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Wall-normal scalar flux within a buoyant plume in a turbulent boundary layer

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1 Introduction

The Reynolds transport equation for the instantaneous concentration field, $\tilde{C} = C + c$ (where C is mean and c is fluctuation), of a plume in a turbulent boundary layer, is not closed because the scalar fluxes, $\overline{u_i c}$ are not known *a priori*. Here we denote the streamwise direction as x and the vertical direction as z. For a plume released within a turbulent boundary layer with the mean flow in the x direction, the wall-normal flux, $\overline{wc}$ dominates the vertical spread of the plume. Typically, the gradient-diffusion hypothesis is used to model the fluxes, e.g.

$$-\overline{wc} = \kappa_z \cdot \partial C/\partial z. \tag{1}$$

It is well-known that the plume spread is different if the source is placed at different heights of the boundary layer. Hence it is not straightforward to specify distinct κ_i for each source height. The present study undertakes a study of the behaviour of $\overline{wc}$ from experimental data.

The theoretical shape of $\overline{wc}$ of an elevated source can be diagnosed by considering that $\overline{wc} = 0$ at the plume centreline due to symmetry and far away outside the plume as concentration vanishes (Wyngaard, 2013). The location of the plume centreline, z_{cl}, is defined as the height of the maximum root mean square (RMS) concentration, $\sigma_{c,\max}$, in this abstract. Packets of concentration ($+c$) moving upwards ($+w$) and negative concentration fluctuations ($-c$) moving downwards ($-w$) result in $\overline{wc} > 0$ above the plume centreline (Wyngaard, 2013). Similarly, $\overline{wc} < 0$ below the plume centreline. Overall the profile has an s-shape.

The data used in this manuscript is an experimental study of buoyant plumes released from a point source in a turbulent boundary layer ($Re_\tau \approx 1600$) at two different source heights. The density of a tracer gas mixture is varied to emulate the release of a neutrally, positively and negatively buoyant plume. Further details of the experiments can be found given in Talluru et al. (2017); Pang & Chauhan (2022).

2 Normalisation of $\overline{wc}$ and non-dimensional eddy diffusivity

Figure 1(a) shows the distributions of $\overline{wc}$ for two elevated sources as a function of z/δ. The overall trend is similar to the prediction and that observed by past studies, where $\overline{wc} > 0$ above the plume centreline and $\overline{wc} < 0$ below. The overall magnitude of $\overline{wc}$, however, decreases with downstream distance as expected. Furthermore, the magnitude of $\overline{wc}$ varies between the upper and lower halves of the plume since the vertical velocity fluctuation profile varies in the wall-normal direction. Since the profile exhibits a near-symmetrical behaviour about the plume centreline, the wall-normal distance relative to the location of the plume centreline, z_{CL}, is normalised using plume half-width, δ_z, as $\xi = (z - z_{cl})/\delta_z$ in figure 1(b). At the same time, $\overline{wc}$ is normalised using the corresponding standard deviations, $\sigma_w(z)$ and $\sigma_c(z)$. Upon normalisation, in figure 1(b), the similarity in shape and magnitude can be observed. The overall trend of the predicted reverse s-shape can be observed. It is noted that the y-axis intercept of $\overline{wc}/\sigma_w\sigma_c$ is not necessarily zero, e.g. the dashed line in dark blue and the solid line in light blue in figure 2(b). This is possibly caused by the displacement zone (Kurbatskii & Yanenko, 1983), which will be investigated in a future study.

In the simplest gradient model as equation 1, the dimensional $\overline{wc}$ is related to the gradient of the C profile. Alternatively, $\overline{wc}$ can also be related to the gradient of the σ_c profile, since σ_c can also be described by the Gaussian or the reflected-Gaussian model, as in figure 1(a). The normalised profiles of σ_c are plotted in figure 2(a) and the derivative of standard Gaussian in figure 2(b). The derivative has a similar shape as the normalised $\overline{wc}$ in figure 1(b), although the magnitude is different. Hence, a new relation of scalar flux is explored,

$$\frac{\overline{wc}}{\sigma_w \sigma_c} = \kappa_\sigma \frac{\partial(\sigma_c/\sigma_{c,\max})}{\partial \xi}, \tag{2}$$

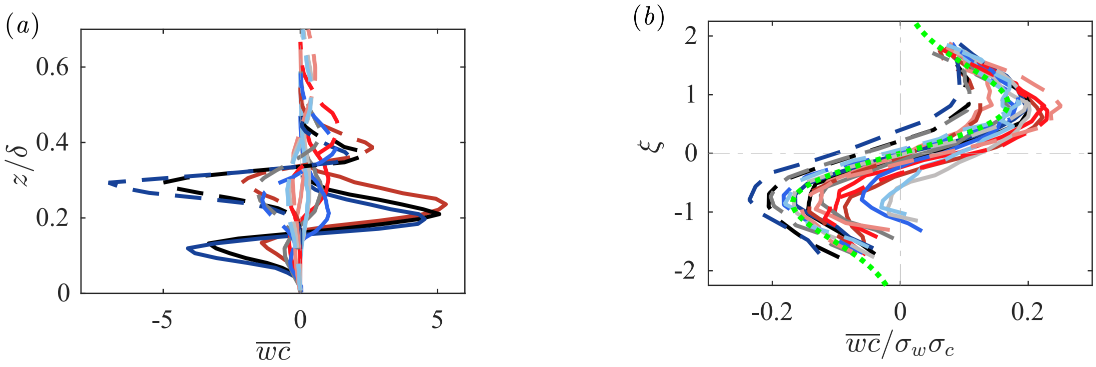

Figure 1. (*a*) Wall-normal fluxes, $\overline{wc}$, for source released at $z/\delta = 0.16$ and 0.32 at three downstream locations. (*b*) $\overline{wc}/\sigma_w\sigma_c$ v.s. normalised wall-normal distance relative to the location of the plume centreline, ξ.

as plotted in figure 2(*c*). Note that κ_σ is a non-dimensional parameter and not the dimensional eddy-diffusivity. In the current study, $\kappa_\sigma \approx -0.11$. Consistency is representative of the two source elevations. The green dotted line in figure 2(*c*) describes the slope of all profiles well, though some scatter is observed.

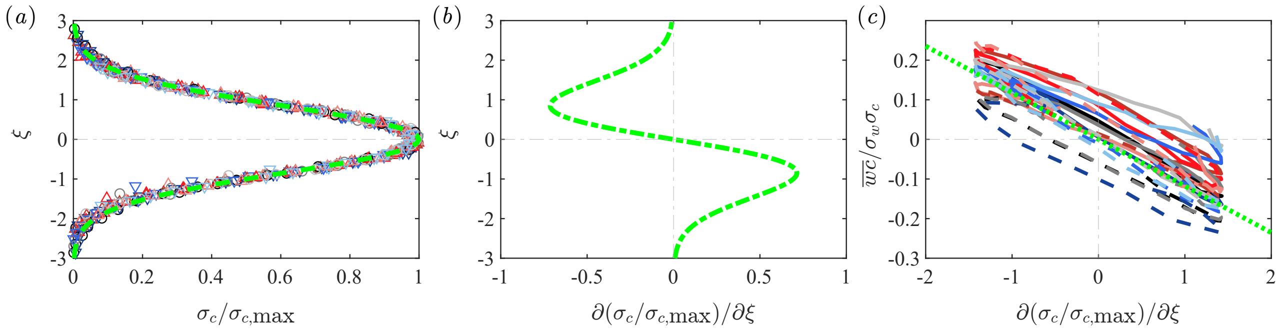

Figure 2. (*a*) Normalised RMS concentration profiles. The green dashed line is the Gaussian model. (*b*) Derivative of the Gaussian model of σ_c. (*c*) Normalised $\overline{wc}$ v.s. derivative of the RMS of concentration. The green dotted line is the best fit of all the points with a slope of 0.11.

3 Conclusions

A novel method is employed to non-dimensionalise $\overline{wc}$, where $\overline{wc}$ is divided by the local RMS of vertical velocity and RMS of concentration. The resulting normalised $\overline{wc}$ data collapse onto a single curve when plotted against the normalised distance to the plume centreline, in line with theoretical expectations. The normalised $\overline{wc}$ is then used to modify the traditional gradient diffusion model. A new non-dimensional parameter, κ_σ, is proposed to linearly relate the normalised $\overline{wc}$ and the gradient of normalised RMS of concentration. The model captures well the shape of normalised $\overline{wc}$ and shows good agreement with data. Unlike the traditional gradient-diffusion model, κ_σ remains constant with downstream distance, introducing an advantage. However, including second-order statistics in the Reynolds-averaged transport equation adds complexity.

References

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