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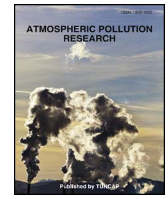

Short-term passive tracer plume dispersion in convective boundary layer using a high-resolution WRF-ARW model

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A B S T R A C T

High-resolution Advanced Research Weather Research and Forecast model is used to understand the role of atmospheric stability on the short-term transport of a continuous release passive scalar plume in three different convective boundary layer regimes: highly convective, combined shear- and buoyancy and shear dominated. Friction velocity to convective velocity ratio and atmospheric stability parameter are used to classify the boundary layer regimes. The effect of release height on the plume transport is addressed by releasing the plumes at surface, near-surface and elevated heights. Total 144 simulations are performed by releasing the plume in the morning and afternoon times of January and August months and at three release heights. Results show that horizontal transport of the plume scales with the initial wind conditions for surface and near-surface releases, and the vertical transport scales with atmospheric stability parameter. Mean plume height and vertical dispersion parameter obtained by convective scaling laws reached their asymptotic values after getting well-mixed in the boundary layer. The dimensionless downwind distance for the mean plume height to reach its asymptote is found to follow a power-law with respect to the atmospheric stability paramter. The coefficient and exponent of the power-law observed are found to be functions of the plume release height normalized by the boundary layer depth.

1. Introduction

Above the ground, a convective boundary layer (CBL) exists due to the forcing by the buoyancy production at the surface of the earth (heating of the ground) and due to the wind shear. The combined effect of convection- (buoyancy) and mechanical- (shear) generation of turbulence result in layer of well-mixed turbulence in CBL (Turner, 1994). On the release of a plume in a CBL, the relative role of buoyancy and wind-shear play a significant role in the plume transport. This is a very challenging problem, and very little is understood of the effect of plume transport under various realistic conditions of the CBL.

Fundamental studies have contributed significantly to our basic understanding on the key CBL dynamics that influence the plume transport. For CBL the Near-Neutral conditions occur when dominant motions are shear-induced. During moderate and stronger convective conditions, depending on their relative strength, both shear- and buoyancy interact resulting in turbulent longitudinal vortices with updrafts and downdrafts originating near the ground. Thus, creating a vertical flux of momentum, buoyancy and scalars. During these conditions, studies have demonstrated that the plume centerline deviates from its emission height and instead loops up and down (Bierly and Hewson, 1962; Briggs, 1965); and the plume spreads about this centerline (Gifford, 1960; Garratt et al., 1992). When averaged over longer time-periods covering many convective circulations, the plume centerline height vs. downwind distance exhibits stationary pattern (Briggs, 1993; Stull, 2012).

The mixing layer height of the CBL and turbulence in this layer play an important role in dictating the vertical transport of the plume. Pollutants released into shallow boundary layer have limited vertical transport (Banta et al., 2005; Petäjä et al., 2016), when compared to those releases into deeper boundary layers (Banta et al., 1998; Stull, 2012). A shallow CBL e.g. occurs during summer early mornings, with limited mixing height restricts the vertical transport of plume elements (Lyons and Cole, 1973; Stull, 2012). Lyons and Cole (1973) observed large degree of mixing (especially in horizontal) and greater horizontal transport of pollutants when they are released into a shallow mixed layer of 135 m from a 20 m height exhaust stack of a fertilizer plant located in Michigan, United States of America (USA). As the boundary layer deepens during late afternoons, the formation of convective eddies carry the plume elements aloft. Banta et al. (1998) observed

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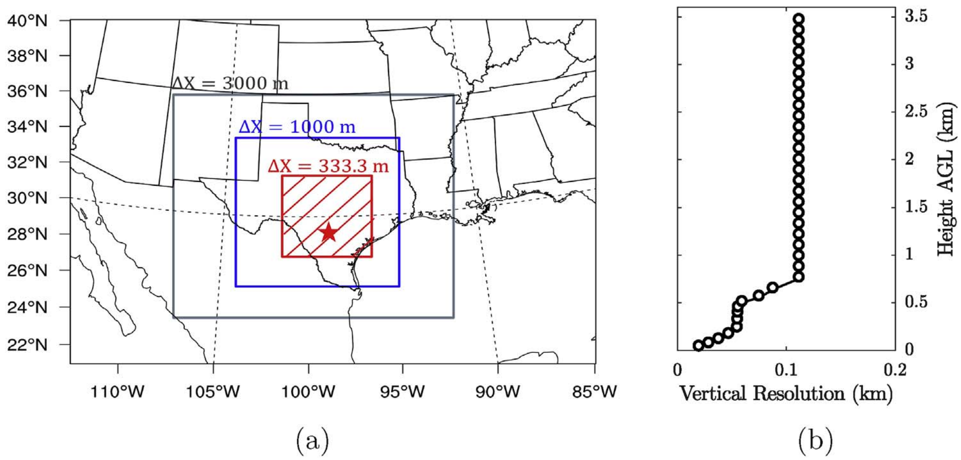

Fig. 1. (a) WRF Model Domain configuration with 3 nested domains. The parent domain has horizontal grid resolution of $12km$. Red Star indicates the passive tracer release location. (b) Model vertical resolution as a function of altitude.

reduction in horizontal transport of Ozone elements because of the existence of deep mixing layer and light winds over Nashville, USA. The horizontal transport scales of the pollutant are governed by the wind shear, wind strength and the local atmospheric turbulence (Barr et al., 1983; Banta et al., 1998). It is clear that the interplay of the wind shear, wind strength, buoyancy, and the turbulence together govern the horizontal and vertical transport of the plume. Thus, the study of plume transport is tightly connected to the understanding of the dynamics of the CBL.

The regimes of the CBL are quantified using CBL metrics shear-buoyancy ratio (u_*/w_*) and the stability parameter ($\zeta = -z_i/L$), (where u_* is friction velocity, w_* is convective velocity, z_i is CBL height and L is the Monin-Obukhov length scale) (Dosio et al., 2003). Based on the above CBL metrics, the atmospheric regimes used in this study are as follows: (1) Pure Convective (B) regime which is mainly dominated by buoyancy forcings and is highly unstable with large subsidence ($u_*/w_* \leq 0.2$, $\zeta \geq 40$), (2) Shear-Buoyancy (SB) regime with both shear- and buoyancy forcings, and is moderately unstable ($u_*/w_* \approx 0.3$, $\zeta \cong 10$), and (3) Near-Neutral (NN) CBL regime, which is shear dominated and is weekly unstable ($u_*/w_* \sim 0.6$, $\zeta \sim 2$). The study addresses an outstanding question on differences in the short-term transport of non-buoyant plumes under these different CBL regimes.

Most of our current understanding of short-term transport of passive plumes from laboratory-based experimental measurements (Deardorff, 1985; Willis and Deardorff, 1976, 1978) or high-resolution large-eddy simulations (Nieuwstadt, 1992; Dosio et al., 2003) use idealized conditions. Recent numerical studies of Dosio et al. (2003), and Nottrott et al. (2014) focused on the dispersion of passive scalars released into various convective conditions use quasi-equilibrium state of the CBL as initial conditions, which does not account for the true state of the atmosphere. Towards this direction, significant work was performed recently on using Advanced Research Version of Weather Research and Forecast (WRF-ARW) as a modeling platform to study plume transport (Yerramilli et al., 2009; Yu et al., 2012; Yver et al., 2013; Nottrott et al., 2014; Blaylock et al., 2017). Further, it was established that simulated meteorological data using WRF-ARW model are closer to the observations(Yerramilli et al., 2009; Coniglio et al., 2013; Avolio et al., 2017).

The present work is different from these existing works, as we use high-resolution WRF-ARW v3.8 (hereafter WRF) (Skamarock and Klemp, 2008); with realistic boundary conditions derived from National Center for Environmental Prediction (NCEP) North American Model Analysis (NAM-ANL) dataset. A scalar transport equation included in WRF represents the transport of the passive tracers. The study includes the effect of large-scale atmospheric forcing on the short-term transport of non-buoyant (passive) and conservative (without chemical reactions or chemical mixing) tracer plumes in different CBL regimes. The objective of the study is to address the question - what is the effect of the atmospheric stability and release height on the dispersion of passive plumes when released in different CBL regimes.

As the input data for WRF model is available at coarser resolution, the initial and boundary conditions to actual domain are obtained by multiple nested WRF domains. The regional domain for all the cases is the Bexar County located in the south-central part of Texas, United States. Passive tracers are initialized in the center of the county (29.4241^o N, 98.4936^o W), which is the downtown area of the City of San Antonio. Before emitting the passive tracers into atmosphere, the WRF model is spun-up for 12 h. The release times are 0700 CST (= UTC-6 hours) and 1300 CST during the months of January and August. For studying the effect of different release heights (z_s), the passive tracers are released at surface level ($z_s/z_i = 0$), near surface level ($z_s/z_i < 0.1$) and far from surface ($z_s/z_i > 0.1$). In this study, cases are simulated for 12 days in each of January and August months with a total of 144 realizations. Post-processed variables are ensemble averaged over their 12 realizations. The individual realizations selected have their wind-speed and temperature deviations of order 1–2 m/sec and 2–5 K from the respective ensemble mean values.

The structure of this paper is as follows: Section 2 summarizes the methodology followed using WRF for configuring the simulations. Section 3 explains different case studies simulated in the study. Section 4 gives the WRF model validation with the observed values from meteorological stations and a chosen field experiment data to validate the tracer transport. Tracer transport results in both horizontal and vertical are presented in Section 5. Detailed analysis of tracer vertical transport using convective scaling laws is presented in Section 6.

2. Methodology

2.1. Domain configuration

The WRF model is configured with four nested domains with the outer domain having the same resolution of 12 km as the data-set used for boundary conditions. Remaining three nested domains are at horizontal resolutions of 3 km, 1 km and 333.33 m in the inner most domain, which is shown in Fig. 1 (a). 38 vertical levels are configured between the surface and 3500 m, with 14 levels located in the lowest 1000 m above the surface, shown in Fig. 1(b). The first model level top is specified at an altitude of 20.8 m above the surface. The initial and lateral boundary conditions needed for WRF are provided by the meteorological datasets obtained from the NAM-ANL dataset over the grid 218 with a spatial resolution of 12 km, 40 vertical levels and 4 samples per day. Run by NCEP, NAM-ANL is one of their major weather forecast models and it is initialized with a 6-hour data assimilation cycle with