Development and application of a long-term atmospheric dispersion model for environmental impact assessment purposes

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ABSTRACT

The computer code AMETISTA has been developed for evaluating the long-term air pollution caused by emissions from more co-located sources. The aim is to have an updated and flexible tool for estimating air concentration levels caused by actual or hypothetical routine emissions, and for comparing them with the air quality standards prescribed for different sampling times and reference periods. AMETISTA is applied in the framework of the ANPA support activity to the Commission of Environmental Impact Assessment of the Italian Minister of the Environment. The code is divided into a Meteorological Preprocessor, an Atmospheric Diffusion module mostly based on the HPDM model (Hanna and Chang [1]), and a Statistical Postprocessor. The main characteristics of the three modules are described, and the methodology applied to estimate the air quality impact in a general case is illustrated. Then, the results of the application of the diffusion module to the Copenhagen tracer data set (Gryning and Lyck [2]) are presented. Observed and computed crosswind integrated and maximum concentrations on sampler arcs are compared through the most commonly used statistical methods.

INTRODUCTION

The computer code AMETISTA (Air Quality based on MEteorological TIme Series and Turbulence Analysis) has been developed for evaluating the long-term air pollution caused by emissions from more co-located sources. The aim is to have an updated and flexible tool for estimating the air concentration levels which derive from actual or hypothetical routine emissions (typically
from thermo-electric power plants), and for comparing them with the law limits prescribed for different sampling times and reference periods.

AMETISTA is written in standard FORTRAN 77 language, and is included in ARIES-W (Atmospheric Release Impact Evaluation System - Workstation), a computer system for the study of the atmospheric dispersion at different space and time scales developed at ANPA on a DEC Station ALPHA 3000 in OSF environment. In ARIES-W, the operations of input, run and output of the models are performed through user-friendly menu, and the editing of the necessary input data and the selection of the the output analysis are performed through guided masks with help functions and control of the validity range of the data.

Two categories of meteorological data can be alternatively used for the estimate of the atmospheric dispersion over long times. The first is represented by the "Joint Frequency Functions" (JFF), i.e. the statistical frequencies of the occurrence, at a certain site, of a meteorological situation generally defined by stability class, wind speed and sector of wind direction. In Italy, such data have been elaborated and published for several stations of the Italian Weather Service, and cover a period of 27 years, from 1951 to 1977. An updating and of this data set is currently under development.

The models based on JFF are relatively simple and require very limited computer times. They have, on the other hand, several drawbacks. Firstly, the characterization of the diffusion properties of the atmospheric boundary layer based on stability classification is not aligned with the current knowledge of the turbulence and the diffusion phenomena, especially in unstable conditions (Weil [3]; Gryning et al. [4]). Secondly, the statistical distribution of the calculated concentration values is valid only for the same sampling time of the meteorological observations from which the JFF are derived (for synoptic observations, 3 hours), and its extension to different sampling times is arbitrary. In particular, the estimates of the extreme values of the hourly concentration distribution (for example the 95th or 98th percentiles) are generally underestimated. The sampling times of law limits, on the other hand, range from 1 to 24 hours for different pollutants and reference periods. Finally, the model results properly represent an "average" year from the meteorological point of view, but don't represent actual and recent time periods.

The second category of data is represented by the time series of meteorological observations (OTS) at time intervals of the order of one hour. The models based on OTS iterate a short-term, straight-line plume model for the number of cycles needed to cover the period of interest, for example one year. This procedure requires a larger amount of computing time, nevertheless a reasonable time, today, on a PC of the last generation or on a RISC workstation. From OTS it is possible, in most cases, to derive the
meteorological scaling parameters, such as sensible heat flux, Monin-Obukhov length and mixing height, which allow the application of an advanced hybrid model (i.e. non-Gaussian in the vertical). By means of time interpolating or averaging algorithms it is possible to reduce original to hourly OTS, and to estimate the statistical distribution of the concentrations for sampling times multiple of one hour.

On the base of the above considerations, it was decided to develop a model based on meteorological scaling parameters. In consideration of the non-homogeneity of the meteorological stations and instruments which may be used for a dispersion evaluation over Italy, and with the purpose of applying the model for different sites, a fundamental requirement is the flexibility with respect to different kinds of available meteorological data. Another requirement is the flexibility with respect to the reference period and the sampling time of the model estimates, to be compared with the law limits. For these reasons, AMETISTA is composed of the following modules.

A Meteorological Preprocessor (MP), is dedicated to the construction of an hourly time series of the meteorological scaling parameters and other variables needed by the diffusion code, starting from OTS. Different versions of MP may be applied, depending on the primary observations available. If OTS representative of the site under study are not available, one MP version that reconstructs a "fictitious" time series from JFF may be used. The Atmospheric Dispersion code (AD), computes, on a regular rectangular grid and at particular points to be specified, the hourly averaged concentrations which derive from continuous emissions by up to twenty sources. Finally, the Statistical Postprocessor (SP), computes at the same points the statistical indexes for the reference periods and the sampling intervals of interest.

THE MODEL

Meteorological preprocessing

MP provides an hourly time series of the meteorological parameters needed by AD: wind speed u and direction d near the surface, air temperature T, friction velocity u*, Monin-Obukhov length L, sensible heat flux H, mixing height h. Four MP versions are available. The first three versions (VI, V2, V3) use OTS, while the fourth version (V4) uses JFF.

The routines for the calculation of u*, H, L and h in V1, V2 and V3 have been developed within the framework of the CEC Research Program for the development of a decision support system for nuclear emergency situations (Mikkelsen and Desiato [5]).

The time interval Δt of OTS is allowed to be either a multiple or an integer fraction of one hour, in a range between 10 minutes and 3 hours. Δt < 1 hour can originate from a meteorological tower or mast near the release
point, while $\Delta t = 3$ hours corresponds to synoptic observations. OTS are initially reconducted to hourly time series, by means of interpolating or averaging algorithms. The input meteorological variables common to versions V1, V2 and V3 are $u$, $d$, and $T$. In versions V1 and V2 the estimate of $u^*$, $H$ and $L$ is based on the "energy budget method", which requires total cloud cover or incoming solar radiation. Version V3 is based on the "profile method", which requires two temperature measurements in the surface layer (van Ulden and Holtslag [6]). Mixing height $h$ in neutral and stable situations ($L \geq 0$) is computed from (Nieuwstadt [7]), while in unstable hours a "slab" model is adopted, based on the integration of a rate equation for $dh/dt$ (Batchvarova and Gryning [8]). In all situations the condition $100 \leq h \leq 2000$ is imposed.

Version V4 prepares hourly values of the meteorological variables needed by AD on the base of JFF. The overall set of calculated variables represents an "average" meteorological year, but the time sequence has no more physical meaning in this case. JFF are transformed into a fictitious time series of about one year. The persistence of a certain condition in hours, $n_{ijk}$, is computed by

$$n_{ijk} = 0.01 \, p_{ijk} \, m_y$$

where $p_{ijk}$ is the percentage frequency of stability $i$, wind sector $j$ and speed $k$, and $m_y = 8760$ is the number of hours in one year. In this way, conditions with an occurrence of less than $0.0057$ % are cut out. This "threshold" frequency could be reduced by extending the period of the fictitious time series, (i.e. enlarging $m_y$) with disadvantages in terms of computing time. $H$ is estimated through the "inversion" of a stability class nomogram (Pasquill [9]). The convective mixing height is derived from a nomogram by Smith which provides typical values in rural environment for given stability category and wind speed (Underwood [10]).

**Dispersion**

The central module of AMETISTA simulates the dispersion of plumes emitted by up to twenty release points through the hourly iteration of a straight-line, hybrid plume dispersion model, mostly based on the latest version of HPDM (Hanna and Chang [1]). In HPDM, four alternate types of parameterizations are used, as a function of $L$ and of a dimensionless plume buoyancy flux, which gives an indication of the plume elevation with respect to the mixing height. The four dispersion regimes are the *Gaussian* for stable conditions and neutral conditions with low plume elevation, the *PDF* and the *Low-wind convective* for convective conditions with low and elevated plumes, respectively, and the *Lofting* for neutral condition and elevated plumes. The parameterizations in the different dispersion regimes are described in Hanna and Chang [1]. Here, only a few differences introduced in AMETISTA are shortly outlined.
The effect of topography during stable conditions is considered by assuming an effective plume height above a receptor given by:

\[ h_{er} = h_{es} + (z_r - z_s) (f_t - 1) \]  
\[ (2) \]

where \( h_{es} \) is the effective height above the terrain at the release point, while \( z_r \) and \( z_s \) are the terrain height at the receptor and at the source, respectively. The factor \( f_t \) ranges between 0 and 1 as a function of \( L \). In the case the plume impinges the terrain (\( h_{er} < 0 \)), a minimum value \( h_{er} = 10 \) m is forced, and the horizontal dispersion is enhanced by increasing the plume horizontal standard deviation \( \sigma_y \).

The horizontal Lagrangian time scale is a linear function of height,

\[ T_{Ly} = 73.7 z + 263 \]  
\[ (3) \]

in consideration of the empirical values \( T_{Ly} = 15000 \) s and \( T_{Ly} = 1000 \) s derived from Hanna and Chang [1] and from Draxler [11] based on tracer data with average release heights of 200 m and 10 m, respectively.

The wind speed at release height is computed using vertical profiles based on the similarity theory. During calm condition, a situation which frequently occurs in the Po valley, the dispersion calculation is switched to a fifth parameterization (Cagnetti and Ferrara [12]):

\[ C = Q (2\pi)^{-1/2} (h r)^{-1} \]  
\[ (4) \]

where \( C \) is surface concentration, \( Q \) is release rate and \( r \) is the distance from the release point to the receptor.

Finally, special modules have been implemented in AMETISTA for the treatment of area sources with the method of "virtual point sources", and for the calculation af accumulated dry and wet deposition with simple algorithms based on assigned values of deposition velocity and washout coefficient.

**Statistical postprocessing**

The third module of AMETISTA is dedicated to the estimate of statistical indexes for the reference periods and the sampling time of interest, to be compared with law limits and reference values. The maximum, average, median, and 25th, 75th, 95th and 98th percentiles of the concentrations are calculated. The reference period and the sampling time over which the above values must be calculated can be specified as input, with the obvious constraints that the reference period must be included in the OTS elaborated by \( MP \), and that the sampling time \( \Delta t \) must be multiple of one hour. Gridded
values of the statistical indexes may be displayed as contour lines against the main geographical features of the model domain.

APPLICATION TO THE COPENHAGEN DATA SET.

Meteorological preprocessing and atmospheric dispersion applications require model testing and calibration against a large number of experimental data. Recently, the need for an harmonization of the existing procedures for preprocessing meteorological data, and for exchanging data sets of meteorological variables measured over a wide range of conditions, has been outlined (Thompson [13]). The AMETISTA dispersion module is based on HPDM, which has been evaluated during its 10-year history against several tracer data sets in US (Hanna and Paine [14], Hanna and Chang [1], [15]. Here, the results of its application to the dispersion experiments carried out in the Copenhagen area under neutral and unstable conditions (Gryning and Lyck [2]) are shortly described.

In the Copenhagen experiment, the SF$_6$ tracer was released without buoyancy from a 115 m tower, and collected at three crosswind sampler arcs located at 2 to 6 km from the release point. A roughness height of 0.6 m was estimated. Although the meteorological measurements performed during the experiment included wind speed and three-dimensional fluctuations at release height, AMETISTA was run at first with the minimum meteorological data available, in order to test its performance in a general case. The meteorological preprocessor used the wind speed at 10 m and the temperature gradient between 2 and 40 m as input data (version V3 of MP). Due to the lack of the morning meteorological time series needed to integrate the rate equation, the mixing height was derived from the radiosounding at Copenhagen and not calculated.

From 9 suitable experiments, 23 1-hour averaged values of crosswind integrated concentrations (CIC) and maximum concentrations (CMAX) on sampler arcs could be used for model evaluation. 17 realizations out of the 23 turned out to be in the Gaussian dispersion regime, the remaining 6 being PDF. The results are shown in Figs. 1 and 2, as scatter diagrams of observed versus computed normalized CIC and CMAX. In Table 1 the same quantities are evaluated by means of the following statistics: mean value, standard deviation, bias, normalized mean square error (nmse), correlation factor and fractional bias (fb).

The computed CIC are generally in good agreement with the observed, being both nmse and fb approximately 0.1. Gaussian and PDF cases don't show different bahaviours. While the CIC comparison indicates that the model parameterization of vertical diffusion is well tuned, CMAX are underestimated by a factor 2.5 on the average. Very similar results have been obatained from the application of other models (Lee [16], Olesen [17]).
the model horizontal plume distribution is Gaussian in all cases, this is due to a general overestimation of the plume standard deviation $\sigma_y$:

$$\sigma_y = \sigma_v \times f_y / u,$$

$$f_y = [1 + 0.9 \times (x / uT_{L_y})^{1/2}]^{-1} \text{ in the Gaussian},$$

$$f_y = [1 + 0.5x / (uT_{L_y})]^{-1/2} \text{ in the PDF}$$

From the comparison with observed values at release height, computed $\sigma_v$ are overestimated by a factor 1.32 on the average. A further effect may be due to a too large value of $T_{L_y}$ (equation (3)). In order to improve CMAX results, a new model run was performed with measured $\sigma_v$ and $T_{L_y} = 1000$ s. The results are shown in Fig. 4 and in the last row of Table 1. CMAX are underestimated by a factor 1.5 on the average in this case, and all statistical indexes improve with respect to the first run.

From the application of AMETISTA to the Copenhagen data set, it may be concluded that the model performance is quite satisfactory in predicting the crosswind integrated concentration, i.e. in modeling the vertical diffusion. The horizontal plume spread, on the other hand, is overestimated. The parameterizations of the turbulence intensity $\sigma_v$ and of the Lagrangian time scale $T_{L_y}$ may account for a conspicuous part of the inaccuracy in the prediction of maximum concentrations.

| TABLE 1 |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| | | | | | | |
| Statistical comparison between observed and computed crosswind integrated concentrations (CIC) and Maximum Concentration on arcs (CMAX) - 23 realizations of the Copenhagen tracer experiments. |

<table>
<thead>
<tr>
<th>CIC (10^{-4} \text{ s m}^{-2})</th>
<th>mean</th>
<th>sigma</th>
<th>bias</th>
<th>nmse</th>
<th>corr</th>
<th>fb</th>
</tr>
</thead>
<tbody>
<tr>
<td>observed</td>
<td>4.49</td>
<td>2.39</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>computed</td>
<td>4.05</td>
<td>1.94</td>
<td>0.44</td>
<td>0.11</td>
<td>0.825</td>
<td>0.102</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CMAX (10^{-7} \text{ s m}^{-3})</th>
<th>mean</th>
<th>sigma</th>
<th>bias</th>
<th>nmse</th>
<th>corr</th>
<th>fb</th>
</tr>
</thead>
<tbody>
<tr>
<td>observed</td>
<td>6.33</td>
<td>4.50</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>computed(1)</td>
<td>2.56</td>
<td>1.96</td>
<td>3.77</td>
<td>1.43</td>
<td>0.864</td>
<td>0.849</td>
</tr>
<tr>
<td>computed(2)</td>
<td>4.13</td>
<td>3.16</td>
<td>2.19</td>
<td>0.36</td>
<td>0.903</td>
<td>0.420</td>
</tr>
</tbody>
</table>
Figure 1 - Scatter diagram of observed versus computed crosswind integrated concentrations. 23 realizations of the Copenhagen tracer experiments.

Figure 2 - Scatter diagram of observed versus computed maximum concentrations. AMETISTA run with computed $\sigma_y$ and $T_Ly$ by equation (3).
Figure 3 - Same as figure 2 but with observed $\sigma_V$ and $T_{Ly} = 1000$ s.

REFERENCES


