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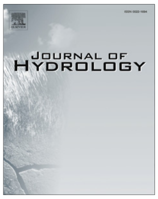

# Interactions of bluff-body obstacles with turbulent airflows affecting evaporative fluxes from porous surfaces

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SUMMARY

Bluff-body obstacles interacting with turbulent airflows are common in many natural and engineering applications (from desert pavement and shrubs over natural surfaces to cylindrical elements in compact heat exchangers). Even with obstacles of simple geometry, their interactions within turbulent airflows result in a complex and unsteady flow field that affects surface drag partitioning and transport of scalars from adjacent evaporating surfaces. Observations of spatio-temporal thermal patterns on evaporating porous surfaces adjacent to bluff-body obstacles depict well-defined and persistent zonation of evaporation rates that were used to construct a simple mechanistic model for surface–turbulence interactions. Results from evaporative drying of sand surfaces with isolated cylindrical elements (bluff bodies) subjected to constant turbulent airflows were in good agreement with model predictions for localized exchange rates. Experimental and theoretical results show persistent enhancement of evaporative fluxes from bluff-rough surfaces relative to smooth flat surfaces under similar conditions. The enhancement is attributed to formation of vortices that induce a thinner boundary layer over part of the interacting surface footprint. For a practical range of air velocities (0.5–4.0 m/s), low-aspect ratio cylindrical bluff elements placed on evaporating sand surfaces enhanced evaporative mass losses (relative to a flat surface) by up to 300% for high density of elements and high wind velocity, similar to observations reported in the literature. Concepts from drag partitioning were used to generalize the model and upscale predictions to evaporation from surfaces with multiple obstacles for potential applications to natural bluff-rough surfaces.

## 1. Introduction

The quantification of fluxes from realistic complex terrains is of considerable importance for hydrological and climatic models. The magnitudes and spatial patterns of land–atmosphere fluxes are affected by the interaction of land surface heterogeneity with incoming solar (shortwave) radiation (Duguay, 1993; Yang and Friedl, 2001; Wang et al., 2005; Helbig et al., 2009) and atmospheric boundary layer turbulence (Finnigan, 1988; Wieringa, 1993; Brutsaert, 1998; Stoll and Porte-Agel, 2006; Haghighi and Or, 2015a). For surfaces with protruding bluff-body elements, studies have shown that the shape of the obstacles, their spacing, and spatial arrangement significantly modify the surface radiation and energy balances (Whiteman et al., 1989; Strahler and Jupp, 1990; Ni and Li, 2000; Müller and Scherer, 2005; Helbig et al., 2010). These geometrical attributes are also important for turbulence generation adjacent to the surface thereby influencing turbulent transport of momentum and scalars (Cai, 1999; Tseng et al., 2006; Bou-Zeid et al., 2007; Cheng and Porte-Agel, 2013).

Turbulent transport to and from surfaces with bluff roughness elements has been the subject of extensive experimental and numerical studies in modern fluid dynamics and transport phenomena due to its importance in many natural and engineering applications (Chamberlain, 1968; Brutsaert, 1979; Goldstein et al., 1985; Chyu and Goldstein, 1991; Ligrani et al., 2003; Giordano et al., 2012; Sumner, 2013). Among the types of bluff roughness elements studied in fluid dynamics research (e.g., Okamoto, 1982; Savory and Toy, 1986; Pattenden et al., 2005; Byun and Simpson, 2006; Martinuzzi, 2008; Wang and Zhou, 2009; Papanicolaou et al., 2012), cylindrical bodies interacting with fluid flows have been extensively studied (see review by Sumner (2013) and references therein). We thus focus in this study on interacting non-evaporating circular cylinders (as bluff-body obstacles) that protrude from an evaporating porous surface to quantify their impacts on evaporative fluxes as models of natural

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roughness elements (e.g., bare soil surfaces partially covered with boulders and shrubs).

We ignore potential interactions of shortwave radiation on surface energy balance, and focus on the characteristics of heat and mass transfer from surfaces containing protruding cylindrical obstacles that are largely shaped by local airflow patterns around the obstacles (Kawamura et al., 1984; Pattenden et al., 2005; Krajnovic, 2011). As air flows over a surface-mounted circular cylinder with a relatively low aspect ratio $AR = h/d$ (where $h$ (m) and $d$ (m) are the height and diameter of the cylinder, respectively) a complex boundary layer in the near surface region forms with a few vortex-pairs rolling over and/or sweeping around the cylinder base (termed horseshoe vortex), as illustrated in Fig. 1a (Fröhlich and Rodi, 2004; Pattenden et al., 2005; Afgan et al., 2007; Lee et al., 2007; Frederich et al., 2009; Palau-Salvador et al., 2010; Krajnovic, 2011). A horseshoe vortex consists of many vortices with complex interactions and oscillatory motions (Baker, 1979, 1980) that produce high surface shear stress thereby enhancing heat and mass transfer to or from the interacting surface (Goldstein and Karni, 1984; Goldstein et al., 1985; Chyu and Goldstein, 1991; Ligrani et al., 2003; Giordano et al., 2012; Sumner, 2013).

This study seeks to simplify the complex picture of bluff-body interactions reported in the literature towards establishment of a simple and physically based model for stage-I evaporation rates from bluff-body covered bare soil surfaces. We consider concepts from surface renewal (SR) theory (Higbie, 1935; Danckwerts, 1951; Harriott, 1962) to extend the pore-scale model of Haghighi and Or (2013) originally developed for diffusive water vapor fluxes from aerodynamically smooth soil surfaces into turbulent airflows (see Fig. 1). As individual eddies are swept along the evaporating surface, they gradually accumulate water vapor (or exchange energy) at rates determined by diffusion across a viscous sublayer forming beneath their footprint, and by the mean water vapor gradient between the surface and the well-mixed turbulent airflow. Following a certain residence time over the surface, an eddy is ultimately ejected back into the turbulent flow and renewed by another drawn from an eddy population defined by airflow conditions.

Focusing on modifications to airflow turbulence near bluff-body roughness elements, this study aims to: (1) extend the SR-based evaporation model of Haghighi and Or (2013) by explicitly incorporating localized viscous sublayers forming around cylindrical elements; (2) experimentally test the model by systematically varying surface roughness elements in evaporation experiments in a wind tunnel; and (3) generalize the results by considering the effective surface drag partitioning with obstacles of different densities and the resulting effects on evaporative fluxes. The important effects of shortwave radiation and associated geometrical interactions on localized surface energy balance are deferred to future studies, and we focus here primarily on the effects of momentum partitioning on surface fluxes.

Following this introduction, Section 2 describes the theoretical background and modeling details for coupling pore-scale stage-I evaporation from bluff-rough porous surfaces with a population of individual eddies forming the interacting turbulent airflow. Section 3 is devoted to describing experimental setup used for evaluating the proposed model by first considering surface thermal patterns observable by infrared thermography (IRT), and then mass

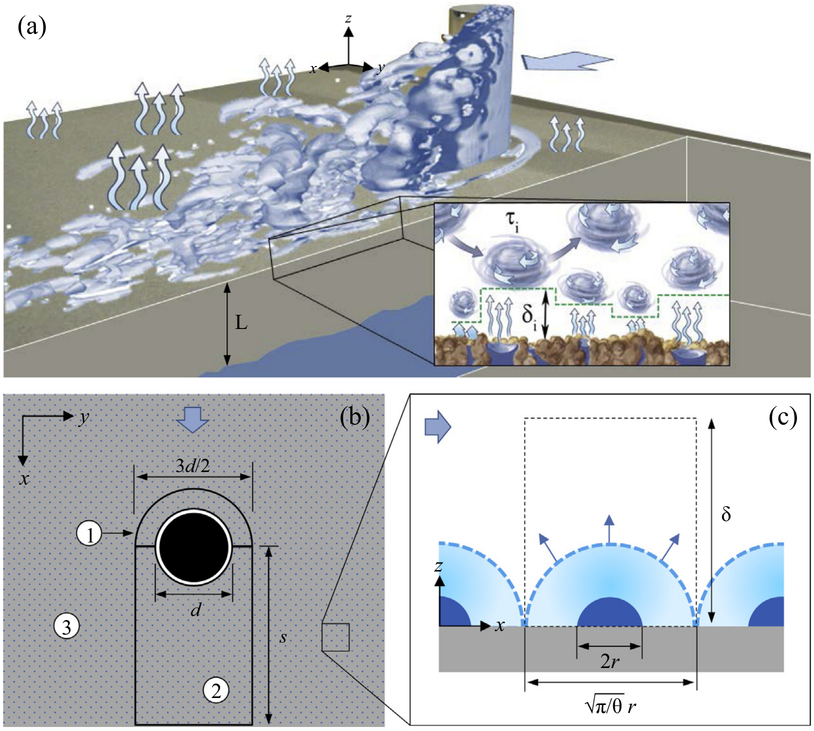

**Fig. 1.** Schematic of (a) formation of typical turbulent structures around a protruding circular cylinder resulting from turbulent airflow interactions with cylindrical obstacle (the picture is inspired from large eddy simulations reported in Afgan et al. (2007)), and (b and c) the building block for quantification of the mean evaporation flux from the base surface of a non-evaporating finite circular cylinder in cross flow. The model considers three distinct zones over the base surface affected differently by airflow turbulence: (1) the region of influence of upstream horseshoe vortex system, (2) the region influence by wake vortices downstream of the obstacle, and (3) the unaffected region. The pore-scale model considers the turbulent airflow interacting with the evaporating surface as a collection of eddies with different characteristics drawn from a statistical distribution. Water vapor transfer (during stage-I evaporation) through a unit surface of the building block into individual eddies is governed by 3D vapor diffusion from individual pores across a local viscous sublayer (c) forming below eddies footprint (green dashed line in the inset of (a)). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)