# THE NATURE OF TURBULENT KINETIC ENERGY IN A DEEP AND NARROW VALLEY UNDER CONVECTIVE (?) CONDITIONS


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**Abstract:** This contribution investigates the nature of turbulent kinetic energy (TKE) in a steep and narrow Alpine valley under fair-weather summertime conditions. The Riviera Valley in southern Switzerland has been chosen for a detailed case study, in which the evaluation of aircraft data (obtained from the MAP-Riviera field campaign) is combined with the application of high-resolution (350 m) large-eddy simulations using the model ARPS. The simulations verify what has already been observed on the basis of measurement data: TKE profiles scale surprisingly well if the convective velocity scale $w_*$ is obtained from the sun-exposed eastern slope rather than from the surface directly underneath the profiles considered. ARPS is then used to evaluate the TKE-budget equation, showing that, despite sunny conditions, wind shear is the dominant production mechanism. Therefore, the surface heat fluxes (and thus $w_*$) on the eastern slope do not determine the TKE evolution directly but rather, as we believe, indirectly via the interaction of thermally-driven cross-valley and along-valley flow. Excellent correlations between $w_*^2$ and the up-valley wind speed solidify this hypothesis.



***Keywords -*** *Convective boundary layer, Large-eddy simulations, Steep valley, TKE budget, Valley winds, Wind shear*


## 1. INTRODUCTION

Little is known about the nature of turbulence over steep mountainous topography. A better understanding of such small-scale processes, however, is very important for the evaluation and improvement of subgrid-scale parameterizations of numerical weather and climate prediction models applied over Alpine terrain.

In order to make a first step towards filling this gap of knowledge, the Riviera Valley in southern Switzerland (length: ≈15 km; base width: ≈2 km; depth: ≈2.5 km; slope angle: ≈30-40°) has been chosen for a detailed case-study on the turbulence characteristics of the clear-sky daytime atmosphere in a steep Alpine valley. We combine the evaluation of measurement data from the MAP-Riviera field campaign (carried out from summer through autumn in 1999; see Rotach et al. 2004) with the application of high-resolution large-eddy simulations using the model ARPS (e.g. Xue et al. 2000). The model is initialized with ECMWF analysis data and nested down (one-way) to horizontal resolutions as fine as 350 m. Details of the model setup as well as sensitivity and verification studies are described by Chow et al. (2005) and Weigel et al. (2005).

The turbulence characteristics of the Riviera Valley as obtained from MAP-Riviera aircraft measurements (temporal resolution of 10 Hz) were evaluated by Weigel and Rotach (2004). It was shown that profiles of TKE scale surprisingly well with a Deardorff-type (1970) scheme if (i) a TKE threshold criterion (TKE $>$ 0.5 $m^2s^{-2}$) is employed as a definition of the boundary layer height and (ii) if the surface fluxes from the sun-lit slope sites are used rather than those from directly beneath the profile considered. An explanation of this phenomenon, however, was not provided. It remained unclear how turbulence is produced in the Riviera Valley and whether the turbulence structure is only *related to* or actually *determined by* the surface heat fluxes on the sun-lit slope. This contribution addresses these open questions by evaluating ARPS output data for three fair-weather days of the measurement campaign, namely August 21, 22 and 25.

## 2. TKE FROM ARPS OUTPUT DATA

We start by evaluating to what extent the aforementioned surprising scaling behavior can be reproduced with ARPS. Like in the corresponding airborne measurements presented by Weigel and Rotach (2004), profiles of simulated total TKE are scaled with the square of a convective velocity scale $w_*(= \{(g/\overline{\theta_0}) \cdot \overline{w'\theta'_0} \cdot z_i\}^{1/3}$, with $\overline{w'\theta'_0}$ = surface heat flux, $\overline{\theta_0}$ = surface potential temperature, $z_i$ = boundary layer thickness). As in Weigel and Rotach (2004), $z_i$ is obtained from a TKE threshold criterion. The threshold has been lowered

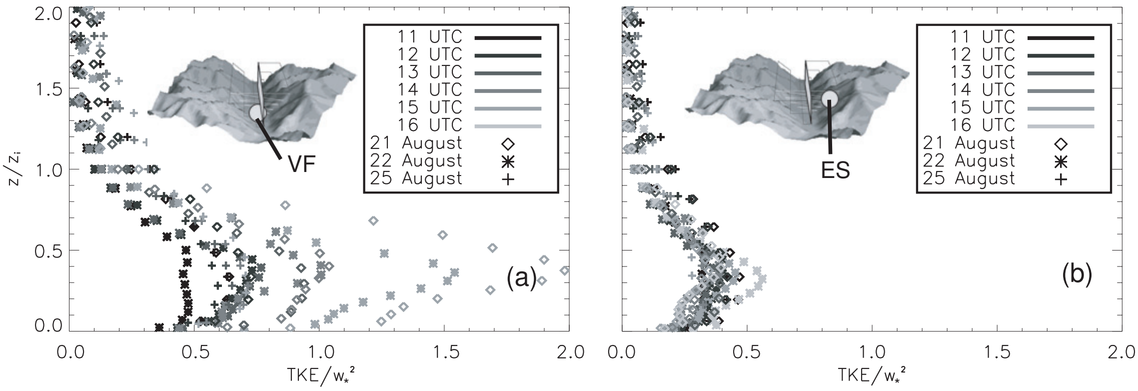


***Figure 1:*** *Scaled profiles of TKE, obtained from ARPS output data in the center of the valley along the valley axis on the three days of simulation. Both plots display the same TKE profiles, but scaled with different values of $w_*^2$ calculated from ARPS surface heat fluxes: (a) at a site on the valley floor ('VF'), (b) at a site on the eastern slope ('ES').*

from 0.5 m$^2$ s$^{-2}$ to 0.3 m$^2$ s$^{-2}$ to account for the generally lower magnitudes of simulated TKE compared to the airborne measurements (not shown). The results are displayed in Fig. 1. Both panels show the same profiles of total TKE, extracted from model output data in hourly intervals between 1100 and 1600 UTC on all three days of simulation. In Fig. 1(a), the TKE profiles are scaled with $w_*^2$ calculated from the surface heat fluxes on the valley floor (henceforth referred to as 'VF'), while the profiles in Fig. 1(b) are scaled with $w_*^2$ from a site on the eastern slope (henceforth 'ES').

Fig. 1(a) shows that scaling TKE with $w_*^2$ from *VF*, i.e. from the surface directly underneath the profiles considered, yields very poor results: The profiles are scattered and do not collapse on one single curve. However, extraordinarily good scaling is achieved if $w_*^2$ from *ES* is used (Fig. 1(b)). The simulated turbulence thus reveals the same surprising scaling characteristics as TKE observed from the aircraft, i.e. TKE obtained from ARPS appears to be produced by the same mechanisms as the measured 'real' turbulence. We try to identify these processes by investigating the TKE budget.

As described in many textbooks, the rate of change in TKE is balanced by TKE production due to wind shear and buoyancy, by advection of TKE, by viscous dissipation, pressure transport and turbulent transport (the latter two processes are henceforth referred to as 'diffusion'). The 1.5-order TKE closure used by ARPS solves a prognostic TKE equation which is based on such a TKE budget. To identify the dominant TKE production mechanisms in the Riviera Valley, the components of the TKE budget equation are analyzed. In Fig. 2, profiles of the TKE budget components in the Riviera Valley are displayed. The profiles are averages over the valley base width and obtained from model output on 22 August, the day with strongest turbulence activity. In the late morning, at 1000 UTC, TKE production is entirely determined by buoyancy (up to 0.0035 m$^2$s$^{-3}$). Shear production and advection of TKE are negligible, while diffusion and dissipation act as sink terms. This is consistent with the picture of a convectively growing boundary layer without wind shear (Moeng and Sullivan 1994). At 1300 UTC, however, the dominating TKE production mechanism is wind shear with a maximum of 0.012 m$^2$s$^{-3}$. Shear production has its maximum at about 500 m altitude rather than at the surface. Buoyancy is an important source of TKE only in the lowest 200 m. The turbulence structure on 21 and 25 August (not shown here) reveals similar characteristics as 22 August, although less pronounced.

## 3. DISCUSSION

The previous subsection has shown that the turbulence structure of the afternoon atmosphere is mainly determined by wind shear and only to a limited degree by buoyancy effects. Weigel and Rotach (2004) showed that the Riviera atmosphere is characterized by a slightly stable stratification on all sunny days, which is due to subsidence of potentially warmer air from above. This explains the surprisingly small and sometimes even negative contribution of buoyancy to the TKE budget. More striking is the strong TKE production due to wind shear and the location of its maximum well above the valley surface. This means that shear production must be primarily a consequence of interacting up-valley winds and cross-valley flow patterns rather than of

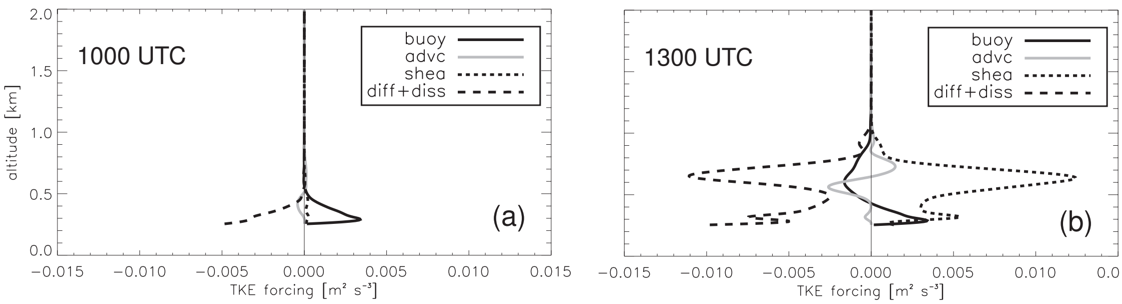


***Figure 2:*** *Profiles of the TKE budget terms at (a) 1000* UTC *and (b) 1300* UTC *in a cross-valley slice. "Buoy" and "shea" denote the production of TKE by buoyancy and wind shear, "advc" is the advection of TKE, and "diff" and "diss" are diffusion and dissipation, respectively.*

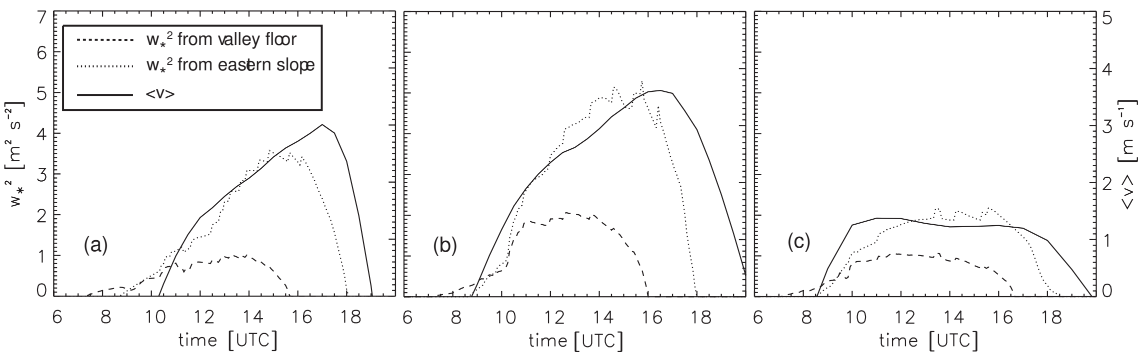


***Figure 3:*** *Time series of $w_*^2$, obtained from ARPS output data at the locations of a surface site on the valley floor and on the eastern slope, and of the valley-averaged up-valley wind speed $\langle v \rangle$ on (a) 21 Aug, (b) 22 Aug and (c) 25 Aug.*

direct friction on the surface.

Given the comparatively small contribution of buoyancy as a source of TKE, the excellent scaling behavior with the convective velocity scale $w_*$ based on the eastern slope (Fig. 1) is very surprising. The dominance of shear production would, at first sight, rather imply a scaling approach based on a friction velocity $u_*$, or at least a combination of $w_*$ and $u_*$ (e.g. Moeng and Sullivan 1994).

Therefore, despite the apparent close relationship to $w_*^2$ obtained from *ES*, TKE cannot be *determined* by $w_*^2$, at least not directly. Scaling with the square of a surface friction velocity $u_*$, on the other hand, turns out to yield very poor results (not shown), indicating that shear production in the Riviera Valley is not a consequence of surface friction but of the direct interaction between the strong jet-like up-valley winds and the local slope winds and cross-valley circulations. This implies that the strength of up-valley winds may be a key variable in this context rather than $w_*^2$ or $u_*^2$. In Fig. 3, time-series of the up-valley wind speed $\langle v \rangle$ (averaged over the entire valley volume up to an altitude of 2000 m) are displayed, together with time-series of $w_*^2$ from *VF* and *ES*. It can be seen that $w_*^2$ from *ES* correlates very well with $\langle v \rangle$, in contrast to $w_*^2$ from *VF*. Thus, if our hypothesis holds and $\langle v \rangle$ is indeed the key variable determining the production of TKE, the observed good scaling with $w_*^2$ from *ES* may be understood as a consequence of their direct proportionality. Of course, it is yet too early to propose a new general similarity theory for the atmospheric boundary layer in steep and complex topography. For dimensional reasons, one cannot simply use $\langle v \rangle$ as a new scaling variable instead of $w_*^2$. It is well possible that a second velocity scale must be included which is associated with the cross-valley flow.

The cause for the surprising agreement between up-valley wind speed and $w_*^2$ on the eastern slope is another aspect yet to be investigated. It is certainly plausible that the surface heat fluxes, and thus $w_*$, are essential for the heating of the valley atmosphere, either directly by heat flux divergence, or indirectly via thermally-driven cross-valley circulations. Therefore, one can expect $w_*$ to have a direct impact on the magnitude of diurnal valley-plain temperature gradients and thus on the strength of the resulting valley winds. As the up-valley winds are strongest in the afternoon, it also appears plausible that the surface heat fluxes on the energetically active side, i.e. on the sun-exposed westward facing slope, are to be considered. However, a quantitative evaluation of the nature and characteristics of the relationship between $w_*$ and the corresponding up-valley winds must still be carried out.

## 4. SUMMARY AND CONCLUSIONS

The structure of TKE in a typical medium-sized Alpine valley as obtained from ARPS simulation output data has been evaluated. A 1.5-order TKE scheme has been applied for subgrid-scale closure. The main results can be summarized as follows:

(i) As in the airborne measurements, the simulated profiles of TKE scale very well with the square of the convective velocity scale $w_*$ obtained from the surface fluxes on the sun-lit eastern slope.

(ii) TKE is mainly produced by wind shear, due to interacting up-valley flow and local cross-valley circulations, while the contribution of buoyancy is comparatively small.

(iii) The paradox of a good scaling behavior with $w_*^2$ despite dominant shear production can possibly be explained by the observation of $w_*^2$ having a similar diurnal pattern as the averaged up-valley wind speed $\langle v \rangle$. This means that TKE may well be directly determined by $\langle v \rangle$, and a scaling with $w_*^2$ on the eastern slope nevertheless works.

All in all, our measurements and simulations show that despite the complexity of the terrain and despite the apparent differences from a 'normal' convective boundary layer, the turbulence structure reveals reproducible patterns and scaling characteristics. A general similarity theory for the structure of TKE over steep and mountainous topography cannot be proposed from this case-study, but the high correlation between $\langle v \rangle$ and $w_*^2$ suggests a direction for future studies.

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