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Comparison of plume lateral dispersion coefficients schemes: Effect of averaging time

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ABSTRACT

Dispersion modeling is an important decision tool for estimating the impact of human activities on the environment and its populations. However, it was proved by researchers that AERMOD and CALPUFF, the current regulatory models, do not account for the effect of averaging time. In consequence, these models do not have the ability to predict short-term time peak concentrations. This inability arises from the errors in the lateral and vertical dispersion estimates, which are reliable only to predict 10 min or longer average concentrations. In this paper, a novel evaluation based on Irwin (1983) was conducted to investigate the effect of averaging time on the lateral dispersion and maximum concentration estimates. The Pasquill-Gifford, Högström, Draxler (embedded in CALPUFF) and AERMOD lateral dispersion schemes were tested using the Round Hill II experiment, developed to investigate the effects of averaging time on atmospheric transport and diffusion. The observed lateral dispersion was derived from the lateral concentration profiles along 3 sampling arcs (50, 100 and 200 m), measured on 3 different averaging times (0.5; 3 and 10 min). The observed lateral dispersion was compared to those estimates. The results of the comparison show that AERMOD and Draxler correlate better with measured data than the PG and Högström methods. However, their estimates are biased and the magnitude of systematic errors tends to grow as the averaging time decreases. Moreover, AERMOD and Draxler, with Peak-to-Mean (P-M) adjustment, tend to overestimate the lateral dispersion farther from the source and underestimate at downwind distances less than 200 m. The analysis also highlights some concerns on the P-M ratio application due its subjectivity. The present investigation on the effect of short-term averaging times on atmospheric transport and diffusion may help to understand some issues related to the use of dispersion models in the case of flammability, malodor nuisance and toxicity

1. Introduction

Dispersion models have been frequently used in air pollution problems to determine the concentration of contaminants downwind from a continuous point source (Draxler, 1976). However, most of the Gaussian and Puff models including Industrial Source Complex 3 (ISC3), AERMOD and CALPUFF, the most used and recommended models by the US EPA, are unable to predict short-term peak concentrations. Several applications require estimates of concentrations averaged over shorter time periods that those estimated with models commonly used for regulatory applications, such as AERMOD and CALPUFF. For example, predicting odor concentrations requires converting AERMOD 1 h estimates to values that correspond to averaging times of a few seconds to few minutes (Venkatram, 2002). According to several researchers, a lack of agreement has been found between the estimated and observed downwind concentrations using these models on shorter averaging times (Beaman, 1988). In fact, those models were not designed to predict short-term peak concentrations.

The widely used Gaussian approximations were calibrated from historical tracer dispersion experiments, with averaging times of 10 min or longer (Irwin et al., 2007). Therefore, estimates are only reliable under these respective temporal scales. Common practice consists of converting model predicted estimates to shorter time periods using Peak-to-Mean (P-M) formula presented on Equation (1) (Dourado et al., 2012; Venkatram, 2002; Vieira de Melo et al., 2012; Wang et al., 2006).

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$$\frac{C_m}{C_p} = \left(\frac{t_m}{t_p}\right)^{-c} \quad (1)$$

This expression relates the maximum mean concentration (C_p) observed for a shorter averaging period (t_p) and the maximum mean concentration (C_m) observed for a longer averaging period (t_m), which is the mean concentration calculated by the model. The values of the exponent, c, in the literature range from 0.2 to 0.5 (Venkatram, 2002), depending on atmospheric stability (Schauberger et al., 2012).

For shorter averaging times, ISC3, AERMOD and CALPUFF require P-M conversion due to the sum of the effects of dispersion and change in the axis of the plume (meandering), which are considered as absolute dispersion in their estimates. These effects are caused by different turbulent scales, which are virtually indistinguishable, except that only the relative diffusion of the plume around its instantaneous centroid is responsible for the effective dilution of pollutants. Plume meandering is the slow lateral back-and-forth shifting of a plume in response to nondispersing lateral eddies that are larger than the plume (Cimorelli et al., 2005). The more the averaging time increases and the distance from the source to the receptor decreases, the more important the meandering influence on the lateral dispersion is. Meandering tends to disappear over longer averaging times and farther from the source, and the fluctuations are mainly internal (Mortarini et al., 2009). Generally odors are no longer perceived further than few kilometers from the source (Guo et al., 2004).

The reason why both meandering and relative dispersion effects are treated as absolute dispersion in the regulatory models, has the critical point in the estimate of the vertical and horizontal growth of the plume. This growth is usually expressed in terms of the standard deviation of the concentrations in the lateral and vertical directions (σ_y–σ_z) (Draxler, 1976). In practice, these terms are very difficult to quantify effectively and in problems of atmospheric diffusion, σ_y and σ_z are estimated by empirical and semi-empirical methods (Hay and Pasquill, 1957). According to Draxler (1976), several methods have been suggested to determine the dispersion coefficients. However, they all share a weakness: the inability to calculate short-term time averages, as in the case of flammability, malodor nuisance and, often, toxicity (Vieira de Melo et al., 2012; Dourado et al., 2014). In spite of this limitation, those methods have been extensively used to predict odor and toxic dispersion. In this sense, more discussion appears to be needed on the communication of the magnitude of errors to decision makers (Irwin et al., 2007).

In this respect, the present work aims to evaluate the lateral plume dispersion parameters compared to field tracer data collected in three different averaging times. Complementing Irwin's (1983) work, this novel evaluation was conducted to investigate the effect of averaging time on the lateral dispersion and arc maximum concentration estimates. The dispersion parameters schemes used in this analysis include Pasquill-Gifford using Turner's technique (Turner, 1997), Högström (1964) and those embedded in AERMOD (Cimorelli et al., 2005) and CALPUFF using Draxler's (1976) method. The performances of these methods are compared with observations of Round Hill II tracer data. The main focus of this work is to help understanding some problems that occur when employing dispersion models to predict short-term peak concentrations.

2. Background

Due the lack of understanding of turbulence, for atmospheric transport and dispersion, it is very difficult to reproduce exactly the observations of a plume at a given time and location. (Yee et al., 1994). Plume dispersion is caused by turbulent eddies of different sizes. While small turbulent eddies tend to spread the plume, large eddies tend to cause it to meander. As the plume becomes wider, larger eddies become effective in dispersing it and smaller eddies become increasingly ineffective (Gifford Jr., 1959; Seinfeld and Pandis, 2006). Therefore, eddies that are larger than the instantaneous plume width will waft around the plume as a whole without changing its internal structure, and contribute to the low-frequency motions of the dispersing material in the form of plume meandering, causing intermittency (periods of zero concentration). On the other hand, eddies of smaller size that are comparable to the size of the plume produce local distortions and convolutions that contribute to the in-plume fluctuations due to clean the air entrainment (Yee et al., 1994).

To mitigate the effects of fluctuations, the best that can be done is to predict the average characteristics of plume dispersion (Irwin et al., 2007). Nevertheless, there are some effects on averaging the plume properties. Figure 1 shows the real case of plume boundaries and concentration distributions of an instantaneous snapshot and exposures of a few minutes and several hours. The meandering behavior of the instantaneous plume can be seen, with the width of the plume gradually growing downwind of the source. As the averaging time increases, the plume assumes a more regular appearance and the concentrations have a smoother distribution (Seinfeld and Pandis, 2006). Due to the sum of the large and small eddies effects, it is typical of observed plumes that the lateral and vertical instantaneous dispersion are smaller than the averages and, consequently, the instantaneous concentrations are at least as large as the mean (Hanna, 1967). The plume meandering dominates the concentration fluctuations of time averaged plumes at short downwind distances (in the range of few kilometers), while the effects of in-plume fluctuation appears farther from the source.

Irwin et al. (2007) reported the influence of averaging time on atmospheric transport and diffusion. Analyzing data from the Round Hill II field experiment, the concentrations measured at 30 s are around 1.66 times higher than those measured at 10 min.

Most of the Gaussian models consider an average concentration for a time period ranging from 10 min to 1 h (De Melo Lisboa et al., 2006). According to Cimorelli et al. (2005), in the AERMOD the lateral dispersion expression was reformulated to better fit the data from the Prairie Grass Experiment. On the respective tracer database, samples were collected over 10 min averages, allowing the AERMOD to estimate lateral dispersion over this averaging time or longer. The limitations of CALPUFF and the Pasquill-Gifford curves are similar. One of the most reliable methods used to calculate the dispersion coefficients in CALPUFF is based on Draxler's (1976) formulation. The semi-empirical method developed by Draxler employed the major part of the data with averaging times of 30 min or longer. Pasquill-Gifford empirical curves were based on samples collected over 10 min averages of near-ground level releases.

According to Mortarini et al (2009) and Franzese (2003), Gifford's (1959) fluctuating plume model proved to be a simple and effective tool for predicting concentration moments of order higher than the mean for stationary releases of contaminant in idealized homogeneous turbulence. The Gifford's model, later adapted by Mussio et al. (2001), De Melo Lisboa et al. (2006) and Dourado et al. (2014), is a Gaussian model capable of providing the percentage of time during which concentration remains above or below a defined threshold. This characteristic turns the respective model a valuable tool for odorant compound dispersion modelling. This model is based on the idea that the plume can be decomposed into two independent parts: a meandering part and a relative-diffusion part (Mortarini et al., 2009). However, it is assumed that there are no fluctuations inside the instantaneous plume (Hanna,