best (1992), or Vogelezang and Holtslag (1996). The bulk Richardson number method can be used both in convective conditions and under conditions dominated by mechanical turbulence. The mixing height is determined as the height where the specific Richardson Number becomes equal to or larger than the Ri_c (generally taken = 0.25, but a wide range of values between 0.2 and 3 have been used based on both theory and optimised data fit). Zilitinkevich and Baklanov (2002) suggest using a functional dependence of the Ri_c number on roughness or free flow stratification to improve this method for the stable boundary layer case. In situations dominated by mechanical turbulence, the bulk Richardson Number approach was found to be the most appropriate whenever temperature and wind profiles are available (Seibert *et al.*, 1999).

The different types of vertical profilers (sodars, lidars, radars, ceilometers etc) have the potential to provide better information on the vertical structure of the atmospheric boundary layer and to provide better estimates of the mixing height than radiosondes. Their main weaknesses arise from the limitation on their use in urban areas (e.g. due to noise) and the need for expert personnel, so that usually they are not in operational use. However for some specific problems (e.g. for nuclear emergency preparedness systems, wind energy and other research purposes) they are permanently used and could be used for mixing height estimation in urban or semi-urban areas. Electromagnetic backscatter is generally the best option for determining the (high) afternoon convective boundary layer heights. Among this category, the ceilometer is found to be a very useful instrument in clear sky conditions as it is the only instrument (compared to RASS/sodar) which gives directly the vertical aerosol profile. The ceilometer is also by far the most low cost/easily handled remote sounding equipment considered here (of potential similar to a single frequency lidar), and its vertical range (from the lowest range gate of 15 m, up to 2 or 3 km) is ideal for atmospheric boundary layer studies.

The quality of mixing height calculations can depend largely on the data source. For instance, Fig. 5.7 shows the partial correlations between results obtained using two sources of data (Karppinen *et al.*, 2001). A simple mixing height scheme, based only on the vertical temperature gradient, was applied to (i) radiosonde data from the rural site of Jokioinen, and (ii) data from the Kivenlahti mast. The station at Jokioinen is located approximately 100 km north from the southern Finnish coast in a rural area, while Kivenlahti is located in a semi-urban environment at a distance of approximately 6 km from the coastline, west of Helsinki.

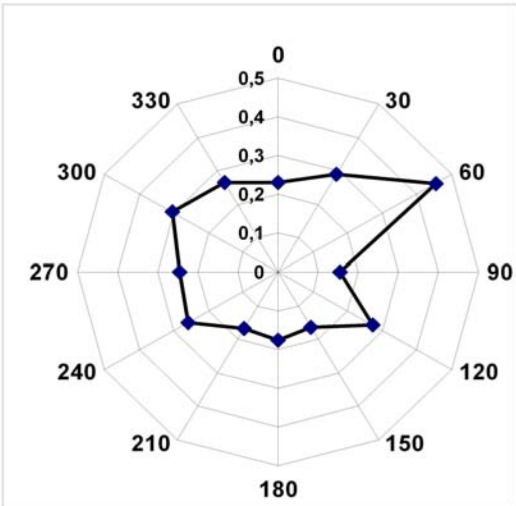


Figure 5.7: Correlation between predicted mixing heights computed using the same model and two different data sets. The mixing height model is based solely on the vertical temperature gradient. The data sets were temperature gradient measurements from the stations at Jokioinen and Kivenlahti (Karppinen et al., 2001).

The correlation between the results from these two datasets is dependent essentially on wind direction i.e on the history of the air mass. The weakest correlation occurs for southerly winds (from the sea), which is to be expected, since under such conditions Kivenlahti is largely influenced by maritime air masses. The most urbanised area is located in the easterly direction from Kivenlahti, and the corresponding correlation also appears to be fairly low. For a non-homogeneous area, it is therefore advisable to include the information on measured wind speeds into the mixing height scheme used, as urban roughness greatly modifies the mixing height behaviour.

An alternative method for the indirect estimate of the mixing height uses the dependence of ionising tracer gas concentrations, like polonium ^{218}Po, on the vertical thermal stratification, that arise from the increased accumulation during steady equilibrium (nocturnal layer of ground temperature inversion) and the decrease in accumulation when the atmosphere becomes unstable. Results from Katowice and Cracow (Fig. 5.8) show however a weak dependence with considerable scatter.

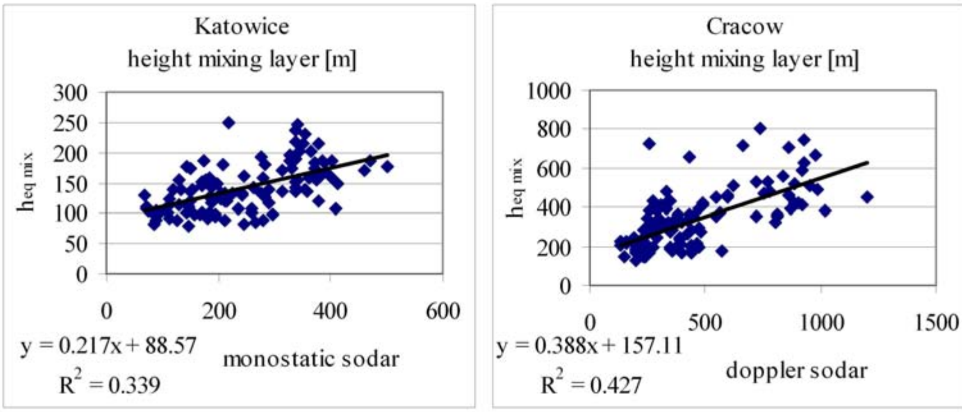


Figure 5.8: Comparison of mixing heights calculated from ^{218}Po tracer gas concentrations ($h_{eq_{mix}}$) and those observed by a monostatic sodar (Katowice) and Doppler sodar (Cracow).

Consideration of the best methodologies (e.g. by profiles, or by remote sensing or via accumulated pollutants in the air) for measuring the mixing height still leads to a contradictory debate, especially on the interpretation of measurements seen by each method or device (see Piringer and Joffre, 2004). It is still difficult to recommend optimum methods for measuring the urban mixing height, as all have some drawbacks. On the other hand, the combination of methods and/or the stratification of available data, based on expert scientific consideration (e.g. no statistical bulk mean values) with due consideration of specific conditions (e.g. upwind conditions, stability, prevailing meteorology) may lead to interesting new knowledge and understanding for practical applications. The effect of climatic differences on the urban mixing height has to be investigated more thoroughly. There are significant differences between northern and southern European cities in this respect.

5.6. Parameterisation and modelling of the urban boundary layer

The most common approach used in dispersion models to get mixing height values is its calculation from specific parameterisations or pre-processors. This approach is suitable to the use of *in situ* measurements or for profiles derived from numerical weather prediction models. Parameterisation schemes for the mixing height have been developed and validated using rural homogeneous conditions, so that their applicability to urban conditions should be verified. Some authors have suggested specific methods for mixing height determination in urban areas. They can be classified in two main categories: (i) using a local correction to the heat fluxes and roughness due to urban effects (see Chapters 3 and 4), and (ii) estimating the internal boundary layer height growth as the flow moves over a city.

For the estimation of the mixing height in urban areas, most authors use a standard 'rural' diagnostic method without any corrections for urban features. The most commonly used diagnostic methods (mostly for stable boundary layers) are listed in Appendix 5A. The properties of the atmospheric boundary layer are primarily described within the theoretical framework of similarity relations, by which the variability of the structure of the atmospheric boundary layer can be explained by the variation in the scales of the phenomena. Thus most formulae are based on the classical scaling quantities: the friction velocity u_*, and the Monin-Obukhov length L. Appropriate estimates of the friction velocity u_* for urban conditions are described in Chapter 3 of this report, while methods for the heat flux and thus the Monin-Obukhov length are discussed in Chapter 4. Additionally, the atmospheric boundary layer structure is determined by the following external parameters: (i) the wind velocity at the top of the layer (or the geostrophic wind speed G), (ii) the Coriolis parameter f arising from Earth's rotation, and (iii) the surface roughness length z_0, In uniform, homogeneous, steady conditions, the atmospheric boundary layer structure and variability is expressed as a function of dimensionless ratios of these scales.

A few tests of the applicability of such simple scaling formulae for specific urban sites yielded mixed results (e.g. Berman *et al.*, 1997, Lena and Desiato, 1999). However a comprehensive analysis of their applicability has not yet been carried out. The main problem of such diagnostic methods is their assumption of horizontal homogeneity. Therefore it is difficult to expect that they are applicable to city peripheries (with sudden changes of roughness), whereas they might be used in central (relatively homogeneous) areas of certain cities, because the physical mechanisms behind the mixing height formation are the same there as for other types of surface. Nevertheless this weak agreement with measured urban mixing heights is not only due to the urban features, since they do not yield very satisfactory results either for rural and/or homogeneous conditions (Seibert *et al.*, 1999, Baklanov, 2002, Zilitinkevich and Baklanov, 2002). Thus for stable boundary layer cases, it is reasonable to use mixing height methods which consider either vertical profiles or roughness and surface fluxes as input parameters, since in the latter case they can be used for urban conditions with corrections for the heat flux and surface roughness.

For long-lived stable boundary layers occurring below the stably stratified free flow (common in Northern Europe), traditional concepts fail and an extended (non-local) version of stable boundary layer theory including the Brunt-Väisälä frequency, N, representative of the layer just above the atmospheric boundary layer top, has been suggested to correctly describe the stable boundary layer (Zilitinkevich *et al.*, 2002, Zilitinkevich and Baklanov, 2002). This extended theory also explains why it is possible that developed turbulence in stable boundary layer can exist at much larger Richardson Number than the classical theory predicts (upward radiation of internal waves from stable boundary layers leaves more room for the generation of turbulence by velocity shear). An equivalent method was independently derived by Kitaigorodskii and Joffre (1988) based on an integrated formulation of the turbulent kinetic energy equation that yields analytical formulae for the mixing height depending on the stability parameter $\mu_N = L_N/L$, where $L_N = u_*/N$ and L is the Monin-Obukhov length. Here again N represents non-local effects through background stratification at the top of the atmospheric boundary layer. Joffre *et al.* (2001) found that under both stable and unstable conditions, a great deal of the variability in the mixing height over a very rough rural surface is explained with the scales L_N and L, while the dimensionless parameter N/f acts as a secondary explanatory parameter.

An extensive comparison of various schemes for estimating the mixing height against new data is being performed within COST 715[2]. This is still under investigation and results will be reported at length in Piringer and Joffre (2005) and Baklanov *et al.* (2004).

For more accurate stable boundary layer height calculations within one and three dimensional models, the diagnostic and prognostic formulations of Zilitinkevich *et al.* (2002) are recommended. Inadequacies in diagnostic methods for estimating the urban mixing height are caused by the strong horizontal in-

[2]Working Group 2

homogeneity and temporal non-stationarity of the urban boundary layer, and the non-local character of the urban mixing height formation. Nevertheless the mechanisms involved in the formation of the daytime mixing height (or the convective boundary layer) are better understood than the corresponding ones at night. Therefore it is strongly recommended that more emphasis should be given to improving the methods for the night-time mixing height determination.

The inhomogeneity in surface types and thermal properties within a city should be taken into account in models. In the context of numerical weather prediction models, one can raise the question whether the mixing layer is still a valid concept. It seems that its practical usefulness in understanding episodes and as an input value for the simpler types of pollution dispersion model renders the concept of mixing height useful, despite the recognised uncertainty in its definition. There is increasing interest in using numerical outputs from numerical weather prediction models to generate formatted data that can be easily put into environmental impact assessment or forecast models, and where the mixing height is an important requirement, alongside the stability. However within numerical weather prediction models, simple closure models for the evaluation of the mixing height do not work well. Nocturnal stable conditions in urban areas present the greatest difficulty for modellers. The performance of these simple methods seems more acceptable for daytime than for nocturnal conditions (Baklanov *et al.*, 2004).

Most dispersion models require an estimate of the mixing height, so that an effective limit on vertical spread can be modelled. Its effect is most important if it is shallow, when low lying plumes may be trapped near to the ground, leading to high local concentrations, while elevated plumes might be unable to reach the ground. Mixing height estimates may be input to models, or calculated by specific routines within models. Regulatory models based on traditional Gaussian plume models, or new Lagrangian models for evaluating dispersion characteristics, also encounter the problem of inhomogeneity over an urban surface. Despite progress in numerical modelling of turbulence during the last decades, the mixing height is still one major uncertainty for most air quality models. Though no direct evaluation of the mixing height is necessary regarding the dispersion of traffic-originated pollution within the roughness sublayer (e.g. within a street canyon), the mixing height is an important parameter for practically all air pollution applications at the urban and the meso-scale.

5.7. Conclusions and recommendations on the urban boundary layer height and inversions

In conclusion to this still ongoing work, the following general recommendations are proposed concerning the applicability of 'rural' methods of mixing height estimation to urban areas:

1. For estimation of the daytime mixing height, applying standard rural methods is more acceptable than for the nocturnal mixing height, provided they allow for the urban heat storage as well as changed surface characteristics.

2. For the convective urban boundary layer the simple slab models (e.g. Gryning and Batchvarova, 2002) were found to perform quite well.

3. The formation of the nocturnal urban boundary layer occurs as a result of the opposing effects of the negative 'non-urban' surface heat fluxes and positive anthropogenic, urban heat fluxes, so the applicability of standard methods for the stable boundary layer estimation is less promising.

4. The determination of the stable boundary layer height needs further development and verification against urban data. As a variant of the methods for stable mixing height estimation, the new Zilitinkevich *et al.* (2001) parameterisation can be suggested in combination with a prognostic equation for the horizontal advection and diffusion terms (Zilitinkevich and Baklanov, 2002).

5. Strong ground-based or slightly elevated temperature inversions can be crucial factors for the formation of peak pollution episodes. The most important inversion types in relation to air quality are radiation and advective inversions in Europe (Sokhi *et al.*, 2003, Kukkonen *et al.*, 2004).

6. The observed temperature inversion can be recommended as predictor for forecasting the likelihood of the formation of air pollution episodes (Kukkonen *et al.*, 2004). On the other hand, these severe inversions are still difficult to model and forecast.

7. Mesoscale meteorological and numerical weather prediction models with modern high-order non-local turbulence closures give promising results (especially for the convective boundary layer). However currently the

urban effects in such models are not included at all, or are included using simple procedures (Baklanov *et al.*, 2002).

In summary more specific definitions of the mixing height for urban areas adapted for various empirical measuring devices are needed. Though useful background information was provided by the previous COST 710 Action, the horizontal inhomogeneity and the vertical structure of the atmospheric boundary layer over urban areas have to be taken into consideration to interpret data and derive mixing height schemes. It is concluded that the mixing height is a useful concept in the context of simpler regulatory dispersion models, although not a very accurate one. Concerning numerical weather prediction models, it is not so clear whether the mixing height is sufficiently accurate to be useful at the present stage of their development.

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Appendix 5A: Some current formulations for estimating the mixing height

Reference	SBL height equations
1. Zilitinkevich (1972)	$$h = c_2 \left(\frac{u_* L}{f}\right)^{1/2},$$ $c_2 \approx 0.4$ (varies between 0.13 and 0.72 according to different authors)
2. Venkatram (1980)	$$h = u_* \sqrt{\frac{2}{fN}}$$
3. Arya (1981) (after Zilitinkevich, 1972)	$$h = a \left(\frac{u_* L}{f}\right)^{1/2} + b; \quad a = 0.43, b = 29.3$$
4. Nieuwstadt (1981)	$$h = L \frac{0.3 u_*}{\lvert f \rvert L} \frac{1.0}{1.0 + 1.9 h/L}$$
5. Zilitinkevich and Mironov (1996)	$$\left(\frac{fh}{0.5u_*}\right)^2 + \frac{h}{10L} + \frac{Nh}{20u_*} + \frac{h\lvert f \rvert^{1/2}}{(u_* L)^{1/2}} + \frac{h\lvert Nf \rvert^{1/2}}{1.7u_*} = 1$$
6. Zilitinkevich *et al.* (2002)	$$h = \frac{C_R u_*}{\lvert f \rvert} \left[\left(1 + C_h \frac{w_h}{u_*}\right) \Big/ \left(1 + \frac{C_R^2 u_* \left(1 + C_{uN} NL/u_*\right)}{C_S^2 L \lvert f \rvert}\right)\right]^{\frac{1}{2}}$$ with: $C_R = 0.4$, $C_S = 0.74$, $C_{uN} = 0.25$ and $C_h = 0.3$.
7. Zilitinkevich and Baklanov (2002)	$\frac{\partial h}{\partial t} + \mathbf{V} \cdot \nabla h = -C_E \lvert f \rvert (h - h_{CQE}) + K_h \nabla^2 h$ with $C_E \approx 1$
8. Joffre and Kangas (2002)	$$h = \frac{b'}{2a'} \mu_N \left\{ -1 + \left[1 + \frac{4a'm'}{b'^2} \mu_N^{-2}\right]^{1/2} \right\} L_N$$ with $a' = 0.12$, $b' = 2.85$ and $m' = 24$ (very rough surface)

6. Analysis and evaluation of European air pollution episodes

Jaakko Kukkonen, Ranjeet Sokhi, Leiv Hårvard Slørdal, Sandro Finardi, Barbara Fay, Millán Millán, Rosa Salvador, Jose L. Palau, Alix Rasmussen, Guy Schayes and Erik Berge

6.1. Introduction

An air pollution episode can be defined as an event, during which concentrations of air pollutants increase considerably, exceeding national and international standards and limit values (e.g. QUARG 1993, 1996). Characteristically the temporal duration of such events can vary from hours to one or two weeks. Pollution originating both from local sources, and from regional and long-range transport, can lead to standards or limit values being exceeded. It is therefore vital to understand the underlying meteorological, physical and chemical processes that lead to the formation of air pollution episodes on local, regional and continental scales.

The causes of air pollution episodes are complex and depend on various factors including emissions, meteorological parameters, topography, atmospheric chemical processes and solar radiation. The relative importance of such factors is dependent on the geographical region, its surrounding emission source areas and the related climatic characteristics, as well as the season of the year (e.g. Sokhi *et al.*, 2002 and 2003, Piringer, Kukkonen, 2002). For example, particulate matter episodes in many cities are experienced in winter and spring. Nitrogen dioxide episodes can occur both in winter and in summer, and ozone levels can be particularly high during summer periods. Episodes can also be influenced by the interaction of phenomena on different meteorological scales e.g. meso-scale processes can perturb the synoptic conditions (Millán, 2002).

Previously selected historic episodes have been analysed by several participants of this COST Action, e.g. in Oslo (Berge *et al.*, 2002), Helsinki (Mäkelä *et al.*, 1998, Berge *et al.*, 2002, Karppinen *et al.*, 2002, Pohjola *et al.*, 2002, 2003 and 2004, Rantamäki *et al.*, 2004), London (Sokhi *et al.*, 2002, 2003) various northern Italian cities (Finardi, 2002, 2004) and in Spain (e.g. Millán, 2002, Gangoiti *et al.*, 2002, Salvador *et al.*, 2004). Sokhi *et al.* (2002, 2003) presented the analysis and evaluation of air pollution episodes in several European cities. Examples of episodes of PM_{10}, NO_2 and O_3 were selected, and the causes were examined in relation to local emissions and meteorological conditions. For both particulate matter and nitrogen oxides, a low-lying inversion and, in some of the cases, locally low wind speeds were particularly important in tending to lead to high concentrations of air pollutants.

One of the goals of this COST Action was to help national and local authorities by developing and evaluating methods for the meteorological forecasting of such episodes. Emergency preparedness plans have been designed for several European cities (e.g. Railo, 1997), whereby local authorities can implement strategies and take air quality management measures to reduce the adverse health impacts on the population. However the characteristic meteorological conditions prevailing in the course of episodes, such as extremely stable conditions with low wind speeds, are also the most difficult conditions to model reliably.

The main objective of this chapter is to discuss the main results and findings of the COST 715 Action regarding European air pollution episodes. Also relevant for the topic of pollution episodes is the previous chapter that addressed relevant matters related to mixing heights and temperature inversions, and the subsequent chapter that specifically addresses the meteorological characteristics of episodes in southern European cities.

6.2. Review of literature on peak pollution episodes

6.2.1 Characterisation of air pollution episodes

Available information concerning European peak pollution episodes has been reviewed within the COST 715 Action by Kukkonen (2001a). The report provides an overview of the main factors that lead to and influence air pollution episodes in 13 countries. The report showed the differences in national approaches, but also the common problems and challenges for improving the computational tools and the effectiveness of methodologies. This report can be utilised as background information by users, such as national or local authorities that are concerned with this problem.

Inversions, which lead to stagnant air, are particularly important in relation to episodes, and are in many cases responsible for very high levels of pollution (e.g. Piringer, Kukkonen, 2002). In addition, the regional and long-range transport of pollution can also lead to standards being exceeded, for example those for fine particulate matter.

Watson and Chow (2002) analysed a wintertime $PM_{2.5}$ episode that occurred in California's San Joaquin Valley in January 2000. The episode lasted for approximately ten days. The influence of regionally and long-range transported $PM_{2.5}$ was substantial, as half or more of the urban fine particulate matter concentrations were also present at surrounding non-urban locations. Primary particles accumulated during the nighttime and early morning mainly due to a shallow radiation inversion; after the inversion layer vanished in the daytime, their concentrations decreased.

Liu and Chan (2002 a, b) analysed a two-day episode with elevated concentrations of NOx, RSP (respirable suspended particulates) and SO_2 in Hong Kong in December 1999. They concluded that local vehicular and stationary emissions were mainly responsible for the elevated concentrations. The stably stratified synoptic conditions combined with sea-land breezes over a complex topography were reported as the main meteorological factors affecting the concentrations.

6.2.2. Evaluation of models for predicting and forecasting air pollution episodes

Traditional models, such as those based on Gaussian plume approaches, cannot take into account the detailed meteorological processes that can lead to episodes, although the latest generation of such models utilises atmospheric boundary layer scaling for deriving the input meteorological variables. Advances in meteorological models, based on more complete descriptions of atmospheric processes, offer the possibility of examining episodes in more detail.

Baklanov *et al.* (2002) have analysed the potential and shortcomings of numerical weather prediction (NWP) modelling for providing meteorological data for urban air pollution forecasting. Clearly numerical weather forecasting models were originally designed for meteorological predictions on the synoptic and meso-scale, rather than for local-scale predictions within the lowest atmospheric layers. As an example, these researchers observed shortcomings in HIRLAM model predictions. For instance temperatures near the ground tend to be too low during the day and too high during the night.

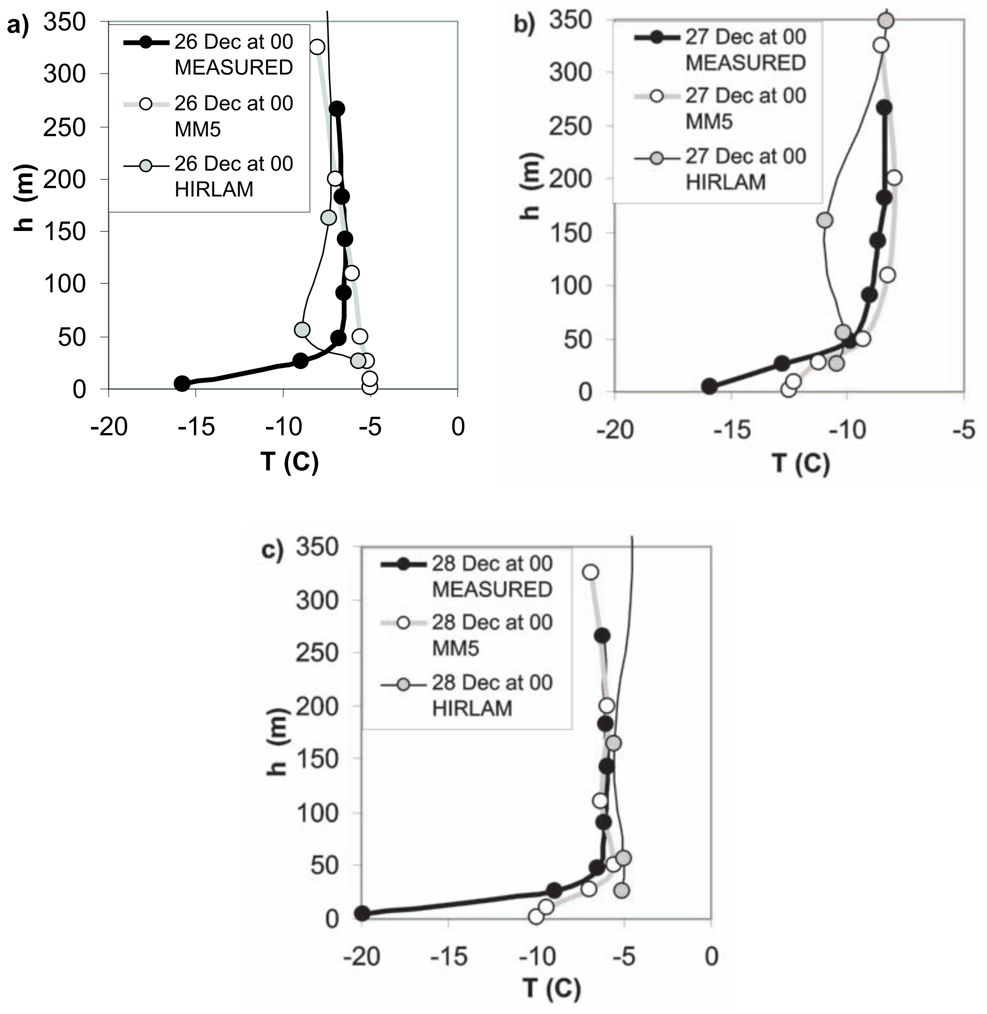
Recently Neunhäuserer *et al.* (2004), Neunhäuserer and Fay (2004), Pohjola *et al.* (2004) and Rantamäki *et al.* (2004a, b) have also evaluated the performance of several numerical weather prediction and meso-scale meteorological models for forecasting urban air pollution episodes.

Neunhäuserer *et al.* (2004) simulated, compared and evaluated against measurements meteorological variables in the course of three selected episodes in winter and spring in Helsinki, using five European NWP and meso-scale models (the Danish, Finnish and Norwegian HIRLAM, the German Lokalmodell LM, the meso-scale model system MM5 and RAMS). The parameterisation set-up was operational, but nested modelling was performed, with fine horizontal resolution down to 1 km. The influence of increased horizontal resolution in the range from 5 km to 1 km, without adapted parameterisations, was generally not substantial for the selected episodes in Helsinki. This is probably caused both by the minor topographic changes with increasing grid resolution (as the area is fairly flat) and by the finite vertical grid resolution in the lowest atmospheric model layers.

Neunhäuserer *et al.* (2004) also found out that the strength of the extreme temperature inversion that prevailed during the winter episode was not correctly simulated by any of the models used. The other relevant meteorological parameters, such as wind speed and stability, were predicted better, the detailed performance depending on model type and resolution. Major factors that caused deterioration in model performance were deficiencies in modelling physiographic parameters, the absence of predicted snow cover or sea ice, and problems in the modelling of stability, soil moisture and heat fluxes. These results highlighted the importance of high resolution urbanised soil and surface layer parameterisations in modelling urban air pollution episodes.

For the above mentioned episodes in Helsinki, Neunhäuserer and Fay (2004) also showed that for the German non-hydrostatic NWP Lokalmodell (LM), the model performance improved, as the horizontal resolution was changed to finer scales, for resolutions of 7, 2.8 and 1.1 km. For the measurement stations in Helsinki in the vicinity of the coastline, the main reason for this improvement of model performance with grid refinement was the finer scale spatial distribution of the land and sea areas, and the associated soil types. Clearly both of these factors influence the computation of the latent and sensible heat fluxes. In the course of the extremely stable episode in winter, the deficiences in modelling the influence of stability on transfer and diffusion coefficients may have caused an over-prediction of vertical exchange, surface temperatures and winds, and therefore an under-prediction of the strength of this extreme inversion.

Pohjola *et al.* (2004) investigated a severe air quality episode that occurred in the Helsinki Metropolitan Area during 26 to 28 December, 1995. During this episode, both the inversion strengths (°C) and the temperature gradients



Figures 6.1. a–c: The nocturnal temperature profiles measured at the radio tower of Kivenlahti, and those predicted by the MM5 and HIRLAM models, at 24 hour intervals during 26 to 28 December 1995 (Pohjola et al., 2004). Note the different temperature scale in Fig. 6.1b. Reprinted with permission from Boreal Environment Research. h denotes height above ground and T temperature

(°C/m) forecasted by the HIRLAM model were substantially weaker, or non-existent, compared with both the corresponding values extracted from the data of a 330 m high mast, and the sounding data (Figures 6.1. a–c). These deviations of the HIRLAM forecasts and data are partly caused by deficiencies in the mathematical treatment of humidity and the state of the ground surface, and partly by the finite computational grid resolution. The finer resolution, non-hydrostatic MM5 model predicted the temperature profiles better than HIRLAM, although both models had problems especially in predicting the daytime temperature profiles.

Rantamäki *et al.* (2004b) evaluated the performance of two versions of the Finnish variant of the HIRLAM model in the course of the above episode. Both model versions had difficulties in predicting strong surface-based inversions correctly. The more recent version was slightly better, in comparison with the measured data.

Salvador *et al.* (2004) analyzed the dispersion and photochemical formation processes that caused high ozone concentrations, using the MM5 meteorological model and the Community Multiscale Air Quality model, CMAQ. They examined an ozone episode that took place near the eastern coast of Spain during 13–15 August, 2000. They reported that this ozone episode was qualitatively well simulated by the above mentioned model combination. There were some discrepancies between the measured and predicted ozone concentrations that were mainly attributed to the lack of an accurate description of the industrial emissions in the area.

Studies of previous particulate matter episodes in the United Kingdom (UK) include those of Malcolm *et al.* (2000) and Ryall *et al.* (2002). Malcolm *et al.* (2000) used the NAME model to determine the source of two episodes during 1996. The March 1996 episode was attributed to long-range transport, whereas the elevated concentrations in July 1996 resulted mainly from emissions in the UK. Ryall *et al.* (2002) discussed an episode in March 2000 that was probably caused by incoming Saharan dust. In this case, elevated levels of PM_{10} and $PM_{2.5}$ were observed over England and Wales in association with strong westerly winds and rainfall, conditions normally associated with low pollutant levels.

Almbauer *et al.* (2000) investigated an episode in the city of Graz (Austria) that occurred from 10 to 13 January, 1998. They used a meso-scale dispersion model to simulate the local flow field and air quality during the episode, and compared the predicted concentrations of NO and NO_2 with the data from a local air quality monitoring network. They concluded that the elevated NO and NO_2 concentrations mainly originated from local traffic and domestic heating. The main factors were reported to be an anticyclonic weather situation, temperature inversions and local wind systems within a mountainous area.

6.3 Assessment of the various factors leading to air pollution episodes in Europe

Sokhi *et al.* (2002, 2003) and Kukkonen *et al.* (2004a,b) analysed selected PM_{10} episodes in four European cities, in relation to prevailing meteorological conditions, local emissions, and regionally and long-range transported background concentrations. They aimed at a structured and homogeneous analysis in all the four cities. A particular aim of those studies was to gain a better insight into the influence of various meteorological variables on the evolution of high pollutant concentrations.

The episodes considered occurred on 4–10 January 2003 in Oslo, on 3–14 April 2002 in Helsinki, on 18–27 February 2003 in London and on 14–19 December 1998 in Milan. They selected for the analysis recent episodes that were predominantly caused by various local emission sources These episodes can also be considered to be characteristic for each region, in terms of their frequency of occurrence.

The above-mentioned researchers analysed the evolution of the measured concentrations, especially in terms of the measured and pre-processed meteorological variables, and the predictions of several NWP models and a meso-scale meteorological model. The episodes were also analysed by comparing the concentrations measured at various types of stations, and by comparing the measured PM_{10} concentrations with those of $PM_{2.5}$ and NO_2. A brief synthesis of these studies is presented in the following.

6.3.1. Characterisation of the selected cities: climate, topography and main emission sources

The cities considered are located in the geographic and climatic regions of northern Europe (Oslo and Helsinki), north-western Europe (London) and southern (Milan) Europe. The areas represent a maritime climate (London and Oslo), a partly maritime influenced and partly continental climate (Helsinki), and a mainly continental climate (Milan). London and Milan are amongst some of the largest cities in Europe (their populations are 7.5 and 3.5 million, respectively), while the metropolitan areas of Oslo and Helsinki are relatively smaller conurbations (the populations are approximately 1.0 million).

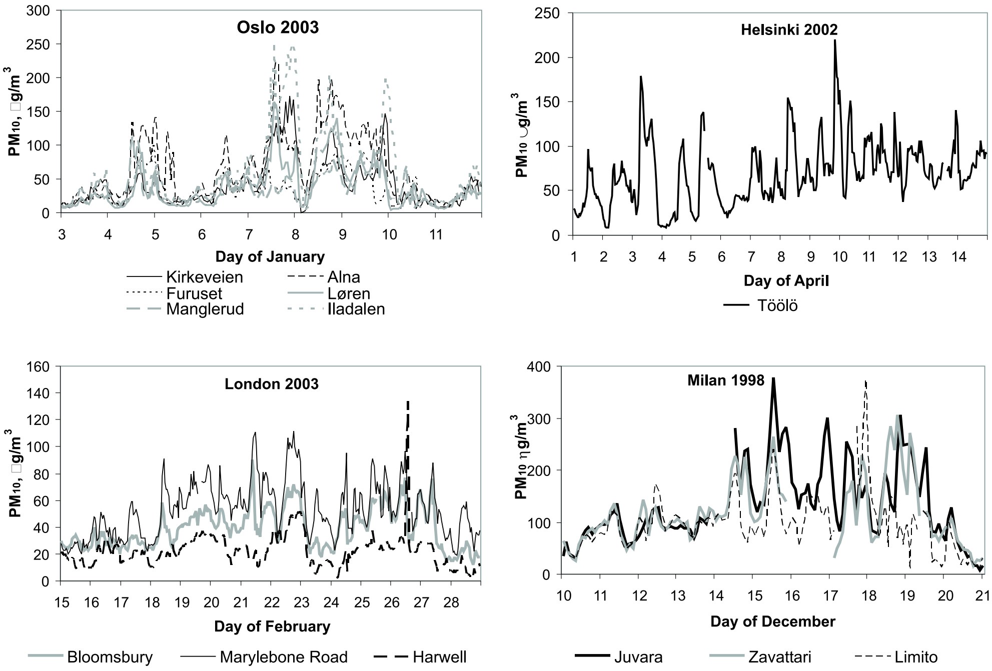
The city of Oslo is located at the northern end of the Oslo fjord, surrounded on most sides by complex topography. The topographical features of the area tend to worsen the dispersion conditions, capturing pollutants emitted within the urban airshed. The most important local sources of PM in Oslo are domestic wood-burning in stoves that are used for wintertime house heating, and vehicular traffic. The city of Helsinki and its surrounding regions are situated in a fairly flat coastal area. The PM_{10} concentrations in street level air are dominated by the combustion, non-combustion and re-suspension emissions originating from vehicular traffic (e.g. Kukkonen *et al.*, 2001b).

London is situated in relatively flat terrain, with shallow hills to the west and south. London is one of the most congested cities in Europe. For example more than half of NOx emissions results from road transport. The city of Milan and its surrounding urban area are located in the central part of the Po River basin, in a flat area. The atmospheric circulation of the Po Valley is characterised by the strong modification of synoptic flow due to the high mountains (Alps and Apennines) that surround the valley on three sides. Road traffic is mostly responsible for the PM_{10} emissions in the Milan region.

6.3.2. Evolution of the particulate matter concentrations

The evolution of measured hourly pollutant concentrations in the four cities is presented in Figs. 6.2a-d. The hourly PM_{10} concentrations at the urban stations exceeded values of 100 μm/m^3 in London, 200 μm/m^3 in Oslo and Helsinki, and 300 μm/m^3 in Milan. The periods of highest concentrations, compared with the more commonly prevailing values in each city, occur in some cases in two periods lasting a few days (for instance, in Oslo from 4 to 5, and from 7 to 10 January 2003), or may extend for a more extensive period (for instance, in London, from 18 to 27 February 2003).

Comparison of concentrations measured at various site categories makes it possible to evaluate the importance of local emissions. For instance, in Helsinki, the regional background PM_{10} levels (measured at the station of Luukki) were



Figures 6.2. a-d: Pollutant concentrations relevant for the analysis of PM_{10} in the course of the selected episodes in a) Oslo, b) Helsinki c) London and d) Milan. Most of the stations represent urban traffic environments (Kirkeveien, Alna, Furuset, Løren, Manglerud, Töölö, Bloomsbury, Marylebone Road, Zavattari and Limito), but a few urban background stations (Iladalen and Juvara) and a rural background station (Harwell) are also included. The ticks on the horizontal axis indicate the beginning (i.e. the time 0.00) of the day marked. References: Sokhi et al. (2002), Kukkonen et al. (2004a, b).

substantially lower than the corresponding highest urban traffic-site concentrations measured at the stations of Töölö and Vallila. This indicates that local sources were mainly responsible for the formation of the highest concentrations.

Based on the examination of the concentrations of PM_{10} and $PM_{2.5}$ measured at various site categories and the emission inventories in the cities, it was concluded that the selected episode in Oslo was caused mainly by local wood combustion, in Helsinki mainly by suspended dust and local traffic emissions, in London by both urban traffic and long-range transport, and in Milan partly by local traffic, and partly by long-range transport.

6.3.3. The meteorological analyses

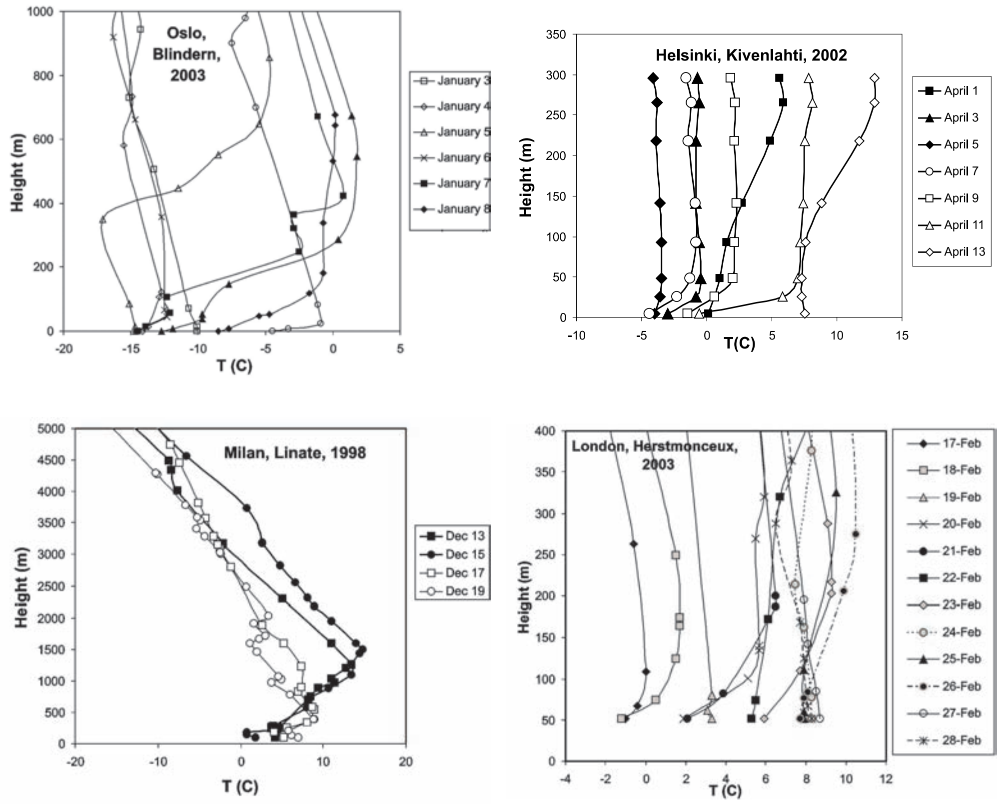
The synoptic meteorological analyses are based on the results computed by the national versions of the NWP HIRLAM model in the case of Norway and Finland, and on the ECMWF model in the case of the U.K. and Italy. The MM5 meso-scale meteorological model has also been used to predict the conditions in London. The synoptic analyses showed that all the episodes addressed were associated with the influence of areas of high pressure (Oslo, Helsinki and London) or a high-pressure ridge (Milan).

Examples of the evolution of the associated vertical temperature profiles are presented in Figs. 6.3a-d. Strong ground-based or slightly elevated temperature inversions prevailed in the course of the episodes in Oslo, Helsinki and Milan, and a slight ground-based inversion was also present in London. A detailed examination of the meteorological conditions shows that the inversions in Oslo and Milan were mainly caused by advection, while that in Helsinki was a radiation inversion.

In Helsinki, for instance, the measured temperature profiles at midnight show that there were moderate or strong ground-based inversions on all days from 7 to 12 April. The maximum ground-based inversion occurred on 11 April; the measured temperature increased 8 °C within the lowest 50 m of the atmosphere. The highest PM_{10} concentrations (during 3 April and from 8 to 13 April, 2002) coincided with the occurrence of the ground-based inversions.

In Milan, the wind speed was low or it was calm during the whole period considered. Prevailing light winds are one of the main features of the Po Valley climatology (Finardi, 2002 and 2004). These conditions are mainly due to the blocking effect of the high mountains that surround the valley on three sides, and usually do not allow synoptic flows to reach down to the lower atmospheric layers in the valley. The wind speed is therefore not an especially good predictor variable in terms of peak pollution episodes within this area.

In Milan, an intense slightly elevated temperature inversion was formed on 13 December, reaching its maximum depth and magnitude (with a temperature increase in height of about 15 °C in the lowest 1500 m) on 15 December and prevailing until 19 December. This period nearly exactly coincided with the occurrence of the highest concentrations from 14 to 19 December. The inversions were caused by the advection of warm air associated with the incoming high-pressure ridge.



Figures 6.3. a-d: The observed temporal evolution of the vertical profiles of temperature in the four cities. For Oslo, Helsinki and London, the profiles are for midnight (00.00 UTC on the date in question), and for Milan, noon (12.00 UTC on that date). References: Sokhi et al. (2002), Kukkonen et al. (2004a,b).

6.4. Conclusions

6.4.1. Characterisation of air pollution episodes

Clearly the comparison of concentrations measured at urban sites and rural background sites makes it possible to evaluate the importance of local emissions in relation to long-range transport. Similarly, the relative influence of local traffic in relation to other local sources can be evaluated by comparing the concentrations measured at urban traffic sites and those at urban background sites. The influence of various local source categories can also be assessed using the ratio of $PM_{2.5}$ to PM_{10} measured at the same station. This ratio is substantially different for pollution originating from local traffic compared with that from wood combustion (Laupsa and Slørdal, 2002).

High atmospheric pressure is often related to stable stratification. However it does not necessarily lead to extremely stable conditions or strong inversions near ground level. Regarding episodes of PM_{10} and NO_2, an elevated atmospheric pressure is commonly a necessary, but not a sufficient condition for the occurrence of an episode. However there is one exception to the above mentioned rule. PM_{10} episodes can also be caused by the increased re-suspension of particles from streets under the influence of strong winds. These are not usually related to stably stratified high pressure conditions (e.g. Nicholson, 1993 and Hosiokangas *et al.*, 2004).

6.4.2. The influence of the most crucial meteorological factors and processes

Radiation and advection inversions are those that occur most frequently in the course of air pollution episodes. Clearly the influence of inversions on air quality crucially depends on their detailed vertical structure and magnitude, and on their temporal evolution. In the cases examined by Sokhi *et al.* (2002) and Kukkonen *et al.* (2004a, b), strong ground-based or slightly elevated temperature inversions prevailed in the course of the episodes in Oslo, Helsinki and Milan, and a slight ground-based inversion was also present in London. The inversions in Oslo and Milan were mainly caused by the advection of warmer air above a relatively colder surface, while that in Helsinki was due to radiation cooling of snow covered ground.

It was also found that a low wind speed is not necessarily a good indicator of pollution episodes when considering all the European regions. In particular, in the Po Valley, wind speed is a poor indicator, due to frequently occurring calm and low wind speed conditions (Finardi, 2004).

In the cases studied in Sokhi *et al.* (2002) and Kukkonen *et al.* (2004a,b), the best meteorological predictors for the elevated concentrations of PM_{10} were the temporal (daily) evolutions of temperature inversions and atmospheric stability (which was described in terms of the meteorologically pre-processed Monin-Obukhov length) and in some cases, wind speed. The temporal variation of highest PM_{10} concentrations was closely correlated with that of ground-based or slightly elevated temperature inversions. The temperature inversions can therefore be recommended as one predictor variable in, for example, statistical models for forecasting in time the potential formation of air pollution episodes.

Episodes can also be influenced by the interaction of phenomena on different meteorological scales. For instance, in mountainous, coastal mid-latitude areas, meso-scale processes can perturb the synoptic conditions This can either suppress or enhance ventilation conditions. For example, the drainage winds of cold surface air may be blocked upon reaching a relatively warmer sea. The temperature contrast between the city air and the sea surface acts as a convective barrier that prevents the advection of air over the sea, and thus the colder polluted air remains confined to the coastal city area (Millán, 2002).

In winter, the western Mediterranean basin is better ventilated due to the increased passage of travelling lows and their frontal systems. However as soon as anticyclonic conditions develop, pollutants can be trapped within industrialised valleys or in large, but confined airsheds (Millán, 2002). As the polluted air masses do not leave their airsheds under such conditions, these autumn-winter episodes are amenable to short-term measures, if such measures are taken before the episode develops. Once the episode is in progress, however, short-term measures may be less effective (Commission Decision of 19 March 2004, 004/279/EC).

6.4.3. Classification of air pollution episodes

The work initiated in this COST Action on air pollution episodes has been continued and extended within the European Union FUMAPEX project. In this latter project, an inventory of European episodes has been compiled that contains relevant information on, and a detailed examination of 21 episodes from seven cities or metropolitan areas in six countries (Valkama, Kukkonen, 2004). The cities include Castellón (Spain), Helsinki (Finland), Turin (Italy), Bologna (Italy), Oslo (Norway), London (UK) and Paris (France). The utilisation of this inventory will provide in the future more general conclusions regarding the meteorological factors leading to the formation of various episodes.

Episodes can be broadly categorised according to the scale of the main source areas, i.e., those originating from local emissions and those from regional and long-distance sources. The local-scale episodes can be further classified as those caused predominantly by mobile or by stationary sources. The so-called 'spring dust episodes' refer to the episodes caused by the particulate matter that is suspended from road and street surfaces. These cases are especially characteristic of northern parts of Europe.

The larger scale episodes can be schematically classified as those involving photochemical pollution either from a mixture of local, regional and long-range sources, or those caused solely by long-range transported air masses. Photochemical episodes are especially prevalent in southern European cities. Characteristically these may involve re-circulation of air masses, caused by meso-scale meteorological effects (such as the land-sea breeze) and orographic flows (e.g. Millán, 2002).

6.4.4. Perspectives for the future

At present, there are no generally applicable theoretical schemes for the interpretation of the data measured in all of the conceivable episodic conditions, such as extremely stable conditions with low wind speeds. These are often amongst the most difficult conditions to predict or forecast reliably. One of the main objectives of the FUMAPEX project is therefore to develop improved theory and models for this purpose, mainly based on the refinement and urbanisation of existing NWP and meso-scale meteorological models, and on meteorological pre-processing models.

Clearly the refined models need first to be systematically evaluated against sufficient meteorological data. Within FUMAPEX, the performance of various currently available NWP and meso-scale meteorological models has been systematically evaluated in the course of several selected air pollution episodes (e.g. Neunhäuserer, 2004, see also Pohjola *et al.*, 2004, Rantamäki *et al.*, 2004a,b). The new COST 728 Action is also expected to substantially improve the scientific tools for understanding the causes and formation of episodes, and for forecasting such cases.

6.5. Acknowledgements

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7. Meteorological aspects of air pollution episodes in southern European cities[1]

Nicolas Moussiopoulos, Louka P., Finzi G., Volta M., Colbeck I, Diéguez J. J., Palau J. L., Pérez-Landa G., Salvador R. and Millán M. M

The meteorological influence on air pollution in southern European cities is dominant during every season of the year but especially during summer. It is associated with high sunlight intensity, low winds or stagnant high-pressure systems, high air temperature, high stability (low mixing heights), low midday relative humidity, and occasionally thermally driven meso-scale circulations, primarily sea-land breezes. However not all high-pressure systems lead to air pollution episodes. Moreover even in winter-time, weather situations may be of relevance to the building up of high pollutant concentration levels in southern Europe. Therefore it is necessary to answer questions like:

1. For which southern European cities is there a synoptic classification developed for indicating the occurrence probability of air pollution?
2. Which of these synoptic conditions would lead to the most severe episodes?

The purpose of this section is to address these questions primarily concerning photochemical air pollution, which is considered to be a significant air quality issue for southern European cities. As a case study, the situation in the city of Valencia, Spain, is discussed in more detail.

7.1. Synoptic classification

In the summer, the atmospheric circulation in southern Europe is affected mainly by the combination of two global scale synoptic systems: the subtropical anticyclone of Azores/Bermudas and the west Asia thermal low. The combination of these two synoptic systems provokes the Etesian winds, a semi-persistent

[1] The first part of this section is based on the document 'Photochemical smog in south European cities' (authors: Louka P., Finzi G., Volta M., Colbeck I.) that appeared as Chapter 8 of the SATURN Final Report (Moussiopoulos, 2003). The case study is derived from the document 'Air Pollution Episodes on the Mediterranean Side of the Iberian Peninsula' (authors: Diéguez J.J., Palau J.L., Pérez-Landa G., Salvador R., Millán M.M.)

wind circulation, consisting of a northerly flow blowing mainly over eastern Mediterranean and especially over the Aegean. The intensity of these winds is controlled by the intensity and the position of the two synoptic systems. When the Etesian winds are strong, the pollution levels are expected to be lower because of the associated strong vertical mixing and diffusion. On the contrary, when the Etesian winds are weak, local circulations prevail due to differential heating. These circulations do not favour the diffusion of the pollutants. This occurs for example in the Athens area, when the land-sea breeze circulation prevails, 'trapping' the pollutants (Kallos *et al.*, 1993, Kassomenos *et al.*, 1998a, b). In addition, due to the presence of the two synoptic systems, large meso-scale circulations develop such as the Iberian, Italian and Anatolian thermal lows which also influence the evolution of the regional flows during the day, while pressure differences of up to 30 to 40 hPa can develop between the Atlantic coast of Portugal and the Arabian Peninsula that favour a general eastward drift of the air masses over the Mediterranean basin (Gangoiti *et al.*, 2001).

In the winter, the depression activity causes a variety of circulation patterns over southern Europe. Some of these patterns are responsible for the accumulation of air pollutants, while some others do not favour high concentrations. The pollution related synoptic conditions differ for different areas and depend on the topography of each city or region. However the synoptic conditions generally accompanied by vertical atmospheric stability lead to high pollution levels, because of the corresponding temperature inversions and the poor vertical mixing. For example the advection of warm air from the south usually leads to atmospheric stability and is responsible for many pollution episodes during winter. This is also the case when an anticyclone prevails over the region, favouring calm and stable conditions. On the other hand, a strong northerly flow has the opposite results, leading to low pollution levels. The question that has to be answered is whether the above synoptic conditions could be accompanied with sunshine in order to also favour photochemical pollution. This remains an object of research and depends mainly on the topography, land-sea distribution and the type of ground cover of each specific region (Kassomenos *et al.*, 1998a).

The Mediterranean is usually divided into three basins, namely, the Western Basin extending from the Iberian Peninsula and from southern France to the northern African coast, the Central Basin from the Adriatic and Ionian Seas to the east coast of Tunisia, and the Eastern Basin including the Aegean and Black Seas (Millán *et al.*, 2002). The synoptic conditions in the Eastern Mediterranean Basin and in particular over Greece have been classified in different categories according to the general circulation patterns at the isobaric levels of 850 and 700 hPa. Fig. 7.1 illustrates eight synoptic patterns over the area. From the pressure patterns observed, the anticyclonic circulation has its maximum occurrence in January and June, the combination of high-low pressure systems predominates in July and August, situations of cyclonic type dominate in February, March and December, while situations of south-westerly flow dominate in November and April. Weak flows favouring trapping of pollutants are mainly associated with open and closed anticyclones and zonal flow during which meso-scale circulations become dominant (Kassomenos *et al.*, 1998b).

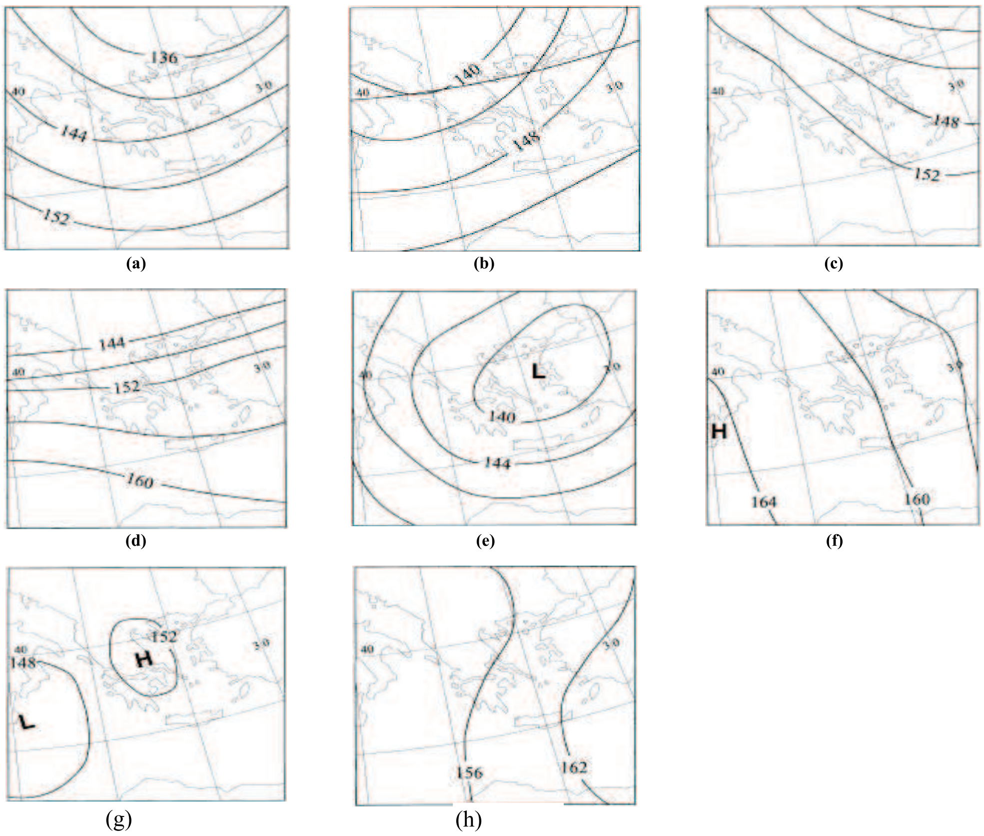


Figure 7.1: Typical examples of the synoptic categories in Greece: (a) Long-wave trough (b) South-westerly flow (c) North-westerly flow (d) Zonal flow (e) Closed low (f) Open anticyclone (g) Closed anticyclone (h) High-Low (from Kassomenos et al., 1998a)

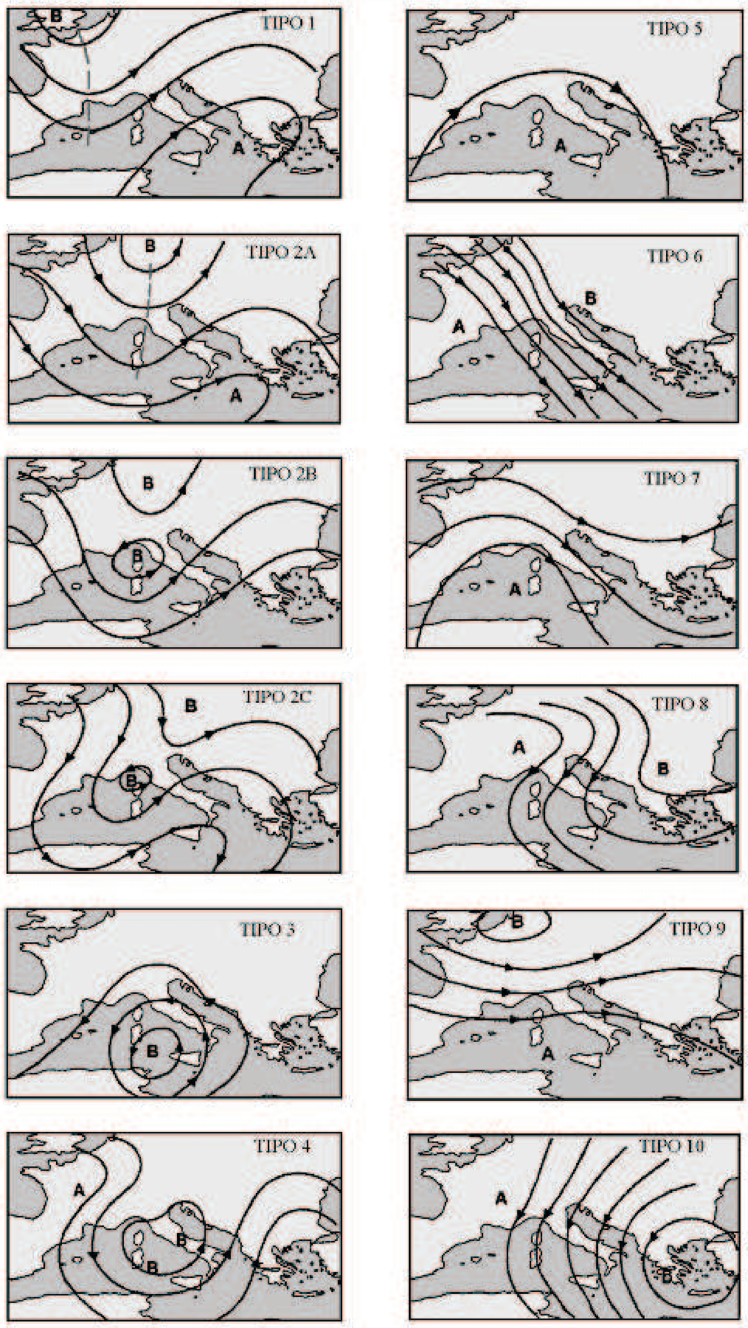
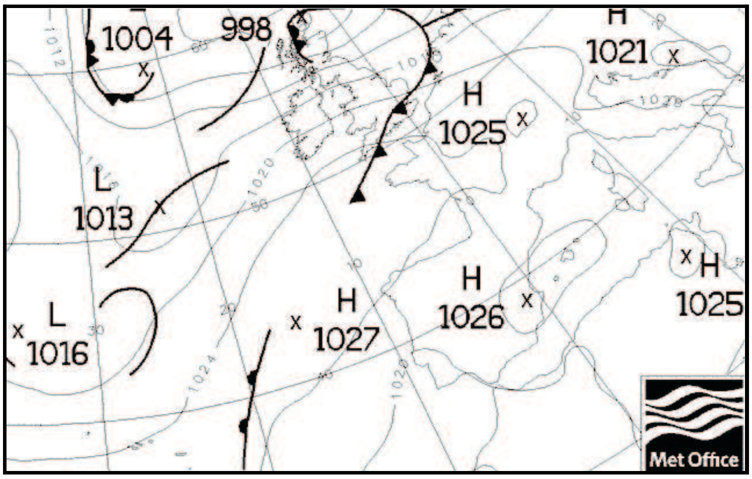
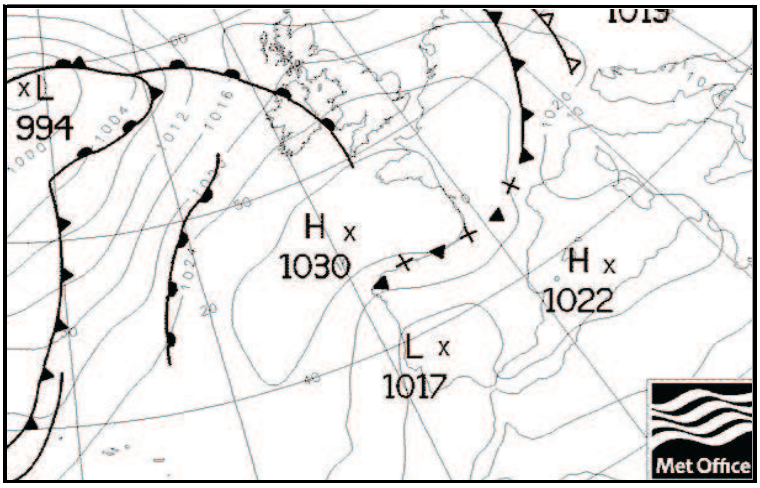


Figure 7.2: Weather type classification based on 12 types, used in Italy (ENEL/Prod ULP, 1998)



A



B

Figure 7.3: Two typical meteorological summer conditions A and B in the Iberian Peninsula (http://www.meto.gov.uk)

Within the Central Mediterranean Basin, synoptic weather classifications derived from the scheme originally proposed by Borghi and Giugliacci (1980), are currently used in Italy for both meteorological and air quality scopes. The classification by Borghi is based on 12 weather types, identified by their geopotential patterns at 850 hPa for the 5-year period 1984-1989 (Fig. 2) (Finardi *et al.*, 1999). Following the cited classification the weather types that are most likely to favour photochemical episodes in Italy are classes 1, 5, 7 and 8 (see Figure 7.2). Classes 1 and 8 can favour pollution episodes in parts of the country depending on the position and extent of the anticyclonic circulation.

In the summer, the Western Mediterranean Basin (including Portugal) is usually characterised by a ridge of the Azores high extending over northern Iberia and southern France. During summer the Azores high expands over the Atlantic or towards France. In association with the horizontal meso-scale air motion in the basin, during daytime the pollutants concentrations tend to increase in the northern part of the Iberian eastern coast, while the night-time flow transports the pollutants towards the south (Gangoiti *et al.*, 2001). Most of the Portuguese ozone episodes appear under the presence of the Azores anticyclone extended in a ridge over the Iberian Peninsula, promoting a continental dry and very hot circulation over Portugal. These synoptic conditions are characterised by slightly above average mean sea level pressure, almost non-existent surface pressure gradients, and are generally associated with weak winds in the lower troposphere, cloudless skies, high maximum temperatures and weak precipitation rates. The strong insolation allows the formation of meso-scale circulation (like a sea breeze) and photochemical production (case A in Fig 7.3). Nevertheless, a considerable number of photochemical ozone episodes also develop under the influence of a thermal surface low-pressure system, common over the Peninsula during summer, and with a strong effect on the development of a typical sea breeze (case B in Fig 7.3) (Borrego *et al.*, 1994, Barros, Borrego, 1995). In the winter, cyclone families either travel from the west to the east or the Azores high expands eastwards.

7.2. Synoptic conditions leading to severe pollution episodes

Air quality episodes are usually observed over a domain of 1000 km or less in which meso-scale dynamics play a significant role. The severity of ozone episodes may be estimated with numerical models by considering surface and upper air meteorological data. High local ozone concentrations observed in episodes are often influenced by meso-scale circulations embedded in large, stagnant synoptic systems. Under a stagnant high-pressure synoptic system, these local flows become a major mechanism for dispersing, mixing and transporting air pollutants.

Severe pollution episodes over the Athens basin have been mainly associated with weak southerly flows and a weak sea breeze, as well as with almost calm conditions. Kallos *et al.* (1993) showed that the worst air pollution episodes in Athens occur during days when there is a critical balance between synoptic and meso-scale circulations and/or during days with warm advection in the lower troposphere. According to the results of Kassomenos *et al.* (1998b), the most favourable synoptic pattern for the accumulation of high concentrations over the Athens basin is the open anticyclonic circulation, and for the occurrence of extreme events the closed anticyclone. In association with meso-scale patterns the most severe pollution problem in the metropolitan area of Athens is the high concentration of ozone in warm periods of the year. The problem is also substantial in cold periods (Kassomenos *et al.*, 1998b).

Although Italian cities are located at geographical positions characterised by different climate and circulation features, the present understanding of photochemical pollution episodes is strongly biased towards the northern part of the country, and mainly focused on the Po Valley, which is characterised by high industrial, urban and traffic emissions. Many experimental research programmes and modelling studies have been carried out over this area e.g. in the frame of the EUROTRAC–2 subprojects SATURN and LOOP. In 1998 the PIPAPO field campaign investigated the ozone production in the Po Valley. The field campaign covered May and June. Two major episodes were observed during the periods 12–13 May and 3–6 June 1998. During the first episode the circulation was associated with weather type 5, while the second episode was characterised by weather classified as type 1 for the Italian peninsula (see Figure 7.2). Other experiments in the Milan urban area during July 2000 detected a typical summer high polluted episode (high ozone and NO_2 levels, strong photochemical potential) (Finzi *et al.*, 2000).

All the cited Italian photochemical episodes that have been analysed concern summer high pressure conditions, when subsidence and weak winds favour pollutant accumulation in the lower atmospheric layers. In the sub-alpine region winter ozone peaks can be observed during northerly Föhn wind periods (weather type 6, or 9 in north-western regions). In these conditions ozone concentrations are due to transport from the upper troposphere or stratosphere, if stratopause breaking occurs. These episodes can be relevant in sub-alpine regions and are normally associated with concentrations up to 100 μg/m^3 without causing exceedences of air quality standards.

A severe pollution episode was observed over the Basque area during 14–16 June 1996. During the episode a blocking anticyclone over Ireland on 13 June moved eastwards and remained over the area until the 16 June. A study of the ozone episodes over the Basque area during the period 1995–1998, based on the available measurements of ozone and the associated meteorology, show that the most important and persistent episodes coincided with the onset of the east and north-easterly winds forced by a European high pressure system (Environment and Systems, 1999, Gangoiti *et al.*, 2002).

In the winter, pollution episodes have been also observed in the Iberian Peninsula. An example of a winter episode associated with synoptic conditions is the case of Madrid in January 1992. During the period 15–20 January 1992 almost the whole region was under the influence of a high-pressure system centred over the British Isles. This situation produced very poor ventilation conditions over the Madrid area, increasing the air pollutant concentrations in the area (Pujadas *et al.*, 2000). An exceptional ozone episode in the same area is that described by San José *et al.* (2001). Exceptional ozone episodes are considered those occurring at 'non-expected' periods and they cannot be easily attributed purely to anthropogenic activities. Such an episode appeared in the night between 02.00–06.00 on 29 April 2000 over Madrid and was attributed to ozone intrusion from elevated layers that might have brought significant amounts of ozone from the stratosphere, as well as to the transfer of ozone generated the day before by the prevailing wind.

7.3. Case study: Air pollution episodes in Valencia

The whole Mediterranean side of the Iberian Peninsula shows very specific pollutant dynamics, which can be explained in large part by the coincidence of three factors: (1) a geographical situation in the middle latitudes and at the edge of the Mediterranean Sea, guaranteeing a high level of year-round solar radiation and the habitual development of breezes with different degrees of penetration, (2) a topography characterised by a flat coastal strip and a mountainous interior, connected to each other by valleys that are perpendicular to the coast and that channel the breezes toward the interior, and (3) a population concentrated in different points along the coast, resulting in a predominantly coastal distribution of the emission sources (large cities, industries, major communication channels etc).

A very extensive set of experimental/historical data as well as meteorological and air quality measurements, resulting from various EC-funded projects (MECAPIP, RECAPMA, SECAP, BEMA, and RECAB) (Millán *et al.*, 1997), is available for the Castellón coastal area, situated in the north of Valencia. The results of these projects and the analysis of monitored air quality data have clearly shown the main characteristics of pollutant dynamics in this region and the spatio-temporal patterns that the pollutant concentrations follow at surface level.

Spatial-temporal behaviour of pollutant concentrations
The combination of the three factors above mentioned ensures the presence of pollutant levels, to a higher or lower degree, throughout the region, and gives rise to characteristic and differentiated types of behaviour dependent on relative position with respect to emission sources, distance from the coast and height above the terrain. Furthermore the concentrations exhibit seasonal patterns showing important differences between the levels observed in autumn and winter, and those in spring and summer. The situation prevailing in the region throughout the year may be summarised in the following way.

In autumn and winter, when the breeze circulations are confined to the narrow coastal strip, the distance to the coast determines a gradient in the characteristics of the circulations and the air mass with which it is in contact. At the shore, the chemical composition corresponds basically to the coastal emissions, which are diluted in a relatively reduced volume in terms of both horizontal dimension (due to the limited development of the breeze systems) and vertical dimension (due to the limited convective activity resulting from the lower incidence of solar radiation). Towards the interior and coinciding with the more elevated terrain, there is a decrease in the influence of the coastal cycles and an increase in that of the synoptic-scale circulation; the latter have a longer trajectory and involve much more extensive air masses with the result that monitoring networks record low concentrations of primary pollutants and relatively low concentrations of secondary pollutants, which can be considered background levels.

In the spring and summer months, when the prevailing situations are anticyclonic with a very reduced barometric gradient and very high insolation levels, the development of breeze systems and up-slope winds, which frequently become coupled due to the proximity of the mountain ranges parallel to the coast, cause the circulation, and thus the air mass transport, to move from the coast to the interior with much higher penetration distances. At this time of year in the coastal urban areas there is an increase in ventilation, mixing-layer height and photochemical activity and a decrease in ground-level primary pollutants. Simultaneously over the interior rural areas, the monitoring network record considerable levels of secondary pollutants, such as ozone, a result of the chemical transformations that take place during the transport of the coastal emissions toward the interior by way of the valleys perpendicular to the coast, covering trajectories of tens of kilometres downwind of the sources. During these trajectories, the southeast-oriented slopes, heated from the first daylight hours, act as ‘orographic chimneys’ that connect the surface flows with the flows aloft, giving rise to the formation of strata at different heights which travel towards the coast with the return flow. Once over sea, the subsidence forces these strata to descend, leaving them available to reinitiate the circulation on the following morning (Millán *et al.*, 1996, 1997). Figure 7.4 shows the basic pattern of the typical dynamics in a Mediterranean basin, under anticyclonic conditions with the predominance of meso-scale circulations.

In a network of non-urban monitoring sites within this scenario, it is possible to recognise five characteristic types, identified in Figure 7.4 with numbers 1 to 5, which correspond to 5 positions inside this scenario: (1) coastal, (2) lower valley, (3) upper valley, (4) at height in the interior, (5) at height on coast (Millán *et al.*, 2000). Figure 7.5 shows the seasonal evolution over an average day for each of the five types.

7.4. Characterisation of ozone episodes in the region of Valencia

Air quality data for the Valencia region show that maximum primary pollutant levels are rarely exceeded and then only in very limited urban zones. On the other hand, pollution episodes in the Valencia region are associated fundamentally with elevated ozone levels (Figures 7.6 and 7.7). Analysis of ozone data series shows that high concentration levels of this pollutant respond to a characteristic pattern. This pattern comprises periods of 3 to 8 days during which stable atmospheric conditions and breeze circulations predominate in the region. It is characterised by marked daily cycles and maximum daily values that increase gradually with each consecutive day. Since 1997, 21 of the 23 ex-

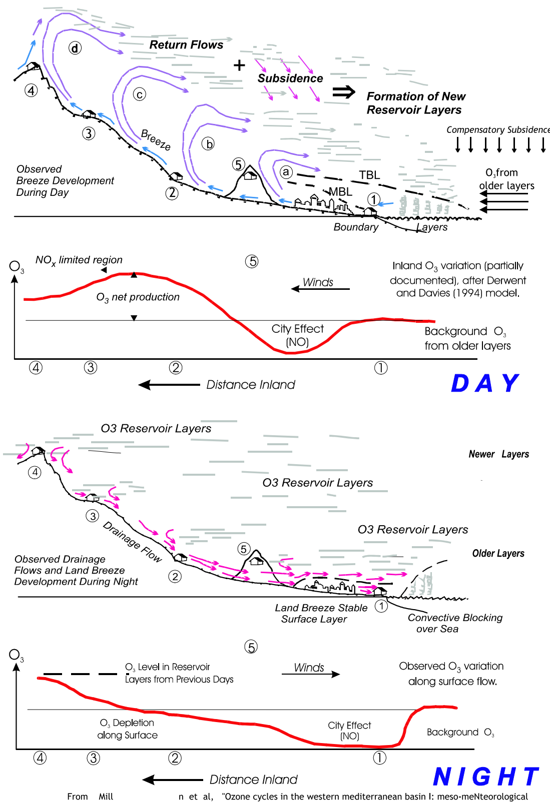


Figure 7.4: Pollutant dynamics in a typical Mediterranean basin scenario under atmospheric conditions dominated by meso-scale circulations (typical spring-summer conditions). Letters a-e indicate successive phases in the development of the breeze system during the day, and numbers 1 to 5 indicate five site positions within this scenario. The alternating day-night circulations, together with the coastal location of the emission sources and the height above sea level, generate cycles of secondary pollutants (ozone) which are characteristic of the relative position of each site within the air basin. Five characteristic cycle types can be distinguished in association with five positions in this scenario: (1) coastal, (2) lower valley, (3) upper valley, (4) at height in the interior, (5) at height near the coast (Millán et al., 1997). The design of the monitoring network was based on the results of the European Union measurement campaigns MECAPIP (Meso-meteorological Cycles of Air Pollution in the Iberian Peninsula) and RECAPMA (Regional Cycles of Air Pollution in the West Central Mediterranean Area), as well as on the Derwent and Davies model, which relates NOx emissions with ozone production.

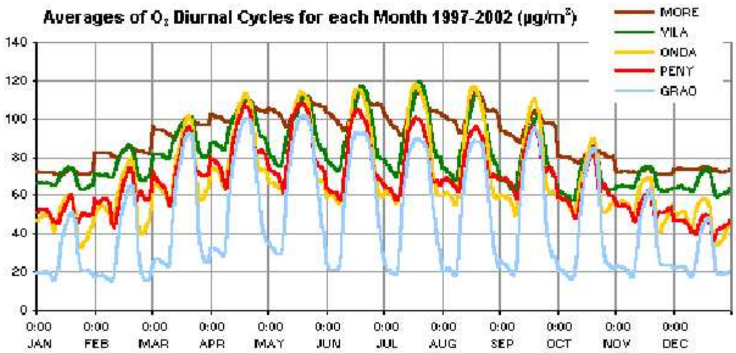


Figure 7.5: Average-day seasonal evolution for the 5 characteristic types in a typical Mediterranean Basin scenario (see Figure 7.4). (1) Grao, (2) Onda, (3) Vilafranca, (4) Corachar, and (5) Peñeta.

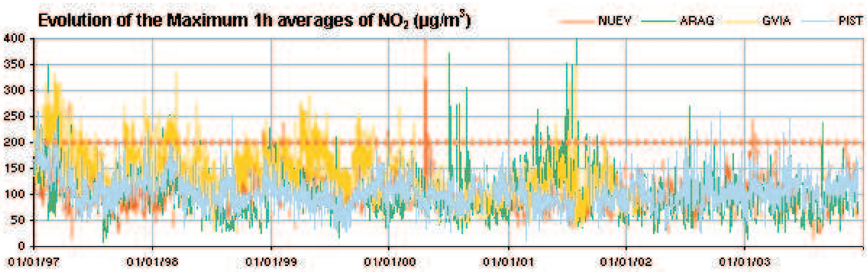


Figure 7.6: NO_2 maximum daily hourly averages for 5 stations in the Greater Valencia area. (Red dotted line indicates the Threshold Value for Health Protection: 200 μg/m^3)

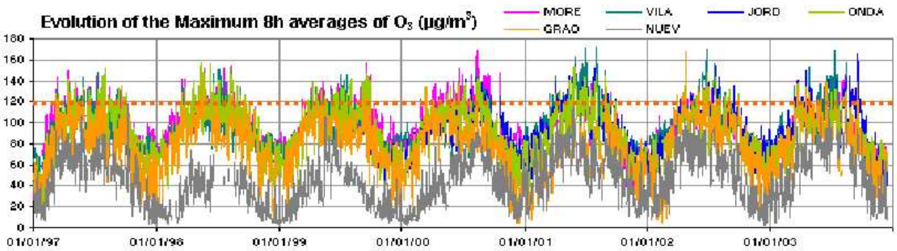


Figure 7.7: Maximum daily 8-hour averages of ozone for 5 stations in the Greater Valencia area. (Red dotted line indicates the Target Value for Health Protection: 120 μg/m^3)

ceedences of the threshold for informing the public (180 μg/m^3) have followed this pattern. Thus forecasting of ozone episodes can be done with a high level of confidence.

The main features of the pattern are described below:

1. The ozone exceedences take place in the spring and summer months under the influence of meso-scale anticyclonic circulations and stable atmospheric conditions.

2. There is a gradual increase in the maximum ozone concentrations from one day to the next (over a recharging period).

3. The time periods consist of 3 to 8 days (4 to 5 days on average) and involve about 30% of the days between the months of April and September (with a maximum in July covering 50% of the days).

4. The ozone recharging periods generally affect all the monitored area, from the coast to the interior. Not all of these cycles give rise to exceedences of the 180 μg/m^3 ozone threshold. However they usually cause ozone levels to surpass the objective value for human health protection (120 μg/m^3 over an 8-hour average).

5. When an exceedence takes place, it rarely surpasses 190 μg/m^3, nor does it last more than 2 or 3 hours. These high levels of ozone are generally observed at coastal sites after 2.00 pm and at inland stations with a delay of 1 or 2 hours with respect to the coastal locations. This delay is associated with the sea breeze transport of pollutants and their photochemical transformations.

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8. Preparation of meteorological input data for urban air pollution models. Part 1

Mathias W. Rotach, Andreas Christen and Working Group 1[1]

In this and the following chapter practical methods for obtaining appropriate meteorological data for undertaking urban air pollution calculations are discussed.

8.1. Estimating wind speed in the urban roughness sublayer using observations at other sites[2]

As a working hypothesis, an urban reference height, z_{refu}, similar to that specified in the World Meteorological Organisation guide for rural sites (z_{refu} = 10 m) will be used. It is proposed that $z_{refu} = d + 10$ m, where d is the zero plane displacement. It would have been interesting to compare wind observations from rural sites to simultaneously observed wind speeds at an urban site and in particular, at the above defined urban reference level, z_{refu}. However for various reasons, observations in urban environments are not usually available at this height. In the following sections a procedure is described on to how to use our knowledge concerning the turbulence structure within the roughness sublayer to estimate the wind speed at z_{refu} from an observation at any other height.

Step 1. Roughness sublayer height and zero plane displacement
For use in later expressions, the height of the roughness sublayer, z^*, and the zero plane displacement, d, for the site under consideration have to be known. If they are not known from other, independent methods, the following methods can be used:

Height of the roughness sublayer z^*

This is a very poorly defined parameter and has not been subject to much

[1] Working Group 1 members were Ekaterina Batchvarova, Ruwim Berkowicz, Josef Brechler, Zbynek Janour, Ewa Krajny, Emilia Georgieva, Douglas Middleton, Leszek Osrodka, Victor Prior and Cecilia Soriano and at the time of devising this procedure, Petra Kastner-Klein.

[2] A procedure devised by Working Group 1 of COST 715 based on a literature review.

investigation. Grimmond and Oke (1999) cite a number of estimates in the context of urban studies. They are all in the range given by Raupach *et al.* (1991), namely

$$z^* = 2z_H \quad \text{to} \quad 5z_H \tag{8.1}$$

where z_H denotes the average building (or rather roughness element) height. Here it is suggested that the lower limit (i.e. $z^* = 2z_H$) is used for typical European cities for the following reasons:

1. In the present context we will use (or interpret) z^* mainly as the height of the maximum Reynolds stress (see below, step 2)[3]. The available full-scale data suggest that the maximum Reynolds stress occurs in the range $1.5z_H < z < 2.5z_H$.

2. In wind tunnel studies, the maximum Reynolds stress is observed around $z = 2z_H$ (Rafailidis 1997, regular array, flat roofs) and sometimes significantly lower (see Kastner-Klein and Rotach (2001) for a 'real' array for Nantes, and Rafailidis (1997) for a regular array with slanted roofs).

3. Using the suggested concept of $z^* = 2z_H$ to simulate urban tracer dispersion experiments (Rotach 2001), yields the best agreement between observations and modelled results.

However if the density of roughness elements is very low, one of the other expressions as presented by Grimmond and Oke (1999) may be considered.

Zero plane displacement d

If d is not known from other independent methods, it may be estimated using the distribution and density of buildings (roughness elements). A comprehensive collection of methods can be found in Grimmond and Oke (1999). As a result of their study, they cannot recommend one single method as being superior to others. The simplest of the methods simply relates the zero plane displacement to the average building height: Grimmond and Oke (1999) suggest $d = 0.7z_H$. Their results indicate that this simple method yields reasonable results for $0.3 \leq \lambda_P \leq 0.5$ and $0.1 \leq \lambda_F \leq 0$. Here the two parameters used are the non-dimensional plan area, $\lambda_P = A_P/A_T$ and the non-dimensional frontal area, $\lambda_F = A_F/A_T$, where A_T denotes the total area, A_P is the area occupied

[3] Rather than the height where the influence of individual roughness elements on mean and turbulence profiles vanishes.

by buildings, and A_F is the frontal area of the buildings (calculated as the product from the average height and the average width). If the above conditions are not fulfilled (in particular, if the density of buildings is low), the method of Kutzbach (1961) may be used:

$$d = \lambda_P^{0.29} h, \quad \lambda_P \leq 0.29 \tag{8.2}$$

(see the discussion in Grimmond and Oke (1999) on the applicability and derivation of this method and the appropriate parameter choice.)

Step 2. Estimating the friction velocity
The basis of this step is that the Reynolds stress has been found to vary with height within the roughness sublayer. A sketch of its typical behaviour is given in Figure 8.1.

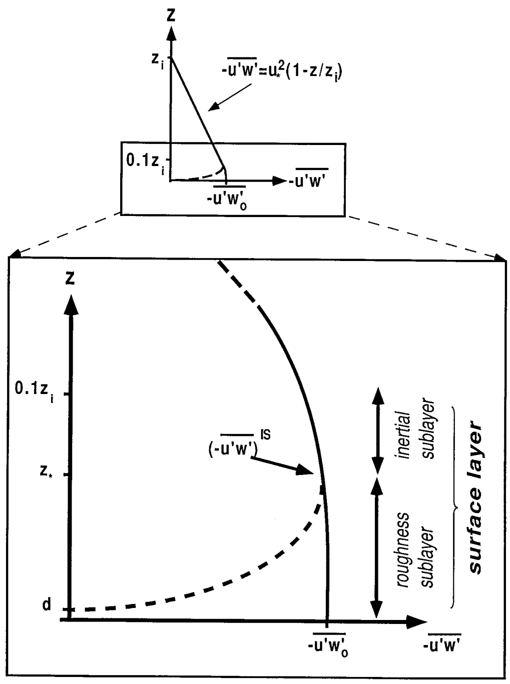

Fig. 8.1: Conceptual sketch of Reynolds stress in the urban boundary layer. The solid line corresponds to a parameterisation according to de Haan and Rotach (1998), which departs slightly from the 'standard' linear profile (the upper part of the figure) in that it assumes an approximately constant value when approaching the surface (from Rotach, 2001). z_i *denotes the top of the atmospheric boundary layer.* u_{*IS} *referred to in the text equals* $-\overline{u'w'}^{IS}$.

Figure 8.2 depicts the available measurements (full-scale) together with a suggested parameterisation, namely

$$\left(\frac{u_{*l}}{u_{*IS}}\right)^b = \sin(\frac{\pi}{2}Z)^a, \text{ when } Z \leq 1 \tag{8.3}$$

where $u_{*l}(z)$ is the local scaling velocity, $u_{*l}^2(z) = -\overline{u'w'(z)}$, u_{*IS} is the friction velocity (evaluated in the inertial sublayer, see Fig. 8.1) and $Z = (z-d)/(z^*-d)$ is a non-dimensional height.

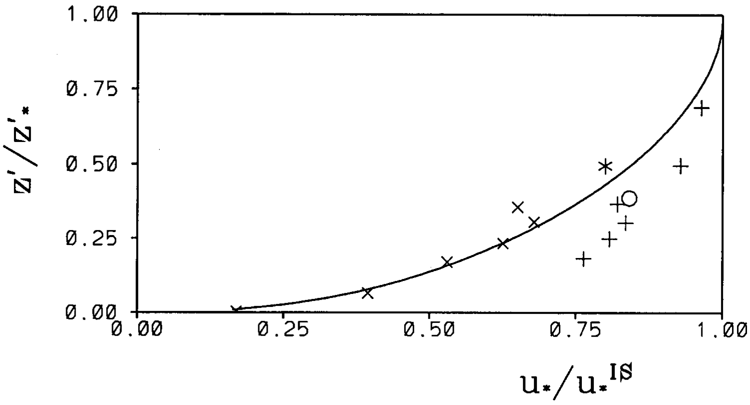

Figure 8.2 Parameterised profile of (local) friction velocity, u_*, as a function of non-dimensional height, equation (8.3). The symbols refer to the full-scale data of Rotach (1993a) $\times$, Oikawa and Meng (1995) $*$ and Feigenwinter et al. (1999) $\circ$. Wind tunnel data after Rafailidis (1997) $+$ are shown for comparison. The latter are not employed to fit the parameters in equation (8.3) since they refer to 'flat roof' experiments with an aspect ratio 1/2 (from Rotach, 2001).

The parameters a and b are fitted to the data of Figure 8.2 to yield $a = 1.28$ and $b = 3.0$. Note that this parameterisation intrinsically assumes that the height of the roughness sublayer, z^*, corresponds to the height where the maximum (absolute value) of Reynolds stress occurs. This maximum value of Reynolds stress is used to derive the friction velocity of the flow 'far away from the surface' i.e. within the inertial sublayer. To make clear where the friction velocity applies and from which layer measurements may be utilised to derive its numerical value, it is denoted with a subscript IS, namely u_{*IS}.

If a measurement of Reynolds stress is available with a measurement height below z^* the next step is to estimate u_{*IS} using equation (8.3).

If a measurement of Reynolds stress is available at $z > z^*$ and the measurement height is not much larger than z^*, the observation may be interpreted as u_{*IS}.

A measurement of Reynolds stress is available, but outside the city, then u_{*IS} may be estimated from (Bottema, 1995)

$$\frac{u_{*1}}{u_{*2}} = \left(\frac{z_{01}}{z_{02}}\right)^{\alpha} \tag{8.4}$$

where α is a parameter that can be estimated to equal 0.0706, u_{*1} corresponds to the urban friction velocity (i.e. $= u_{*IS}$) and u_{*2} is the rural friction velocity and z_{01} and z_{02} the corresponding roughness lengths.

If no measurement of Reynolds stress is available then the parameterisation according to Hanna and Chang (1992) may be used, which is not repeated here.

Step 3. Estimation of the wind speed at $z_{refu} = d + 10$ m
Within the roughness sublayer the non-dimensional gradient for wind (as is familiar from Monin-Obukhov Similarity Theory) can be used (Rotach, 1993b) provided that the local scaling velocity, $u_{*l}(z)$, is used rather than the friction velocity which corresponds to u_{*IS} (see Fig. 8.3). Thus

$$\frac{du}{dz}\frac{\kappa z'}{u_{*l}(z')} = \phi_m(z'/L_l(z') = \left(1 - 19.3\frac{z'}{L_1(z')}\right) \tag{8.5}$$

for unstable conditions, and

$$\frac{du}{dz}\frac{\kappa z'}{u_{*l}(z')} = \phi_m(z'/L_l(z') = \left(1 + 6\frac{z'}{L_1(z')}\right) \tag{8.6}$$

for stable stratification, where $z' = z - d$. Note that equations (8.5) and (8.6) are based not only on a local scaling velocity, but also on a local Monin-Obukhov length

$$L_l(z') = \frac{-\bar{\theta}u_{*l}^2}{\kappa g\overline{w'\theta'}} \tag{8.7}$$

where θ is the mean potential temperature, κ is the von Karman constant ($\kappa = 0.4$) and g is the acceleration due to gravity. The turbulent heat flux $\overline{w'\theta'}$ is assumed to be constant in the absence of more detailed information and can be derived from the energy balance (see Chapter 4). Integrating equations (8.5) or (8.6) numerically either down or up, the mean wind speed at a required level

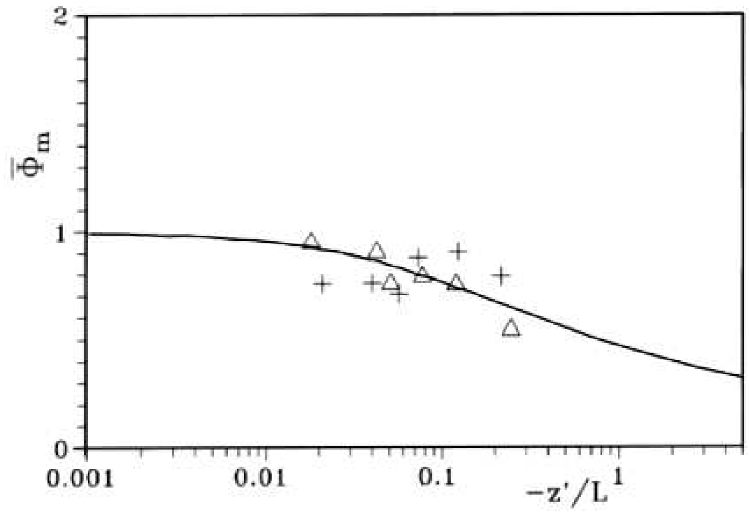

Figure 8.3: Non-dimensional gradient of wind speed averaged over bins of stability under unstable conditions. Data from Zürich, Switzerland (Rotach, 1993b). Δ 10m above roof level, + 5m above roof level (from Rotach, 1993b).

can be found from an observation at any height within the roughness sublayer. If the observation stems from above the roughness sublayer (but below 10% of the boundary layer height), equations (8.5) and (8.6) can be used with u_{*IS} rather than $u_{*l}(z)$ down to z^*, and from there the procedure described above can be used.

8.2. Verification of the COST 715 procedure with data from BUBBLE

8.2.1. Sites and Methods

As part of BUBBLE (see Chapter 10), two micrometeorological towers were operated in dense urban areas in the city of Basel over seven months. The urban surface in the source area of these two towers consists of residential multi-storey row houses, enclosing large inner courtyards with a height between 10 and 15m. This city structure can be typically found in many European cities constructed before the 1950's. The sites were chosen in order to achieve homogeneous source areas for the upper tower levels in terms of terrain (flat), building height and building structure. On average, the urban surfaces have an aerodynamically determined roughness length of $z_0 = 2.1$ m at Sperrstrasse and 1.4m at Spalenring.

Amongst other instruments, both towers supported six ultrasonic anemometer-thermometers arrayed in a vertical profile with an enhanced vertical resolution around rooftop (Table 8.1). The triangular lattice tower at Sperrstrasse was deployed within a vegetation-free street canyon and provides a vertical profile from street level up to 32 m. The profile at Spalenring was divided into two parts: measurements were carried out within a vegetated canyon (A to C) and a tower part that was shifted toward the backyard (D to F) extended the set

Table 8.1: Instrumentation and surface characteristics of the two sites in Basel

Site Canyon Co-ordinates Scales$^{(1)}$	*Basel-Sperrstrasse* Non-vegetated urban street canyon 611890/268365$^{(2)}$, 255 m a.s.l. $z_H = 14.6$ m, $W/z_H = 1.0$	*Basel-Spalenring* Vegetated urban street canyon 610360/267140$^{(2)}$, 278 m a.s.l. $z_H = 15.1$ m, $W/z_H = 1.8$
Instrumentation	Ultrasonic anemometers F 31.7 m Gill HS (20Hz) E 22.4 m Gill R2 (20.8Hz) D 17.9 m Gill R2 (20.8Hz) C 14.7 m Gill R2 (20.8Hz) B 11.3 m Gill R2/Metek USA-1 (20Hz) A 3.6 m Gill R2/Metek USA-1 (20Hz)	Ultrasonic anemometers F 37.6 m Metek USA-1 (20Hz) E 29.9 m Metek USA-1 (20Hz) D 21.8 m Metek USA-1 (20Hz) C 16.6 m Metek USA-1 (20Hz) B 13.9 m Metek USA-1 (20Hz) A 5.6 m Metek USA-1 (20Hz)

$^{(1)}z_H$: building height, W: canyon width
$^{(2)}$co-ordinates in m easting/northing (CH1903).

up to 38m. Both towers cover roughly the vertical domain from street level up to two times the mean building height.

20 Hz raw data from the ultrasonic anemometer-thermometers were stored at both sites for the period November 2001 to July 2002. The instruments were checked and compared in a wind tunnel before and/or after the experiment. In order to minimise flow distortion effects, individual instrument correction matrices were derived from wind tunnel runs and used to correct the wind vectors (Vogt and Feigenwinter, 2004). Angles of attack where the flow distortion effects of a particular instrument are large or the tower obstructs the flow, have been excluded from analysis.

8.2.2. Measured characteristics of the urban flow field in the roughness sublayer – mean wind profile

It is no surprise that flow channelling increases continuously with decreasing height into the street canyon. This is illustrated for Sperrstrasse in Fig. 8.4, where the average local wind direction for different directions of the approaching flow is shown. Below the mean building height the majority of all cases showed wind directions channelled either from 67 ° or 247 °, which corresponds exactly

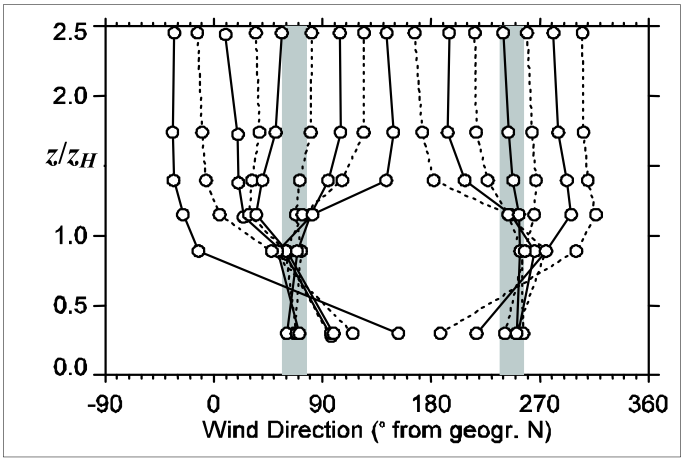

Figure 8.4: Channelling of the flow into the street canyon. Shown is the local horizontal wind direction at the six measurement heights, z/z_H, as a function of the overlying wind direction sector at the tower top for Sperrstrasse, Basel. The grey bars indicate the street canyon orientations 67 ° and 247 ° from geographical north (from Christen et al., 2003).

to the axis of the canyon, as indicated by the grey bars. An asymmetry in the channelling effect was observed in both street canyons because instruments were mounted closer to one building wall ($y/W = 0.37$ at Sperrstrasse, $y/W = 0.16$ at Spalenring where y is distance to canyon centre and W is canyon width). Under flow situations perpendicular to the canyon axis, a simple vortex was developed on average. Then, the wind direction at the canyon floor was opposite to the direction above the roofs.

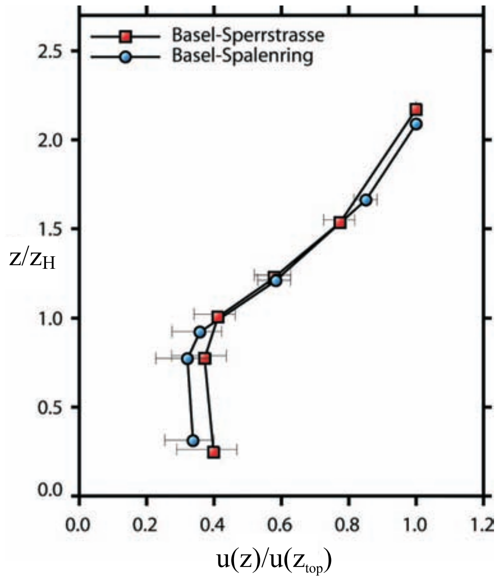

Figure 8.5: Ensemble wind profiles normalised by wind speed at the tower top, $u(z)/u(z_{top})$, as a function of height z/z_H derived from the sonic anemometers for the whole operation period. Error bars indicate the 20% and 75% percentile of all data (Christen et al., 2003).

Figure 8.5 shows mean profiles of scalar mean wind speed. Well above the roofs, the profiles follow the logarithmic law. Similarly to profiles measured over and within plant canopies (e.g. Finnigan, 2000), the canyon profiles show an inflection point at $1.1z_H$ and a second maximum in the canyon itself. As a consequence of the inflected velocity profile, it is very likely, that Kelvin-Helmholtz instabilities are arising. This has major implications to turbulent exchange, and the related scaling. Raupach *et al.* (1996) proposed that flows within and in the layer directly above rough canopies can be compared to a turbulent plane mixing layer, and there are indications that urban surfaces, if horizontally averaged, show many analogies to plant canopies, even if they are not as permeable.

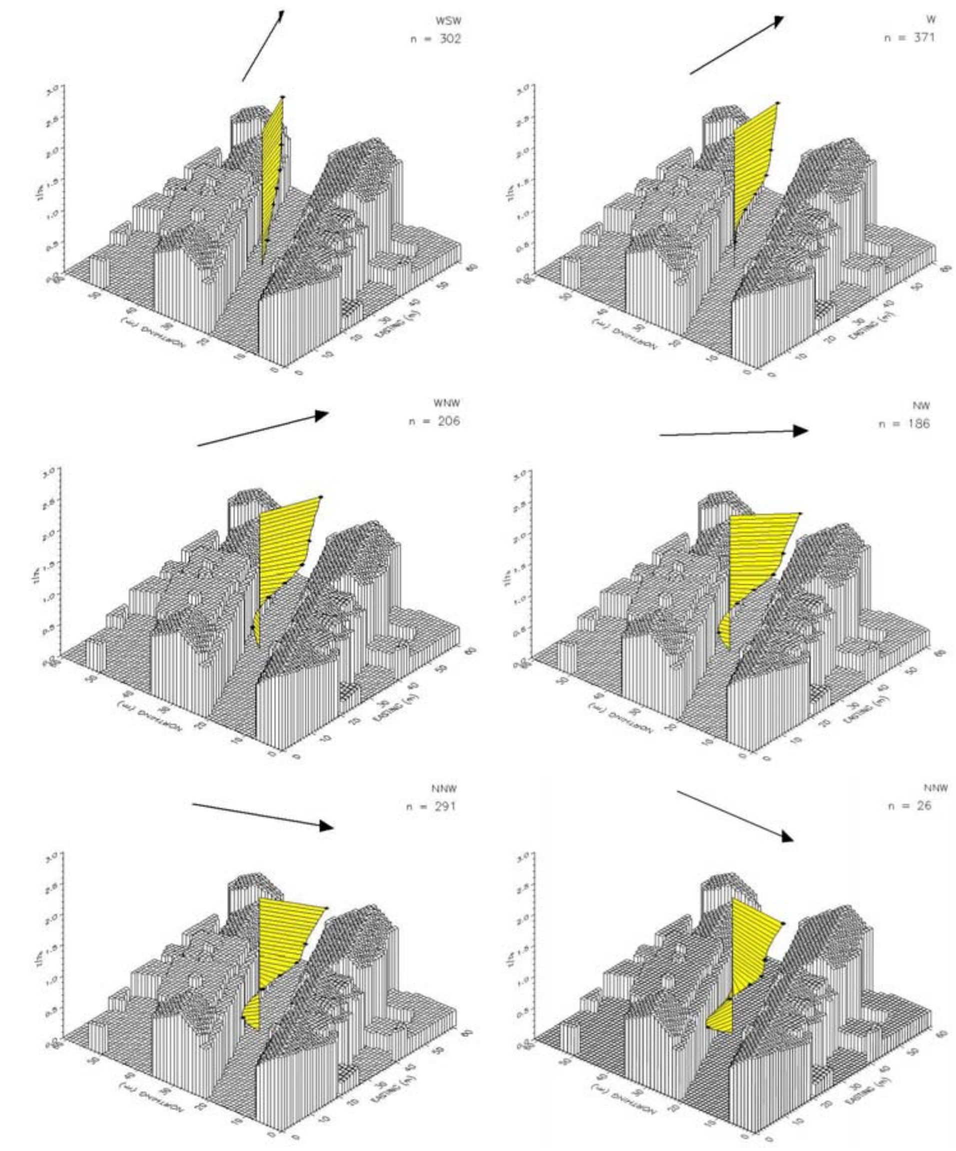

Figure 8.6: Three dimensional visualisation of the average horizontal wind speed in the street canyon at Sperrstrasse, Basel for selected cases. The yellow profiles show the mean horizontal vector wind speed and wind direction normalised by its value at tower top. Data are from the period November 1, 2001 to July 15, 2002, and include all stabilities. Each panel shows average data from the indicated wind direction sector and n refers to the number of hours included in the average. Black dots represent the exact values at measurement heights. Between the measurements a cubic spline interpolation was performed.

8.2.3. Measured characteristics of the urban flow field in the roughness sublayer – Reynolds stress profile

The local Reynolds stress $u_*(z)$ at the two towers was calculated taking lateral contributions into account with the formula $u_{*l}(z) = [\overline{u'w'}(z)^2 + \overline{v'w'}(z)^2]^{0.25}$ and a vertical orientation of w. The rotation of the wind direction due to the channelling of the flow into the canyon (Figs. 8.4 and 8.6) makes the contribution of $\overline{v'w'}$ to $u_{*l}(z)$ relevant.

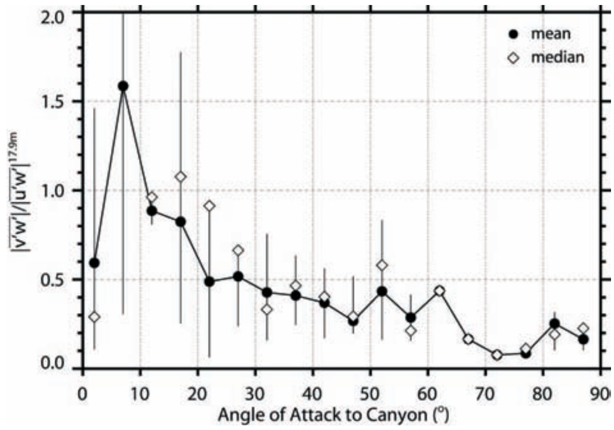

Figure 8.7: The ratio $\overline{v'w'}$ to $\overline{u'w'}$ shows the relative importance of lateral contribution to the importance of longitudinal contributions to the vertical flux of momentum at Sperrstrasse. The plot shows the ratio as function of the flow direction relative to the street canyon directly above roof top ($z/z_H = 1.23$) at a height of 17.9m.

On average $\overline{v'w'}$ enhances $u_{*l}(z)$ between 5% (at $2z_H$) and 20% (at z_H and inside the canyon). Figure 8.7 shows the ratio between the absolute values of $\overline{v'w'}$ and $\overline{u'w'}$ at Sperrstrasse at $z/z_H = 1.23$ (17.9 m). It is a measure of the relative importance of the lateral contribution to the overall local $u_{*l}(z)$. The dependence of the ratio on the overlying wind direction relative to the street canyon is shown. An angle of 0 ° corresponds to an overlying flow along the canyon; an angle of 90 ° denotes flow perpendicular to the canyon. In a narrow band with a overlying wind direction between 0 ° and 20 ° offset to the street canyon's axis, the lateral contributions are largest, due to a continuously rotating wind direction with height (corresponds to the cases WSW and W in Fig 8.6.). With higher angles, (i) the wind gradient around rooftop gets stronger and (ii) the flow in the street canyon is no longer channelled, and deformed helix-shaped vortices develop on average (cases WNW and NW). In the ideal case of 90 ° (case NNW) a simple vortex forms within the canyon. In

Table 8.2: The relative frequency of measuring the highest $u_{*l}(z)$ at each of the six measurement levels at Sperrstrasse under different flow situations. A, B and C represent the approach direction of the main synoptic flow (A, $270\,° - 310\,°$), a convective summertime wind system (B, $310\,° - 360\,°$) and the main nocturnal cold air drainage flow (C, $90\,° - 160\,°$).

Sector	All	*A*	*B*	*C*
Samples	3752 h	760 h	535 h	1489 h
$z/z_H = 2.17$	19.3%	18.4%	19.1%	2.4%
$z/z_H = 1.53$	**61.5**%	**40.1**%	**59.4**%	**95.2**%
$z/z_H = 1.23$	11.9%	27.2%	12.7%	1.2%
$z/z_H = 1.01$	4.4%	10.5%	5.6%	0.2%
$z/z_H = 0.77$	1.1%	0.9%	1.5%	0.5%
$z/z_H = 0.25$	1.7%	2.8%	1.7%	0.6%

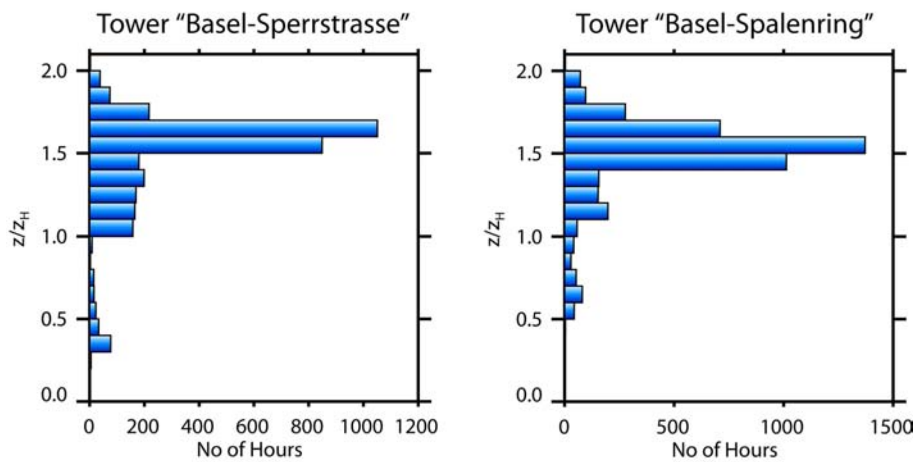

Figure 8.8: The histograms illustrate the height of maximum u_* at the two urban towers. Data include all stabilities and all wind directions. In the majority of cases, the maximum u_* is measured close to $1.55z_H$. A cubic spline interpolation was performed between measurement levels to enhance the height resolution.

the case when a vortex develops, the rotation with height is weaker, and hence the lateral contributions are less relevant.

On average, at Sperrstrasse the level at 22.4 m shows the highest probability of measuring the highest Reynolds stress $u_{*\max}$ (Table 8.2). The height where $u_{*\max}$ is found is surprisingly constant for different flow situations. Figure 8.8 shows the histogram for all wind directions (0−360 °) and for both urban towers. The analysis of local Reynolds stress values at the site Spalenring leads to a very a similar result with a $u_{*\max}$ at $1.5z_H$. Britter and Hanna (2003) suggest that the height of $u_{*\max}$ corresponds to the height of the highest obstacles extending into the urban roughness layer. It is shown in Figure 8.9 that there are numerous building obstacles present above the mean building height z_H[4]. These obstacles form an initial point for the development of strong local shear layers, and the flow below such a point is already decelerated by friction and within wakes. At the present sites the initial roughness elements are mainly pitched roofs. However the exact height of z^* is above the most relevant obstacles, so that dynamical effects are likely to be affecting the momentum profile.

In a horizontal averaged view the roughness sublayer below the initial roughness elements corresponds to a less permeable layer. In fact, most wind tunnel experiments with obstacles of uniform height show their $u_{*\max}$ directly at z_H (Macdonald *et al.*, 2000, Cheng and Castro 2002). An elevated $u_{*\max}$ is reported from wind tunnel results with variable obstacle heights (Kastner-Klein and Rotach, 2004). The height of $u_{*\max}$ is indicated with the thin dashed-dotted line in Figure 8.9.

In any case locally measured $u_{*l}(z)$ values near the roofs and inside the canyon must be interpreted carefully because the theoretical assumptions (horizontal homogeneity) cannot be fulfilled at all. Inside the canopy not only is vertical transport of momentum important but also lateral transport towards the walls. Hence the momentum transport is not totally described by a one-dimensional u_{*l}.

Highest values for $u_{*l}(z)/u(z)$ were observed at both urban stations between heights of $0.8z_H$ and z_H, where high drag is caused by the large and exposed roof areas. In general the drag coefficients from the two BUBBLE experiment

[4]It must be noted that single storey buildings in backyards lower the average z_H significantly at both sites, but aerodynamically they are not important. The mean building height is calculated as the area-weighted average roof height of all surfaces in the city occupied by buildings, regardless of whether these roofs are below d.

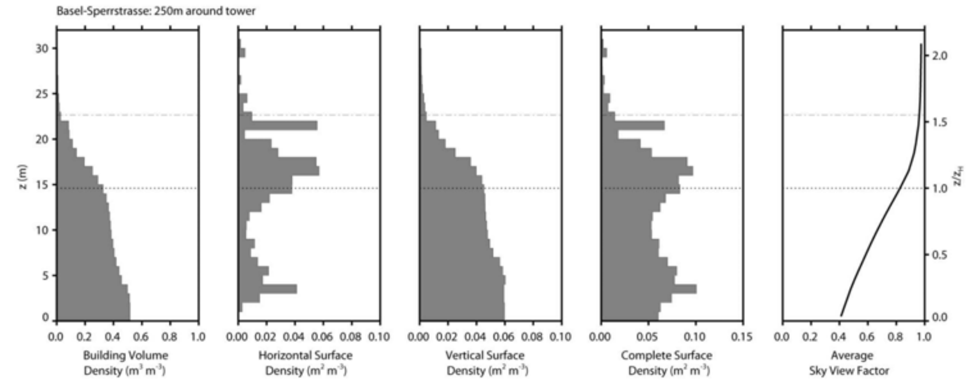

Figure 8.9: Vertical profiles of morphometric properties of the surface in a 250 m circle around the site Sperrstrasse. Data extracted from the digital 1m building model of the city authorities (GVA Basel-Stadt). The dash-dotted line denotes the height of $u_{*\,\mathrm{max}}$. The dotted line denotes the mean height of the buildings.

towers are slightly higher than values reported from previous studies at equivalent heights (Rotach, 1995, Feigenwinter *et al.*, 1999, Roth 2000). The ratio $u_*(z)/u(z)$ strongly depends on the wind direction of the approaching flow relatively to the canyon. At roof level the flow perpendicular to the canyon leads to values which are twice the ones observed in flow parallel to the canyon. This is mainly an effect of a slower u at roof level during cross canyon situations. At a height of $2z_H$ the ratio $u_*(z)/u(z)$ is around 0.2 at both sites and nearly independent of wind direction. This indicates that single roughness elements and the canyon orientation do not have an influence anymore.

8.2.4. Verification of the procedure

Calculation of zero plane displacement

For an increasing number of cities, authorities provide digital three dimensional building data sets, which are a powerful tool for the analysis of urban surface forms. Such high resolution models can provide detailed measures of three dimensional parameters. Many empirical relations are described in the literature to relate morphometric parameters to aerodynamic properties of the urban surface (e.g. Grimmond and Oke, 1999). In the COST 715 procedure, the zero plane displacement d is simply estimated with the urban 'rule-of-thumb', $d = 0.7z_H$ (Grimmond and Oke, 1999). This value is compared to other empirical relations, aerodynamic and spectral methods in Table 8.3 for the site Sperrstrasse. The analysis was done separately for three flow directions. The sectors represent the approach direction of the main synoptic flow (A, 270 ° – 310 °), a convective summertime wind system (B, 310 ° – 360 °), and the main nocturnal cold air drainage flow (C, 90 ° – 160 °). The three wind sectors incorporate 75% of all situations. The surface in the directions of A and B is remarkably homogeneous, and consists of residential multi-storey houses in rows, enclosing large inner courtyards ($z_H = 13.6$ m, plan aspect ratio $\lambda_P = 0.46$). The sector C is more heterogeneous with commercial building blocks, which are higher and larger ($z_H \approx 20$ m, $\lambda_P = 0.55$) than the typical residential areas in the source area of A and B. The morphometric data was deduced from a high resolution digital building model with 1 m raster size and for a circle of 250 m around the sites. The values deduced from the neutral logarithmic wind profile were calculated using the three highest measurement levels.

Table 8.3: Ratio between zero plane displacement and mean building height d/z_H calculated for the site Sperrstrasse for the different flow situations and with different approaches.

Sector	All	A	B	C
z_H (m)	14.6	14.0	3.2	19.4
Morphometric method				
COST 715 procedure	0.70	0.70	0.70	0.70
Kutzbach (1961)	0.84	0.79	0.80	0.84
Counihan (1971)	0.73	0.60	0.63	0.74
Raupach (1994)	0.62	0.64	0.63	0.57
Bottema (1995)	0.69	0.62	0.64	0.70
Macdonald *et al.* (1998)	0.79	0.72	0.73	0.80
Kastner-Klein and Rotach (2004)	0.92	0.87	0.89	0.92
Measurements				
Neutral wind profile	0.74	0.82	0.78	0.78
Jackson (1981)	0.67	0.61	0.73	0.58
Spectral method[5]	0.74	0.83	0.89	0.59

[5] In surface layer scaling, the normalised peak frequencies $n_{\max}$ of the neutral power spectra scale only with height above the zero plane displacement. n_{max} is defined as the natural peak frequency f_{max} scaled by a scaling length $(z - d)$ and mean vector wind speed u. Even above rough surfaces the neutral limits are fairly constant with values of $n_{\max}(u) = 0.08$, $n_{\max}(v) = 0.22$ and $n_{\max}(w) = 0.55$ (Kaimal and Finnigan, 1994). This is used to solve for d from the meas ured peak frequencies $f_{\max}$ of vertical velocity w, which is best predicted in the inertial sublayer. Also u and v result in plausible estimates. This method has the advantage, that only one measurement height (in the inertial sublayer) is required. In this study, measurements at the tower top are used.

Both the neutral wind profiles and the spectral method suggest a slightly higher$d$ for this dense urban surface. However, the 'rule-of-thumb' is a pragmatic approximation and for further verification steps $d = 0.7z_H$ is considered.

Determination of the roughness sublayer height
The determination of the roughness sublayer height from measurement data is not a well investigated problem, and no standard procedures exist. This may be due to the fact that the roughness sublayer does not have a well-defined upper boundary and different definitions exist. More realistic is a gradual transition from a three-dimensional, horizontally inhomogeneous flow in the roughness sublayer to a horizontally homogeneous flow in the inertial sublayer. From the data we can retrieve different indicators that help us to define the height of the roughness sublayer.

(a) The height, where the maximal local Reynolds stress u_{*max} is found (Rotach 2001).

(b) The height, where under neutral conditions surface layer values are reached (the constant flux layer)

(c) The height were the vertical divergence $\partial Q/\partial z$ of turbulent fluxes of heat Q_H and water vapour Q_E reach zero (the blending height).

(d) The height were the horizontal variability of a locally scaled turbulence parameter (or the variability at a single point under different wind directions) approaches zero, or more realistically drops below a threshold value.

The different definitions result in a large variability of estimates and there is no reason why the heights derived from different definitions should coincide. Previous field and wind tunnel measurements focused mainly on definition (d). In the wind tunnel, profiles taken at different locations converge with increasing height, and usually this 'convergence height' can be as low as $1.5z_H$ in densely built-up sites, but up to $4z_H$ in low density areas (Grimmond and Oke, 1999, Rotach, 1999). In the present context, we are mainly interested in definition (a) the height z^* of the maximum Reynolds stress $u_{*\,\mathrm{max}}$ which was determined to be a height of $1.55z_H$ (see Section 8.2.3 on the Reynolds stress profile).

Comparable low values of the roughness sublayer are suggested by neutral surface layer values of the wind components (but with local scaling) and by the vertical divergence of sensible heat flux, which is negligibly small above $z/z_H > 1.4$

(Christen and Vogt, 2004). Other turbulence statistics like dissipation rate ε or spectral characteristics are disturbed up to at least $2z_H$, and also transport terms of the turbulent kinetic energy budget are still important at $2z_H$ (Christen et *al.,* 2004). Wind tunnel results from the surface around Sperrstrasse show that horizontal inhomogeneities are measurable up to a height of $3.5z_H$ (Feddersen *et al.*, 2004).

Parameterisation of the vertical u_* profile
Figure 8.10 illustrates the parameterisation for u_* according to equation (8.3) at the two towers. Symbols denote measured values of $u_{*l}(z)/u_*(z^*)$ for different wind direction classes. Observational data are processed with an individual z_H for each of the wind sectors. $d = 0.7z_H$ and $z^* = 1.55z_H$.

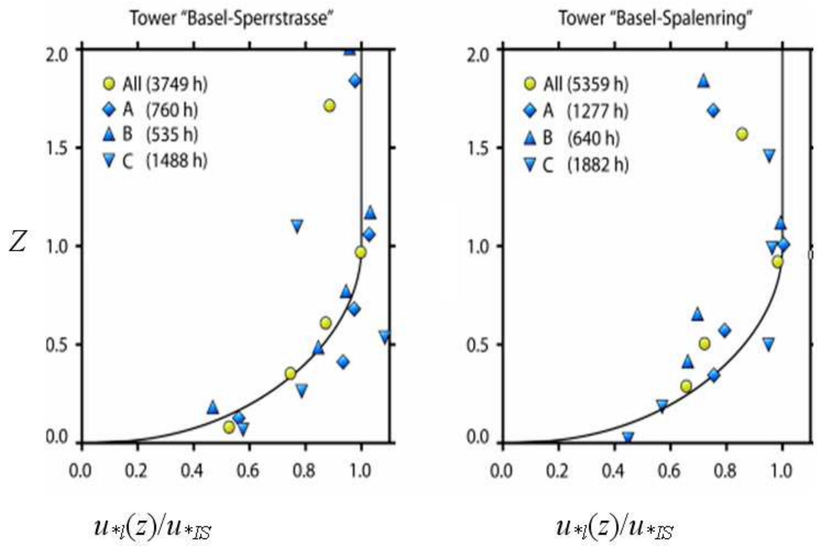

Figure 8.10: Parameterisation of the u_* profile (black line, equation 8.3) as a function of height $Z = (z-d)/(z^*-d)$ in comparison with measured values of $u_{*l}(z)/u_{*IS}$ for all data and for the different wind direction classes A, B and C separately. Observational data are processed with an individual h for each of the wind sectors, $d = 0.7z_H$ and $z^* = 1.55z_H$.

The temporally averaged profile of $u_{*l}(z)$ ($0\,^\circ - 360\,^\circ$, circles in Fig. 8.10) fits the parameterisation well and different flow situations are also in agreement. However at Sperrstrasse, the cold air drainage from Sector C shows poor agreement. This suggests that either the attributed z_H or z^* do not represent the real forcing, or the more heterogeneous source area modifies significantly the local structure of the momentum transport.

Equation (8.3) suggests interpreting any measured $u_{*l}(z)$ above z^*, as $u_*(z^*)$. The observations show, that the measured profile of u_{*l} above z^* is decreasing in most cases. At Spalenring the decrease of u_{*l} above z^* is most obvious under all wind directions, while in sectors A and B at Sperrstrasse the difference between u_{*l} at tower top and $u_*(z^*)$ is only -4% on average. Here also, sector C shows a clear decrease of u_* above z^* of the order of 20%.

Determination of u_* from a rural measurement
In the case when a measurement of Reynolds stress is only available outside the city equation (8.4) is applied to model the urban $u_*(z^*)$. The modelled urban u_* can be used with equation (8.3) to determine the profile of $u_{*l}(z)$. During BUBBLE, a micrometeorological tower was located 4 km north of the city in an ideal and flat area with agricultural land use. Data from this rural site (Village Neuf) were used to test the scenario. The roughness length z_0 at this rural site was determined to be 0.07 m with the neutral logarithmic wind profile (3 levels).

Figure 8.11 shows the comparison between the measured urban u_{*IS} and the modelled urban u_{*IS} according to equation (8.4). Shown are only flow situations from sector B, when the rural site is in the upwind direction of the city. In this case, applying equation (8.4) leads to a systematic underestimation of the urban u_{*IS} by 30%. The underestimation is noticeably stronger in periods when the rural site lies downwind of the city (i.e. sector C not shown). Then the procedure shows an underestimation of the urban $u_*(z^*)$ by 70% on average. Flow from sector A results in an underestimation of 50%. This suggests when the wind flow at the rural site is undisturbed by the city, the procedure gives only reasonable results, apart from local effects at the urban site.

Determination of the reference wind speed
Table 8.4 compares the modelled wind speed at the chosen reference height, z_{refu} ($= d + 10$ m, 20.3 m) to measured (interpolated) values at the same height. The table lists the overall statistics for different input configurations in terms of the slope of a linear regression, a, where $u_{modelled} = au_{measured}$, the square of the linear Pearson correlation coefficient between measurement and modelled wind speed (r^2) and the root mean square error in ms^{-1} (rms).

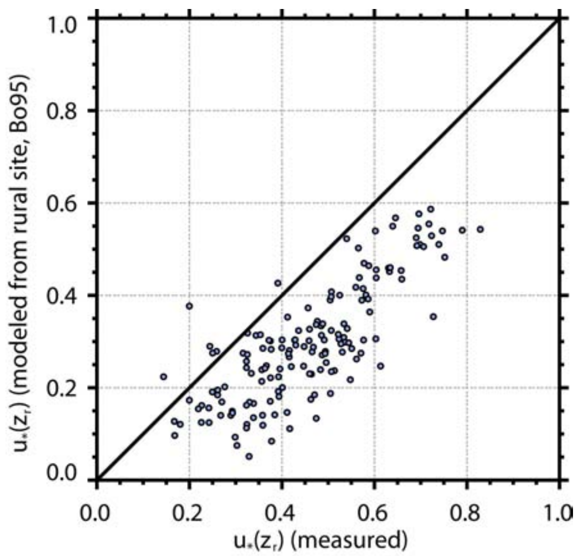

Figure 8.11: Comparison of the measured urban Reynolds stress at z^* with its modelled values based on the measurements from the rural site Village Neuf and by applying the formula of Bottema (1995), equation (8.4). Shown are hourly averages from May 6 to July 13, 2002, with the wind from Sector B. Under this flow, rural measurements are undisturbed by the city.

It is no surprise that results are sensitive to the distance $z_{input} - z_{refu}$ i.e. levels that lie close to z_{refu} (e.g. 22.4 m) result in a better performance and a higher correlation than levels with a larger vertical distance to z_{refu}. In general modelled values with input parameters from below z_{refu} systematically overestimate the measured wind speed at z_{refu}. The overestimation is most pronounced when an overall wind direction along the canyon axis is observed. The associated flow channelling within the street canyon increases local values of the input $u(z)$ and $u_{*l}(z)$ close to the roofs and in the upper canyon zone, relative to the horizontal average, and as a consequence also u_{refu} is overestimated by integrating upwards.

Taking the topmost measurement level as the input for both u_* and u (31.7m $> z_{refu}$), the model underestimates $u(z)$ typically by 10%. This is mainly an effect of the disturbances in Sector C at Sperrstrasse, where the topmost $u_*(z)$ is markedly lower than $u_*(z^*)$.

The calculations with rural u_* values (i.e. estimated urban u_*) result in higher scatter between the modelled and in-situ measurements. The modelled urban

Table 8.4: Comparison between the modelled wind speed at a reference height (z_d + 10 m, 20.3 m) and measured (interpolated) values at the same height for Sperrstrasse. The table lists overall statistics for different input configurations in terms of the slope, a, of a linear regression ($u_{modelled} = au_{measured}$), the square of the linear Pearson correlation coefficient between the measured and modelled wind speed (r^2), and the root mean square error in m/s.

Height z of input u		u_* from urban measurement			u_* from rural measurement		
z	z/z_H	a	r^2	rms	a	r^2	rms
31.7 m,	2.17	0.93	0.73	0.66	1.22	0.71	0.97
22.4 m,	1.53	0.95	0.97	0.20	1.02	0.72	0.64
17.9 m,	1.23	1.03	0.97	0.25	0.89	0.68	0.87
14.7 m,	1.01	1.00	0.90	0.62	0.52	0.47	1.31
11.3 m,	0.77	1.08	0.41	3.90	0.16	0.16	1.62

u_{*IS} determined by the empirical expression (8.4) are strongly underestimated, which in consequence lowers the local gradients du/dz in (8.5). Calculations with numerical integration downward (input from a higher level than the reference height) result in an overestimation and those with an upward integration (input from a lower level than the reference height) show an underestimation. This is especially pronounced for an input level deeply within the street canyon. This effect could be avoided by altering the empirical factor α in equation (8.4) and by using a rural site, which is not at all influenced by the city.

8.3. Conclusions

Overall, the results of the procedure are encouraging, and most configurations result in reasonable estimates (some 10% error on average) of the wind speed at the reference height. This conclusion holds true if an urban u_* is available and the input (wind speed) level is not within the street canyon. If only a rural u_* is available to use to estimate the urban friction velocity, or if the wind speed observation (from which wind speed at the reference level is to be determined) stems from within the street canyon, the performance is clearly seen to be worse (see Table 8.4).

The estimation of z^*, interpreted here as the height of maximum local Reynolds stress, is clearly the most problematic input parameter of the procedure. It is suggested z^* equals $1.55z_H$, based on the present data set, but further full-scale and wind-tunnel experiments are needed to verify this empirical relationship and relate it to the morphometric structure of other urban areas.

The overall performance of the procedure is strongly dependent on how representative the input wind measurements $u(z)$ are in the horizontal average. Larger errors are associated with flow directions that have strong inhomogeneities and a highly variable building height. Also input data from below the street canyon height z_H and close to z_H should be avoided. Here the procedure could be enhanced by a parameterisation, which accounts for the inflected velocity profile within the street canyon.

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9. Preparation of meteorological input data for urban air pollution models. Part 2

Michael Schatzmann

9.1. Urban dispersion calculations

Besides emission data, any dispersion model needs meteorological input to predict air quality properties. The meteorological input required depends on both the sophistication of the model and the complexity of the site.

Inevitably urban sites of practical interest are always complex. The meteorological characteristics within an urban conglomeration differ from location to location. In the lower part of the boundary layer they are quite distinct from those measured outside the built-up urban zone, at airports or other routine synoptic stations. It is not trivial to derive from the data measured at such sites, a climatology of wind and stability parameters which is representative of a specific urban site.

In order to investigate the state of the art in this field, COST 715[1] organised a workshop on the Preparation of Meteorological Input Data for Urban Site Studies, held on June 15, 2000 in Prague, Czech Republic (see Schatzmann *et al.* (editors), Appendix D).

The presentations at the Workshop compared and contrasted the various methods routinely applied to urban dispersion. All the methods were concerned with producing a climatology of stability categories/dispersion classes for urban areas, following approaches used in rural areas. All methods would benefit from more observations in urban areas but all suffered from difficulties regarding objective ways of defining representative sites, the appropriate height at which urban wind speeds and directions should be measured and how to deal with low wind speeds. More advanced methods for describing the atmospheric boundary layer, such as in terms of boundary layer scaling, do not necessarily improve the description of the urban boundary layer because the fetch in urban areas is not generally long enough to establish an atmospheric boundary layer in equilibrium with the ground surface below. Rather than abandon the problem as

[1] Working Group 4

too difficult, somewhat arbitrary corrections have been introduced to allow for urban characteristics. These are based on sensible corrections and insight into the physics (e.g. adjusting for greater roughness leads to changes in wind speed and turbulence profiles near the surface but with consistent winds aloft). Similarly a limit on the extreme stability expected in a city might be introduced. However there appear to be no national or international guidelines as to how these corrections may be applied. The problem is especially severe in a city where there are few urban observations and the terrain is complex. Although urban dispersion calculations are therefore undertaken regularly in all countries, they may often be performed under inappropriate conditions.

One alternative proposed in some countries is the use of an appropriate urban scale model nested within larger meso-scale models. In principle this can take account of the changes in the surface roughness and surface heat flux within an urban area. However there are problems too. The resolution of the models may not be on a fine enough scale to resolve features affecting dispersion and they may not be able to produce the climatology of dispersion statistics required by dispersion modellers. Increasing computer power would lessen these difficulties but they remain at the present time.

Another alternative approach is to use measured winds, possibly just at the surface, or prescribed wind data, and by various techniques such as optimisation or by using a dynamical wind flow model, generate information on wind fields on a finer scale appropriate to the topography of the city. The Workshop contained several examples of these so-called down-scaling methods. Although they have potential, they cannot deal with every situation. In particular they will not resolve a feature of the urban wind field which is not seen by the available wind measurements used as input to the down-scaling model.

With these conclusions, that there are limits to the applicability of existing methods to defining the urban boundary layer structure, it is vital to have new concepts regarding the structure of the urban boundary layer. This is to enable measurement programmes to be defined and for a theoretical framework to be tested. The Workshop contained two papers outlining frameworks for defining urban boundary layer structure: one concerned the urban wind profile and the other concerned heat fluxes, and thus the atmospheric stability of urban atmospheres. The former[2] proposes a generalisation of boundary layer scaling, which should enable wind statistics within an urban area to be estimated.

[2] This is outlined in Chapter 8

The latter proposes a method for deriving urban surface heat fluxes requiring only standard meteorological observations and basic knowledge of the surface character of the urban area. This scheme (LUMPS) has been developed and applied in North America and needs to be tested on European cities with different typical building densities, structure and shape (slanted roofs, for example). The development of the urban wind profile scaling method also needs to be tested on cities, on which it was not originally developed, and should be supported by more extensive data sets. The two new approaches need to be closely linked. The wind profile scaling method places great emphasis on the height of the roughness sublayer (thought to be approximately twice the mean building height) which is not well known or investigated. The surface heat flux derived from LUMPS refers to the heat flux defined at something like this height but this needs further clarification. The moisture content, and hence precipitation, may also need to be included in the parameterisation.

The final part of the Workshop was devoted to recommendations and conclusions. Concern was expressed that there might be an important user community which is currently applying suspect methods in the preparation of meteorological input data for urban site studies. With respect to the proposed improved methods for parameterising the urban wind profile and surface heat flux, validation was considered to be essential. This requires suitable data from urban sites.

9.2. Survey and characteristics of available meteorological data sets

As validation data for testing the methods are scarce, it was decided to find out what is presently available. COST 715 decided that a survey of urban meteorological and air pollution stations is undertaken. The next step would then be to select those stations which have the potential to provide validation data capable of testing 'transfer functions' or models, which calculate the wind field and other meteorological parameters for urban sites from data collected at regular synoptic station (at airports etc). National weather services, as well as regional and local environmental authorities in all member states participating in COST 715 were contacted and asked to provide information on stations located either in city environments or close to urban areas. The task has been completed successfully: a database has been created on the internet which presently contains 377 station entries. Figure 9.1 gives an impression of the general layout of the COST 715 inventory of urban monitoring stations. The data are freely available under `http://www.mi.uni-hamburg.de/cost715/index.html`.

Despite the large number of stations from which data were collected, only very few of them deliver data which can be used for validating the various methods currently in use for transferring data from a nearby synoptic station to the urban site. Most of the stations are air quality monitoring stations only. They focus on the measurement of pollutant concentrations.

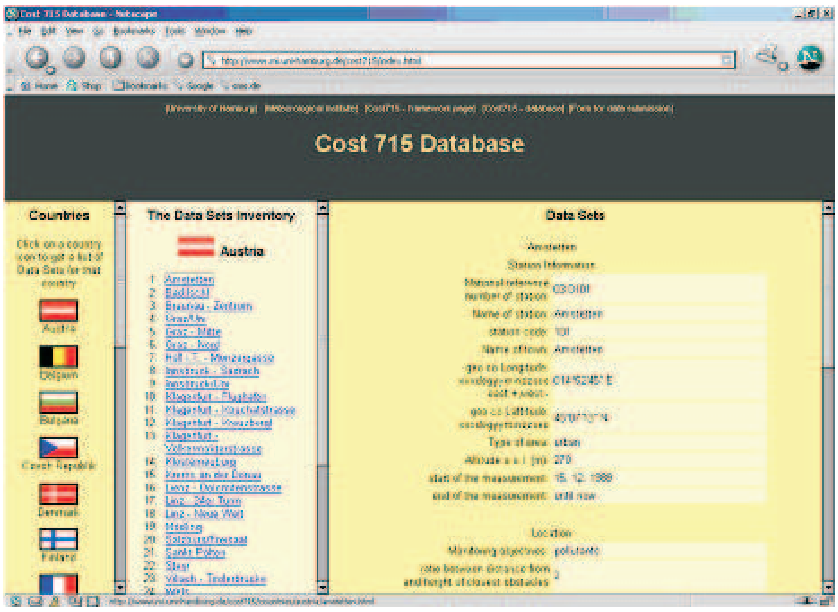


Fig 9.1: General layout of the introductory web page of the COST 715 inventory of urban monitoring stations

The meteorological parameters measured at some stations are also in most cases not representative of the area surrounding the site. Although the standard requirements expressed in the Guide to Meteorological Instruments and Methods of Observation (WMO, 1996) are not directly applicable for urban meteorological stations, they nevertheless give some guidance. For a wind measuring instrument they require a height of 10 m above ground and a distance to the next obstacle which must be at least ten times the height of this obstacle.

Urban meteorological stations often have an above roof station and a street canyon station. Applied to the above roof stations, the WMO restraint can be translated into a measurement height of 10 m above roof level. Surrounding obstacles that exceed the height of the building at which the above roof station is positioned, should therefore be a distance of at least 10 exceedence heights from the measurement point. The mast carrying the sensor should be positioned at the centre of the roof in order to minimise errors due to building effects on the wind vector.

The flow within the street canyon is usually parallel to the street. Street canyon station measurements are nevertheless important, since they determine for which range of above roof wind direction the canyon wind blows in one street direction or the other. Another important parameter is the wind velocity within the canyon in relation to the wind speed above roof level. In order to keep the possible effects of traffic on the velocity signal small, the usual 10 m measuring height seems to be acceptable. The ideal position of the street canyon station would be in the centre of the canyon, but there are other constraints which usually require the street canyon station to be sited to one side of the canyon.

The flow within the canyon is rather complex, most notably when the above roof wind has a component perpendicular to the street direction. In addition the velocity within the canyon is often small. Therefore, sensors are needed which are able to cope with such conditions. At present the preferred instrument is a 3-D ultrasonic anemometer (VDI 3786 part 12, 1994), which monitors the time series of a velocity vector. However even if the velocity measurements in the canopy are carried out with sonics, the data have to be interpreted with care. When as is typical for measurements adjacent to solid walls, the mean wind vector diverges from horizontal, the error in the data might be significant. Helpful suggestions are given in the guideline VDI 3786, part 2 (2000).

Both mean and turbulent velocity components should be calculated and stored. It is also desirable to use the same instrument at the above roof station. The wind measurements at the station above roof level should be complemented by pressure, temperature and radiation measurements.

9.3. The example of Göttinger Strasse, Hanover

As an example of an already existing urban meteorological station, which fulfils most of the requirements given above, the Göttinger Strasse Monitoring Station in Hanover, Germany has been selected. This station maintained by the Lower Saxony State Agency for Ecology (Heits *et al.*, 1991, 1993) has been operational since 1989. The Göttinger Strasse is a busy inner-city street with four traffic lanes. The traffic load is about 30,000 vehicles/day. The width of the street and the height of the buildings alongside the street are both approximately

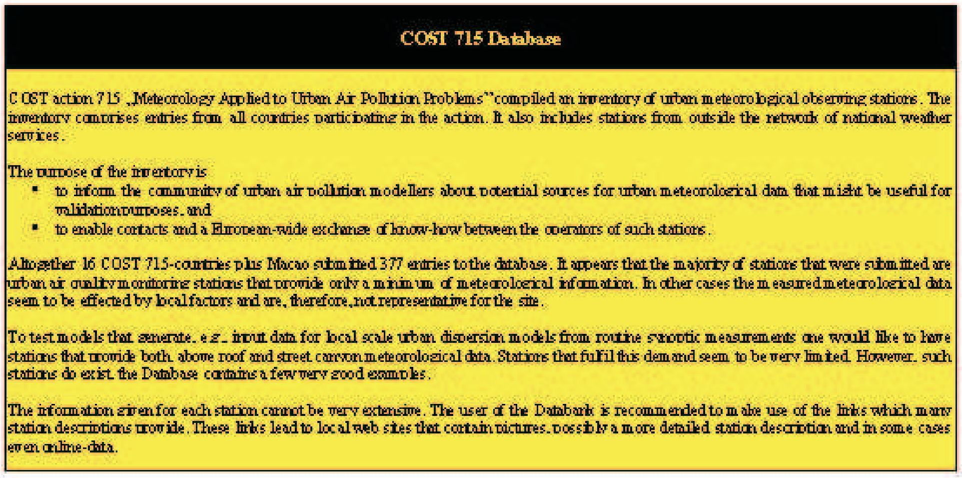
25m. Most of the buildings are attached, thereby forming a street canyon with an aspect ratio of about 1. The orientation of the street canyon is virtually perpendicular to the prevailing wind direction.

The meteorological measurements cover wind direction and wind velocity within the canyon and above the roof (10m above street, or roof level). The wind measurements both at the station above roof level and the street canyon station are made with ultrasonic anemometers, which provide the three components of the mean wind and the turbulent wind velocity fluctuations. Routinely only 30 minute averages are stored, but for special episodes complete time series can be made available. Pressure, temperature, global radiation and precipitation (amount and duration) are also measured (only above the roof). In association with measuring meteorological parameters, air quality data are also collected at the Göttinger Strasse urban meteorological station.

Since large velocity and concentration gradients are typical features of urban canopy layer flows, one would like to test the quality of model predictions not only at a single point. Sponsored by the German Ministry of Education and Science, the research project Development and Validations of Tools for the Implementation of European Air Quality Policy in Germany (VALIUM) was launched which provided the means for a significant increase in the density of measurements, at least for a limited period of time. Within a radius of 500m around the continuous monitoring station, additional measurements have been carried out at several positions using sodar, wind-temperature radar (WTR) and ceilometer instruments. The number of simultaneously operating air quality stations in and around the Göttinger Strasse was increased to seven. In addition to the traffic emission sources, an artificial line source releasing the passive tracer SF_6 was utilised. Last but by no means least, a physical model of the site was built. Experiments were carried out in Hamburg University's large new boundary layer wind tunnel. The field experiments were replicated and the field data generalised and enhanced through laboratory experiments. The objective of the wind tunnel experiments was to close gaps in the data for meteorological situations not met during the field campaigns, and to generate velocity and concentration fields for specific cross-sections, at the same spatial resolution as they are produced by numerical computational fluid dynamics codes. The data were made available to the general public in the summer of 2004 (Schatzmann *et al.*, 2004).

9.4. COST 715 urban meteorological station database

The COST 715 database of urban meteorological stations on the web contains the following introduction, which is reproduced for completeness:


COST 715 Database

COST action 715 „Meteorology Applied to Urban Air Pollution Problems" compiled an inventory of urban meteorological observing stations. The inventory comprises entries from all countries participating in the action. It also includes stations from outside the network of national weather services.

The purpose of the inventory is

- to inform the community of urban air pollution modellers about potential sources for urban meteorological data that might be useful for validation purposes, and
- to enable contacts and a European-wide exchange of know-how between the operators of such stations.

Altogether 16 COST 715-countries plus Macao submitted 377 entries to the database. It appears that the majority of stations that were submitted are urban air quality monitoring stations that provide only a minimum of meteorological information. In other cases the measured meteorological data seem to be effected by local factors and are, therefore, not representative for the site.

To test models that generate, e.g., input data for local scale urban dispersion models from routine synoptic measurements one would like to have stations that provide both, above roof and street canyon meteorological data. Stations that fulfil this demand seem to be very limited. However, such stations do exist, the Database contains a few very good examples.

The information given for each station cannot be very extensive. The user of the Databank is recommended to make use of the links which many station descriptions provide. These links lead to local web sites that contain pictures, possibly a more detailed station description and in some cases even online-data.

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10. Basel UrBan Boundary Layer Experiment (BUBBLE)

Mathias W. Rotach

10.1. Introduction

BUBBLE stands for the 'Basel UrBan Boundary Layer Experiment' and is a research project directly associated with COST 715. Due to special funding conditions in Switzerland in relation to COST activities, the 'core project' was initiated by a number of Swiss research groups active in urban boundary layer meteorology. These include the Swiss Federal Institute of Technology (IAC-ETH and LPAS-EPFL), the University of Basel (the local host), MeteoSwiss and the Observatory of Neuchâtel. As a contribution to COST 715, BUBBLE was funded by the Swiss Federal Office for Science and Education. However during the planning stage of the project, a number of research institutes expressed their interest in joining BUBBLE, so that it soon became a truly international research project (Table 10.1). The Swiss 'core project' mainly covered the continuous long-term observations and many of the supplementary projects during period of intensive observation in the summer 2002 were covered by research groups from all over the world.

The philosophy of BUBBLE is based on the recognition that over complicated and essentially inhomogeneous urban surfaces both the near-surface turbulence exchange processes and the entire boundary layer structure have to be observed at the same time. Often in the past only detailed near-surface observations were performed over urban surfaces, without taking into consideration the larger scales (e.g. Rotach, 1993, Feigenwinter *et al.*, 1999). On the other hand, in studies dealing with the entire urban boundary layer (e.g. Argentini *et al.*, 1999, Menut *et al.,* 1999) the near-surface observations are often missing or very sparse. Only in very recent urban studies, such as ESCOMPTE (Mestayer *et al.*, 2004, see also Chapters 4 and 5 of this report), have similar attempts as in BUBBLE been undertaken in order to combine remote sensing and near surface in situ observations. The main experimental phase of BUBBLE started in summer 2001 and ended in summer 2002. Thus a number of surface sites, a wind profiler as well as an aerosol lidar were operated for roughly one year, yielding not only detailed process information on the urban boundary layer, but also allowing for climatological studies (Christen and Vogt, 2004). Finally, between June 10 and July 10, 2002, an intensive observation period was carried out allowing for additional, more specialised projects within BUBBLE.

Table 10.1: Partners in the BUBBLE experiment

Institution	Country	Area of interest	Responsible scientist(s)
Swiss Federal Institute of Technology, IAC ETH	Switzerland	Scientific co-ordination, near-surface turbulence and pollutant dispersion, wind profiler	M. W. Rotach, H. Richner
University of Basel	Switzerland	Local co-ordination, near-surface turbulence, satellite products	R. Vogt, E. Parlow
MeteoSwiss	Switzerland	Wind profiler	D. Ruffieux
Swiss Federal Institute of Technology, LPAS-EPFL	Switzerland	Numerical modelling	A. Clappier
Observatory Neuchâtel	Switzerland	Lidar	V. Mitev
The University of British Columbia	Canada	Radiative and thermal properties of street canyon	T. R. Oke
University of Western Ontario	Canada	Thermal properties of street canyon	J. Voogt
National University of Singapore	Singapore	Turbulent exchange in the urban roughness sublayer	M. Roth
University of Freiburg	Germany	Urban boundary layer structure	H. Mayer
TU Dresden	Germany	Near-surface processes	C. Bernhofer
Risø National Laboratory	Denmark	Pollutant dispersion, tracer experiment	S.-E. Gryning
Birmingham University	England	Near-surface turbulence, CO_2 exchange	J. Salmond
Hamburg University	Germany	Wind tunnel modelling	M. Schatzmann
National Institute of Meteorology and Hydrology	Bulgaria	Near-surface turbulence and pollutant dispersion	E. Batchvarova
University of Tasmania	Australia	*Instrument provider:* Radiative and thermal properties of street canyon	M. Nunez
Forschungszentrum Karlsruhe	Germany	*Instrument provider:* Near-surface processes	N. Kalthoff
University of Padova	Italy	*Instrument provider:* Near-surface processes	A. Pitacco
Indiana University	USA	*Instrument provider:* urban energy balance	S. Grimmond

The present contribution summarises the observational and modelling strategies within BUBBLE and gives an overview over the first results obtained so far. For more detail the reader is referred to Rotach *et al.* (2004) or to the project's web site (`http://www.unibas.ch/geo/mcr/Projects/BUBBLE/`).

10.2. Description of observational setup

Near-surface sites

Two main urban, one suburban and several rural reference surface sites were set up. They usually consisted of the following components:

1. profiles up to a height larger than twice the obstacle height,
2. urban sites: 6 levels of sonic anemometers (at some of the levels: fast response hygrometers were added), suburban and rural sites: 2 to 3 levels,
3. full radiation balance,
4. additional observations such as mean meteorological observations.

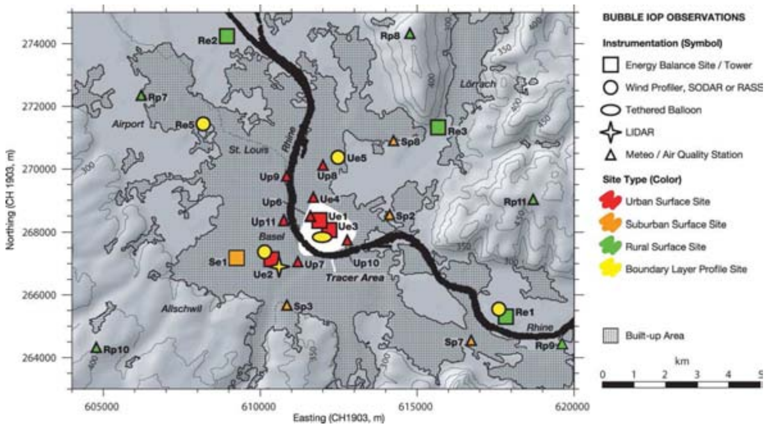

Fig. 10.1: Overview over the BUBBLE observations in the surrounding area of the city of Basel. The thick black line denotes the river Rhine. All other symbols explained in the caption. Note that sites Re4, Sp4, Sp5, Sp6 and Rp6 are outside the domain shown.

An overview of the city of Basel is given in Fig. 10.1, where the sites are indicated. The long-term aspect of the project was guaranteed by operating two of the urban sites (Ue1 and Ue2) for nearly one year. Also rural sites Re3 and Re4 were operated continuously for a whole year, although not equipped with turbulence sensors over that entire period. For the period of intensive observation, June 10 to July 10, 2002, additional urban (Re3), suburban (Se1) and rural (Re1 and Re2) surface sites were set up and operated according to the above overall standards.

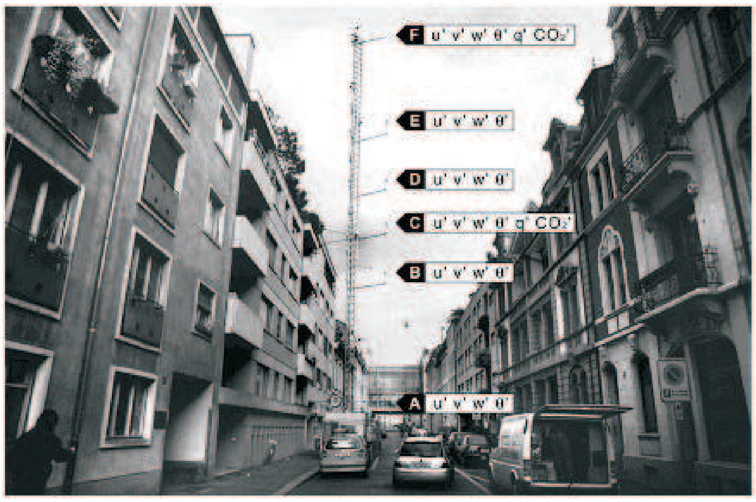

Fig. 10.2: Experimental tower at site Ue1.The arrows indicate the variables measured at the respective levels.

Fig. 10.2 shows the experimental tower at Ue1. Preliminary results on mean profiles of turbulence variables (Christen *et al.*, 2002a, 2002b, 2003a) and flux partitioning over urban areas (Christen *et al.*, 2003b) have already been worked out and presented. An instrument inter-comparison has been performed for most of the sonic anemometers involved prior to the mounting of the instruments. The analysis of this data set was performed in a similar manner as in earlier projects (Christen *et al.*, 2000) and allows for a distinction between measurement uncertainties and true physical differences in the turbulence statistics of interest.

Remote sensing

A wind profiler (pulsed Doppler radar operating at 1290 MHz) was installed at site Ue2 (Fig. 10.3) and measured continuously the profile of the three-dimensional mean wind speed from June 2001 to July 2002 (Ruffieux *et al.*, 2002, Ruffieux and Perroud, 2003). The instrument can be operated in a high resolution mode (first gate at 83m, vertical resolution 45m) or at a lower resolution (first gate at 165m, vertical resolution 400m) and reaches a height of 4300m under ideal atmospheric conditions. It is also possible to retrieve profiles of some turbulence statistics from the profiler observations.

Fig. 10.3: The wind profiler (left) in the backyard of site Ue2 and the lidar (right) on rooftop of site Ue2, both operated during BUBBLE for about one year.

An aerosol backscatter lidar (Martucci *et al.*, 2003) was installed at site Ue2 and continuously recorded the aerosol distribution within the urban boundary layer and aloft between October 2001 and July 2002. Its vertical resolution was of the order of 10m and it technically ranges up to a height of about 19 km. From the aerosol profile observations a surrogate for the mixed layer height (namely the aerosol mixed layer height) can be detected.

In addition to these continuous measurements, two sodars, a RASS and a tethered balloon were operated during the intensive observation period in summer 2002. Two Doppler sodar systems (MFAS, Scintec, Germany) were operated from May to July 2002 (thus spanning the intensive observation period) outside the urban area, in order to monitor the up and downwind conditions of the wind field (sites Re5 and Re1). Both sodars were operated in a multi-frequency mode. This limited the data availability and the reliability of the measurements to heights below 300 m. One system was therefore changed to single frequency pulse mode towards the end of the campaign and then had a data availability $> 90\%$ up to 480 m.

One Doppler sodar/RASS system (MODOS and 1290MHz RASS MERASS, METEK, Germany) was operated in the northern part of the urban area of

Basel (site Ue5) for the period June 6 to July 9, 2002 (i.e. approximately the intensive observation period). Profiles of wind, temperature and some turbulence variables were measured between 40 m and 500 m with a vertical resolution of 20 m.

As part of two of the tracer release experiments (Section 10.2.3), a couple of tethered balloon soundings were carried out in the centre of the city (Ue3). During the first experiment the balloon escaped halfway through, but the second experiment was successful and a 24h period of profiles of wind speed, wind direction, temperature and humidity was sampled.

10.3. Special projects during the intensive observation period

Street canyon energetics
The dense array of long-term measurement systems at the Ue1 canyon site (Sperrstrasse canyon, Fig. 10.2) was designed to gain understanding of the one-dimensional exchange and microclimatic response of this densely developed central urban neighbourhood. During the intensive observation period, aspects of the two- and three-dimensional characteristics of the canyon system, such as the detailed temperature structure, the flux partitioning among various surface exchange mechanisms and the relative contributions to temperature changes due to radiative and turbulent fluxes, were investigated (Aldred, 2003). To accomplish these objectives the canyon instrument array was supplemented by additional thermal and flux sensors and notably a newly developed dual-channel long-wave radiometer (Soux *et al.*, 2003). Most attention was paid to the perimeter of a two-dimensional cross-section across the canyon near the long-term tower. Altogether 41 additional sensors were deployed. The measurements provided information concerning both micro-scale spatial patterns of canyon surface and air temperature and their temporal evolution. A combination of direct and remote measurement systems provided a unique view of urban canopy layer level thermal characteristics not previously available, including the ability to make some assessment of canyon surface emissivities.

Flux exchange between the urban canopy layer and the overlying air
The Sperrstrasse canyon site (Ue1) provided the opportunity to study the exchange of heat, mass and momentum between the canyon volume and the above-canyon flow in more detail than has been previously possible. Therefore two CO_2/water vapour flux sensors were added to the available instrumentation;

one at the top of the mast (at 31.7 m) and another over the street near the top of the canyon (at 14.7 m). With this arrangement it was possible to study the vertical variation of the turbulence statistics and fluxes throughout and just above the roughness sublayer (Christen *et al.*, 2002c, Vogt *et al.*, 2003, Roth *et al.*, 2003a) and their representation within a local scaling framework (Roth *et al.*, 2003b).

Horizontally representative turbulent fluxes are extremely difficult to obtain in the urban roughness sublayer, where the mosaic of rooftop and street canyon surfaces present a particularly complex three-dimensional surface. Little is known about the actual spatial heterogeneity of turbulent fluxes within the roughness sublayer, nor the relative importance of rooftop versus street canyon characteristics in determining the turbulent structure of the urban boundary layer. To address such questions two small aperture scintillometers (Scintec, Model SLS 20) were installed near the Sperrstrasse canyon tower during the intensive observation period (Salmond *et al.*, 2003a, b). One was installed around roof-level at 15.8 m above the street (with an optical path of 116 m, diagonally across the street canyon). The second path of 171 m was located at 19.3 m above ground, which was approximately 3 to 5 m above the variable roof height along the path.

Satellite ground truth
Even with detailed in-situ measurements the radiation balance can only be measured for point locations and not over the whole urban area. However heat fluxes can exhibit a large heterogeneity over urban areas. One option is therefore the application of satellite remote sensing of the solar and terrestrial wavelengths in combination with modelled atmospheric corrections. A first goal of BUBBLE-SARAH (Satellite Analysis of Radiation And Heat Fluxes) was therefore to compute the spatially distributed net radiation as a key factor for heat flux studies. Short-wave reflection and long-wave emission can be computed from multi-spectral satellite data. Solar irradiance and atmospheric counter radiation are integrated from numerical modelling results.

With the available radiation measurements from the many BUBBLE sites, it was possible to compare and calibrate the satellite data with ground measurements (Parlow *et al.*, 2003, Rigo and Parlow, 2003, Rigo *et al.*, 2003, Zecha *et al.*, 2003). Furthermore at site Ue1 a number of specialised supporting observations were performed during the intensive observation period in order to understand better these relationships and possibly improve them.

The BUBBLE tracer experiment
Taking advantage of the wealth of meteorological information available, a series of atmospheric dispersion experiments were carried out. Both the tracer release and sampling sites were located near roof level, above and outside the street canyons. Due to logistic difficulties in a city, tracer samplers cannot be laid out in predefined arrays downwind of the source location according to the prevalent wind direction. Instead arrangements have to be made beforehand, and one must wait for flow conditions which suit the layout. Due to topographical features of the city a thermal wind system develops on cloud-free summer days that creates a north-westerly flow in the afternoon, known as the Clara wind. The experiment was designed to accommodate this thermal wind system.

The experiments were carried out in a fairly homogeneous part of the city near sites Ue1, Ue3 and Ue4 (the white area in Fig. 10.1). The tracer SF_6 was released from the roof of a multi-storey car park at about 1.25 times the average local building height. Samplers were located in a downwind sector subtended by an angle of about 90 ° and at 1.5 m above roof level, typically 15 m above the street. For most of the tracer releases, samplers were located on two approximate arcs at 700 and 1000 m distance from the source. Additionally, a profile along the centreline of the expected plume extended out to about 2.4 km. The release of tracer started 60 minutes prior to the sampling and was kept constant. Sampling was performed in bags, of which 6 were filled in sequence at each location with a filling duration of 30 minutes for each. Thus a time series of 6 half-hourly averaged values of near-roof concentrations is available at each of the sampling sites. Bags were subsequently analysed in the laboratory and a background concentration, measured separately for each release in the experimental area, was subtracted from the analysed concentrations. Reproducibility of the observed concentrations was excellent. More detail about this tracer experiment can be found in Gryning *et al.* (2003) and Rotach *et al.* (2003, 2004). Also an internal report is available (Gryning *et al.*, 2004).

10.4. Modelling

Meso-scale numerical modelling
The observational activities within BUBBLE yielded a detailed data set covering the entire urban boundary layer over several months duration. This probably unprecedented data set is being exploited in order to investigate, validate and improve surface exchange parameterisations of urban areas. Especially

attention has been paid to the scheme of Martilli *et al.* (2002), which takes into account not only the roughness characteristics, but also the modified thermodynamic and radiative properties of an urban surface. While the 'urban modification' in meso-scale numerical models is often restricted to modifying the roughness length (Craig and Bornstein, 2002) or only takes into account the thermodynamic aspects (e.g. Masson, 2000), this approach allows for the assessment of the relative importance of roughness and thermodynamic properties over urban surfaces. Martilli *et al.* (2002) show that this surface exchange parameterisation is able to reproduce many observed near-surface turbulence characteristics and Martilli *et al.* (2003a, b) successfully apply the numerical model in a case study to the region of Athens. First results of this surface exchange parameterisation based on BUBBLE data (Roulet, 2002, 2003, Roulet *et al.*, 2004 submitted) indicate that the Martilli parameterisation indeed reproduces quite nicely the observed characteristics of the near-surface turbulence and flow fields at the site Ue1.

Pollutant dispersion modelling

The dispersion modelling part of the project was clearly related to the tracer experiment. First of all the characteristics of the observed surface concentrations were analysed using similarity approaches (Gryning *et al.*, 2003) as they are employed in operational dispersion models. Using a Lagrangian particle dispersion model, as in Rotach (2001), the tracer release experiments were then modelled in detail. For this, first the available turbulence profiles were analysed (Rotach *et al.*, 2003) and then the pollutant dispersion was simulated (Rotach *et al.*, 2004). The turbulence (input) part of the Lagrangian particle model has been modified in such a way that observed near-surface turbulence characteristics were reproduced. As a preliminary result, it appears from both observations and numerical modelling, that the plume over the urban surface is wider than any of the estimates would yield. Where this additional horizontal spread comes from is the subject of active investigation.

Physical modelling in the wind tunnel

The physical model study for BUBBLE is currently being carried out in the new large boundary layer wind tunnel WOTAN at Hamburg University. The 25 m long facility provides an 18 m long test section equipped with two turntables and an adjustable ceiling. The cross section of the tunnel measures 4 m in width and 2.75 to 3.25 m in height (variable ceiling). For precise probe positioning and automated measurements, the tunnel has a computer controlled probe carriage system.

A detailed aerodynamic model of the BUBBLE test site was constructed (Fig. 10.4). The geometric scale of the model was chosen to be 1 : 300. This scale allows an urban area with a diameter of about 1km around site Ue1 to be represented in the wind tunnel. For the boundary layer flow to adjust to local conditions before entering the core area, the model was extended a further 1km into the prevailing wind direction (330 ° namely the dominating wind direction during the tracer experiments).

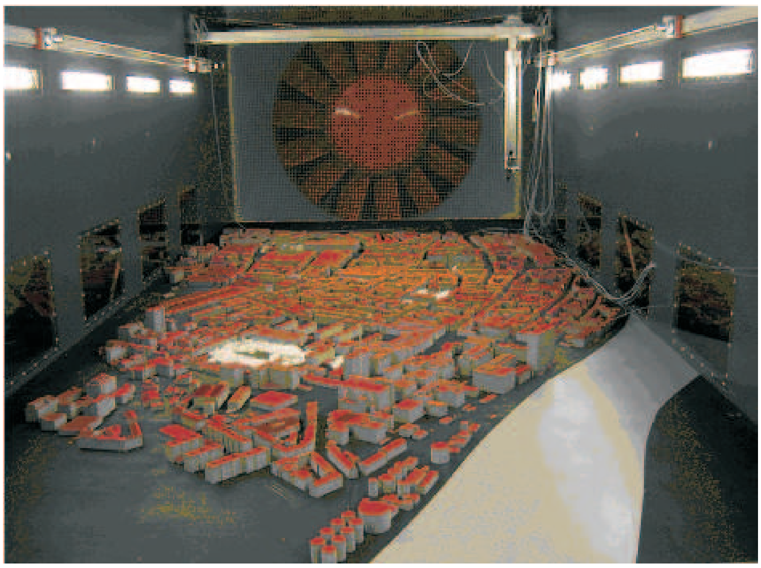

Fig. 10.4 Model of the inner part of the City of Basel in the Hamburg wind tunnel. The white stripe in the foreground corresponds to the River Rhine.

When choosing the geometric scale, one has always to compromise. The smaller the scale, the larger the area covered, but the poorer the spatial resolution in a physical model. With the present choice, buildings of 30 m height have a model height of 0.1 m, which is well above tractable limits. Transferred to field scale, velocity measurements carried out with the laser Doppler anemometer are representative of a volume of about $(0.15\ \mathrm{m})^3$. The spatial resolution of fast flame ionisation concentration measurements is even better. Compared to the resolution of numerical grid models, the measurement volumes can be regarded as small.

For the simulation in the wind tunnel, field episodes with moderate to strong winds were chosen (Feddersen *et al.*, 2003). Under such conditions it can be assumed that the vortices shed by the urban roughness elements are sufficiently intense to establish a well-mixed and neutrally stratified inertial sublayer. Control over the boundary layer structure in the wind tunnel can be obtained by use of specific combinations of vortex generators and artificial roughness elements distributed over the bottom of the flow generation section (upstream of the model domain). At the time of writing this report, the tracer experiments are being simulated in the wind tunnel.

10.5. Conclusions

The overall goal of BUBBLE was to address a number of unresolved issues in urban boundary layer meteorology as emerged from a series of workshops within COST 715 (Schatzmann *et al.*, 2001, Piringer 2001, Piringer and Kukkonen 2002, Rotach *et al.*, 2002a, b).

The philosophy of BUBBLE can be summarised as follows:

1. To provide a long-term data set specifically suited to investigate the meteorological conditions determining pollutant dispersion processes in urban areas. Specifically it was decided that both near-surface turbulence observations and remote sensing boundary layer observations would be made. With this in mind two urban turbulence sites (each with 6 levels), a wind profiler and a lidar monitored the boundary layer in the city of Basel for a period of about one year.

2. To investigate spatial inhomogeneity of features emerging from the long-term observations by establishing many more sites during an intensive observation period of about one month duration. This led to setting up additional surface (suburban and rural) turbulence observation sites as well as remote sensing sites (RASS, sodars, tethered balloon) in the area of Basel.

3. To yield the background meteorological observations for a number of specific research topics in the urban environment. Thus during the intensive observation period specific measurement campaigns were made to investigate urban street canyon energy exchange, exchange of CO_2 from an urban surface, pollutant (tracer) dispersion and radiation properties with respect to satellite retrieval algorithms.

4. To combine full-scale observations with numerical and physical modelling in order to make optimum use of the advantages of these three basic approaches to the investigation of atmospheric processes. Thus not only numerical modelling studies were advanced in parallel to the observations, but also a wind tunnel model was constructed.

5. BUBBLE was probably one of the longest, and most detailed urban boundary layer research programmes. Preliminary data analysis has shown the potential and richness of this data set, as well as the value it will have in advancing the work of devising appropriate turbulence exchange parameterisations, be it for numerical models (including operational weather forecast models) or for air pollutant dispersion models. Due to its close links to COST 715, many BUBBLE activities were tailored to the needs and wishes of scientists within COST 715, and many questions raised in its working groups can be addressed using BUBBLE data or modelling concepts.

10.6. Acknowledgements

The core project was financed by the Swiss Ministry of Education and Science (Grant C00.0068). Additional support for the tracer experiments and the wind tunnel study was provided though an ETH grant (TH 35/02-1). The involvement of the Bulgarian project partner was partly supported through an Institute Partnership financed by the Swiss National Science Foundation (grant 7IP 065650.01) and the analysis of the dispersion data was supported by a NATO Linkage Grant (EST-CLG-979863). The analysis of the satellite data was supported by the Swiss National Science Foundation grant No. 2100-067964. Internal funding of Risø National Laboratory Denmark, the University of British Columbia Canada, the University of Hamburg Germany, the University of Western Ontario Canada, TU Dresden Germany, the National University of Singapore, Indiana University USA and the University of Padova Italy made the participation and contributions of many of the BUBBLE principal investigators possible.

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11. Bilateral co-operation on urban boundary layer studies. Turbulence measurements for urban boundary layer research in Sofia

Ekaterina Batchvarova and Mathias W. Rotach

11.1. Purpose and main features of the experiment

Starting from the collaboration within COST 715[1], a project on turbulence measurements for urban boundary layer research was initiated between the Swiss Federal Institute of Technology, IAC-ETH, Zürich and the National Institute for Meteorology and Hydrology, Bulgaria (NIMH). Through a programme of the Swiss Science Foundation to support the development of up to date equipped research in institutions from Eastern Europe, two METEK ultrasonic anemometers and a KH20 fast hygrometer were delivered to NIMH. The researchers from Bulgaria were introduced to calibration, installation and use of the equipment through participation in the BUBBLE experiment in June and July 2002 in Basel.

Wider dissemination of the activities was reached through the participation in the project of two related institutions from Skopje, Macedonia, namely the Meteorological and Hydrological Institute and the Republic's Authority for Urban Planning.

Figure 11.1: View of the research tower at NIMH. Sonics are mounted at booms 4 m away from the tower

[1] Working Group 1

Within the scientific plan of the partnership, a small experimental campaign was carried out in Sofia in September and October 2003. The sonic anemometers and the fast hygrometer were mounted on the research tower of NIMH at 20 and 40 m height above ground (10 and 30 m above roof level respectively) (see Figure 11.1). The goal of the study was to contribute to the understanding of the complex layer structure of the urban atmosphere. The site is typical of suburban areas in large cities in Eastern Europe with blocks of apartments of different size and configuration, and vast open areas between them. High resolution radiosoundings were performed with Vaisala equipment from NIMH and the sondes were provided by the project (see Figure 11.2).

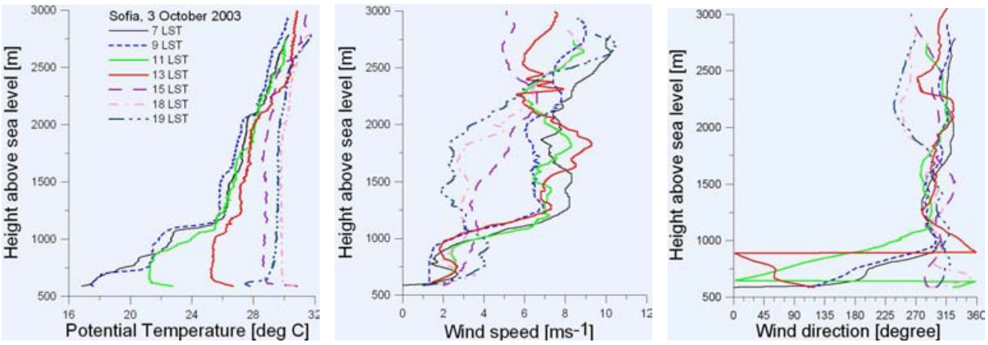

Figure 11.2: Sequence of high-resolution aerological soundings on 3 October 2003. Local summer time (LST) is used. Sunrise is at 7.24 and sunset at 19.06. Potential temperature (left), wind speed (middle) and wind direction (right) profiles are shown.

11.2. Illustration of some results on urban boundary development in Sofia

Days with typical convective conditions were chosen for the campaign. A total of 7 soundings per day were performed providing data for the growth of the mixed layer with a 2 hour time interval. Five days with such conditions were identified in the period 18 September to 8 October 2003.

The data set for the experiment consists of (1) vertical profiles of air temperature, humidity and wind speed and direction from high-resolution radiosoundings, (2) turbulence measurements of wind and temperature at two levels on the tower and humidity fluctuations at the top position, (3) routine meteorological data from the observatory situated at NIMH.

The growth of the mixing layer is clearly seen on the left panel of Figure 11.2 It starts at the ground in the morning and reaches more than 2km in the afternoon. This indicates that on that day the aggregated heat flux that controls the growth of the mixing height over Sofia is large.

The values of the turbulence parameters at both levels were found to show typical urban features. The heat flux and the standard deviations of lateral and vertical wind speed components were clearly bigger at 40 m compared to 20 m above ground level (Figure 11.3). This result shows that the tower is within the roughness sublayer for this type of urban structure and is in agreement with the findings for profiles from the BUBBLE experiment (Rotach *et al.*, 2004).

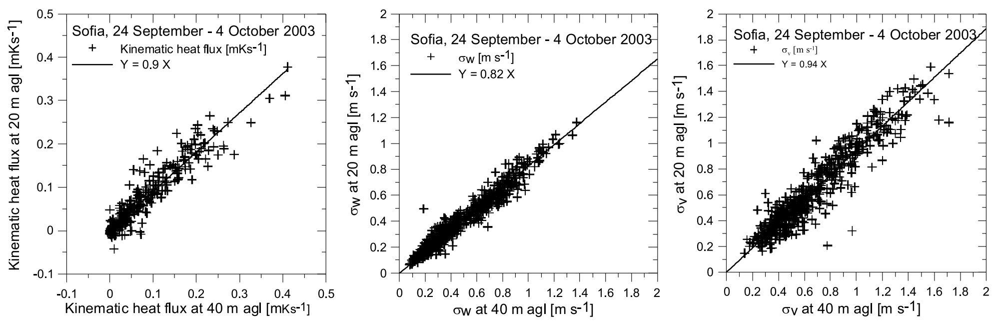

Figure 11.3 Turbulence parameters at both levels: kinematic heat flux (left), standard deviation for lateral (middle) and vertical (right) wind components.

According to our current understanding of the aggregation of fluxes over heterogeneous areas (Gryning and Batchvarova, 1999, Batchvarova *et al.*, 2001), the observed convective boundary layer was considered to be forced by the blended thermal and mechanical fluxes over the area. The site was in the south west part of the city and the urban characteristics and the area which influences it (its footprint) range to about 5 km to the south and east, about 15 km in northerly and about 25 km in westerly directions. Depending on wind direction, the aggregated fluxes represent different percentages of urban conditions.

A comparison of measured and aggregated sensible heat fluxes was performed. The complete description of this topic can be found in Batchvarova *et al.*, (2004). On 29 September and 3 October the aggregated and measured values were close, suggesting that blended fluxes are representing urban conditions in western and north-western weak winds. On the 1 and 2 October, the aggregated fluxes are smaller than the measured, leading to the conclusion that large rural areas east of the measuring site are making a significant contribution to the blended values of the heat flux, while the tower remains within the roughness sublayer of the urban atmosphere. These results show that the Sofia measurement campaign was not only successful in transferring expertise (in this case on urban turbulence measuring techniques) but also resulted in advancing our knowledge of the urban boundary layer for another type of city.

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12. Forecasting Urban Meteorology, Air Pollution and Population Exposure (FUMAPEX)

Alexander Baklanov

12.1. Introduction

The main problem in forecasting urban air pollution is the prediction of episodes with high pollutant concentrations in urban areas, where most of the well-known methods and models based on in situ meteorological measurements, fail to realistically produce the meteorological input fields for the urban air pollution models.

Urban air pollution models in operational urban air quality information and forecasting systems, as a rule, use simple in-situ meteorological measurements which are fed into meteorological pre-processors (Figure 12.1). Lacking an adequate description of physical phenomena and the complex data assimilation and parameterisations of numerical weather prediction (NWP) models, these pre-processors do not achieve the potential of NWP models in providing all the meteorological fields needed by modern urban air pollution models to improve urban air quality forecasts.

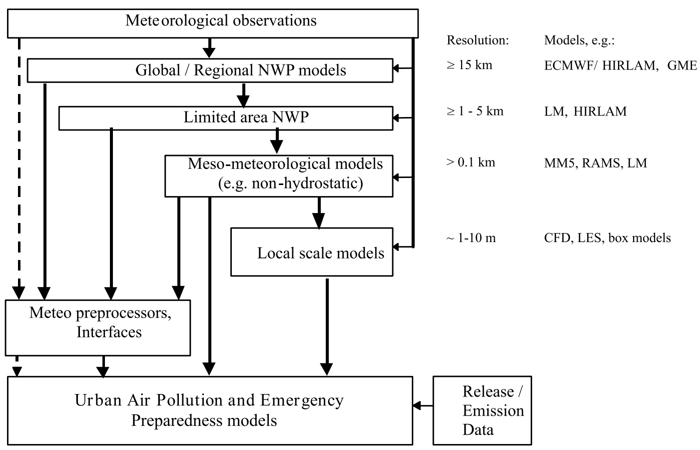

Figure 12.1: Current regulatory (dashed line) and suggested (solid line) ways for systems of forecasting of urban meteorology for urban air quality information and forecasting systems

During the last decade substantial progress in numerical weather prediction modelling and in the description of urban atmospheric processes has been achieved. Modern nested NWP models are utilising land-use databases down to one hundred metres resolution or finer, and are approaching the necessary horizontal and vertical resolution to provide weather forecasts for the urban scale. In combination with the recent scientific developments in the field of urban sublayer atmospheric physics and the enhanced availability of high-resolution urban surface characteristics, the capability of the NWP models to provide high quality urban meteorological data will therefore increase.

Despite the increased resolution of existing operational numerical weather prediction models, urban and non-urban areas mostly contain similar sub-surface, surface, and boundary layer formulations. These do not account for specifically urban dynamics and energy exchange and their impact on the numerical simulation of the atmospheric boundary layer and its various characteristics (e.g. internal boundary layers, urban heat island, precipitation patterns). Additionally numerical weather prediction models are not primarily developed for air pollution modelling and their results need to be designed as input to urban and meso-scale air quality models. Therefore the situation in urban air quality information and forecasting systems is changing and requires a revision of the conventional concept of urban air pollution forecasting.

12.2. Project Objectives and Implementation

In response to the above research needs, a new European Union research project Integrated Systems for Forecasting Urban Meteorology, Air Pollution and Population Exposure (FUMAPEX, web-site: `http://fumapex.dmi.dk`) was initiated within the COST 715 community, and submitted to the Fifth Framework Programme, Subprogramme: Environment and Sustainable Development, Key Action 4: City of Tomorrow and Cultural Heritage. FUMAPEX started in November 2002 and will continue for a period of three years. It is also a member of the Cluster of European Urban Air Quality Research CLEAR (`http://www.nilu.no/clear`).

The main objectives of FUMAPEX are to improve meteorological forecasts for urban areas, to connect numerical weather prediction models to urban air pollution and population exposure models, to build improved Urban Air Quality Information and Forecasting Systems, and to demonstrate their application in cities subject to various European climates. The FUMAPEX scheme for the improvement of meteorological forecasts in urban areas, interfaces and integration with urban air pollution and population exposure models for urban air quality information forecasting and information systems (UAQIFS), is presented in Figure 12.2.

The improvement of urban meteorological forecasts will also provide information to city managers regarding other hazardous or harmful urban climates (e.g. urban runoff and flooding, icing and snow accumulation, high urban winds or gusts, heat or cold stress in growing cities and/or a warming climate). Moreover the availability of reliable urban scale weather forecasts could be of relevant support for the emergency management of fires, accidental toxic emissions, potential terrorist actions etc.

In order to achieve the goal of establishing and implementing an improved new urban air quality information forecasting and information system to assist sustainable urban development, the following steps are being undertaken:

1. improve predictions of the meteorological fields needed by urban air pollution models by refining resolution and developing specific parameterisations of the urban effects in numerical weather prediction models,
2. develop suitable interface/meteorological pre-processors from numerical weather prediction to urban air pollution models,
3. validate the improvements in numerical weather prediction models and meteorological pre-processors by evaluating their effects on the urban air pollution models against urban measurement data,
4. apply the improved meteorological data to urban air quality information and forecasting systems, emergency preparedness and population exposure models and compare and analyse the results, and
5. link meteorologists and numerical weather prediction modellers with urban air pollution scientists and the end-users of urban air quality information and forecasting systems.

The necessary steps are divided in separate, interlinked work packages involving 16 participants and 6 subcontractors (see list below). They represent numerical weather prediction centres, research organisations, and organisations responsible for urban air quality, population exposure forecasts and control, and local authority or city authorities from ten European countries.

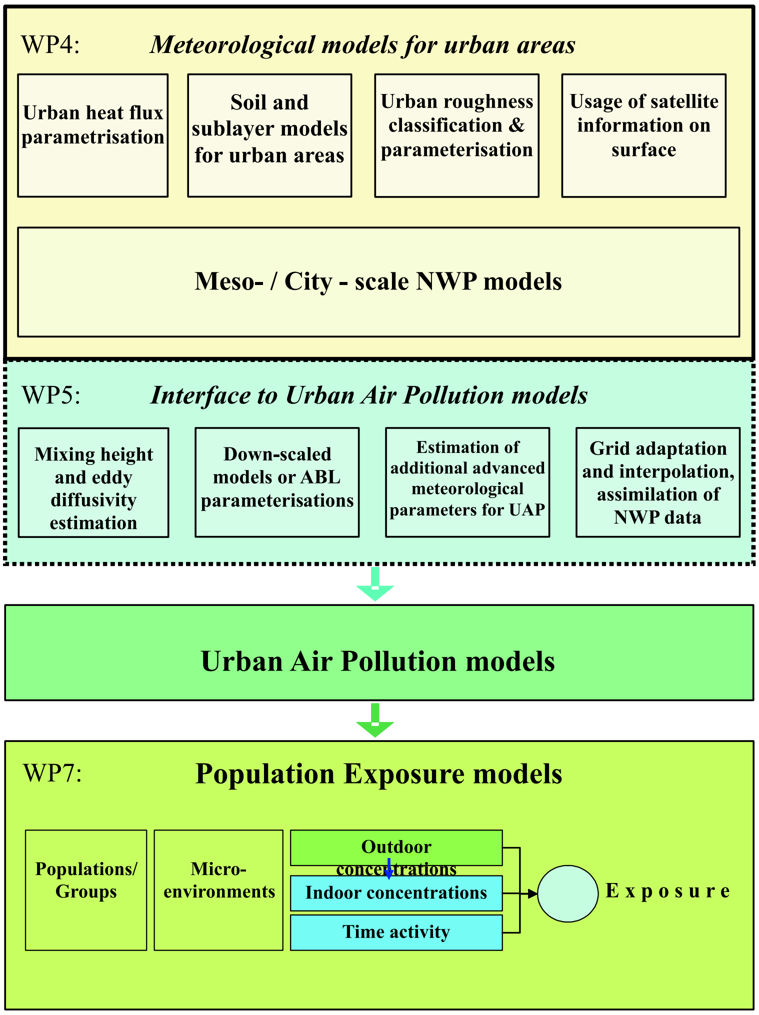

Figure 12.2: FUMAPEX scheme for the improvement of meteorological forecasts (numerical weather prediction) in urban areas, interfaces and integration with urban air pollution and population exposure models for urban air quality information forecasting and information systems.

The work packages consist of:

1. Analysis and evaluation of air pollution episodes in European cities (led by J. Kukkonen, Finnish Meteorological Institute)
2. Assessment of different existing approaches to forecast urban air pollution episodes (led by R.S. Sokhi, University of Hertfordshire UK)
3. Testing the quality of different operational meteorological forecasting systems for urban areas (led by B. Fay, German Meteorological Service DWD)
4. Improvement of parameterisation of urban atmospheric processes and urban physiographic data classification (led by A. Baklanov, Danish Meteorological Institute)
5. Development of interface between urban-scale NWP and urban air pollution models (led by S. Finardi, Arianet, Italy)
6. Evaluation of the suggested system (UAQIFS) to uncertainties of input data for urban air pollution episodes (led by N. Bjergene, Norwegian Meteorological Institute DNMI)
7. Development and evaluation of population exposure models in combination with urban air quality information forecasting and information systems (led by M. Jantunen, National Public Health Institute KTL, Finland)
8. Implementation and demonstration of improved urban air quality information and forecasting systems (led by L.H. Slørdal, Norwegian Institute for Air Research NILU)
9. Providing and dissemination of relevant information (led by A. Skouloudis, EU Joint Research Centre, Ispra)
10. Project management and quality assurance (led by A. Rasmussen, Danish Meteorological Institute).

The project involves the following steps.

Classification of air pollution episodes focusing on relevant meteorological variables

1. Identification and classification of various types of air pollution episodes in cities located in different European climatic and geographic regions.

2. Key pollutants relevant to EU Air Quality Directives and Daughter Directives (EC/96/62; EC/99/30) will be selected for different regions/city characteristics.
3. Classification of meteorological conditions leading to pollution episodes and identification of the more relevant meteorological parameters to define these conditions in various European climatic regions.
4. Compilation and analysis of existing data sets of concentration and meteorological data measured during pollution episodes in different European climatic and geographic regions.

Improvement of the quality of urban meteorological forecasting for urban air pollution and exposure models

1. Improvement of urban weather forecasts and calculation of key meteorological parameters for pollution episodes. A hierarchy of numerical weather prediction models from large-scale global circulation models to local-scale obstacle-resolving meteorological models will be employed (see Figure 11.1).
2. Improvement of boundary layer formulations and parameterisations, and the physiographic data description of urban areas.
3. Development of assimilation techniques with satellite remote sensing data in numerical weather prediction models.
4. Development of interfaces to connect numerical weather prediction to urban air pollution models.

Verification of the improved numerical weather prediction, urban air pollution and population exposure models

1. Evaluation of improved urban meteorological forecast models based on urban air pollution episodes.
2. Estimation of sensitivity of urban air pollution models to uncertainties in meteorological input data.
3. Evaluation of the impact of the improved output of the urban air quality models on simulations of an urban population exposure model.

Application of Urban Air Quality Information Forecasting and Information Systems (UAQIFS) and emergency systems

1. Integration of the improved numerical weather prediction, urban air pollution and population exposure models into urban air quality information and forecasting systems.
2. Implementation of the new improved urban air quality information and forecasting systems in air quality forecasting mode to be applied in four target cities, in urban management or public health and planning mode in one selected target city, and of the emergency preparedness system in one selected target city.
3. The six target cities for testing the improved systems implementations in association with end users are: Oslo (Norway), Turin (Italy), Helsinki (Finland), Castellon/Valencia (Spain), Bologna (Italy), and Copenhagen (Denmark).

12.3. Current Urban Meteorology Achievements

Testing the quality of different operational meteorological forecasting systems for urban areas
The focus of this aspect of the work is on the description of existing forecasting systems and the evaluation of their capability to forecast key meteorological parameters in urban areas. Partners in FUMAPEX use different operational numerical weather prediction (NWP), or research meso-scale models, for providing the meteorological input data for the urban air pollution models in the urban air quality information and forecasting systems. Therefore the tasks comprise:

1. the description and comparison of the selected operational NWP models
2. the harmonised analysis and evaluation of the model simulations with original, and increased model resolution, but unaltered physics for agreed cities and episodes, and
3. the controlled inter-comparison of the simulations of the various models.

These results provide the basis for explaining and quantifying the model improvements planned in subsequent work and also supply useful information to modellers and regulatory authorities. The numerical weather prediction and meso-meteorological models for which 'urbanisation' are considered include: 1. DMI-HIRLAM model (DMI); 2. Lokalmodell (LM) (DWD); 3. MM5 model (DNMI, UH); 4. RAMS model (CEAM, Arianet); 5. Topographic Vorticity-Mode Mesoscale (TVM) Model (UCL); 6. Finite Volume Model (FVM) (EPFL); 7. SUBMESO model (ECN).

A model overview (Fay, 2003) has been completed of operational meso-scale numerical weather prediction models, plus established research meso-scale models used in four European national weather services, one regional weather service, and in many European and international research centres/universities as operational numerical weather prediction models and as input to air pollution modelling. It contains detailed information on all model aspects including information on the different interfaces, or pre-processors, converting the numerical weather prediction output data into input data for urban air pollution models. For an effective comparison of model characteristics, summary tables are provided for all models concerning model scales, initialisation, nesting capabilities, parameterisations and especially turbulence treatment which is a basic requisite for the work of improving and exchanging parameterisations and for some of the interfaces and pre-processors used.

A model comparison design study has also been completed on model comparison and evaluation (Fay, 2003a). It deals in detail with the choice of cities and episodes, and the various theoretical and applied aspects of evaluation methodology for episode, as well as for longer-term evaluation. The choice of cities, the proposed evaluation strategy, and the harmonised use of the GRADS visualisation software and of the MMAS evaluation tool (FMI) have been discussed and agreed upon. Information has been collected on standard numerical weather prediction evaluation and verification in the European CityDelta, ENSEMBLE and AUTOOIL-II projects.

With focus on winter and spring episodes in Helsinki, simulations have been undertaken using the operational numerical weather prediction/meso-scale models HIRLAM, LM, MM5 and RAMS. Results show improvements with increasing model resolution (down to 1.1 km) but the need for adapted external parameters and urbanised parameterisations was apparent. Harmonised model evaluation and comparison was discussed in detail (Neunhäuserer *et al.*, 2004) and will be performed for all target cities.

Improvement of parameterisation of urban atmospheric processes and urban physiographic data classification
The following urban features can influence the atmospheric flow, microclimate, turbulence regime and, consequently, the transport, dispersion, and deposition of atmospheric pollutants within urban areas:

1. local-scale non-homogeneities, sharp changes of roughness and heat fluxes,
2. the building effect in reducing wind velocity,
3. redistribution of eddies, from large to small, due to buildings,
4. trapping of radiation in street canyons,
5. effect of urban soil structure on diffusivities of heat and water vapour,
6. anthropogenic heat fluxes, including the urban heat island effect,
7. urban internal boundary layers and the urban mixing height,
8. effects of pollutants (including aerosols) on urban meteorology and climate,
9. urban effects on clouds and precipitation.

Accordingly the following aspects of urban effects have been considered in improved urban-scale numerical weather prediction models:

1. higher spatial grid resolution and model downscaling,
2. improved physiographic data and land-use classification,
3. calculation of effective urban roughness,
4. calculation of urban heat fluxes,
5. urban canopy and soil sub-models,
6. simulation of the internal boundary layers and mixing height in urban areas,
7. urban measurement assimilation in numerical weather prediction models.

Since these involve many complexities, the FUMAPEX project has decided to concentrate on three main steps, or levels of complexity in NWP urbanisation (Baklanov, 2003):

1. corrections to the surface roughness for urban areas (Baklanov and Joffre, 2003), and heat fluxes (by adding an extra urban heat flux e.g. via heat/energy production/use in the city and albedo change) within the ex-

isting non-urban physical parameterisations of the surface layer in higher resolution NWP models with improved land-use classification. Furthermore an analytical model for wind velocity and diffusivity profiles inside the urban canopy is suggested (Zilitinkevich and Baklanov, 2004).

2. improvement and testing of a new flux aggregation technique, suggested by the Risø National Laboratory in co-operation with DMI (Hasager *et al.,* 2003) for urban areas. Recently this module was coupled to the DMI-HIRLAM model for non-urban areas. The approach can be extended for urban canopies as well. However experimental data are needed to verify parameterisations for urban areas.
3. implementation of special physical parameterisations for the urban sublayer into the numerical weather prediction models. It is planned to incorporate into both the HIRLAM and LM models a new urban module, developed within FUMAPEX, and based on the following two different urban submodels:

   bullet the urban surface exchange parameterisation, developed by the Swiss team, (the model description is given by Martilli *et al.,* 2002);

   bullet the SM2-U urban area soil submodel, developed by the French team, (the model description is given by Dupont *et al.,* 2002).

At the current stage of progress the following examples of 'urbanisation' within models have been completed (Baklanov *et al.*, 2003).

1. Increased resolution and surface data bases for the roughness length calculation in operational numerical weather prediction models have been tested in DMI-HIRLAM, LM, MM5 and RAMS models. For instance, DMI-HIRLAM has been run semi-operationally for Denmark with a horizontal grid resolution of 1.4 km and 1 km land-use classification including 21 land classes and subclasses of urban areas. DWD finalised and successfully tested the LM2LM that provides initial and boundary values of the local model with coarser resolution needed to calculate the LM with higher resolution. Using the LM2LM, three level nested LM forecasts (7, 2.8, 1.1km) have already been performed.
2. Modified parameterisations and algorithms for roughness parameters in urban areas based on the morphometric method are being developed. Urban database analysis for mapping morphometric and aerodynamic parameters is tested using the St. Jerome case study, from the ESCOMPTE experiment (see Chapters 4 and 5).

3. Improved models for urban roughness sublayer simulation, including (i) effective roughness and flux aggregation techniques, (ii) effect of stratification on the surface resistance over very rough surfaces, (iii) roughness lengths for momentum, heat, and moisture have been suggested.
4. It has been shown that the roughness length depends on the atmospheric temperature stratification, new parameterisations for the effect of stratification on the surface resistance over very rough surfaces are suggested. The roughness lengths for momentum, temperature and moisture are different for urban areas. Several possible parameterisations for the scalar roughness length for urban areas have been recommended for urban-scale numerical weather prediction models, but they need to be verified and improved.
5. As the next step in the 'urbanisation' of numerical weather prediction, it is suggested that the urban roughness sublayer is parameterised by the Martilli model. This method is more advanced than the roughness approach, but more expensive computationally in NWPs. This urban sublayer model, which combines the thermal and dynamical effect of the urban canopy, has already been introduced in the TVM model.
6. Experimental studies of urban roughness inhomogeneity effects on the urban boundary layer development has been undertaken by the University of Hamburg and the results have been made available for model verification.
7. EPFL improved the Martilli's module to simplify its introduction in other models and tested it using the BUBBLE measurements. They are preparing the computer code as a separate module, suitable for implementation into numerical weather prediction models.
8. ECN further developed a 1-dimensional, 2-dimensional and box version of the SM2-U model and implemented SM2-U and a simplified Martilli parameterisation in the MM5 model. ECN tests of SM2-U on CLU-ESCOMPTE Marseilles data are in progress.
9. The sea surface temperature data, obtained from an algorithm based on NOAA satellite high-resolution images, have been incorporated by CEAM into the RAMS model. The land categories (from CORINE and PELCOM data sets) have been reclassified following the USGS categories.

Development of interface between urban scale numerical weather prediction and urban air pollution models

The possibility of obtaining reliable air quality forecasts in urban areas depends on the exploiting appropriately meteorological and air quality models' technical features. To reach this objective the communication between models has to be physically consistent and finalised to practical applications. This includes specifically the need to incorporate the improved description of the urban boundary layer introduced in numerical weather prediction models. The main activity has been to identify interfaces: what physical variables have to be processed or estimated, which computational methods are normally used and what kind of improvements are desired to better exploit the new features of parameterisations and 'urbanised' meteorological models that are under development in the FUMAPEX project (Finardi, 2003).

The analysis of typical output parameters of numerical weather prediction models and their comparison with the urban air pollution models identified the necessary main computations to be performed by interface modules and what improvements in the existing software are desirable and can be achieved. Urban air pollution models have been grouped into four classes for which the interface modules have to perform similar processing of meteorological data. The first class includes statistical models, which do not need any particular calculation from the interface system. They simply need to be given single valued meteorological data extracted from the coupled meteorological model.

A more numerous class of simple models includes all the approaches based on a steady state solution of dispersion equation. The models included in this class normally require meteorological data at a single point or possibly a vertical profile. Moreover they normally require evaluation of turbulence scaling parameters.

A third class of three-dimensional models includes all the models based on a Lagrangian description of dispersion phenomena. These models usually need 3-D fields of average quantities (wind, temperature, humidity and possibly turbulent kinetic energy), 2-D surface fields (precipitation, sensible heat flux, friction velocity and Monin-Obukhov length), and 3-D turbulence fields that are usually described by wind variances and Lagrangian time scales. The turbulence describing variables have to be evaluated from mean variables, turbulent kinetic energy or K_H, K_Z and scaling parameters.

The final class includes 3-dimensional Eulerian models. The Eulerian dispersion coefficients (K_H, K_Z) produced by numerical weather prediction models could be directly used by these air quality models. Nevertheless the direct use of dispersion coefficients calculated by NWP models is not always possible or advisable, and therefore interfaces for Eulerian models have often to compute turbulence parameters from mean variables and scaling parameters. This last possibility can also use the meteorological data provided by the numerical weather prediction models, supplemented by high resolution physiographic data, or even observations.

The possible and desirable improvements for each model interface class have been identified in a preliminary way. Progress in the description of urban meteorology and turbulence can be obtained from both the urbanisation of meteorological models and from the improvement of the built-in turbulence models implemented by the interface modules. Progress in this domain will be a critical step in enhancing our capabilities to simulate and forecast urban meteorology and air quality.

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13. The issues of dealing with different scales

Michael Schatzmann

13.1. Introduction

The FUMAPEX project, summarised in the previous chapter, involves numerical modelling on finer and finer scales. This raises issues as to the extent to which the urban problem can be solved by more and more detailed numerical calculations. In this chapter some of these issues associated with limits to numerical modelling are discussed.

In most current numerical modelling, a full treatment of the relationship between the meso-scale and micro-scale flow processes (at the street canyon level) is not undertaken. Instead two-way nesting between the micro-scale (1-1000m) and the meso-scale (1-100km) should be investigated. Validation of meso-scale models has also been limited. For example in the MESOCOM exercise only one idealised hill has been used in comparisons (Thunis *et al.*, 2003).

The issue of comparing grid-averaged quantities and quantities defined at a point, has never been fully resolved. This question of defining representative quantities is a weakness in most previous validations. The representativeness of measurements requires a better understanding of urban footprints. For practical application one is interested in the source-receptor relationship between traffic and people at ground-level. The grid resolution in numerical models is often not sufficient to describe the relationship. Grid independence of results is rarely demonstrated.

The basic assumption used in urban modelling is that the urban boundary layer is in equilibrium. In reality the urban boundary layer is always changing. This issue will be investigated in the new COST Action 728, Enhancing Meso-scale Meteorological Modelling Capabilities for Air Pollution and Dispersion Applications.

Numerical weather forecast models have potential uses when predicting air pollution episodes. They are designed to perform well when predicting temperature, wind and precipitation on the regional scale. However the current generation of models still have some difficulties in predicting precipitation amount, or cloud formation for limited areas. These weaknesses limit the usefulness of such models for forecasting air pollution concentrations. Air pollution episodes are sometimes associated with very stable conditions in specific orographic conditions, which are very difficult to predict.

Refined numerical models sometimes use continuously varying grids. However the turbulence parameterisations applied are the same regardless of the grid scale of the model. In addition to the mis-match between the grid spacing needed to resolve urban flows, which would require more refined grids, there is potentially a mis-match between time averaging periods. Modelling usually refers to quasi-steady situations producing average, or ensemble estimates, which are compared with fluctuating measurements.

The $k - \varepsilon$ turbulence models treating flow around bluff bodies do not perform well. Large eddy simulation (LES) does better. However LES is not generally available in normal urban street calculations. Additionally measurements of dissipation rates (ε) require advanced observing techniques which are not routinely available.

Measurements of urban heat and mass fluxes are not made routinely either, but are undertaken only during special measurement periods. The partitioning of fluxes is not generally available in real time and depends on parameterisations (see Chapter 3 and 4). In practice models are used to assess long-term averages, so potentially some of these errors may cancel out. This has led to interest in ensemble calculations in which the initial and boundary conditions are perturbed leading to a forecast, which is expressed as a probability. Assimilation techniques are also finding favour in order to reduce model errors.

The development of spatially varying internal boundary layers within the urban boundary layer, has not been observed in the field. This is an example of a useful concept, which has not been validated.

Many practical models are simple idealisations, which have been tested on a few streets. This is useful as a way to extrapolating to other streets, as a first approximation. However for street canyons, the buildings roofs are known to affect wind direction, so that one-way downscaling may lead to errors. Not many turbulence measurements have been made above the surface layer, say above 50m. Nevertheless data sets from some tall towers are available and these measurements would need to be analysed in detail in order to provide a better insight into the vertical turbulent structure of the urban lower atmosphere.

13.2. Effect of spatial resolution on numerical model results

Numerical models are frequently used for the simulation of pollutant dispersion within the urban canopy layer. Complex numerical tools for urban dispersion modelling have been developed during the last decade and most of them prove themselves as a more or less adequate representation of reality in terms of the quality of physical modelling of scalar transport phenomena, as well as of the quality and accuracy of the model results. On the other hand comparisons of model results with independent field data, or results of physical dispersion modelling in boundary layer wind tunnels still show significant discrepancies (Schatzmann and Leitl, 2002).

When searching for reasons behind these differences one has to subdivide the problem into two major categories of sources of error. One group is represented by differences due to the simplified physics implemented in numerical models. There is still no generally accepted turbulence model that can be recommended for flow and transport simulation within complex urban canopy layers. The proper consideration of internal boundary layers at building surfaces within a domain is another example of an unsolved problem.

The second group of differences is caused by the limited domain size and the limited spatial representation of the physical complexity of urban sites in numerical grid models. As a result, buildings in the numerical simulation may have flat roofs instead of the actual variation in roof configurations. In addition, building dimensions are adapted to the numerical grid, causing significant differences between the full-scale building dimensions and the numerical representation. Moreover buildings might not be well aligned with the regular structured grid that is commonly used. Oblique street canyons must then be represented by step-like structures that might clearly affect the flow. It is obvious that the uncertainty caused by geometrical simplification of the physical reality may play an important role in assessing the quality of results from numerical models. Even if the physics of numerical modelling might be improved in the foreseeable future, significant geometrical simplifications will still be necessary for practical applications in urban environments.

The following example demonstrates that the problem of spatial resolution is not purely academic. In Fig. 13.1 photographs of two wind tunnel models of the Göttinger Strasse field site in Hanover are presented (see also Chapter 9). The picture on the left hand side shows the detailed wind tunnel model whereas on the right hand side the physical representation of the obstacle array that 'survived' the gridding process carried out in preparation of the numerical model run can be seen. The grid used had about $60 \times 60 \times 30$ grid points (Chauvet *et al.*, 2001). Both configurations were mounted into a boundary layer wind tunnel and tracer gas was released through a line source positioned at ground level in the centre of the Göttinger Strasse street canyon. The (non-

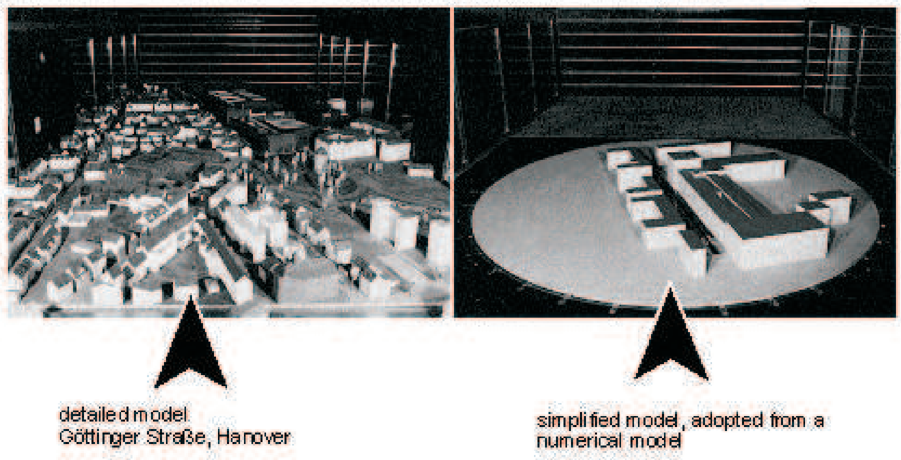

Figure 13.1: Complexity of the building structure of the real site in comparison to the building structure that was accommodated in the numerical model run

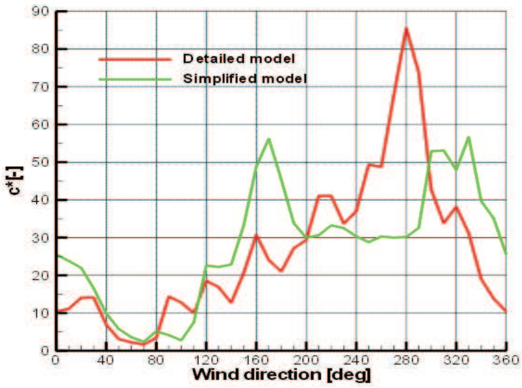

Figure 13.2: Comparison of concentrations measured in the wind tunnel using the detailed and the 'numerically simplified' model under otherwise identical conditions

dimensionalised) concentrations measured at the same receptor point for a variety of wind directions under otherwise identical conditions are shown in Fig. 13.2. As expected, for certain wind directions remarkably different results were found.

Clearly the grid resolution that was chosen at the time the study was made is poor compared with present standards. Even with today's computer power, one has to compromise. Since in the previous run not only the spatial resolution but also the size of the domain was insufficient, a substantial part of the additional computer capacity had to be used for increasing the model area. The spatial resolution would continue to be inadequate.

Another practical problem especially for model applications in urban environments is the uncertainty in choosing inflow boundary conditions that are representative for the site. This is a further serious problem which requires a separate discussion.

13.3. Limits on fine scale in meso-scale models

Clearly one needs to assess the potential of numerical methods and this requires running numerical models. The activities of FUMAPEX (see Chapter 12) will play a vital role in testing pollution transport models on a fine scale. It will permit specific models to be tested at various scales. As is already apparent the meteorological variables are not the only ones for which scaling effects may be important.

In order to describe meteorological phenomena on a smaller scale, there has been a trend in developing non-hydrostatic meso-scale models. Non-hydrostatic meso-scale models are available e.g. ALADIN/AROME, UM, HIRLAM, COSMO, LM, MM5 and RAMS. Models such as MM5 are more commonly employed as meteorological pre-processors for photochemical models, such as CMAQ as part of the USEPA Models-3 System, and have demonstrated their usefulness for air pollution assessment down to spatial resolutions of 1km and temporal resolutions of 1 hour. Other research models which have been similarly employed include MEMO, MESO-NH, METRAS, RAMS and VADIS.

Though meso-scale models developed outside Europe, such as MM5, or its successor, the Weather Research and Forecast (WRF) Model, or similar models, such as RAMS (Regional Atmospheric Modelling System) or TAPM (The Air Pollution Model), address some of the complex situations listed above, these meso-scale models may need adjustment in European pollution calculations based on a model's relative strengths and weaknesses under various conditions. Corresponding tests have only rarely been performed in a harmonised way for the European meteorological models (one example is MESOCOM) and meteorological chemical transport models (e.g. FVM, GRAMM, MESO-NH, MEMO, METRAS, SUBMESO and VADIS). There is, therefore, the need to assess the benefits of coupling more recent meteorological models, such as the UM and WRF, to chemistry transport models for possibly more accurate applications, especially for the urban environment.

The meso-meteorological capabilities of meteorological models are generally not specifically optimised for pollution applications. For example, meteorological models conventionally contain options for treating processes which users must select for themselves e.g. which atmospheric boundary layer parameterisation to use, or the meteorological models may contain implicit assumptions which need to be adjusted for application in Europe. Several meteorological models, such as WRF and RAMS, have a capability to run in a Large Eddy Simulation mode to simulate atmospheric boundary layer processes. Hence it is important to offer advice to less experienced users on how a model should be run. A common framework for employing meteorological models and chemical transport models for European air pollution and dispersion applications would assist all users. The new COST Action 728 will address the issue of making meteorological models, chemical transport models and meteorological chemical transport models accessible to a wider community of potential users. This is an important point as this will be a tangible benefit of this activity.

Although it is important to be aware of the assumptions within models and that reducing grid sizes is not necessarily a solution to the problem of scale, it is essential to try out these tools in real situations to be able to be able to assess their capabilities. As emphasised throughout this report urban applications are especially challenging.

13.4. Chapter References

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Schatzmann, M., Leitl, B., 2002. Validation and application of obstacle resolving urban dispersion models. *Atmospheric Environment* **36**, 4811–4821.

Thunis, R., Galmarini, S., Martilli, A., Clappier, A., Andronopoulos, S., Bartzis, J., Vlachogianni, M., de Ridder, K., Moussiopoulos, N., Sahm, P., Almbauer, R., Sturm, P., Oettl, D., Dierer, S., Schlünzen, K. H., 2003. An inter-comparison exercise of meso-scale flow models applied to an ideal case simulation. *Atmospheric Environment* **37**, 363–382.

14. Achievements and gaps in knowledge

14.1. General remarks

The underpinning purpose of this Action, COST 715 Meteorology Applied to Urban Air Pollution Problems, was to review, assess and contribute to the development of methods for providing meteorological information specifically for urban pollution dispersion and transport models. The urban situation is a major issue as pollution levels are generally highest in urban areas, where the majority of European citizens live (ca. 70%). The critical meteorological challenges relate to routine observations; modelling and pre-processing methods should be tested against a new generation of dedicated measurements. Besides long-term monitoring data can be used to raise awareness of decision-makers in order to define and assess protection measures (e.g. legislative, technical, social). One of the main benefits of meso-scale air pollution models is that they enable predictions of air pollution episodes to be made. Urban meso-scale models also enable a better scientific interpretation of observational data due to their higher resolution and their more comprehensive mathematical treatment of air pollution physics and chemistry.

Another related incentive for COST 715 was the expressed or potential requirement of pollution protection agencies in European countries to be able to forecast and explain why high pollution levels have occurred on a specific day. Although a pollution episode is expressed in terms of chemical concentrations exceeding a specific threshold value, predicting and describing the meteorological situation before, during and after the episode is crucial to the interpretation.

14.2. Achievements

The past years have seen a growth in practical urban measurements in Europe and North America. Results from some of these very extensive measurement sets will lead to improvement in our understanding of urban dispersion. From COST 715 activities, a clear picture of the flow and turbulence structure within an urban roughness sublayer has emerged.

A most important contribution from COST 715 to the problems of spatial inhomogeneity has been the BUBBLE project and its experimental layout in both the full-scale and in wind tunnel measurements. BUBBLE, Basel UrBan Boundary Layer Experiment was probably one of the longest and most detailed urban boundary layer measurement programmes ever undertaken. Due to its close link to COST 715, activities were tailored to the needs and wishes of scientists within COST 715 working groups.

There is a need for an urban reference level z_{refu} for wind speed.[1] It is hoped that wind speeds determined at this height are representative of the upstream urban surface and are not unduly influenced by local factors. This means that they can be used in dispersion models as representative of the urban area. Guidelines for measurements, particularly for urban areas, must be applied intelligently and flexibly, taking account of what is practical and not applying rigid rules. As a working hypothesis, an urban reference level of $z_{refu} = d + 10$ m, where d is the zero plane displacement, was adopted by COST 715. A procedure is described on to how to use our knowledge concerning the turbulence structure within the roughness sublayer to estimate the wind speed at z_{refu} from an observation at another height. We note here that the hypothesis for z_{refu}may not be optimal in environments with large buildings. The suggested procedure on how to estimate wind speed at a reference level from input stemming from any other level, which is presented and tested in Chapter 8, can be used for any other suitable reference level.

A parameterisation of the variation of the Reynolds stress within the roughness sublayer up to the height at which it merges with the friction velocity in the inertial sublayer, has also been proposed. Available full scale measurements have been made to test the parameterisation.

The most striking feature of the energy balance is the magnitude of the storage heat flux, both during the day (positive) and at night (negative). Since the storage heat flux takes such a large share of the available radiant energy, relatively little is left during daytime for the sensible heat flux to warm the atmosphere. Even though urban surface temperatures can be significantly warmer than their surroundings, the heat they inject into the atmosphere may in fact only be marginally higher. This means that the impact of vegetation changes on urban daytime atmospheric circulation patterns may be less important than anticipated.

The situation at night is quite different from that during the day, because after

[1] The World meteorological Organisation will shortly be publishing guidance on urban observations, Oke, T. R., 2004. Urban Observations. Instruments and Methods of Observation Programme, IOM Report, WMO, Geneva in press. See also Oke, T. R., 2004. Siting and exposure of meteorological instruments at urban sites, paper at 27 NATO CCMS International Technical Meeting on Air Pollution and its Application, 24–29 October 2004, Banff, Canada, pp. 339–352.

sunset the city starts liberating this large amount of heat stored during the day. Therefore heat flux values remain positive throughout the night over the city, whereas rural sensible heat flux values plunge towards negative values of a few tens of Wm^{-2}.

A number of European research groups run meso-scale meteorological models with sub-models of fluxes for urban areas. These models are not operational yet, but advances are encouraging. Preliminary simulations indicate that the influence of the urban canopy, buildings energy flows and thermal properties, along with effective albedo reduction by radiative trapping between canyon walls is important and need to be properly described in models.

Meso-scale meteorological and numerical weather prediction models with modern high-order non-local turbulence closures give promising results (especially for the convective boundary layer). However currently the urban effects in such models are at best included using simple procedures.

COST 715 has provided an overview of the main factors that lead to and influence air pollution episodes in 13 countries. It shows the differences in national approaches, but also the common problems.

The Action has also analysed selected episodes in European cities, in relation to prevailing meteorological conditions, local emissions, and regionally and long-range transported background concentrations. In particular, a structured and homogeneous analysis was presented of PM_{10} episodes in four European major cities. A particular aim of those studies was to gain a better insight into the influence of various meteorological variables on the evolution of high pollutant concentrations.

High atmospheric pressure is commonly related with stable stratification. However it does not necessarily lead to extremely stable conditions or strong inversions near the ground level. Regarding episodes of PM_{10} and NO_2, in northern European cities, an elevated atmospheric pressure is probably a necessary, but not a sufficient condition for the occurrence of an episode. The meteorological influence on air pollution in southern European cities is dominant during every season of the year but especially during summer. It is associated with high sunlight intensity, low winds or stagnant high-pressure systems, high air temperature, high stability (low mixing heights), low midday relative humidity, and occasionally thermally driven meso-scale circulations, primarily sea-land breeze. However not all high-pressure systems lead to air pollution episodes.

It was also found that a low wind speed is not necessarily a good indicator of pollution episodes when considering all the European regions. For instance, in the Po Valley, wind speed is a poor indicator, due to frequently occurring calm and low wind speed conditions. The temperature inversion can be recommended as one predictor variable in statistical models, for example, for forecasting the potential formation of air pollution episodes.

National weather services as well as regional and local environmental authorities in all member states participating in COST 715 were asked to provide information on stations located either in city environments or close to urban areas leading to the creation of a data base on the internet, which currently contains 377 station entries. This is a valuable resource for those required to undertake routine urban air pollution assessments.

To test models that generate for example input data for local scale urban dispersion models from routine synoptic measurements, one would like to have stations that provide both, above roof and street canyon meteorological data. Stations that fulfil this demand seem to be very limited. However such stations do exist, and the COST 715 Database contains a few examples. It is hoped that the COST 715 Database will alert the wider scientific community to the limitations of most current urban meteorological measurements.

14.3. Gaps in knowledge

Profiles of turbulence statistics, such as velocity variances, throughout the entire urban boundary layer are essential for pollutant dispersion modelling. As outlined in Section 3.3 no attempts were made within COST 715 to systematically evaluate characteristics of these variables.

Estimating the upwind influence region (footprint) for an observation at a given point is essential to assessing its representativeness for a specified purpose. While suitable footprint models exist in non-urban surfaces, 'urbanised' models still need to be developed.

The internal boundary layer that is built up due to the change in surface roughness and thermal surface properties at the 'edge' of a city or between different city districts, is a concept that is well known from theoretical arguments and observations on much smaller scale than the urban. It is very difficult, however, to thoroughly observe and hence investigate at full-scale.

More measurement of surface fluxes at meteorological stations is desirable, as such measurements have only been undertaken in research programmes of limited duration. Urban meteorological measurements should be performed above the roughness sublayer, in the inertial sublayer, specifically to test the recommended guidelines for the siting of meteorological instruments in urban areas.

For estimation of the daytime mixing height, applying standard rural methods is more acceptable than for the nocturnal mixing height, provided they allow for the urban heat storage as well as changed surface characteristics.

The nocturnal urban boundary layer occurs as a result of the net balance between the negative 'non-urban' surface heat fluxes and positive anthropogenic/ urban heat fluxes, so the applicability of standard methods to stable night-time boundary layer estimation is less promising. The determination of the stable boundary layer height needs further development and verification against urban data.

At present there are no generally applicable theoretical schemes for the interpretation of the data measured in all episodic conditions, such as extremely stable conditions with low wind speeds. These are often amongst the most difficult conditions to predict or forecast reliably. It is therefore essential to develop improved theory and models for this purpose, mainly based on the refinement and urbanisation of existing numerical weather prediction and meso-scale meteorological models, and on meteorological pre-processing models.

Clearly, the refined models need first to be systematically evaluated against sufficient meteorological data. Within the EU-funded project FUMAPEX, the performance of various currently-available numerical weather prediction and meso-scale meteorological models has been systematically evaluated in the course of several selected air pollution episodes. The new COST 728 Action is also expected to substantially improve the scientific tools for understanding the causes and formation of episodes, and for forecasting such cases.

For many of these issues remote sensing techniques have potential. For example, to estimate urban features, such as roughness element distribution and surface thermal properties, remote sensing should be used to develop better representative urban canopies in models. Furthermore remote sensing methods may be more widely used to get representative data over wider city districts than in situ observations are able to do.

15. Conclusions

The Inventory of Urban Meteorological Sites produced within the COST 715 project (`http://www.mi.uni-hamburg.de/cost715/inventory.html`) may be consulted as the starting point to urban meteorological pre-processing. More complex urban relationships are provided in COST 715 publications, but no simple guidance could yet be given on representative urban meteorology for dispersion calculations. Other authors have made practical suggestions[1].

There is a need for an urban reference level z_{refu} for wind speed. As a working hypothesis, the reference level $z_{refu} = d+10$ m, where d is the zero plane displacement, was adopted by COST 715. Although this has the advantage of being similar to the rural definition, it has the disadvantage the risk that the urban reference level might be below or too close to mean roof level (see Section 8.1). Alternatives have been considered but are not generally suitable for practical applications. It is also necessary for urban air quality assessments to be able to estimate wind speed at a given height from observations at any level within the urban roughness sublayer. Based on a literature review and results concerning the general structure of flow and turbulence within the urban roughness sublayer, a procedure was devised by COST 715 (see Section 8.1 for details) to estimate the urban wind speed from observations at other locations than the one required.

It is apparent that to perform practical dispersion calculations within urban areas assumptions have to be made. However given the other uncertainties in dispersion calculations, such as emissions, dispersion, chemical transformation and background concentrations, errors arising from urban meteorology appear may not always be dominant. Incorporating urban factors can improve agreement with measurements. A complete treatment appears to be only possible in a numerical calculation performed with a fine enough resolution to describe urban homogeneities, or by comparison with appropriate physical models. These are currently areas undergoing active investigation.

Other factors which are relevant to pollution dispersion within the urban boundary layer, such as mixing height, are discussed within this report and COST 715 publications listed in Appendix D.

[1] Hanna, S., Britter, R., Franzese, P., 2003. A base urban dispersion model evaluated with Salt Lake City and Los Angeles tracer data, 2003. Atmospheric Environment 37, 5069-5082.

APPENDICES

Appendix A: Definitions of terms relating to the urban boundary layer

Zbynek Jaour

In this section definitions of the key terms used to describe the urban boundary layer area are given. The emphasis is on the key parameters needed by pollution transport models.

Urban atmospheric boundary layer
Schematic representations of the urban atmospheric boundary layer and its components are illustrated in Fig A.1.

Atmospheric boundary layer

The atmospheric boundary layer lies in the lowest 100 to 3,000m of the atmosphere and describes that part of the troposphere which is directly influenced by the presence of the Earth's surface, and responds to surface forcing with a time scale of about an hour or less. The forcing includes frictional drag, evaporation and transpiration, heat transfer, pollutant emission, and terrain induced flow modification.

Urban atmospheric boundary layer

The urban atmospheric boundary layer is the atmospheric boundary layer over an urban area. Its structure, at least in its lowest layers, is modified by the high drag and specific heat fluxes of the urban area, especially their strong inhomogeneity.

Surface layer

The surface layer spans the bottom 10% of the atmospheric boundary layer. Frictional drag, heat conduction and evaporation from the surface cause substantial changes with height of the mean wind speed, temperature and humidity. However the turbulent fluxes are relatively constant with height in the surface layer. Hence the surface layer is also known as the constant flux layer under ideal homogeneous and stationary conditions. The relationships between mean and turbulent parameters are described by the Monin-Obukhov Similarity Theory (MOST).

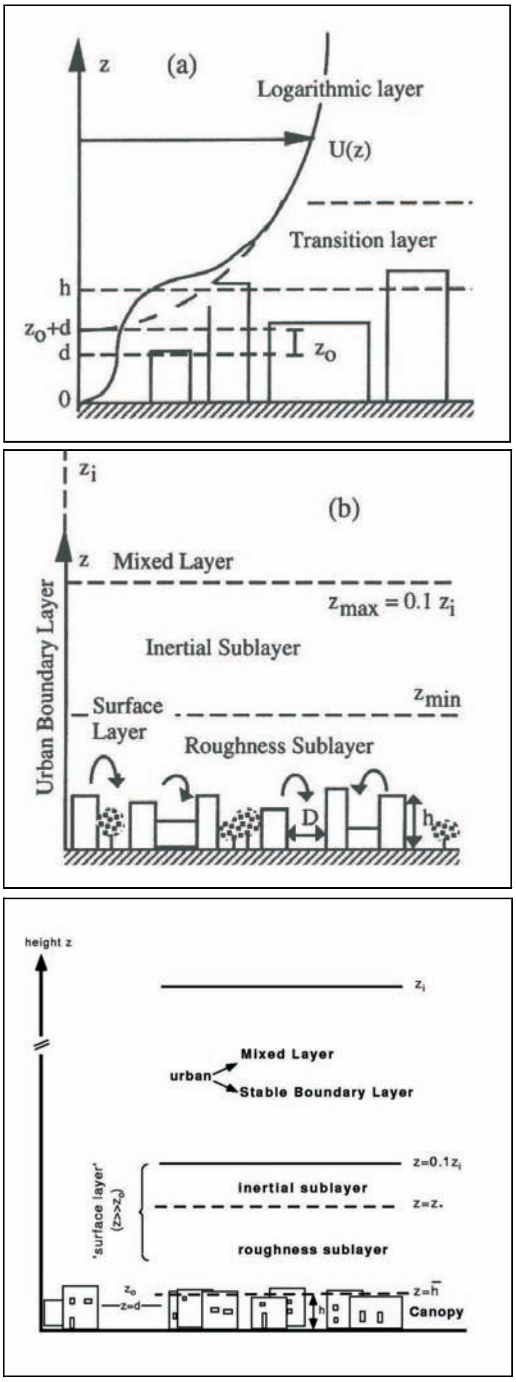

Fig A.1: Schematic representations of the urban boundary layer: (a) after Karlsson (1986), Fochter (1989); (b) after Oke (1988), Rotach (1991), (c) after Rotach(1999)

Urban atmospheric surface layer

The urban atmospheric surface layer is the lower part of the urban boundary layer, up to the approximate altitude of the upwind atmospheric surface layer. Perturbed by the presence of the urban canopy and urban processes, the urban atmospheric surface layer has not usually the structure of a classical atmospheric surface layer in equilibrium, namely horizontal homogeneity and a constant vertical flux. In the urban environment, the atmospheric surface layer is composed of a roughness sublayer beneath an inertial sublayer.

Roughness sublayer

The roughness sublayer is the lowest part of the urban surface layer, where the strong influence of the buildings and roughness elements shape the turbulence properties. In the roughness sublayer which is not in equilibrium, it is not possible to express simply the wind velocity and turbulence parameters by means of Monin-Obukhov Similarity Theory.

Inertial sublayer

The inertial sublayer is the remaining upper part of the atmospheric urban surface layer above the roughness sublayer where surface layer scaling (Monin-Obukhov similarity) applies.

Convective boundary layer

The convective boundary layer is the atmospheric boundary layer under strong insolation, which causes positive buoyancy, enhanced generation of turbulence (as opposed to the stable boundary layer) and thus strong mixing.

Mixed layer

The mixed layer makes up the major part of the convective boundary layer above the surface layer. Within the mixed layer the vertical profiles of most meteorological variables are roughly constant with height due to the intensive vertical mixing.

Stably stratified boundary layer

Under conditions of surface cooling, turbulence is suppressed by negative buoyancy and sustained only by wind shear. Turbulence and mixing are weak and gravity waves can occur. The stably stratified boundary layer is generally the lower part of a surface temperature inversion.

Mixing height

The mixing height is the height of the layer next to the ground over which pollutants or any constituents emitted within this layer, or entrained into it, become vertically dispersed by convection or mechanical turbulence within a time scale of about half an hour (as defined by COST 710).

Internal boundary layer

The internal boundary layer is an atmospheric layer that develops after a change in ground roughness and/or surface temperature. Its height h_{IBL} increases with the distance from the change It includes a lower layer ($h_{IBL}/10$) in local equilibrium with the underlying ground and a transition layer ($9/10 h_{IBL}$) which is not yet in equilibrium, see Figure A.2.

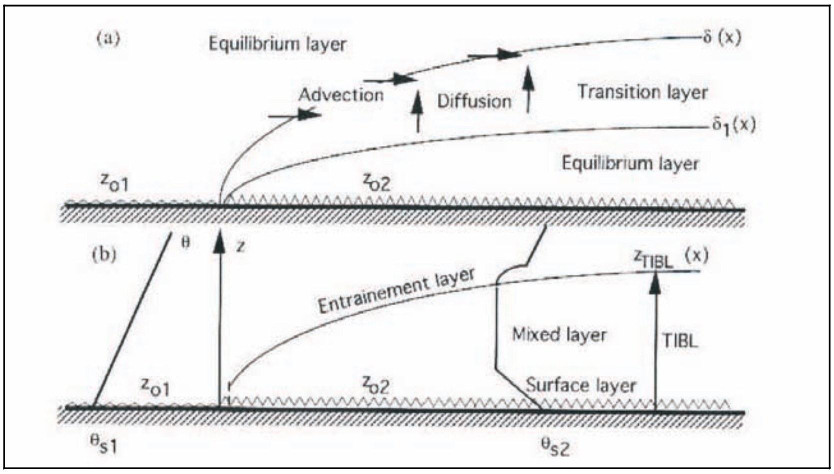

Figure A.2: The development of an internal boundary layer at a transition to a rougher surface: (a) after Hunt and Simpson(1982), (b) after Melas and Kambezidis (1992)

Entrainment layer

The entrainment layer is a transition region between the mixed layer and the stably stratified quasi non-turbulent free atmosphere above. It is characterised by two counteracting processes: the penetration of the most energetic thermals into the stable air aloft, and the downward mixing of air from the free atmosphere into the atmospheric boundary layer.

Urban canopy or urban canopy layer

The urban canopy layer is the air layer that is partly confined by the presence of buildings and other obstacles such as vegetation. The air circulation is partially canalised by the streets. The specific characteristics of the urban canopy are the following.

(i) It is thick, since building heights vary between a few metres in city outskirts and 20 to 40 metres in city centres. A typical canopy height is 30 m.

(ii) It is semi-confined. The basic structures (buildings) have vertical walls, the layer is open to the atmosphere and the interface is ill-defined due to the variability in roof heights and shapes.

(iii) It is complex, partly regular, partly irregular in shape, including various types of natural and artificial grounds and surfaces, also including isolated tall obstacles like towers.

(iv) It is highly heterogeneous in space with regard to the dynamical fields (wind velocity and turbulent diffusion), the radiation and thermodynamics, as well as the production and transformations of the pollutants, all resulting in a high heterogeneity of pollutant concentrations. The typical length scale of heterogeneity, the quarter, is 0.5 km.

(v) It includes many horizontal exchanges, through radiation and ventilation.

(vi) The numerous vertical surfaces may be thermally influenced by reflecting, emitting or shading radiation.

Blending height

The blending height is the height above the ground where the ground inhomogeneity is not perceived anymore, and at which the various internal boundary layers merge into a layer having a quasi-horizontally homogeneous structure.

Quarter

A zone, neighbourhood or district, of a city that presents a certain structural homogeneity (building heights, shapes, densities, arrangements, ground characteristics etc), in a meaning close to the French 'quartier'.

Heat island

The concrete and asphalt in a city absorb and store a large amount of heat in addition to intrinsic urban anthropogenic heat emissions. The heat island describes the increase by several degrees, of the temperature of the atmosphere over the city compared to that of the neighbouring rural area. The effect of the urban heat island on the local circulation is shown in the Figure A.3 below. Warm air over the city rises and cooler air from the countryside moves into the city.

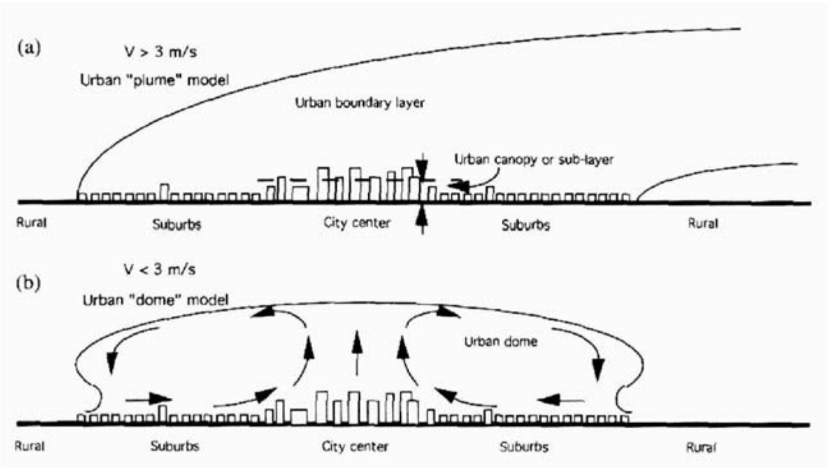

Fig A.3: Schematic representation of the urban heat island in conditions of (a) moderate to strong winds and (b) weak winds

Specific characteristics of atmospheric processes in the urban boundary layer

The presence of the urban canopy generates a series of specific processes, either in the canopy layer or in the urban surface layer, concerning radiation, thermodynamics, dynamics, pollution emission, dispersion and transformations.

(i) Radiation

The urban canopy radiative budget is complex due to the artificial materials covering many surfaces and to the presence of a large number of non-horizontal surfaces. The buildings generate mutual shadowing and radiation trapping (multiple reflections and refractions of solar radiation). As a consequence, individual canopy surfaces present a very high variability in temperature, and the apparent 'surface' temperature of the canopy (as seen from or sensed by the atmosphere) is ill-defined.

Within the streets, in addition to the radiation trapping, high concentrations of gaseous and particle pollutants may transform the radiation budget, such that the photolysis rates may differ markedly from their values in the atmosphere.

(ii) Thermodynamics

Within the canopy, heat exchanges occur between the artificial surfaces, the building walls and the artificial heat sources such as vehicles and heating systems. The assessment of the instantaneous net heat flux, and of the heat storage, over a district or quarter is therefore complex.

Over the canopy, the high differences between the thermodynamics of the different quarters generate local thermal convection motions, quarter breezes when the wind is very weak, thermal internal boundary layers otherwise. Over the whole city, and over the city centres, the urban heat island process is well known. Less well known are the cooling effects over some suburban quarters resulting from the combination of vegetation and water draining systems.

(iii) Dynamics

The flow within the urban canopy layer is partially canalised by the streets, accelerated along the street axis direction and slowed down in the normal direction, resulting in elongated vortex-type flow structures. These structures strongly depend on the geometry of the street volumes. In these partly confined volumes, the differences in wall and ground temperatures may generate thermal convection motions in low wind conditions, that combine or interfere with wind-driven dynamic convection. In addition, the turbulence induced by the vehicle motions may be a non-negligible mixing process close to the ground.

Over the urban canopy layer, the tall buildings may be considered as high roughness elements generating the atmospheric surface drag. Due to their tall height, the roughness sublayer immediately over the roofs, composed of the superposition of the building wakes, has a thickness of about 2 or 3 times the building height z_H.

At a larger scale, the succession of quarters with different dynamic and thermodynamic structures generates a succession of internal boundary layers. Thus the urban atmospheric boundary layer is composed of air layers which are mostly out of equilibrium and strongly inhomogeneous: the canopy layer of thickness z_H, the roughness sublayer with a first blending height at 2-3 z_H, a succession of piled-up internal boundary layer transition layers, eventually topped by a large-scale blending height, and a well-mixed layer. Over the first blending height, an internal boundary layer equilibrium lower layer may eventually be observed, but most often no equilibrium layer is observed.

(iv) Pollution emission

The main source of air pollution in an urban environment is pollution emitted by vehicles, within the canopy, taking into account the available surface concentrations or local background pollution. The evaluation of the actual traffic emission involves aggregating four factors: the emission factors of the various vehicle types, the actual composition and engine state of the vehicle fleet, the actual driving practices, the actual vehicle distribution and flow rates in the area under study. These functions entering in the traffic emission and circulation models are constructed by combining bottom-up and top-down approaches and therefore contain extensive data sets.

The traffic emissions are extremely heterogeneous in space from one street to the other, and even within different portions of a street. They also vary in amount and composition with time due to the rapid changes in personal travel patterns, with a typical time scale of a quarter of an hour.

(v) Pollution dispersion

Four types of interrelated dispersion processes must be taken into account when considering the behaviour of vehicle pollutants, their measurement within streets, and their fluxes to the atmosphere. After release from exhaust pipes, the pollutants are entrained in the vehicle turbulent wakes, which may accelerate mixing. The partly canalised horizontal air circulation within the canopy transports pollutants from one street to the neighbouring streets. The street ventilation transports pollutants upwards from the most polluted layer at the pedestrian or vehicle level to the less polluted parts of the canopy, and eventually to the canopy-atmosphere interface, and transports downwards the local background pollution. The interaction of the flow and turbulent field within the lower atmospheric layer over the roofs with the turbulent flow structures in the canopy determines the pollutant fluxes at this interface. Furthermore the turbulent fields in the urban atmospheric boundary layer play a key role in the mixing of pollutants from different sources and different quarters, and their further incorporation into the local background pollution in downwind quarters, especially in relation to ozone availability.

(vi) Pollution transformation

The chemical transformations within the canopy in the gaseous phase concern essentially the NO-NO_2 conversion system via ozone and peroxy radical reactions. For particles, condensation of water vapour, coagulation and dilution of the exhaust plume and heterogeneous processes between gas and particles may be important, as well as dry deposition and re-suspension. Immediately over the canopy, all the faster reactions of the high NOx urban photochemistry become important, leading to the major process of ozone chemical destruction.

Investigation tools

The present knowledge of the urban boundary layer is based on:

(1) Wind tunnel and water tank simulations which allow studies of flow and dispersion around special arrangements of buildings and structures. Only a few experiments include systematic studies with parameter dependence.

(2) Full scale measurements using in situ measurements may consist of single point or single station data sets. Remote sensing techniques provide a very useful tool for line- or volume-averaged and high resolution investigation of the evolution of the urban boundary layer. Useful instrumentation include sodars and lidars.

Sodar can provide high resolution information about the wind fields and thermal structure of the urban boundary layer over a maximum range of 800–1000 m. Lidar has the capability of several scanning patterns (vertical, horizontal and 3-D scans). Backscatter lidar is very useful for studying the evolution of the convective boundary layer, and the profile of the internal boundary layer above the city. The maximum range of lidar is several kilometres. Best matching schemes between aerosol structures can be used to determine wind fields remotely.

(3) Numerical studies can include various types of numerical models which are distinguished by their different spatial/temporal resolution, chosen to handle or exclude specific phenomena or features. By numerical model, it is generally understood a piece of software allowing one to simulate an ensemble of processes taking place in (or in a part of) the urban atmosphere. It is usually structured into individual modules and includes sub-models and parameterisations for individual processes and relationships, often reflecting conceptual models (as for example in Monin-Obukhov Similarity Theory). Large models may be model systems in which the modules are individual models of their own. They include:

Computational fluid dynamical predictions of the flow and concentration field (over scales of order 2–2000 m). The flow over urban area is similar to the flow over a rough surface with a large roughness length z_0 and a defined surface heat flux (details of the surface structure do not greatly influence the transport and diffusion). The internal boundary layer development along the wind direction can be simulated.

Submeso-scale models (over scales of order 0.2–20 km) to study the interactions of the city fabric and urban sources of heat and pollution with surrounding orography. In meso-γ scale models the urban canopy structure is replaced by a surface composed of a patchwork of homogeneous neighbourhoods, for which specific wall laws have to be defined. In canopy-scale models, high resolution and complete turbulence models of the in-canopy flows are resolved with atmosphere exchanges as a function of building geometries and surface temperature.

Meso-scale models (over scales of order 2–200 km) for the prediction of the air flow and dispersion at the regional scale without details, above roof level. They simulate perturbations induced by large cities on the meso-scale climatology, such as the heat island radiative and energy budget.

Appendix B: Published work related to COST 715

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Appendix C: Field experiments stimulated by or co-ordinated with COST 715

- BUBBLE (Basel UrBan Boundary Layer Experiment)
  See chapter 10 and http://www.unibas.ch/geo/mcr/Projects/BUBBLE/
- ESCOMPTE model intercomparison
  `http://medias.obs-mip.fr/escompte/exercice/HTML/overview.html`
- Cracow and Katowice urban measurement programme
  See Godlowska *et. al.* (2004).
- Sofia urban boundary layer experiment
  See Chapter 11.
- Bologna field experiment
  See Chapter 4, Bonafè *et al.*, (2003), and Deserti *et. al.* (2003).

Information on the ESCOMPTE modelling exercise

The European campaign ESCOMPTE took place in the Marseille region in the south of France. Besides the chemical and physical understanding of pollution episodes, this campaign aimed at the validation of existing models dedicated to pollution analysis, scenarios and forecast, by establishing a appropriate high quality three dimensional data base from emissions, transport and air composition measurements during urban photochemical pollution episodes at the meso-scale:

(`http://medias.obs-mip.fr/escompte/maquette/pagef.php3`).

The measurement (ground-based platforms, profilers, balloons and aircraft) campaign was scheduled between June 4 and July 16, 2001 (ESCOMPTE intensive observation period days). During this period, four episodes of 3 to 4 days were documented which represent more than 30% of the ozone pollution days in this region. The measurements are associated the following interesting features:

- an urban area of one million inhabitant surrounded by various summits,
- an large industrial area (refineries, power plants etc.) which interacts with an extended rural zone. It is separated from the agglomeration of Marseille by the Estaque hills (300m), and is located 15 km north-west of Marseille, around the Etang de Berre,

- strong biogenic emissions over the extended rural zone,
- favourable meteorological conditions for air pollution events (hot and sunny regions).

Model evaluation and validation is a key element in the determination of the reliability of models and their results. Such a model evaluation and validation study can be performed by comparing model results with observations and by inter-comparing results from different models. The ESCOMPTE model inter-comparison project aims to evaluate the meteorological fields and ozone budget prediction from regional meteorological or/and air chemical transport models. However the goal of these project is less to rank modelling systems according to specific performance, but rather to establish uncertainties in processes involved in photochemical ozone production and provide pointers for future research and studies in air pollution modelling.

Full participation in the exercise involved modelling all the ESCOMPTE intensive observation period days (around 20 days) but partial participation (simulation of only few days or only some of the observation systems) was also encouraged.

The evaluation strategy should ideally allow an independent evaluation of the different model sub-systems. In particular, differences in transport patterns and meteorological parameters (temperature, humidity, wind field, atmospheric boundary layer height, radiation etc) can be evaluated independently of the chemical fields. Thus three groups of compounds or parameters are defined according to the experimental data sets:

- the meteorological variables, especially focused on the wind fields,
- ozone concentrations,
- other species concentrations and processes linked to the ozone budget.

For each intensive observation period days, the procedure required two types of simulation:

- free runs where participating groups have the complete freedom of choice of parameterisation to treat physical and chemical processes, grid resolution and input data,

- forced runs where all models involved use the same grid resolution in the horizontal, as well, as boundary conditions and meteorological input data concerning the chemical part of the exercise.

The use of data assimilation was excluded because the observed and predicted meteorological fields were required to be independent.

Participating modelling groups were able to use their own meteorological driver or data sets. For those who require meteorological data, the ALADIN/ ARPEGE (`http://www.cnrm.meteo.fr/aladin/`) data with a spatial resolution of 0.1° have been made available on the ESCOMPTE domain by Meteo-France to interested participants for the intensive observation period days and one day before for spin up.

For a correct interpretation of the results, all the participant model groups would have to use the similar regional emissions. The emission inventory used in the ESCOMPTE project and provided for this exercise, was prepared by AIRMARAIX (air quality network) in collaboration with ARIA Technologies, MVA Consultancy and ENSIACET. The anthropogenic and biogenic emissions inventories and the methodology used, is detailed in AIRMARAIX/LPCA (2003). The land-use class and soil parameters were also given to participating modelling groups who did not have their own data base.

For the models that do not produce their own boundary conditions, boundary concentrations were prescribed for photooxidant formation over longer lifetimes using a numerical simulation with hourly data from the chemical transport model MOCAGE with horizontal resolution of $0.08^\circ \times 0.08^\circ$ and 47 vertical layers up to 5 hPa. Among the complete list of MOCAGE model species, a selection of gas RACM (Stockwell *et al.*, 1997) for the troposphere, and REPROBUS (F. Lefèvre *et al.*, 1994) for stratosphere) were available to the participants.

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Appendix D: List of COST 715 reports

(1) Surface energy balance in urban areas. Extended abstracts of an expert meeting, Antwerp 12 April 2000, COST report EUR 19447.

(2) Preparation of meteorological input data for urban site studies. Proceedings of the workshop 12 June 2000 Prague, COST report EUR 19446.

(3) Meteorology during peak pollution episodes. Working Group 3 status report. COST report EUR 19448.

(4) Workshop on urban boundary layer parameterisations. Extended abstracts. Zurich 24-25 May 2001. COST report EUR 20355.

(5) Mixing height and inversions in urban areas. Proceedings of the Workshop 3-4 October 2001 Toulouse. COST report EUR 20451.

(6) The urban surface energy budget and mixing height in European cities: data, models and challenges for urban meteorology and air quality. Final report of Working Group 2 COST-715 Action, (Eds Martin Piringer and Sylvain Joffre), ISBN 954-9526-29-1, Demetra Ltd Publishers, Sofia, 2005, 239 p.

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Surface energy balance in urban areas. Piringer M. (editor), Extended abstracts of an expert meeting, Antwerp, Belgium, 12 April 2000, 2002. COST 715 Meteorology applied to urban air pollution problems. Report EUR 19447, 103pp., Office for Official Publications of the European Communities, ISBN 92-894-1413-8.

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Appendix E: Web addresses:

COST715 http://www.dmu.dk/atmosphericenvironment/cost715.htm

Working Group 1
http://www.iac.ethz.ch/en/research/cost715/cost715_2.html

Working Group 2 http://cost.fmi.fi/wg2/

Working Group 3 http://cost.fmi.fi/

Working Group 4 Urban Meteorological Station Survey
http://www.mi.uni-hamburg.de/cost715/form.html

Urban Meteorological Station Survey Results
http://www.mi.uni-hamburg.de/cost715/

Appendix F: A perspective from Macao on the achievements of COST Action 715 – Meteorology applied to urban air pollution problems

Antonio Viseu[1]

Since 1999 when Macao, a non-COST country organization, started to participate in COST Action 715, a great deal has been learned from the experts who made up this Action. The Meteorological and Geophysical Bureau of Macao, is a small meteorological institution located in the southern part of the vast Asia continent. Macao is subject to the influence of the air pollution, which is a major concern of China itself.

At the beginning of its participation in COST Action 715, Macao was monitoring air quality with automatic analysers located strategically at different points of the city. With the knowledge and contact acquired during the participation in the meetings and working groups of COST Action 715, we realised that Macao was going in the right direction in the operation of its air quality monitoring.

The natural evolution was also to provide air quality forecasts with the inputs from meteorological parameters and the measured concentrations of different pollutants in the Macao region. With the inputs from COST Action 715, Macao started to provide air quality forecasts, firstly jointly developed with Macao University, using a neural network forecasting system, then with the ISCST industrial model, using statistical and extrapolation methods linked to forecast meteorological conditions. All these models are running with the fully support from products and experience of the staff in the forecasting field.

The major role from the participation in COST Action 715 is the bringing together of experts in the European area, and their contribution and collaboration, to benefit the work of Macao in the area of air quality monitoring and forecasts. The other major contribution is the co-operative spirit among members and Macao, which is fully demonstrated in the course of the Action.

Major benefits to Macao from the participation in COST Action 715 are:

1. Technical and scientific co-operation among Macao and the participating EU members.

[1]Meteorological and Geophysical Bureau of Macao

2. Technical and scientific knowledge and information deriving from the participating members.

3. Software on air quality models that can be adapted for using in Macao area (German AUSTAL2000 model).

4. Experiences gained in the preparation of meteorological and air pollution data sets for the analysis and forecasting of air pollution episodes.

5. A pool of experts from EU in the area of air pollution meteorology that Macao can consult and exchange experiences.

Summarizing, the participation of Macao in this forum of the European Scientific Community is a necessity for the future independent development, not only of the meteorological service, but also for the expertise of its staff members.

Appendix G: List of participants

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Appendix H: Acknowledgements

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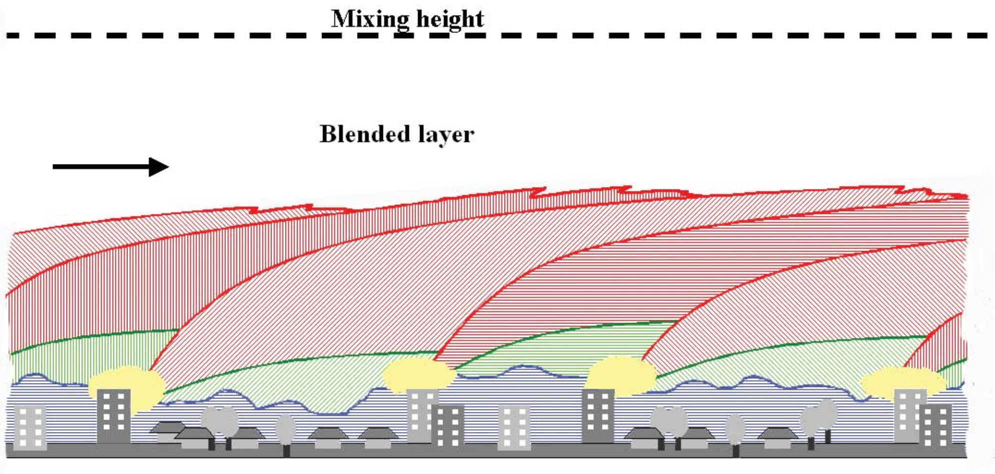

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