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Experimental investigation of slope flows via image analysis techniques

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ABSTRACT

A vessel filled with distilled water is used to simulate the local circulation in the surroundings of an urban area that is situated in a mountain valley. The purpose of this study is to establish if the experimental setup is suitable for the investigation of katabatic and anabatic flows and their interaction with an urban heat island. Flow fields are derived by means of Feature Tracking and temperature fields are directly measured with thermocouples. The technique employed allows obtaining a high spatio-temporal resolution, providing robust statistics for the characterization of the fluid-dynamic field. General qualitative comparisons are made with expectations from analytical models. It appeared that the experimental setup as used in this study can be used for reproducing the phenomena occurring in the atmospheric boundary layer.

1. Introduction

Slope flows are one of the typical atmospheric phenomena driven by the differential heating of the Earth's surface. It is generated by the horizontal temperature difference between air adjacent to a mountain slope and the ambient air at the same altitude over the neighboring plane (or over the valley center). The thermal heterogeneity is a consequence of the daily heating due to solar radiation and the nightly cooling related to the infrared radiation emitted by the ground. Assuming clear sky and weak synoptic wind conditions, the slope flow is upslope (or anabatic) during the daytime and downslope (katabatic) during the nighttime. Both these buoyancy-driven winds are typically in the range of 1–5 m s^{-1}, while their depth is in the interval 20–500 m for the anabatic winds and 3–100 m for the katabatic ones (Whiteman, 2000; Simpson, 1994). In areas where basins are largely sheltered from synoptic effects, katabatic and anabatic flows are the building blocks of local weather (Fedorovich and Shapiro, 2009). In heavily industrialized regions of variable topography, these local flows exert a major control over energy usage, visibility, fog formation and air pollutant dispersion. While nocturnal stable flows trap pollutants close to the ground (on the order of tens of meters) and disperse horizontally via meandering motions, daytime upslope convective flows mix pollutants over greater heights (of the order of 1 km) and transport them over longer distances. Upslope flow may then contribute to transport of pollutants originally located within valley to suburban mountain areas (Princevac and Fernando, 2007).

The thermal circulation along inclined planes has been studied by many investigators, principally using field experiments (Mahrt, 1990; Monti et al., 2002; Reuten et al., 2005). Field experiments are generally costly and their findings are often limited to the particular orography. Further, the simultaneous presence of complex wind systems that develop on the same scale or on different scales makes the observation of a "pure" slope flow an exceptional case rather than the rule. This is a serious complication when data gathered from experiments aimed at reproducing a pure slope flow have to be compared to field data.

Among the analytical investigations, Prandtl (1952) describing both downslope and upslope flows, Manins and Sawford (1979) for downslope flows and Hunt et al. (2003) for upslope flows can be considered as useful tools for describing idealized slope geometries and will be reviewed herein.

Assume x and z are the coordinates of the reference system with axis parallel and perpendicular to the inclined plane respectively, while u and w are the related velocity components. The simplified theory of slope flows by Prandtl (1952) is based on the following assumptions (Fig. 1):

- the slope is an infinite plane with angle α;
- the Boussinesq hypothesis is valid for the fluid;
- the motion is steady, laminar, two-dimensional and planar;
- the flow is fully developed in the x direction, i.e. $\partial \bullet / \partial x = 0$;
- the potential temperature θ is linearly distributed along the vertical direction $\tilde{z}$ ($\theta_a = \theta_0 + \Gamma \tilde{z}$) when no-flow conditions

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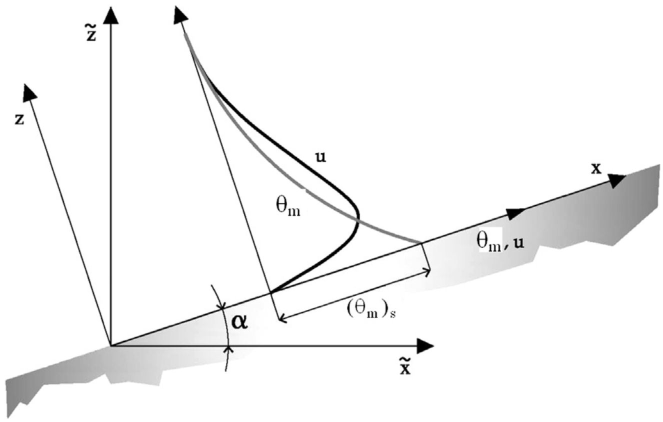

Fig. 1. Schematic of the model proposed by Prandtl (1952) for the investigation of slope flows (for the symbol meaning refer to the text).

occur (θ_a ambient temperature, θ_0 ambient temperature at the ground surface, $\Gamma = \partial\theta_a/\partial\tilde{z}$ background vertical potential temperature gradient);

- the deviations of potential temperature θ_m and density ρ_m, function of z only, with respect to the no-flow background conditions are small;
- the advective terms in the balance equations are negligible.

With these simplifications, the governing equations of motion can be solved yielding the profile normal to the slope of the downslope velocity u and θ_m.

$$u = \hat{\theta}\, B \exp(-z/A)\sin(z/A) \tag{1a}$$

$$\theta_m = \hat{\theta}\exp(-z/A)\cos(z/A) \tag{1b}$$

where

- $\hat{\theta} = (\theta_m)_s$ is the potential temperature perturbation at the ground with respect to the initial value,
- $A^4 = 4\theta_0\kappa\nu/g\Gamma\sin^2\alpha$, κ and ν are the fluid thermal diffusivity and kinematic viscosity, g is gravity acceleration,
- $B^2 = g\kappa/\nu\Gamma\theta_0 = g^2\kappa/\nu N^2\theta_0^2$, and
- $N = (g\beta\Gamma)^{1/2}$ is the Brunt–Vaisala frequency, β is the thermal volumetric expansion coefficient.

The maximum velocity value, u_{max}, does not depend on the slope angle, but the height where u_{max} is reached decreases with increasing slope. For a given slope angle, u_{max} decreases with increasing N. It seems that Prandtl's most substantial constraint is the assumption of flow laminarity, since turbulence is the principal mechanism of energy transfer from the surface into the atmosphere (Gutman, 1983). Oerlemans (1998) modeling the turbulent fluxes for momentum and heat via first order closures, derived equations similar to (1) where two exchange coefficients K_b and K_m replace κ and ν respectively.

Manins and Sawford (1979) derived a model of katabatic winds based on the so-called “extended hydraulic approach”, in which information on the flow structure along the direction normal to the slope is absorbed into three profile factors (S_1, S_2, S_3) which are assumed known. S_1, S_2 and S_3 take the value of unity for well-mixed katabatic flow. Therefore, a layer with equivalent velocity, depth and buoyancy scales replaces the detailed structure of the flow. Compared with the Prandtl's theory, the analytic solution of Manins and Sawford (1979) is valid also in non-stationary conditions and takes into account the entrainment of ambient fluid. The full two-dimensional unsteady governing equations of motions are integrated along the direction normal to the slope from the surface ($z=0$) out to a constant height H sufficiently far to be unaffected by the downslope wind, for which solutions are obtained using closure assumptions. Therefore, along-slope velocity scale U, current thickness scale h and buoyancy deficit scale δ are defined by (Fig. 2):

$$Uh = \int_0^H u\,dz; \quad U^2h = \int_0^H u^2 dz; \quad Uh\delta = \int_0^H u\frac{gd}{\theta_r}dz \tag{2a}$$

$$S_1h^2\delta = \int_0^H \frac{gd}{\theta_r}z\,dz; \quad S_2h\delta = \int_0^H \frac{gd}{\theta_r}dz; \quad w_HH - S_3w_Hd = \int_0^H w\,dz \tag{2b}$$

- H is the distance from the slope surface in the z direction to a point largely unaffected by the katabatic flow
- θ_r is the reference potential temperature, i.e. the ambient temperature for $\tilde{z} = 0$ (for the reference system refer to Fig. 2)
- $d = \theta_a - \theta$
- w_H is the velocity component normal to the slope at distance H from the slope.

Hunt et al. (2003) suggests a model to study the anabatic currents that is based on the subdivision of the currents into three layers, namely, a surface layer, a middle layer and an inversion layer. In each of these sublayers the momentum and the heat equations written in terms of mean quantities are solved, matching the results at the boundary of each sublayer to the next. Consider a flat surface of constant slope α interposed between two horizontal layers (Fig. 3) and assume that

the slope length is limited to ensure that no separation of the boundary layer will occur (Fernando, 1991);

- the Boussinesq hypothesis is valid;
- the thermal forcing due to buoyancy is $g\beta\Delta\theta$;
- non linear terms are negligible;
- small slope angle, so $\sin\alpha = \alpha$
- A mean upslope flow velocity, U_M, of the form

$$U_M = \lambda_U w_* \alpha^{1/3} \tag{3}$$

can be derived. Here λ_U is a factor related to the depth of the surface layer, $w_* = (\beta g h H_0/\rho_0 c_p)^{1/3}$ is the convective velocity, h is the total thickness of the anabatic layer for Hunt's model, ρ_0 is the reference density, c_p is the specific heat at constant pressure, H_0 is the surface heat flux.

Recent investigations of buoyancy-driven atmospheric flows like Urban Heat Island (UHI) circulations and sea- and land-breezes showed that laboratory simulations allow basic features

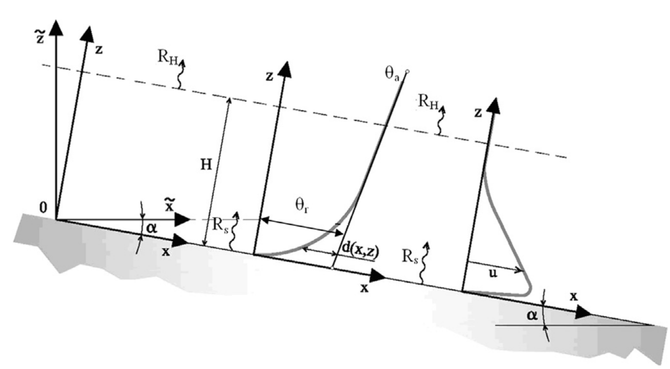

Fig. 2. Schematic of the model proposed by Manins and Sawford (1979) for the investigation of katabatic currents (for the symbol meaning refer to the text; $R_H - R_S$ is the divergence of radiation R over height H).