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A NEW PUFF MODEL FOR AN ACCURATE NON-STATIONARY PLUME DESCRIPTION IN BOTH TRANSPORT AND CALM CONDITIONS

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ABSTRACT

A new puff scheme is presented which allows the Gaussian formula (as well as other methods using non-Gaussian concentration distributions) to be applied when non-homogeneous, non-stationary effects, typical of multi-hour simulations required for intermediate range dispersion phenomena, strongly affect the diffusion process. The proposed method improves the accuracy in the representation of the non-stationary plume for short-term average concentration computation and, in particular, allows the treatment of both transport and calm conditions, and the transition from one case to the other.

INTRODUCTION

The most common modeling approach in air pollution dispersion simulation is the Gaussian model. The relative simplicity of the Gaussian approach and, especially, its elevation to the quantitative decision-controlling level by the EPA, have stimulated research aimed at removing the limitations of this theory, which basically requires the main assumptions of 1) spatial homogeneity, 2) stationary conditions, and 3) flat terrain. To this end, methods have been developed which break up the plume into a series of independent elements (segments [1] or puffs [2]) that evolve in time as a function of temporally and spatially varying meteorological conditions.

This paper will not deal with the important problem of the determination of the diffusion parameters in such complex conditions. On the contrary, by assuming a fairly good knowledge of meteorology and dispersion conditions in the three-dimensional domain, a new computational algorithm will be developed for a more accurate, and computationally more efficient, simulation of plume characteristics by a series of puffs in both transport and calm conditions.

Recent improvements of the puff model have been developed for taking into account wind shear effect [3], dynamic plume rise [3], and determining the correct time increment for puff advection and diffusion [3][4]. Especially the latter problem (Δt determination) is very important, since a too large time step produces inaccuracy in the plume description, while a too small Δt causes serious problems of computer storage and CPU running time. The solutions proposed for this problem consist of a puff merging algorithm (Ludwig et al. method [4]), and the incorporation of the mean-wind advection into the streamwise dispersion coefficient (Sheih method [3]). However, both methods work only in nearly steady-state conditions, since a sudden change of wind direction can cause overestimation and/or underestimation in some receptors, as illustrated in Fig. 1. Fully non-stationary simulations with such puff models can then require a computationally prohibitive Δt of a few seconds for a correct dispersion simulation at receptors near the sources.

THE AVPPM(*) METHOD

A more detailed description of this method is contained [5] in an article recently submitted by the author for publication in an international journal. In the present paper the main features of such an algorithm are summarized and, in particular, the handling of puffs and the calm condition treatment are discussed.

Handling of Puffs

The algorithm handles general non-stationary conditions without creating serious computer storage and CPU time-consumption problems, since Δt, the time increment chosen, is sufficiently large (e.g., 5 to 20 minutes for intermediate range simulations). All the mass emitted from a source in the interval $[t_0, t_0 + \Delta t]$ is concentrated in the puff generated at the source at t_0. However, since a large Δt is used, the plume description has a poor resolution. Therefore, in this algorithm, a string of consecutive puffs from the same source gives only the geometry of the plume evolution, and the puff masses cannot be directly used for computation of the contribution at the receptors.

At each time step (say, $t + \Delta t$), all information about the status of the present puffs (at time $t + \Delta t$) and previous puffs (at time t) must be available and an array "chain" is used for relating each puff to its original source according to its age.

If a given source has generated a plume which is described by n puffs in the domain at time t (and, therefore, n + 1 puffs at time $t + \Delta t$), it can be seen in Fig. 2 that n three-dimensional quadrilaterals can be defined, where the vertices of each quadrilateral are determined by the positions of two consecutive puffs at times t and $t + \Delta t$. The quadrilaterals need not lay on a plane and may be degenerate. Each of the n quadrilaterals must be analyzed for the computation of its contribution to each receptor, and the entire method must be repeated for all sources at every time step.

(*) AeroVironment Puff Plume Model

This computation first requires an analysis to see if the quadrilateral gives a non-zero contribution at a receptor. To this end, the closest point in the quadrilateral to the receptor is found. If the distance of this point from the receptor is more than, say 4 or 5 σ's, the contribution is zero. Otherwise (see Fig. 3), the mass of the puff at A, which has been moved to A' (but could have lost mass due to deposition or chemical decay), must be redistributed in the quadrilateral according to the real physics of the non-stationary dispersion. To this end, a splitting technique is applied to the quadrilateral, with artificial generation of a sufficient number of puffs in its area so that sufficient resolution is obtained(*). This can be done, for example, as illustrated in Fig. 3 (using the more critical upwind puffs which have smaller σ's).

The first downwind quadrilateral contains the source. Some information on initial spread of the plume (e.g., as a function of the exit diameter of the source and/or the plume rise) can be used for supplying σ values at the source point to allow the interpolation computation in this first quadrilateral.

It must be noted that this splitting technique will be applied only when required for a particular receptor. In this way, we solve our computer storage and time problems without losing the accuracy of the computation.

Treatment of Calm Conditions

This problem has been solved by allowing the puffs to grow as a function of time (more exactly, their age) instead of downwind distance.

For example, let us assume the common exponential law for the puff σ's as a function of the downwind distance, d

$$\sigma = a\ d^b \quad . \tag{1}$$

Then, if $t - t_0$ is the age of the puff, Equation (1) is equivalent in some way to

$$\sigma = a\left[u(t - t_0)\right]^b = au^b(t - t_0)^b = a'(t - t_0)^b \quad , \tag{2}$$

where u is the average wind speed, and $a' = a\ u^b$.

(*)It has been shown [4] that a string of puffs is a good approximation of a Gaussian plume if the separation between two consecutive puffs is less than the streamwise standard deviation of their concentration distribution. This criterion can then be used for generating a sufficient number of artificial puffs in the quadrilateral.

For wind speed less than a fixed value u_{min} (e.g., the instrument minimum significant value), a' is kept fixed to the value a'_{min}, where

$$a'_{min} = a\, u_{min}^{b} \quad , \tag{3}$$

which allows Equation (2), with $a' = a'_{min}$, to work for calm conditions as a function of the age of the puff.

The above methodology is not restricted to the σ function of Equation (1) and similar considerations can be developed for virtually any σ function.

Virtual Distances and Ages

It has been recognized that in non-stationary simulations the size of each puff at time t depends upon the many different past diffusion conditions encountered during its entire life $[t_0, t]$ since generation at t_0. For this reason, the computation of the growth of the puff sigmas between t and $t + \Delta t$ has required [4] the computation of the puff virtual distance, defined as the downwind distance that the same puff, to have the same sigmas, would have had to travel from the source if the turbulence state had always been the present one (at t) during its entire life $[t_0, t]$.

In the AVPPM method, the horizontal turbulence state is allowed to differ from the vertical turbulence state(*), then requiring the computation of horizontal and vertical virtual distances, respectively, for the horizontal and vertical standard deviations of the puff. Moreover, due to the possibility of a puff growing as a function of its age, the corresponding computation requires the definition of equivalent horizontal and vertical virtual ages.

For example, assuming Equation (1) for transport conditions, and Equation (2) with $a' = a'_{min}$ for calm conditions, the virtual distance of a puff at time t is

$$d_v = \left[\sigma(t)/a^*\right]^{1/b^*} \tag{4}$$

where $\sigma(t)$ is the current "size" of the puff (horizontal or vertical standard deviations) and a^* and b^* are the coefficients of (1) for the current (at time t) turbulent state j* computed at puff center location. In a similar way, the virtual age is

$$t_v = \left[\sigma(t)/a'^*\right]^{1/b^*} \tag{5}$$

with $a'^* = a^* u_{min}^{b}$.

(*) Stable plume transport with light wind is a typical important intermediate range dispersion case where vertical and horizontal diffusion cannot be characterized by the same turbulence state. In fact, while vertical turbulence is generally low, horizontal wind meander can produce a considerable horizontal spread of the average plume.

The method can easily be extended to segment, area, and volume sources by describing each vertex of the quadrilateral (Fig. 2) with 2, 4, or 8 puffs, respectively. Deposition and chemical decay are considered by exponentially decreasing the mass of each puff. Ground and inversion reflections are easily computed and, if the suitable input data are available, the entire method can work properly in complex terrain situations.

As a final important remark on the method, it must be pointed out that neither the use of the sigma exponential law (1) nor the Gaussian distribution hypothesis are essential for the algorithm; they only simplify the analytical computation. Any other law can be assumed even though, with formulae more complex than (1), the computation of virtual distances and ages is not straightforward as in (4) and (5) and, consequently, an iterative algorithm may be required.

The Computer Package

The puff method discussed above has been codified into a computer package. The current version of this programming code (AVPPM/2A) requires suitable input data on wind, turbulence, and emission characteristics, and allows the computation of the concentration values at the required receptor points, according to the methodology discussed above.

Various options allow use of different σ parameters, plume rise functions, ground and inversion reflection parameters, etc. Moreover, for complex terrain situations, the elevation over the ground of the center of each puff is forced, from one time step to the next, to remain within a pre-fixed range in order to better take into account terrain irregularities.

The package is relatively fast. The CPU requirement is strongly dependent upon the number of puffs to be generated by splitting into each quadrilateral, and then on the number and position of sources and receptors used in the numerical simulation.

CONCLUSIONS

Experimental data are expected to validate this approach, especially the algorithm which allows the treatment of calm conditions. Data are also expected to suggest puff concentration distributions different from the Gaussian one and easily incorporable into the method.

Acknowledgements

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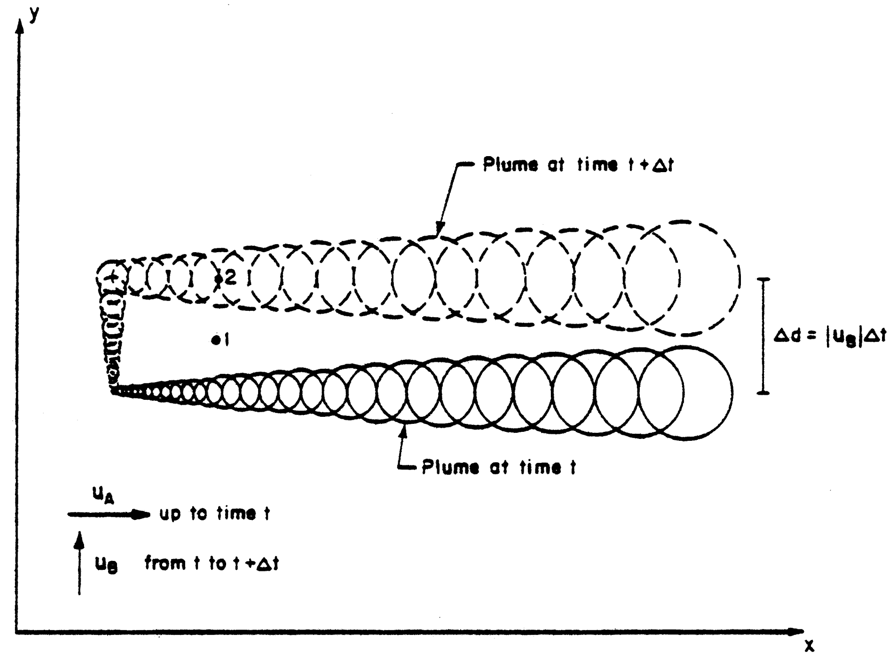
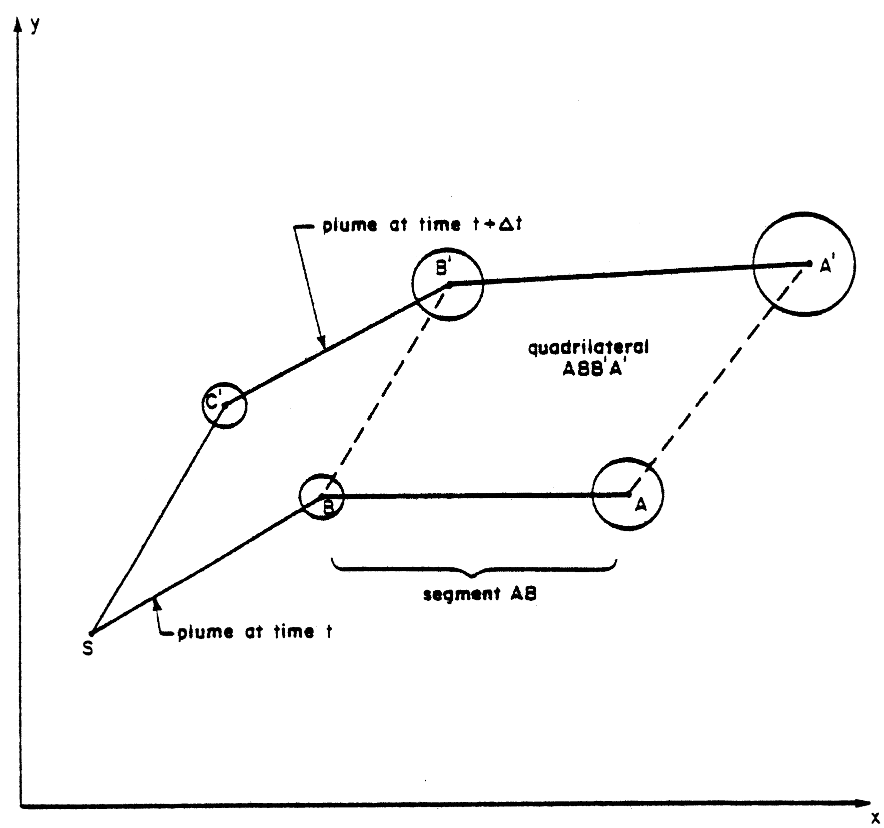

y
Plume at time $t+\Delta t$
2
1
$\Delta d = |u_B|\Delta t$
Plume at time t
u_A
up to time t
u_B from t to $t+\Delta t$
x


y
plume at time $t+\Delta t$
B'
A'
quadrilateral
ABB'A'
C'
B
A
segment AB
S
plume at time t
x

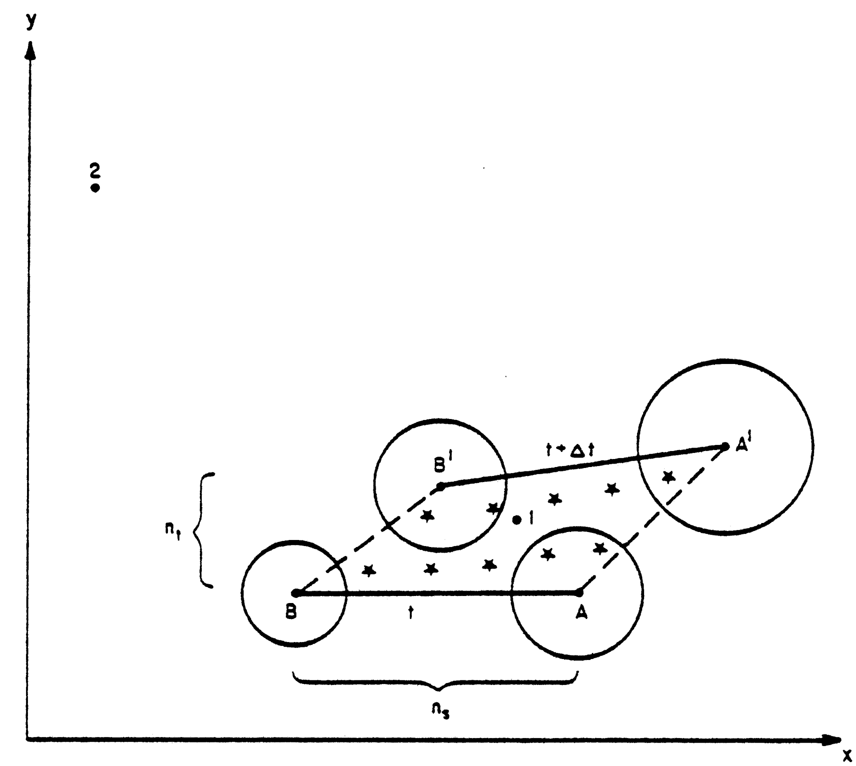

y
2
B'
t + Δt
A'
n_t
1
B
t
A
n_s
x

FIGURE LIST

Figure Number	Caption
1	Fig. 1. A sudden change of wind direction at time t can produce underestimation at receptor 1 and overestimation at receptor 2 during the interval [t, t + Δ t]. The circles indicate one standard deviation from the center of each puff.
2	Fig. 2. In the AVPPM method all mass emitted from S and located at time t in the segment AB is concentrated in A, which moves to A' in the time interval [t, t + Δt]. Actually, this mass has affected the quadrilateral ABB'A' during the interval [t, t + Δt]. The circles have the same meaning as in Fig. 1.
3	Fig. 3. Analysis of one quadrilateral (the circles have the same meaning as Fig. 1). The contribution to receptor 2 is zero while, for computation at receptor 1, $n_t \times n_s$ puffs are generated (splitting technique with σ's interpolation) in the quadrilateral ABB'A' and are indicated by asterisks (n_s = 5, n_t = 2). The characteristics of each new puff (center position and σ's) are obtained by interpolation among the known characteristics of the four puffs, A, B, B', A'.