A modelling package for air quality management in Lisbon

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Abstract

The development of effective air quality management strategies at regional and urban level requires the preparation of several actions belonging to different scientific areas and analysis of its complex interactions. A well structured management system must be based on efficient tools that integrate a diverse set of informations - emissions, traffic, meteorological variables and air quality data. Ideally such a system should include appropriate modelling tools that could be used to perform spatial interpolation and air quality forecasts.

The present work describes the modelling system developed for the air quality management of the city of Lisbon. This system is incorporated in a visual environment and coupled with the modelling package allowing a fast analysis of the air quality situation over the city and the consequent development of on-line control measures.
1. Introduction

Urban air pollution is one of the major environmental problems currently confronting the world’s population. Air pollution is a growing concern because of the increasing urban populations causing a high density of motor vehicles traffic, greater electric power generation needs and expanding commercial and industrial activities.

The high density of emissions released from great urban centres have such a significant magnitude that a healthy air quality can not be achieved only by natural regeneration processes. A major problem related with urban air pollution is the urban transport system and its interaction with the city, as motor vehicles produce different emissions when driven under different conditions of speed, acceleration and idle [1].

The result of the complex set of activities occurring in urban centres are high concentrations of products such as CO, NO\textsubscript{x}, SO\textsubscript{2}, particulate matter and volatile organic compounds (VOC’s) that present a potential threat in terms of public health. Poor air quality usually occurs during several days in which the peak concentrations of one or more pollutants reach health-threatening levels. Such air pollution episodes of smog can begin in periods of stable weather conditions associated with the presence of an anticyclone (high air pressure). Typically, smog occurs either during warm and sunny stable weather conditions (summer smog type) or during cold and foggy stable conditions (winter smog type).

To be able to assess the seriousness of the air pollution threat and to take effective actions, authorities need to set up an appropriate framework that will enable them to achieve and sustain healthy urban air quality.

The components of an urban air quality management system should include an air quality monitoring network, an emission inventory, numerical dispersion models, air quality standards and a public information network. Simultaneously it is necessary to develop a range of cost-effective pollution control policies and define the resources and powers to impose them.

The main purpose of the developed modelling system is to provide a technical support to the air quality management in the city of Lisbon (Figure 1).

The strategy that seems more efficient, on this case, is to act on pollution control policies on road traffic. Based in this idea, the modelling system was connect to the traffic control system (Gertrude network).

2 The Lisbon case

The Lisbon airshed was chosen for this study taking into account the geographical distribution of the main industrial resources and of the most important urban centres, with a population of 3.5 million inhabitants.
Lisbon is built in a very complex topographic region, dominated by a large estuary and multiple hills, surrounded by small mountains ranges reaching heights over 400 m above sea level. The need to understand the behaviour of this airshed is most felt as a substantial increase in air pollutant emissions in the region foreseen for the near future, mostly caused by the increase of roadway traffic. On this context, the connection of the traffic control system with the modelling system assumes a stronger importance. In figure 2 is presented the Lisbon roadway network.

3 Modelling system components

The air quality system integrate four modules - an emission pre-processor, a meteorological model, a dispersion model and a photochemical model - producing concentration maps of some of the most important pollutants, such as CO, SO₂ and O₃, that may be compared with regulatory values established by the Portuguese law.

3.1 Emissions pre-processor

This module uses traffic data obtained from traffic counters located in the main intersections streets of the city, to estimate primary pollutants emissions resultant from the vehicle circulation. These pollutants are: CO, NO₂, NO, hydrocarbons, particulate matter and SO₂. In order to obtain the pollutants
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emissions based on the on-line information given by the Gertrude network, specific emission factors are applied. When this information is not available, traffic emission are taken into account using the fuel consumption in Lisbon and applying appropriated emission factors.

![Lisbon roadway network and air quality network](image)

**Figure 2** - Lisbon roadway network and air quality network.

Industrial emissions, are calculated using emission factors, based on fuel consumption or on the type of industrial process and production quantities.

### 3.2 Meteorological pre-processor

The meteorological pre-processor is structured on a diagnostic wind field model, The NUATMOS model [2].

This model was developed from the ATMOS1 model [3], which is based in the concepts of the MATHEW model [4], a three-dimensional diagnostic wind field model capable of generating potential flow solutions associated with simple terrain features. ATMOS1 employs terrain-following coordinates and
variable vertical grid spacing, features that are essential if complex terrain is to be adequately incorporated.

The NUATMOS model produces a 3D mass consistent wind field based on observations arbitrarily located. This is achieved by interpolating throughout the domain of interest, and then making minimal adjustments to eliminate divergence. The divergence elimination phase is based on the minimisation procedure suggested by Sasaki (1958, 1970) and applied by Sherman (1978) in developing the MATHEW model. The variational problem is to minimise the difference between the initial (interpolated) wind field \( V_0 \) \( (u_0, v_0, w_0) \) and the final wind field \( V \) \( (u, v, w) \), subject to the constraint that the divergence should vanish. Mathematically, the problem is to minimise the functional:

\[
E(u, v, w) = \iiint \left\{ \alpha_1^2 (u - u_0)^2 + \alpha_1^2 (v - v_0)^2 + \alpha_2^2 (w - w_0)^2 \right\} dV
\]  

subject to the constraint

\[
H(x, y, z) = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\]  

where:

- \( x, y \) are the horizontal coordinates;
- \( z \) is the vertical coordinate;
- \( V_0 = (u_0, v_0, w_0) \) is the corresponding initial (interpolated) velocity;
- \( V = (u, v, w) \) is the final velocity;
- \( \alpha_1, \alpha_2 \) are the Gauss precision moduli.

It is assumed that \( \alpha_1 \) and \( \alpha_2 \) are constant throughout the domain. The parameters \( \alpha \) represent the relative amount of adjustment of the vertical component to the horizontal component. The distinction between the adjustments made to the horizontal and vertical velocity components is made via different values for \( \alpha_1 \) and \( \alpha_2 \). Large values imply minimal adjustments (e.g., if the velocity component is known exactly) while small values imply that large adjustments are permitted as consequence of known observational errors.

The objective analysis method used by this model performs the following numerical steps:

1. The surface wind field is computed by interpolating wind measurements;
2. The wind field is adjusted to the terrain by solving the Poisson equation

\[
\nabla^2 \phi = \psi(x,y)
\]
where $\phi$ is the wind velocity potential and $\psi$ is a forcing function based on the thickness of the planetary boundary layer and terrain elevation gradient;

3. Upper level winds are interpolated in a terrain-following coordinates system, using the following changes in the co-ordinate system:

$$
\begin{align*}
\bar{x}' &= x \\
\bar{y}' &= y \\
\sigma &= \frac{(z_1 - z)}{(z_1 - z_0)} = \frac{(z_1 - z)}{\pi} 
\end{align*}
$$

where: $z_t = \text{Top of the solution domain}$

$z_s = \text{Height of the terrain}$

4. Iterations are performed until the maximum divergence of the interpolated wind fields is reduced to an acceptable level.

The main capabilities of NUATMOS include the adoption of correct terrain-following boundary conditions for an arbitrary terrain surface and the development of an objective basis for determining the parameter controlling the degree of adjustment made to the vertical wind component compared to the horizontal component during the divergence reduction phase.

To simulate the wind fields over the Lisbon region there are used five meteorological stations (Figure 3) distributed in the domain. In figure 3 is represented a wind field for 7 June 1994 at 0.00 LST.

3.3 The Gaussian dispersion model

One of the most important part of the air quality system described in this paper is the dispersion model. A Gaussian dispersion model was chosen because it is versatile and runs in a short time period which is compatible with an on-line system, contrarily to mesoscale models that require much more time for running and a heavy hardware.

The implemented model is based in the original version of the PAL-2 model [5], developed by the Environmental Protection Agency (EPA), that can consider point, area and line sources.

The PAL-2 model was selected because it allows the simulation of different types of line sources. The inclusion of this kind of sources in a urban air quality system is very important for traffic emissions play a major role on the air quality of the great urban centres.

The original model was modified to be able to consider orography effects and heterogeneous wind fields. The orography effects are introduced by correcting the effective emission height for elevated sources (point and area sources), taking into account the difference between the emission height, the receptor elevation and the atmospheric stability.
On the other hand heterogeneous wind fields are included assuming that the pollutant's concentrations depend on the wind velocity and wind direction, estimated for each receptor point. Furthermore, wind direction are sequentially backwards compared, with the wind direction estimated for all the receptor points existing between the actual receptor point and the source location.

The Gaussian model is used to calculate the concentration fields for passive pollutants such as CO, and the initial concentrations of reactive pollutants. The final concentration field for the photochemical pollutants is determined using a photochemical box model. In Figure 4 can be seen an example of application of the described system using as point source a sugar refinery industry.

3.4 The photochemical model

The photochemical model that is connected with the gaussian model is the OZIP model [6]. This model can be considered as a variant of a box model. The domain is a variable-volume, well mixed reacting cell within which the physical and chemical processes responsible for photochemical smog are simulated.

These include the transport and dispersion of pollutant species through the cell, the injection of primary precursor species by emissions sources, and the
chemical transformation of the reactive species into intermediate and secondary products. Figure 5 schematically illustrate these processes.

One of the most important aspects of the OZIP model is the inclusion of relatively complete chemical reaction mechanisms - the Carbon-Bond IV [7]. This chemical model has recently incorporated in the EPA’s regulatory model - Urban Airshed Model [8].

To connect this model with the Air Quality System several starting considerations were made:

1. The total domain was divided in several equal parts to create small reactive cells;
2. For each of these cells, the precursors initial concentrations are calculated using the Gaussian dispersion model. In addition the previously hourly concentration of the reactive compounds, as well as the previously hourly concentrations of the adjacent cell, are taking into account. As the same for the Gaussian model, the wind direction is considered to evaluate the relative importance of each boundary cell concentrations of the pollutants in analyses.
3. The final reactive pollutants concentrations for each cell are a product of the chemical transformation of all the inputs. The concentrations are
homogeneous for each cell. The concentration field is the outcome of the interpolation of the calculations made for the total domain.

Figure 2 - Scheme of the box model processes.

3 Research Needs

It was found that the most important research needs in developing urban scale dispersion models are:

- evaluation and validation of models against good quality data bases, including urban and regional background concentrations;
- influence of buildings, obstacles and terrain;
- statistical aspects of dispersion like the chemical interaction of pollutants from a large number of sources;
- particle wet deposition;
- good quality emission inventories (considering time and spatial scales);
- modelling of emissions and dispersion using also urban air quality networks (data assimilation techniques).
4 References