Swiss Federal Institute of Technology Zurich (ETH)

Institute for Atmospheric and Climate Science

semester thesis

Relation between low level inflow and heavy precipitation in Southern Switzerland

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Contents

Abstract

In this study, precipitation events in Ticino are analysed with the Monte Lema Doppler radar and a rain gauge network. Heavy precipitation events in the southern Alpine region are usually due to a trough west of the Alps with a strong low level flow from south-southwest to south-southeast bringing moisture laden air towards the southern slopes of the Alps. A relation between the direction of the low level inflow towards the southern Alps and the rain rate and between the wind speed of the low level inflow and the rain rate could be proven with the use of only Lema radar data and synoptic weather charts. It would be useful for the operational service of the MeteoSuisse to have a heavy precipitation nowcasting and warning system, to be able to react early on natural hazards like floods (often observed in autumn in Ticino) or debris flows (mudslides). It could be shown, that the amount of daily rain is depending on the inflow velocity component perpendicular to the slopes (v-component). This velocity component can be gained from the Lema radar or in advance from the LM (Swiss local model) forecast.

Chapter 1

Introduction

1.1 Motivation

Weather radars can not only be used to localize humidity and precipitation in the atmosphere, but also to derive the wind field of a humid airmass. In this semester thesis observations from the MeteoSwiss radar on the Monte Lema and a MeteoSwiss ANETZ rain gauge network are used to confirm or reject the hypothesis, that precipitation amounts in Southern Switzerland (Ticino) are related to the direction and intensity of the low level inflow coming from the Po-Valley and moving towards the Alps. This presumption was already confirmed by Grebner and Rösch (1998) and Medina, Houze and James (2001), but not with the use of only Lema radar data.

An upper level jet from southwest an a humid and warm low level inflow from south to southeast are a typical constellation for heavy precipitation in Ticino. The aim of this study is to find out whether it is possible to nowcast heavy precipitation events in the Lago Maggiore region with the use of only the Lema radar and the LM forecasts.

1.2 Weather radar basics

A radar instrument (RAdio Detection and RAnging) sends an electromagnetic microwave pulse and measures the backscattered wave. Not only cloud and rain particles can be detected but also several properties of the scattering object can be derived with the Doppler signal such as: number, size, terminal fall velocity and phase (ice, water) of particles or even turbulence. The high spatial (200-1000 m) and temporal (about 20 seconds to few minutes) resolution is a huge advantage of weather radars for measuring mesoscale phenomena (10-100 km) compared to common meteorological networks. The following table shows the most common wavelengths and their designation and usage.

band	frequency[GHz]	wavelength[cm]	usage
L	1.0 - 2.0	15 - 30	wind, eddies
C	4.0 - 8.0	3.75 - 7.5	hail, rain
X	8.0 - 12.5	2.4 - 3.75	rain
K	18 - 26.5	1.13 - 1.67	clouds, haze

1.2.1 The Doppler velocity

Modern radars are also capable to measure the phase shift of the objects echoes which can be used to derive their radial velocity, the so called Doppler velocity. This ability is a powerful means for investigating the dynamics of a precipitation system (Wüest, 2001).

returned phase:

$$\phi = \phi_\circ + \frac{4\pi r}{\lambda} \tag{1.1}$$

phase change:

$$\frac{\mathrm{d}\phi}{\mathrm{d}t} = \frac{4\pi}{\lambda}\frac{\mathrm{d}r}{\mathrm{d}t} \tag{1.2}$$

Doppler velocity:

$$v = \frac{\lambda}{4\pi}\triangle\phi PRF \tag{1.3}$$

where PRF = pulse repetition frequency

1.2.2 The Nyquist velocity

Because larger phase shifts than 2π can not be measured, they can be aliased (folded). The maximum Doppler velocity $\mathrm{v_a}$ can only be detected within a range given by the velocity producing a phase shift of π. Using the PRF, the maximum unfolded Doppler velocity can be written as the Nyquist velocity $\mathrm{v_a}$:

$$v_a = \frac{PRF\lambda}{4} \tag{1.4}$$

The Nyquist velocity can be increased by either enlarging the PRF or the wavelength λ (Wüest, 2001).
The following equation is a universal radar equation which is valid for all radar systems:

$$r_{max}v_{max} = \frac{c\lambda}{8} \tag{1.5}$$

Where $\mathrm{r_{max}}$ = maximum range and $\mathrm{v_{max}}$ = Nyquist velocity. As soon as the radar band is chosen the right side of equation 1.5 and also the product $\mathrm{r_{max}}$*$\mathrm{v_{max}}$ are determined. Now either the radar system is configured with a low range and a high Nyquist velocity or with a high range and a low Nyquist velocity (danger of aliasing). The latter configuration is true for the Lema radar.
The correction of aliased wind information is called dealiasing (unfolding), and can be done either manually or automatically (Wüest, 2001).

1.2.3 Different radar plots

There are several ways to plot the gained radar information:
- A-scope: plot of incoming signal against distance from radar.
- PPI (Plan Position Indicator): polar plot of a 360° rotation with a given constant elevation. Figure 2.2.
- RHI (Range Height Indicator): vertical cross section through space.

- HTI (Height Time Indicator): plot of incoming signal against time with a vertical radar (wind profiler).
- CAPPI (Constant Altitude PPI): polar plot of a 360° rotation with elevation zero, calculated out of several PPIs (horizontal cross section through space). Figures 2.3 / 2.4.

1.2.4 Interpretation problems for radar data

There are some difficulties to get the precipitation intensity from the measured signal due to several error sources, like for instance:
- sphericity of the earth.
- evaporation can reduce the actual amount of rain at surface.
- orographic precipitation can increase the amount of rain.
- objects with high reflectivity can cover precipitation regions behind them (terrain shadowing).
- different air masses have different optical properties (defraction).

One should always remind all these possible error sources for the following considerations.

1.3 The Ticino climate

The following table shows the most important features of the annual climate in Ticino. It is a climate diagram from Locarno with precipitation and temperature distribution. Typically for Ticino are warm and humid summers and cold and dry winters (a mixture between the Mediterranean climate and a climate typical for the Alpine mid latitudes).

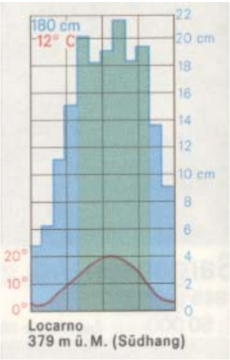

Figure 1.1: climate diagram of Locarno

In the further considerations only the climate of the rainy days will be relevant. The most active precipitation periods are usually from May to October. There are several circulation types which can lead to rich amounts of rainfall in Ticino (detailed discussion in Grebner and Rösch, 1998). Usually there is a trough west of the Alps. Figure 1.2 shows the geographical precipitation distribution depending on the different inflow directions (Grebner and Rösch, 1998).

In general heavy precipitations events in Ticino are often due to a deep baroclinic trough moving towards the Alps. But not every trough does necessarily lead to a heavy precipitation event. In such cases the 500 and 850 hPa upper level flow patterns (geostrophic flow) of events with heavy precipitation are usually quite similar to those without (Medina and Houze, 2003). But the low level flow can differ a lot due to thermodynamic stability. The low level flow

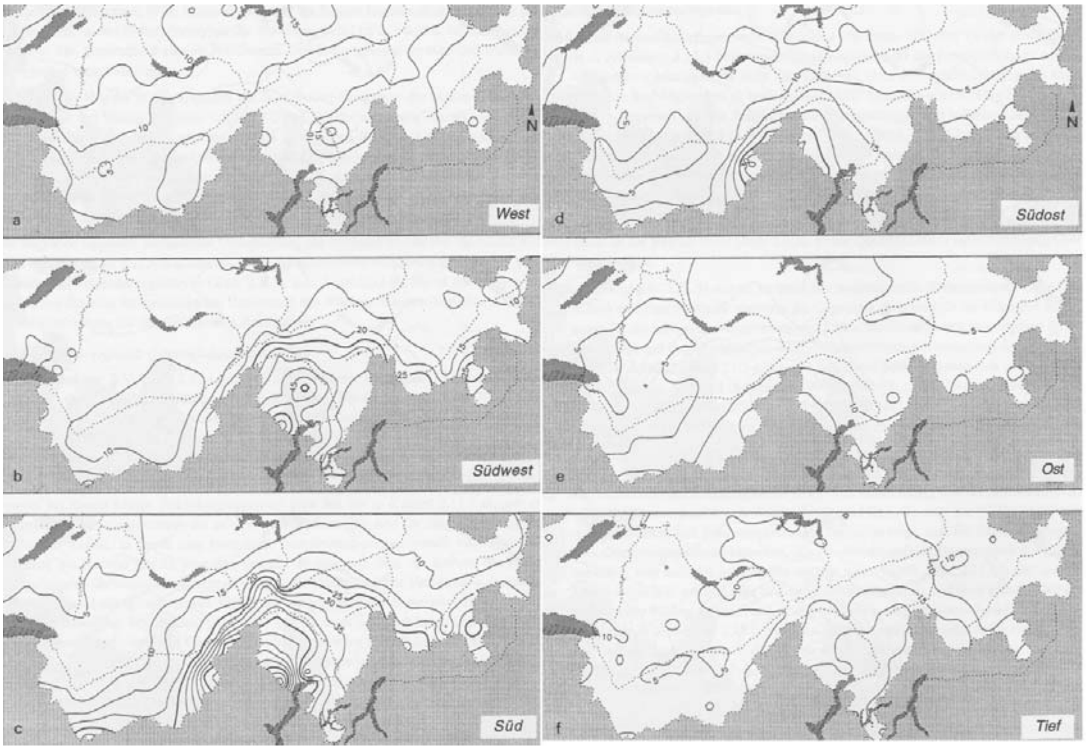

Figure 1.2: rain amounts depending on the inflow direction (Grebner and Rösch, 1998). Dense isohypses show the area of maximum precipitation, which is usually in the western Ticino (around the Lago Mggiore region).

is usually turned a little bit anticlockwise compared to the upper level flow, because of the ageostrophy. Also the topography can effect on the flow direction.

These troughs are propagating eastwards and the largest amount of rain occurs ahead of them, in the so called upstream area. The reason therefore is a strong and moist southerly low level flow ahead of the cold front moving towards the southern slopes of the Alps (Georgis, Roux, Chong and Pradier, 2003). Due to the special concave geometry of the Alps, the southerly flow can be divert and get a southeasterly component in the eastern regions of the Po-Valley. This Mediterranean southerly and southeasterly flow can lead to confluence in front of the southern slopes of the Alps. A confluent flow means convergence with upward vertical movement and convection. The amount of rain due to the convection is depending on the stability of the air mass and microphysical processes. Additionally to the convection due to convergence the orographic lifting effect can also lead to convection and enhances the cyclonic precipitation. So there are thermodynamical, microphysical and dynamical reasons for the occurrence of heavy rains in Ticino. In this semester thesis only the latter are examined.

A similar research was made by Medina, Houze and James (2001), which were using radar data from the Lema radar plus additional radar data from two radars located at lower levels in the Po-Valley. They also included soundings from Milano to calculate the Froude number (*Fr*), a dynamically important non-dimensional number, that combinates the roles of wind speed (U), stability (N=Brunt-Vaisala-frequency) and terrain height (H).

$$Fr = \frac{U}{NH} \tag{1.6}$$

The result of the study was, that a high *Fr* means an unblocked condition and the low level inflow can rise directly up the terrain and can lead to an enhancement of the precipitation. On the other hand a low *Fr* (blocked case) causes less precipitation on the slopes and also a different precipitation pattern.

In the following chapter the results of a detailed examination of the heavy precipitation of the 20.8.2004 will be presented. Therefore data from the Lema Doppler radar, gauge precipitation measurements and synoptic flow charts were used.

1.4 The Monte Lema Doppler radar

The Monte Lema radar is an operational radar run by the MeteoSwiss in Ticino. It is a C-band radar with a fixed elevation angle (tilt) sequence of 20 tilts per 5-minute period. Since the radar is located at an altitude of 1630 m [1], the 2000 m level is about the lowest available Cartesian grid level (Medina, Houze and James, 2001). There is a negative elevation of $-0.3°$, but it could not be used in this study, because it always indicated too many error signals in the PPI-plots. As a consequence the low level coverage is limited for this study.
The reflectivity data undergo rigorous quality control. To classify echoes as either clutter, system noise or precipitation a decision tree algorithm consisting of several filters and thresholds is used (Medina, Houze and James, 2001). The Doppler data on the other hand is filtered less restrictive because it is not used for commercial products by now but only for scientific research.

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[1] All heights quoted in this study are above mean sea level.
All time indications are done in UTC.

Chapter 2

Case study of the heavy rain event on the 20.8.2004

The 20.8.2004 was carefully analysed to get a feeling for a possible relation between the low level inflow direction measured by the Lema radar and the precipitation amount.

2.1 Synpotic constellation

On this day there was a line of strong convection stretching from Camedo (Centovalli) to Lavertezzo (Verzasca-valley) which was stationary from about 01:00 until 06:30[1]. This event was characterized by the propagation of a trough moving towards the Alps from west. At the time mentioned above a cold front was approaching the Alpine region and stayed stationary along the Alps for a couple of hours. The upper level flow chart shows a quite strong southwest jet (figure 2.1). In the PPI-plots this strong upper level jet is also detectable with windspeeds of more than 40 m/s (figure 2.2, right). The situation in the lower atmosphere was analysed with PPI-plots with elevations of 0.5° and 1.5°. The problem is that the Lema radar is not able to provide solid meteorological information below a height of 2 km (Medina, Houze and James, 2001). That means that the low level flow can only be analysed at a height of 2000 m. In our case a stationary southerly to southwesterly low level inflow with a windspeed of about 15 m/s was detected. This flow with moisture laden air coming from the Mediterranean was directed towards the southern Alpine slopes. It might have been responsable for the stationarity of the convective line.

After 06:30 this line was getting weaker and was moving south. Responsable for this motion could have been the weaken of the southerly inflow or a northern down-valley return flow inside the deep river valleys. Such down-valley flows usually occur in the early mornings when the atmosphere is most stable. Medina, Houze and James (2001) speculate that the outflow of the down-valley flow from the valleys converge with the synoptic-scale flow and thus enhance the upward air motion and precipitation in the Lago Maggiore region. In our case a down-valley flow could not be detected with the Lema radar. Due to this described synoptic constellation rain amounts of about 100 mm in 12 h (Locarno 103 mm/12 h) were measured in the Lago Maggiore region.

For further investigations the Doppler-velocity PPI-plots of only one particular moment (05:00 / 05:02) with largest precipitation were analysed in detail. Figure 2.2 shows two

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[1] All time indications are done in UTC.
All heights quoted in this study are above mean sea level.

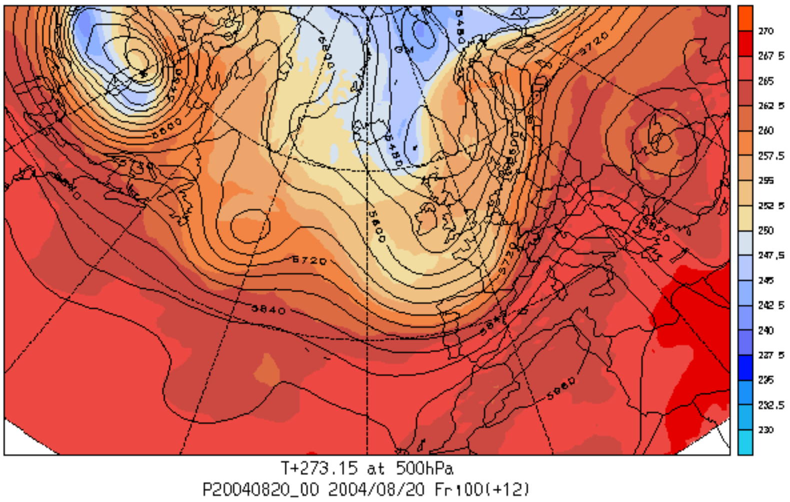

Figure 2.1: 500hPa flow chart: Trough west of the Alps with a strong geostropic southwest flow towards the southern Alps.

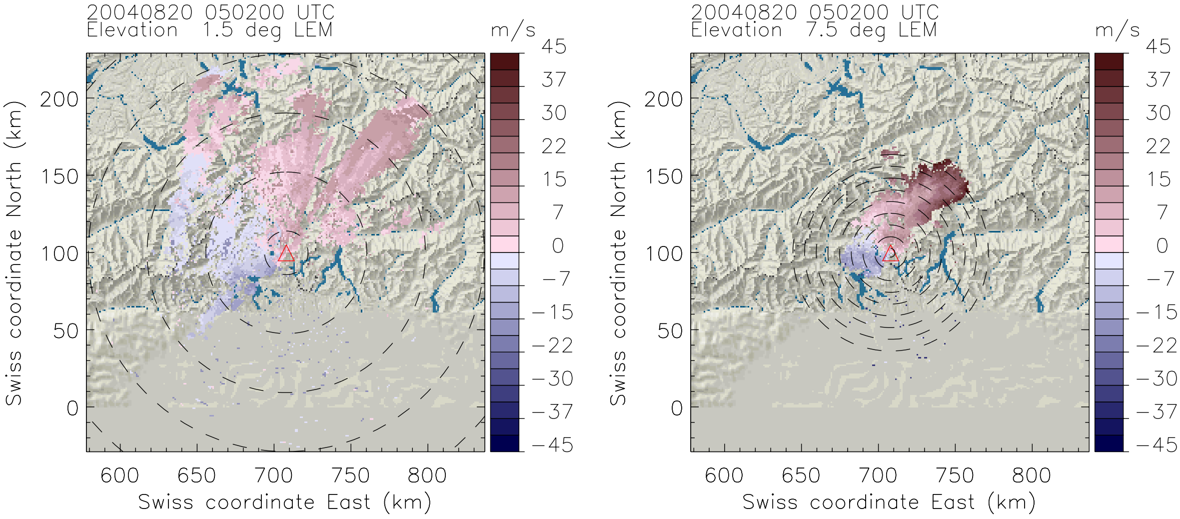

Figure 2.2: Left: Dealiased PPI with 1.5° elevation: Southern low level inflow towards the Alps with windspeed of 15m/s. Right: PPI with 7.5° elevation: Southwestern upper level jet with windspeed of about 40m/s.

elevations which were dealiased manually with an IDL-program. To enhance the precision of the Doppler-velocity field a wind model was used (Wüest, 2001). Therefore a CAPPI had to be generated first. Any additonal information about the wind can be put in the wind model program to increase the accuracy of the wind field. In our case wind speed and wind direction had been estimated out of the PPIs. The result is a PPI-plot with an additional wind field shown by arrows (wind vectors) (figures 2.4 / 2.5). Figure 2.3 shows a VAD (velocity azimuth display), a plot that gives information about the wind speed (velocity) and its direction (azimuth) on the different height levels. The VAD is plotted as a hodograph.

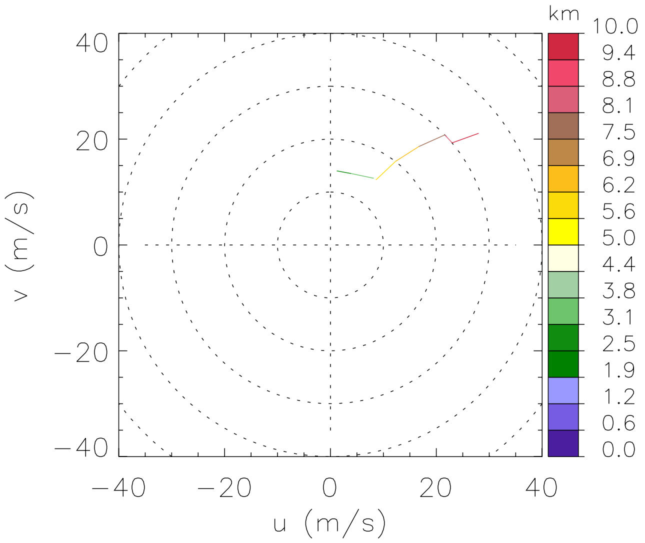

Figure 2.3: Hodograph of the estimated vertical wind profil (VAD): Low level flow from south with wind speed of about 15 m/s. Upper level flow from southwest with wind speed of about 40 m/s. Flow is turning clockwise with height.

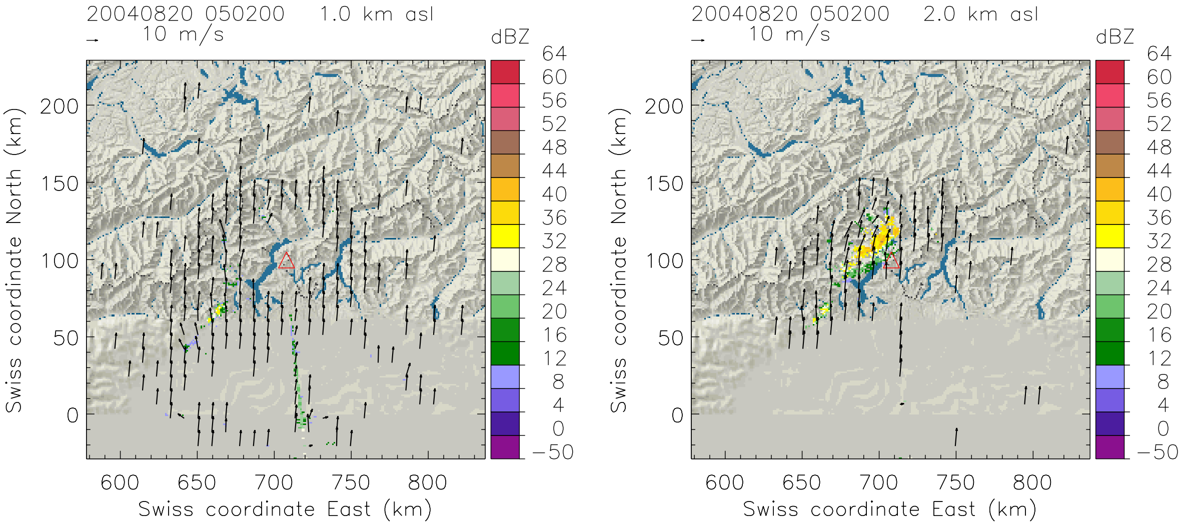

Figure 2.4: Left: CAPPI on the 1 km level: Southerly inflow is visible. Right: CAPPI on the 2 km level: Inflow is still from south.

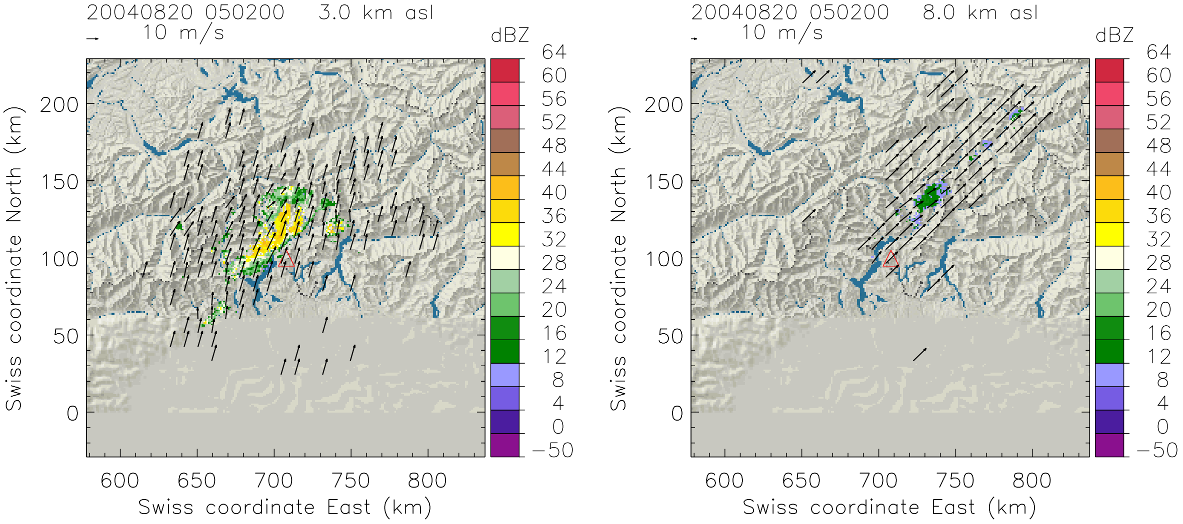

Figure 2.5: Left: CAPPI on the 3 km level: South flow is turning clockwise with height to southwest. Right: CAPPI on the 8 km level: Strong upper level jet from southwest.

Chapter 3

Data analysis

3.1 Data selection

For the study of our hypothesis 40 rain events of the past five years had been analysed. Therefore an IDL-program was written to average the rain gauge data of the ANETZ stations pictured in figure 3.1.

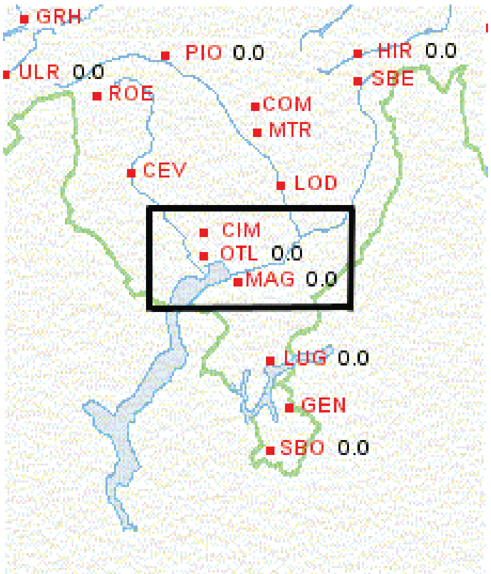

Figure 3.1: All ANETZ stations in Ticino. Only the stations in the square were taken: MAG = Magadino, OTL = Locarno-Monti, CIM = Cimetta.

The chosen stations are all in the interesting Lago Maggiore region, where the precipitation maximum usually occurs or is closest to (see figure 1.2).
The following histogram shows the distribution of the rain events as a function of the rain rate in mm/day (figure 3.2). It is important to mention that mean precipitation amounts per day and not per hour had been examined. To see whether or not there is a correlation between the low level inflow and the rain amount, 20 events with little rain and 20 events with heavy rain had been chosen. Those days with little rain have precipitation amounts of 18 to 30 mm/day, those with heavy rain more than 66 mm/day which is definitely a huge amount. Therefore they can be considered as a heavy rain event, even though there is no

clear defintion for heavy rains. Less than 18 mm/day does not provide enough signal in the reflectivity and Doppler PPI-plots to gain any useful wind information.

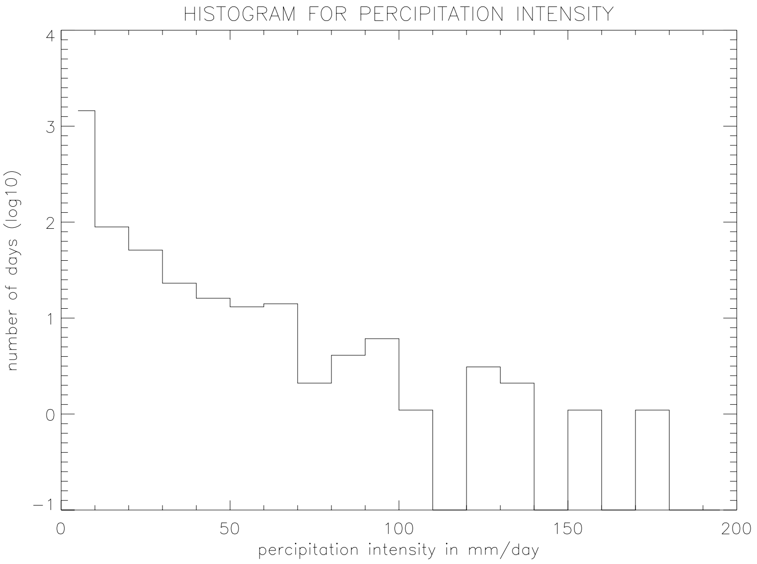

Figure 3.2: Histogram of all days between 2000 and 2004 as a function of precipitation amount. Y-axis is logarithmic.

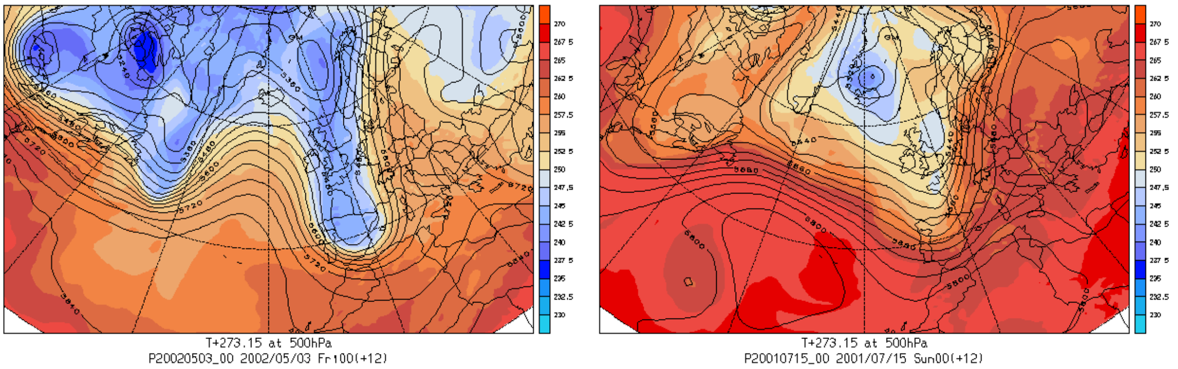

Figure 3.3: 500 hPa flow charts showing a "trough situation": trough in the west of the Alps with an inflow from west to south toward the Ticino.

3.2 Data processing

The 40 days could not be examined as thorough as the 20.8.2004 due to terms of time. Only the 1.5° and the 11° elevations of the Lema radar were analysed and only every hour. Except for the 23.5.2002, which was subdivided into two seperate events, only one moment per day with the strongest reflectivity signal was chosen to examine. In the 1.5° PPI-Doppler-plot the low level inflow direction and wind speed were picked out. The information about the upper level flow is from the 11° PPI. Additionally the 500 hPa flow chart was used to check the synoptic situation and to decide, if it was a trough situation. This explanation of the synoptic situation is very vague and therefore a few examples are shown in figure 3.3. Important is the existence of a trough in the west of the Alps with a flow towards the southern Alps from about west to south. The table 4.1 in the appendix shows the 40 events with their analysed variables.

3.3 Results

It was detected that the correlation between the low level inflow windspeed and the rain rate was less good than the one between the v-component of the low level flow vector and the rain rate. A physical explanation therefore is, that it is the wind speed perpendicular to the obstacle (in our case the v-component) which mainly influences how strong the orographic lifting with orographic precipitation will be (another important factor is the thermodynamic stability). Figure 3.4 shows the rain rates versus the v-component with a regression. The calculated correlation is about $R^2 = 0.54$.

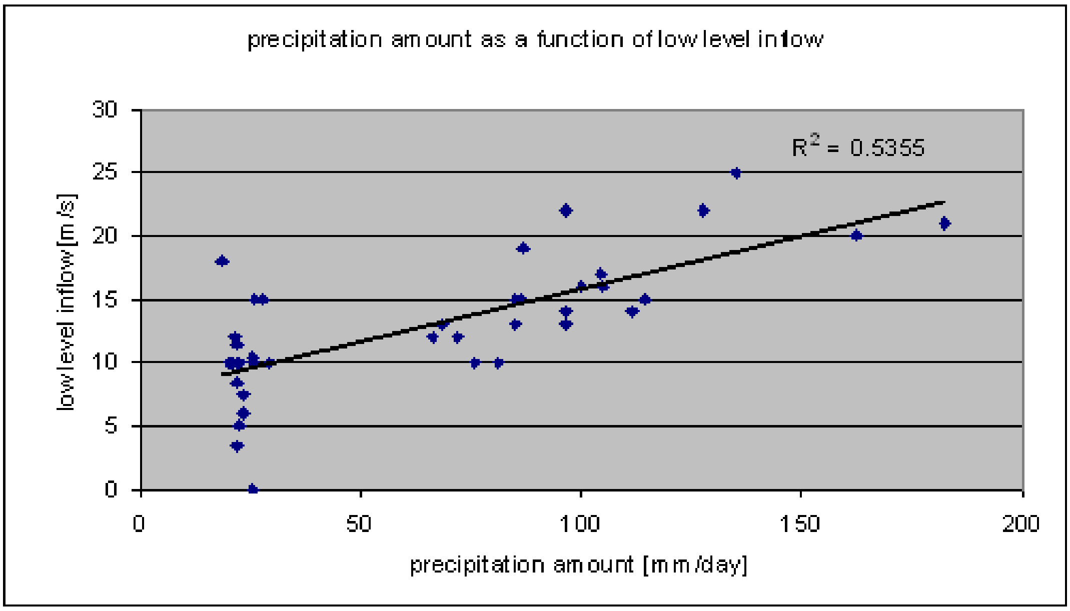

Figure 3.4: Rain rates plottet against v-component of the low level inflow. All events (no filter).

If we only focus on those days with a trough west of the Alps, we have to ignore nine events. This is more or less permitted because only one of them is a heavy rain event. So from the 21 days with heavy precipitation (including the 20.8.2004) only one is not due to a trough passing the Alpine region. If our goal is to find a procedure to nowcast heavy precipitaion, we obviously have to take care of troughs approaching the Alps from the west. Now we get a much better correlation coefficient of about $R^2 = 0.67$ (figure 3.5).

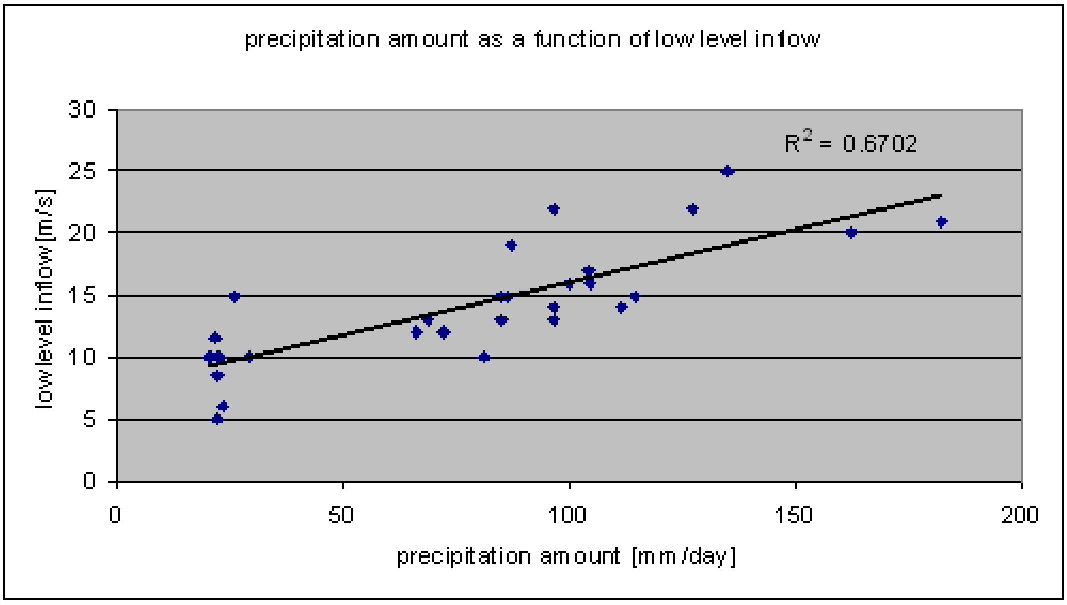

Figure 3.5: Rain rates plottet against v-component of the low level inflow. Only rain events due to a trough passing the Alps from the west are considered.

To get a plot of the rain rates as a function of the low level inflow direction, we divide the flow directions in the following eight classes:
1 = wnw-wsw 2 = wsw-ssw 3 = ssw-sso
4 = sso-oso 5 = oso-ono 6 = ono-nno
7 = nno-nnw 8 = nnw-wnw

The following graphic (figure 3.5) shows quite obviously that low level inflow direction and rain amounts are strongly related. Only *ssw* to so inflows can lead to heavy precipitations (the two events between *sso* and *oso* had a *so* inflow). Of course this graphic would look slightly different if more than only 40 days had been examined.

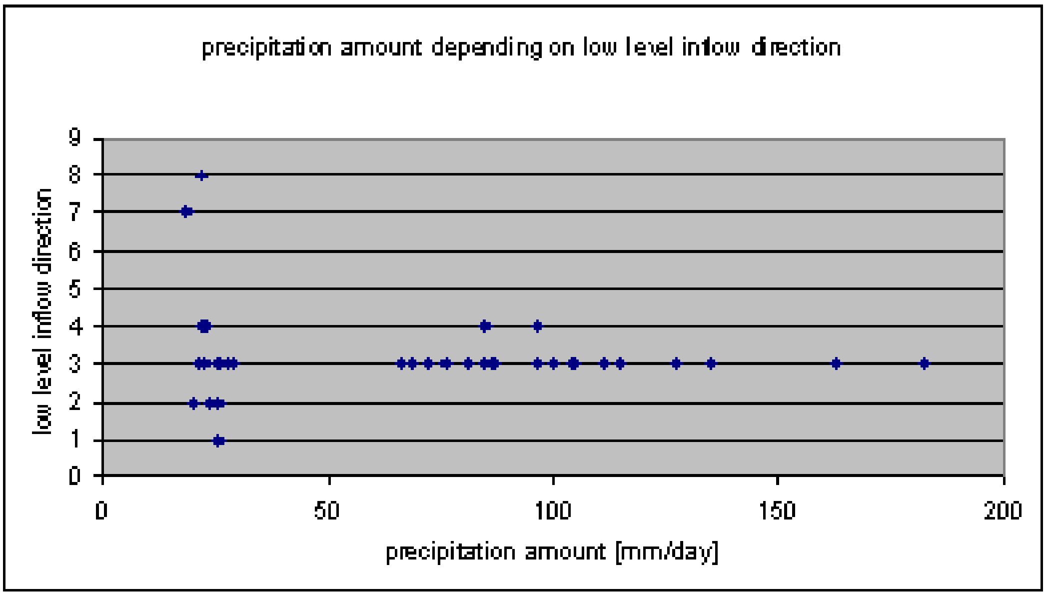

Figure 3.6: Rain amounts plottet against direction of the low level inflow. All events (no filter).

3.4 Errors

There are several possible errors which can modify the result. One of the main errors is, that the Doppler radar provides only the radial component of the wind vector and not the vector itself. This can lead to missinterpretations. A second error is, that even though the measured velocities are very precise, it is difficult to gain the exact wind speed out of the PPIs due to the used colour scale. This can lead to an error of maximum 2 m/s. Another error source might come from the fact that the wind speed and direction changes a lot during one event. Usually the moment with the strongest reflectivity signal was chosen and was averaged with moments a few hours before and after it. Only in one case a one-day-event was seperated into two, because the whole synoptic constellation changed a lot (23.5.2002). Events of more than one day were analysed day by day as different events. To decide whether a vertical wind shearing exists or not is a matter of discretion. It can mean a turning of the wind direction with height or a increasing wind speed with height. Therefore it had not been used for any further analysis.

Chapter 4

Conclusions and outlook

4.1 Conclusions

This study should be seen as a successful first approach to find a method for nowcasting heavy precipitation in Ticino. In most of the cases with heavy rain occurrence a low level inflow from south-southwest to southeast could be detected only by the use of the Lema Doppler radar. Even though all the results have a possible error it should be tried to use them to nowcast heavy rain events in Ticino. A simple procedure to nowcast heavy precipitation events could be the following:

1. *Whenever a trough is approaching the Alps from the west be careful.*
2. *Consult the LM forecast to check if there is a low level inflow from ssw-so.*
3. *Estimate the v-component of the inflow; it has to be more than 10 m/s.*
4. *As soon as the radar provides first Doppler and reflectivity signals, watch out for a low level inflow in the* 1.5° *PPI (the* 0.5° *and the* -0.3° *elevations might also be helpful).*
5. *Release a heavy precipitation warning or forecast.*

Without any indication of a low level inflow in the LM it will be hard to nowcast heavy rain events, because radar data are not useful until the precipitation has already started. But a helpful warning should be released at least a couple of hours in advance.

4.2 Outlook

In a further research forecasted Milano soundings should be evaluated to calculate the Froude number. It can provide additional information about the precipitation amount depending on the flow being blocked or not. Events with a high Fr (unblocked cases) have a potential to enhance the precipitation amount, whereas events with low Fr (blocked cases) tend to lead to less precipitation. There could also be a connection between the temperature of the inflow and the precipitation amount, due to the fact that warm air can hold more water vapour. It might also be useful to study microphysical processes of the origin of precipitation. Different mechanism of rain growth can have a huge influence on the amount of rain.

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Appendix

data	rr	lldir	llsp	uldir	ulsp	ws	trough
26.03.2000	22.5	s	10	ssw	13	×	√
11.07.2000	18.3	n	18	sso	22	√	×
04.05.2001	22.1	sso	12	sso	18	×	√
09.06.2001	111.5	s	14	wsw	25	√	√
02.05.2002	182.4	sso	22	ssw	32	√	√
03.05.2002	162.4	s	20	s	30	×	√
08.06.2002	22.2	so	7	so	10	×	√
15.11.2002	127.4	s	22	ssw	35	√	√
10.03.2004	21.4	sso	14	ssw	20	√	×
08.07.2004	114.6	s	15	ssw	35	√	√
15.07.2001	104.8	sso	18	ssw	32	√	√
23.05.2002	96.4	sso	16	ssw	25	√	√
23.05.2002	96.4	so	18	ssw	25	√	√
14.11.2002	135.0	s	25	sw	35	√	√
16.11.2002	96.5	sso	25	s	35	√	√
28.08.2003	100.0	s	16	wsw	30	√	√
31.10.2003	104.3	sso	20	ssw	30	√	√
24.07.2000	84.9	s	15	sw	30	√	√
30.09.2000	85.0	so	18	sso	22	√	√
12.10.2000	72.1	s	12	ssw	35	√	√
10.06.2001	66.2	s	12	sw	30	√	√
05.07.2002	81.1	s	10	ssw	15	√	√
03.09.2002	76.0	sso	12	sw	18	√	×
25.11.2002	87.0	sso	20	ssw	22	√	√
26.11.2002	68.6	sso	15	ssw	25	√	√

data	rr	lldir	llsp	uldir	ulsp	ws	trough
05.05.2004	86.2	s	15	s	22	×	√
03.08.2000	29.2	s	10	sw	28	√	√
30.10.2000	27.7	s	15	sw	20	√	×
07.02.2001	20.9	s	10	-	-	-	√
25.09.2001	25.5	w	7	ssw	15	√	×
17.10.2002	26.0	s	15	sw	35	√	√
17.08.2003	20.2	wsw	20	ssw	18	√	√
19.02.2004	23.1	oso	15	sso	18	√	×
30.04.2004	22.0	so/sso	14	sso	16	×	√
18.08.2000	23.4	sw	9	sw	18	×	√
27.06.2001	25.5	sw	15	sw	18	×	×
27.11.2002	25.3	sso	12	s	15	×	×
23.09.2003	20.8	s	10	sw	18	√	√
02.12.2003	22.5	so	14	s	30	√	√
26.08.2002	22.1	sso	10	so/sso	22	×	√
27.06.2003	21.9	nw	5	wnw	20	×	×

Table 4.1: The 40 events with their analysed variables: rr=rainrate [mm/day], lldir=low level flow direction, llsp=low level wind speed, uldir=upper level flow direction, ulsp=upper level wind speed, ws=vertical wind shear, trough = synoptic situation with a trough in the west of the Alps.

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