Numerical simulation of meso-gamma scale features of föhn at the ground level in the Rhine valley

By G. JAUBERT, P. BOUGEAULT, H. BERGER, B. CHIMANI, C. FLAMANT, C. HAEBERLI, M. LOTTHON, M. NURET and S. VOGT

1 CNRM/GAME, Météo-France, Toulouse, France
2 MétéoSuisse, Payerne, Switzerland
3 University of Vienna, Austria
4 Institut Pierre-Simon Laplace, Paris, France
5 MeteoSchweiz, Zurich, Switzerland
6 Laboratoire d’Aérologie, Lannemezan, France
7 Institut für Meteorologie und Klimaforschung, Karlsruhe, Germany

(Submitted 16 October 2003; revised 30 July 2004; final 13 December 2004)

SUMMARY

This paper examines the impact of a mesoscale analysis (2.5 km grid distance) on the simulation of the meso-gamma scale aspects of föhn in the Rhine Valley. The föhn event, documented during IOP 15 (5 November 1999) of the Mesoscale Alpine Programme, was standard in terms of intensity and was characterized by an important temporal variability. Many instruments operating in the Rhine Valley target area are used to validate the simulation, in particular the airborne nadir pointing lidar LEANDRE 2 (flown over the Lower Rhine Valley) as well as a windprofiler and a radio acoustic sounding system colocated in Rankweil, Austria. The large observational dataset acquired during the IOP allowed documentation of the entire föhn life cycle. For most of the IOP, a cold pool remained near the ground in the lower northern part of the valley. The non-hydrostatic model meso-NH, used in a grid-nesting configuration with two nested models and initialised with a mesoscale analyse, allowed to simulate realistically the location and depth of the cold pool. The relationship between the föhn intensity and the large scale environment is also examined. The flow regime is a flow around the Alps. The variability of this flow at the western tip of the Alps could explain some of the temporal changes observed at low level in the Rhine valley.

KEYWORDS: Föhn, Cold pool, Mesoscale Alpine Program, Mountain airflow, Mesoscale analysis

1. INTRODUCTION

Föhn conditions are observed on the northern side of the Alps when synoptic flow favours southerly or south-westerly winds in the low troposphere around the Alpine range, for instance upstream of a frontal system approaching from the west (Hoinka 1980). It is resulting in a dry and warm southerly wind, sometimes severe downstream of the crests. Föhn occurs in a large variety of synoptic environment, from shallow föhn (Seibert, 1990; Zängl, 2002) where westerly flow at crest height is associated with south-westerly flow at low levels, to the deep föhn related to a strong southerly flow (Jaubert and Stein, 2003). Associated flow regimes over the Alps are mainly related to flow splitting, or mixed regime between flow splitting and wave breaking (see Schär, 2002 for a review). The breakdown of the föhn occurs in relationship with the mesoscale changes, in many cases linked to the arrival of a frontal system. The effect of the föhn on cold fronts was studied by Hoinka (1987) and Heimann (1992). Interactions between fronts and the Alpine range have been analysed in the framework of the Front Experiment 1987 (Hoinka and Volkert, 1992), where the acceleration of the flow at the northwestern part of the Alps is mentioned. However, to our knowledge, very few studies have concerned the interaction of the flow around the Alps and the föhn flow, in real case of southerly flow.

* Corresponding author address: CNRM/GAME, 42 Av Coriolis, 31057 Toulouse Cedex, FRANCE
The meso-beta scale aspects of these meteorological situations are nowadays simulated in real-time by several operational numerical weather prediction models in Europe, with grid sizes close to 10 km. These simulations are generally considered to be quite reliable. As demonstrated for instance during the Pyrénées Experiment (PYREX, Bougeault et al., 1996), numerical models are able to predict the drying and warming effects associated to the subsidence downstream of major mountain ranges, as well as many aspects of the surface wind field and mountain waves. In contrast to these meso-beta scale aspects, little is known about the processes occurring at meso-gamma scale inside the valleys themselves. Recent works using research models at a higher resolution pointed out the role of gaps, passes and/or valleys in channelling the flow, e.g. Saito (1993) for the yamaji-kaze in the Shikoku mountains, Colle and Mass (1998) for a windstorm observed in the Washington Cascade mountains, Zängl (2003a) who performed semi-idealized simulations to study the föhn in the region of the Wipp valley, in the Alps. Observations reveal that the floor of Alpine valleys is often occupied by a layer of cold air, created by radiative cooling during night time. This 'cold pool' prevents the upper-level föhn flow from reaching the ground during the most of the duration of föhn episodes. Only when föhn intensity is sufficient, does the föhn flow touch the floor of Alpine valleys. Three mechanisms are likely to govern this penetration of the föhn flow to the valley floor (Gubser and Richner, 2001): (i) the diurnal heating of the cold pool by solar radiation may diminish the stability and allow vertical mixing, (ii) turbulent entrainment induced by Kelvin-Helmholtz instability at the top of the cold pool may eventually destroy the cold pool (Nater et al., 1979), and (iii) the occasional intensification of the mountain wave at the upper level may force the föhn flow down to the ground level, and flush the cold pool downstream (for instance in the case of a breaking wave aloft). These three processes may also occur simultaneously.

The Special Observing Period (SOP) of the Mesoscale Alpine Programme (MAP, Bougeault et al., 2001) took place between 7 September and 15 November 1999. It was organized into eight Scientific Projects, among which the FORM (föhn in the Rhine Valley during MAP) project, which aimed at documenting the meso-gamma scale, unstationary aspects of föhn episodes in the Rhine valley, between Chur and the Lake of Constance (see Fig. 1). Available observing systems dedicated to this project comprised a network of surface mesonet, numerous sounding stations, a radio acoustic sounding system (RASS), a Doppler lidar, and several research aircraft. The objectives were to clarify the role of mechanisms (i)-(iii) listed above and document the capability of present generation meso-gamma scale numerical models to simulate the detailed characteristics and evolution of föhn flows at the level of the valley floor.

Föhn events occurring in the framework of MAP have been studied by Jaubert and Stein (2003) (IOP2), Drobinski et al. (2003)(IOP12), Zängl (2003) (IOP10), Lothon et al. (2003) and Beffrey et al. (2003) (IOP8). In spite of their specific features, linked to föhn intensity, these studies allowed to build a comprehensive scheme of the temporal evolution of the föhn in a large valley, useful to validate numerical simulations.

The practical applications of numerical prediction of meso-gamma scale aspects of föhn inside a large Alpine valley are important, as föhn represents a major weather risk for air activities, all outdoor activities and also influences air quality. Moreover, it is expected that this type of flow will offer one of the
first opportunities for real-time, meso-gamma scale numerical weather prediction. Necessary ingredients for such a capability are assumed to be (i) a good simulation of larger-scale aspects, such as the upstream and downstream wind and stability, (ii) a good initial analysis of low-level parameters inside the valley under consideration, and (iii) a high-resolution model with a high-quality representation of orography, diurnal cycle and turbulence processes.

Previous work performed at CNRM/GAME on data acquired in the framework of the FORM project evidenced that a satisfactory simulation of the larger-scale aspects, as well as the meso-gamma aspects of the deep föhn case observed during IOP 2 of MAP can be achieved using operational meteorological analyses (supplied by the Météo-France ARPEGE system) and the triply nested, non-hydrostatic model MesoNH (Jaubert and Stein, 2003). Using the same protocol, Berey et al. (2003) simulated the interaction of the cold pool and the föhn flow in the shallow föhn case of MAP IOP 8. However, in these two studies, the depth of the cold pool was unrealistic probably due to the weakness of the initial analyses. With a different numerical tool, Zangl (2003) used the sounding measurements to modify the low levels of the large scale analysis close to the Alps in order to get a more realistic surface temperature, particularly in the Rhine valley. The purpose of the present paper is to go one step further and explore the benefits of introducing some mesoscale features, such as the presence of a cold pool, at the valley scale, using an operational mesoscale analysis scheme. The case under study here is IOP 15 (5-6 November 1999), one of the best event of the whole field experiment. We focus (i) on the simulation of surface level parameters inside the valley, in relationship with the vertical structure of the cold pool, and (ii) on the temporal evolution of the flow during 18 hours (including the entire föhn event) over a specific location (Rankweil where a windprofiler and a RASS were collocated) to verify the accuracy of the model initialisation at small scale. The influence of the evolution of the flow over and around the Alps on the intensity of the föhn in the Rhine valley is also explored.

In section 2, we briefly present the numerical model, the objective analysis method and the synoptic situation. Section 3 presents the available observations on IOP15 and their use for valuating high-resolution numerical simulations. Section 4 discusses the influence of the flow intensity and direction over the foothills on the temporal changes of the föhn flow in the valley.

2. CHARACTERISTICS OF THE SIMULATIONS AND SYNOPTIC CONDITIONS

(a) Model

The French community non-hydrostatic meso-scale model MesoNH (Lafore et al., 1998) is used in this study. Two nested domains are used with the two-way interactive grid-nesting technique described by Stein et al. (2000). The outer domain covers western Europe with a 10 km grid size, while the inner domain covers the Alpine region with a 2.5 km grid size (see Fig. 2). Domains and physical parametrisations are the same as those used by Jaubert and Stein (2003), except for the use of the most recent radiation scheme of ECMWF (Morcrette et al, 2001). This scheme accounts for aerosols and provides better infra-red and solar radiation fluxes, a point of importance for the diurnal evolution of the cooling in the valleys. A fourth-order horizontal numerical diffusion is applied to the
difference between the actual variable and a reference profile. The numerical diffusion intensity is reduced by three in the inner model in this study with regards to the previous studies of Jaubert and Stein (2003), Beffrey et al. (2004) and Vogt and Jaubert (2004). This tuning improves the simulation of the cold pool, in accordance with the sensitivity experiments of Zängl et al. (2004) for the IOP10 MAP fohn case. In particular, it improves the fohn break intensity for the IOP15 simulations presented here. Lateral boundary conditions are provided by time-space interpolation between operational analyses of the ARPEGE system of Météo-France, available every 6 hours.

(b) Initial Conditions

Four different initial conditions are considered. The reference simulations
TABLE 1. Tuning of the Mesoscale analysis statistical model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Standard error of the guess ($\sigma_g$)</th>
<th>Standard error of the observations ($\sigma_o$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (K)</td>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td>Humidity (%)</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>wind (m/s)</td>
<td>6</td>
<td>3 to 4</td>
</tr>
<tr>
<td>Geop. height (mgp)</td>
<td>70 to 300</td>
<td>8</td>
</tr>
</tbody>
</table>

(REF00 and REF12) are initialised by the ARPEGE analysis valid at 00UTC and 12UTC on 5 November 1999. Simulations A00 and A12 are initialised by a mesoscale analysis valid at 00UTC (12UTC) on 5 November 1999. The mesoscale analysis is performed on both the 10 km and 2.5 km domains. It uses all the available operational surface stations and soundings observations, together with the additional ones acquired specifically during MAP. As example, for the 2.5-km domain, 129 observations are actually used for the analysis at 12 UTC. These include 12 soundings, among which 7 are located within the Rhine valley. Most of the surface stations provide both 2m temperature, 2m humidity and 10m wind measurements. observations of surface pressure are fewer. The analysis tool is based on the CANARI/DIAGPACK Optimal Interpolation (O/I) scheme, that has been tuned for mesoscale (Calas et al., 2000, Ducrocq et al., 2000 & 2002). Such mesoscale analysis scheme is used operationally at METEO-FRANCE to produce spatial interpolation of automatic surface observations over plains and low-elevation terrains on a 10 km grid (Bouyssel et al. 2002). It provides analysed fields of upper-air wind, temperature and humidity, as well as 10 m wind, 2 m temperature and humidity and sea-level pressure. The vertical resolution of the analysis consists of 31 levels, with 10 levels between the 20 m AGL and 2 km. For our simulations, the initial guess is provided by the ARPEGE analysis valid at the same time. According to the high density of the network, we use the same observation and guess-field error statistics as those tuned for mesoscale applications of CANARI/DIAGPACK (see Table 1). No additional tuning has been performed to account for use in mountainous regions. The same statistics are used for the 10 km and 2.5 km domains. The tuning of the characteristical length scale of the background error allows the presence of 'meso-$\beta$' scale features such as the cold-pool in the mesoscale analysis. This length is set at the surface to 60 kilometres for the temperature and humidity analyses, 100 kilometres for the wind analysis, and 200 kilometres for the surface pressure. These values increase with height for the altitude analysis. Surface level observations influence upper-air parameters up to 150 hPa above the surface, due to the prescribed vertical correlation structure function. This vertical length scale has been chosen to ensure that, on average, surface observations impact the planetary boundary layer only. Surface observations from stations higher than 1500m ASL were rejected, as well as those showing a difference between the model orography and the station height larger than 800 m.

The initial states of the simulations REF12 and A12 are compared in Figures 3a and 4a with the Buchs-Grabs and Diepoldsau soundings at 12 UTC in the Rhine valley. Cooling above the ground surface is completely missed in the ARPEGE 12 UTC (REF12), as the narrow valley is not represented by the coarse resolution of the ARPEGE analysis. In opposite, the low-level cooling is depicted
in the mesoscale analysis with a correct magnitude near the surface, thanks to the
detailed orography available on the 2.5 km grid and the mesoscale observation
analysis. However, the top of the cold pool is too high and the thickness of the
interface between the cold pool and the warmer air of the föhn jet is too large;
the operational tuning of the mesoscale analysis has some difficulties to describe
large vertical gradients as those observed at the top of a cold pool.

(c) Synoptic situation

Geopotential maps at 850 hPa valid at 18 UTC on 5 November and at 06
UTC on 6 November are shown in Fig. 2. The main low was moving towards
the east over northern Europe, generating a secondary low, centered on Sardinia
on 5 Nov 18 UTC and hardly visible the following day. A related frontal system
reached the upper Rhine valley at 06 UTC on 6 November. To the north of the Alps, the winds were from the west-south-west during this period. To the south of the Alps, the winds were from southeast during the first part, then veering to southwest. These are paradigmatic föhn conditions.

3. Comparison of simulations with observations

(a) Observations used in this study

Special observations available during MAP in the Rhine Valley comprised 7 additional sounding stations (operated by the Swiss Army) and a dense network of surface mesonets (hourly measurements). A subset of these stations (shown in Fig.1) have been used to conduct the spatio-temporal analysis of the föhn characteristics at the ground level inside the Rhine valley, shown in Fig. 5. Around 15 UTC on 5 November, the Rhine valley was overflown by the two French research aircraft, the Merlin IV of Météo-France and the multi-agency ARAT (Avions de Recherche Atmosphérique et Télédétection). The latter was equipped with the nadir pointing water vapor differential absorption lidar LEANDRE 2. The UHF-RASS system of the Institut für Meteorologie und Klimaforschung (IMK) was also operating from the ground within the valley (Vogt and Jaubert, 2004). This radar has a five beam geometry for two bi-static radio-frequency and acoustic antennas. Both antennas are emitting continuous waves that are frequency modulated with a saw tooth pattern (FM-CW-Doppler-Radar) and provide high average transmitted power. Thanks to this unique design, redundant wind profiles are derived from both the UHF and RASS signal with high resolution in time and height. The temperature profile is estimated simultaneously from the RASS signal. Finally, several constant level balloons were launched by MeteoSwiss and the Laboratoire d’Aérologie from the city of Malans and flew over the Rhine valley on 5 November, providing observations of airmass trajectory, wind, temperature, humidity and pressure.

(b) The episode of föhn in the Rhine valley
Figure 5. Hovmoeller diagram of the surface parameters in the Rhine valley between 5 November, 00 UTC and 6 November, 12 UTC and the latitude of Chur (47.22°N) and Altenrhein (47.48°N). Left: Potential temperature, contour interval 1 K, shading starting 287 K with steps every 3K. Middle: northward component of the wind, contour interval 1 m s⁻¹, shading pale grey < 0 m s⁻¹, dark grey > 5 m s⁻¹. Right: difference in reduced pressure at 430 m above mean sea level (MSL) between each station and the station of Chur, shading pale grey > 0 hPa, medium grey between -3 and 0 hPa, dark grey < -3 hPa. From top to bottom: measurements, then simulations REF00, REF12, and A12.
The observations of potential temperature, wind intensity (northward component) and surface pressure from the mesonet network have been used to construct the Hovmöller diagram shown in Fig. 5 (top three panels, from left to right). Data are interpolated using an inverse distance averaging technique. They are showing the complex evolution of the föhn episode at the valley floor level. First, a temperature maximum is evident throughout the valley from 10 UTC to 18 UTC on 5 November. Additional warming for Chur to Malans (in dark grey) is well correlated with the southerly wind and evidences the föhn. The föhn starts in the upper Rhine valley (south of Malans) at 12 UTC on 5 November. From this time, until 15 UTC, there is no evidence of föhn at ground level in the lower Rhine valley, except near Balzers. Weak northerly winds are observed north of Vaduz, which are the signature of the cold pool. Indeed, the sounding taken in Buchs-Grabs at 15 UTC (Fig. 6) clearly shows a 300 m-deep cold pool surmounted by a 15 m s\(^{-1}\) föhn jet at 1.5 km above mean sea level (MSL). In fact the föhn jet at ground level is leaving the Rhine valley at Vilters to enter the Seez valley, as already discussed by Beffrey et al. (2003) in the case of IOP 8. This ensures mass conservation. However, the increase of temperature, associated with southerly wind at Balzers at 14 UTC, could indicate that a part of this air comes in the lower Rhine valley. After 15 UTC, the föhn intensity diminishes in the upper valley (south of Malans), but increases in the lower part of the valley: the föhn reaches the ground near 18 UTC at Weite and 19 UTC in Buchs-Grabs. During this episode the cold pool is pushed towards Diepoldsau (Fig. 3b and 4b). The föhn then rapidly weakens between 22 UTC on 5 November and 00 UTC on 6 November. A second wind maximum is observed between 01 and 06 UTC on 6 November. Then the wind decreases rather abruptly. The pressure field was rather flat along the valley and everywhere lower than in Chur during the föhn event. However, after 6 UTC the 6th, the pressure rises by about 3 hPa in the whole valley and a northerly wind signals the arrival of a cold air mass from the north. This is the end of the föhn episode of IOP 15.

Similar parameters have been plotted from simulations REF00, REF12 and A12 (Fig. 5, lower three panel lines). For that purpose, simulation results have been extracted at the location of the observations and interpolated, as done for...
observations. The three simulations reproduce reasonably well the main patterns discussed above. The simulations reproduce the warmer temperature in the whole valley around noon, and the temperature maximum during the föhn event in the southerly part of the lower Rhine valley, south of Ruggell. The föhn intensity south of Malans is however underestimated at the beginning of the föhn episode. Later the simulations capture well the time evolution of the wind near Weite, despite an underestimation of its intensity. Likewise the potential temperature where the föhn reaches the ground is underestimated by 5K. One reason may be the very poor description of the 3 km wide valley at Weite by the 2.5 km grid model. The northerly wind which occurs near Diepoldsau during the episode is well simulated. The föhn weakening between 22 UTC and 00 UTC is present in the three simulations as well as the föhn break in connection with the arrival of the front cold air. However, the surface signature of the föhn differs slightly between the three simulations. The REF12 simulation is too warm until 22 UTC, and the föhn reaches the ground between Balzers and Ruggell from 14 UTC on 5 November to 06 UTC on 6 November, and as far as Dornbirn between 18 UTC and 22 UTC. The A12 simulation is closed to the REF00 simulation. The two simulations produce too cold temperatures over the northern part of the valley. The A12 simulation increases however slightly the surface temperature error. In opposite, the A12 simulation better simulates the föhn area before 00 UTC by limiting it to the south of Goetziz, and after 00 UTC by a more marked föhn.

This can be explained by the fact that the cold pool was better depicted in the initial conditions of simulation A12. Indeed, as seen in Fig. 6, the cold pool depth in Buchs-Grabs at 15 UTC is reasonably well captured by A12, whereas in REF00 and REF12, the cold pool is not present. The upper föhn jet above the cold pool is also remarkably well captured in simulation A12 and error in wind direction is reduced. At 18 UTC (fig. 3), the sounding shows that the cold pool has disappeared; the cooling is limited to the ground surface, surmounted by a 200-m transition zone characterized by large vertical temperature gradients. Simulation A12 succeeds in simulating this transition zone near the ground, whereas REF00 and REF12 fail to reproduce it. The sounding launched at Diepoldsau at the same time (fig. 4) still shows a cold pool thick of 250 m, surmounted by a 250 m transition zone, near the outlet of the valley. Simulation A12 reproduces correctly both the cold pool and the transition zone. In opposite, the cold pool is too warm in REF00, and misses completely in REF12. At 00 UTC on 6 November, the föhn intermittence is depicted in the three simulations at Diepoldsau, but not at Buchs-Grabs.

The time-height cross-sections of potential temperature and northward wind component obtained by the RASS in Rankweil (Fig. 7, see location on Fig. 1) confirm the overall quality of the simulations. During the morning of 5th, the depth of the cold pool observed in Rankweil diminishes slowly at first, and then more rapidly between 07 and 09 UTC, reaching then 250 m. The cold pool is separated from the föhn layer (7 K warmer) by a 300-m deep transition zone. The wind has a small southerly component. In the meantime, the wind speed near ground surface has increased, with a southerly flow of 4 m s$^{-1}$ around noon. The same conditions prevail until 17 UTC, when the depth of the cold pool again starts diminishing abruptly, leading to a föhn touchdown at approximately 19 UTC on 5 November. The cold pool reappears briefly between 22 UTC on 5 November and 00 UTC on 6 November (light northerly wind, colder potential
Figure 7. Time-height cross-section of potential temperature (left) and northward component of the wind (right) at Rankweil, in the Rhine valley. From top to bottom: Rass measurements, then simulation REF00, REF12, A12. The location of the measurements are indicated by the circles in the upper panels. The thin horizontal line materializes the lowest limit of the RASS measurements. Left: Potential temperature, contour interval 1 K, shading starting 291 K with steps every 4K. Right: northward component of the wind, contour interval 1 m s$^{-1}$, shading pale grey < -4 m s$^{-1}$, middle grey > 0 m s$^{-1}$, dark grey > 4 m s$^{-1}$.
temperature), followed by a second föhn episode at the ground until 06 UTC on 6 November, when the föhn layer is pushed back aloft. The föhn episode is then brought to an end by the arrival of the moist perturbation on the northern side of the Alps, around 06 UTC. REF00 and A12 simulations capture the overall evolution of the time-height cross-sections quite well, but only simulation A12, benefiting from the most recent and detailed observations inside the valley, is able to capture with a good intensity the short föhn break in the middle of the night. The simulation already compared with the RASS measurements in Vogt and Jaubert 2004, initialised with the same analysis as simulation A12, but computed with a larger coefficient for the numerical diffusion, allows to capture the föhn break, but with a weaker intensity.

\[ \text{(c) a cross-section of the cold pool at 15 UTC, 15 Nov} \]

The vertical structure of the cold pool has been documented from reflectivity measurements made along the Rhine valley between 1445 and 1505 UTC by the nadir pointing differential absorption lidar LEANDRE 2 (Fig. 8), flying onboard the ARAT. The Lidar reflectivity depends on the relative humidity and aerosol concentration (Flamant et al., 2002). In the reflectivity measurements, the cold-pool is identified as the region of high reflectivity (350 arbitrary units (a.u.) or higher). Above the cold pool and below 2 km MSL, the reflectivity is generally very low, indicating the presence of the dry föhn layer. The southern tip of the cold pool is located just north of Weite, in agreement with the surface measurements. The depth of the cold pool increases slowly to the north, and reaches 250 m north of Rankweil, where the reflectivity also increases, indicating moister conditions (provided that aerosol number concentration is unchanged, reflectivity increases with relative humidity). This depth was also observed over the Lake of Constance (not shown, see Flamant et al., 2003).

Relative humidity fields for the three simulations along the ARAT flight track
are shown in Fig. 10 (right panels). The structure of the cold pool, as defined for relative humidity above 70% (shaded areas in Fig. 10) bares resemblance to that observed by lidar in simulation A12. The cold pool is too thin in simulation REF00, and missing in simulation REF12.

Finally, we propose a composite picture of the potential temperature and northward component of the wind near 15 UTC based on all the observations available near and along the research flight track. It is based on 15 UTC surface observations, 15 UTC radiosoundings launched at Malans, Buchs-Grabs, Feldkirch and Diepoldsau, constant volume balloon launched at Malans at 1522 UTC (trajectory on Fig. 1), Merlin aircraft legs over the Rhine valley (1533-1613 UTC) and Rankweil profiler measurements (Fig. 9). To build the composite, the data positions are projected on the vertical plan defined by the track of the research aircraft (see Fig. 1), and then the data are spatially interpolated over this plan using an inverse distance averaging technique. When interpreting the composite, one must be aware that it gives only an approximate picture of the phenomena in the valley as the data are not all in the vertical plan of the flight track. This composite picture shows a cold pool depth of about 300 m, with a temperature difference between the cold pool and the föhn layer about 8 K. The slight northerly wind component at the center of the cold pool is also discernible. In contrast, a southerly jet reaching 17 m s$^{-1}$ characterizes the föhn layer, with some subsidence in its southern flank as evidenced by the constant volume balloon trajectory.

Most of the features seen on Fig. 9 are reproduced by the simulations (Fig. 10). However, REF00 and A12 give a closer picture than REF12, with again a small
Figure 10. Vertical cross-section of potential temperature and vertical velocity (left), northward component of the wind (middle) and relative humidity (right) from the 4 simulations at 15 UTC on 5 November (cross-section axis on Fig.1). Contour interval and shading for θ and V as in Fig.9, contour interval for relative humidity 10 %, shading starting 70 %. 
Meso-gamma scale aspects of föhn

22 UTC Advection
22 UTC Turbulence
22 UTC Numerical diffusion

0 20 40 60
X (km)

0 20 40 60
X (km)

0 20 40 60
X (km)

Figure 11. Instantaneous potential temperature budget at 16 UTC (top) and 22 UTC (bottom) on 5 November (unit: $10^{-3}$ K s$^{-1}$) from the A12 simulation: (a and d) advection by the mean flow, (b and e) turbulent tendency, (c and f) numerical diffusion along the same cross-section as previously (Fig. 10). The same shading is used for all the figures: pale greys $<-0.1$ and $-0.5 \times 10^{-3}$ K s$^{-1}$, dark greys $>0.1$ and $0.5 \times 10^{-3}$ K s$^{-1}$. The potential temperature is drawn on each figure with a contour interval of 1 K.

advantage for A12 on REF00. As exemple, the cold pool in A12 extends more southward like in the observed composite picture, and the föhn fairly touches the ground in A12 whereas the touchdown is more pronounced in REF00. The vertical velocity in Fig. 10 shows a strong downdraft just downstream of the main slope (-0.75 m s$^{-1}$) and a double updraft for REF12 and REF00. The first updraft is due to a low level jet connecting the upper Rhine valley and the Seez valley, resembling the pattern described in detail by Beffrey et al. (2003). The second updraft is induced by the cold-pool that forces the föhn jet aloft. In A12, the two updrafts have merged into a single updraft, due to the close location of the southern tip of the cold pool and of the bifurcation towards the Seez valley.

(d) Duration of the mesoscale initialisation benefit

The mesoscale analysis performed at 12 UTC improves the simulation, in particular during the first twelve hours. To evaluate the duration of the mesoscale initialisation benefit over a longer period, vertical profiles from the simulation initialised with the mesoscale analysis at 00 UTC (A00) are provided at Buchs-Grabs (fig.3) and Diepoldsau (fig.4). At Buchs-Grabs location, results from the A00 simulation are very similar to the REF00 and REF12 results, except at 12 UTC where the föhn is reaching the ground, too early with respect to the measurements. In opposite, at Diepoldsau 12 UTC, the cold pool is colder in A00
than in REF00, even if it is not enough deep. At 00 UTC on 6 November, twenty four hours after the simulation beginning, the colder air mass going from north in the Rhine valley, is better depicted in A00 than in REF00. Similar results are deduced from the vertical cross-section along the Rhine valley at 15 UTC (fig.10): the cold pool is moister, colder and thicker in A00 than in REF00. However, the fohn reaches the ground a few kilometers further in A00, just near the location of Buchs-Grabs. The intensity of the mountain wave, driven by meso-alpha features, are not clearly modified by the mesoscale analysis. The stagnant cold pool, due to the equilibrium between radiative cooling and warming and turbulent mixing, benefiting longer of the mesoscale analysis. This long time benefit depends also of the model diffusion, which can destroy this weak equilibrium. In our case, we conclude that the mesoscale initialisation is benefit in the twelve first hours of the simulation, and that its benefit is still visible in some regions after twenty four hours.

4. Detailed analysis from the best simulations

\(a\) Heat budget of the cold pool

In this section we investigate the heat budget of the cold pool using simulation A12 in order to quantify the processes governing the penetration of fohn, namely (i) vertical mixing in connection with the diurnal heating of the cold pool, (ii) turbulent entrainment induced by Kelvin-Helmholtz instability at the top of the cold pool, and (iii) intensification of the mountain wave. The evolution of the potential temperature results from an imbalance between the contribution of several physical and dynamical processes, mainly the advection, the turbulence and the radiation. The contribution of the phase changes is negligible here and the corresponding terms are not considered in the budget equation. In contrary, the fourth-order numerical diffusion may locally contribute at a significant level to the potential temperature evolution and has to be taken into account in the budget equation.

The potential temperature budget is obtained by averaging during 2 min (18 time steps) the thermodynamic equation terms. Figure 11 presents the preponderant terms of the budget at 16 UTC and 22 UTC along the same cross-section as Figure 10. The radiation term is weaker, and seems to exclude radiation as a main process in the evolution of the cold pool during the evening of 5 November. At 16 UTC, the advection by the northerly cold wind near the ground contribute to the cooling of the cold pool just near the ground surface, whereas the southerly warm fohn flow contributes to warm the upper layer of the cold pool. The turbulent tendency is important close to the mountain owing to the turbulent nature of the fohn. Turbulence is also important near the valley floor on the foothills of the Alpine range in connection with the fohn touchdown and surge upward south of the cold pool. Turbulence is also active at the leading edge of the cold pool as well as at the secondary bump of the cold pool at the north of Rankweil. So that turbulence tends to warm up the lower levels of the cold pool and to cool the top of the cold pool at these specific locations. This is in accordance with the Merlin flight, which documented a strong turbulence in its lowest leg at the southern part of its only. Concerning the numerical diffusion, it also mainly contributes to warm up the lower levels of the cold pool. At 22 UTC, the preponderant terms tends to contribute in the same way. Nonetheless, it can be noticed
that the turbulence contribution induced by föhn and the one associated with the cold-pool are separated at that time. Also, advection by the northerly flow is limited to the southern low-level part. With these budget analyses, we point out that the intensification of the mountain wave (through the advection term) is the dominant process to erode the top of the cold pool, while the turbulent entrainment induced by Kelvin-Helmoltz instability at the top of the cold pool is more localized. We note however, that the partitionning between the advection and turbulence terms at the southern tip of the cold pool has to be considered with caution due to the significant numerical diffusion at this place. The diurnal heating of the cold pool cannot significantly contributes, considering the time of the budget analyses presented here. However, this process has been identified as a contrbutor to the warming of the cold pool during the morning (from REF00 budgets, not shown). Also, after the sunset, the influence of radiation in regenerating the cold pool is evidenced, as one would expect.

(b) **Relationship between the föhn and the upstream flow characteristics**

In order to establish a correlation between the föhn behaviour and the upstream flow characteristics, the inverse Froude number (or non-dimensional ridge height) of the upstream flow is computed for the whole duration of the föhn episode. To define the upstream flow, the origin of the air flowing into the Rhine valley was first searched for using a back-trajectory technique developed...
by Gheusi and Stein (2002) (not shown). Because of the non-stationarity of the weather situation, the trajectories are rather complex; they evidenced that air parcels were brought to the Rhine valley from the south-east at the beginning of the föhn event (flowing around the secondary low over Sardinia), and then afterwards from the south-west (driven by the main low over northern Europe). However, most of the air was shown to flow a 'common' final track over the Po valley, between 1500 and 3000 m MSL, and passing through a 50 km wide area centered on 45.5°N/8.8°E. The 'upstream' values of the Brunt-Váisälä frequency $N$ and the upstream normal velocity $U$ are defined as the average of these quantities over this 50 km wide area between 1500 and 3000 m, while the ridge height $H$ was set to 2500 m. The results of this computation are shown in Fig. 12(left). The upstream air is very stable throughout the episode, with $N$ larger than 0.013 s$^{-1}$ except after 06 UTC on 6 November. The upstream normal velocity $U$ increased steadily during the period, reaching 10 m s$^{-1}$ at 05 UTC on 6 November, and decreased rapidly after 08 UTC. As a consequence, the inverse Froude number $NH/U$ is decreasing during the period, at the exception of the maximum observed around 17 UTC on 5 November. This maximum is not related to a possible föhn break observed at the valley floor, as the potential temperature simulated above Rankweil increases during this period (Fig. 7c). Likewise, the clear minimum ($NH/U \approx 3$) observed at 08 UTC on 6 November comes after the end of the föhn event and the maximum of föhn in the Rhine valley occurs at 20 UTC on 5 November, when the inverse Froude number value is closed to 5. It appears that unlike the IOP 2 föhn case which occurred in southerly föhn conditions (Jaubert and Stein 2003), the southerly component of the inflow did not drive the föhn intensity in the Rhine valley in the IOP15 case. The föhn event is here clearly connected to a flow splitting regime, which evolved toward a less strongly split regime, in relation with the decrease of the inverse Froude number.

The behaviour of the pressure field upstream and downstream of the range was also studied. The reduced pressure at 500 m altitude at two points located over the Po valley (Lugano) and in the lower Rhine valley (Vaduz) is plotted in Fig. 12e, together with the difference between these two quantities (Fig. 12d) which is related to the pressure drag exerted by the atmosphere on the range (see e.g. Bessemoulin et al., 1993). The REF00 and A12 simulations are both in good agreement with these observations. The pressure difference is roughly proportional to the föhn intensity, as expected from the Bernoulli theorem and from studies of breaking mountain waves. However, no short time scale correlations can be found with the variations of the föhn at ground. Moreover, the time evolutions of the pressure upstream and downstream are rather different: on the upstream side, the pressure decrease is rather smooth and related to the approaching pressure low. On the downstream side, several oscillations are visible, and may be related to the mesoscale variability of the soutwesterly flow around Alps on this side, as will shown in the following.

(c) **Relationship between the föhn and the soutwesterly flow around the Alps**

Figure 13 shows the wind field at 1000 m MSL over the foothills closed to the Rhine valley for 22 UTC and 06 UTC during the night from 5 to 6 November from A12 simulation. At 22 UTC, the southerly föhn flow concerns all the Rhine valley and extends northwards. A soutwesterly wind jet associated with colder air and deviated by the Alps interacts with the föhn jet to produce a pronounced
convergence zone downstream of the Alps. The position of this southwesterly jet changes quite a lot during the night in response to the eastward progression of the primary low over northern Europe. It comes close to the Lake of Constance at 22 UTC, then drifts to the north. At 06 UTC, it has been replaced by the colder westerly flow associated with the cold front, that progressed rapidly to the east. This will soon bring the föhn episode to an end. These features are closed of those described by Zängl et al. (2004) just before the passage of a shallow cold front and the sudden break up of the föhn in the lower part of the Rhine valley.

This is further documented by a series of vertical cross-sections of wind
and temperature across the range at 19 UTC and 22 UTC (Fig. 14). At 19 UTC, there is a classical mountain wave pattern with a maximum southerly wind just downstream of the range. At 22 UTC, this pattern is perturbed by cold air associated with the westsouthwesterly jet (on the northern side of the range, intensity of more than 20 m s\(^{-1}\) at 2 km, in dark grey on fig. 14b). At 01 UTC (not shown) the flow is veering to a more south component wind and the jet is located 35 km further north of the Rhine valley. These temporal variations in low-level flows explain the oscillations of the downstream pressure (see section 4b).

The local topography also plays an important role in the detail of this evolution near ground surface. Figure 15 displays the topography around the Lake of Constance, together with the horizontal wind field at 600 m MSL. Figure 16
shows potential temperature and wind (component perpendicular to the cross-section) along two cross-sections, S1 and S2, running east-west. The orography along the cross-section S1 (Fig. 16, left panel) is characterized by a 450 m (MSL) plateau at the west of the Lake of Constance, whereas at the east of the Lake, a north-south oriented hill (top at 800 m MSL) can act as an obstacle in adequate conditions. As example, when south-westerly winds increase to the north of the Alps, the cold air pool over the Lake of Constance cannot drift to the east because of the barrier effect of the hill. It is then forced to enter into the Rhine valley and interacts with the föhn flow. This phenomenon is clearly illustrates at 21 UTC (Fig. 15, left panel and fig. 16, left panel). The depth of this northerly flow associated with the cold pool is about 400 m depth, surmounted by the föhn jet. This phenomenon is however intermittent during the föhn episode as can be seen for example with Figure 15 (right panel) taken one hour later. Same intermittence has been also found between 05 and 06 UTC in the simulation; there exist also some evidences in the observations as can be inferred for example from the RASS data. These are accompanied by pulsations in the southwesterly flow. The cross-section S2 (passing through Rankweil) shows that also there exists an asymmetry between the western and eastern flank of the Rhine valley. The cold air coming from the outlet of the Rhine Valley affected the bottom of the valley and its eastern flank, whereas the western flank is concerned by the warm föhn jet (Fig. 16, right panel). It can also be noticed that the southwesterly flow around jet and the föhn jet are only separated by about 20 km.

5. SUMMARY AND CONCLUSION

The interaction between the cold pool and the föhn in the Rhine valley was well documented during IOP15 of MAP (5 and 6 November 1999) by the important network of instruments involved in the FORM project, as well as by aircraft measurements. The event was simulated using the non-hydrostatic model meso-NH, with two nested model (meshes 10 and 2.5 km) in a two way interactive mode, with great realism.

The use of a mesoscale analysis and the associated detailed orography, over the whole domain of simulation, improves the result. The comparison between simulations A12 and REF12 (guess) shows clearly the impact of the mesoscale analysis by introducing the cold pool that was missing in the large scale analysis at noon. This effect is not limited to the first hours of the simulation, but is still effective twelve hours after the beginning of the run. First, a realistic cold pool height prevents the föhn to touch the ground too early, and allows us to simulate an accurate timing of the föhn onset. Second, this simulation represents well the stagnant cold air which remains over the foothills for several hours after the föhn breakdown and its penetration upslope against the föhn flow for few hours, depending of the large scale forcing.

Analysis of the interactions between the cold pool and the föhn jet above during the late afternoon and evening of 5 November, based on a heat budget approach, shows that the leading terms appear to be the advection by the mean flow and the turbulent tendency, whereas radiation tendency is weak. The turbulent mixing occurs mainly close to the terrain, in the regions where the föhn air subsides in the lee of the mountain range and where it interacts with the cold pool.
At the scale of the Alpine range, the flow regime is a flow around the Alps during the whole event, with an inflow value increasing from 3 m s\(^{-1}\) to 10 m s\(^{-1}\) and an inverse Froude number larger than 3. The föhn reaches the ground in the Rhine valley north of the Seez valley bifurcation when the ground pressure difference across the Alps is greater than 6 hPa. The jet associated with flow splitting at the scale of the Alps and flowing along the western flank of the range influences on the altitude of the föhn jet in the Rhine valley. The air passing over the Alpine range that subsides in connection with the mountain wave, is channelled in the Rhine valley where it encounters the colder and more stable air coming from the north. The flow around jet appears to modulate the intrusions of cold air from the north in the Rhine valley. These intrusions are favored when the strong flow-around jet is positioned close to the Rhine valley outlet and is oriented orthogonally to it. Local topography, i.e. the small mountain range east of the Lake of Constance basin, makes it easier for the air to enter in the Rhine valley, due to channelling.

As the arrival of the föhn at the ground is connected to the intensity of the mountain wave and to the erosion of the cold pool, three ingredients are necessary to forecast it at short range: an accurate mesoscale model, a model resolution sufficient to resolve the topography of the major valleys, a model initialisation of the local features in the valleys. The results of this study shows the ability of the future mesoscale operational models to forecast this type of events, and stress the importance of adjoining a mesoscale data assimilation to the future operational models.

Acknowledgements

The authors would like to thank the scientists of the MAP FORM working group, coordinated by H. Richner, and particularly R. Steinacker, T. Gutermann, B. Bénéch, P. Drobinski, M. Furger and R. Werner for fruitful discussions. We would also like to thank the mesoscale team at CNRM, and particularly J. Stein for early suggestions, P. Jabouille for his help in the use of meso-NH, V. Ducrocq for her guidance for the use of the mesoscale analysis. The MAP archive is kindly acknowledged for the data management.

References


Meso-gamma scale aspects of föhn


<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Year</th>
<th>Title and Details</th>
</tr>
</thead>
</table>