3.5 OBSERVATIONS AND NUMERICAL MODELING OF THE DAYTIME BOUNDARY LAYER STRUCTURE IN THE RIVIERA VALLEY, SWITZERLAND

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1. INTRODUCTION

The boundary layer structure in valleys has been a topic of many research papers in the past. Early investigations were mainly focussed on the wind evolution. Observations showed that during daytime, winds blow up the valley and that during nighttime, winds blow down the valley with corresponding flows up and down the sloping sidewalls. Starting from the middle of the 19th century, various theories were developed to explain this behaviour. Simultaneous observations of the wind- and temperature structure only came much later, leading to a conceptual model of the temporal evolution of the convective boundary layer in deep valleys (Whiteman 1982). This conceptual model has been confirmed by many observations since then.

In contrast to the temporal evolution, the spatial structure of wind and temperature along and across a valley has not been given much attention in previous research. In many studies, such as those where mass budgets are calculated, it is assumed that cross-valley temperature- and wind structure is homogeneous and that the along-valley structure is simple, i.e., monotonically increasing/decreasing or constant flows along the valley. Similarly, little is known about turbulent energy exchange in valleys despite the well-known fact that turbulent sensible heat input from the valley surface is crucial for the evolution of wind systems and boundary layers in valleys.

In this contribution, data from the MAP-Riviera field study (Rotach et al. 2002) and a three dimensional, non-hydrostatic and fully compressible numerical model are used to study the wind and temperature structure and turbulent surface sensible heat exchange in a deep and narrow valley. Since it is our objective to examine the boundary layer structure in conditions where thermally-driven flows are expected, data from a fair-weather day during the field study are used. The high resolution simulations and data make it possible to resolve flow features that have seldom been studied before in valleys.

2. DATA

A comprehensive boundary layer field study was carried out from August to October 1999 in the Riviera Valley in the southern part of Switzerland (Rotach et al. 2002). This field study was part of the larger scale Mesoscale Alpine Programme (MAP) field project and is referred to as the MAP-Riviera field study. A map of the topography in the area is shown in Fig. 1. The Riviera valley is located in the southern Alps, about 100 km north of Milan. The valley is narrow and steep with a valley floor width of 2 km, an average depth of about 2 km, and slope angles exceeding 30º. The valley floor has a length of about 15 km, and an average slope angle of less than 0.5º. The topography of this valley is typical for the southern Alps. The valley floor consists of agricultural land and a number of small villages. A highway and railroad run along the valley. The slopes are covered mainly with deciduous trees up to 1000 m above sea level (asl), with conifers above. The treeline is at about 1800 m asl with areas of bare ground and short grass at higher elevations. During six days in a variety of weather conditions ('flight days'), a light aircraft flew specified patterns within the valley. A succession of two different flight patterns was flown, one with cross-valley flight legs at different heights and another with along-valley flight legs on both sides of the valley at different heights. During the flight days, rawinsondes were released at the valley center once every three hours. The present study concerns the 25 August 1999

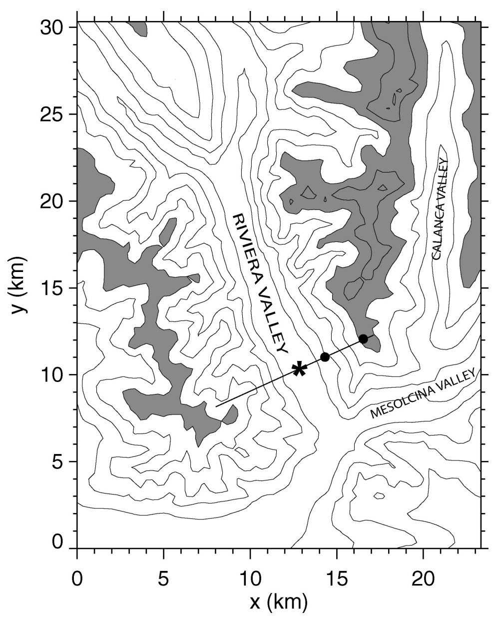

FIG. 1. Topography of the Riviera Valley and surroundings. Contour lines are drawn every 400 m. Terrain above 2000 m asl is shaded. The straight line depicts the location of the cross-valley cross section in Fig. 3. The asterisk and two black dots depict the locations of the main valley site (Bosco di Sotto, 46.26ºN, 9.01ºE, 250 m asl), and the two slope sites in Fig. 4.

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flight day in a dry, convective weather situation. Synoptic flows were weak to moderate and from northwesterly directions (~300º). The combination of northerly synoptic flows with southerly valley flows is known as *inverno* in this region and is a common wind pattern in the southern Alps (Furger et al. 2000). The aircraft operated between 0649 and 0942 UTC and between 1112 and 1541 UTC. In this study, some of the afternoon observations will be presented. In addition to the airborne observations, the data set for this case study also includes a unique set of surface turbulence data obtained at ten different measurement sites on the valley floor and sidewalls. A few sites are selected for comparison with model output in this study.

3. MODEL

The numerical mesoscale model used is the Regional Atmospheric Modeling System (RAMS). RAMS (Pielke et al. 1992) is a non-hydrostatic model with a terrain-following coordinate system employing a Mellor-Yamada level 2.5 turbulence closure scheme. RAMS employs a surface parameterization scheme in which surface turbulent fluxes are calculated according to the Louis (1979) parameterization. Land-surface processes are represented by the Land Ecosystem Atmosphere Feedback Model, version 2 (Walko et al. 2000).

The 3-D simulations use two-way interactive, nested grids. The model domain consists of four nested grids with horizontal grid spacing of 9, 3, 1, and 0.333 km, respectively. The outermost grid covers central Europe including the Alps while the innermost grid is the area shown in Fig. 1. All four grids have 38 vertical levels, with a grid spacing from 70 m near the surface to 1000 m near the model top at about 16 km. Thirteen soil nodes were used to a depth of 1 m below the surface. High resolution (i.e., 100 m) topography and land use data are used for the innermost grid.

The simulations cover 36 hours from 1200 UTC 24 August to 0000 UTC 26 August 1999. The five outermost lateral boundary points in the largest domain were nudged toward ECMWF objective analysis fields and rawinsonde data to allow changes in large-scale conditions to influence the model simulations. Top boundary nudging towards analysis fields is used to suppress gravity wave reflections at the model top. The magnitude of the boundary forcings varies linearly in time between 6-hour intervals on which ECMWF analysis fields were available. No interior nudging was applied. The spatial variability of soil moisture in complex mountainous terrain is expected to be very important for boundary layer processes but is usually neglected or inadequately initialized because of a lack of data. To improve the surface boundary conditions, soil moisture output for the Riviera catchment area from a sophisticated hydrological model with a resolution of 500 m was used. These soil moisture values compared well with some observations of soil moisture at selected locations in the valley. Soil moisture in the Riviera Valley and adjacent sidewalls was rather inhomogeneous with typical values around 0.31 m^3 water/m^3 soil, which is about 75% of saturation for loamy sand, the predominant soil type in this area. At locations where bare soil is present, soil moisture was considerably less.

4. RESULTS

Figures 2a and 2c show observed vertical profiles of potential temperature and wind direction on 25 August 1999 at four selected times at the valley center. At 0739 UTC, an inversion from the previous night is present and light variable winds are observed, primarily directed down-valley (~335º). Surface observations show a change from down-valley to up-valley winds after about 0800 UTC (not shown). At 0915 UTC, a well-mixed layer is observed up to 650 m asl capped by a weak inversion. The mixed layer grows only a few hundred meters between 0915 and 1208 UTC and stays around 700-800 m asl after that. During the day, significant heating takes place up to about 1800 m asl, which is below the average ridge height. More heating occurs in the morning than in the afternoon and the heating is uniform in a major part of the valley atmosphere. Thus, roughly three layers can be identified in the lower troposphere: a well-mixed lower layer, a middle stable layer up to about ridge height, and a less stable, almost neutral layer aloft. The lower and middle layer are expected to be affected by the sensible heat exchange at the valley floor and sidewalls and the thermally driven wind sys-

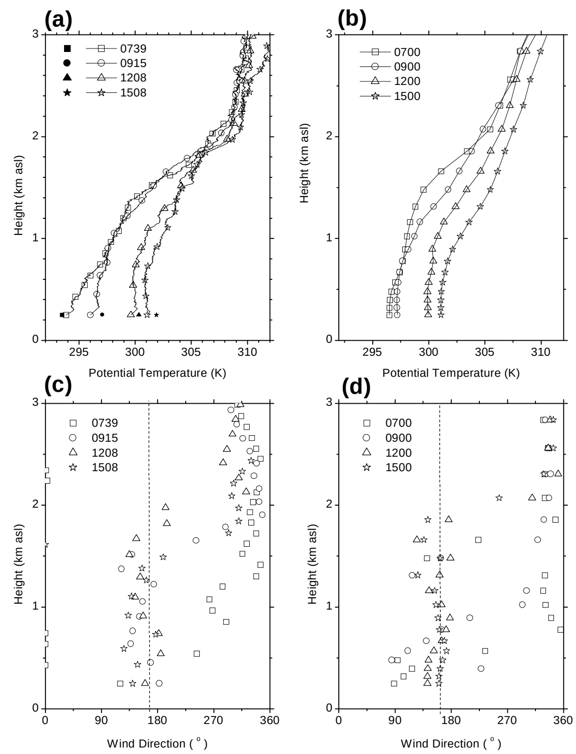

FIG. 2. Vertical profiles of observed and modeled potential temperature (a and b, respectively) and observed and modeled wind direction (c and d, respectively) at the valley center at four selected times. The surface potential temperature measured at 1.5 m at the different times is indicated in (a) with the filled symbols.

tems while the near-neutral layer aloft probably represents a larger scale mountain boundary layer. A transition from upvalley flows to large-scale northwesterly flows takes place in a layer between 1500 and 2000 m asl during the day. The simulated profiles of potential temperature and wind direction are shown in Figs. 2b and 2d. The three-layer structure with the shallow mixed layers in the afternoon is well captured by the model, although it was unable to simulate the capping inversion just below ridge height. This may be due to the rather coarse vertical grid spacing (~200 m) at that elevation.

Figures 3a and 3c show aircraft observations of temperature and along-valley wind in a valley cross section between 1138 and 1220 UTC. The temperature structure is rather homogeneous with a mixed layer up to about 1000 m asl, roughly corresponding with the rawinsonde profile in Fig. 2a. The structure of the along-valley flows is more complex with stronger flows on the eastern side of the valley than on the western side. Upvalley flows fill the entire valley cross section up to ridge height and are not confined to the mixed layer.

Fig. 3b and 3d show the modeled temperature and wind structure at 1200 UTC. There is a good overall qualitative agreement with the observations. Some aspects of the asymmetric wind field are seen in the modeled wind field as well.

Aircraft observations along the valley (not shown) show that wind speeds are generally larger on the eastern side of the valley than on the western side. This also implies that the inhomogeneous wind structure seen in Fig. 3c is not limited to this particular cross section but is found at other locations along the valley. Reiter et al. (1983) observed a similar behaviour in German and Austrian valleys. This behaviour was explained as a result of the asymmetric heating between the two sidewalls. It is questionable whether such an explanation applies to this case since the larger wind speeds were consistently present on the eastern side of the valley during the day and did not shift from one side of the valley to the other as in Reiter et al.'s (1983) observations

Compared to the wind structure, the temperature structure appears rather homogeneous in the along-valley and cross-valley direction. Modeled fields show more spatial structure than the observations and it is difficult to assess whether these structures are real or artifacts of the model.

From the observed and simulated wind fields, one can conclude that the wind field is inhomogeneous in the along- and cross-valley directions. It can be argued that these inhomogeneities induce divergence/convergence patterns and thus vertical motion fields that enhance the exchange of air between the valley atmosphere and the atmosphere aloft. On the other hand, modeled wind fields show that the asymmetric wind field across the valley can induce a horizontal eddy of the scale of the valley-width near the surface, resulting in stagnating flows at certain locations on the valley floor. This could imply that air pollutants are trapped in those areas rather than being efficiently transported up the valley.

It is important to recognize that the topographic setting of the Riviera Valley induces a boundary layer structure that may not be typical for valleys that open towards a plain. The Riviera valley flow is not entirely induced by the valley itself but is part of a larger-scale upvalley flow that splits off near the mouth of the valley and flows partly towards the Calanca and Mesolcina valleys to the north (see Fig. 1). Such bifurcations are rather common in this area and differences in boundary layer structure associated with valleys that open into a

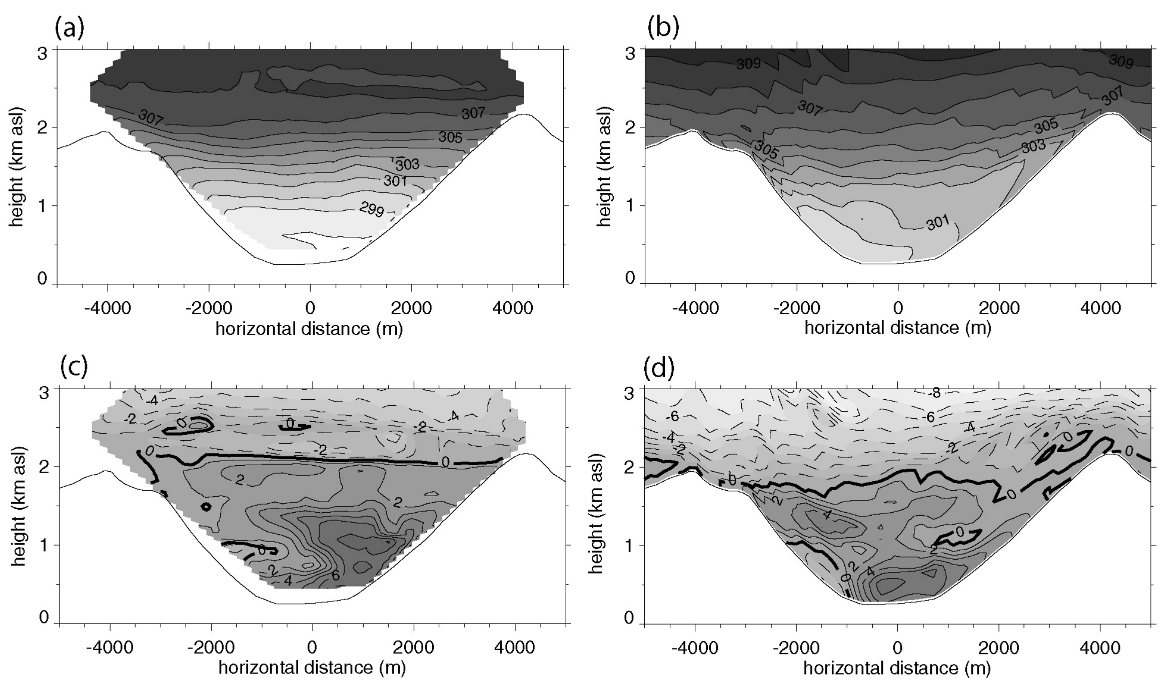

FIG. 3. Interpolated cross sections of potential temperature (in K) and along-valley wind component (in ms^{-1}; up-valley is positive) from aircraft data between 1138 and 1220 UTC (a and c, respectively) and from model output at 1200 UTC (b and d, respectively). The location of the cross section is depicted in Fig. 1.

plain need more investigation. Furthermore, the presence of tributary valleys may also have contributed to the complex flow pattern in the Riviera Valley. Idealized numerical simulations are planned to investigate these possible effects of the topography on the wind field in the Riviera Valley. The question whether these flow patterns are specific to this topographic setting or are more general can then hopefully be answered as well.

The simulations were also compared with measured surface turbulent fluxes. The observed and simulated turbulent sensible heat fluxes at three locations on the valley floor and west-facing slope are shown in Fig. 4. Sensible heat fluxes are larger over the slopes than on the valley floor and generally increase with elevation. Complex topography and surface conditions cause a spatially heterogeneous distribution of surface fluxes. Measurements on the slopes are therefore often not representative of a larger area represented by a grid box in a mesoscale numerical model, even with the high resolution used in this model. This makes evaluation of the modeled heat fluxes very difficult. In general, however, it can be stated that the model produces values that are within the range of observed values. The large inhomogeneity in the modeled fluxes with, for example, larger heat fluxes on the sun-facing slopes, is realistic. Since sensible heat fluxes over the slopes affect the vertical temperature structure in the valley, the good correspondence of the vertical temperature structure indirectly indicates that the model performs well. A simulation where surface characteristics were simplified and soil moisture initialized homogeneously produced results that deviated significantly from those presented here. This demonstrates the importance of incorporating high resolution land surface data in the model initialization with a resolution that is similar to model resolution.

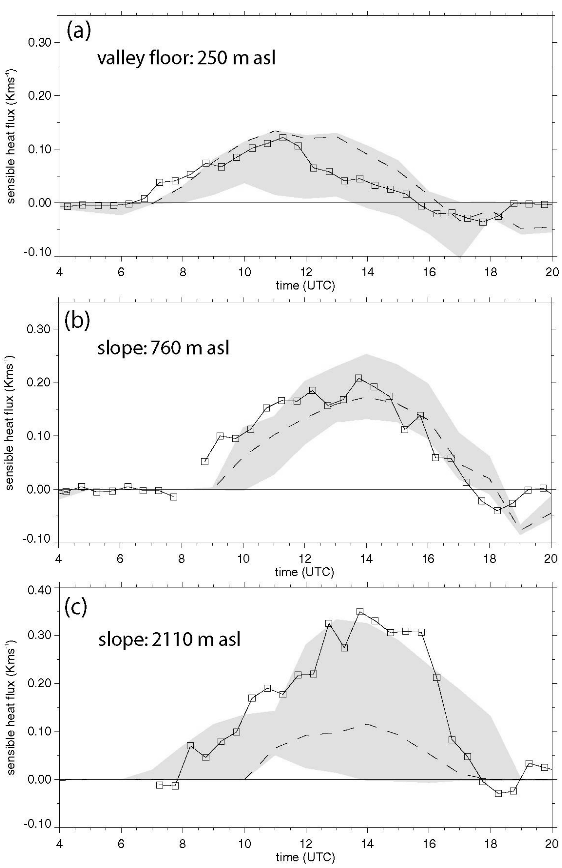

FIG. 4. Observed (open squares) and modeled (dashed line) surface turbulent fluxes of sensible heat at the valley floor (a) and at lower (b) and upper (c) slope sites. The location of the sites is depicted in Fig. 1. The shaded area indicates the range of modeled heat flux at ten adjacent grid points.

5. SUMMARY

Very high resolution model simulations of the narrow and deep Riviera Valley during one fair weather day were performed and evaluated with airborne data and surface observations of sensible heat flux. There was qualitative agreement between simulations and observations. The spatially inhomogeneous wind field, which has important consequences for air quality modeling in this area, was well reproduced by the model.

An evolution of the temperature structure as in Whiteman's (1982) conceptual model is not clearly present in the results. This may be due to the inhomogeneous wind field and associated vertical motions which are not accounted for in the conceptual model.

In future work, the factors that cause the complex spatial wind- and temperature structure in the valley atmosphere and aloft will be investigated further with more emphasis on the variability of the mixed layer depth. The question whether the observed behaviour is specific to the topography of the Riviera Valley or is more general will be investigated as well. Idealized simulations and analysis of the forcing terms in the modeled momentum and temperature budget equations will be used.

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