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# Measuring pollutant exposure using large-eddy simulation and virtual walkers: Analysis of tracer age statistics of idealised urban boundary-layer flows

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ABSTRACT

Pollutant exposure in the urban air quality literature has been typically interpreted from data for fixed locations, which provides an incomplete picture of exposure for pedestrians (or moving receptors). The current study proposes a simple model to parameterise the exposure time for a virtual walker to cross a pollutant cloud during its sweeping downstream across the avenue. The parameterisation, which depends on the centre-of-mass translation and the cloud size, shows satisfactory performance in areas away from the outlet, whence a substantial portion of the pollutants is removed from the control domain and a well-defined centre of mass geometrically vanishes. Applying the tracer age diagnostics, the occurrence time of first exposure for the moving receptors is quantified with no particular caution required for the outlet region. The mean tracer age recorded by the virtual walkers is shown to be up to 25%–75% smaller than conventional spatial averages, implying earlier exposure to the pollutants and hence a reference timescale relying on the latter may lead to delayed emergency response. Evacuation route prioritisation based on virtual walker measurements coincides with that indicated by the parameterisation, suggesting the potential usefulness of the model for exposure risk evaluation against atmospheric air pollution incidents.

## 1. Introduction

Rapid urbanisation and industrialisation have significantly modified urban microenvironments (United Nations, 2018). Pollutant emissions due to accelerated anthropogenic activities in and around urban areas either for keeping factories operating or released accidentally are imposing increasingly growing risks to public health (Wong et al., 2019; Xing & Brimblecombe, 2018). Accurate prediction of pollutant exposure is vital for effective emergency response and optimal evacuation route planning against environmental pollution incidents, particularly hazardous emissions of high toxicity.

In the pollutant dispersion literature, people typically focus on the time-mean or statistically-steady statistics (Alameddine et al., 2016). Irrespective of numerical modelling (e.g. Lo & Ngan, 2020; Masoumi-Verki et al., 2021) or measurements (e.g. Jiang & Yoshie, 2018; Marucci & Carpentieri, 2020; Mo & Liu, 2018), pollutant fields or flux exchanges across the canopy have attracted most of the attention. While there is increasing interest in the unsteady processes, such as distributed ventilation (Blocken et al., 2016), scalar mixing (Duan et al., 2019) or time-varying perturbations (Duan & Ngan, 2018), exposure has been marginally discussed. For studies which were directly targeted on pollutant exposure (Cui et al., 2021; Scungio et al., 2018; Wang et al., 2019), the assessment was generally made for fixed receptors, which may not accurately reflect the actual exposure of walkers (or moving receptors).

An emerging concern of the moving aspect is mostly relevant to impacts of vehicle-induced flow disturbances (e.g. Cai et al., 2020; Zheng & Yang, 2021) or moving pollutant emissions from traffic (Zhao et al., 2021), whereas consideration of moving receptors has been missing. Although exposure has remained indirectly interpreted from results for fixed receptors (namely via pollutants recorded in the Eulerian framework) (e.g. Ng & Chau, 2014; Tiwary et al., 2011), the high inhomogeneity in ventilation (Xu et al., 2022) and scalar fields (He et al., 2017) in urban districts strongly imply the varying exposure risks at different spatial locations. The spatial variability of exposure has been observed via in situ measurements (Kaur et al., 2007; Quiros et al., 2013).

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