P3.1 FOEHN ANALYSIS IN THE RHINE VALLEY WITH A FM-CW BOUNDARY LAYER RADAR-RASS DURING THE MAP EXPERIMENT

S. Vogt*
Institute for Meteorology and Climate Research,
Forschungszentrum Karlsruhe, Germany

1. INTRODUCTION

One of the scientific objectives addressed The term foehn is derived from the Latin "favonius" meaning spring wind. In central Europe, it normally refers to a warm, dry, and often gusty downslope wind on the northern side of the Alps (South foehn) or southern side of the Alps (North foehn). Foehn has attracted the scientists' interest for more than a century. As early as 1866, Hann recognized that adiabatic warming is the primary reason for the warmth and dryness of the foehn rather than air advection from the Sahara. South foehn in the Rhine Valley has already been observed and described for many decades. Peppler (1926, 1935) investigated kite soundings and pilot balloon ascents which were conducted on Lake Constance and at Friedrichshafen (north of Lake Constance) for more than 20 years. Gutermann (1970) was the first to lookinto local scale differences of the foehn air in the Rhine Valley and studied the interaction of foehn flow with the valley wind based on long time series of surface observations.

Two major field experiments were conducted in the Alps, foehn being one of the scientific targets. The first one, ALPEX (Alpine Experiment), (Kuettner 1982), was quite unlucky with weather conditions, as the first strong south foehn occurred as late as four days after the end of the SOP (Special Observing Period). (Steinacker 1991). Thus, foehn observations were continued in the following years. Comprehensive reports of the foehn studies conducted at that time are given by Seibert (1985, 1990, and 2000) and Hoinka (1990). In the second field experiment, called MAP (Mesoscale Alpine Programme, September-November, 1999), more than ten foehn days occurred, yielding a huge amount of valuable data that are currently being analysed. An overview of the measurements conducted during MAP is given by Bougeault et al. (2001).The subprogramme FORM (Foehn in the Rhine Valley during MAP) was dealing with South foehn episodes in the Rhine valley south of Lake Constance.

Observations reveal that the floor of Alpine valleys often is occupied by a layer of cold air, which is generated by radiative cooling during the night. This "cold pool" prevents the upper-level foehn flow from reaching the ground during the most of the duration of foehn episodes. Lee et al. (1989) show that the structure of the mountain wave can be modified greatly by the presence of the cold pool. The interaction of foehn flow with the cold air pool in the valley is discussed thoroughly by Hoinka (1991). Only when foehn intensity is sufficient, does the foehn flow touch the floor of Alpine valleys.

Three mechanisms are likely to govern this penetration of foehn flow to the valley floor (Gubser and Richner, 2001): The diurnal heating of the cold pool by solar radiation may reduce the stability and allow vertical mixing, 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 the occasional intensification of the mountain wave at the upper level may force the foehn flow down to the ground level and flush the cold pool downstream. These three processes may also occur simultaneously. Beffrey et al. (2004) show that the advection by the downslope wind is the main source of warming at low levels in the southern part of the valley.

The objectives of FORM are to study:

- The dynamics of that part of the blocked, potentially cooler air mass

---

* Siegfried Vogt , Institute for Meteorology and Climate Research, Forschungszentrum 76021 Karlsruhe, Germany
Siegfried.vogt@imk.fzk.de

that typically reaches up to the mean crest height on the windward side of the main ridge, which is flowing through deep Alpine passes towards the lee-side valleys.

- The interaction between low-level and mid-tropospheric foehn flows on the scale of large alpine valleys, with the understanding and forecasting of foehn-related phenomena like turbulence being improved.
- The mechanism of temporal and spatial evolution and cessation of foehn flows in complex valley systems on a local scale.
- Interaction of foehn with the boundary layer, and the process of removal of the cold air pool.

2. EXPERIEMENTAL DESIGN

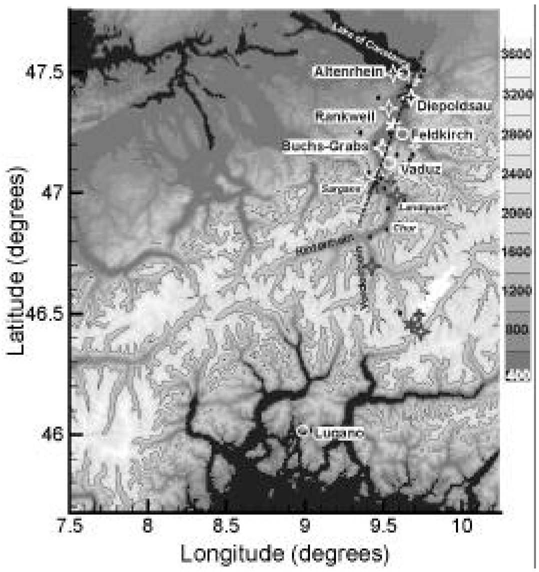
Reasons for choosing the Rhine valley as the FORM target area included:

- The spatial extension of the target area should include the crest of the Alps and parts of the Alpine foothills.
- Several low passes in the main crest of the Alps should allow the development of shallow foehn.
- It is well equipped with existing routine observation networks.
- Improvement in forecasting the breaking-through or ending of foehn is of crucial importance to storm warnings for Lake Constance.

The Alpine Rhine Valley (Fig.1) extends over about 80 km between the confluence of Vorder- and Hinterrhein and Lake Constance. In the south several tributaries are located. They start at the main Alpine crest and may feed the foehn flow in the main valley. Further to the north, there are several kinks in the valley axis. These changes in direction often are quite abrupt. In the area of Sargans, another valley opens westward to the Seez valley and the Walensee. Further to the north, the Walgau runs into the Rhine valley.

At the bottom of the valley, the prevailing land use is agriculture with some forests mainly along the rivers and creeks. Vineyards are very common in the Rhine valley, especially on the gentle eastern slope in the area between Landquart and Sargans. As for the rest, the slopes are mainly forested. Above about 1500 m asl, alpine meadows prevail. The population density is highest in the valley floor. The most densely populated areas are found in the Austrian part of the Rhine valley towards Lake Constance and in the region of Chur. In the same areas, significant industrial zones have been established.

Fig. 1 Experimental setup and terrain elevation in the FORM area



radio sonding stations,

two wind profiler sites,

sodar sites,

lidar sites,

automatic and micrometeorological stations

The location of the Radar-RASS is at ***Rankweil***, Altenrhein, Feldkirch and Vaduz are synop stations used,

Radio sonde stations used are at Diepoldsau and Buchs-Grabs.

During the period of the field campaign of FORM, from 7 September to 15 November 1999, the following unique observation network was deployed. (see also Fig. 1):

- 7 radio sounding stations with three soundings made per hour during the IOPs by the Swiss army,
- 2 wind profilers, one with RASS, continuous operation,
- 3 sodar, continuous operation,
- 2 lidar,
- 2 aircraft,
- numerous automatic and micro-meteorological stations for meteorological and chemical measurements,
- special instrumentation, e.g. a scintillometer, constant level balloons, one tethersonde, a cable car sonde, and several video and photo cameras.

One of the two wind profilers was the boundary layer Radar-RASS of the Institut fuer Meteorologie und Klimaforschung. It was located near Rankweil in the middle of the Rhine Valley. The Radar-RASS is a mobile system, especially designed for probing the lower atmosphere, i.e. the planetary boundary layer. More details will be found in Bauer-Pfundstein (1999). All measurements are based on the backscattering of electro-magnetic waves in the atmosphere. Waves are scattered either on microturbulent fluctuations of the atmospheric refraction index which is associated with fluctuations of the temperature and humidity, or on artificial fluctuations of the refraction index, which are generated by the transmission of an appropriate sound source.

The Radar-RASS works in two modes: the RASS-mode and the clear-air-mode. In the RASS-mode the Radar-RASS records the air temperature by detecting the propagation of sound pulses with a RADAR. Rain does not disturb much. In the clear-air-mode the Radar-RASS observes the electro-magnetic structure parameter of the refractive index C_n^2, which in contrast to its acoustic counterpart is mainly dominated by moisture fluctuations but much less by temperature fluctuations. The Radar-RASS has a five-beam geometry with two bistatic radiofrequency (rf) and one acoustic (ac) antenna. The antennas are quadratic phased arrays, each of them consisting of 64 elements. The ac antenna is a 1:2 scaled copy of the rf-array to match the rf-beam at the Bragg-wavelength. The rf-antenna emits continuous waves that are frequency shifted with a saw tooth modulation (FM-CW Doppler Radar) in order to provide a fine range gate resolution. Contrary to a conventional pulse Radar the height resolution is not calculated by means of the travel time of the rf-waves but is proportional to the frequency shift between the transmitted and received signal.

The sound source is not only used to measure the vertical sound velocity and hence the temperature, but also to estimate the wind components in the so-called RASS-mode. This is possible because the ac-beam is simultaneously shifted in the same four oblique beam directions like the rf-beam. The combination of the RASS-mode and the clear-air-mode allows estimating two independent and redundant wind profiles.

Tab.1 Technical data of the wind profiler-RASS (left column: electro-magnetic waves, right column: acoustic waves)

Frequency	1290 MHz	2700 – 3000 Hz
Power	6400 W	320 W
Antenna aperture	3.2m x 3.2m	1.6m x 1.6m
Antenna gain	33.5 dB	33.5 dB
Beam direction	± 8.5° off zenith in N-S-W-O	±8.5° off zenith in N-S-W-O
Antenna type	8 x 8 pyramidal horns	8 x 8 exponential horns
Number of range gates	78	24
Width of range gate	60 m (variable)	60 m (variable)
Averaging time per beam	10 sec (variable)	10 sec (variable)
Averaging time wind and temperature	30 min (variable)	30 min (variable)

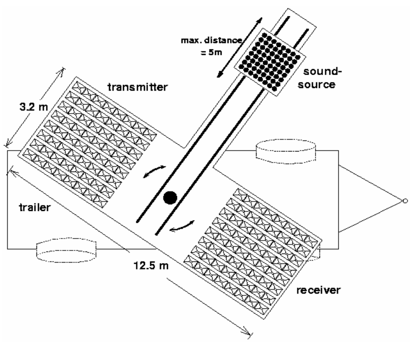
Measuring the acoustic wave speed yields in a straightforward way the virtual temperature T_v. The virtual temperature is defined as the temperature the air would have if it were completely dry and is at the same pressure. The local speed of sound v_{ac} is related to the virtual temperature by:

$$v_{ac} = (\gamma\ RT_v)^{½} \sim 20\ T_v^{½}$$

where v_{ac} is speeding m s^{-1}, γ is the ratio of the specific heats and R is the universal gas constant of air.

The Radar-RASS can be rotated on the trailer, and the distance separating the acoustic antenna from the rf antennas can be varied by means of a sliding boom, allowing the acoustic source to be positioned for maximum efficiency upwind on the rf-antennas in dependence on wind speed and wind direction.

Fig. 2 Bird's eye view of the Radar-RASS



3. SYNOPTIC DESCRIPTION

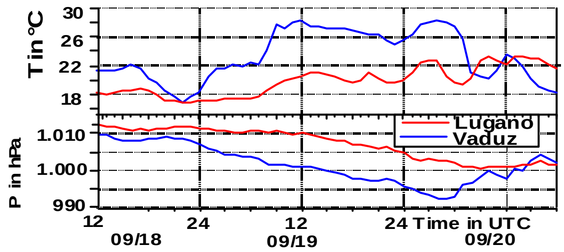
During 77 days of measurements there were 17 days with South foehn at the Radar-RASS site. We have selected three different foehn situations (IOP2, IOP15, and IOP16) for our presentation. foehn event IOP2 was a strong deep foehn event. Its origin was essentially dynamic. In the second event (IOP15) the cold air pool in the valley was removed very slowly but steadily. In the third event (IOP16) the warm foehn air did not reach the valley floor, very sharp gradients of temperature had been detected only some 100 m above ground level

3.1 *IOP2*

The Synoptic situation of IOP2 is characterized by a cut-off low above a surface cyclone located west of Ireland and an anticyclone over Eastern Europe. A cold front, associated with this cyclone, is very elongated along a North-South axis. The front crosses France during Sep.19th and reaches Italy and Germany during the next day. The Foehn maximum happens during the night. A permanent Southward flow drives air coming from North Africa towards the Alps before the arrival of the front. The front arrives in the Rhine valley on Sept. 20th around 12 UTC and this was the end of the foehn.

The synoptic situation near ground level is characterized best by time series of temperature and pressure of one location South of the Alps (Lugano) and another location North of the Alps right in the lower Rhine valley (Vaduz), see Fig. 3. IOP2 is a strong deep Foehn. All the measurements and the simulation outputs (Jaubert et al. 2003) confirm the essentially dynamical origin of the Foehn.

Fig. 3 Time series of temperature and pressure of Lugano and Vaduz during IOP2. (Lugano is South, Vaduz is North of the main crest of the Alps).

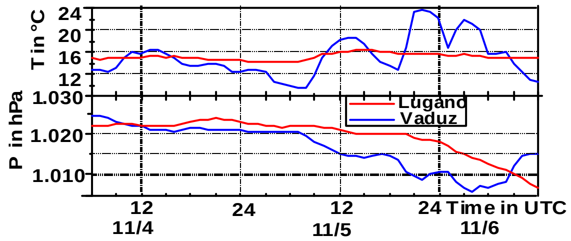


3.2 *IOP15*

The synoptic situation of IOP15 was characterised by an extensive trough extending from the North Sea to France with strong cold air advection over the British Isles (-28°C in 500 hPa) and a very strong positive vorticity advection ahead. East of Iceland, a surface cyclone was located over Ireland on November 5th, 12 UTC, and moved to the East. The cold front associated with this cyclone was SW-NE-oriented. Just south of the Alps, a secondary low located over Corsica slowly filled up.

On the surface, the cross-alpine pressure gradient (Lugano-Vaduz) increased first between 5 and 11 UTC, November 5th, to reach 5 hPa. (Fig.4). This was in relation with the first warming measured by the wind-profiler-RASS in the Rhine valley. These are classic south foehn conditions.

Fig. 4 Time series of temperature and pressure of Lugano and Vaduz during IOP15.



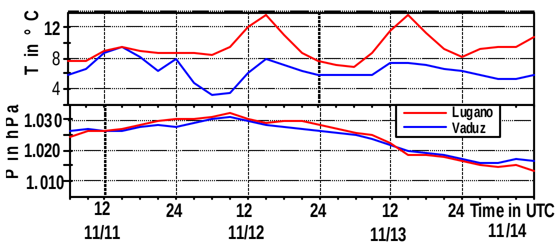
The cold air pool in the Rhine valley in the area of the Radar-RASS became increasingly shallow until the warm foehn air touched the valley floor in the early evening of November 5th. However, the foehn stayed intermittent. Around 22 UTC, the flow was lifted up by colder air for about 2 h. Foehn re-established until the frontal system reached the Rhine valley around 6 UTC on November 6th. The cold front reached the outlet of the Rhine valley near 8 UTC, November 6th. Then, a strong and cold northerly wind flooded the Rhine valley at a low level.

3.2 *IOP16*

This IOP event was a shallow South foehn event triggered by a retrograding vortex southeast of the Alps. On Nov. 11th the surface pressure filed showed a shallow and only temporarily deepening Low in the area of Sardinia-Corsica. A High pressure field was still spreading North of the Alps with a pronounced centre over the British isles (max. > 1040hPa).

The upper level cut-off Low shifted towards West on Friday Nov. 12th reaching from the Gulf of Biscay to the Iberian Peninsula. The surface pressure field showed the cyclone South of the Pyrenees over the western Mediterranean Sea. Surface pressure gradient over Eastern Alps was weakening, while it becomes a little bit stronger over the Western Alps. Pressure difference of Lugano-Vaduz was still positive but only weak (< 3hPa, see Fig. 5).

Fig. 5 Time series of temperature and pressure of Lugano and Vaduz during IOP16.



On Sunday Nov. 13th foehn reached its maximum in the Rhine Valley, but only at higher altitudes (> 1400m asl.) Contrary to the other foehn events, the present foehn was not stopped by an approaching front from the West. But the upper level cut-off Low was connected with the deepening through from Northeast Europe.

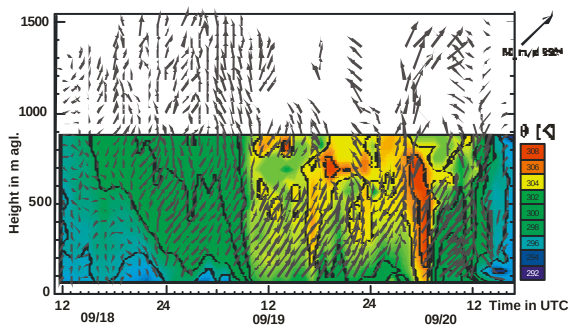
4. DEVELOPMENT OF FOEHN AS SEEN BY THE RADAR-RASS:

Foehn structures are illustrated best by time-height cross section of wind and potential temperature at the Radar-RASS location. (Figs. 6, 8 and 10) Due to the slow sound speed the height coverage of temperature is always less than that of the wind. In case of IOP2, where the wind speed in the valley goes up to 20ms^{-1}, the Radar-RASS temperature reaches only up to 800m agl.

4.1 *IOP2*

First indications of the beginning of South foehn at the Radar-RASS location was increasing wind speed and a change in wind direction from South to South-East beyond 900m agl in the early morning hours on September 19th (Fig 5). One hour later the temperature simultaneously increased at all heights (Fig.7) and the wind speed increased even more (> 15 ms^{-1} at the lower range gates).

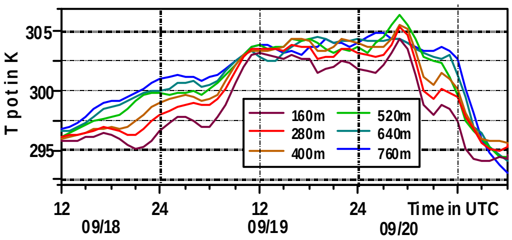
Fig. 6 Time series of temperature and wind during IOP2.



The warm and dry foehn air became evident in the bad S/N ratio of the clear-air signal. Therefore the estimation of wind barbs was nearly impossible. But we do have wind barbs at the lower heights (<500m agl) because of the RASS-mode used, see Sect. 2. These Foehn condition lasted more than 15h.

Foehn maximum happened during the early morning hours of September 20th. This coincided with the maximum of the pressure difference between Lugano and Vaduz (10hPa). Soon after the pressure difference was decreasing Foehn was ceasing. The front mentioned in Sect. 3.1 arrived in the Rhine Valley on Sept. 20th around noon and this was the final end of the Foehn.

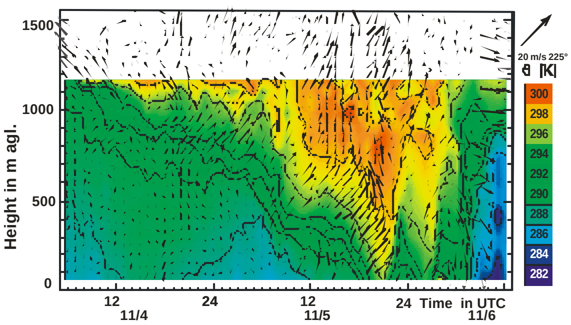
Fig. 7 Time series of potential temperature at selected heights.



4.2 *IOP15*

Warm south wind was detected first at an altitude of 1.2 km around midnight November 4th, (Fig. 8). It lasted nearly 19 h until the foehn penetrates down to the valley floor. The descending was not uniform but with some intermittent periods. An overall descending rate of 40 m h^{-1} is estimated, see also Fig. 9

Fig. 8 Time series of temperature and wind during IOP15



Five time periods of IOP15 can be detected at the wind profiler site.

i. Growing of cold pool during the night and warming in the morning, 0-7 UTC.

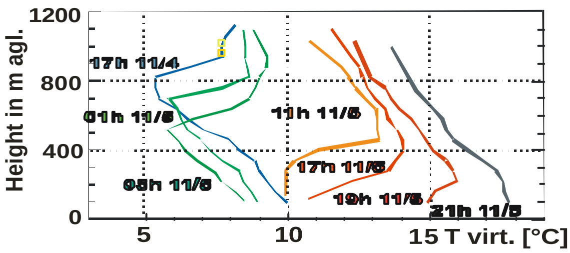
ii. Onset of foehn and eroding of the stagnant cold pool mainly due to advection (see Jaubert et al. 2003), 8-17 UTC.

iii. Break through of foehn to the valley surface after November 5th, 18 UTC.

iv. Intermittence of foehn and growing again of the cold air pool around midnight November 5/6th.

v. End of foehn due to the arrival of the perturbation after November 6th, 6UTC.

Fig. 9 Selected height profiles of virtual temperature for time periods 1-3.



At 00 UTC on November 5th , the cold pool observed is 600 m deep and is separated from the foehn layer (7 K warmer) by a 300 m deep transition zone. The wind has a small southerly component. The depth of the cold pool diminishes slowly at first, and then more rapidly between 7 and 10 UTC, reaching then 250 m while the wind turned to the south.

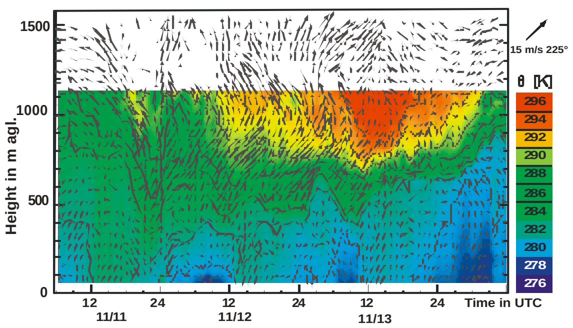
The same temperature conditions prevail until 16 UTC November 5th, when the depth of the cold pool again start diminishing abruptly, leading to a foehn touchdown at approximately shortly after 18 UTC on. The cold pool reappears between 21 UTC on November 5th and 1 UTC on November 6th. Then foehn is re-established at the ground until 6 UTC on November 6th, when the foehn is stopped by the arrival of the perturbation. It is noteworthy that northerly winds are already present after 4 UTC on November 6th at lower levels up to 500 m above ground level. A temperature cooling of 2 K is simultaneously to be seen.

As already described by Beffrey et al. (2004), at the location of the confrontation between the foehn air and the cold pool, the foehn air is suddenly rejected above the cold pool, in hydraulic jump behaviour. The interface location, located south of Vaduz before 19 UTC, changes suddenly to reach a location between Rankweil and Diepoldsau during a large part of the foehn event. However, this point is not stationary. Near 21 UTC, the intensity of the southward wind in the cold pool increases, the interface location is rejected to the south for two hours. This is the beginning of a new period, where the lee wave structure is perturbed from the North West, in relation with the arrival of the perturbation. Finally, at 05 UTC the cold air floods the Rhine valley from the North.

4.3 *IOP16*

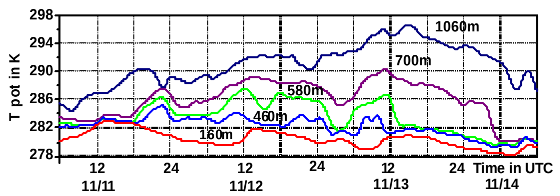
Around 9UTC on Nov. 11th wind velocity was speeding up beyond 1000m agl and a first warming was detected. (Fig. 10)

Fig. 10 Time series of temperature and wind during IOP16



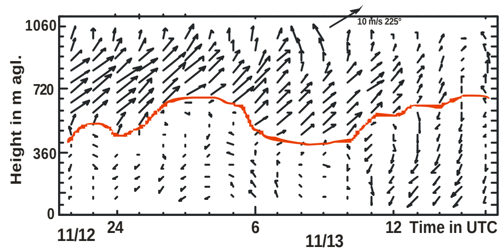
In the course of the day until 23UTC the warm Foehn air came down till 300m agl. Afterwards Foehn retreated for some hours to upper heights, but Foehn re-established in the morning hours of Nov. 12th and came down again till 600m.

Fig.11 Time series of potential temperature at selected heights.



Later on very pronounced up and down oscillations of the interface of warm Foehn air with wind velocity around 7 ms^{-1} and the cold and calm air near ground level were observed, see the wind profiles in Fig.11.

Fig. 11 Wind barbs on Nov. 13th. The red line is indicating the discontinuity of foehn and cold air near ground level.



Contrary to IOP2 and IOP15 the end of Foehn during IOP16 was not abrupt due to an approaching front, but gradually due to changing large scale pressure conditions. (see Fig. 5)

5. CONCLUSION

Thanks to the excellent resolution in time and height of temperature and wind measured by the Radar-RASS it is possible to get a very detailed picture of the evolution of the all three foehn events. This is not possible with other profiling systems like radio soundings even with the present dense ascent intervals of 3h during the FORM experiment.

The events IOP2 and IOP15 were simulated using the Non-hydrostatic model Meso-NH with great realism.(Beffrey et al. 2004; Jaubert et al. 2003). These simulations allow describing detailed characteristics and evolution of Foehn flow at the level of the valley floor. The documentation of the interaction between the down slope winds, the stagnant cold pool and the large scale flow of the valley is a first step in the understanding of the phenomena.

6. REFERENCES

BAUER-PFUNDSTEIN, M., 1999: Bestimmung von Turbulenzparametern und der Schallabsorption mit einem Wind-Temperatur-Radar. – *Wiss. Berichte, FZKA* **6281**, 1-152.

BEFFREY, G. G. JAUBERT, A. DABAS, 2003: Foehn flow and stable air mass in the Rhine valley: the beginning of a MAP event. – *Quart. J. Roy. Meteorol. Soc*., accepted.

BEFFREY, G. G. JAUBERT, A. DABAS, 2004: Spatial evolution of foehn flows in the Rhine valley area: quantification using high resolution simulations. – *Quart. J.Roy. Meteorol.Soc*. **130.** 541-560

BOUGEAULT, P., P. BINDER, A. BUZZI, R. DIRKS, R. HOUZE, J. KUETTNER, R.B. SMITH, R. STEINACKER, H. VOLKERT, 2001: The MAP Special Observing Period. – *Bull. Am. Meteorol. Soc.* **82**, 433-462.

GUBSER, S., H. RICHNER, 2001: Investigations into mechanisms leading to the removal of the cold pool in foehn situations. – Map newsletter **15**.

GUTERMANN, T., 1970: Vergleichende Untersuchungen zur Föhnhäufigkeit im Rheintal zwischen Chur und Bodensee. – Master's thesis, Veröffentlichung der Schweizer Meteorologischen Anstalt, Zürich.

HANN, J., 1866: Zur Frage über den Ursprung des Föhns. – *Z. Meteor.* **1**, 257-263.

HOINKA, K.P., 1990: Untersuchung der alpinen Gebirgsüberströmung bei Südföhn. – *DLR-FB* **90-30**, 186 pp.

HOINKA, K.P., T.L. CLARK, 1991: Pressure drag and momentum fluxes due to the Alps. Part 1: Comparison between numerical studies and observations. – *Quart. J. Roy. Meteorol. Soc.* **117**, 495-525.

JAUBERT, G., P. BOUGEAULT, H. BERGER, B. CHIMANI, C. FLAMANT, C. HAEBERLI, M. LOTHON, M. NURET, S. VOGT, 2003: Numerical simulation of meso-gamma scale aspects of föhn at the ground level in the Rhine valley. – accepted *Quart. J. Roy. Meteorol. Soc*.

KUETTNER, J.P., 1982: ALPEX, experiment design. – *GARP-ALPEX (WMO)* **1**, 1-226.

LEE, T.J., R.A. PIELKE, R.C. KESSLER, J. WEAVER, 1989: Influence of cold pools downstream of mountain barriers on downslope winds and flushing. *Mon. Weather Rev.* **117**, No. 9, 2041-2058.

NATER, W., H. RICHNER, P.D. PHILLIPS, 1979: Shear instabilities and their characteristics during foehn. – *Geophys. Astrophys. Fluid Dynamics* **13**, 215-223.

PEPPLER, W., 1926: Zur Aerologie des Föhnes. – *Beiträge zur Physik der freien Atmosphäre* **12**, 128-214.

PEPPLER, W., 1935: Über die südlichen Luftströmungen auf dem Säntis und in der freien Atmosphäre über dem Bodensee – *Beiträge zur Physik der freien Atmosphäre* **22**, 1-11.

SEIBERT, P., 1985: Fallstudien und statistische Untersuchungen zum Südföhn im Raum Tirol. – Innsbruck: Ph.D. thesis, University of Innsbruck, 367pp.

SEIBERT, P., 1990: South foehn studies since the ALPEX experiment. – *Meteorology and Atmospheric Physics* **43,** 91-103.

SEIBERT, P., 2000: South foehn and ozone in the Eastern Alps – case study and climatological aspects. – *Atmospheric Environment* **34**, No. 9, 1379-1394.

STEINACKER, R., 1991: ALPEX-Daten. – *Promet* **21**, 79-83.