

## 6.4 HIGH-RESOLUTION LARGE-EDDY SIMULATIONS OF THE RIVIERA VALLEY: ASSESSMENT OF THE FLOW STRUCTURE AND THE HEAT AND MOISTURE BUDGETS

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### 1. INTRODUCTION

Atmospheric processes over steep and mountainous terrain are characterized by a high degree of complexity. On days with fair weather conditions, complicated flow patterns can evolve in mountain valleys. Such flow patterns are often a superposition of several scales of motion, including local slope winds and cross-valley circulations, channeled and thermally-induced valley winds as well as mountain-plain winds on the regional scale (e.g. Barry 1992; Whiteman 2000). While these flow structures are now quite well understood, still very little is known about the small-scale turbulent fluxes over such terrain, as experimental evidence is limited and difficult to obtain. Moreover, theoretical approaches such as linear theory (Jackson and Hunt 1975) fail in very steep terrain. A better understanding of the turbulence structure in mountainous terrain is, however, necessary to improve numerical weather and climate prediction models (Rotach et al. 2004). The subgrid-scale parameterizations of such models are typically based on similarity functions which have been verified over flat and homogenous terrain, but which do not necessarily hold in steep and complex topography.

With the advances in computer technology, large-eddy simulations (LES) are becoming a more and more important tool for the investigation of small-scale processes over mountainous terrain. Together with the companion paper of Chow et al. (2004), this contribution investigates the physical processes of the daytime atmosphere in a typical Alpine valley by applying the Advanced Regional Prediction System ("ARPS", Xue et al. 2000, 2001) as a simulation tool. We have chosen the Riviera Valley (base width: 1.5 km, length: 15 km, depth: 2.5 km) in southern Switzerland for simulation. An extensive observation data-set exists for this valley from the MAP-Riviera project, enabling us to evaluate the performance of ARPS over such a complex topography. The MAP-Riviera measurement campaign (comprehensively

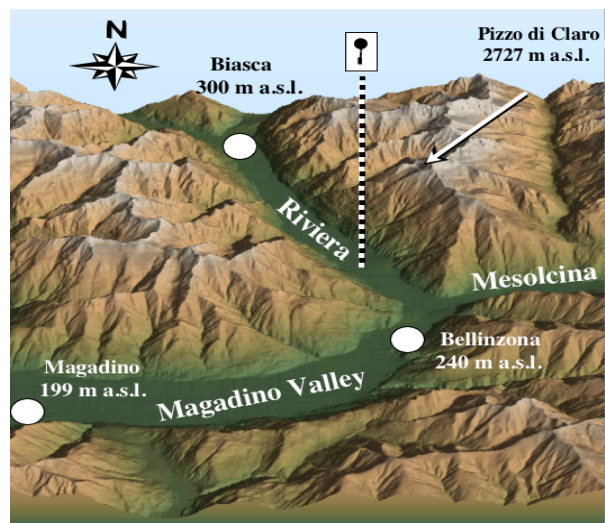


Figure 1: Topography of the Riviera Valley, located in southern Switzerland.

described in Rotach et al. 2004) was carried out summer through autumn in 1999 and focused on the investigation of both the mean and the turbulence structure in this typical, medium-sized alpine valley. The data-set includes radio soundings and aircraft data as well as sonic and profile measurements at various surface stations, making it a data-set of unprecedented completeness w.r.t. to boundary layer studies in such a complex topography.

We have chosen two clear-sky days of the measurement campaign (22 and 25 August 1999) for simulation. ARPS is applied in a one-way nesting mode, initialized from ECMWF analysis data and nested down to a maximum horizontal resolution of 150 m. Our setup follows the "MOISLU-run" as described and quantitatively evaluated in the companion paper of Chow et al. (2004). Here we elaborate on the three-dimensional flow structure in the valley and compare our model results with aircraft measurements (section 2). In section 3, an analysis of the heat and moisture budget in the valley atmosphere

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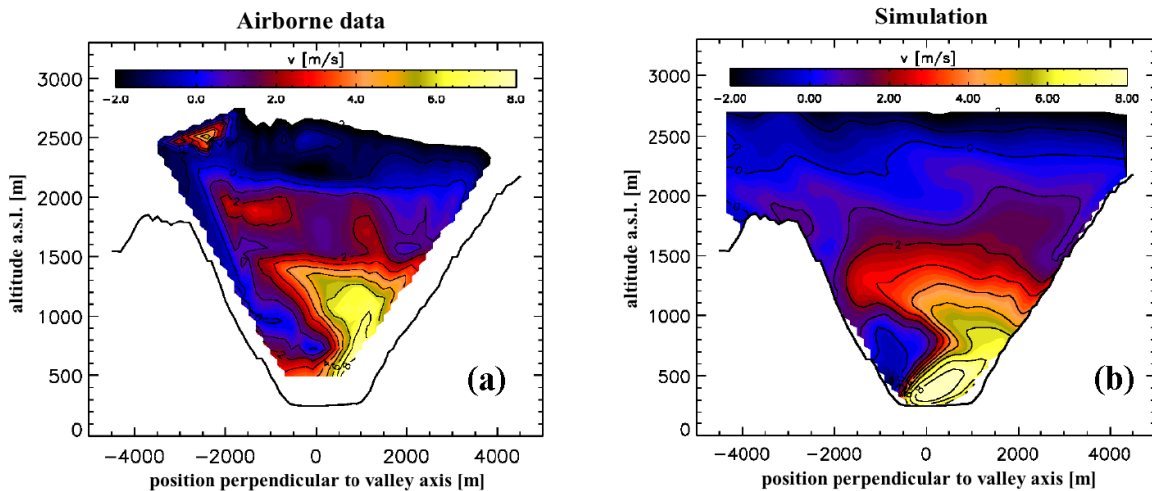


Figure 2: Along-valley wind component in a valley cross-section approximately 3.5 km north of the valley entrance at around 13 UTC on 25 August. Both the aircraft data **(a)** and the simulations **(b)** reveal the same flow structure.

is presented and discussed.

## 2. THE FLOW STRUCTURE

From the airborne data, Weigel and Rotach (2004) have obtained a consistent picture of the flow structure in the Riviera Valley on convective days such as 22 and 25 August. They observe the development of strong up-valley winds in the afternoon, which reveal a jet-like structure in the southern part of the valley. The core of these jets is seen to be shifted towards the eastern slope (as shown in Figure 2a). This is due to centrifugal forces, because the valley wind - coming from the Magadino Valley (see Figure 1) - has to flow around a sharp bend at the town of Bellinzona in order to get into the Riviera Valley. Weigel and Rotach (2004) have shown that this shifted up-valley jet induces a clock-wise cross-valley circulation at the southern mouth of the Riviera Valley, driven by local imbalances between counteracting centrifugal and pressure-gradient forces (as described by Kalkwijk and Booij 1986). This so-called secondary circulation is strong enough to suppress the development of a 'classical' thermal cross-valley circulation, which would have the opposite rotation sense in this topography. Further north, the valley wind spreads over the entire valley cross-section and the secondary circulation disappears.

Our simulations with ARPS are able to reproduce all these features. Figure 2 shows a comparison of measured (2a) and simulated (2b) along-valley winds in the afternoon of 25 August in a valley cross-section approximately 3.5 km north of the southern valley mouth. The jet-like structure with the core of the jet being pushed to the eastern side is clearly reproduced. Further north, the simulated valley flow spreads over the whole valley diameter as does the observed one (not shown).

In Figure 3, the simulated cross-valley flow pattern of 22 August is displayed for two slices perpendicular to the valley axis (one close to the valley entrance and one in the valley center). The upper panels show the flow structure at 10 UTC, the lower ones at 13 UTC. The colors indicate vertical velocity. In the late morning (10 UTC) both slices reveal the pattern of a classical symmetric double-circulation with air rising along the heated slopes and subsiding in the valley center. In the afternoon (13 UTC), when the up-valley winds have started, a different picture emerges; the southern slice shows a very pronounced clockwise circulation with subsidence next to the eastern slope and an upward movement of air on the western side of the valley. This is consistent with the observed secondary circulation described above. The circulation in the northern slice has the opposite rotation sense and can be understood as a thermal asymmetric cross-valley circulation: air rises along the sun-exposed eastern (actually east-north-eastern) slope and subsides in the valley center and along the (meanwhile) cooler western slope. Equivalent results have been obtained for 25 August.

ARPS is thus able to reproduce the highly complex flow structure of the valley atmosphere which includes the existence of two simultaneous cross-valley circulations of opposite rotation sense. This strengthens the positive conclusion of Chow et al. (2004) on the performance of ARPS in the Riviera Valley, and we proceed with a closer look at the thermal structure of the valley atmosphere.

## 3. ANALYSIS OF THE HEAT AND MOISTURE BUDGET

Weigel and Rotach (2004) have shown that the diurnal evolution of the profiles of potential temperature in the Riviera Valley on clear-sky days reveal characteristics that appear to be quite different from the growth of

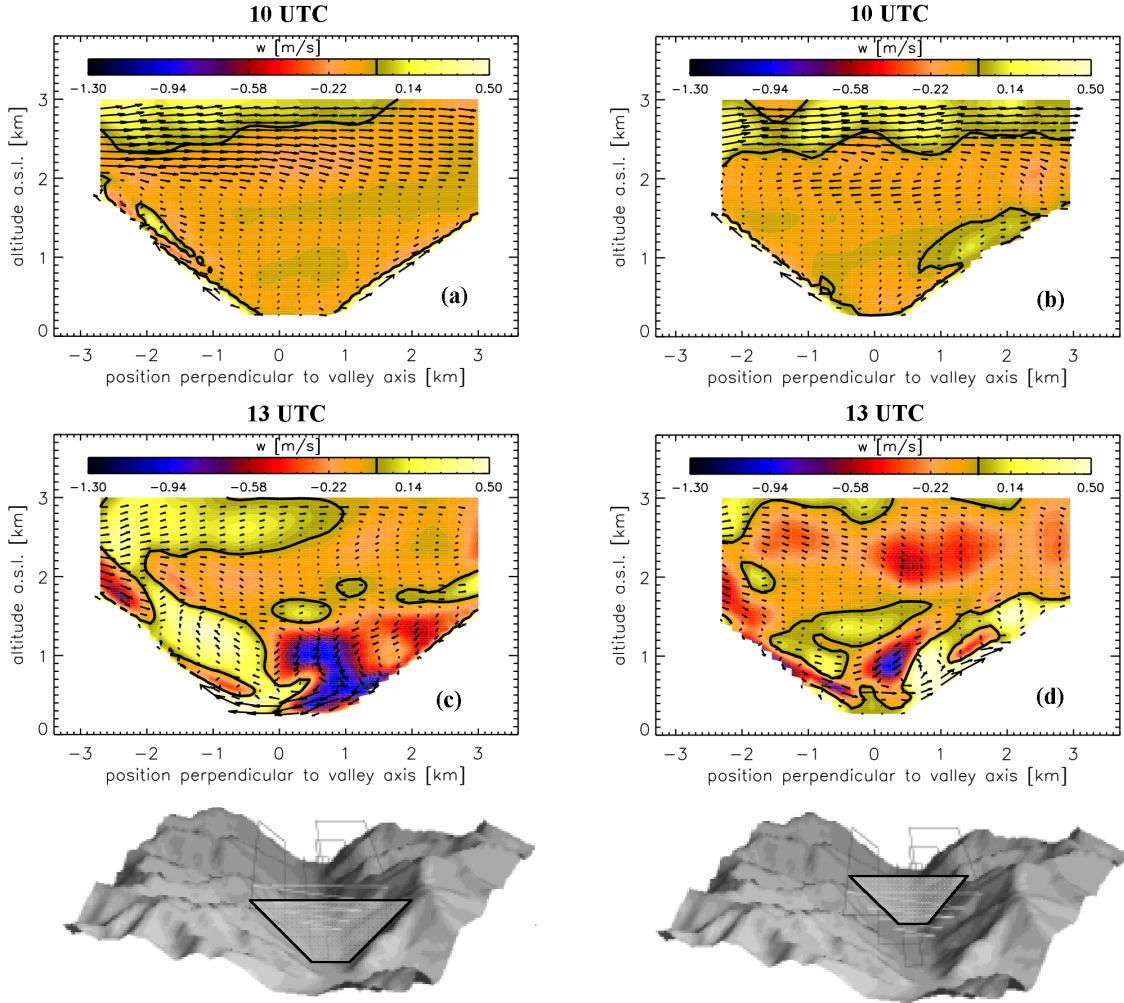


Figure 3: Cross-valley winds in two slices as indicated in the bottom panel (left: valley entrance, right: valley center) on 22 August at 1020 UTC (a,c) and 1320 UTC (b,d). The colors indicate the vertical wind component.

a standard boundary layer. On all these days - including 22 and 25 August - only a relatively shallow well-mixed layer develops which stops growing by noon and sometimes even decreases in depth in the afternoon. Weigel and Rotach (2004) attributed this behavior to the combined effect of vertical advection of warm air and along-valley advection of cool air. However, a thorough analysis was not possible due to problems in the airborne heat flux measurements. This deficiency can now be overcome with ARPS, which well reproduces the general feature of a suppressed mixed layer growth (see e.g. Figure 4 and Chow et al. 2004).

To investigate the physical reasons for this characteristic behavior, the terms of the tendency equation of potential temperature  $\theta$  are extracted from the model and analyzed. Neglecting heating due to moist processes (no condensation occurred during the simulation period), this equation reads:

$$\frac{\partial \theta}{\partial t} = -u \frac{\partial \theta}{\partial x} - v \frac{\partial \theta}{\partial y} - w \frac{\partial \theta}{\partial z} + T_T + R \quad (1)$$

The coordinate system is oriented such that the x-axis points normal to the valley axis and the y-axis is aligned with the valley axis. The horizontal wind components  $u$  and  $v$  are defined accordingly. The left hand side of this equation is the overall heating rate. The terms on the right hand side are heating (cooling) due to cross-valley advection of potential temperature, along-valley advection, vertical advection, subgrid-scale turbulent heat flux divergence ( $T_T$ ) and radiation flux divergence ( $R$ ).

Figures 5(a) and 5(c) show profiles of the heating (cooling) contribution terms of Eq. (1) at 10 UTC and 13 UTC on 22 August ('advection' is shown as 'total advection'). The profiles are averaged over one hour (centered at plotting time) over the valley base width in a slice approximately 3.5 km north of the valley en-

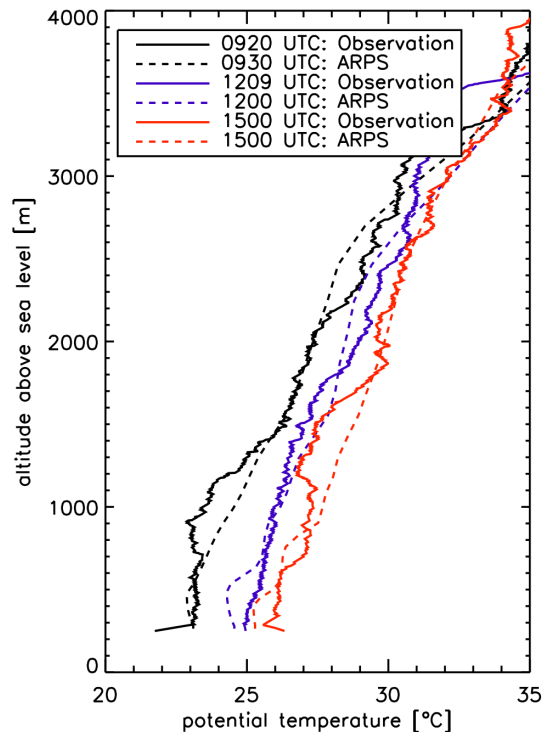


Figure 4: Profiles of potential temperature on 22 August as obtained from radio soundings and ARPS.

trance (as in Figures 3a,c). The respective individual advection terms in the valley coordinate system are displayed in Figures 5(b) and 5(d). In the late morning (10 UTC, upper panels) the valley atmosphere experiences a net warming over the whole valley depth (up to approximately 2500 m). The warming is almost entirely due to vertical advection (apart from the lowest 200 m where radiation and heat flux divergence are also important). This is consistent with the picture of subsiding warm air as a consequence of the symmetric cross-valley circulation as seen in Figure 3(a). The heating rate has its maximum close to the ground, leading to the development of a mixed layer.

In the afternoon (13 UTC, lower panels) strong up-valley winds have started, advecting potentially colder air in the lower valley atmosphere (up to about 1500 m) and thus providing a pronounced cooling contribution to the heat budget. Between 500m and 1500m, this strong cooling is slightly over-balanced by heating due to vertical advection. Therefore, despite the cold up-valley winds, the sum of the three advection components yields a positive heating rate. The vertical advection appears to be a consequence of subsidence induced by the secondary circulation. Close to the ground, the cold-air advection cannot be balanced by subsidence any more; the total heating rate decreases and the atmosphere stabilizes until turbulent heat flux divergence becomes large enough to balance further advective cooling. This means, that - despite significant positive surface heat fluxes - the mixed layer is restricted to a very shallow layer close to the surface,

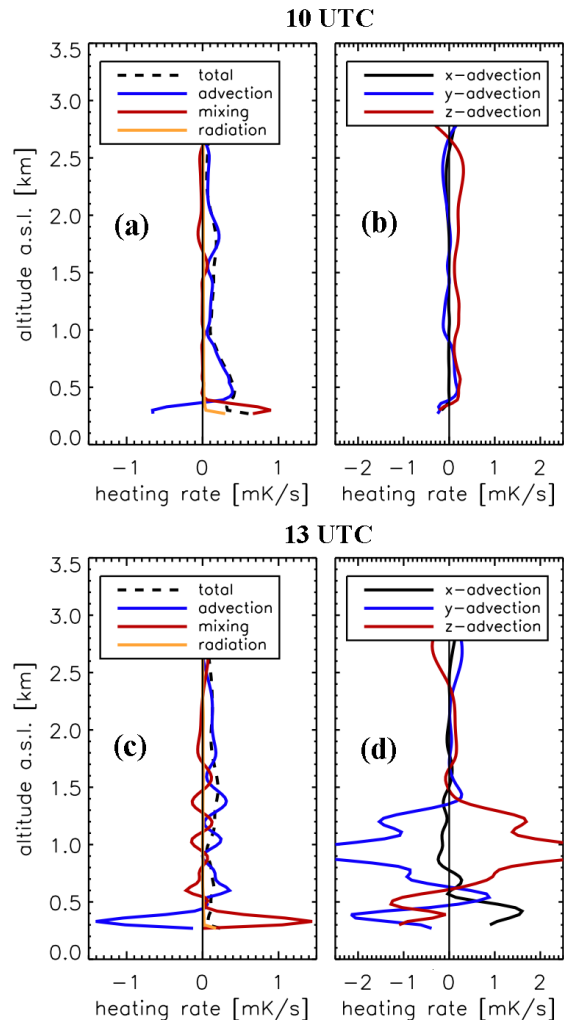


Figure 5: Profiles of the heat budget contributions (a,c) and the respective advection terms in the valley coordinate system (b,d) on 22 August in the valley entrance region (as in Fig. 3a,c). The profiles are averaged over the valley-base width from 0930-1030 UTC (upper panels) and from 1230-1330 UTC (lower panels).

resulting in the unusual structure of the profiles of potential temperature as described above.

Further north, the subsidence is induced by a thermally forced cross-valley wind circulation of opposite rotation sense (Figure 3d). When averaged over the valley base width, a similar heat budget structure is obtained as in the southern slice (Figure 6). The only major difference is that the close-to-surface advective cooling is somewhat lower, because the valley-wind has spread over a larger area in the valley cross-section (section 2) and thus has a decreased flow speed. Consequently, turbulent heat fluxes can penetrate slightly further up into the valley atmosphere and turbulent heat flux divergence becomes the dominant heating source over a depth of about 300 m from the ground. Simulations of 25 August

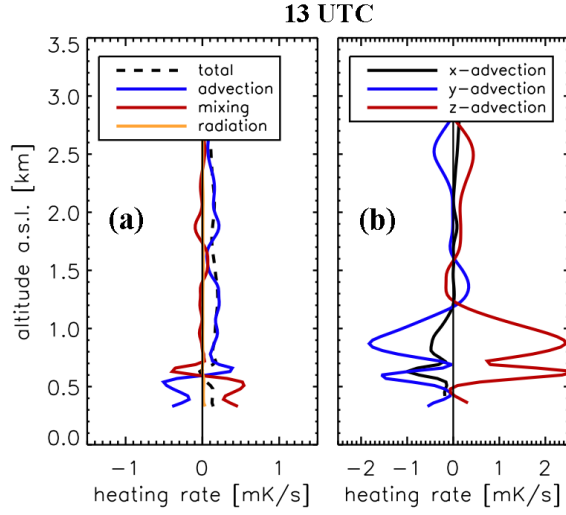


Figure 6: Same as in Figure 5(c,d), however in a slice located in the valley center (as in Fig. 3d).

confirm these findings (not shown), though they are less pronounced as the up-valley winds are weaker on that day.

Similarly to Eq. (1), the tendency of specific humidity  $q$  can be written as a budget equation:

$$\frac{\partial q}{\partial t} = -u \frac{\partial q}{\partial x} - v \frac{\partial q}{\partial y} - w \frac{\partial q}{\partial z} + T_q \quad (2)$$

$T_q$  is the divergence of turbulent moisture flux. Condensation and evaporation processes can be omitted on 22 and 25 August outside the surface layer. Figure 7 shows a plot of the moisture budget contributions at 13 UTC on 22 August (analogous to Figures 5a,c). As in the heat budget profiles, turbulent flux divergence is relatively unimportant apart from a shallow layer of about 200 m depth close to the ground. Also here, the significant advective effect of the up-valley wind (below 1500 m) is accompanied by strong vertical advection, which has the same order of magnitude but opposite sign. However, the drying due to subsidence cannot completely balance the along-valley advection of moist air, resulting in a net increase in specific humidity throughout the lower valley atmosphere. This explains, why - in contrast to what one may expect in the case of a thermally induced cross-valley circulation (Kimura and Kuwagata 1995) - no drying of the valley atmosphere is observed in our simulations or measurements (see also moisture profiles in Chow et al. 2004).

#### 4. CONCLUSIONS

The LES-code ‘ARPS’ has been applied to simulate the atmosphere in the Riviera Valley on two summer days with fair weather conditions. The performance of the code has been evaluated with comparisons to data

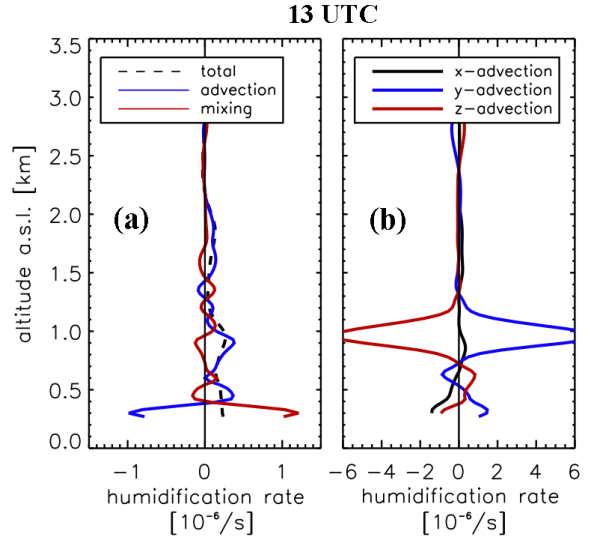


Figure 7: Profiles of the moisture budget contributions (a) and the respective advection terms in the valley coordinate system (b) on 22 August. The profiles are averaged over the valley-base width from 1230-1330 UTC in a slice approximately 3.5 km north of the valley entrance (analogous to Fig. 5). The abscissa shows the rate of change of specific humidity in ( $10^{-6}$  g/(g s)).

from the MAP-Riviera field campaign. From our work, we can conclude that ARPS is able to very well reproduce both the thermal and dynamic features of the atmosphere over topography as steep and complex as the Riviera Valley. This not only refers to the stratification and surface winds (as shown by Chow et al. 2004), but also to the resolution of very distinct circulation patterns which have been identified from airborne measurements. Given the good performance of ARPS, the components contributing to the heat and moisture budgets have been investigated. The major findings can be summarized as follows:

(i) When no valley winds are present (late morning), the valley heats almost over the entire valley depth due to subsidence of warm air as a consequence of a ‘standard’ thermal cross-valley double-circulation.

(ii) As soon as the strong up-valley winds start (afternoon), potentially colder and moist air is advected up the valley in a layer reaching from the valley ground up to about 1000-1500 m a.s.l.

(iii) In the upper two thirds of this up-valley wind layer, the strong cooling and humidification due to along-valley advection is almost entirely balanced by vertical advection of warmer and dryer air. Dependent on the geographical position, this subsidence is either due to a dynamically induced secondary-circulation (southern valley entrance) or due to a thermally induced cross-valley circulation (central and northern part of the valley).

(iv) Only in the lowest 100-300 m is turbulent flux divergence a relevant source of heating and humidification. As subsidence cannot balance the cooling effect of the up-valley flow in this layer close to the ground,

stabilization occurs, suppressing the growth of a well-mixed turbulent layer.

From these results one can conclude that the thermal structure of the valley atmosphere is largely determined by the combined effect of along-valley advection and subsidence (as part of a cross-valley circulation), i.e. by length scales which are on the order of or even larger than the valley dimensions and therefore completely resolved in our simulations. While additional increases in resolution and better sub-grid scale parameterizations are likely to further improve the simulation of the close-to-surface atmosphere, the reproduction of the valley atmosphere as a whole is not expected to be significantly enhanced by such measures. Surface characteristics, especially soil moisture, appear to be much more important parameters in this context (see also Chow et al. 2004; Weigel et al. 2004), as they directly influence the structure and behavior of the valley winds. A generalization of these results to other valley topographies is subject to future research.

## ACKNOWLEDGEMENTS

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