On the boundary layer structure over highly complex terrain: key findings from MAP and related projects

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1 Overview

Within MAP one of the scientific projects was devoted to 'Boundary Layers in Complex Terrain'. In this contribution an attempt is made to summarize the key findings from all these studies and put them into a joint perspective. Furthermore, results from related (not strictly MAP) studies are employed to determine whether or not these findings are of general validity. The Analysis of data is addressed as well as findings from numerical modelling and problems with instrumentation. The present compilation relies on information provided by colleagues (Kathrin Baumann-Stanzer, Markus Furger, Stefan Emeis, Stefan de Wekker, Max de Franceschi) and will have to be completed by others to yield a final overview.

2 MAP Boundary Layer Projects

- **MAP Riviera**: Detailed field observations (3-dimensional turbulence, mean flow, surface hydrology) during roughly the MAP SOP. Surface based high-resolution observation as well as aircraft data, radio soundings and remote sensing. Data analysis, concepts of exchange processes and numerical modelling. Detailed description: Rotach et al. (2004b), observational results published in van Gorsel et al (2003), Matzinger et al. (2003), Weigel and Rotach (2004).
- **Rhine Valley (FORM)**: Continuous remote sensing measurements with SODAR, LIDAR; soundings of meteorological parameters and pollutants during South Foehn events with additional ground based and airborne systems. Main objectives interaction of Foehn flow with boundary layer (esp. cold air pool) and impact on air quality. Description of observations: Richner et al. (2005a), Piringer et al. (2001), Lothon et al. (2003). Synthesis paper about results: Richner et al. (2005b).
- **Wipp Valley**. Boundary Layer observations in connection with the GAP flow project (e.g. Durran et al 2003, Rucker 2003).
- **Toce catchment**: micrometeorological observations in connection with the hydrological project in the Toce catchment (Ranzi et al. 2003) and comparison between measured and simulated energy fluxes using a Snow-Soil-Vegetation-Atmosphere-Transfer (SSVAT) model (Grossi and Falappi 2003)

Related studies

- **CHAPOP** (Characterization of Alpine Pollution Plumes): Airmass budget estimation for the whole Alps during fair weather days, extrapolated from extensive field measurements in the Leventina Valley, Ticino, Switzerland. Study of topographic venting Description: (Henne et al. 2004b).
- **River Adige Valley** Meteorological investigation of air-quality related valley characteristics (Rampanelli et al 2002) and the 'Garda breeze' (de Franceschi et al 2002)
- **EU-project VOTALP** (Vertical ozone transports in the Alps), 1996-2000: SODAR soundings of wind and turbulence (σ_w) on a pass north of Milano and LIDAR soundings of aerosol concentrations nearby (see Emeis et al. 1999 for details)
- **VERTIKATOR**, 2001-2004: SODAR soundings of wind and turbulence on top of the crests of the Black Forest and in the northern Alpine forelands, together with vertical aerosol soundings with a lidar in and near Garmisch-Partenkirchen. The measurements documented the enhanced turbulence (σ_w) in the boundary layer over the Black Forest mountain crests and the daytime upward transport of air pollution by mountain venting in the area of the Zugspitze (see Emeis 2004).

3 Main Findings

Spatial variability: Is substantial due to the influence of terrain – even for quasi-steady state conditions (e.g., Matzinger et al. 2003, Piringer et al., 2001). Clearly, 'one representative observation' (e.g. for surface turbulent fluxes) is not enough. However, the turbulent fluxes follow to a large extent the radiation patterns (Rotach et al. 2004a), which in turn can relatively easily be parameterized.

Textbook valley atmosphere: Several aspects of valley flow structure as known from larger valleys (mostly in the US) are not observed. These comprise (among others)

- No break-up of the night time inversion through turbulent mixing (e.g, Weigel and Rotach 2004, Henne et al. 2004b). Hence, even in summer in the *southern* alps one finds *stably stratified* valley atmospheres throughout the day. Exchange with the free troposphere is only to a certain extent through turbulent exchange – local thermally driven circulations can contribute substantially (Weigel 2005, Henne et al. 2004a). Numerical simulations (see below) indicate that a mechanism to heat up the valley atmosphere is subsidence of potentially warmer air from aloft (Rampanelli et al 2004; Weigel et al 2005).
- Flow patterns are determined by local topography (Drobinski et al., 2001); this is even true for a cross-valley circulation *against* the local heating rate pattern due to valley curvature (Weigel and Rotach 2004). Curvature also seems to influence the BL height, e.g. in the Wipp Valley (Rucker, 2003).
- Classical scaling approaches (from flat horizontally homogeneous terrain) for turbulence variables need to be modified. Examples include the Surface Layer scaling velocity, which is influenced by the interaction of along-valley and slop winds (Andretta et al 2002, Van Gorsel et al. 2003) and profiles of turbulent kinetic energy throughout the valley which show astonishing (but consistent) behaviour (Weigel and Rotach 2004, Weigel 2005). Still, some general aspects of *surface layer scaling* are often found to hold even in complex terrain provided proper similarity functions are evaluated (de Franceschi et al. 2005).

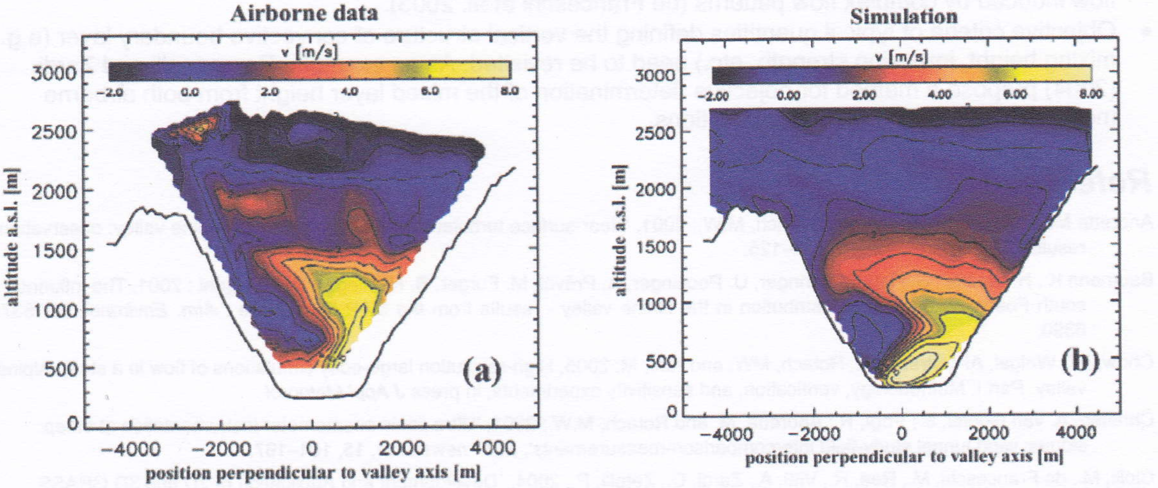

Figure 1: Observed (a) and simulated (b) along-valley wind component in the Riviera Valley sowing the large spatial variability of a sample variable and the ability of the model to reproduce the observations. Afternoon of 23 August 1999. Adapted from Weigel (2005).

Long-range transport and air quality: During the MAP SOP, the vertical distribution of ozone and aerosols has been observed in the Rhine Valley and, with airborne sensors, across the Alps, during South Foehn events (Richner et al., 2005b). Ozone-rich air-masses originate from levels at crest-height of the Alps and from the (polluted) boundary layer in the Po Basin (Baumann et al., 2001). The ozone soundings furthermore indicate that the persistence of an inversion layer within the valley or the penetration of the Foehn flow to the valley bottom determine the evolution of the ozone concentrations within the valley as observed by the air quality stations. A stratified aerosol layer is found above the Rhine valley under strong anti-cyclonic conditions (Frioud et al., 2003), which becomes highly variable during Foehn development (Frioud et al., 2004).

4 Numerical Modelling

- High-resolution numerical modelling with several steps of nesting from a global grid to a resolution of a few hundred meters horizontal resolution has been found to be necessary to adequately simulate the boundary layer flows in highly complex terrain. In the Riviera Valley, RAMS was successfully used at 330m resolution (De Wekker et al. 2005) and ARPS in LES mode was used down to 150m resolution (Chow et al. 2005 and Weigel et al. 2005).
- The *soil moisture distribution* is found to be one of the most critical parameters in obtaining good correspondence between simulated and observed flow characteristics (Chow et al. 2005, De Wekker et al 2005). A successful approach consists in using a detailed distributed hydrological model in order to obtain enough spatial detail in the soil moisture distribution.
- Preliminary results from use of Geographic Information System (GIS) tools for simplified evaluation of thermally driven flows has provided promising results (Ciolli et al., 2004)
- Simulations in LES mode can be made so accurately that the model runs may be used to investigate flow mechanisms such as driving mechanisms for valley flow or the heat budget in a valley (Weigel et al. 2005; Weigel 2005).

5 Observations

- The spatial variability and relative importance of different processes requires careful *calibration of instruments*. Preferably wind tunnel and field calibrations are recommended. With such an approach relative accuracy for e.g. turbulence statistics in on the order of 10-20% (Christen et al 2001; Rotach et al 2004). Thus only ‘patterns of larger magnitude’ need to be (can be) explained.
- Post-processing of data is essential. Recent studies indicate that the *planar fit* approach is superior to the double (triple) rotation (Finnigan 2004). Various results of 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). Moreover, suitable filtering procedures and time lags are required to extract turbulent fluctuations out of a non-stationary mean flow induced by complex flow patterns (de Franceschi et al. 2003).
- Objective criteria of typical quantities defining the vertical structure of convective boundary layer (e.g. mixing height, inversion strength, etc.) need to be revisited. As an example, Rampanelli and Zardi, (2004) propose a method for objective determination of the mixed layer height from both airborne measurements and numerical simulations.

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