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On the boundary-layer structure over highly complex terrain: Key findings from MAP

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ABSTRACT: Within MAP, one of the scientific projects was devoted to 'Boundary Layers in Complex Terrain'. In a number of subprojects, boundary-layer issues were addressed and detailed high-resolution multi-sensor observations were combined with simulation by models allowing for adequate parametrization of turbulence processes. In this contribution, the projects are briefly introduced and an attempt is made to summarize their key findings and to put them into a joint perspective. Spatial variability is found to be large but strictly related to topography and therefore allowing for possible parametrization. Traditional boundary-layer scaling approaches cannot simply be applied over highly complex topography, but some of the MAP findings suggest the potential for suitable extensions of those scaling relations to cover various cases of complex terrain. The mean boundary-layer structure and thermally driven flows in narrow valleys are found not to be generally in line with previous results from larger valleys elsewhere. Furthermore, local circulations are reported to contribute considerably to exchange between valley and free troposphere. In particular, the range of their effects on the lower atmosphere seems to be larger than just turbulent transport within the planetary boundary layer would suggest. Thus in larger-scale numerical models where the topography is not resolved, possible sub-grid parametrizations for local exchange seem to be in order.

KEY WORDS valley wind; slope wind; turbulent exchange; high-resolution numerical modelling; turbulence parametrization

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1. Introduction

In the decades after the seminal work of Monin and Obukhov (1954), Willis and Deardorff (1974) and Nieuwstadt (1984) on similarity theory, Kolmogorov (1941) or Kaimal *et al*. (1972) on spectral characteristics of atmospheric turbulence, boundary-layer (BL) meteorology was mainly concerned with flows over *flat and horizontally homogeneous terrain*. The need for an experimental benchmark to test theoretical insight and similarity relations culminated in the grand BL experiments on the large plains of Kansas (Haugen *et al*., 1971) or Wangara (Clarke *et al*., 1971).

From a theoretical point of view, the assumption of horizontal homogeneity allowed reduction of the 'degrees of variability' of the problem of turbulence dynamics in the atmospheric BL and investigation in detail of its vertical structure and time evolution, especially under convective conditions. Concentrated on the archetypal case of a horizontally homogenous planetary BL (PBL) were also the pioneering simulations by Deardorff (1972, 1974), who first explored a large-eddy simulation (LES), as well as the subsequent valuable contributions of various authors (see Nieuwstadt *et al*., 1993 for a review). Among the earliest simulation attempts to reproduce a thermally driven flow over a non-horizontal (although still homogeneous) surface is that of Schumann (1990).

First attempts into inhomogeneous surfaces concentrated on 'simple complications' such as a step change in surface roughness (see e.g. the review by Garratt, 1990) or BL development over smooth sinusoidal hills (Jackson and Hunt, 1975; Doernbrack and Schumann, 1993). Also, the near-surface structure of flows over very rough surfaces was studied by splitting up the *surface layer* (traditionally the layer next to the surface) into a roughness sub-layer (roughness influence) and an overlying inertial sub-layer (Raupach *et al*., 1991). Over real complex terrain, such as mountain valleys or saddles/ridges with more than, say, 10° slopes, BL studies for a long time concentrated on investigating the mean (thermo-) dynamic structures (see Whiteman, 2000, for an excellent review). Knowledge about characteristic mean flow structures like valley- and slope-wind systems and speed-up over ridges, as well as the corresponding thermodynamic structure, was relatively well established by the end of the 1990s. Still, whenever it came to the necessity of assuming or knowing something on the *turbulence structure* over highly complex terrain, the concepts of flat and horizontally homogeneous BLs had to be invoked – even if it was clear that theoretically they could not be expected to hold. Similarly, numerical models of all scales, from global climate and weather prediction models to mesoscale and even LES models,

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employ turbulence parametrizations that are based on similarity arguments stemming from the theoretical predictions for flat and horizontally homogeneous terrain. This approach was acceptable, and to some extent also consistent, as long as the requirement of smoothing the real topography in order to prevent numerical instabilities led to run numerical weather prediction (NWP) models over a quasi-flat smoothed Earth's surface. However, as soon as higher spatial resolutions were reached, adequate parametrizations have clearly appeared to become necessary, not only to provide more realistic simulations but also to keep track with the increased numerical simulation capabilities.

At the outset of the Mesoscale Alpine Programme (MAP; Bougeault *et al*., 2001; Volkert and Gutermann, 2007) in the mid-1990s, one of MAP's scientific projects was devoted to the study of the 'Structure of the Planetary Boundary Layer over Steep Orography' and a working group on planetary boundary layers (WG-PBL) was established. Given the virtual absence of knowledge concerning the *turbulence structure* in BLs over complex terrain and the lack of data (to say nothing of a theoretical treatment), one of us (MWR) used the famous saying of Socrates ('I know that I don't know') as a metaphor for the state of knowledge on BL turbulence in complex terrain in an outline of WG-PBL's plans during one of the preparatory workshops of MAP. Clearly, all three of the difficulties in the description of the BL structure outlined above (i.e. horizontal inhomogeneity, flow modification over steep slopes, and effects of rough surfaces) usually occur simultaneously and with interactions (which are not yet very well investigated) over typical topographical features in the Alps.

The overall goals for MAP project P8 on the PBL structure over complex terrain were defined (Emeis and Rotach, 1997) to

(1) investigate turbulent fluxes of momentum, latent and sensible heat over complex terrain;
(2) contribute to the general description of the BL over complex terrain;
(3) examine the interaction of Alpine BLs and hydrology;
(4) study the interaction of Alpine BLs and local (thermally driven) winds;
(5) explore the interaction of Alpine BLs and the free troposphere;
(6) investigate the influence of BL processes on transport of pollutants over complex terrain.

The present paper aims to summarize the key findings from MAP projects on the above research themes. Section 2 gives an overview on those MAP projects where BL characteristics were investigated, and in section 3 we compile the most salient results. Section 4 is devoted to aspects of numerical modelling, while section 5 presents an evaluation of the results. Finally some comments are reported in section 6 on issues that, owing to MAP achievements, have been acknowledged as further developments for future research work and on still-open questions.

2. MAP Projects Related to BL Processes

Within the MAP programme, four different projects had specific connections to BL processes and explored their occurrence under different meteorological phenomena as well as in geographically different environments (Table I).

The *MAP Riviera* project was entirely devoted to the goals of the PBL research theme of MAP: detailed field observations, combined with high-resolution numerical modelling, were performed in the Riviera Valley in southern Switzerland, i.e. within one of the 'target areas' of MAP. The valley is approximately straight, north–south oriented and U-shaped, with a depth of about 2300 m. The valley floor is some 1.5 km wide, and the slopes are roughly 30° and 35° on the eastern and western sides, respectively. The surface network consisted of ten towers equipped with probes measuring 3D turbulence, radiation components and mean meteorological variables at up to six levels, as well as surface hydrology. These sites were distributed on a cross-section through the valley and observations were taken over a period of two months roughly (but not entirely) corresponding to the MAP Special Observing Period (SOP). On a total of eight days of intense observation (IOP) and the periods preceding them, radio soundings from the valley floor, scintillometric (turbulence) measurements (Weiss *et al*., 2001), a tethered balloon, a passive microwave temperature profiler (Kadygrov *et al*., 2001) and two sodars complemented the observations. Furthermore, a light research aircraft of Metair (Neininger *et al*., 2001) provided turbulence (and mean meteorological) information on the entire valley atmosphere. More detail, and in particular considerations on data quality and calibrations, can be found in Rotach *et al*. (2004).

The *FORM project* (Föhn in the Rhine Valley during MAP; P5) was devoted to the investigation of föhn and associated BL processes in the approximately north–south oriented and relatively wide Rhine Valley

Table I. Overview of the four MAP projects related to boundary-layer processes.

Project	Connected meteorological phenomena	Geographical environment
MAP Riviera	Turbulence structure in a valley; slope and valley winds	Riviera Valley (Switzerland)
FORM	Föhn wind	Rhine Valley (Switzerland)
GAP-Flow	Gap flow	Brenner Pass (Austria–Italy)
Toce catchment	Hydrological flux budget	Toce Valley (Italy)

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north of the Alps and south of Lake Constance. Continuous remote-sensing measurements were performed using sodar, lidar (Frioud *et al*., 2004), wind profilers (Vogt and Jaubert, 2004) and large-aperture scintillometers (Furger *et al*., 2001). Additionally, meteorological soundings were launched from eight sites along the valley axis. Surface turbulence was measured at one site on the valley floor (Piringer *et al*., 2001) in connection with air quality and föhn studies. Aircraft observations yielding turbulence information were conducted with the Météo-France Merlin IV aircraft (Lothon *et al*., 2003) and with the Metair light research aircraft. A compilation of all the observations during FORM can be found in Richner *et al*. (2005).

The *GAP-flow project* in the Wipp Valley (P4). BL observations in connection with the GAP flow project were performed in the north–south Wipp Valley between Innsbruck in the north and the Brenner Pass in the south. Instrumentation included a large network of conventional weather stations distributed over the valley and three sites of turbulence observations at two levels along the valley axis. Sodars and a wind profiler were employed to map the characteristics of the wind field while a scanning Doppler lidar placed in the 'middle' of the valley yielded detailed information on the BL development and structure in the valley (Rucker, 2003). A detailed description on the instrumentation and performance can be found in Mayr *et al*. (2004).

Toce catchment. In connection with the hydrological project of MAP in the Toce catchment (P3; Ranzi *et al*., 2003), micrometeorological observations were performed at an experimental site comprising turbulence observations at two levels, as well as the measurement of radiation and standard meteorological/hydrological variables. For validation of a hydrological model, measured and simulated energy fluxes were compared (Grossi and Falappi, 2003) using a Snow-Soil-Vegetation-Atmosphere-Transfer (SSVAT) model.

In addition to the above projects, explicitly and directly aimed at the MAP Programme, other activities and projects, loosely connected to MAP, were performed by researchers having multiple mutual exchange with the MAP community and were the subject of presentations and discussions during MAP events. Some account of the above activities and results will also be given briefly below and generally identified as 'post-MAP studies'.

3. Main Findings

In this section, the key results from the BL-related projects of MAP are summarized, thereby following the sequence of goals as defined in section 2 above.

3.1. Turbulent fluxes (and other turbulence statistics) over complex terrain

3.1.1. Post-processing of turbulence data

Due to the largely novel character of turbulence observations over highly complex terrain, large efforts were put into some basic issues, which had been extensively treated in the literature for flat uniform terrain, but raise non-trivial questions over complex topography. Among these, the question of data quality assessment (e.g. Christen *et al*., 2001; Rotach *et al*., 2004) and the investigation of what the effect would be on the results when using different post-processing approaches. The 'traditional approach' consists of a double- (triple-) rotation in order to align the coordinate system with the mean wind. However, for complex terrain Finnigan *et al*. (2003) show that this method has theoretical flaws and the 'planar fit' approach (Wilczak *et al*. 1999) is preferable. Various results from the Riviera project proved not to be sensitive to the post-processing method *in principle* (the phenomenon under consideration can be seen in any case) but very much so in the detail (Andretta *et al*. 2002). Furthermore, post-MAP investigations of de Franceschi and Zardi (2003) show that suitable filtering procedures and time lags are required to extract turbulent fluctuations out of a non-stationary mean flow induced by complex flow patterns.

3.1.2. Spatial variability

The most salient observation with respect to turbulence variables is certainly – and not entirely unexpectedly – their spatial variability. While being substantial due to the influence of terrain, even for quasi-steady state conditions (e.g. Piringer *et al*., 2001), the turbulent fluxes close to the surface follow to a large extent the radiation patterns (Matzinger *et al*., 2003), which in turn might be parametrized relatively easily. As an example, Figure 1 shows a comparison of mean daily cycles of net radiation at different sites in the Riviera Valley and the corresponding surface heat fluxes. Clearly, it is not enough to choose 'one representative observation', as is sometimes chosen to represent the 'turbulence state' in an entire valley system. As an alternative to the 'point observation' approach, Weiss (2002) investigated in detail the applicability of small-aperture scintillometry in order to obtain spatially averaged turbulence fluxes over highly complex terrain. Although invalid *in principle* due to violation of basic assumptions, scintillometry technique proved very successful. This is most likely due to the fact that essentially *small-scale (i.e. inertial subrange) properties* of turbulence are employed in setting up the deduction algorithm for the scintillometer. In a similar fashion, large-aperture scintillometers were used to explore the structure of vertical wind across the Rhine Valley for situations with and without föhn (Furger *et al*., 2001).

3.1.3. Scaling

Classical scaling approaches (from flat horizontally homogeneous terrain) for turbulence variables need to be suitably extended and/or modified. Examples include the scaling velocity for the surface layer (i.e. the friction velocity), which is influenced by the interaction of along-valley and slope winds (Andretta *et al*., 2002; van Gorsel *et al*., 2003). The latter, concentrating on

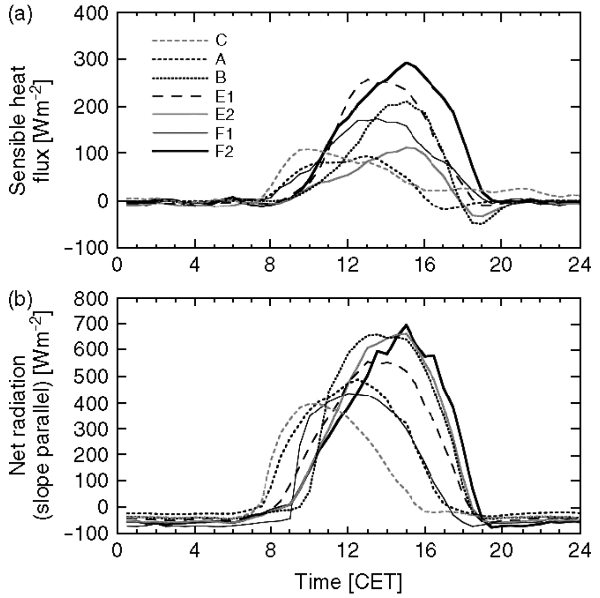

Figure 1. Mean daily cycles of (a) turbulent heat flux and (b) net radiation flux for 15 'valley wind days' (i.e. sunny convective days with weak synoptic forcing) in the Riviera Valley. Site identification in this approximately north–south oriented valley: C western (east-facing) slope; A valley floor; B eastern slope (forest); E1 eastern slope (grass); E2 eastern slope (forest); F1 eastern slope (rubble); F2 eastern slope (rock). General trend from the east-facing slope to the top of the west-facing slope is a shift in the time of the maximum and an increase in magnitude of both fluxes. Figure by courtesy of Marco Andretta.

the flow and exchange characteristics within and above a steep vegetated slope, showed that many statistical properties typical for both mixing layers and canopy flow from flat terrain were retained in a highly complex setting. Similarly, in a post-MAP study, de Franceschi (2004) indicated that some general aspects of *surface layer scaling* are often found to hold even in complex terrain, provided proper similarity functions are evaluated.

The most remarkable finding concerning scaling of turbulence characteristics in a steep valley concerned profiles of turbulent kinetic energy (TKE) throughout the Riviera Valley atmosphere. Under daytime conditions *in a homogeneous BL* the profile of TKE, scaled with the *convective velocity scale*, w_*, would be expected to be a function of the non-dimensional height, z/z_i, alone, where z_i is the mixed-layer height. In this scaling regime, w_* is determined from the surface heat flux, the buoyancy parameter and z_i. However, given the spatial variability of the turbulence characteristics (see above), such a standard scaling approach for the atmospheric BL (Holtslag and Nieuwstadt, 1986) that relies on spatial homogeneity cannot be expected to work *a priori*. Nevertheless, profiles of TKE in the centre of the valley from different days and times under sunny daytime conditions proved to be *similar*, provided that w_* was determined using the surface heat flux from a slope site rather than the position in the centre of the valley (Weigel and Rotach, 2004). Using a numerical model at very high spatial resolution, Weigel *et al*. (2005, 2007a) showed very similar characteristics (Figure 2) and used a TKE budget analysis to find that, despite the convective conditions (sunny, daytime summer conditions in the southern Alps, positive surface heat fluxes), it was mainly shear production (as opposed to buoyancy production) responsible for the TKE present. Shear, in turn, could be related to the core of the valley wind and it was thus found that this 'suitable' scaling velocity (determined from the surface heat flux on the slope) was strongly related to the strength of the valley wind. Despite the apparent success of this scaling exercise, the question remains unresolved as to how to select the appropriate position on the slope (if ${w_*}^2$ were to be used in order to scale TKE) or, alternatively, how the strength of the valley wind should be complemented in order to obtain a physically consistent squared velocity for scaling TKE.

3.2. General description of the BL over complex terrain

The break-up of the night-time inversion through turbulent mixing, as was known from earlier studies in large US valleys, was generally not observed (e.g. Weigel and Rotach 2004; also Henne *et al*., 2004 in a non-MAP study). Hence, even in summer in the *southern* Alps, one finds *stably stratified* valley atmospheres topping a shallow (or even absent) convective mixed layer throughout the day (Rampanelli and Zardi, 2004). In a straight idealized valley, Rampanelli *et al*. (2004) ascribe this effect to the subsidence compensating cross-valley circulations induced by sidewall heating; the downward flow of stable air seems to produce the two-fold effect of further stabilizing and thickening the inversion layer and reducing the intensity of turbulence. On the other hand, for a non-straight valley, Weigel and Rotach (2004) attribute the stabilizing to a secondary cross-valley circulation due to *valley curvature*. This secondary circulation is found to be due to cross-valley density differences emanating from centrifugal force (exerted on the fluid, i.e. the air, in the curved part of the valley) being height dependent, while the compensating hydrostatic pressure gradient force is not. The resulting circulation brings potentially warm air from above into the valley, thus stabilizing the entire system. It is interesting to note that at specific positions in the Riviera Valley (i.e. close enough to the curved portion of the valley and with the 'appropriate' direction of curvature), this secondary circulation resulted even in a *downslope* flow over the sunlit heated surface and upslope flow over the cooler (shaded) slope. This behaviour is remarkably different from the text-book type of symmetric upvalley/upslope flow (e.g. Whiteman, 2000) as were found in larger and straighter (i.e. more ideal) valleys elsewhere.

Curvature also seems to influence the BL height, e.g. in the Wipp Valley (Rucker, 2003). Similarly, dynamical flow patterns such as flow splitting in the Rhine Valley were found to be determined by local topography (Drobinski *et al*., 2001).

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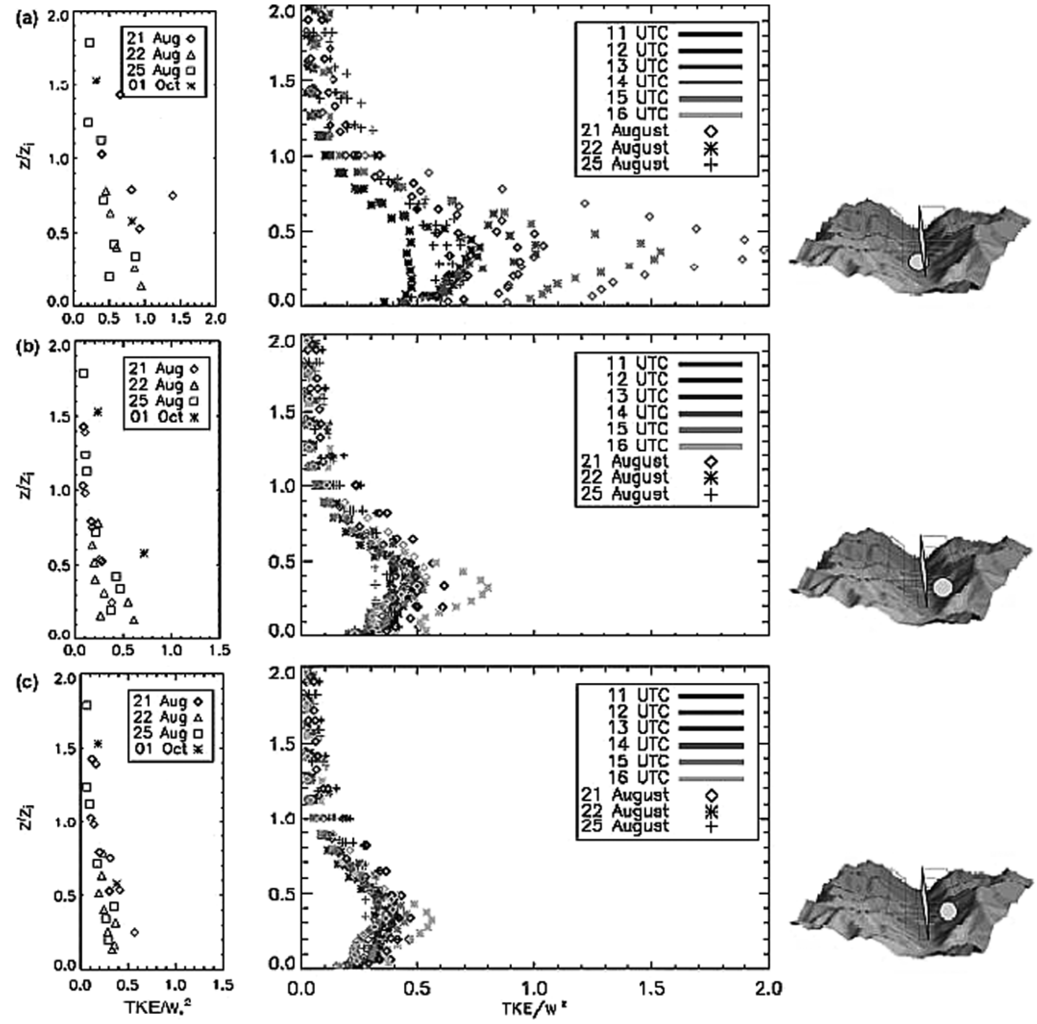

Figure 2. Profiles of TKE in the centre of the Riviera Valley on different days and times (see legends) scaled with a convective velocity scale based on surface heat fluxes from different sites (indicated by the grey dots in the respective topographic sketches at right). Each row depicts observations on the left (from Weigel and Rotach, 2004) and high-resolution numerical modelling in the centre (from Weigel, 2005).

3.3. Hydrological aspects

Basically, the findings concerning near-surface turbulent exchange (section 3.1) directly translate into hydrological applications. First of all, aspects of spatial inhomogeneity and representativity need to be carefully addressed when estimating or modelling hydrological parameters from single stations (Grossi and Falappi, 2003). Simple model approaches such as the Bowen ratio method for estimating latent heat fluxes (which relies on the assumption of spatial homogeneity) are prone to systematic errors (Rotach *et al*., 2004) of substantial magnitude that are, most likely, site specific. Still, and despite some of the shortcomings in the turbulence parametrizations involved and uncertainties deriving from adopting spatially interpolated data for distributed applications (Zappa and Gurtz 2003), hydrological *runoff modelling* usually proves quite successful thus emphasising the averaging or filtering effect of the hydrological system (Jasper *et al*., 2002; Gurtz *et al*., 2003; Ranzi *et al*., 2007). The skill of hydrological models proves best if models are run in reanalysis mode; real-time realizations for flood forecasts (e.g. Benoit *et al*., 2003) provided only qualitatively promising results. Overall, results showed that uncertainty in coupled hydrometeorological forecast systems requires further investigation.

It is worth noting that data from distributed hydrological modelling proved to be very useful to provide proper boundary conditions for high-resolution numerical models (DeWekker *et al*., 2005; Weigel *et al*., 2005; Weigel 2005). Ranzi *et al*. (2003) provide more detail on hydrological aspects of MAP.

3.4. Local thermally driven winds

In general, the well-known ingredients of valley wind and slope wind characteristics were observed in all the MAP BL studies (e.g. Rucker, 2003; Weigel, 2005). Some of the observations in high spatial density added considerable detail concerning the 3D structure of these thermally driven flows.

In theoretical modelling studies, Rampanelli *et al*. (2004) and Serafin (2006) address the question as to whether the Topographic Amplification Factor (TAF),

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which relates the smaller valley volume to larger heating rates triggering valley winds (Steinacker, 1984), could serve as a mechanism explaining valley wind systems. They find that in the process of heating up a valley atmosphere, subsidence of potentially warmer air from aloft might be the dominant factor. As a consequence, the geometry of a valley cross-section does play a crucial role in determining the features of the cross-valley circulation (intensity, spatial pattern and upper extension of the circulation cell), but TAF might not be the proper parameter to understand this effect. Similar conclusions were drawn by Weigel (2005), who investigated the heat budget in the Riviera Valley. Both from observations and numerical modelling, he concluded that the main mechanism heating up the valley atmosphere was due to vertical advection from the free atmosphere above the valley. As a consequence, the thermal structure of the atmosphere, both within the valley and above the surrounding ridge top (see also the following section), is expected to play a key role in the process.

3.5. Interaction of Alpine BLs with the free troposphere

This subtopic was probably the most complex among all the subjects treated within the MAP BL studies. First, the mere *definition of the system* poses some serious problems. De Wekker (2002) investigated in detail the characteristics of the mixed-layer height (MLH, i.e. daytime BL height). Objective criteria of typical quantities defining the vertical structure of the convective BL (e.g. mixing height, inversion strength, etc.) need to be revisited. In a non-MAP study, Rampanelli and Zardi (2004) propose a method for objective determination of the MLH from both airborne measurements and numerical simulations. This method proposes a simple mathematical algorithm to decipher the upper thermal structure of the convective BL by means of best-fit analysis of soundings or airborne measurements with a smooth ideal profile, including a mixed layer of constant potential temperature, a strongly stratified entrainment layer, and a free atmosphere with constant lapse rate. Thus the resulting profile depends on five parameters amenable to physical variables defining the vertical structure of the layers. The method allows an objective evaluation of parameters involved in the test profile and easy comparison of measurements with theoretically expected structure. The method *per se* seems to perform satisfactorily even in retrieving the main parameters of a CBL developing over a valley floor, although the meaning of these parameters in such a context requires deeper investigation.

3.5.1. Exchange mechanisms

Not only does the definition of the MLH itself become problematic in complex terrain, but also exchange processes with the 'free troposphere' are no longer governed by entrainment at turbulence scales alone. Figure 3 sketches the three processes relevant in valleys of size comparable to the (maximum) turbulence scales. These are mass exchange due to (a) changes in the valley cross-section, (b) local circulations (cf. section 3.2) and mountain venting and (c) turbulent exchange. Results from numerical modelling (Weigel *et al*., 2007b) reveal that all three processes can contribute substantially, depending on the mesoscale flow properties (stability, flow direction with respect to valley axis). As an example, Table II summarizes estimated moisture export from the Riviera Valley to the free troposphere indicating that, firstly, the contribution of subgrid-scale local circulations and topography-related flows can vary substantially from day to day and, secondly, that it can exceed several times the contribution of turbulent transport alone. This is different from the result obtained by a typical numerical model's turbulence parametrization. De Wekker (2002) used a Lagrangian particle dispersion model in a case-study for the Riviera Valley, showing that indeed a substantial amount of mass can be exchanged between the 'valley' and the 'free troposphere' even if a non-negligible (upper) part of the valley atmosphere is stably stratified. Any conceptual model (or simple dispersion model) would not find this exchange to be important, emphasising the need for detailed dynamical numerical modelling (section 4). Within non-MAP studies, the specific role of thermally driven local flows in transferring heat from close to the surface to upper levels has been pointed out through suitable modelling by Noppel and Fiedler (2002). Also Henne *et al*. (2004) present some further experimental evidence for the potential importance of local circulations in determining the exchange between a narrow valley atmosphere (in their case the Leventina and Mesolcina Valleys, also in southern Switzerland) and the free troposphere. In this latter study, very large exchange rates were determined (to some extent comparable only to the largest reported in Table II) from relatively limited atmospheric observations, thus requiring quite substantial assumptions concerning horizontal and vertical variability in the flow characteristics in order to perform the budget estimates.

3.6. Influence of BL processes on transport of pollutants over complex terrain

For the impact of local sources on air quality on a larger scale, the processes and their relative importance discussed in the previous subsection are clearly relevant.

During the MAP SOP, the vertical distribution of ozone and aerosols were observed during south föhn events in the Rhine Valley and, with airborne sensors, across the Alps. While air pollution from local emissions was observed to be removed by föhn flow, ozone-rich air masses in the valley were found to originate from levels at crest height of the Alps and from the (polluted) BL in the Po basin (Baumann *et al*., 2001). Furthermore, soundings indicate that ozone concentrations within the valley as observed by the air-quality stations was determined by the extent and persistence of an inversion layer within the valley (section 3.2) or the penetration of the föhn flow to the valley bottom (see above).

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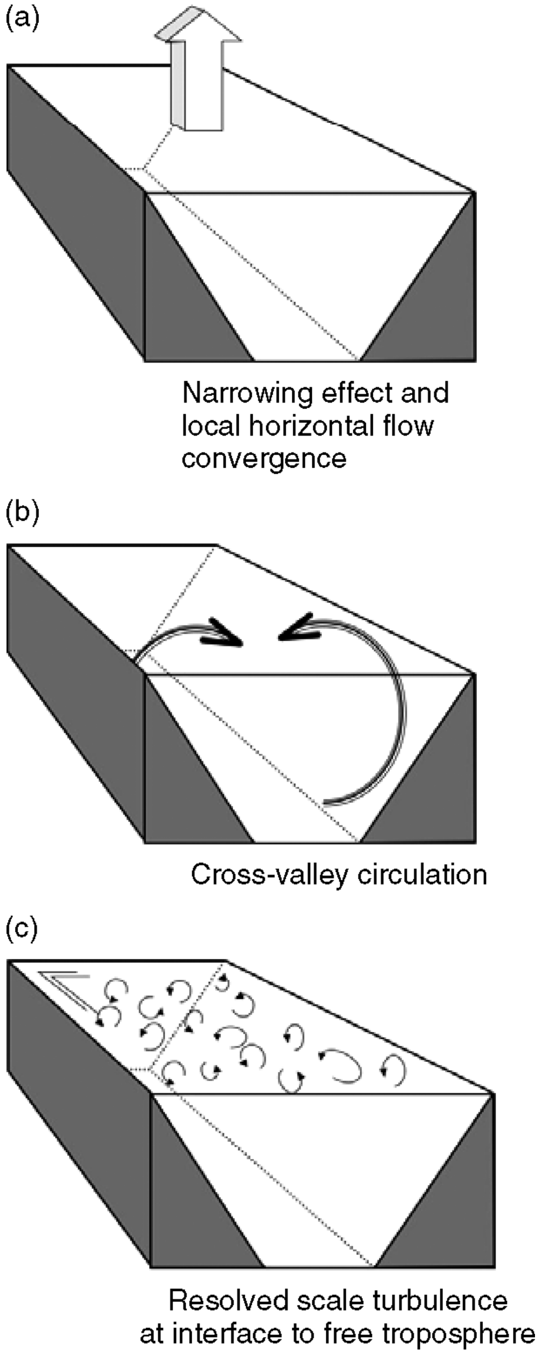

Figure 3. Schematic representation of the processes responsible for vertical moisture fluxes over a steep idealized and straight valley.

A stratified aerosol layer is found above the Rhine Valley under strong anticyclonic conditions (Frioud *et al.*, 2003), which becomes highly variable during föhn development (Frioud *et al.*, 2004).

4. Numerical modelling

In essentially all the MAP BL studies, numerical models were used to reproduce the observed characteristics on the one hand, and to employ the higher spatial resolution and detail of information to investigate physical processes on the other hand. In general, high-resolution numerical modelling with several steps of nesting from a global grid to a few hundred metres horizontal resolution was found to be necessary to adequately simulate the BL flows in highly complex terrain. In the Riviera Valley, RAMS (Pielke *et al.*, 1992) was successfully used at 330 m resolution (De Wekker *et al.*, 2005) and the Advanced Regional Prediction System LES code (Xue *et al.*, 2000) was used in a horizontal resolution as fine as 150 m (Chow *et al.*, 2006; Weigel *et al.*, 2006) with excellent results (i.e. very good correspondence to observations). For the (broader) Rhine Valley, numerical simulations were performed also using nested grids (highest resolution 625 m). The sub-kilometre resolution was found necessary in order to resolve fine-scale structures of the föhn flow and associated dynamical features such as hydraulic jumps (Jaubert and Stein, 2003). The föhn simulations of Zängl *et al.* (2004a) indicate that mesoscale structures can successfully be simulated at moderate (1 km, in their case) horizontal resolution, but the details (e.g. near-surface characteristics) exhibit considerable discrepancies between observation and simulation. This conclusion is also supported by investigating intermediate resolutions in the nesting chain (e.g. Weigel, 2005, for the Riviera Valley). Gohm *et al.* (2004) used the MM5 model (Grell *et al.* 1995) at a resolution of 267 m to simulate a south föhn windstorm in the Wipp Valley with good success. At somewhat coarser resolution, Zängl *et al.* (2004b), again using MM5, concluded that the sub-kilometre resolution was necessary in order to obtain satisfying correspondence between observations and simulation.

Table II. Estimates of moisture export from the Riviera Valley on three sample days (during daytime conditions, between 10 and 20 UTC) and their contribution due to different processes.

	21 August 1999	22 August 1999	25 August 1999
Total moisture flux (kg m^{-2})	21.9	7.9	1.8
Contribution due to changes in geometry (%)	84.8	81.9	38.9
Contribution due to local circulation (%)	15.2	18.1	61.6
Surface evapotranspiration (kg m^{-2})	~1.6	~1.6	~1.6

The turbulent flux at the interface between the valley atmosphere and the free troposphere was negligible in all three cases. For comparison, the turbulent flux of latent heat at the valley surface (integral of the entire surface area) is given in the last row. Results are based on high-resolution (LES type) numerical modelling. Summarized from Weigel (2005).

Figure 4 shows, as an example, the degree of correspondence that can be achieved with a multi-nesting approach (i.e. several nesting levels starting from a large-scale or global model) and a resulting horizontal resolution well below one kilometre. The above summary might suggest that *reducing the resolution* is the one

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(and only) necessary task when modelling the BL structure in highly complex terrain. This is clearly not the case; it turns out to be a necessary but not a sufficient condition.

As the single most critical parameter in obtaining good correspondence between simulated and observed flow characteristics, the *soil moisture distribution* was identified (De Wekker *et al*., 2005; Chow *et al*., 2006). A successful approach to obtain enough spatial detail in the soil moisture distribution consists of using a detailed distributed hydrological model. In a post-MAP study, Ciolli *et al*. (2004) successfully used Geographic Information System (GIS) tools to provide spatially detailed surface information for simplified evaluation of thermally driven flows. Being a first step, the model includes a very simple parametrization of slope winds (essentially, an extension of the Prandtl model including turbulent viscosity and heat diffusivity). However, it might be the starting point for a suitable tool for proper downscaling to be used in connection with the output of larger-scale models.

Modelled net radiation shows improvement around sunrise and sunset if the models take shadowing effects into account (Colette *et al*., 2003; De Wekker *et al*., 2005; Antonacci and Tubino, 2005; Chow *et al*., 2006). However, effects on the overall flow are limited because of the strong lateral boundary forcing from the larger grids in the nesting procedure where terrain slopes are not well resolved.

In the LES simulations, the influence of the (subgrid-scale) turbulence closure was found to be limited (Chow *et al*., 2006), again due to strong lateral forcing and hence limited residence time of air inside the valley under consideration and – for the cases studied – because of the stable stratification that limits turbulent exchange to the lowest few hundred metres near the surface.

Overall the numerical modelling studies showed that simply increasing spatial resolution without incorporating

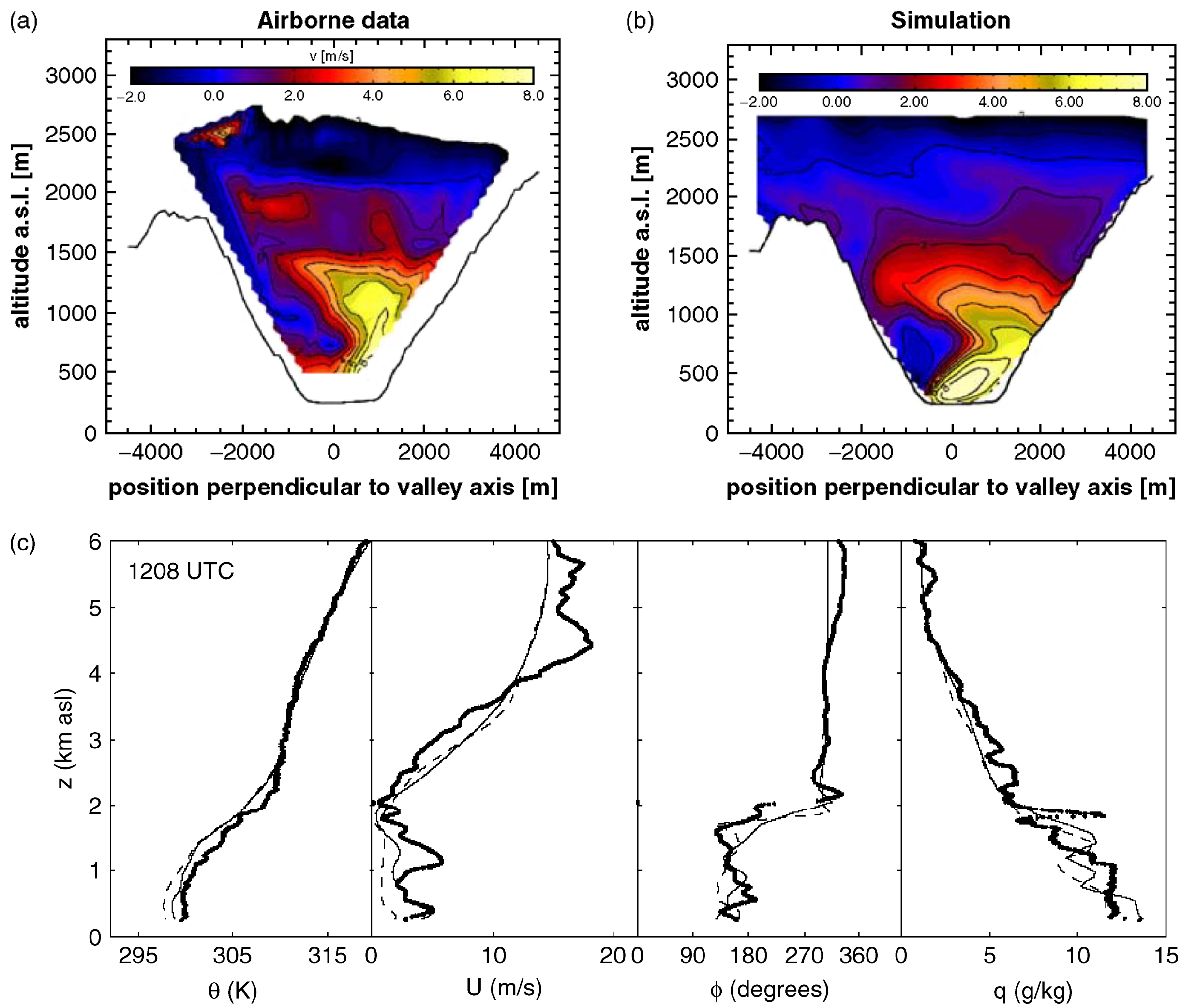

Figure 4. Interpolated cross-sections of along-valley wind component (m s^{-1}) in the Riviera Valley from (a) aircraft observations and (b) simulated by ARPS, for one example day (25 August 2005, around 1300 UTC). (c) shows comparison of two model versions (thin and dashed lines, respectively) to radio soundings (bold line) for a near-matching time (1208 UTC): from left to right, potential temperature, mean wind speed, wind direction, and specific humidity. Data (a, b) by courtesy of Andreas Weigel and (c) from Figure 8 in Chow *et al*. (2006). This figure is available in colour online at www.interscience.wiley.com/qj

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improved surface data gives unsatisfactory results. The encouraging conclusion is that simulations using LES-type models can be made so accurately that the model runs may be used to investigate flow characteristics such as driving mechanisms for valley flow or the heat budget in a valley (Weigel, 2005; Weigel *et al.*, 2006).

5. Evaluation of the results

The MAP BL projects started with the premise to fill in the gap between, on the one hand, the apparent need and importance of knowledge concerning turbulent exchange processes in highly complex terrain given the ever-increasing resolution of numerical models and, on the other hand, the virtual absence of experimental data, to say nothing of a suitable theory. This goal was certainly met with a number of high-quality studies and findings, as summarized in the previous sections. The documented spatial variability of BL flows over the relatively small-scale Alpine topography could have been expected, but not necessarily the degree of generality with which at least some of the results could be explained and governing processes could be identified.

It was shown that an appropriate numerical simulation of BL processes over complex terrain requires spatial resolution of the order of a few hundred metres in connection with detailed knowledge of surface conditions. Still, operational models for NWP and climate simulations will have to operate on much coarser resolutions than that (i.e. of the order of kilometres) for the next decades. Thus parametrizations of subgrid-scale turbulence processes will be required, which take into account the relation between true topography (on which the studied processes act in nature) and the model topography where the topographic entity (valleys, ridges) under consideration is entirely absent or at least much weaker than in reality (Figure 5(a)). In a schematic manner, Figure 5(b) depicts how the BL is represented in present-day operational numerical models – even at high spatial resolution: basically, a 'terrain-following' lowest layer in which exchange is maintained through parametrizations for turbulent transport. However, the presented studies on the BL structure (section 3.2) have indicated that often the *turbulent BL* in highly complex terrain is confined to a relatively shallow region near the ground (Figure 5(c)). Furthermore, MAP and non-MAP studies have pointed to the importance of local (thermally induced) circulations (sections 3.4, 3.5) and topography

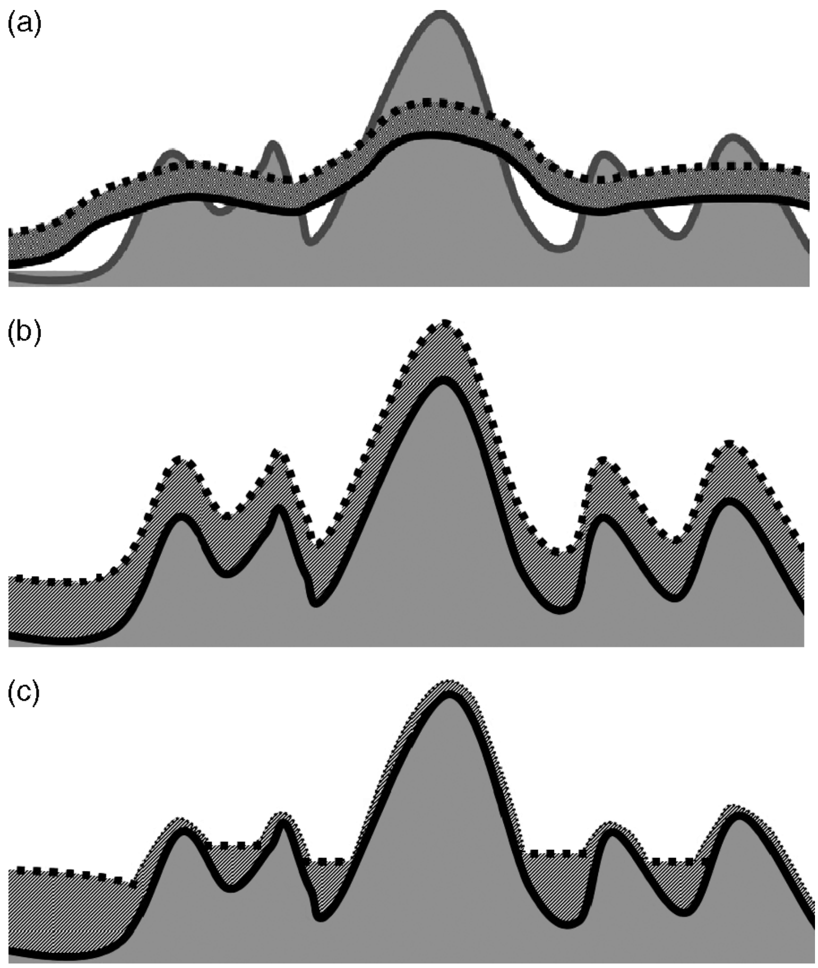

Figure 5. Schematic representation of the boundary layer in (a) a low-resolution numerical model, (b) a high-resolution operational numerical model, and (c) the turbulent boundary layer as found from different MAP boundary-layer studies.

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on the exchange between 'a valley/ridge' and the free troposphere. Under certain conditions, this exchange can become several times larger than just the contribution of turbulent exchange (e.g. Henne *et al*., 2004; Weigel *et al*., 2007b). Thus, for subgrid-scale valleys and ridges (and there are many in mountain ranges like the Alps, given a horizontal resolution of numerical models of the order of a few kilometres), it is essential to parametrize this exchange in order to obtain a realistic transport of mass, momentum and energy from and to 'the surface'. While the MAP BL studies only pointed to the importance of such processes, numerical modelling (LES at a horizontal resolution of a few hundred metres) could and should be used to systematically investigate their relative importance and dependence on mesoscale flow conditions and (subgrid-scale) topography. The MAP datasets (and hopefully others in equal detail to follow) could then serve as validation datasets for the numerical models. From these limited case-study results of the MAP BL projects, parametrization of 'local-flow-induced exchange' over complex topography can be hypothesized to substantially improve the mass, energy and momentum budgets, at least under certain conditions.

The most important result of the MAP BL studies is certainly the fact that, despite the highly complex and heterogeneous structure of typical valley atmospheres, it could be shown that characteristic, reproducible and transferable patterns in the turbulence structure can be found and successfully simulated with numerical models. Although the MAP studies only provided a first step with a limited range of cases (e.g. topographic settings such as valley size or orientation, large-scale meteorological conditions, etc.), they still showed that there is a path to the understanding and hence description or parametrization of turbulent exchange processes over complex topography, and that this path is accessible. Moreover, they probably added the first detailed datasets comprising detailed *turbulence observations* over highly complex terrain.

6. Outlook

Based on the results obtained through the efforts of MAP and related activities, some lines can be traced to future necessary achievements in the field of atmospheric turbulence over complex terrain.

The theoretical analysis of processes occurring over complex terrain still calls for a systematization of concepts and variables, connecting the quantities characterizing turbulence and properties of terrain where phenomena occur. Any progress in the definition of a suitable theoretical framework would serve as a basis for further progress in the schemes for numerical simulation.

Continuously increasing availability of computational resources is offering ample opportunities for increasingly refined simulations of the processes described above by means of numerical modelling. However, at higher resolution many numerical schemes need to be radically re-thought (e.g. the representation of non-vertical components of turbulent fluxes, innovative methods for the evaluation of fluxes through suitable grid cells over irregular terrain). This issue also raises non-trivial challenges concerning the connection between high-resolution local-scale modelling and NWP operational models.

BL measurements capable of capturing both local-scale phenomena and the overall BL structure have been set up in the MAP Riviera Project, setting a basis for future experiments that, eventually covering a variety of topographic features, may provide an ensemble of benchmark cases.

Finally, it is worth recalling various fields of applied meteorology seeking suitable input in terms of proper application of 'standard BL concepts' in complex terrain. These range from air-quality management (e.g. how can the mixing height be evaluated operationally within a narrow valley?), through noise propagation, agricultural meteorology (e.g. water resources management, prevention of damage from late frost), to road traffic safety (e.g. control of icing on roads) and many others.

This motivation will hopefully stimulate future research in the field and provide suitable cases to test the advances in the understanding of BL processes over complex terrain.

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