Atmospheric Environment 43 (2009) 778–786

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

A simple urban dispersion model tested with tracer data from Oklahoma City and Manhattan

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ARTICLE INFO

Article history:
Received 20 June 2008
Received in revised form
28 October 2008
Accepted 3 November 2008

Keywords:
Urban dispersion
Simple urban dispersion model
Joint Urban 2003 (JU2003) field experiment
Madison Square Garden 2005 (MSG05) field experiment
Air quality model evaluation
New York City air pollution

ABSTRACT

A simple urban dispersion model is tested that is based on the Gaussian plume model and modifications to the Briggs urban dispersion curves. An initial dispersion coefficient (σ_o) of 40 m is assumed to apply in built-up downtown areas, and the stability is assumed to be slightly unstable during the day and slightly stable during the night. Observations from tracer experiments during the Joint Urban 2003 (JU2003) field study in Oklahoma City and the Madison Square Garden 2005 (MSG05) field study in Manhattan are used for model testing. The tracer SF_6 was released during JU2003 near ground level in the downtown area and concentrations were observed at over 100 locations within 4 km from the source. Six perfluorocarbon tracer (PFT) gases were released near ground level during MSG05 and sampled by about 20 samplers at the surface and on building roofs. The evaluations compare concentrations normalized by source release rate, C/Q, for each sampler location and each tracer release, where data were used only if both the observed and predicted concentrations exceeded threshold levels. At JU2003, for all samplers and release times, the fractional mean bias (FB) is about 0.2 during the day (20% mean underprediction) and 0.0 during the night. About 45 –50% of the predictions are within a factor of two (FAC2) of the observations day and night at JU2003. The maximum observed C/Q is about two times the maximum predicted C/Q both day and night. At MSG05, for all PFTs, surface samplers, and release times, FB is 0.14 and FAC2 is about 45%. The overall 60 min-averaged maximum C/Q is underpredicted by about 40% for the surface samplers and is overpredicted by about 25% for the building-roof samplers.

1. Objectives and background

Observations from urban field experiments are being analyzed to aid in the development and evaluation of models for urban flow and dispersion. A simple urban dispersion model is suggested and compared with data from the Joint Urban 2003 (JU2003) field experiment in Oklahoma City (Allwine et al., 2004; Allwine and Flaherty, 2006a) and the Madison Square Garden 2005 (MSG05) field experiment in Manhattan (Allwine and Flaherty, 2006b, 2007). Both of these recent short-term research-grade experiments involved continuous releases of tracer gas near street level in the downtown area, sampling of the tracer gas over a broad area in the downtown area, and extensive supporting meteorological information.

The simple urban dispersion model that is tested is a slight variant of the urban dispersion model developed by the author in the 1970s (Hanna 1971; Gifford and Hanna 1973) and updated in the past ten years (Hanna et al., 2003). The model uses dispersion coefficients, σ_y and σ_z, consistent with the so-called Briggs urban formulas (Briggs, 1973; Hanna et al., 1982), which were primarily based on tracer observations from a field experiment involving tracer gas releases in St. Louis in the 1960s (McElroy and Pooler, 1968). Venkatram (2005) reanalyzed those data from a modern vantage point and compared them with his recent observations and updated theories. As he points out, McElroy and Pooler (1968) suggested that there may be an initial σ_y and σ_z of about 40 m, due to mixing around building obstacles near the source. However, their best-fit lines and the formulas of Briggs (1973) did not use this initial value, perhaps because they felt that there were insufficient data close to the source (the nearest samplers were 800 m away). The simple model used in the current paper reincarnates the initial σ_y and σ_z of 40 m assumption and tests it with data near the source.

In the past 10–20 years, there have been several other detailed urban meteorology and dispersion field experiments, including a few outside of the U.S., such as the Basel Urban Boundary Layer Experiment (BUBBLE) (Rotach et al., 2004), and the London field experiment known as Dispersion of Air Pollutants and their Penetration in Local Environments (DAPPLE) (www.dapple.org.uk, 2008). However, most of the "urban" field data from the European studies are from areas of cities where buildings have heights of no more than a few stories. Besides the JU2003 and the MSG05 field

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doi:10.1016/j.atmosenv.2008.11.005

experiments, there are few tracer gas observations in built-up downtown areas with deep street canyons and nearby tall buildings with height exceeding 100 m.

2. Simple Gaussian model description

Urban dispersion model development over the past ten years has covered a broad range of complexity. At the high end of complexity, Computational Fluid Dynamics (CFD) models with high-resolution grids with dimensions of a few meters are being developed and satisfactorily applied over urban domains (e.g., Hanna et al., 2006). These models require input of detailed 3-D building geometry, and can account for flow and dispersion around specific buildings. At the low end of complexity, simple urban dispersion models have been proposed and tested by several groups (e.g., Batchvarova and Gryning, 2006; Neophytou et al. 2005; Hanna et al. 2003; Venkatram 2005). The simple models account for enhancements of turbulence (and hence dispersion), reductions of mean wind speeds, and a tendency towards neutral stabilities in urban areas. These authors argue that it is sufficient to parameterize the average flow speeds and turbulence in urban canopies.

The simple Gaussian urban model that is used in this paper is described below, including the justifications for some key assumptions. It is assumed that the source is emitted at height, h, within the urban canopy with mean building height, *H*. The Gaussian formula can be written:

$$C/Q = (1/(\pi u \sigma_y \sigma_z)) \times \exp\left(-y^2/2\sigma_y^2\right) \exp\left(-(z-h)^2/2\sigma_z^2\right) \quad x > 0 \tag{1}$$

where C is concentration in g m^{-3} and Q is continuous release rate in g s^{-1}. The variables and parameters are assumed to represent time averages over a period approximately equal to the continuous release period and not exceeding 60 min.

For the field experiments used for model testing in this paper, the tracer gases are released a meter or two above street level and the sampler height is about 3 or 4 m. It can be assumed that the release height, h, and the sampler height, z, are at ground level (0 m). This would be a valid assumption even if the release height is as high as 10 m in an urban environment, because of the large initial plume spread.

The following variables are used in eq. (1):

z (m) is height of the receptor or sampler above ground level.
y (m) is the lateral distance from the plume centerline or axis. The plume axis is lined up with the wind direction during the period of interest, where the wind direction could be measured a number of ways but should represent an average flow over the domain.
u (m s^{-1}) is the averaged vector wind speed for the plume as it is transported in the urban canopy.
σ_y (m) is the lateral cross-wind standard deviation of the concentration distribution.
σ_z (m) is the vertical cross-wind standard deviation of the concentration distribution.

The standard deviations σ_y and σ_z are assumed to be made up of two parts, an initial σ_o due to the mixing in the street canyons at the source location, and a turbulent σ_t due to the usual ambient turbulence, which exists over all types of terrain. The turbulent part is a function of downwind distance, x (m), defined as the along-wind distance from the release point to a point on the plume axis (centerline). Earlier field experiments in urban areas (e.g., the St. Louis tracer data reported by McElroy and Pooler, 1968) suggest that the initial $\sigma_{yo} = \sigma_{zo} = 40$ m. The following formulas are assumed for σ_y and σ_z for day and night conditions in urban built-up areas:

$$\sigma_y = \sigma_{yo} + \sigma_{yt} = 40 \text{ m} + 0.25x \quad \text{day} \tag{2a}$$

$$\sigma_y = \sigma_{yo} + \sigma_{yt} = 40 \text{ m} + 0.08x \quad \text{night} \tag{2b}$$

$$\sigma_z = \sigma_{zo} + \sigma_{zt} = 40 \text{ m} + 0.25x \quad \text{day} \tag{3a}$$

$$\sigma_z = \sigma_{zo} + \sigma_{zt} = 40 \text{ m} + 0.08x \quad \text{night} \tag{3b}$$

The parameters (or "constants") 0.25 and 0.08 are based on Briggs' (1973) urban sigma formulas for day and night conditions, respectively. The Briggs formulas indicate a slight difference between the parameters for σ_y and σ_z, but we assume that they are equal here for simplicity. The parameters 0.25 and 0.08 can also be thought of as turbulence intensities (turbulent standard deviation divided by wind speed). In built-up urban downtown areas, the Briggs' dispersion curves account for the fact that the effective stability is always more nearly-neutral than in rural areas because of the strong mechanical mixing generated by the large buildings even in the presence of a large sensible heat flux. Also, during the night, the urban area has significant anthropogenic heat fluxes that counter any tendency towards downward sensible heat fluxes. This is confirmed by observations of JU2003 and MSG05 heat fluxes and Obukhov length, *L*, which consistently indicate nearly-neutral conditions (Hanna et al., 2007).

On the plume centerline ($y = z = 0.0$) at large downwind distances, x, during the day, Eq. (1) approaches the limit $Cu/Q = 5.1/x^2$, which is nearly identical to the relation observed at JU2003 and MSG05 (Hanna et al., 2007) and suggested by Neophytou et al. (2005). Eq. (1) approaches $Cu/Q = 50/x^2$ during the night, which also agrees with the JU2003 average observations. However, because of the initial plume size of 40 m at $x = 0.0$ assumed in Eqs. (2a), (2b) and (3a), (3b) Cu/Q becomes independent of x near the source, approaching about 0.0002 m^{-2} as x approaches 0.0 during both day and night.

Because of use of the initial σ, it is implied that the cloud of material spreads out into a hemispherical shape around the source area. Thus there is material dispersing even in the upwind direction (at $x < 0.0$). This can be accounted for by the following correction for $x < 0$, where the along-wind σ_{xo} is assumed to also equal 40 m.

$$C/Q = (1/(\pi u \sigma_{yo} \sigma_{zo})) \times \exp\left(-y^2/2\sigma_{yo}^2\right) \exp\left(-z^2/2\sigma_{zo}^2\right) \exp\left(-x^2/2\sigma_{xo}^2\right) \quad \text{for} \quad x < 0 \tag{4}$$

This formula is designed to handle the JU2003 and MSG05 samplers that are located in an upwind ($x < 0$) sector.

An additional correction is applied for MSG05, where high concentrations are observed at samplers within about 100 m of the source. These high concentrations occur even at samplers upwind or perpendicular to the wind direction. Consequently, for the MSG05 samplers at distances from the source less than about 100 m, or when the line-of-sight is unobstructed between the release point and the sampler, it is assumed that the plume remains in the initial street canyon or courtyard and travels more or less unimpeded without being extensively mixed laterally by the multiple large buildings. In this case, we assume that the initial lateral dispersion ($\sigma_{yo} = \sigma_{xo}$) is smaller. A value of 10 m is assumed because that value appears to produce minimum bias for the MSG05 near-field samplers, but this is subject to further analyses. The turbulent dispersion remains the same.