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An improvement of the two-stream model for vertical mixing of passive tracer in the convective boundary layer

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Abstract

The two-stream model (TSM; Chatfield and Brost, J. Geophys. Res. 92 (1987) 13263–13276) was developed to account for advection-like vertical mixing features of a passive tracer in the convective boundary layer (CBL). In the TSM, the tracer is advected by two-streams (that is, mean updraft and downdraft), of which the vertical profiles are prescribed as functions of the CBL similarity scales, that is, the CBL height and velocity scales. Compared to the results from large-eddy simulation (LES) and laboratory model, the TSM shows similar plume propagation behavior, but the plume propagation speed appears to be too slow. This drawback of the TSM is found to be mainly due to too weak updraft and downdraft. To improve the TSM, therefore, we modify the prescribed vertical profiles of the mean updraft and downdraft using the LES data. Compared to the original up and down draft velocity profiles, the modified profiles have significantly larger magnitudes in the lower CBL while having similar magnitudes in the upper CBL. The realism of the modified TSM simulation of vertical mixing in the CBL is tested for near surface and elevated tracer sources against the LES results of which validity has been well verified with laboratory experiments and observation. For comparison purpose, we introduce other non-local closure models such as the Blackadar model, the asymmetric convective model, and the transilient turbulence parameterization as well as a local K-theory-based scheme. The modified TSM not only predicts much more improved tracer propagation than the original TSM but also yields the most superior results among the models introduced in this study, showing a remarkably realistic description of the temporal behavior for the concentration distributions and the ground and source level concentrations.

Keywords: Closure model; Air quality; Vertical transport; Large-eddy simulation

1. Introduction

Mixing in the convective boundary layer (CBL) is dominated by large coherent eddies which are driven by heating at the surface, fill the entire CBL, carry most of the vertical flux, and contain most of the turbulent kinetic energy (TKE) in the CBL. In a very idealized sense, the large eddies can be pictured as broad regions of gentle downdrafts surrounding smaller regions of strong updrafts (Stull, 1988). Therefore, vertical mixing of air mass in the CBL is essentially advection-like and asymmetric. In their ingenious laboratory experiments, for example, Willis and Deardorff (1976, 1978, 1981) have found that the plume from a near surface source of a passive tracer lifts from the ground and gives rise to an

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elevated maximum concentration in the upper CBL, while the plume from an elevated source descends until it impinges on the surface causing a surface concentration maximum there. Willis and Deardorff's laboratory results have also been confirmed by field experiments (Moninger et al., 1983).

The use of large-eddy simulation (LES) model to investigate dispersion of a passive contaminant in the atmosphere (e.g., Lamb, 1978; Nieuwstadt and de Valk, 1987; Sykes and Henn, 1992) as well as interior turbulence structure (e.g., Moeng, 1984; Mason, 1989; Schmidt and Schumann, 1989) has become increasingly common. In particular, excellent agreement of the LES results with laboratory experiments and field experiments aforementioned has demonstrated the usefulness of the LES for studying contaminant dispersion. In LES, the large-scale eddies are explicitly resolved, while small-scale eddies are parameterized through a closure model. One reason for the success of this approach is that the small-scale eddies tend to be more isotropic and universally similar, and are therefore more amenable to parameterization than the large-scale eddies, which are much more dependent on the type of flow. One of the basic requirements of LES is that the grid size should be much smaller than the integral length scale to guarantee the isotropy of the subgrid scale eddies. Therefore, direct application of LES to a three-dimensional regional air quality model with horizontal grid size from few kilometers to few hundreds kilometers is almost impossible with the presently existing computer resources.

While many Eulerian air quality models use a local eddy-diffusion (K-theory) concepts to represent the vertical turbulent mixing in the atmospheric boundary layer, it is well known that the K-theory not only limits the vertical mixing within adjacent layers but also mixes air mass symmetrically. Especially in the CBL, it cannot adequately represent the turbulent mixing process caused by the large asymmetric thermal eddies. The poor representation of the vertical mixing with the K-theory is mainly caused by the neglect of this advection-like (non-local) and asymmetric vertical mixing process. In order to overcome the shortcomings of the local eddy-diffusion, various non-local closure models described later in the text have been developed for meteorological applications. In non-local closure models, turbulent fluxes are computed as functions of large-scale gradients rather than local gradients as in local K-theory-based schemes. While these models are somewhat successful for meteorological applications where the most important task is the proper simulation of heat and moisture fluxes, they are not much successful for air quality applications where there are a greater variety of situations such as emission of chemical species in the middle of the CBL that results in severe vertical gradients of concentration around the source level.

Chatfield and Brost (1987) developed a two-stream model (TSM) to describe the vertical mixing of a passive tracer in the CBL. The TSM is basically an advective model, where the tracer is advected by two streams (that is, mean updraft and downdraft) with a relatively small diffusive component. Compared to the results from a LES model and laboratory model, the TSM showed a surprisingly similar downward propagation of the maximum concentration for the elevated source although the propagation speed appeared to be too slow. To our knowledge, the TSM appears to be most realistic in parameterizing vertical turbulent transfer in the CBL among existing closure models that can be used in Eulerian air quality models. Based on a LES result, in this study we have modified the TSM to improve the slower plume propagation problem. In particular, we focus on a realistic description of a short-term transient concentration transport feature before air contaminants are well mixed. The realism of the TSM simulation of vertical mixing in the CBL is evaluated for near surface and elevated tracer sources through comparison to the LES. In addition to the TSM, we introduce some other closure models in the literature for comparison purpose.

In Section 2, the TSM and some existing local and non-local closure models are described. In this section, input parameters required for the models are also derived from the LES data. In Section 3, modification of the model parameter for the TSM is described. In Section 4, we present and discuss results from the original TSM, the modified TSM, and the other models in comparison with those from the LES. Finally, in Section 5 we summarize our results and draw some conclusions.

2. Models and initial conditions

In their TSM, Chatfield and Brost (CB, 1987) considered the CBL to be divided into two types of air (i.e., two streams), thermal air (updrafts) and environmental air (downdrafts). Then, they derived a prediction equation for average concentration in each stream, assuming an incompressible and constant density flow. For the updrafts,

$$\alpha_\mathrm{u}\frac{\partial \bar{c}_\mathrm{u}(z)}{\partial t} = -\frac{\partial}{\partial z}(\bar{w}_\mathrm{u}\bar{c}_\mathrm{u}\alpha_\mathrm{u}) + \frac{\partial}{\partial z}\left(\alpha_\mathrm{u}K_\mathrm{u}\frac{\partial \bar{c}_\mathrm{u}}{\partial z}\right) - r_\mathrm{u}\bar{c}_\mathrm{u} + r_\mathrm{d}\bar{c}_\mathrm{d} \tag{1}$$

and for the downdrafts,

$$\alpha_\mathrm{d}\frac{\partial \bar{c}_\mathrm{d}(z)}{\partial t} = -\frac{\partial}{\partial z}(\bar{w}_\mathrm{d}\bar{c}_\mathrm{d}\alpha_\mathrm{d}) + \frac{\partial}{\partial z}\left(\alpha_\mathrm{d}K_\mathrm{d}\frac{\partial \bar{c}_\mathrm{d}}{\partial z}\right) - r_\mathrm{d}\bar{c}_\mathrm{d} + r_\mathrm{u}\bar{c}_\mathrm{u}, \tag{2}$$

where z is the vertical direction, over-bar represents grid volume average, the subscripts u and d represent