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Field and wind tunnel modeling of an idealized street canyon flow

K. Blackman [a, b, *], L. Perret [b, c], E. Savory [a], T. Piquet [b]

[a] University of Western Ontario, London, Ontario, Canada
[b] LUNAM Université, Ecole Centrale de Nantes, LHEEA UMR CNRS, 6598 Nantes, France
[c] Institut de Recherche en Sciences et Techniques de la Ville (IRSTV), FR CNRS, 2488 Nantes, France

HIGHLIGHTS

- Field experiment compared with a wind tunnel model of equivalent geometry.
- Mean turbulence statistics in agreement to within 20%.
- Spanwise velocity and turbulence intensity influenced by changing wind direction.

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ABSTRACT

The present work examines the flow field in a simple street canyon that has been modeled at full-scale and at 1:200 scale in a wind tunnel. It relies on the detailed analysis of statistics of both flows including two-point correlation coefficients, an approach not commonly done for canyon flows. Comparison between the field and wind tunnel study has demonstrated good agreement for the mean velocity and turbulence statistics, which are typically within 20%. However, significant differences in the along-canyon mean and turbulent components have been observed and are shown to be a result of the changing of the ambient wind direction and low frequency motion present in the field. As the wind direction changes over time the result is a channeling of flow along the canyon axis. This phenomenon cannot be accurately reproduced by the wind tunnel model, which produces nominally 2D flow. The turbulence dynamics were investigated through two-point spatial correlation of the streamwise, spanwise and vertical components, which show agreement to within 15–30% between the field and wind tunnel results. From estimation of boundary layer log-law parameters it has been shown that using a single point reference velocity measurement at 10 m height to estimate the boundary layer log-law parameters is unreliable in the present case.

1. Introduction

Wind tunnels are frequently used to model urban street canyon turbulence and ventilation dynamics (Cook, 1985; Kastner-Klein and Rotach, 2004; Inagaki and Kanda, 2010). Using simplified wind tunnel models reproduces the main features of most common street configurations, in relation to pollutant transport and air quality, but care must be taken to ensure the boundary layer is scaled correctly. As will be shown by this introductory review there have been few studies in which the mean and unsteady flow dynamics from a wind tunnel and field study have been quantified and compared in order to justify the validity of the wind tunnel results. Urban areas vary drastically with geographic location, not only in regard to natural landscape but also to the style of architecture and building density. Field studies have been conducted in dense urban areas including skyscrapers in North America (DePaul and Sheih, 1986; Arnfield and Mills, 1994; Brown et al., 2004; Hanna et al., 2007; Klein and Clark, 2007; Hanna and Zhou, 2009; Zajic et al., 2011) and Asia (Inagaki and Kanda, 2008, 2010), as well as more low-rise urban areas in Europe (Rotach, 1995; Vachon et al., 1999, 2002; Nielsen, 2000; Kastner-Klein and Rotach, 2004; Rotach et al., 2005; Dobre et al., 2005; Eliasson et al., 2006; Balogun et al., 2010; Drew et al., 2013). In addition, some studies have opted to conduct measurements in simplified roughness arrays within the atmospheric boundary layer (Louka et al., 2000; Inagaki and Kanda, 2008, 2010). The variety of these studies makes

* Corresponding author. LUNAM Université, Ecole Centrale de Nantes, LHEEA UMR CNRS, 6598 Nantes, France.
E-mail addresses: Karin.blackman@ec-nantes.fr (K. Blackman), Laurent.perret@ec-nantes.fr (L. Perret), esavory@uwo.ca (E. Savory), thibaud.piquet@ec-nantes.fr (T. Piquet).

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comparison difficult because the aspect ratio (AR, the ratio of height, h, to width, W, of the canyon), packing density (λ_p, the ratio of the plan area covered by building structures to the total plan area) and ambient wind and temperature conditions differ considerably from study to study.

Much previous full-scale work has been completed to study the dispersion of pollutants in urban areas. Some major field studies, such as the Mock Urban Setting Test (MUST) (Biltoft, 2001; Biltoft et al., 2002; Yassin et al., 2005) and a study in the Hamamatsu-cho Minato-ku area of Tokyo, Japan (Tominaga et al., 2013), have focused on pollutant concentration measurements, with only limited wind velocity and turbulence measurements. While some work, such as MUST, comprise of simplified roughness arrays, most have conducted measurements within existing urban areas, such as the study in Tokyo (Tominaga et al., 2013). Other work has also included the effects of traffic flow on the dispersion in existing urban areas, such as in Gottinger Strabe, Hanover (Ketzel et al., 2000; Schatzmann et al., 2000) and Jagtvej, Copenhagen (Ketzel et al., 2000; Nielsen, 2000). Although these concentration measurement studies are important to the understanding of the dispersion of pollutants in urban areas they will not be considered further in the present paper since the focus here is on the mean and unsteady wind flow field in urban canyons. As such, this review will only include studies where significant flow measurements have been conducted within or above an urban street canyon.

Table 1 summarizes the literature that includes significant flow measurements as part of their field study. The most common method for field studies is *in-situ* measurements within urban areas. In North America, the Oklahoma City Joint Urban 2003 (JU2003) (Brown et al., 2004; Hanna et al., 2007; Zajic et al., 2011) and Manhattan Midtown-2005 (MID05) (Hanna and Zhou, 2009) urban field experiments both conducted near street level and building roof level flow measurements. Similarly, a study in Columbus, Ohio included measurements above the canyon, at the height of the canyon building roofs and within the canyon (Arnfield and Mills, 1994). Finally, *in-situ* measurements were conducted in Chicago, Illinois within the street canyon and above the building roofs (DePaul and Sheih, 1986). In Europe major field campaigns such as the Nantes'99 experiment (Vachon et al., 1999, 2002; Kastner-Klein and Rotach, 2004), the Basel UrBan Boundary Layer Experiment (BUBBLE) (Rotach et al., 2005), the Dispersion of Air Pollution and Penetration into the Local Environment (DAPPLE) project (Dobre et al., 2005; Balogun et al., 2010; Drew et al., 2013), the Zurich Urban Climate Program (Rotach, 1995), air pollution from traffic in urban areas conducted in Jagtvej, Copenhagen (Nielsen, 2000) and a study in Goteborg, Sweden (Eliasson et al., 2006) included *in-situ* measurements within and above street canyons. The majority of these studies used sonic anemometers (SA) for the flow measurements within and above the canyon. However, in some cases high frequency LiDAR (Rotach et al., 2005; Drew et al., 2013) was used and, in another, helium balloons (DePaul and Sheih, 1986) were released into the canyon and cameras were used to track their trajectory. The studies were each conducted for a different purpose and, thus, the acquisition frequency of the instrumentation varied for each case, with some having a sampling frequency as low as 1 Hz (DePaul and Sheih, 1986; Arnfield and Mills, 1994). The length of sampling time is also dissimilar between cases and ranges from less than one day to over one year. This is likely due to the differing purpose of each study, as some required specific ambient conditions, thus requiring longer sampling periods to filter out undesired conditions while others did not. Generally, the averaging period for the results was between 30 and 60 min, with some studies using averaging periods as low as 5 min. This short averaging period could present issues, as statistical flow averages may not have had sufficient time to converge. Also, when processing the data several studies used filtering methods to remove interference from instrumentation or low frequency winds while several studies did not report any filtering prior to calculating flow statistics. Finally, in contrast to most wind tunnel investigations, the number of wind velocity measurements locations is very limited, between 4 (Nielsen, 2000) and 10 (Eliasson et al., 2006), in the majority of these field studies, due to the cost and installation difficulties of implementing a large array of single point sensors. This has hampered our ability to study canyon wind flow dynamics in any detail.

Table 1
Field studies including significant velocity measurements.

Location	W/h	*In-situ* or idealized	Terr. Rough.	Meas. Quan.[a]	Device	Hz	Sample length	Prefiltering	Author
Oklahoma City, USA	0.5	*In-situ*	Urban	U V W T	SA	10	6–9 h	Not stated	Brown et al. (2004).
				U V W T					Klein and Clark (2007).
				U V W T					Hanna et al. (2007).
				U V W T					Zajic et al. (2011).
Goteburg, Sweden	2.1	*In-situ*	Urban	U V W T	SA	10	13 days	Yes	Eliasson et al. (2006).
Saitama, Japan	1	Idealized	Aligned Cubes	U V W	SA	50	~1 yr	Yes	Inagaki and Kanda (2008).
				U V W					Inagaki and Kanda (2010).
				U V W	PIV	30	1 h	Yes	Takimoto et al. (2011).
Manhattan, NY, USA	–	*In-situ*	Dense urban	U V W T	SA	10	~7.5 h	Not stated	Hanna and Zhou (2009).
UK	1.43	Idealized	Rural	U V W	SA	21	5 months	Yes	Louka et al. (2000).
Zurich, Switzerland	1	*In-situ*	Urban	U V W	SA	1	18 months	Yes	Rotach (1995).
Columbus, Ohio, USA	0.66	*In-situ*	Urban	U W	SA	1	11 days	Not stated	Arnfield and Mills (1994).
Copenhagen, Denmark	1	*In-situ*	Urban	U W	SA	Not given	185 days	Not stated	Nielsen (2000).
BUBBLE Basel, Switzerland	No data	*In-situ*	Urban	U V W T CO_2 q'	LiDAR, wind profiler	5000–6000	~1 yr	Yes	Rotach et al. (2005).
Nantes, France	0.7	*In-situ*	Urban	U V W T CO	SA	4	12 h	Yes	Vachon et al. (1999).
				U V W					Vachon et al. (2002).
				U V W T CO					Kastner-Klein and Rotach (2004).
Chicago, USA	0.71	*In-situ*	Urban	U W	Balloons, camera	1	~3 days	Not stated	DePaul and Sheih (1986).
London, UK	1.3	*In-situ*	Urban	U V W	SA	20	5 weeks	Not stated	Dobre et al. (2005).
									Balogun et al. (2010).
									Drew et al. (2013).

[a] *T* temperature, *q′ heat flux*.