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Investigation of local winds in a closed valley: An experimental insight using Lagrangian particle tracking

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ABSTRACT

An experimental study of two-dimensional katabatic and anabatic flows, and their interaction with an urban heat island centred in a closed valley is presented. Down- and up-slope flows are generated via cooling and heating 20° inclined plates. The urban heat island is simulated by an electric heater centred in the valley. In order to understand the main features of the circulation established by thermal effects in an initially stably-stratified environment, an advanced Lagrangian particle tracking technique (Hybrid Lagrangian Particle Tracking) is employed. This allows one to obtain the velocity and acceleration of passive tracer particles as the first and second derivatives of a moving spline function that filters the particle trajectory coordinates. Experiments show the dependence of mean quantities and turbulent statistics on different slope heating. Furthermore, the effects of the slope flows on the circulation in a large city located in a narrow valley appear significant. During day-time simulations the urban heat island circulation is opposed by anabatic winds, creating critical situations for pollutant dispersion. During night-time simulations, the katabatic winds increase the city updraft motion.

1. Introduction

Slope winds are common mesoscale to local scale phenomena driven by the differential heating of the Earth's surface. They are generated by the horizontal temperature difference between air adjacent to a mountain slope and the ambient air at the same altitude over the neighbouring plane. The thermal inhomogeneity is a consequence of the daily heating due to the solar radiation and to the nightly cooling related to the infrared radiation emitted by the ground. Assuming clear skies and weak synoptic wind conditions, the slope flow is up-slope (or anabatic) during the day-time and down-slope (katabatic) during the night-time. Both these buoyancy-driven winds are typically in the range of 1–5 $\mathrm{m\,s^{-1}}$, while their depth is roughly 20–500 m for the anabatic winds and 3–100 m for the katabatic ones (Monti et al., 2002; Whiteman, 2000).

Thermal circulation along inclined planes has been studied by many researchers, principally using field measurements and Large Eddy Simulation (among these, Catalano and Cenedese, 2010; Monti et al., 2002; Reuten et al., 2005). Few water tank laboratory-scale studies of slope flows have been carried out (Deardorff and Willis, 1987; Giorgilli et al., 2009; Princevac and Fernando, 2007; Reuten et al., 2007).

Another common local scale air circulation is the one related to the urban heat island (UHI) which is associated with the temperature anomaly of a city with respect to neighbouring rural areas. The circulation is characterised by a horizontal convergence at the central zone, close to the ground and an upward motion taking place in the island centre. A divergent motion closes the circulation, bringing air from the central area, at the height where the upward motion ends, towards the periphery.

Many measurements in an urban environment have been able to capture the typical circulation and thermal field of a city, as in the study of Puygrenier et al. (2005) in Marseille. In addition, numerical simulations combined with measurements in an urban environment allowed for the reconstruction of the circulation in Tokyo (Yoshikado, 1992). The experimental laboratory investigation presented by Lu et al. (1997a, 1997b) reproduced a heat island in a thermally stratified environment.

In large industrialized urban centres located in areas with complex topography, both slope winds and UHI assume an important role and control air pollution dispersion, energy usage and fog formation (Fernando et al., 2000, 2001; Hunt et al., 2003; Lee et al., 2003). Contributions on the circulation due to the interaction of slope flows and urban heat island have been presented via numerical models (Fujino et al., 1999; Savijarvi and Liya, 2001), while no laboratory studies have been carried out yet.

In this work the principal features of slope flows in a closed valley were investigated by using a laboratory model based on a temperature-controlled water tank and an advanced two-dimensional (2D) Lagrangian particle tracking measurement technique. Furthermore, the interaction between the slope flow and a simulated large city was investigated. Although the model is idealised and simple, the experiments presented in this contribution allow the

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basic flow features of a typical large city in a narrow valley to be understood and analysed. The simultaneous measurement of both the temperature and the kinematic fields allows the cross-validation of methods for detecting the quantities of interest for the phenomenon under investigation. It is worth noting that the methodology for detecting particle trajectories combines optical flow theory and classical particle tracking techniques, allowing for the analysis of high seeding density images. Since more than 2000 particles are tracked per each frame, the first and second order statistics of the velocity field are more robust than with traditional methods. Furthermore, a moving cubic spline function is introduced to filter the particle trajectory coordinates (trajectory signal) and obtain more accurate velocity and acceleration data than with finite difference methods.

The paper is organised as follows: the model set-up and the image analysis technique are described in Section 2; in Section 3 the results of the simulated pure slope flows, without the city, and the effects of different surface heat fluxes on the triggered circulation in terms of mean quantities (velocity and acceleration) and turbulent statistics are shown; then the interaction of the slope flows with the urban heat island circulation are analysed, with the aim of understanding critical conditions for pollutant dispersion; the paper ends with a concluding section.

2. Materials and methods

2.1. Experimental setup

Experiments were conducted with the same apparatus used in Cenedese and Monti (2003) and Giorgilli et al. (2009) to simulate land/sea breeze, urban heat island and slope flows. The model is a rectangular tank (Figs. 1 and 2) with a length of 1.700 m, a height of 0.120 m and a width of 0.600 m that is open at the top and has a horizontal aluminium surface at the bottom. Two flat

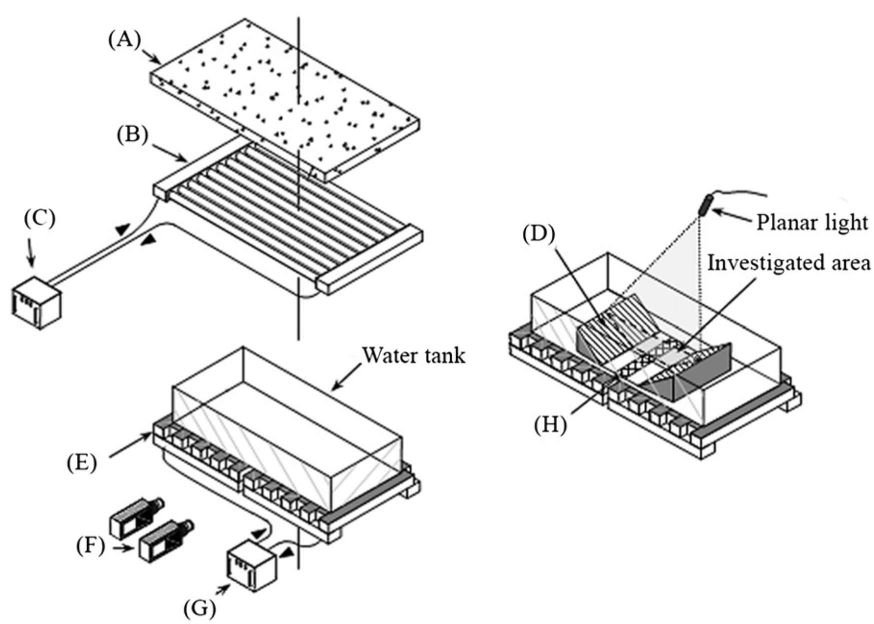

Fig. 1. Experimental apparatus: (A) polystyrene sheet, (B) free surface heat exchanger, (C) free surface thermostat, (D) valley model, (E) bottom surface heat exchanger, (F) cameras, (G) bottom surface thermostat and (H) rectangular-shaped electric heater.

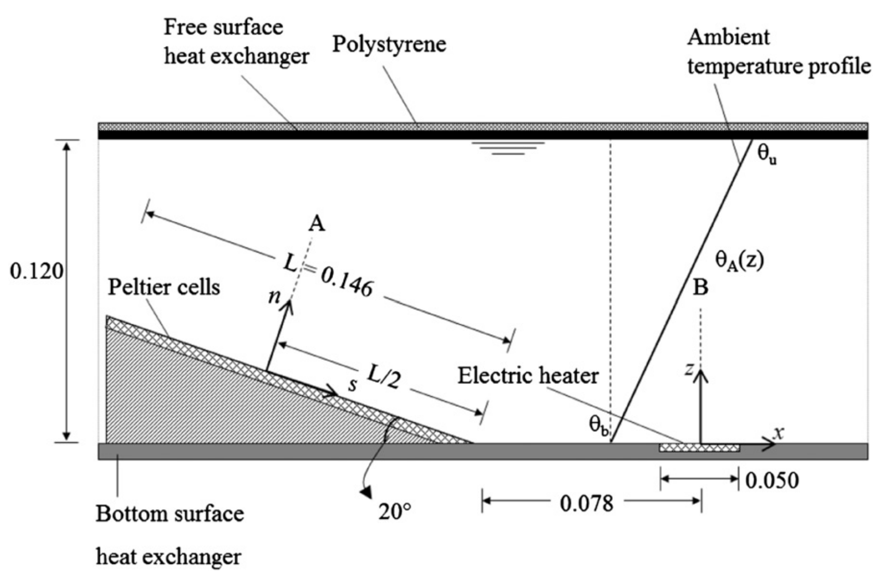

Fig. 2. Schematic representation (not in scale) of a portion of the investigated area (all the measurements are in metres).