P3.5 FOEHN ANALYSIS IN THE RHINE VALLEY: FROM SYNOPTIC SCALE TO TURBULENCE ONE

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1. INTRODUCTION

When a southerly flow collides with the Alps, a warm and dry wind – the so-called "foehn"– can rush into the northern Valleys in a gusty way. This phenomenon, which can occur in the vicinity of any mountain ridge, has been studied worldwilde for decades, because of the damage it can cause (Brinkman, 1974). Hoinka (1985) conducted a first analysis of the large-scale, mesoscale and local features of a foehn event in Northern Alps, including a turbulence analysis. Most of the studies dealing with the turbulence in the lee of a mountain ridge focus on the high level of the troposphere (Lilly, 1971; Hoinka, 1984), less deal with the lower level turbulent areas (Lester and Fingerhut, 1974).

A synthetic study of the foehn-induced turbulence observed during five flights of MAP experiment operated by the Merlin IV aircraft is presented here. The general features of the synoptic situation and the characteristics of the mean parameters of each foehn event during the flight are given, in order to describe the context in which the turbulence is observed. In section 2, the experimental set up and the analysis method are presented. In section 3 and 4, the large and meso- scale features of the five foehn events are described. And in the last section 5, the aircraft turbulent data are analyzed from a synthetic point of view in order to pick out some general features of the foehn-induced turbulence.

2. INSTRUMENTATION AND ANALYSIS METHOD

The aircraft data used here were collected with the Météo-France Merlin IV aircraft, which is instrumented in dynamic, thermodynamic, aerosol and chemistry in situ measurements. The aircraft took off from Milano/Linate airport and performed one leg across the Alps at about 5500 m ASL from the south of the Alps (A in figure 1) to the Rhine valley (C). It flew three additional legs in the longitudinal axis of the valley (BC) and three legs in each of three transverse axis corresponding to secondary valleys (D_1D_2, E_1E_2 and F_1F_2), exploring the lower atmosphere within the valley between 900 m and 3000 m. The Rhine Valley target area is surrounded by a bright frame in Fig. 1. The five foehn flights of IOPs 2, 5, 8, 13 and 15 are considered here.

Aircraft turbulence data processing was applied to the three wind components (u, v and w), the potential temperature (θ) and specific humidity (q) from which the mean value and linear trend has been eliminated. A high-pass filter has been applied, with a cut-off frequency of 0.018 Hz. The corresponding wavelength, depends on the aircraft velocity Vp, and ranges between 4.4 km for Vp=80 $m.s^{-1}$ to 5.5 km for Vp=100 $m.s^{-1}$.

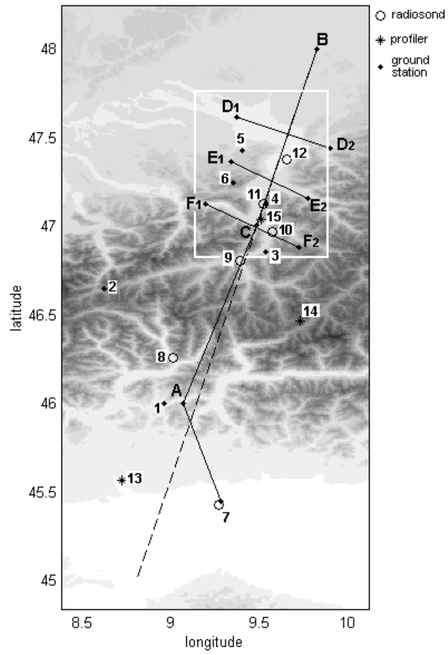

Figure 1 : Experimental set up and flight plan

The mesoscale context is analyzed through the experimental data of several ground stations, radiosoundings and two wind profiler localized and labeled in Fig. 1. In particular, the pressure and potential temperature difference between Lugano (1) and Vaduz (4) are calculated, as director parameters of the foehn (Bessemoulin, 1993). The upwind conditions are characterized by the Froude number calculated within the layer comprised between 2000 m and 4500 m above Milano (7) , and the wind at 5000 m above Lonate (13). The crest conditions are given by the wind at 3600 m above the Julier Pass (14) and in Guetsch Pass (2). The penetration of the foehn in the Rhine Valley is described through the ground stations Chur (3), Vaduz (4) and Sankt Gallen (5).

IOP	2	5	8	13	15
Date	19.09.99	02.10.99	20.10.99	02.11.99	05.11.99
flight time /event	mid.	beg.	beg.	end	beg.
Real time observations					
Waves ?	*		*		*
Turbulence	H	HM	HM	M	MW
Synoptic and upwind conditions					
Synoptic flow	S	SW	SW	SW	SW

Table 1 : Description of the five flights

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Table 1 presents general information about the five studied flights. First, the number of the IOP and the date are indicated, as well as the position of the flight time as regard the whole event duration, in order to put the flight in the context of the foehn event. Then, a qualitative index of the presence of waves and of the intensity of the turbulence observed in the Rhine Valley are also specified. The first synoptic index is the flow observed on the high level leg AB. In four cases (IOP 5, 8, 13, 15) where the aircraft flew at the beginning or the end of the event, the synoptic flow was south-westerly. IOP 2, when the aircraft flew in the middle of the event, is the only case of southerly synoptic flow and high turbulence.

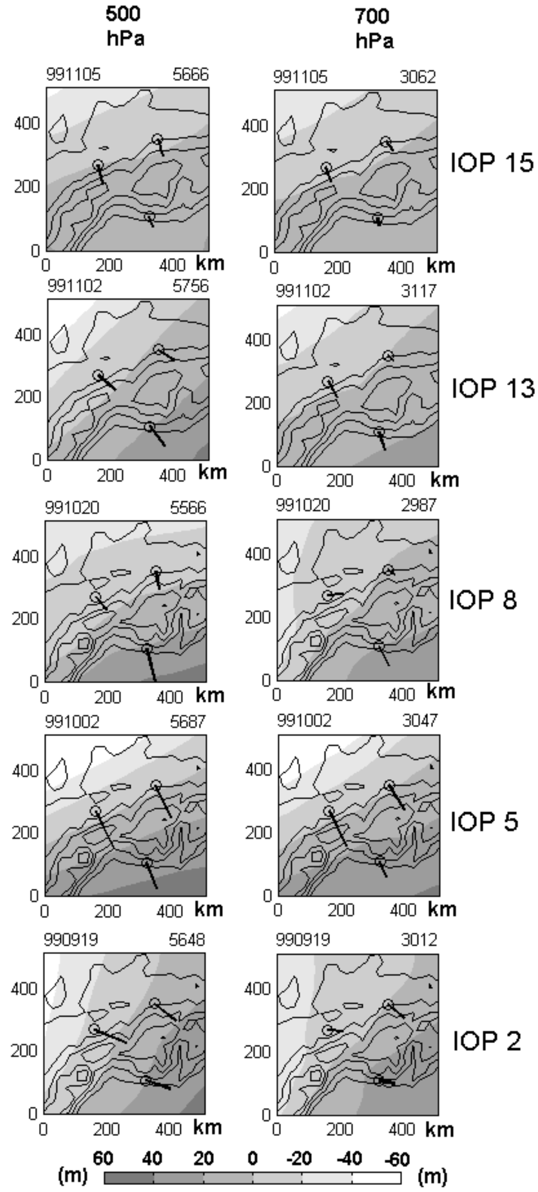

Figure 2 : Relative geopotential at 500 hPa and 700 hPa (gray scale) around their mean altitude, and local slope at three point.

3. LARGE SCALE FORCING

The synoptic condition favorable to the foehn events usually corresponds to a low coming from the west and moving eastward, generating a southerly or southwesterly flow over the Alps (Hoinka, 1980). This is the case of the five events studied here. In order to study the synoptic forcing for the five foehn events considered here, and from the Rhine Valley point of view, the isohypses fields at 700 and 500 hPa within a 500x500 km^2 horizontal domain, centered on the Rhine Valley are analyzed (Fig. 2). These fields are provided by the analyses of the French ARPEGE model at 1200 UTC for the five cases, at about 80 km length scale. The local slope of the isohypses at three points surrounding the valley, at two different levels, allows to compare the local pressure field for the different cases. Five characteristics of this field differentiate the cases: the direction and intensity of the gradients, their rotation and variation of intensity with height, and horizontal homogeneity. As a first glance, we deduce from these fields the synoptic wind direction and speed above the target area. As regard the direction, IOP 2 is the case in which the flow is the most southerly. The flow is more south-westerly in IOP 13, 5 and 8, and almost westerly for IOP 15. The strongest intensities of the gradients are observed for IOP 5, 2 and 8. In IOP 13 and above all 15, the gradients are very weak. As regard the rotation of the gradients with height, IOP 8 is the only one in which the flow is clearly more southerly at 700 hPa than at 500 hPa. For IOP 2, 8 and 13, the intensity of the gradients increases with height, whereas it remains constant for IOP 5 and 15. IOP 2 presents the most horizontally homogeneous fields. Finally, considering the five synoptical characteristics discussed above, IOP 2 is the strongest and most typical event, whereas IOP 15 is the weakest one.

4. UPWIND AND DOWNWIND CHARACTERISTICS OF THE FOEHN DURING THE FLIGHTS

The mesoscale context is summarized in table 2 through steering parameters that are averaged over the duration of Merlin IV flight, in order to characterize the foehn conditions and compare the events between each other. First, the large scale pressure difference between Vaduz and Lugano and potential temperature difference between Lugano and Vaduz are given, as ruling parameters. Upwind conditions are represented by the Froude number, the mean south wind above Lonate, at 5000 m. Crest conditions are represented by the mean horizontal wind above Julier Pass (3600 m ASL) and the mean south component of the wind in Guetsch ground station. Penetration of the foehn in the Rhine Valley is characterized by the south component of the wind in Chur, Vaduz and Sankt Gallen ground stations. The south component of the wind in Saëntis is also specified in the table. Finally, the mean rain rate and cumulated rain along the same flight period in Lugano ground station are indicated.

IOP	2	5	8	13	15
ΔP (hPa)	8.6	6.6	11.8	5.9	5.8
Δθ (°C)	7.7	3.9	9.9	4.9	0.2
Lonate V (ms^{-1})	13.2	5.4	12.3	7.1	3.7
Froude number	0.63	0.16	0.31	0.13	0.14
Julier V ($m.s^{-1}$)	15.6	9.8	12.9	7.5	10.9
Rhine Valley surface stations wind direction (deg)/wind speed ($m.s^{-1}$)					
St Gallen	149/6	243/1.6	36/1.7	204/2.0	208/0.9
Vaduz	169/10.3	225/3.5	325/3.2	216/2.0	327/3.0
Chur	229/5.7	220/4.3	214/ 5.8	211/4.4	211/4.2
Saëntis	184/7.3	233/1.5	203/6.0	226/2.8	211/4.2
Guetsch	167/24.3	164/17.9	188/11.6	166/13.3	168/12.6
Precipitation in Lugano surface station					
rain rate, $mm.h^{-1}$	0.3	0	0.5	0	0
cumulated, mm	2.1	0	2.5	0	0

Table 2 : mean steering parameters of the foehn during the flights.

In spite of the complexity and the diversity of the situations that were observed when studying the five events separately, table 1 stands out some important features. First, IOP2 foehn event of 19 September 1999 is the most important event in the valley. It corresponds to the greatest south component of the wind upwind, and is the only event with an exactly southward incident flow. The pressure difference between Lugano and Vaduz is about 9 hPa and the potential temperature between Vaduz and Lugano is about 8K. The IOP8 event of 20 October 1999 is also quite a strong event, with an even larger pressure difference (12 hPa), and potential temperature difference (10 K). The flow is more SW oriented, and weaker upwind and downwind. These two events are the only ones among the five which are associated with rain in Lugano, during the flight period. They are associated with the largest Froude numbers, in particular in the case of the strongest IOP 2 event, in which it reaches 0.6. The three other IOPs 5, 13 and 15 have weak Froude numbers about 0.15.

The wind in Guetsch ground station is always stronger than in the other stations, because of its location in a high pass. It is quite well correlated to the upper level upwind south component. Rather weak in the 4 other events, the wind in St Gallen (north part of the valley) seems to be sensible to the strong IOP2 event. On the opposit, the wind speed at the close-to-ridge Chur ground station seems not to depend strongly on the intensity of the event, just increasing from 4 to 6 $m.s^{-1}$ from a weak to a strong event.
These results show the spatial inhomogeneity of the penetration of the foehn.

5. ANALYSIS OF THE FOEHN-INDUCED TURBULENCE WITH AIRCRAFT DATA

The synthetic results of the turbulence analysis of the five foehn flights has been elaborated through the analysis of filtered kinetic energy and the dissipative scale, which will be discussed here. The TKE (Figure 15a), which is the half the sum of the variances of the u, v, w components, has been calculated with the high pass 5-km filter. The energy removed in the 5-km filter quoted above can correspond to un-stationarities induced by the mean flow, by the spatial evolution of the turbulent structure, or by coherent vorticies. The ratio of the raw data divided by the filtered data can characterize this un-stationarities. The highest this ratio, the less stationary the series are. During MAP foehn events, it could reach the value of ten, which had not been

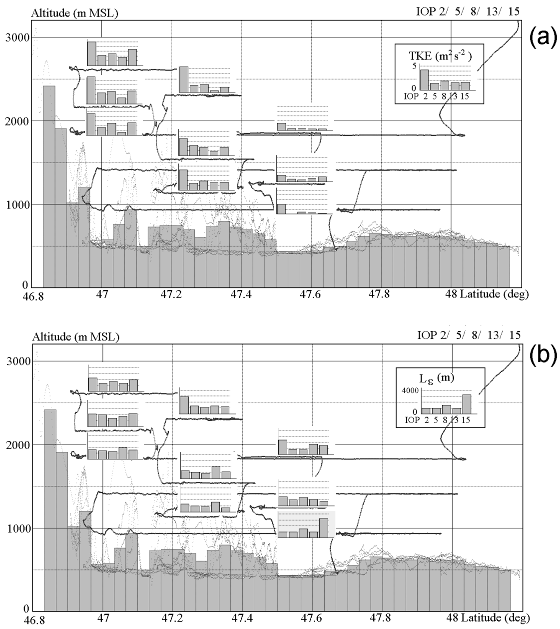

Figure 3 : (a) Turbulent kinetic energy calculated with 5 km high pass filter from aircraft data and (b) turbulent dissipative length scale, found above the Rhine Valley on each transverse leg during the five flights.

observed until now. The dissipative turbulent length is calculated by the ratio of TKE powered 3/2 divided by TKE dissipation rate ε. Figures 3 a and b display the histograms of the TKE and dissipative length scale, found in the transverse legs (see the flight plan Fig. 1). The value of one of this parameter is given for each of the flight in each histogram.

The TKE field in Fig. 3a shows that the IOP 2 event is the strongest event as regard the turbulence, agreeing with the analysis of the mesoscale field described in previous paragraph. Both IOP 8 (October 20) and 15 (November 05) events reveal moderate turbulent kinetic energy. For every event, turbulence is maximum close to the mountain ridge and decreases with the distance northward.

If figures Fig. 3a showed the heterogeneity and complexity of the two-dimensional structure of the flow within the Rhine Valley, Fig. 3b shows that the dissipative turbulent length remains quite homogeneous in space and over the events. It can mean that the production of TKE and the dissipation occur at the same place. Its value, of the order of 1000 m, is the same order as the usual values found within homogeneous boundary layer. This parameter seems therefore to remain a relevant parameter to use in modeling the boundary layer even in the case of complex terrain.

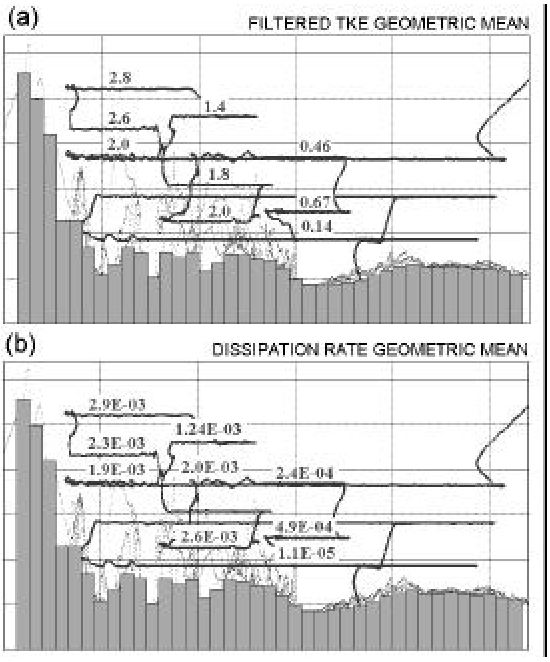

Figure 4 : Geometric mean of (a) the turbulent kinetic energy and (b) the dissipation rate, calculated from the 5 km scale turbulent kinetic and dissipation rate of the five events.

Finally, Fig. 4 presents the geometric average of the 5 km-filtered turbulent kinetic energy (Fig. 4a) and of the dissipation rate (Fig.4b) over the five cases, in order to display the general two-dimensional structure of these turbulent parameters. The geometric average aims at attenuating the extreme values. It shows how the turbulent plume extends from the mountain ridge down to the north, and emphasizes the spatial correspondence between the production of turbulence and its dissipation. This result seems important for the understanding of the mechanisms of the turbulence in complex topography.

6. CONCLUSION

The objective of the study was to investigate the foehn-induced turbulence. This study was based on the data obtained during MAP experiment on five foehn events. For this study, the atmospheric turbulence induced by the foehn has been investigated from Merlin IV aircraft data. The context of the flights, that is the characteristics of the foehn during the flight, has been described by steering parameters calculated from the data of experimental means such as radiosoundings, surface stations and profilers, from places just as well upwind as downwind of the flow.

To synthesize the results for the five foehn flights, each foehn event has primary been characterized during the flight by the value of steering parameters such as Froude number, cross-alpine pressure gradient, wind intensities upwind, at the crest and within the valley. This characterization has been compared to the 5 km filtered turbulence parameters.

The main results of this synthetic study are the following ones:

- The strongest events, relative to the wind and thermodynamics effects, are associated to the strongest turbulence.
- The turbulence is non-homogenous and un-steady.
- Third, the dissipative turbulent lengthscale is homogenous in space and for the five events.
- The production and the dissipation of the turbulent kinetic energy occur at the same place, with a maximum close to the ridge, at the top of the lower layers.

The two last results should allow to better understand the foehn-induced turbulence and to improve its parameterization in forecasting models.

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