Boundary Layer Processes and Thermally Driven Flows over Complex Terrain

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Abstract

The physical mechanisms underlying the small scale atmospheric motions occurring in mountain areas have been well known and understood for a few decades now. In particular, the theory explaining the basic features of the onset of thermally driven slope- and valley- wind systems is consolidated and universally accepted. Nevertheless, the available quantitative descriptions of these phenomena seem to be oversimplified, even for application in idealized conditions. This is true both for local analytical models (e.g. Prandtl's wind and temperature profiles over a slope) and bulk theories (e.g. the volume effect theory and the Topographic Amplification Factor and Area Height Distribution concepts). The purpose of this work is to highlight some limits of such theories, and lay down a basis for a more consistent description of what happens in a sunny day within a valley atmosphere. The task is not devoid of practical interest in the field of environmental engineering, in particular in the assessment of air quality in mountainous areas, where slope and valley winds may enhance the ventilation within a valley atmosphere and favour the dispersion of pollutants.

The results obtained with simple numerical simulations of the relevant processes are emphasized: the greatest effort was devoted to the interpretation of model results, in order to gain further insight into the physics of the daytime valley- and slope- wind system. A nonlinear, nonhydrostatic, Boussinesq, fully compressible system of equations is considered, and finite-difference explicit methods are used to discretize it with an accuracy of second order both in space and in time. Due to the physical features of the phenomenon under consideration, which is characterized by rather smooth gradients, it is assumed that such methods give reliable results when implemented at a fairly high resolution.

Numerical model outputs are used in the first place to provide an evaluation of how the assumption of a vertically varying eddy viscosity affects the wind and potential temperature profiles expected over a flat infinite heated slope. This is basically an extension of Prandtl’s historical model of slope winds, which originally described anabatic currents by means of a constant exchange coefficient. Numerical results have also been interpreted in order to provide a simple theory of the transient phenomena occurring at the onset of upslope flows.

Further simulations over various idealized topographies led to the main novelty of this work, i.e. a revised theory explaining the onset of upvalley winds during daytime. The current understanding of the phenomenon is that, being the heated air volume smaller in a valley than above the plain, the same heat input provides larger temperature increases within the former, hence an imbalance between the air density and pressure between the two environments arises. Consequently, an evaluation of the ratio between the air volumes confined by topography below the level of mountain tops in the valley and plain should provide an approximate estimation of the magnitude of downvalley pressure gradients and of the intensity of the upvalley wind (volume effect theory).

The numerical experiments performed in this study confirm the common notion that a closed convective circulation is formed in a valley, with ascending air motions at its sides and subsidence above its bottom. Anyway, thermally driven circulations are shown to extend well beyond the ridgetop level, thereby invalidating the basic assumption of the volume effect theory. Further, it is demonstrated that subsidence in the valley core, fed by the diabatically heated air transported by upslope flows, also drags potentially warm air downwards from the free atmosphere. Accordingly, heat appears to be provided to the valley from above rather than from below, hence the greatest temperature deviations between the valley and plain are located at a relevant height above the ground surface. Heating aloft anyway reduces the weight of the air column above the valley bottom, thus favouring a local decrease of pressure at the surface, although cooling usually takes place there.

The interaction between turbulent mixing and subsidence warming, responsible respectively for the bottom-up and top-down heating of the atmosphere of a valley, have been related to simple geometric parameters describing the shape of a valley cross-sectional profile. This allows for a revised theory of geometric effects, yet oversimplified, but hopefully more realistic than the volume effect approach.

Another particular focus of this work is the parameterization of processes occurring in the convective boundary layer (CBL). A comprehensive review of commonly used parameterizations of dry CBL processes suggests that some phenomena are usually modeled quite roughly, while their understanding based on recent advances from both theory and measurements would allow physically sounder representations. An example of such aspects is the evaluation of nonlocal fluxes in the mixed layer, i.e. air motions not directly determined by local gradients. The parameterization of such fluxes is essential to achieve a more accurate modeling of CBL dynamics, while it also suggests a possible framework for the parameterization of local thermally driven circulations. A parameterization method well suited to model both phenomena over flat uniform terrain and airmotions over complex topography has been recognized in the two-scale mixing approach; preliminary modelling attempts in this framework have been performed, by analysing the dynamics of thermal plumes in a flat uniform CBL by means of large-eddy simulation.