METEOROLOGY APPLIED TO URBAN AIR POLLUTION PROBLEMS

Final Report COST Action 715

Editors: Bernard Fisher, Sylvain Joffre, Jaakko Kukkonen,
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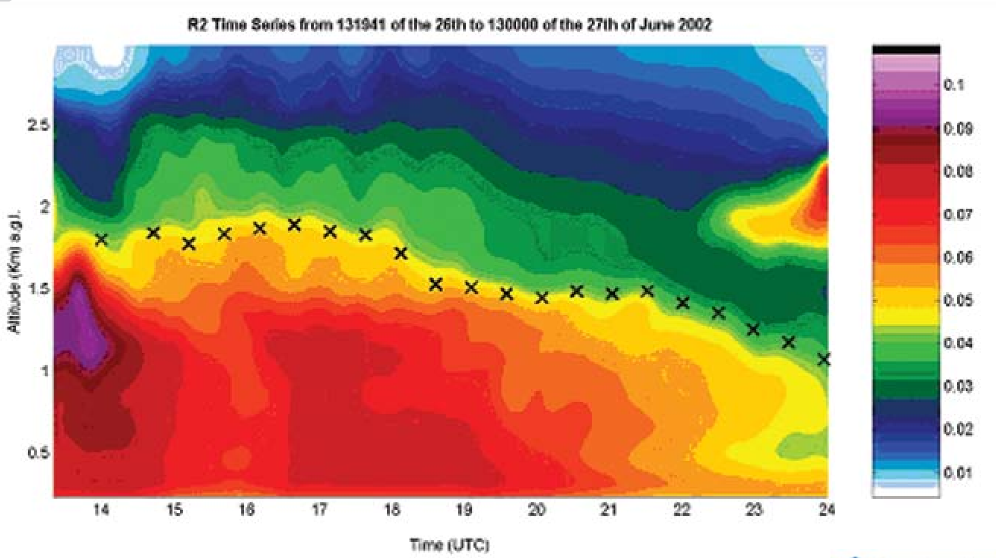

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COST – the acronym for European **CO**operation in the field of **S**cientific and **T**echnical Research – is the oldest and widest European intergovernmental network for cooperation in research. Established by the Ministerial Conference in November 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.

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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 Práger, 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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