Preparation of Meteorological Input Data for Urban Site Studies

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1. Introduction

Many European cities suffer from the similar problems that originate from a high number of inhabitants living in relatively small area. The population density is very high in urban areas and is accompanied by a great concentration of industry and traffic. Industry and traffic, mainly car traffic, is associated with air pollution that degrades the urban environment. The behaviour and spatial distribution of air pollution depends on meteorological conditions, especially processes within the urban boundary layer (UBL). Meteorological data that would characterise processes within the UBL differ from meteorological data measured in a standard way and very often they are not available because there is only limited number of meteorological sites in the cities where these data are measured. More frequently it is possible to find out these measurements located in the airports that are far from city centres and do not provide us with necessary information about the state of the boundary layer in the city. The situation becomes even more complicated when a city is located in an area with complex topography. Presented paper tackles some of the above mentioned problems and it is possible to divide it into three issues.

One issue of this paper deals with the alternative approaches proposed in some countries. This was considered at a COST 715 Workshop on the Preparation of Meteorological Input for Urban Site Studies (Schatzmann, Brechler and Fisher, 2000). The most sophisticated approach can be characterised as one using some appropriate urban scale models nested within larger meso-scale models. In principle these methods can take account of the impact of terrain irregularities, changes in the surface roughness and surface heat fluxes within urban areas. Possible problems concerning this approach deal with the resolution of the nested models – they may not be fine enough in order to resolve features affecting dispersion – and the ability of this numerically demanding approach to produce a climatology of dispersion statistics required by dispersion modellers. These difficulties would become less important with increasing of computer power but they still remain at the present time. This approach has been widely adopted in European countries to predict pollution episodes for which synoptic conditions is the main driver (see Section 2).

Another approach is based on the use of measured surface wind data or prescribed wind data and by various techniques such as optimisation or by using a dynamic wind flow model to generate information on a wind field at a high resolution appropriate to the topography of the city. Several examples of these so-called dynamic ‘down-scaling’ methods were presented at the Workshop and can be divided into two groups.

The first one (Kerschgens *et al*, 2000) based on variational techniques utilises measured wind data both at the anemometer level (10m above terrain) and data from radiosonde ascents. This method can supply users of dispersion models with data that in case of not too complex orography could be close to a desired wind climatology (the calculated distribution of the wind from all sectors of the wind rose) in locations where this information is needed. The large scale forcing (the measured upper level wind, for example) can be given a weight and some other weight can be given to the near surface measured wind, so that the weights are normalised to unity. In this way the local conditions (orography) is reflected in the calculated wind roses as well as the large scale forcing. It is necessary to emphasise that this method has some shortcomings that mainly arise from the impacts of the unresolved (sub-grid) local irregularities, or from too few direction classes in the calculated wind distribution. This approach enables wind roses to be computed in the locations where they are needed. These wind roses would reflect both local orographic conditions and the large scale forcing but are not real wind climatologies, but are synthetically created wind roses that would ideally be similar to real measured wind roses.

The second group of ‘down-scaling’ methods presented in the Workshop (Baumueller, 2000 or Brechler and Janousek, 2000) can be characterised as being based on the utilisation of some kind of dynamical model, such as a mass consistent wind field model in the case of wind field diagnostics. This approach consists of calculating a wind field from data utilising output of some larger scale (meso-scale) prognostic model or from an upper level (above the UBL) wind field obtained from the nearest radiosonde ascent. This information is used in the initial iteration. Measured ground-level winds, if available, can be used to tune the computed wind field to the observed one. An example of this method (Baumueller, 2000) was given for the city of Stuttgart. This method is suitable, firstly of all, for computing instantaneous wind field distributions, which reflect all the main local terrain features in the wind field deformation. This approach also enables one to compute synthetic wind roses but these wind roses do not reflect the real wind climatology or dispersion statistics of the place where they are computed and the same reservation applies as in variational methods.

The second issue is the current status of methods used to define the meteorological conditions under which dispersion within urban areas takes place. In most European countries the same approach as that adopted in rural areas is adopted using the meteorological conditions observed at the standard height at a nearby airport. The assumption is that these meteorological measurements are representative of the urban area. In cities associated with complex topography some form of 'downscaling' is used to define a more realistic wind field.

These approaches are adopted in the absence of any widely accepted description of the lower part of the UBL. The third issue concerns new concepts regarding the structure of the UBL which are being developed based on the current approaches used in rural areas. This is not an easy task because of the small scale variations in the urban surface layer, but approaches have been proposed. These suggest ways of describing the UBL wind profile (Rotach et al., 2000) and the surface heat flux and thermal stability of the UBL (Grimmond and Oke, 2000) in terms of a few readily available parameters. Finally these methods need testing at full scale and two measurement programmes are briefly described.

2. Meso-scale Models

A COST 715 report on Meteorology during Peak Pollution Episodes has been produced, which surveys the national situation in each country (http://www.fmi.fi/index.html) and demonstrates that the approach to predicting peak pollution episodes in the main urban areas of European countries is broadly similar. The methods for dealing with episodes rely on numerical weather prediction models of various scales to predict weather conditions some days in advance and urban scale dispersion models to predict urban air quality one or two days in advance. Taking Norway as a specific example, the weather prediction modelling system is built on HIRLAM (High Resolution Limited Area Model) run operationally at the Norwegian Meteorological Institute (DNMI http://www.dnmi.no/eng_index.html). A version with 50km resolution (HIRLAM50) in the horizontal and 31 layers in the vertical covering a large part of the Northern Hemisphere is run twice per day. A fine scale version of HIRLAM with 10km horizontal resolution (HIRLAM10) is also run twice per day for north west Europe and the adjacent seas. Both models incorporate meteorological measurements and boundary values taken from the ECMWF global model.

The non-hydrostatic MM5 model (Fifth Generation NCAR/Penn State University Meso-Scale Modelling System) is nested within HIRLAM10 with two nests. The outer nest has a 3km horizontal resolution covering south-east Norway and the inner nest has a 1km resolution covering Oslo. MM5 is a non-hydrostatic terrain-following sigma-coordinate model designed to simulate or predict mesoscale and regional scale atmospheric circulation (http://www.mmm.ucar.edu/mm5). Sigma surfaces near the ground tend to follow the terrain, and the higher sigma surfaces approximate isobaric surfaces. In its application to Oslo MM5 was able to simulate local scale circulation patterns in the Oslo area involving topography and spatial gradient in the surface heating and cooling. MM5 contains a description of the atmospheric boundary layer. This cannot treat urban structure in detail because of the limited horizontal resolution but attempts to parameterise the surface processes in terms of physically realistic bulk average processes. Hence a roughness length based on land use classification and Monin-Obukhov similarity theory are used to estimate momentum and sensible heat exchange near the surface and a moisture availability coefficient is used to estimate the surface latent heat flux. MM5 therefore only partly sees a large urban area. Other countries use somewhat similar methods, which may differ in the models used and in the detailed parameterisations. This is one of many examples in the environmental literature of attempts at downscaling, running a model at one length scale and attempting to extract extra information on a finer length scale. In this example the approach is based on an understanding of the physics of the situation, rather than statistical method or one based on a classification of the less detailed atmospheric flow situation.

The detailed meteorological information derived from the meso-scale model is then used in combination with an urban dispersion model and emissions inventory to calculate pollution levels (http://www.nilu.no/first-e.html). The forecast situation is therefore expected to take account of the broad air flow, recognising general features leading to high concentrations in urban areas e.g. low winds, influence of topography, high emissions, but its is not clear to what extent they would accurately describe the processes influencing dispersion near the ground. For situations which do not involve short-term forecasts of pollution conditions dispersion models are used in the countries surveyed based on meteorological pre-processors.

The method relies on processing meteorological data sets collected routinely at synoptic stations.

3. Meteorological Input Data for Urban Dispersion Studies

The COST 715 Workshop reviewed ways in which the meteorological data is prepared and processed for application to dispersion models in urban areas. It turns out that the 'state of the art' on the preparation of meteorological input data for urban site studies of air pollution dispersion is not very advanced. All operational methods concerned with producing a climatology of stability categories/dispersion classes for urban areas follow approaches used in rural areas. In recent years these have been developed so that the main boundary layer parameters describing dispersion are derived, rather than parameters associated only with surface conditions. Much of the theory is based on the same physical principles as used in the meso-scale models, adopting parameterisations but with some similar difficulties concerning latent heat and soil moisture. The advantage relative to meso-scale models is that they are tied firmly to meteorological measurements and can be tested. The disadvantage is that they may neglect spatial horizontal variations and temporal fluctuations, which a dynamical model can better allow for.

All methods would benefit from more observations in urban areas. All suffer from difficulties regarding differences between urban and rural areas and differences in the aim for which purposes and what kind of data are measured in 'standard' meteorological stations and what kind of data would be necessary for climatology of stability categories/dispersion classes in urban areas. In summary in routine urban dispersion calculations not much adjustment to urban meteorological conditions is usually made, apart from adopting an urban roughness length. At heights well above the buildings the wind speeds over the urban and rural area are assumed to be similar. In fact, this approach also do not improve the situation because the limited fetch in urban areas means that the UBL is developing so that the wind field should be a function of distance from the edge of the city. The mean feature of the urban wind profile is the reduced wind above roughness elements in the urban area. Some correction to the surface sensible heat flux is made, for example by assuming that very extreme atmospheric stability does not occur in urban areas i.e. there is an upper bound on the rate of cooling.

These approaches are very different from the application of meso-scale models, but in cases of complex topography dynamical flow models such as mass consistent flow models can be used to generate a wind field and wind field climatologies realistic frequency distributions of near surface winds, which are more consistent with the underlying topography. Examples by Brechler and Janousek(2000) and Baumueller(2000) which illustrate the approach were presented at the COST 715 Workshop. Kerschgens, Bruecher and Sperling (2000) show that problems can arise if the dynamical model covers a limited domain. Large scale features can introduce their own flows and these authors recommend the use of empirical surface wind data and optimisation techniques.

We have seen that features of urban areas are treated explicitly in episode predictions or in climatological dispersion models. The assumption is that by applying the methods the wind field is well enough defined to permit reasonably pollution assessments. These methods are not adequate for calculating small scale variations in the concentrations near the surface, such as those within street canyons where some of the highest concentrations are expected to arise. Two examples of the way operational street canyon models allow for urban meteorology are briefly reviewed.

4. Street Canyon Models

The Operational Street Pollution Model (OSPM) (Berkowicz et al, 1997) takes the wind measured on a mast some height above roof level and extrapolates this to a roof level wind. In light winds the length of the re-circulating zone is allowed to decay since no re-circulating region is assumed to exist in zero winds. The length of the re-circulating zone also depends on wind direction. A street level wind determines dispersion and turbulence within the street in both the direct and re-circulating components. Logarithmic interpolation of the wind profile is generally applied. The street level wind is taken to be proportional to the roof level wind and to the wind direction and height of buildings. Winds parallel to the street axis are taken to be greater than the across the street wind, by up to 20%. Developments of OSPM by Sacre, Chiron and Flori (1995) depend on interpolating winds down to street level. No dependence on ambient air stability is included as one is concerned with vehicle pollution and there is always some vehicle turbulence very short distances within the street, and extreme conditions are assumed not to arise.

The AEOLIUS model (Middleton, 2000) uses the standard 10m wind speed and direction at the nearest airport. Wind profile assumed to be neutral with no adjustment for urban effects. In later versions of the model the user can adapt results using empirical relationships between the airport and roof level wind.

Both models make use of the greater roughness length in urban areas. The roughness length relates to turbulence in layers where the log profile is valid e.g. above the roughness elements. Both model use measured wind from masts located either near the centre of the city (OSPM) or at the nearby airport (AEOLIUS). Neutral vertical wind profiles are constructed using the measured data. The profiles are modified for urban and stability conditions via modification of friction velocity u_* (OSPM) to obtain an adequate wind on roof level and on the street level. If data from nearest airport are used some empirical rules (Manning *et al*, 2000) can be adopted. These empirical rules, in fact, reflect consequences of transformation of energy of average wind into turbulence thanks to increased roughness in the urban areas. Roughness is categorised by visual observations in the city. Though both models make adjustments of the wind speed within the street canyon these have not been fully validated.

5. Urban Wind Profile

A more advanced method for describing the UBL near the surface in terms of local scaling has been proposed by Rotach *et al.* Improvements to describing the urban wind profile have been suggested by Working Group 1 of COST 715 (http://www.geo.umnw.ethz.ch/research/cost715/cost715.html). A method for estimating the wind speed at an urban reference height is proposed using an observation at another height. Provisionally the reference height has been defined to be at the displacement height + 10m. This approach does not rely on applying a meso-scale model, but on an adjustment to conventional Monin-Obukhov similarity theory (MOST). MOST is assumed to still apply above the roughness elements, in the so-called inertial sub-layer. Typically the inertial sub-layer is taken to be between 0.1 × boundary layer height and 2 × height of the buildings (h). Below the inertial sub-layer is the roughness sub-layer typically 2h high, which incorporates the roughness elements and buildings. Within the inertial layer the friction velocity can be defined as a constant, with the Reynolds stress decreasing almost linearly with height above the inertial layer. Below 2h within the roughness sub-layer the friction velocity is found to decrease with height. Scaling similar to MOST can still be applied within the roughness sub-layer but with a height dependent friction velocity.

The method assumes that the roughness length and displacement height (Davenport, Grimmond, Oke and Wieringa, 2000), other constant parameters in the urban wind profile, can be defined in terms of properties of the urban area, such as the average building height and fractional surface area covered by buildings. Provided the number of buildings is sufficiently dense, changing the number of obstacles does not change the roughness illustrating that detailed surface characteristics are unimportant to the flow above the surface. Other assumptions such as assuming a relationship between the friction velocity inside and outside the city have also to be made. The overall effect is to reduce turbulence levels and the mean wind speed above and between the roughness elements. The method only enables a mean wind speed at a specified height to be derived. It does not give the wind speed variation on either side of the street. Hanna and Britter (2000) cite a simple relationship between the average wind speed below building height and the friction velocity within the inertial layer. Experimental data on the relationship between the wind speed at a standard 10m height outside a city to the wind speed on a mast within the city have been reported e.g.

Roof-top wind (Leek U.K.) =0.63 (airport wind at 10m)
Urban wind at 32m (Lisbon)=0.65 (rural wind at 10m) + 1.24
Urban wind at 30m (Copenhagen)=0.51 (airport wind at 10m)

These results cannot be directly compared unless a standard height for defining urban winds is selected. This has not been generally agreed and would depend on further measurements in urban areas.

6. LUMPS

The generalisation of UBL scaling has been proposed for deriving urban surface heat fluxes requiring only standard meteorological data routinely observed at synoptic stations and basic knowledge of the surface character of the urban area. This methodology is known under the acronym LUMPS - a Local-scale Urban Meteorological Pre-processing Scheme. At the present time this scheme has only been developed for and applied in North America and it needs to be tested in different European conditions i.e. cities with different building densities, shapes and structure (slanted roofs, different building material used, for example). The LUMPS scheme is based on a surface radiation budget to estimate the net all-wave radiation. It differs from conventional approaches for rural areas in incorporating a storage heat flux in the building fabric. The partitioning between the turbulent sensible and latent heat fluxes depends on a parameterisation which involves the surface moisture status. That depends on the fraction of the vegetated city surface which may range from 5% in a city centre to more than 50% in the residential suburbs. The estimated sensible heat flux would therefore vary with location in the urban area and measurements would only be representative of the source area (upwind foot print) of a measurement site. Measurements of the heat flux from say eddy covariance instruments should be taken from measurements mounted in the inertial sub-layer. This work is at an early stage and other factors such as precipitation may need to be included into the parameterisation. It is apparent that to calculate atmospheric stability using the Monin Obukhov length for subsequent calculations of dispersion treatment of the wind profile and the surface heat flux need to be combined. It is also apparent that many of the ideas involved in the wind profile and surface heat flux treatments have application in the way the surface conditions in meso-scale models are parameterised.

There are plans to test the LUMPS scheme on European cities with different surface characteristics for which the net radiation and sensible surface heat flux have been measured. Such a comparison is to be made for Birmingham(UK), Basle(CH) and Graz(A) (Piringer, Baklanov, De Ridder, Ferreira, Joffre, Karppinen, Mestayer, Middleton, Tombrou and Vogt, 2001). Given the important links between the surface and the developing UBL, it also necessary to investigate urban boundary layer as a whole. Two such experiments are planned (http://cost.fmi.fi/wg2/furtherwork.html).

In one such experiment given the name BUBBLE (the Basle Urban Boundary Layer Experiment) the urban boundary layer over Basle will be investigated for one year by monitoring near-surface turbulence characteristics, as well as the UBL's vertical structure. The experiment includes rural reference station measurements, tracer experiments in and above streets and remote sensing equipment (http://www.mcrlab.unibas.ch/projects/BUBBLE/). A meso-scale numerical model will be used to validate and improve urban surface parameterisations.

In the other experiment an intensive measurement campaign will be conducted over the Berre-Marseille region during June and July 2001. The experiment involves wind profilers, sodars and lidars, a ground network of pollution and meteorological measuring equipment and aircraft measurements (http://medias.obs-mip.fr:8000/escompte/maquette/mesures.php3). The project involves photochemical modelling and sea breeze circulations, which are not the subject of this paper. However this will rely on the meso-scale models (Bouzom, 2000) to describe the chemical transport and specifically will concern the analysis of the momentum flux and the energy budget at the city surface. It will also include the interaction with surrounding surface fluxes. It deals with the exchanges at the top of the urban boundary layer with the marine boundary layer, continental or suburban boundary layer according to the conditions arising.

7. Siting of Meteorological Instruments in Urban Areas

As a consequence of European Directives and UNECE Protocols there are mandatory requirements for monitoring air pollutants at fixed site. The purpose of the monitoring is to assess the air pollution climate of member states. The assessment will inevitably mean some interpolation between monitoring and comparisons of measurements made at different sites. Many of the monitoring sites will be in urban areas. When comparing monitoring sites one will wish to be able to interpret reasons for differences. Apart from differences in emissions influencing the site the next major factor is the meteorology. It therefore seems sensible to require local meteorological measurements to be co-located with air pollution monitors. One of the main reasons that this is not done already is not the cost but difficulties in deciding where the meteorological instruments should be sited.

Problems exist as how to define objectively a position where the meteorological instruments should be placed, at what height the parameters like radiation fluxes or wind speed and direction, for example, would be measured and how to deal with the low wind speed situations. Rather than to abandon the problem as too difficult, somewhat arbitrary corrections have been introduced to allow for urban characteristics. These are based on sensible corrections and insight into the atmospheric physics e.g. adjusting for greater roughness leads to changes in wind speed and turbulence profiles near the surface but are consistent with winds aloft. However there are no national or international guidelines as to how these corrections may be applied. The problem is especially important in cities with few urban observations (or no observations) located in complex terrain. Urban dispersion calculations, that are performed in all countries, are often undertaken under probably totally inappropriate conditions

The responsibility of the national weather services would be enlisted to tackle the problem of the methodology for siting meteorological measurements within the urban areas (including recommendations dealing with where and how to place meteorological instruments). It is also necessary to provide guidelines on the number of instruments that should be established. The type of instruments should also be considered e.g. whether to measure long wave and solar radiation or to use net all-wave radiation. The use of remote sensing instruments – sodars, lidars or wind profilers should be incorporated into the guideline.

8. Conclusions

Numerical weather forecast models do not really see cities. Routine dispersion calculations apply basic corrections to obtain urban meteorological data sets and sometimes no correction at all. As the first step to correcting this situation it would be useful to know what is available at the present time. It was proposed that a survey is undertaken of national weather services as well as national and local environmental authorities to find out the number and type of instrumentation and location of urban meteorological observing stations and of stations close enough to urban areas, either to be influenced by the urban 'plume' or to provide information on the incident air flowing over the urban area. The COST 715 Management Committee approved this as an activity to be undertaken under this action. The Management Committee also supports the suggestion that a letter should be sent to the European Environment Agency pointing out the current weaknesses in the information available on urban boundary layers for the purposes of dispersion calculations.

Testing of the two proposed improved methods for parameterising the urban wind profile and surface heat flux was considered essential. The new ideas were found very promising. Now there is a need to find a number of data sets from test sites where more than routine information is available. This information is vital for verification of these methods. There are several European studies put forward which would be enable to assure various data sets from different areas for testing.

9. References

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