6.1 ON THE TURBULENCE STRUCTURE OVER HIGHLY TERRAIN: KEY FINDINGS FROM THE MAP-RIVIERA PROJECT

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1 INTRODUCTION

During the Mesoscale Alpine Programme (MAP, Bougeault et al. 2001) a working group on *Planetary Boundary Layers in Complex Terrain* had as a goal to coordinate and foster research on to boundary layer processes in the Alpine region (Emeis and Rotach 1997, Rotach and Emeis 2000). At a time towards the end of the analysis phase of MAP it seems appropriate to trying to summarize the results from the various studies concerning boundary layer processes in complex terrain during MAP. In this contribution we review the most salient findings from *one of the boundary layer projects* during MAP, namely the MAP-Riviera project (Rotach et al 2000, 2004). The purpose of the present paper is thus to stimulate discussion on whether the findings from the Riviera project might be general (similarly observed/modeled in other valleys or locations) or very specific to the sites in the Riviera Valley. We concentrate hereby on observations/data analysis – simply because some of the most recent results from numerical modeling are being presented in the same conference (Chow et al 2004, Weigel et al 2004). More results concerning numerical modeling can be found in De Wekker (2002) and De Wekker et al 2004. Results from hydrological modeling are reported in Zappa and Gurtz (2003).

During MAP SOP through summer and fall 1999 very detailed observations were made in the Riviera Valley in southern Switzerland. An overview over all the activities is given in Rotach et al. (2004). These included detailed turbulence measurements on a cross-section through the valley, as well as research flights accompanied by radio soundings, tethered balloons, temperature profiling, etc. (Fig. 1). Thereby the emphasis was on the turbulence structure and turbulent exchange mechanisms rather than (only) the mean boundary layer structure. In this respect a total of 20 sonic anemometers were operated on the cross-section through the Riviera Valley (Fig. 1) and scintillometers were used to assess spatially averaged fluxes (Weiss et al. 2001). Also, the airborne observations on a light research aircraft of MetAir were made with a sufficient temporal resolution for deriving turbulent statistics (Weigel and Rotach 2004).

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2 THE MAP RIVIERA PROJECT

3 KEY RESULTS

3.1 Spatial inhomogeneity

Large *spatial inhomogeneity* in the atmospheric fields had been expected before the project had started and its investigation indeed was one of the driving forces for the MAP Riviera project. Clearly, it was anticipated that one reference turbulence observation may be too little in order to, for example, define the situation for air pollution modeling in a valley.

Figure 2 shows average daily cycles of the net radiation on a cross-section through the valley (from Matzinger et al. 2003). Clearly, the spatial inhomogeneity is huge in the sense that at the same time net radiation may already be negative at one site while it is still close to its maximum at another site (e.g., around 16 CET). Similarly, the near-surface turbulent heat flux (averaged over 15 selected clear-sky days) shows a significant spatial variability (Fig. 3). Comparing Figures 2 and 3, however, indicates that the sensible heat flux is to a large extent driven by the net radiation, which in turn is strongly determined by i) the local slope and ii) by the local exposition (and to some extent by the local surface characteristics through the albedo; see Matzinger et al 2003).

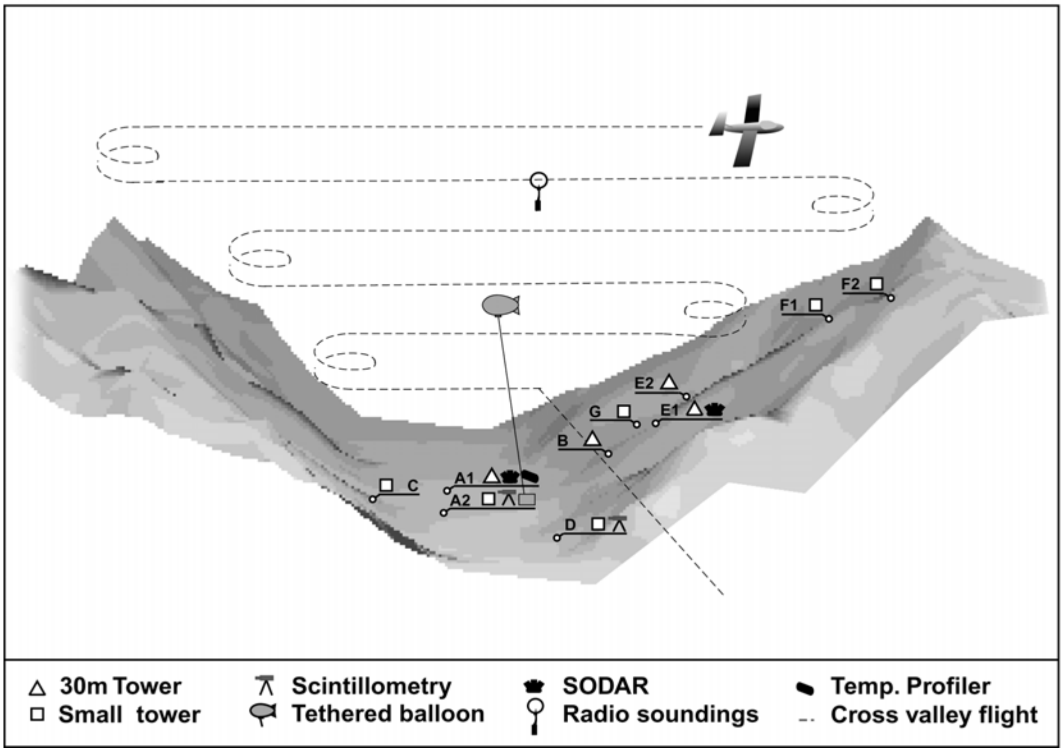

Figure 1 Topography of the Riviera Valley and instrumentation at various sites.

Hence, spatial variability in the near-surface turbulence characteristics is large indeed, but connected to topographical features and may be modeled accordingly.

3.2 Breakup of inversion

Even under clear-sky conditions in summer (thermal valley and slope wind development) only a shallow mixed layer develops in the morning, which usually ceases to grow (or even re-stabilizes) in the afternoon. Thus the bulk of the valley atmosphere shows a (near-) *stable stratification* above a shallow (if at all) mixed-layer (see Fig. 3 in Chow et al 2004, and Weigel et al 2004 for details). The layer of significant turbulence does usually *not correspond to this mixed layer* but rather to a layer of roughly half the valley depth (Weigel and Rotach 2004). Hence a profile of potential temperature may not yield appropriate information concerning the dispersion characteristics in a deep valley. Weigel and Rotach (2004) and Weigel et al. (2004) suggest that it is mainly *vertical advection* of potentially warm air from aloft in connection with along-valley advection of potentially cooler air due to the up-valley winds that lead to the stably stratified (potential) temperature profile. They also find that in the case of the Riviera Valley its curvature (i.e., at the 'valley entrance' south of the actual Riviera Valley, see Fig. 1 in Weigel et al 2004) leads to a secondary cross-valley circulation, which indeed brings warm air from the free troposphere above the valley to the ground. To what extent vertical advection from only the 'classical' cross-valley symmetric slope wind circulation could be effective enough remains yet to be shown.

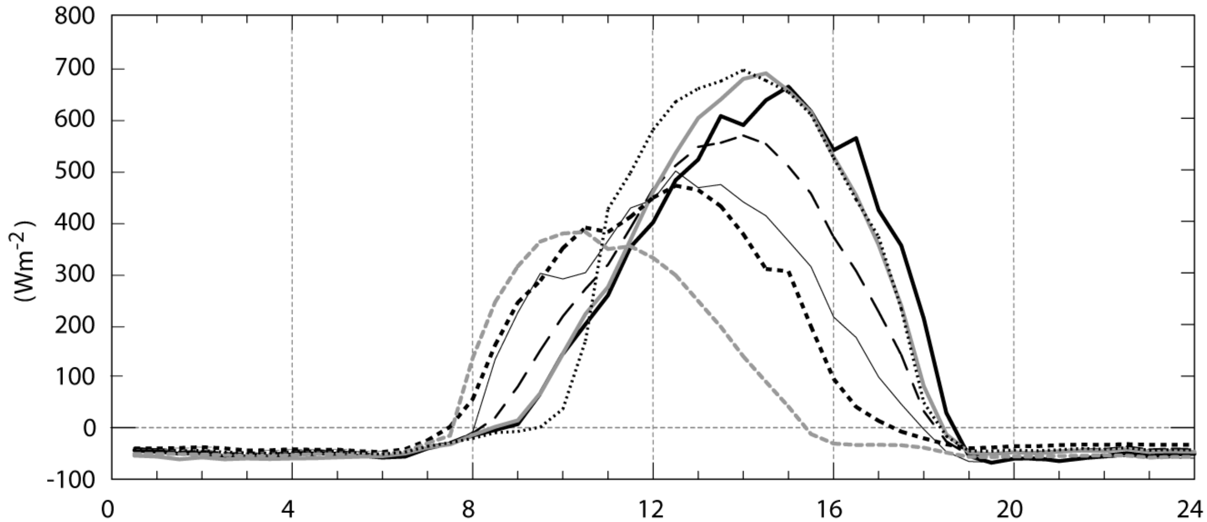

Figure 2 Average daily cycles of net radiation (Wm^{-2}) for 15 clear-sky 'valley wind' days at various sites in the Riviera Valley: gray dashed line: site C; black dashed line: site A1; thin black line: site F1; long dashed line: site E1; black dotted line: site B; gray line: site E2, bold line: site F2 (adapted after Matzinger et al. 2003).

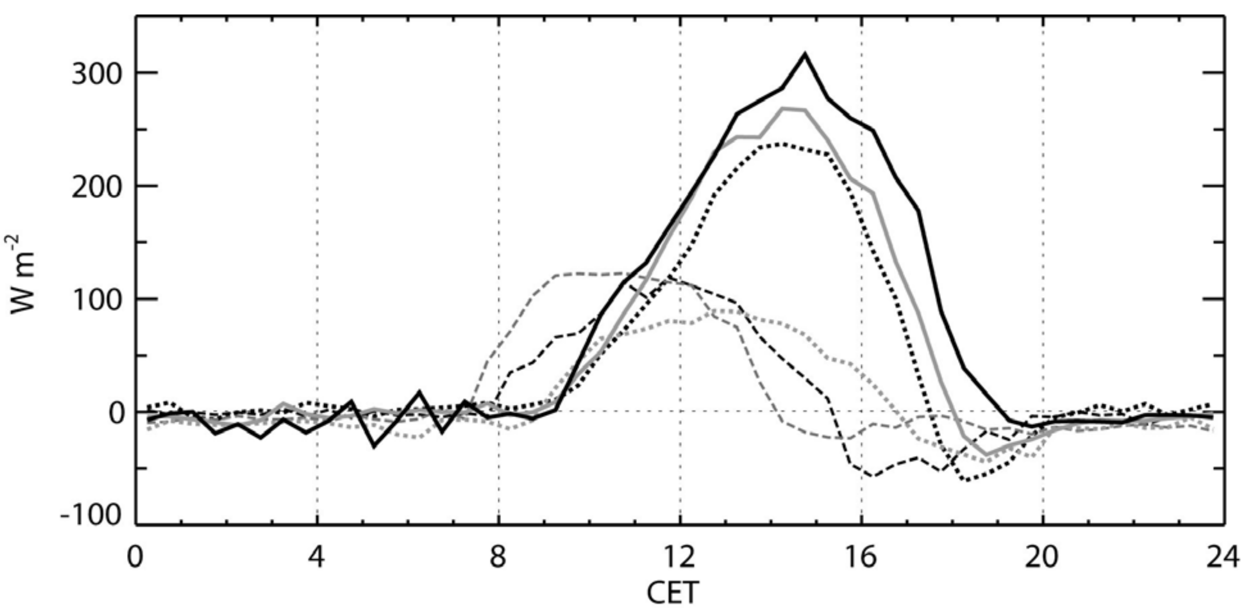

Figure 3 Same as Fig.2 but for near-surface sensible heat flux. Gray dashed line: site C; black dashed line: site A1; gray dotted line: site D; black dotted line: site B; gray line: E2; bold line: site F2.

3.3 Interaction of slope and valley winds

Both observations and high-resolution numerical simulations show that the valley winds do not – as it is portrayed in the classical picture of Defant – completely 'fill the valley' in the afternoon. Rather, slope winds occur in a shallow layer close to the surface and there is transition towards dominating valley wind direction with increasing height. This interaction between slope and valley winds leads to the occurrence of *directional shear* in addition to and at least equal in magnitude as the frictional shear (Fig. 4). This behavior is found regardless of the post-processing approach (Andretta et al. 2002) and is observed at all slope sites and ranges even into the forest canopy (Van Gorsel et al 2003). Numerical models, in which traditionally the momentum flux is diagnosed from friction alone, seem therefore to be prone to underestimating the total momentum exchange and hence also turbulent exchange of scalars.

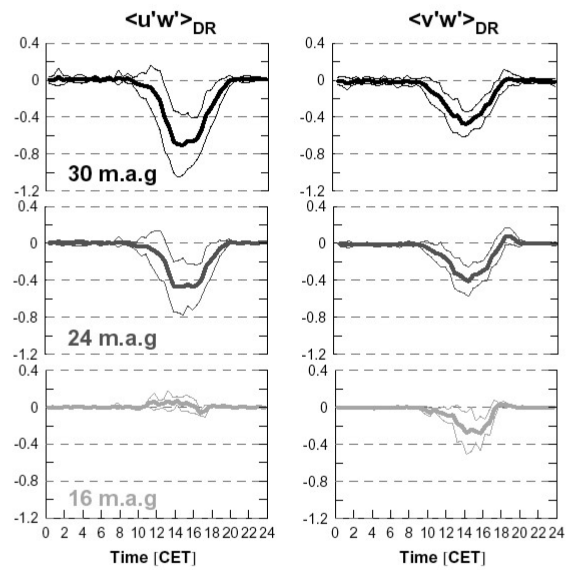

Figure 4 Profiles of longitudinal <u'w'> and lateral <v'w'> vertical momentum transport (both [m^2s^{-2}]) at various heights at site B. Data from 15 clear-sky days. Average (bold line) and standard deviation (two thin lines). Subscript 'DR' refers to double rotation in the analysis of the turbulence data.

3.4 Scaling in the valley atmosphere

Even if the mean thermodynamic state of the valley atmosphere does not call for convective scaling (see section 3.2), so do the surface heat fluxes (Fig. 3) during clear-sky conditions. The airborne data from all available clear-sky days were therefore analyzed in terms of turbulent kinetic energy (TKE) and scaled using different velocity scales (Weigel and Rotach 2004). Airborne turbulence data were analyzed from along-valley flight legs of roughly 10 km length. Here, only flight legs from the center of the valley are presented.

In Fig. 5, the airborne TKE data are scaled using a convective velocity scale:

$$w_* = \left(\overline{w'\theta'}_o z_i \, g/\overline{\theta}\right)^{1/3}, \qquad (1)$$

where $\overline{w'\theta'}_o$ is the surface turbulent heat flux and $g/\overline{\theta}$ the buoyancy parameter. Due to the apparent lack of a mixed layer signal in the temperature profiles (section 3.2) the mixed layer height z_i was determined using a TKE threshold criterion (Weigel and Rotach 2004). As an apparent first choice, the surface turbulent heat flux from the site just beneath the flight legs was chosen (Fig. 5a). Although there is some overall decrease of scaled TKE with height, the data do by no means support the chosen scaling approach. However, and astonishingly, the situation changes drastically if the TKE data from the middle of the valley are scaled using surface data from the sunlit slope (white dots in the lower panels of Fig. 5). Similar results were also obtained for the TKE data from the other flown 'planes' (i.e., close to the western and eastern slopes respectively). It appears therefore that the energetically most active surface within the valley rather than the 'surface point beneath the profile' drives the turbulence structure within the entire valley (Weigel and Rotach 2004).

If instead of a convective velocity scale a friction velocity was used, the results were similar (not shown) thus emphasizing the importance of mechanical turbulence through the thermally driven valley wind regime - even under clearly convective conditions with weak synoptic forcing. Also, the scaling approach proved successful for other turbulence statistics such as momentum transport (Weigel and Rotach 2004).

4 CONCLUSIONS

The results as presented here from the MAP-Riviera project cast some light on the atmospheric structure of a narrow alpine valley. They are to some extent at odds with earlier findings, which predominantly stem from much larger valleys (see Whiteman 2000 for an excellent overview). The key findings so far may be summarized as follows:

- There is a significant *spatial inhomogeneity* in surface turbulence characteristics throughout the valley, which is to a large extent determined through topographical features (local slope and surface exposition).
- Even on clear-sky days in summer in the southern Alps only a shallow mixed layer develops (if at all) and the remainder of the valley atmosphere exhibits a *stable*

stratification. This stabilization of the valley atmosphere is found to be due to the combined effect of vertical advection of potentially warm air from aloft and cool air advection due to the up-valley winds. In the case of the Riviera Valley it is found that the *curvature* of the valley largely contributes to this vertical advection through a secondary cross-valley circulation.

- Under clear-sky conditions there is strong interaction between slope winds and valley winds resulting in important contributions to turbulent vertical transport of momentum from *directional shear*. This vertical transport of lateral momentum component contributes significantly to the local friction velocity for scaling.

- Despite a predominantly stable stratification on clear-sky days, profiles of turbulence statistics in the valley atmosphere can be scaled using a convective velocity. However, the employed surface heat flux must stem from the energetically most active (i.e., the sunlit) slope surface rather than from directly beneath the profile.

- Last but not least it must be emphasized that results from high-resolution numerical simulations are very encouraging (De Wekker et al 2004, Chow et al 2004, Weigel et al 2004). The major features of the flow and turbulence structure in the valley atmosphere can be reproduced.

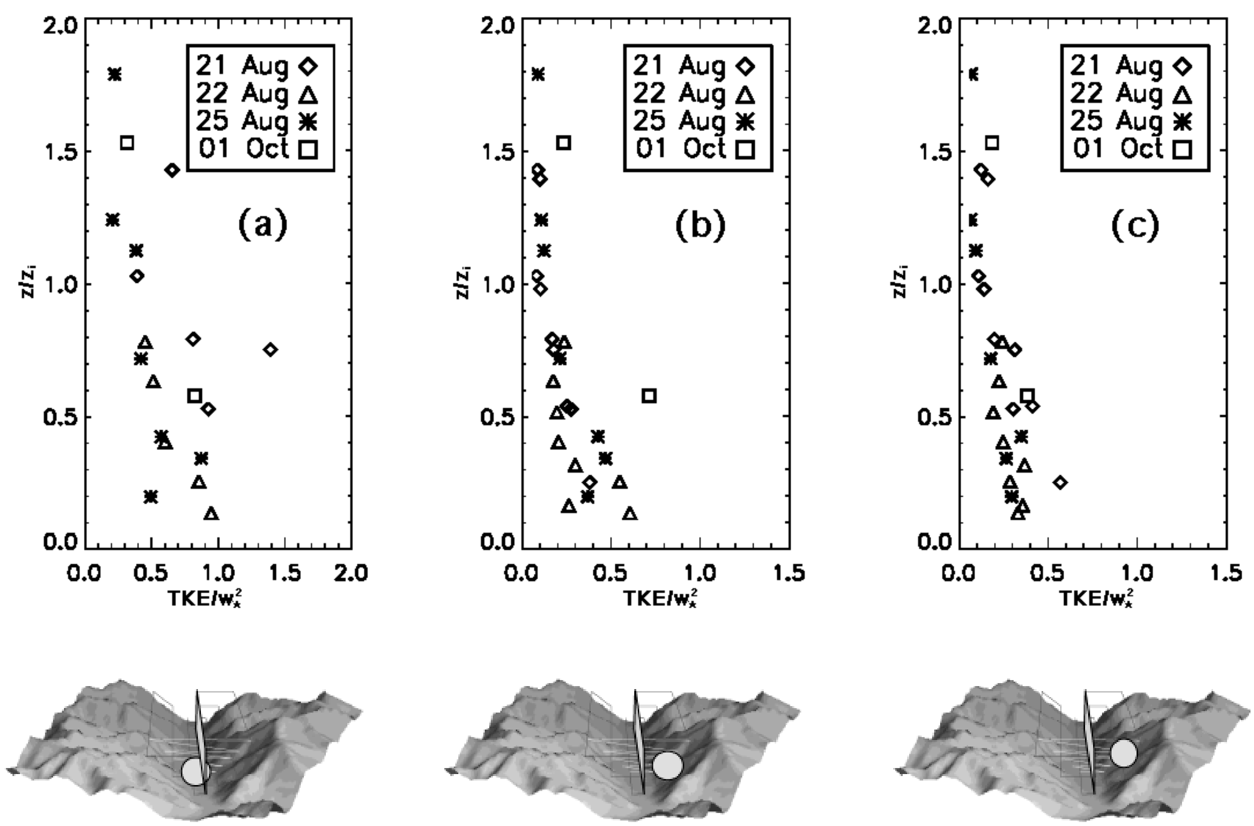

Figure 5 Scaled profiles of turbulent kinetic energy from four days during the MAP-Riviera project. Each symbol corresponds to the data from an *along-valley* flight leg at the respective height in the middle plane of the valley (see lower panels). Data from morning and afternoon flights. The white dots in the lower panels indicate for each panel (a to c), where the surface turbulence information stems from in order to determine the scaling velocity.

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