Application of new generation models over complex coastal areas

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Abstract

Air quality dispersion models of new generation are becoming widely used for regulatory air quality modelling. An important feature of these models is the use of boundary layer and surface energy flux parameterizations to provide turbulence parameters for estimating diffusion rates. These models are, in fact, based on the principles of the ‘new generation’ meteorology, which employs continuous variables to characterise atmospheric conditions, rather than a fixed number of categories used by traditional Gaussian models. In this paper a new generation model, namely AERMOD, was applied over a complex coastal area that comprises valleys, hills, urban zones, and an industrial zone.

1 Introduction

AERMOD is a steady-state plume dispersion model for the assessment of pollutant concentrations from point, volume, and area sources. Sources may be located in rural or urban areas, and receptors may be located in simple or complex terrain. Complex terrain is defined as terrain in which ground elevations are above the stack tip or release height and the complex terrain capabilities of AERMOD are of particular interest.

The AERMOD modelling system consists of two pre-processors and the dispersion model. AERMET (EPA, [1]) is the meteorological preprocessor and AERMAP (EPA, [2]) is the terrain preprocessor that characterizes the terrain, generates receptor grids and facilitates the generation of hill height scales. Meteorological data processing can be an extensive process if the surface and upper air data are not in one of the expected formats, and terrain processing is limited to areas in which USGS DEMs data are available. The sensitivity
analysis of AERMET input parameters revealed the importance of these in determining model-predicted maximum concentrations.

A preliminary assessment of AERMOD dispersion model was evaluated against observed concentrations for impacts emitted from a refinery and surrounding sources. Observed concentrations were obtained from monitoring stations located in the complex coastal area.

Figure 1: The investigated area.

2 The Gaussian steady-state dispersion model

Air dispersion models are basically used to simulate the downwind dispersion process and to simulate the movement of an emission plume and its behaviour. Although different types of models exist to accomplish these objectives, Gaussian models are widely used for regulatory purposes.

The basic Gaussian diffusion equation assumes that atmospheric stability and all other meteorological parameters are uniform and constant throughout the layer into which the pollutants are discharged, and in particular that wind speed and direction are uniform and constant in the domain. Turbulent diffusion is a random phenomenon and therefore the dilution of the pollutant can be described in both horizontal and vertical directions by the Gaussian or normal distribution. Figure 2 depicts a typical Gaussian plume.

The pollutant is released at a height above the ground that is given by the physical stack height and the rise of the plume due to its momentum and buoyancy (together forming the effective stack height). The degree of dilution is inversely proportional to the wind speed and pollutant material reaching the ground level is reflected back into the atmosphere. The pollutant is conservative thus it does not undergo any chemical reactions, transformation or decay.
The spatial dynamics of pollution dispersion is described by the following type of equation in a Gaussian model:

\[ C(x, y, z) = \frac{Q}{2\pi V \sigma_x \sigma_y \sigma_z} \sum_{j=-\infty}^{+\infty} \left( e^{-\frac{(x-H_z+2jL)^2}{4\sigma_x^2}} + e^{-\frac{(x+H_z+2jL)^2}{4\sigma_x^2}} \right) \]

where:
- \( C(x, y, z) \) is pollutant concentration at point \((x, y, z)\);
- \( U \) is the wind speed (in the \( x \) "downwind" direction, m/s);
- \( \sigma \) is the standard deviation of the concentration in the \( x \) and \( y \) direction, i.e., in the wind direction and crosswind, in meters;
- \( Q \) is the emission strength (g/s);
- \( H_z \) is the effective stack height.

### 2.1 The AERMOD model

AERMOD is a Gaussian steady-state plume dispersion model. Special features of AERMOD include its ability to treat the vertical inhomogeneity of the planetary boundary layer, special treatment of surface releases, irregularly-shaped area sources, a three plume model for the convective boundary layer, limitation of vertical mixing in the stable boundary layer, and fixing the reflecting surface at the stack base. AERMOD also includes an improved treatment of dispersion in the presence of complex terrain.

AERMET is the meteorological preprocessor for the AERMOD. Input data can come from hourly cloud cover observations, surface meteorological observations and upper air soundings. Output includes surface meteorological observations and parameters and vertical profiles of several atmospheric parameters.
The AERMAP pre-processor is a terrain preprocessor designed to simplify and standardize the input of terrain data for AERMOD. Input data include receptor terrain elevation data. The terrain data may be in the form of digital terrain data that is available from the U.S. Geological Survey. Output includes, for each receptor, location and height scale, namely the elevation used for the computation of airflow around hills.

AERMOD simulates transport and dispersion from multiple point, area, or volume sources based on an up-to-date characterization of the atmospheric boundary layer. Sources may be located in rural or urban areas, and receptors may be located in simple or complex terrain. The model employs hourly sequential pre-processed meteorological data to estimate concentrations for averaging times from one hour to one year. Specifically, it is appropriate for the following applications:

- Point, volume, and area sources;
- Surface, near-surface, and elevated releases;
- Rural or urban areas;
- Simple and complex terrain;
- Transport distances over which steady state assumptions are appropriate, up to 50 km;
- 1-hour to annual averaging times;
- Continuous toxic air emissions.

3 The investigated area

Air pollution phenomena in the Mediterranean Coastal Areas are driven by high temperatures, intense photochemical activity, low relative humidity and presence of sea-land breezes. These climatic conditions, coupled with complex orography and specific emissions, can increase the pollutant concentrations. Previously we have investigated the NO$_x$ concentrations (Latini, 1999 [3]) in a complex coastal region, namely Esino Valley, as well as ozone concentrations (Latini, 2000 [4]).

The Esino Valley (Fig 3) is surrounded by hillsides in increasing height as they distance from the coast: the first hills rise close to the coast and at this distance the height does not exceed 100 m; a further 20 km inland the height does not exceed 200 m but at about 30 km the valley undergoes a sharp narrowing where the height exceeding 1000 m.

The climate in this area is classified under subcoastal where there is an all year round sea breeze although of different intensity and influenced by a heavy component from NW. The sea-breeze/land-breeze circuit (SBLB) is a meso-scale circulation of air caused by the differential heating and cooling of the land- and sea-surfaces in the coastal zone.
Typical sea breeze winds are usually on the order of four to ten meters per second depending on location and factors already mentioned. The duration of the circulation at any one location in coastal areas can last as long as four or five hours before the winds become calm or shift away from the onshore flow. The horizontal extent of the sea breeze front is greatly dependent upon the strength of the thermal gradient between the land and the sea surfaces and also upon the strength of the gradient winds. Convection caused by the sea breeze can move inland for kilometres by late afternoon if there are onshore winds that push convergence zones along the front inland.

Horography can also influence the sea breeze in two cases. Hills and valleys in the vicinity of a coastline can increase the velocities associated with the circulation and change the direction of these winds as well. The sea breeze winds can be channelled through steep terrain in coastal ranges, thus increasing the velocity.

4 The model application

AERMOD is recommended by the EPA as the preferred dispersion model for general industrial modelling scenarios. Its performance was evaluated against observed concentrations for impacts emitted from Esino Valley refinery located by the sea.

The required source data input (EPA, [5]) includes source type, emission rate, location, stack height, stack gas exit velocity, stack inside diameter, stack gas temperature, area and volume source dimensions, and source elevation. Building dimensions and variable emission rates are optional.

The source configuration is shown in tab. 1.
For what concerns terrain data and their pre-processing the 7.5-minute Digital Elevation Model (DEM) data was used for this modelling analysis. Receptor elevations were determined from USGS 7.5-minute (1:24,000 scale) Digital Elevation Model (DEM) data. The DEM data file was generated from the topographical maps, and contains point elevations at regularly spaced horizontal intervals of 30m. Figure 3 shows the topographic features of the geographic area used in this analysis.

The meteorological data used as inputs to the model include the closest Local Airbase upper air, namely Pratica di Mare Airport and hourly surface station.

The surface data collected by the meteorological Falconara station included:

- Horizontal wind speed
- Horizontal wind direction
- Ambient temperature
- Humidity
- Pressure
- Net solar radiation

AERMET organizes data from the upper air and hourly surface observation stations, and then estimates the necessary parameters for dispersion calculations.

Representative climatological variables such as albedo, Bowen ratio and surface roughness (tab.2) were also used by the considered model. The effects of changes in land use parameters and variants of complex orography on the modelled design concentrations in AERMOD are extremely complex. The values for surface roughness, Bowen ratio, and albedo reflect the surface characteristics

**Table 1: Source configuration.**

<table>
<thead>
<tr>
<th>Point Source</th>
<th>Pollutant emission rate [g/s]</th>
<th>Stack Height [m]</th>
<th>Stack gas exit temperature [K]</th>
<th>Stack gas exit velocity [m/s]</th>
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<tr>
<td>stk1</td>
<td>2.63</td>
<td>60</td>
<td>473</td>
<td>3.5</td>
</tr>
<tr>
<td>stk2</td>
<td>1.31</td>
<td>52</td>
<td>470</td>
<td>3.5</td>
</tr>
<tr>
<td>stk3</td>
<td>1.31</td>
<td>35</td>
<td>714</td>
<td>28.9</td>
</tr>
<tr>
<td>stk4</td>
<td>0.8</td>
<td>54</td>
<td>811</td>
<td>5.9</td>
</tr>
<tr>
<td>stk5</td>
<td>1.31</td>
<td>60</td>
<td>505</td>
<td>4.3</td>
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<td>stk6</td>
<td>3.94</td>
<td>60</td>
<td>463</td>
<td>20.9</td>
</tr>
<tr>
<td>stk7</td>
<td>1.31</td>
<td>55</td>
<td>637</td>
<td>10.9</td>
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<td>stk8</td>
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<td>22</td>
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<tr>
<td>stk9</td>
<td>0.92</td>
<td>50</td>
<td>657</td>
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<td>stk10</td>
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<td>28</td>
<td>553</td>
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<td>stk11</td>
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<td>stk14</td>
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<td>50</td>
<td>393</td>
<td>11.4</td>
</tr>
<tr>
<td>stk15</td>
<td>0.3</td>
<td>50</td>
<td>423</td>
<td>2.1</td>
</tr>
</tbody>
</table>
and are representative of the modeling domain. Reasonably accurate estimates of these characteristics (Latini 2001, [6]) are necessary for AERMOD to provide accurate results

Table 2: Land use parameters.

<table>
<thead>
<tr>
<th>Albedo</th>
<th>Bowen Ratio</th>
<th>Surface Roughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>2</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Choosing the right AERMOD input data is an all-important first step in a successful assessment of pollutant concentrations.

5 Sensitivity studies

An initial set of sensitivity analyses were performed to assess the importance of topographic information. AERMOD assumes that the concentration at a receptor is a weighted combination of two concentration estimates: a purely horizontal plume and a plume that is vertically displaced by the terrain.

Since terrain processing is limited to areas in which USGS DEMs data are available, sensitivity analysis of AERMAP input data has been performed to reveal the importance of these in determining model-predicted maximum concentrations. Two types of terrain (area), namely flat (Fig.4a) and complex (Fig.4b) were considered.

![Figure 4: Maximum predicted concentration for a) flat area and b) complex area.](image)

The results of these initial sensitivity studies showed that modelled concentrations are very sensitive to terrain pre-processing.
6 Modelling results

The model run to predict short-term concentrations averaged over one hour at each receptor using one month of winter meteorology. A discrete Cartesian receptor grid network containing 400 receptors with a resolution of 500 meters was used.

The highest 1-hour AERMOD concentration is 142.2 µg/m³ and occurs on 12/04 at (x,y) location 368270,4828392 m. This location is approximately 5 kilometers to the southwest of the considered point source.

Table 3: Maximum predicted 1-hr concentration.

<table>
<thead>
<tr>
<th>Concentration (µg/m³)</th>
<th>Maximum location (x,y)</th>
<th>Time Period (mm-dd-hh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>142.2</td>
<td>368270,4828392</td>
<td>12-04-19.00</td>
</tr>
</tbody>
</table>

The relative locations of the source and the predicted 1-hour maximum impact locations are depicted in Figure 5.

Figure 5: AERMOD maximum predicted 1-hr concentrations.

In order to explain the predicted pollutant concentrations, meteorology of the considered day was also examined in detail. Figure 6 shows the wind rose for the same time periods. The wind speed values are plotted as a function of the wind direction. The windrose indicates predominate wind-direction, which can partially be attributed to the influence of onshore winds. More significantly, the data indicate calm winds approximately 8 percent of the time. Treatment of calm winds poses a special problem in model applications since steady-state Gaussian plume models assume that concentration is inversely proportional to wind speed.
AERMOD, although being fundamentally a steady-state Gaussian plume model, contains improved algorithms for dealing with low wind speed (near calm) conditions. As a result, AERMOD can produce model estimates for conditions when the wind speed may be less than 1 m/s.

As final step AERMOD's performance was evaluated against maximum observed concentration (Tab.5) for impacts emitted from Falconara refinery and surrounding sources.

Table 5: Comparison between predicted and observed NOX concentrations.

<table>
<thead>
<tr>
<th>AERMOD</th>
<th>48 ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Falconara Station</td>
<td>60 ppm</td>
</tr>
</tbody>
</table>

From these results it is readily apparent that AERMOD predicted slightly lower concentrations than monitored values.

7 Conclusion

The dispersion model AERMOD has been applied to evaluate maximum pollutant concentrations in a complex coastal area, namely Esino Valley.

A preliminary sensitivity analysis was carried out to provide information on dependency of concentration levels on terrain characteristics. AERMOD evaluated all three types of sources (point, volume and area) in two types of terrain (flat and complex).
The results showed that AERMOD predicted short-term averaged concentrations in agreement with observed values. These results assure further model applications to evaluate pollutant dispersion in a complex coastal area.

References