LES analysis of the effect of source heights on the longitudinal distribution of plume concentration in the convective boundary layer capped by a temperature inversion

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Abstract

A convective boundary layer (CBL) capped by a temperature inversion is one of common cases of atmospheric boundary layers during daytime conditions. With solar heating after sunrise, large-scale convective flows are generated, which leads to substantial plume meandering. Consequently, a part of the plume suddenly touches the ground with high concentrations. Fedorovich and Thater (2002) conducted wind tunnel experiments and investigated the influence of different plume source heights on the longitudinal distribution pattern of concentration in a CBL capped by a temperature inversion. However, the properties of plume dispersion have not been fully discussed in conjunction with the turbulence characteristics with thermal effects.

With the rapid development of computational technology, large-eddy simulation (LES) technique has been recognized as an effective tool for providing a better understanding of physical mechanism of airflow motions, heat, and mass transfer. In this study, we perform LESs of plume dispersion in the CBL capped by a temperature inversion and clarify the mechanism of the longitudinal distribution of concentration depending on different source heights.

The model used here is LOcal-scale High-resolution atmospheric DIspersion Model using LES (LOHDIM-LES) developed by Japan Atomic Energy Agency (Nakayama et al., 2016). The model size and the number of grid points are $12\delta \times 5\delta \times 3\delta$ (δ: the inversion layer height) and $300 \times 250 \times 94$ in the streamwise, spanwise and vertical directions, respectively. The Reynolds numbers Re_δ and the bulk Richardson number Ri_δ is set to 12,000 and -0.45 which are almost the same values as those of the wind tunnel experiments (Ohya and Uchida, 2004).

In order to simulate plume dispersion in a CBL flow by LES, first, in the driver region, the very weak unstable boundary layer flow with an inversion part is generated by the

turbulent inflow technique. Then, the instantaneous wind velocities and temperature are imposed at the inflow boundary of the main analysis region. The release points are located at a downwind distance of 6δ from the inlet boundary of the driver region and are elevated with three different heights of $h_s/\delta = 0.16$, 0.50, and 0.95, respectively. Here, h_s is the source height.

In our LES results, vertical profiles of the mean velocity and temperature are nearly constant within the CBL due to the large-scale convective flows. The turbulence intensity for the vertical component also shows nearly constant in the main part of the CBL ($0.2 < z/\delta < 0.6$) due to the buoyancy-driven turbulent flows. However, the vertical turbulent motions begins to be constrained by the inversion layer. The turbulence intensity gradually decreases in the upper part ($0.6 < z/\delta < 1.0$) and rapidly decreases in the inversion layer ($1.0 < z/\delta$). These turbulence characteristics are in good agreement with the wind tunnel experiments of Ohya and Uchida (2004).

Focusing on the plume dispersion behaviors, it is found that for the case of $h_s/\delta = 0.16$ the plume is rapidly dispersed in the vertical direction with a downwind distance due to the buoyancy-driven turbulent flows. For the case of $h_s/\delta = 0.5$, the plume is also rapidly dispersed near the source location. However, at a large downwind distance from the source, the upward plume spreads are constrained by the inversion layer. For the case of $h_s/\delta = 0.95$, the vertical plume spreads are highly constrained due to the capping effects and the high concentration regions are formed for the streamwise direction at the release height. However, at a large downwind distance from the source, a part of the plume begins to touches the ground due to the large-scale convective flows. It is concluded from these results that the longitudinal distribution patterns depending on the different source heights are clarified in conjunction with the turbulence characteristics of the inversion-capped CBL flow by the LES.

References:

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