OROGRAPHIC FLOW IN THE VICINITY OF THE ALPS

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Summary: In the first part the flow patterns of moving air in the vicinity of a mountain range are discussed from the synoptician's point of view (P. Rauh).
The second part is dedicated to the ECMWF model performance: how well does it forecast the air flow near the Alps (A. Rubli).

1 INTRODUCTION

Compared with the already complicated flow patterns of water around an obstacle the movement of air around and over a mountain or a range of mountains is extremely complex. ALPEX - the well known experiment on the flow over the Alps - was aimed to increase the knowledge and understanding of this flow. There is still a lot of research going on. Here we are not dealing with the problem of Alpine flow patterns on a research level but on the level of the forecaster who is confronted with the synoptic features which are initiated by the fact that the Alps disturb the air flow over central Europe.
The paper is divided into a first part on the basic synoptic features observed in the vicinity of the Alps and a second part showing how the current model deals with the problem.

2 OROGRAPHIC FLOW IN GENERAL

When a stream of air hits a mountain range like the Alps there are three possible consequences:

- the air stream is divided in two parts which flow around the obstacle
- the air is forced to flow over the top of the obstacle
- both possibilities occur

2.1 Flow around a mountain range

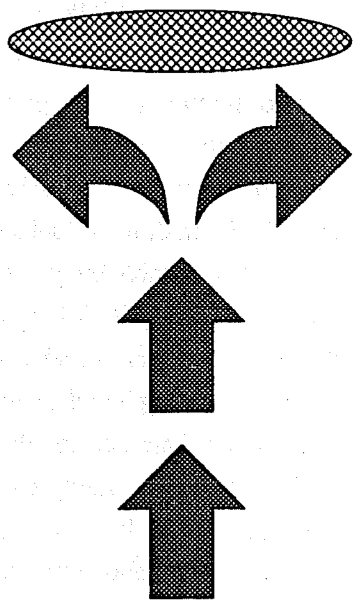

Fig. 1 Flow around a mountain range that lies at right angles across the wind.

If the mountain range lies at right angles to the flow, the lower part of that air stream is divided and forced to flow around the obstacle. Now we look at the curvature of the two arms of our flow pattern. The left arm is cyclonically curved, the right half is anticyclonically curved. Cyclonic curvature means ascending vertical motion, anticyclonic curvature means descending motion. Any frontal system which is carried with this air stream and hits our mountain range head on is torn apart. The left part stays under the influence of ascending motion which means more cloud and heavier precipitation, the right part is being dried out by subsidence: cloud and precipitation decrease. For the forecaster it is of vital interest to know where the flow is divided and under which influence his area is going to be (Fig. 1).
A mountain range which is streamlined and lying parallel to the air stream divides the flow more or less undisturbed by turbulence. If we consider what happens to the flow at an altitude of about 3000 m or 700 hPa - that is the height below quite a number of the Alpine peaks - we expect that the side of the air stream which passes along the mountain range is subject to a negative acceleration due to frictional

forces. This means that the Coriolis force decreases and we have an ageostrophic component changing the direction of the flow. Over Europe and the whole northern hemisphere this means a rotation to the left. In the case of awesterly flow split by a mountain range extending in the west - east direction we observe along the northern slopes an ageostrophic component away from the mountain range converging towards the flow not influenced by the friction. Along the southern slope we expect the opposite. The model flow should react the same way, provided the model orography reaches the heights of the real topography but of course we all know, in reality it does not.

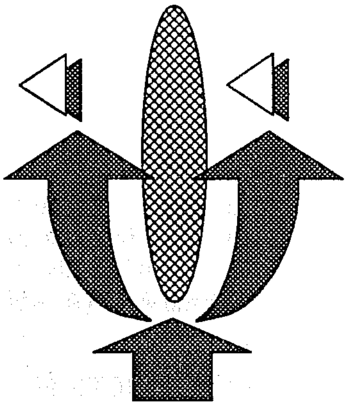

Fig. 2 Flow along a mountain range.

2.2 Flow over the top of a mountain range

Mountain ranges are never ideally streamlined and there is always some air being pushed against the mountain slopes or into a valley. If it cannot escape to the side or downwards it is forced to go over the top. On the windward side of any mountain range we therefore observe some ascending air. Ascending air is cooled either at the dry adiabatic lapse rate - if unsaturated - until it reaches the dew point temperature or at the saturated adiabatic lapse rate when condensation is taking place. Clouds are being formed or intensified and so is precipitation. We call this the barrage effect (Fig. 3).

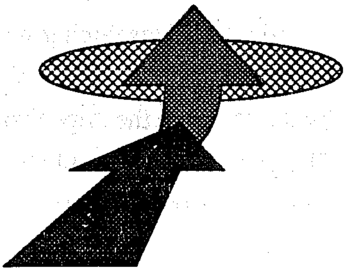

Fig. 3 Flow over the top of a mountain range.

On the lee side of the mountain range the descending air warms at the dry adiabatic lapse rate as soon as the clouds are disolved. We are talking of the foehn effect. If the temperature is known at the top of the range one can easily work out the temperature of the air when it reaches the foot of the mountain. Of course the model is doing the same but only with the height difference it is based on the model orography.

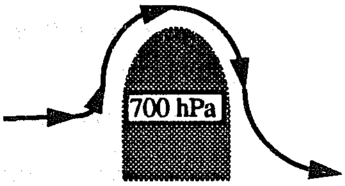

Fig. 4 Profile of flow over the top of a mountain range.

2.3 Flow both around and over the top

ALPEX has shown that in reality probably always both happens: flow around the mountain range well below the peak level and flow over the top in the upper part. The air mass which is forced to flow over the top is not usually from the lowest layer on the windward side as indicated in the traditional foehn models we learnt at school. Either owing to a thick and stable body of cold air in the lower layers or for dynamic reasons it is the 850, 700 or even 600 hPa air mass that is lifted over the ridge and then warmed as well as dried by katabatic processes when descending into the depth of the foehn valleys. Here again stable layers of cold air can stop the descending airmass from rushing along the bottom of the valley causing gusty winds and conditions like a fierce hair dryer. In many cases the foehn winds stream several hundreds of meters above the ground away from the mountain range. It often leaves the boundary layer practically undisturbed where as above a marked temperature inversion, strong winds are prevailing causing low level wind shear.

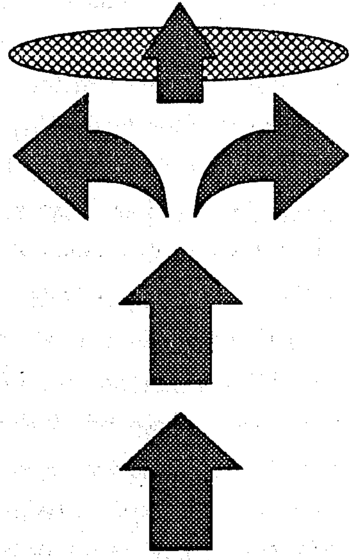

Fig. 5 Flow around and over the top of a mountain.

3 ALPINE FLOW PATTERNS

Since the Alps are neither stream-lined nor a nice ridge with a straight axis but a rather rugged range shaped a bit like a croissant the application of the above thoughts is not so simple as it may have sounded. Three typical flow patterns are chosen to show the relevance of an accurate flow forecast.

3.1 Northerly flow

Stronger winds from a northerly direction - westnorthwest to northnortheast - heading towards the Alps cause a barrage situtation with ascending air in those areas where the jet core is at about right angles to the ridge axis and - at lower levels. It also causes a splitting of the flow around the Alps creating Mistral in the French Rhone Valley and eventually a lee cyclone over the gulf of Genoa.

South of the Alps strong and often cool gusty winds swoop down the valleys, bringing clear skies and sweeping away the intense haze of the moist Mediterranean air covering the plains of the river Po.

With a favourable wind speed and direction [500 hPa: 20 - 40 knots from 290 - 350 degrees, anticyclonic curvature and geopotential above average, north-south surface pressure gradient 2 - 5 hPa and no lee cyclone yet, (Käslin, 1991)] and enough influence of the subsidence on the cloud cover north of the Alps daring balloonists attempt to cross the Alps from north to south. They expect an accurate wind forecast.

3.2 Westerly flow

This direction is for many parts of the Alps more or less parallel to the ridge axis. North of the Alps westerly foehn occurs, partly owing to the lee effect of the 1500 m high Jura mountains partly due to the ageostrophic effect described on the previous page.

Two interesting but totally opposite effects are observed in different inner Alpine valleys: while the Rhone valley above Lake Geneva is open only to winds blowing from 260 - 280 degrees carrying moist polar air masses (and clouds as well as precipitation) all the way up the valley, the area of the Grisons with the valleys of the Alpine part of the river Rhine is completely sheltered from cloud and rain in this situation.

The Canton Ticino on the southern side of the Alps enjoys the katabatic shelter of the French part of the Alps.

3.3 Southerly flow

Barrage for our southern territories, frontal precipitation in the Geneva area and foehn winds in the Alpine valleys of the four major rivers Aare, Reuss, Linth and Rhine - with these features we could summarise the classic foehn situation for Switzerland.

Using pressure gradients rather than wind direction and speed or the position of the 500 hPa trough axis and the flow pattern at 850 hPa our machine applies daily a fairly simple but surprisingly helpful routine we call the Widmer Foehn Index [$I_w = x_1 + x_2 > 18$, where x_1 = 850 hPa gradient and x_2 = 500 hPa gradient (Widmer, 1966)]. It gives the forecaster an objective, transparent and clear indication at what time within the next four days (based on the date of the model analysis) he may expect the break-through of the foehn winds at the automatic station of Altdorf in the lower part of the Reuss valley, a bit south of the upper end of Lake Lucerne.

The original index developed by Widmer based on the principle of the perfect prognosis and used real-time or even past data for a short range forecast. Later it was adapted to numerical products and since then it can be used in the short and medium range of the time scale of weather forecasting.

Of course the effect of the expected foehn wind on the cloud cover and the distribution of precipitation is still open to the judgement of the forecaster but at least he has a useful tool to time the onset and the end of the foehn wird itself.

It goes without saying that the success of this statistical tool depends entirely on the accuracy of the numerically forecast flow pattern in the vicinity of the Alps.

4 THE REPRESENTATION OF THE ALPS IN THE ECMWF MODEL

The model represents the Alps as a smooth ridge (Fig. 6). Valleys, small planes and isolated mountains in the Alpine foreland are not resolved. The "Jura" mountain range, in reality geographically clearly separated from the Alps, is part of the main Alpine range in the model orography. The French "Massif Central" is represented by the model, but it is connected to the Alps by a less elevated ridge, causing a barrier in the Rhone Valley to the south of Lyon. The highest peaks of the real Alps are located in the French Alps near the Italian and Swiss border with an elevation of up to 4800 metres above sea level. The highest part of the model Alps is placed further to the east with a height of approximately 2700 metres. On the other hand, the model tends to spread the Alpine slopes into less elevated land.

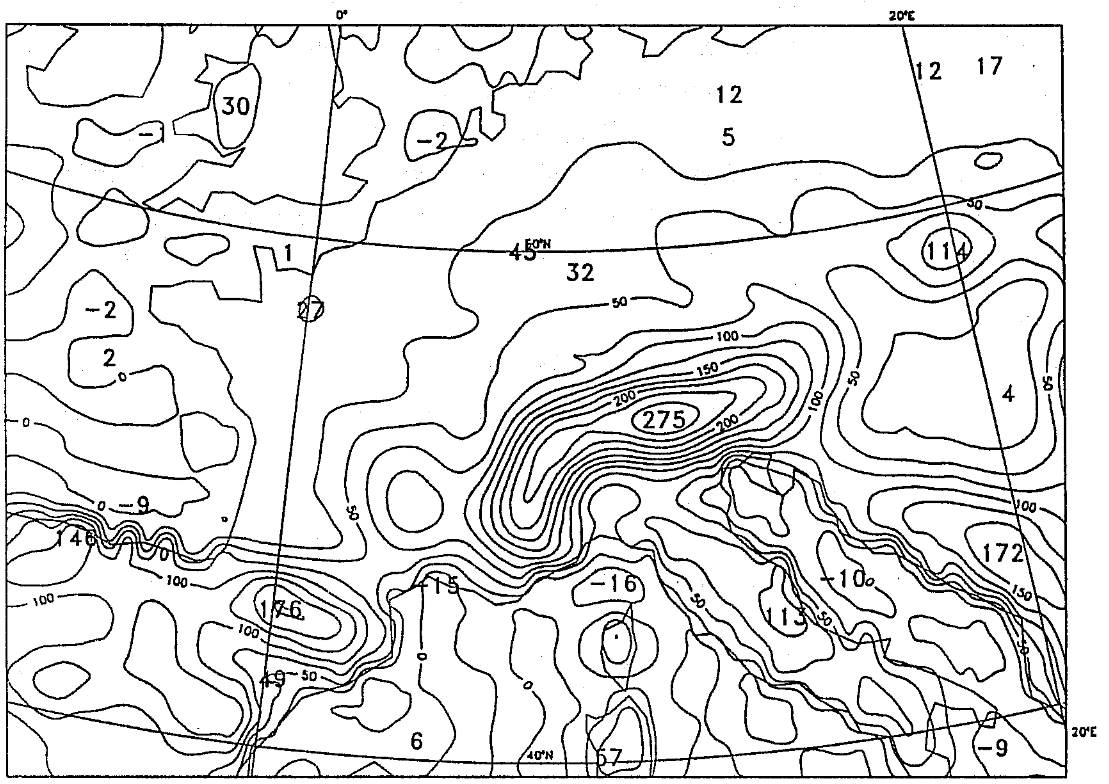

Fig. 6 ECMWF T213 model orography. Isoline intervals are 25 dam.

5 NORTH WESTERLY FLOW

5.1 Alpine Trajectories

One of the important questions concerning the flow in the vicinity of the Alps is whether the air goes over or around the mountain range. This problem has been widely discussed in the context of ALPEX by Smith (1982), Wen-Dar Chen (1987), Jaeger (1992) and others. Wen-Dar Chen observed that the flow tends to split, i.e. trajectories would go around the Alps near Lyon in the west and Vienna in the east, but by various degrees and not in all cases. In general terms the ability of an low level air parcel to cross a mountain range depends on its velocity, the stability of the air mass and the horizontal and vertical scale of the mountain range. From RASOND data Binder (1989) estimated the climbing potential of an air parcel approaching the Alps. This investigation suggests that the flow is likely to pass over the mountain shortly behind a passing cold front, when the winds have turned to north west and the air mass is still in an unstable state.

In order to demonstrate the flow as analysed by the ECMWF model analysis, surface trajectories for the case of 15-17 April 1992 have been computed using the SMHI (Kallberg 1988) 3-dimensional trajectory program.

ECMWF analysis wind and vertical velocity fields were used as input data. The synoptic situation was characterized by a cold front which crossed the Alps on April 15. The starting times for the trajectories were chosen after the cold front passage on April 16 at 06UTC when the air mass was at maximum instability and 18 hours later on April 17 at 00UTC when the air mass was stabilized due to subsidence. The starting points (i.e. the releasing points of virtual air parcels) of the trajectories were at 48N/0E, 48N/2E, 48N/4E, 48N/6E, 48.5N/8E and 49N/10E (Figs. 7 and 8).

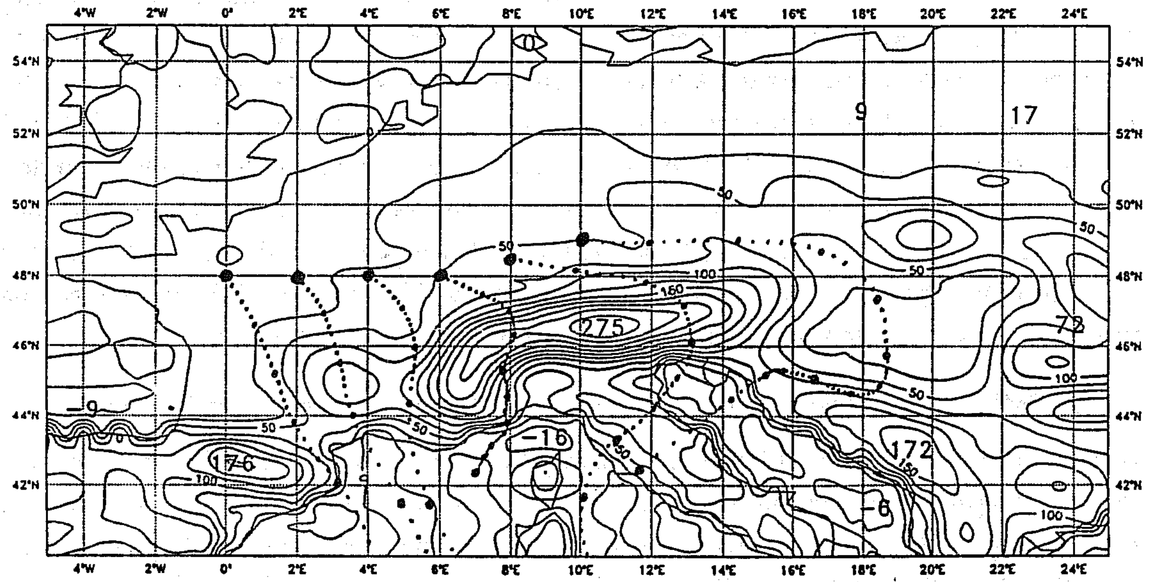

Fig. 7 Alpine trajectories and ECMWF T213 orography (isolines). Database is ECMWF initialized analysis of 16 April 1992 06UTC and following analyses (6 hour steps). Level at start is 1000hPa. Dots represent hourly intervals, filled circles represent 6 hourly intervals.

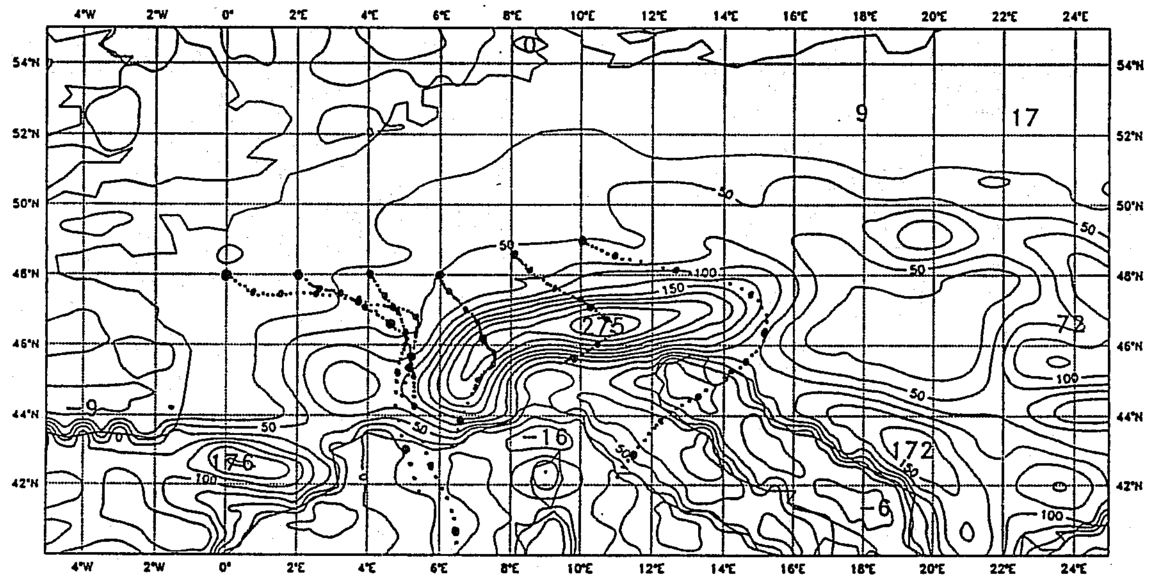

Fig. 8 Same as figure 7, but database is analysis of 17 April 00UTC and following.

At 06UTC (**unstable air mass**) trajectories show little deflection over the massive Central. No **canalization** through the Rhone valley is present. The trajectory starting at 6E crosses the Alps with deflection to the west

during the climbing phase, whereas the trajectories starting further to the east tend to go around the Alps. At 00UTC (stable air mass Fig. 8) a clear canalization through the Rhone Valley is evident. The parcels released at 6E and 8E show little deflection and cross the Alps. Apparently the increased stability at 00UTC does not prevent these parcels from crossing the Alps, though their speed is slowed down compared with the parcels released at 06UTC from the same position. On April 17 at 00UTC Swiss observation stations north of the Alps (elevation between 500 and 1500 metres above sea level) reported easterly winds of considerable strength. Direction and velocity of these winds are influenced by mesoscale effects (canalization between Jura and Alps). Nevertheless, it is rather surprising that the parcels released to the east of 4E cross the Alpine crest rather than being deflected to the west and pass the Alps via the Rhone Valley. The model analysis seems to take little notice of the increased stability, as the paths of the trajectories look very similar at 06UTC and 00UTC.
Other authors which used trajectories based on observations, found that the accuracy of their trajectories was limited due to unevenly spread locally influenced data. Here the trajectories are based on well defined grid point values. The problem is rather whether the analysis deals correctly with the flow in the vicinity of the Alps, since near the Alps there is no proper forcing of the analysed low level winds by the observations. It is, however, by no means clear to what extent in reality the low level flow is deflected to the west.

5.2 The ECMWF forecast with regard to a very strong north westerly current over the Alps

The synoptic situation of December 20-23 1991 was characterized by an exceptionally strong north westerly flow which built up between a high pressure system over the eastern Atlantic and a trough over Eastern Europe (Fig. 9). Large precipitation amounts were caused by continuous warm advection, as the jet was slowly moving across the Alps to the east. Incidentally this event led to a severe threat by avalanches and later, as the temperature was rising, to inundation due to the melting snow. The subjective judgement of the ECMWF forecast maps (Fig. 9) reveals that the model forecast of the pressure field as well as the temperature field was remarkably accurate for the critical time period.

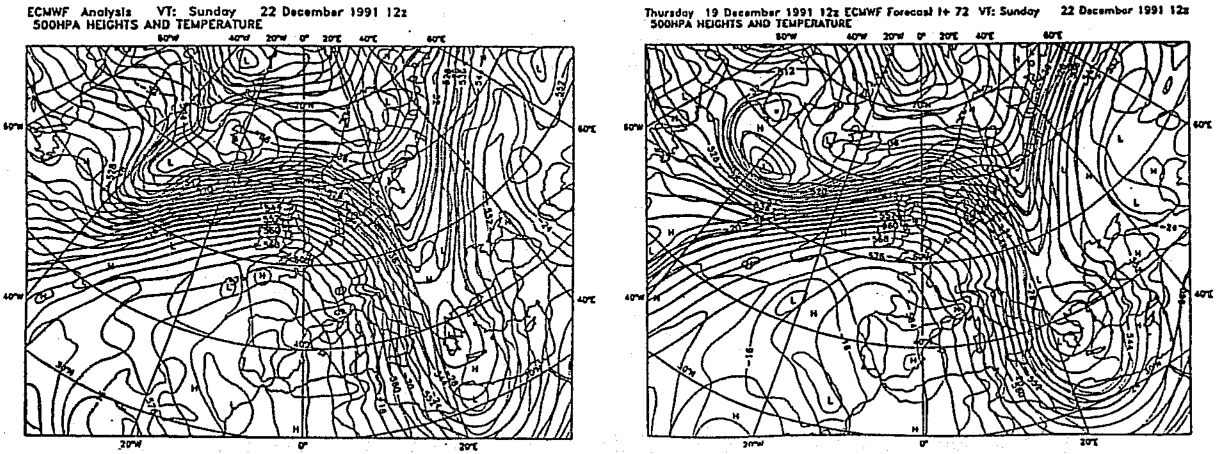

Fig. 9 ECMWF 72 hour forecast of 19 December 1991 (right) and verifying analysis of 22 December 12UTC (left).

The 24 hour forecast vertical velocity field (Fig. 10) shows an interesting downstream wave pattern with a wave length of approximately 300 Kilometres. The phenomena is present in upper levels as well and also in the analysis. Satellite pictures (not shown) from 12UTC give no evidence of the presence of this wave, neither does the ECMWF relative humidity field indicate increased humidity in the upwind zones of the wave. However the infrared picture of 22 December 00UTC shows cloud patches over Italy and the Mediterranean Sea, which could be caused by waves.

If the earth's rotation is neglected, mountain gravity waves propagate only vertically. It was therefore suggested (Jürg Trüeb, personal communication) that the model produces inertia gravity waves, a concept which includes the earth rotation.

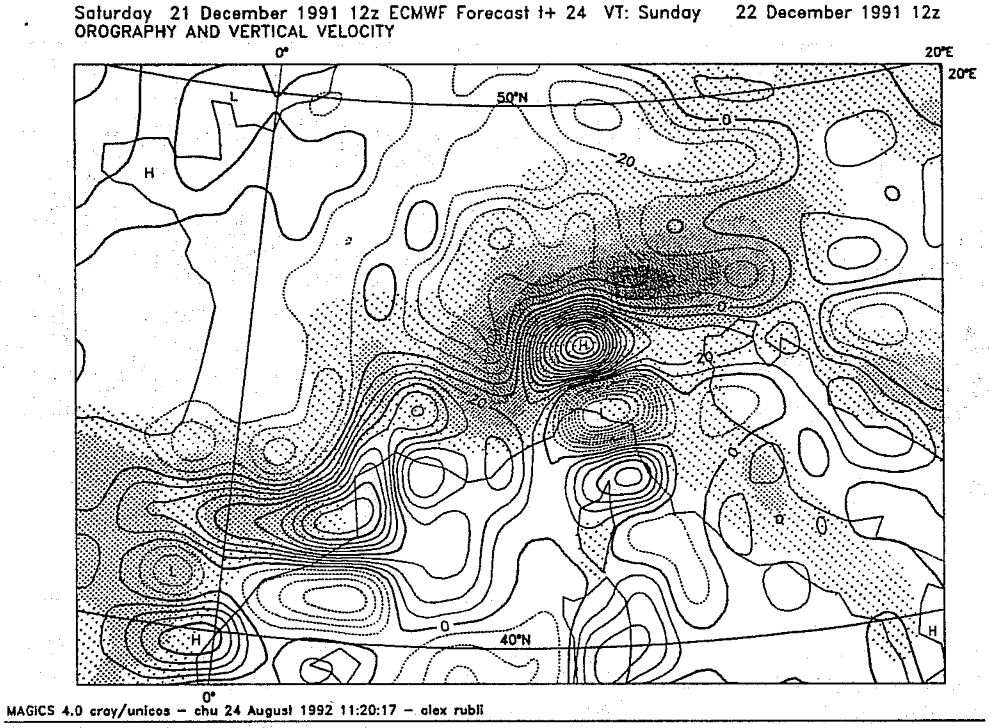

Fig.10 ECMWF forecast 850hPa vertical velocity pattern (isolines) and ECMWF T213 orography (shaded). Isolines are 10hPa per hour intervals, dotted lines mean upward motion, solid lines mean downward motion.

6 SOUTH WESTERLY FLOW

The main phenomena associated with a southwesterly flow over the Alps are heavy precipitation on the southern slopes of the Alps and "Foehn winds" in the northern mountain valleys.

The Foehn is a mesoscale feature. It can not be forecast directly by the ECMWF model. There are, however, indirect methods to forecast the appearance of Foehn with the use of the synoptic scale pressure fields. The Widmer Foehn index used at the Swiss Meteorological Institute has proved to be very useful in this respect. This shall be demonstrated with a typical Foehn-case which occurred between 30 March and 1 April 1992, when a low centred near South West England caused a moderate south westerly flow over the Alps: The mountain valley station Altdorf recorded Foehn between 30 March 13UTC and 31 March 13UTC. The main characteristics of Foehn are abrupt turning of the wind direction from north to south at the beginning of the Foehn in connection with increased wind speeds and relatively high temperatures with only little night-time drop (Fig. 11). The critical value of the Foehn index in spring is 21 points. The Foehn-index calculated from the ECMWF analysis fields indicates the occurrence of Foehn from 16UTC onwards, which is 3 hours after the actual occurrence (Fig. 11). This is mainly due to second order effects like the degree of stability of the air mass. The Foehn index which is based on the forecast of 28 March is nicely in agreement with the analysis Foehn index, and also with the actual events. The Foehn index is tolerant against minor forecasting errors. This is one of its strong points.

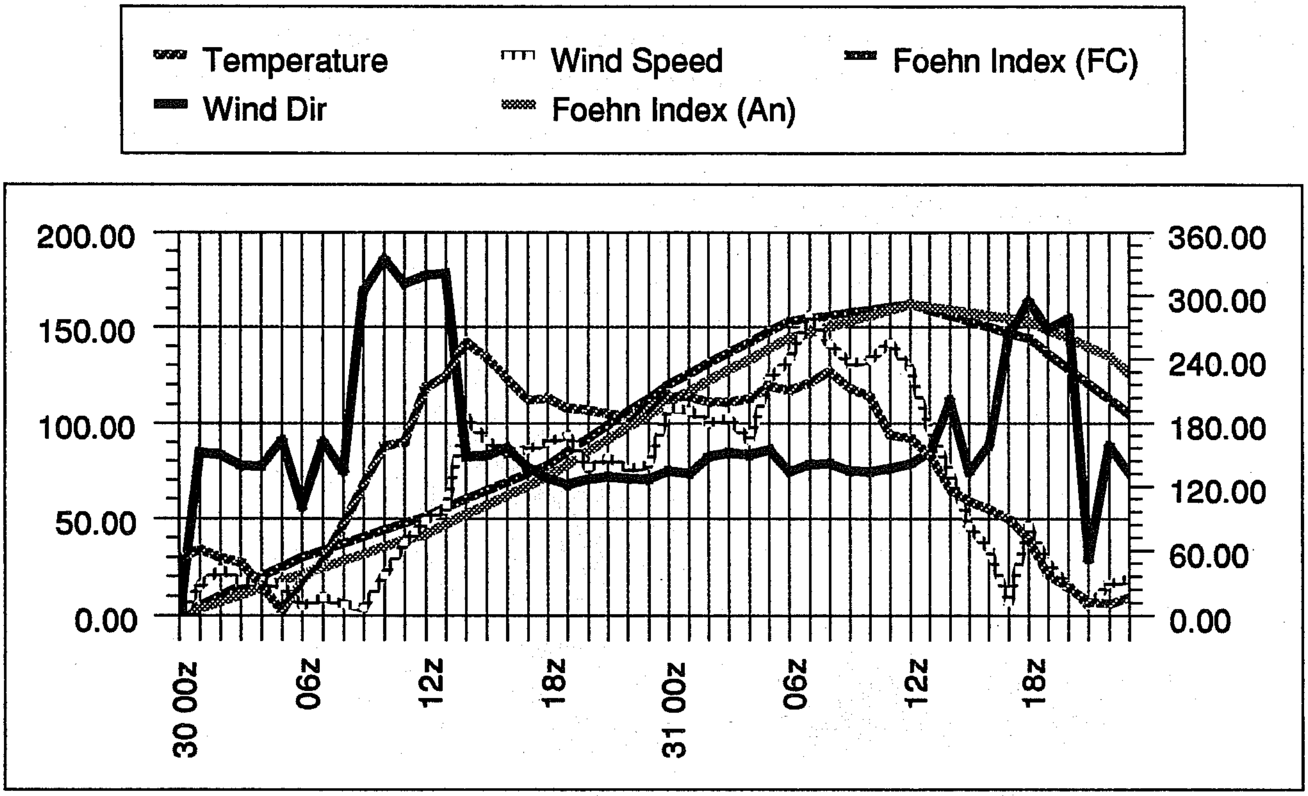

Fig.11 Time series of wind direction (degrees, left axis), wind speed (1/10 m/s) and temperature (centigrades) as recorded in Altdorf (Switzerland) between 30 March 1992 00UTC and 31 March 23UTC. Also displayed: (scaled by three) Foehn index values calculated from ECMWF analysis, respectively ECMWF forecast of 28 March 1992.

Heavy rainfall in the southern parts of the Alps has been recorded in many cases with a south westerly flow. Humid subtropical air can be forced to rise for several days at the southern slopes of the Alps bringing continuous rain. These cases are rather easily foreseen with the knowledge of the forecast pressure fields, as small scale features like the characteristics of the local air mass play a minor role.

Extremely large amounts of rainfall can be caused in connection with Atlantic cold fronts during Summer time (Spinedi 1992). In and ahead of the frontal zone often violent thunderstorm activity takes place. In these cases a successful forecast is not only based on the knowledge of the synoptic scale pressure and temperature fields at the time of the occurrence, but also on the careful consideration of the stability, humidity and temperature of the expected air mass. These properties are rather inaccurately forecast by the current synoptic scale models.

7 CONCLUSIONS

Trajectories have been used to demonstrate analysed low level flow, crossing the Alps from the north west. Canalization through the Rhone Valley has been evident and also deflection of the winds to the east. There was, however little deflection of the flow to the west, around the western edge of the Alps. Whether this is a deficiency in the ECMWF analysis can not be assessed without detailed knowledge of the real low level flow.

In an exceptionally strong flow the ECMWF forecast and analysis propagate mountain gravity waves downstream. These waves can be interpreted as inertia gravity waves.

Southwesterly flow over the Alps can cause strong mountain valley winds as well as heavy precipitation in a small area. To a certain extend both mesoscale features can be predicted with the knowledge of forecast synoptic scale pressure and temperature fields.

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