# Reverse valley winds in the Stanzer Valley

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*to my grandfather*

# Preface

Es ist egal, welchen Berg man besteigt. Oben wird man immer weiter sehen.

*Reinhold Karl*

# Abstract

The goal of the presented diploma thesis was to examine the valley wind systems in the Arlberg region where reverse valley winds occur - similar to Maloja winds in the Upper Engadine. Several valley stations within the Kloster and Stanzer Valley as well as mountain stations taken for reference were used to the valley wind system in the Stanzer Valley. By means of statistic analysis it turns out that down-valley winds blow in the afternoon and up-valley winds blow in the forenoon at St. Anton and farther downstream which is in contrast to the textbook-like valley wind systems where down-valley winds rule during the night (induced by radiative cooling) and up-valley winds are present during the day (induced by solar radiation). The reversal of the valley winds is favoured by fair weather conditions and less pronounced when synoptic-scale winds are strong. In the latter case, foehn winds can become established downstream of the pass characterized by continuous down-valley winds without a period of up-valley winds. Furthermore, the thesis attached importance to prove different hypotheses: turbulent downward mixing and gap flow which may explain the reverse valley winds. The results of the case studies suggest that turbulently downward mixed upper-level winds and gap flows could produce down-valley winds in the Stanzer Valley in the afternoon, but up-valley winds are not explained by these hypotheses. Two further hypotheses accounting for the area-height distribution in the Kloster and Stanzer Valley, respectively, as well as the different heating and cooling alongside the Stanzer Valley itself were not be tested.

# Zusammenfassung

Das Ziel der vorliegenden Diplomarbeit war die Untersuchung der Talwindsysteme in der Arlbergregion, wo umgekehrte Talwinde - ähnlich zu den Malojawinden im Oberengadin - auftreten. Mehrere Talstationen im Kloster- und Stanzertal sowie für Referenzzwecke verwendete Bergstationen wurden benutzt, um das Talwindsystem im Stanzertal zu untersuchen. Mit Hilfe statistischer Auswertungen stellte sich heraus, dass Talauswinde nachmittags und Taleinwinde vormittags in St. Anton und weiter talabwärts wehen, was im Gegensatz zu lehrbuchhaften Talwindsystemen steht, wo Talauswinde (bedingt durch nächtliche Auskühlung) nachts und Taleinwinde (bedingt durch Sonneneinstrahlung) tagsüber regieren. Die Umkehr der Talwinde wird durch Strahlungstage begünstigt und ist schwächer ausgeprägt, wenn die synoptischen Winde stark sind. In letzterem Fall können Föhnwinde auf die talabwärtige Seite des Passes übergreifen, die durch einen beständigen Talauswind ohne Taleinwindphase gekennzeichnet sind. Des Weiteren wurde Wert auf die Prüfung verschiedener Hypothesen - turbulente Herabmischung und Strömung durch Passeinschnitte (gap flows) - gelegt, welche als Erklärung für die Entstehung der umgekehrten Talwinde dienen könnten. Die Ergebnisse der Fallstudien deuten darauf hin, dass turbulent heruntergemischte Höhenwinde und gap flows nachmittägliche Talauswinde im Stanzertal erzeugen können, doch Taleinwinde am Vormittag werden durch diese Hypothesen nicht erklärt. Zwei weitere Hypothesen, die die Flächen-Höhen-Verteilung sowohl im Stanzer -als auch im Klostertal sowie die unterschiedliche Erwärmung bzw. Abkühlung entlang des Stanzertals selbst berücksichtigen, konnten nicht geprüft werden.

# Contents

# Chapter 1

# Introduction

In the central northern Alps, there is a region - the *Arlberg region*- acting as a meteorological divide seperating the high-precipitation part to the west of the Arlberg pass from a low-precipitation part to the east of the Arlberg pass. Sometimes the climate zones beyond the pass are denoted as *maritime* and *continental* (Ekhart 1956). In contrast to many inner Alpine valleys, the valley to the east of the Arlberg pas do not show a usual valley wind system, with down-valley winds during the night and morning and up-valley winds during the day, but reveals *reverse* valley winds, with up-valley winds in the forenoon and down-valley winds in the afternoon. Early studies in the thirties (e.g. Ekhart (1936, 1937) and inhabitants of the valley confirmed the existence of these reverse valley winds. Since the establishment of additional automatic weather stations, it is now possible to gain further insight into the wind systems of wide part of the valley adjacent to the Arlberg pass region.

In the present work, partly high-resoluted data from weather stations in the valleys beyond the pass as well as reference mountain stations were taken to examine the respective valley wind system. The investigations mainly aim to answer the following questions:

(1) How do the valley wind systems in the valleys beyond the pass look like?

(2) When do reverse valley winds preferably occur and how far do they reach downstream the valley?

(3) Why do reverse valley winds exist?

As a result, the main goal of the diploma thesis is to prove the existence of reverse valley winds in one of the valleys beyond the pass and to identify the mechanisms being responsible for their occurrence.

In chapter 2, the basics of valley and slope winds as well as foehn winds are introduced. Chapter 3 presents the area of interest and available weather data. Chapter

4 illustrates the results of the wind climatology by means of wind rose plots for the total (October 2007 to October 2009) period (section 4.2) and limited (December 2008 to September 2009) period (section 4.3), and statistical examinations of the daily course of winds at the valley stations (section 4.4). In chapter 5, the hypotheses for the explanation of reverse valley winds in the Stanzer Valley are introduced and the respective methods to prove them are given. Finally, chapter 6 uses case studies to reveal which thesis best fits the phenomenon of reverse valley winds. Conclusions with a short outlook of what may be considered in future studies complete the diploma thesis.

# Chapter 2

# Basics of Mountain Wind Systems

## 2.1 Introduction

The topic of the diploma thesis is strongly related to the fundamentals of the valley and slope winds as well as the generation of foehn winds in the Alpine region. In general, mountain wind systems are the result of the interaction between mountainous terrain and atmosphere. The most pronounced features develop with fair weather conditions, i.e., in the vicinity of high pressure areas. For this reason, the following statements concerning valley and slope winds will refer to fair weather conditions without a pronounced superimposed flow. In reality, both synoptic and local winds interact with each other and make a clear distinction rather difficult. It should be kept in mind that these conceptual models of mountain wind systems are designed in a very idealized manner.

## 2.2 Valley Winds

There is a long tradition exploring the most important features and mechanisms of mountain winds starting with a short article about the theory of valley and slope winds (Hann 1879). A few decades later Defant (1910) set up the generally-accepted theory of valley winds caused by periodic cycles of pressure differences between the valley and the plain. He also stated that the pressure minimum lags behind the temperature maximum. His theoretical calculations let him conclude that valley winds do not drain sufficient air mass away from the valley to reach the observed pressure amplitudes. Defant hypothesized that the reason should be found in the mass flux over the mountains - later known as slope winds.
In 1949 Defant (1949) summarized the latest findings about slope and valley winds building amongst others on theories of Ekhart (1932), Prandtl (1942) and Wagner (1932b). His well-known scheme displaying the interaction between valley and plain

respectively slope and valley is still valid today (figure 2.1). Defant emphasizes the

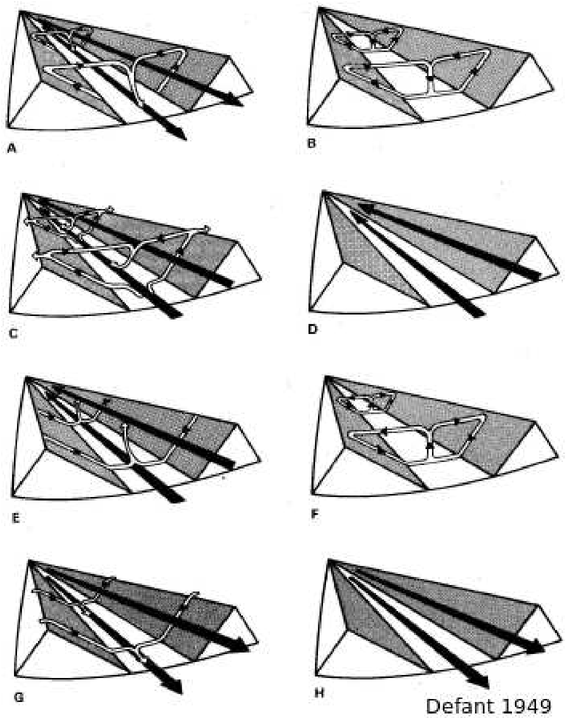


**Figure 2.1:** Schematic illustration of the diurnal cycle of valley winds with fair weather conditions (after Defant 1949)
(a) Sunrise: generation of upslope winds (white arrows), persisting down-valley winds (black arrows). The valley is cold, the plain is warm. (b) forenoon: strengthening slope winds, change from down-valley to up-valley winds. Valley and plain possess the same temperature. (c) Noon and early afternoon: decreasing slope winds, well-developed valley winds. The valley is warmer than the plain. (d) Late afternoon: slope winds have stopped, valley wind continues. Valley is still warmer than plain. (e) Evening: generation of down-slope winds, decreasing valley wind. Still little warmer valley. (f) Early night: fully developed down-slope winds, change from up-valley to down-valley winds. Again, valley and plain possess the same temperature. (g) Middle of the night: down-slope winds persist, down-valley winds are well developed. The valley is colder than the plain. (h) Early morning: down-slope winds have stopped, deep down-valley winds govern the valley. The valley is colder than the plain.

typical widening of the valley towards its exit. It is then possible to consider the lower part of the valley as a plain and the temperature amplitudes will increase up the valley.
However, there is still uncertainty about the mechanisms leading to the strong daily temperature amplitudes which are larger in the valleys than over the plain. Wagner (1932a) suggested that the smaller volume of the valley compared to the plain volume (assuming the same top of the volume) will play the decisive role. Under the

assumption of equal solar radiation flux, the valley will be warmed more than the plain. This theory has been commonly accepted and Steinacker (1984) carried out further calculations taking the area-height distribution of the valley into account, that is, not only the volume plays an important role, but also the extent of the horizontal area between the lateral walls. He found that the volume effect is confined to below-crest inversions because heat energy from the valley floor and the slopes will then remain below the inversion. In the case of deeply mixed valley atmospheres, the heating rate of the plain and the valley become equal. Whiteman (1990) derived a formula in which the ratio of the volume-averaged valley to plain temperature is proportional to the ratio of plain to valley volume: the TAF (**T**opographic **A**mplifying **F**actor). The return component of the slope winds contributes a large part of the warming of the valley atmosphere as already stated by Wagner (1932b).

> Die Erwaermung der Talluft erfolgt hauptsaechlich in der Weise, dass ein Teil des Hangwindes gegen die Talmitte zurueckkehrt und so der Hauptmasse der Talluft ueber der Talmitte eine kleine Bewegungskomponente abwaerts erteilt.
>
> The warming of the valley air is mainly produced by the return of part of the slope wind to the valley center giving a small descent component to the main valley air mass over the valley center.

Wagners theory of subsidence warming did not attract interest for a long time. Recently, numeric simulations were carried out to study the role of subsidence of returning slope winds (Rampanelli and Zardi 2004). The authors pointed out that a well-mixed boundary layer only exists in the plain while the valley atmosphere is characterized by a slight increase of the potential temperature with height. Therefore, the resulting deep, stable core can only be produced by strong subsidence. This is in line with observations in the Riveria Valley (Rotach et al. 2004).

## 2.3 Slope Winds

Slope winds are driven by horizontal temperature differences along the slope and between the valley bottom and the slope, respectively. They can be considered as *the small-scale end of a whole spectrum of thermally-induced local circulations* (Vergeiner and Dreiseitl 1987). To describe the slope winds in a comprehensive way, it is necessary to distinguish between up-slope (anabatic) and down-slope (katabatic) winds.

### 2.3.1 Up-slope Winds

The driving mechanism of up-slope winds is solar radiation on the slope surface immediately inducing a sensible heat flux which warms adjacent air masses. Subsequently, the pressure falls at the slope and a pressure gradient normal to the slope is established. As the rising air parcel is less dense than the air at some distance from the slope, the resulting pair of forces excites an upward directed motion parallel to the slope, when friction and inhomogenities within the underlying topography are neglected (Prandtl 1942).
Considering actual up-slope flows, the inclination of the slope (angle of incidence) and its underlying terrain play a central role in determining the heating rate of the slope surface. The azimuth angle and inclination of the slope affect the sunshine period and corresponding daytime energy input (Whiteman 2000). The *Bowen Ratio*, defined as the sensible heat flux divided by the latent heat flux, is another important quantity for the energy available for warming the air above the slope surfaces. High Bowen Ratios are required to generate well-defined slope wind systems. Snow or wet ground reduce the Bowen Ratio as the major part of the net radiation contributes to evaporation, while dark and dry surfaces enhance sensible heat flux. Exemples are dry areas with little vegetation found at higher altitudes and in the central Alps. Vegetation might produce up-slope winds even with snow cover, e.g. over forested slopes when the vegetation itself is (partially) free of snow. The kind of forest also affects the absorption of solar energy, e.g. deciduous forest possesses 15-20 % albedo whereas coniferous forest has 10-15 % albedo (Heyer et al. 2004). Less stable layering and more inclined topography and terraces cause a more vertically aligned motion and flow separation, respectively.
Summarizing, up-slope winds are most pronounced during the summer season when the maximum of solar energy is available. Furthermore, slightly stable stratification and a moderately inclined slope (i.e. no possible flow separation) promote up-slope flows. High Bowen ratios are generally necessary to produce well-defined slope and valley wind systems. According to Prandtl's solution (Prandtl 1942) there is a returning flow closing the slope wind circulation. It descends above the valley bottom and warms the air by subsidence. The more pronounced the up-slope winds, the stronger the subsidence warming and the resulting valley winds.

### 2.3.2 Down-slope winds

The sensible heat flux also controls down-slope winds. Given clear skies during the night, the surface strongly cools by longwave radiation. The sensible heat flux is then directed from the air towards the slope and a pressure gradient towards the air builds up. Detrainment occurs between the potentially cooler slope air and the potentially warmer valley atmosphere. The major part of the flow, however, runs parallel to the slope as the strong radiative cooling of the slope surfaces contributes to the gravity force which is directed downward. In contrast to up-slope winds, the down-slope winds are more shallow and laminar since the thickness of the catabatic flow is reduced by radiative cooling and sinking potential energy, respectively. The nighttime cooling is enhanced with snow-covered ground. Another important feature is the *sky view factor* influencing the surface energy budget (Matzinger et al. 2003). Multiple radiation from the lateral walls is found within narrow valleys whereas ridges and plateaus will have a larger net radiation loss during the night (Whiteman 2000)

## 2.4 Maloja Winds

Besides the ordinary valley wind systems, with up-valley flow during the day and down-valley flow during the night, *reverse* valley winds exist. They were first documented northeast of the Maloja pass which is situated in the southern central Alps in canton Grisons between the Italian border and St. Moritz, a famous spa and winter sport center close to Samedan in the Upper Engadine. The Inn river origins there. The region is divided into the steep Bergell Valley (325 m in Chiavenna at the mouth of the valley) southwest of the Maloja pass (1815 m) and the rather flat and elevated valley floor (1822 m at St. Moritz) of the Upper Engadine northeast of the Maloja pass. Surfers on the large lakes *Lej da Segl* and *Lej da Silvaplana* just to the northeast of the pass benefit from the diurnal winds blowing down the valley with significant force. Mörikofer (1924) reported that "the up-valley wind of the Bergell Valley reaches with unrelieved strength across the Silvaplaner Lake". At the beginning of the 1930s (a decade with a bulk of publications about valley winds and the Maloja phenomenon in particular), Wagner expressed the following explanation approach to the Maloja winds (Wagner 1932b):

> Winde vom Typus des Malojawinds sind an jeder Passhöhe möglich, wenn die seitlichen Kämme nicht in der Paßlinie kulminieren, sondern über diese Linie hinaus in der Richtung des abfallenden Tals noch weiter ansteigen.
>
> Winds of the type of Maloja winds are possible with every pass height when the crests of the lateral walls do not culminate in the pass line but still increase through this line towards the direction of the descending valley.

Braak (1933) contradicted the theory of Wagner since he stated that the effective crest height does *not* increase towards the lower part of the Upper Engadine. Braak proposed another explanation attaching importance to the abrupt transition of the Maloja pass into the Bergell Valley. He attributes the Maloja wind to the differential heating of the pass height and the "free" valley air at the same altitude in the Bergell Valley. As a result, a temperature and pressure gradient evolves towards the pass and induces a down-valley wind. Moll (1938) hypothesized the Maloja wind could be the result of the well-defined Bergell up-valley wind encroaching the pass region as the flat bottom of the Upper Engadine would not allow for a significant up-valley wind. Klainguti-Schaumann (1937) principially questioned whether the Maloja wind is a pure "Schönwetterwind" (fair weather wind) but highlighted the connection of the Maloja wind to the occurrence of gradient winds, i.e. superimposed flows. She based this conclusion on wind measurements in the summer of 1936. Georgii et al. (1974) found three maxima of the Maloja winds related to superimposed flows :

1. the superimposed flow generates a southsouthwesterly wind parallel to the valley. The Maloja wind will be strengthened and it will encroach into the Engadine

2. the superimposed flow generates a strong northnortheasterly wind counteracting the Maloja wind and preventing it from spreading into the Engadine

3. the superimposed flow generates a weak northnortheasterly wind overcompensated by the Maloja wind

This corresponds to the assumptions of Klainguti-Schaumann and is restated with an explanation of the well-known "Maloja serpent", a narrow and shallow cloud band that forms ascending from the Bergell Valley across the Maloja pass into the Upper Engadine, in a paper of Gross (1985). He carried out simple numeric simulations to explain the generation of that cloud serpent with a "counter-current". Most of the explanation approaches over the last decades are based on asymmetries of the valley geometry and the TAF, respectively, refering to Wagner (1932b), e.g. Vergeiner and Dreiseitl (1987), Whiteman (1990) or in the mountain meteorology script from Dr. Haiden [1]. Indeed, to the author's knowledge, there were not any precise calculations to corrobate that theory.
Reverse winds of the kind of Maloja winds also exist in the Arlberg region. Using surface and aerological observations, (Ekhart 1936, 1937) found evidence of them in the Stanzer Valley with down-valley winds during the day. Sounding ascents revealed shallow down-valley winds at the surface at St. Anton and a reverse flow above, both decoupled due to radiative cooling. Ekhart suggested that the necessary energy to overcome the steep top of the valley is produced by the horizontal temperature

[1]Haiden, T., Mountain Meteorology, Lecture in Meteorology and Geophysics, Innsbruck, Summer Semester 2005

difference exciting "slope winds alongside the valley bottom" (Ekhart 1937). From his state of knowledge it was not possible to ascertain whether the encroaching valley wind is a pure inertia motion or a "true Maloja wind".
Karl Gabl, head of the regional weather service in Innsbruck, told me of a cloud phenomenon similar to the Maloja serpent which is observed at the Arlberg pass summit and farther upstream, and is called *Maiennebel* by vernacular, named after *Maienwasen*, a place where a ventilation shaft of the Arlberg Tunnel exists. In August 1985 wind measurements at that place showed a continuation of the Kloster Valley wind into the Stanzer Valley (Karl Gabl, personal communication).

## 2.5 Foehn winds

In this section, the definition and history of foehn will be presented. Thereafter the ingredients and types of foehn are introduced.

### 2.5.1 Definition

> "Foehn is a wind which is warmed and dried by descent, in general on the lee side of the mountain." (World Meteorological Organization 1992)

"Gusty winds might be added to highlight the unsteadiness of the foehn winds. The attribute "in general" indicate that foehn might also occur downstream of a level gap.

The researcher's positions keep on diverging whether the foehn can be considered as density-driven ("fallwind") or as a result of a "complex balance of forces in the 3-dim momentum equation" (Petra Seibert, personal communication) - which is, however, valid for *each* flow. Regarding the foehn flow as being warmer than the original (underlying) air mass would contradict the picture of a (cold) fall wind. Then the foehn could be conceived as descending flow in the wake of "sucked cold air" according to Ficker's "passive substitute flow" (Ficker 1931) where the cold air of the valleys drains off due to a horizontal pressure gradient between the valley and the foreland. However, I am inclined to accept the theory of a potentially cooler air flow as it will be discussed in the next subsection.

### 2.5.2 Results of Foehn research since MAP 1999

The definition of foehn, which is given in section 2.5.1, dates back to the pioneering work of Hann (1866), who explained the dryness of the foehn as a consequence of adiabatic compression and put less emphasis on a competing explanation relying on

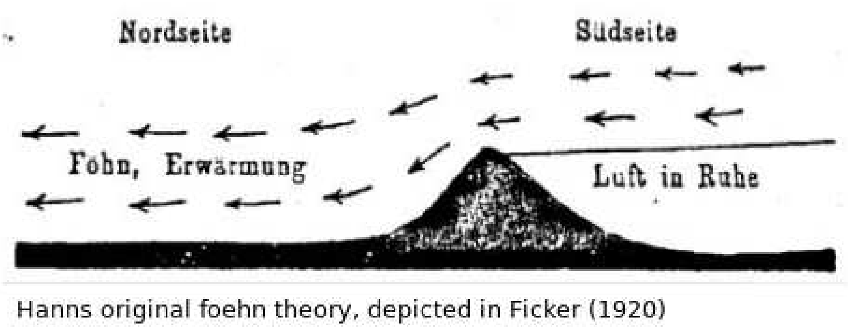


**Figure 2.2:** Hann's original foehn theory depicted in Ficker (1920) illustrating a pool of stagnant air on the upstream side of the mountain range and a southerly flow above descending downstream of the mountain range

the presence of upstream precipitation. Although Ficker (1920) presented Hann's original foehn theory (see figure 2.2), Ficker and De Rudder (1943) later introduced the new foehn paradigm basing upon symmetric ascent and descent on both sides of the mountain ridge, without any hints to Hann's previous studies. While the "thermodynamic foehn theory" - with release of latent heat by condensation as a main contributor of the downstream warming - found its way into the textbooks until day, Hann's original concept of resting upstream air fell into oblivion for a long time. Seibert (2005) presented the origins of the different foehn theories from Hann and Ficker and underlined that upstream precipitation is not necessary in order to obtain a temperature excess on the downstream side. In den 1980s and 90s, Austrian Scientists could corroborate the hydraulic aspects of Hann's theory with the large field experiments ALPEX (**Alp**ine **Ex**periment) 1982 and MAP (**M**esoscale **A**lpine **P**rogram) 1999. The results from ALPEX mainly address the question whether upstream cloudiness and/or precipitation are necessary to develop a foehn flow: Statistics for Innsbruck show that at least 50 % of the foehn events do not have precipitation on the windward side of the main crest (Seibert 1990). 1-5 % of the strong foehn events exhibit less than 20 % cloudiness to the south of the Alps (Fliri 1983). Moreover, measurements revealed that the release of latent heat only contributes 1-2K net gain to downstream warming (Seibert 1990). The key findings of MAP are listed in Steinacker (2006). Of major importance for the goals and interpretation of the results of my work is the statement that mountain gaps (passes) allow the relative cool upstream air to flow on the downstream side. These processes were examined in Mayr and Gohm (2006) and Mayr et al. (2007) in the framework of MAP and observations in the Wipp Valley. Recently, the role of the upstream air mass was presented by Mayr and Armi (2008) by means of sounding ascents which show significant potential temperature differences between Milano and Innsbruck during south foehn events. Haas (2006) studied the role of north foehn and precipitation in the Inn Valley and demonstrated that 20% of the north foehn events are linked to measureable precipitation on the downstream side.

### 2.5.3 Ingredients

Foehn winds are mainly caused by horizontal pressure differences, which are a consequence of horizontale temperature differences independent of whether the terrain is level or elevated. Solely dealing with mountainous terrain, the driving mechanisms will be related to the existence of mountain ranges. The modern ingredients-based forecasting method, introduced by Doswell et al. (1996), brings these driving mechanisms together. The crucial question determining the generation of foehn is: Is there a difference in potential temperature between upstream and downstream side of the mountain range? That difference can develop as a result of one or more of the following "ingredients" (Mayr et al. 2007)

1. differential horizontal advection of air masses
2. air mass formation beneath anticyclones
3. warming through compensating subsidence
4. differential cloud cover
5. upstream precipitation
6. gap flows due to well-defined valley wind systems

In the vast majority of foehn cases, a diversity of these ingredients comes together. It is important to note that upstream precipitation is *not* a necessary ingredient to obtain temperature excess downstream, but it can enhance the upstream cold air dome by melting (and initial evaporative cooling), and with strong foehn winds, the achievement of the necessary temperature for foehn breakthrough can be facilitated when precipitating clouds move downstream and cause evaporative cooling within the foehn air. This is often observed in the case of north foehn in Innsbruck [2].

### 2.5.4 Types

Depending on the depth of the horizontal potential difference between upstream and downstream side, *shallow* or *deep* foehn is produced. Principially, shallow foehn (the term has been used by Kanitscheider 1932 for the first time) is a gap flow as the upstream cold pool is limited to below the crest line. Deep foehn requires a sufficiently deep cold pool to overcome the mountain ridge which mostly happens

[2] see e.g. http://www.inntranetz.at/foehn/foehn-101107.html

with a deep synoptic flow.
With strong deep foehn, precipitating clouds may be drawn over the crest and may cause foehn and measureable precipitation simultaneously - which is called "Dimmerfoehn". Kuhn (1989) defines Dimmerfoehn as follows:

> Situation, in der bei starkem Föhn die Mauer einige Kilometer im Lee liegt, im hinteren Talboden geringe Windstärken herrschen und die Luft dort durch Niederschlag, Treibschnee oder Nebelfetzen getrübt ist.
>
> Situation with strong foehn when the foehn wall lies some kilometers on the lee side, weak winds dominate in the upper valley floor and the air is clouded by precipitation, snow flurry or fog patches.

Etymologically, dimmerfoehn traces back to an old dialect word of the Glarner Hinterland for "Dämmerschein" ( equal for *Dimmer* which means hazy, obscure) where this foehn type often occurs.
A special type of the foehn is "Sandwich foehn" (Vergeiner and Mayr 2000) occuring when the foehn flow is sandwiched between up-valley winds and a superimposed counter-flow - another example apart from the cited one can be gleaned from my website [3].

### 2.5.5 Gap flows as a sub-category of foehn

As mentioned in section 2.5.1, gap flows represent a sub-category of foehn which is independent on whether the terrain is level or elevated. The term "gap wind" dates to Reed (1931) and has been elaborated by Scorer (1952) in the context of strong easterly winds (called "Levanters") in the Strait of Gibraltar which is bounded by two mountain ranges in Spain and Morocco. Dorman et al. (1995) took up the subject again and found out that a simple 2-dim Venturi model is not applicable to explain to the strongest winds well downstream of the narrowest part of the constriction. The Venturi effect solely works in case of a constant lid, that is an invariable inversion height. Therefore, a model with a stratified flow through a 3-dim mountain barrier was used where the Froude number is smaller than 1.

> Under these conditions, most of the incident near-surface air flow is blocked and funnelled through the Strait and adjacent low topography. The air flow up above is partially blocked resulting in some flow over the topography, and leeside adiabatic heating. Additional descent is forced by divergence over the coast, caused by the decreased drag over water and acceleration of low-level winds. Subsidence heating lowers the

[3] http://www.inntranetz.at/foehn/foehn-18-10-05.html

> surface pressure, creating a mesoscale low in the lee which is centered over water in the western portion of the Strait. It is this lee-side, mesoscale low pressure that accelerates the air to the west of the narrows and caused the high-speed winds observed in the mesoscale levanters. (Dorman et al. 1995)

Further examples for gap flows in narrows are illustrated by Bond and Stabeno (1998) for the Shelikof Strait between Alaska Peninsula and Kodiak Island or by Colle and Mass (1999) for the Strait of San Juan de Fuca (marking a part of the border between Canada and United States of America). Naturally, well-known foehn locations are situated downstream of mountain gaps, e.g. the Brenner Pass between the upper and lower Wipp Valley (eg. Seibert 1990,Mayr et al. 2007 or Armi and Mayr 2007) or the Kearsage Pass with Onion Valley and Independence in the Owens Valley (Holmboe and Klieforth 1954)

The key factors behind gap flows are given by Arakawa (1969, eqn. 5.9) who set up the equation of mass conservation for a flow in a narrow valley:

$$UHB = const. \tag{2.1}$$

$U$ denotes the flow velocity, $H$ is the depth of the fluid and $B$ is the channel width.

Equation (2.1) says that with this decreasing $H$ and $B$ the flow velocity has to increase. This follows from the law of mass conservation. However, the equation does not yield an explanation *why* the depth of the fluid decreases. Therefore, it is necessary to consider the initial flow speed (in terms of the Froude-Number) related to the mountain height:

$$Fr = \frac{u_0}{\sqrt{gh_0}} \tag{2.2}$$

$Fr$ is the Froude number, $u_0$ is the initial (upstream) flow velocity, $g$ is the gravity acceleration, $h_0$ is the initial (upstream) depth of the fluid and the denominator is the speed of the gravity wave. According to the results of Houghton and Kasahara (1968), leeside hydraulic jumps with strong downslope winds will occur with supercritical (Froude number above 1) leeside flows and subcriticial (Froude number below 1) luvside flows, that is, either low upstream velocities or large depths of the fluid, or both have to be present. The relationship between Froude number and mountain height can be seen e.g. in the regime diagram of Houghton and Kasahara (1968, pg. 5). In that case, the fluid depth is forced to descent downstream of the pass. Bernoulli's law declares that the total mechanical energy is conserved *along a streamline*, which is an isentrope to a good approximation, with frictionless processes before the jump. As a result, the kinetic energy has to enlarge with the

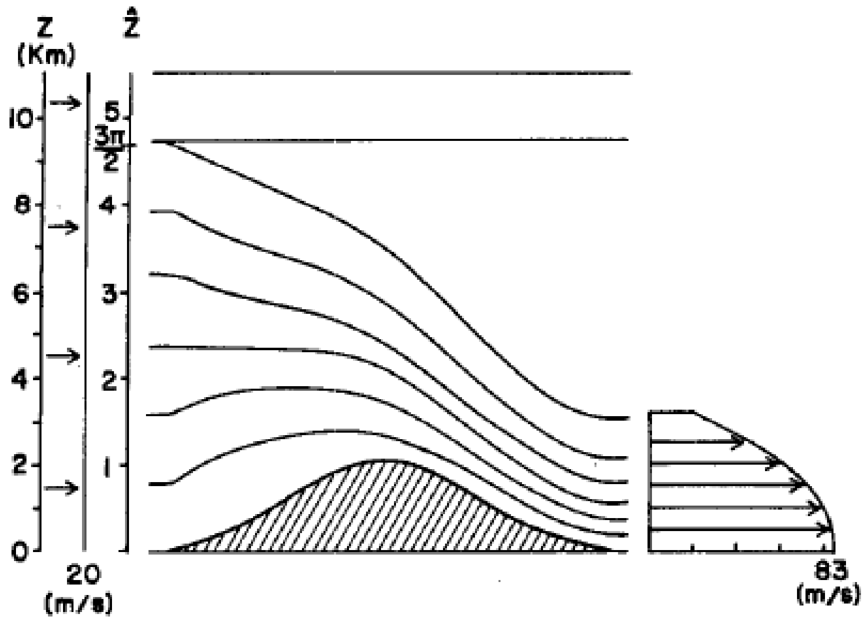


**Figure 2.3:** Bernoulli's effect applied to a stratified flow over a single mountain ridge, with free slip as a lower boundary condition, according to Smith (1985)

decline of the fluid depth. The picture will then look like in figure 2.3: As the air descends it warms through adiabatic compression. For this reason, gap flows fulfill the definition of foehn. The downstream warming strengthens the pressure gradient alongside the gap maintaining the process itself. This resembles the 'ordinary' foehn case in which the descending air flow reduces possible cloudiness downstream allowing for enhanced solar radiation and a deepening lee trough.

While most of the aforementioned situations with gap flows refer to lateral constrictions between *two* sidewalls, gap flows also occur with *one* sidewall and an adjacent infinit sidewall, e.g. east of the East Alps between Eastern Styria, South Burgenland and Eastern Lower Austria and North Burgenland when a southerly flow accelerates northeast of the Vienna Basin. The flow experiences a sudden widening of the left sidewall which is equivalent to the situation of a valley exit (Manfred Spatzierer, personal communication).

# Chapter 3

# Area of interest and station data

## 3.1 Topography and situation of weather stations

The area of interest (fig.3.1) is located in the northern central Alps between the Rhine and Inn Valley. It consists of a broad longitudinal barrier dividing the region into an orographic-precipitation dominated northwestern part and a relative dry inner alpine southeastern part where foehn effects are often present.
Taking a closer look (fig.3.1), the reference mountain stations for synoptic-scale winds - Säntis (2502m), west of the Rhine Valley, and Zugspitze (2963m), north of the Upper Inn Valley - mark the western and eastern border of the area of interest. The station Galzig (2089m) at the Arlberg pass is located between the Kloster Valley to the west and the Stanzer Valley to the east. The Kloster Valley exiting into the Walgau (see fig.3.4) close to Bludenz (575m) is entirely laterally orientated whereas the Stanzer Valley exiting just upstream of Landeck (798m) continues with the Verwall Valley southeastward into the Verwall mountains.

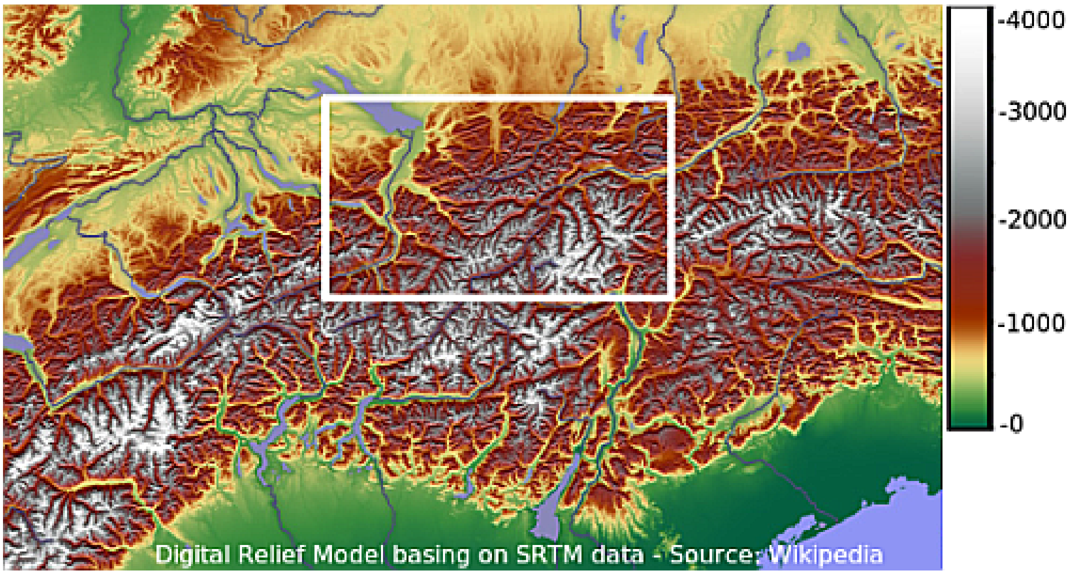


**Figure 3.1:** Central part of the Alps with the location of the area of interest, the color map on the right side shows the altitudinal zones [m]

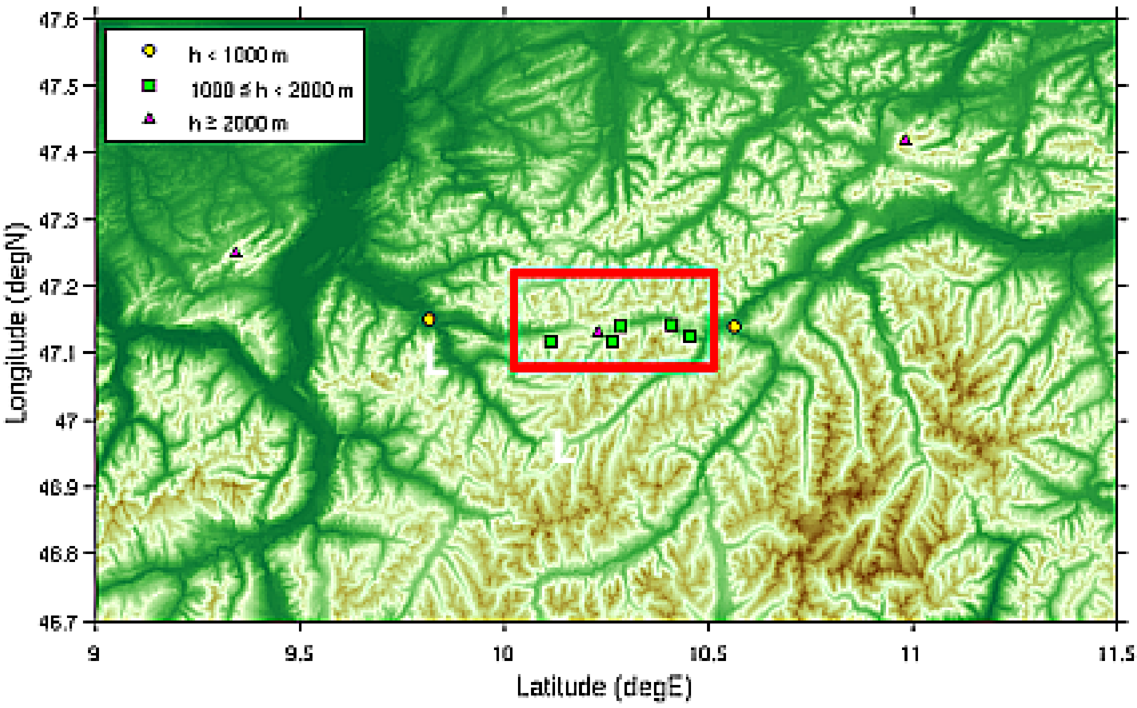


**Figure 3.2:** Area of interest with used weather stations, the altitude of the stations is displayed by coloured symboles, the red frame indicates the area of figure 3.3 below.


**Figure 3.3:** The aerial photograph shows the Kloster and Stanzer Valley with the location of the weather stations: L = Langen (1250m), G = Galzig (2081m), A = St. Anton (1310m) - all ZAMG (TAWES); W = St. Anton/Wolfsgrubentunnel (1257m), F = Flirsch (1125m), S = Strengen (1030m) - all ÖBB (Davis Pro); R = Alpe Rauz (1629m) - METAR from Austro Control, red S indicates the junction of the Stanzer Valley with the Paznaun Valley (red P) to the Sanna Valley exiting at Landeck (not shown)

Several weather stations depicted in the aerial photograph (fig.3.3) were chosen to cover the valleys beyond the Arlberg pass, with Langen and Alpe Rauz in the Kloster Valley west of the pass and St. Anton in the upper Stanzer Valley east of the pass. Wolfsgrubentunnel is located in the central part and Flirsch and Strengen in the lower part of the Stanzer Valley.

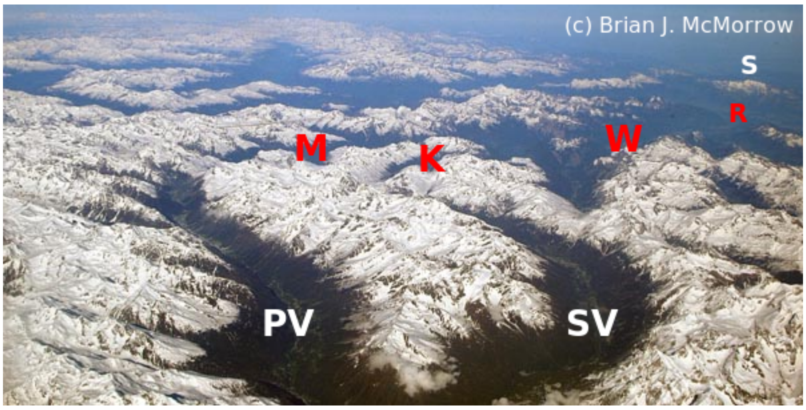


**Figure 3.4:** The picture from a pilot taken to the east of Landeck and directed to the west. PV = Paznaun Valley, SV = Stanzer Valley, K = Kloster Valley, M = Montafon, W = Walgau. Farther to west, the Rhine valley (R) is aligned south-north, with the Säntis (S) to the west.

The area of interest from the bird's eye view is presented in fig. 3.4.

## 3.2 Temporal resolution and quality

The name, location and respective provider of the used weather stations are listed in table 3.1 with the respective parameters (table 3.2).

| Id | Station name | Abbrev. | Alt. [m MSL] | lon | lat | Provider |
|---|---|---|---|---|---|---|
| 06680 | Säntis | SAE | 2510 | 9.3433 | 47.2492 | MeteoSchweiz |
| 10961 | Zugspitze | ZUG | 2963 | 10.9833 | 48.4167 | DWD |
| 11102 | Bludenz | BLU | 575 | 9.8167 | 47.1512 | ZAMG |
| 11307 | Langen | LAN | 1250 | 10.1167 | 47.1167 | ZAMG |
| 11110 | Galzig | GAL | 2081 | 10.2308 | 47.1308 | ZAMG |
| 11311 | St. Anton | STA | 1310 | 10.2667 | 47.1167 | ZAMG |
| 11112 | Landeck | LDK | 798 | 10.5642 | 47.1386 | ZAMG |
| 22986 | Wolfsgrubentunnel | WOL | 1257 | 10.2878 | 47.138 | Ubimet/ÖBB |
| 22984 | Flirsch | FLI | 1125 | 10.4139 | 47.1425 | Ubimet/ÖBB |
| 22985 | Strengen | STR | 1030 | 10.4581 | 47.1261 | Ubimet/ÖBB |

**Table 3.1:** Weather stations of several providers.

| Provider | Res.[min] | Period | Parameters | Type |
|---|---|---|---|---|
| MeteoSchweiz | 360 | 20071001-20091001 | tl2,pst,dd10,ff10,rr | SYNOP |
| DWD | 60 | 20071001-20091001 | tl2,pst,dd10,ff10,rr | SYNOP |
| ZAMG | 10 | 20071001-20091001 | tl2,pst,dd10,ff10,ffx10,rr,ssd,rh | TAWES |
| ÖBB | 60 | 20081118-20091109 | tl2,pred,dd4,ff4,ffx4,rr | DAVIS |

**Table 3.2:** Temporal resolution and parameters. tl2 = air temperature in 2m, pst = station pressure, pred = pressure reduced to MSL,dd10 = wind direction in 10m, dd4 = wind direction 4m, analog to ff (average wind) and ffx (wind gusts per resolution interval), rr = precipitation/10min, ssd = sunshine duration/10min, rh = relative humidity; Abbreviations: DWD = **D**eutscher **W**etter**d**ienst (German Weather Service), ÖBB = **Ö**sterreichische **B**undes**b**ahnen (Austrian Federal Railways), TAWES = **T**eil**a**utomatische **We**tter**s**tation (semi-automatic weather station), SYNOP = observations, DAVIS = Davis Vantage Pro weather station (full automatic)

All data are quality controlled by the providers. Missing values or values out of physical bounds (e.g. negative pressure) are denoted with NaN (Not a number). However, it should be taken into account that the ÖBB stations are Davis Pro stations with the following limitations:

- the anemometers are situated in 4-5 m height instead of WMO conformal 10 m

- lowest measureable wind speed 1-1.5 m/s (instead of 0.5 m/s)
- ventilation works only when the sun shines which may lead to temperature errors given strong cloudiness and during nighttime

The second limitation leads to many calm wind periods where north wind (zero degree) is recorded automatically. To exclude these "false" wind directions, the limit of average winds was raised to 2 m/s resulting in about 95 % of wind directions below this threshold.

In addition to that, METAR data with limited quality ( wind speeds and directions estimated by a wind sock) from Alpe Rauz were used for the case studies in chapter 6.

# Chapter 4

# Wind climatology

## 4.1 Introduction

In this chapter, a diversity of wind roses is provided to describe the wind directions of the valley stations related to different parameters like wind speed, sunshine and precipitation. Section 4.2 gives an overview of all stations, with all registrated wind directions of at least 0.5 m/s to exclude false north winds (leading to a loss of 3-8% with TAWES data). Section 4.3 illustrates the shorter period for which ÖBB-data were available in addition to ZAMG-data of the valley stations. The different temporal resolution (ÖBB: 60min and ZAMG: 10min) should be taken into account when the plots are interpreted. In section 4.4, the mean course of daily winds in St. Anton and adjacent stations is considered, taking (by hand) 149 days between October 2007 and October 2009 when reverse valley winds could be observed.

## 4.2 Wind rose plots of the total period

At first, wind rose plots of the total period ranging from October 2007 to October 2009 will be presented.The plots contain relative frequencies of wind directions indicated by the dashed circles (in %). Main focus is the wind regime at the stations in the Kloster and Stanzer Valley as well as Galzig at the pass region. To compare a more textbook-like valley wind system with the reverse valley wind system of St. Anton, Bludenz and Landeck were chosen as "reference" stations in the adjacent valleys.

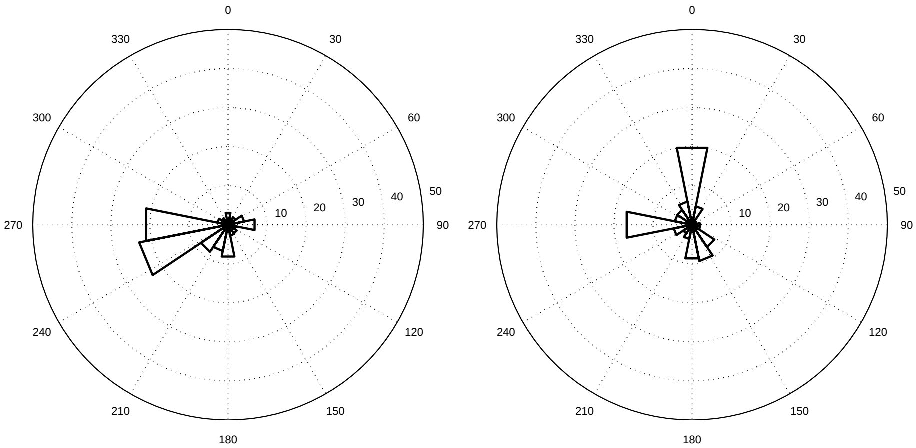


**Figure 4.1:** Frequencies of sectoral wind directions for the period 20071001-20091001 at the mountain station (left) Säntis (# 16856) and (right) Zugspitze (# 18446)

Säntis (fig.4.1,left) reveals a majority of westerly winds (above 44 %) which is in line with the synoptic-scale westerly wind regime dominating in central Europe. Southwesterly winds are less frequent (about 25 %) but still significant in contrast to northerly and easterly wind directions, due to foehn winds channelled in the Rhine Valley south of the mountain.
Zugspitze (fig.4.1,right) has three maxima of wind directions, with northerly and westerly winds due to the westerly wind regime and a southerly peak due to foehn situations.

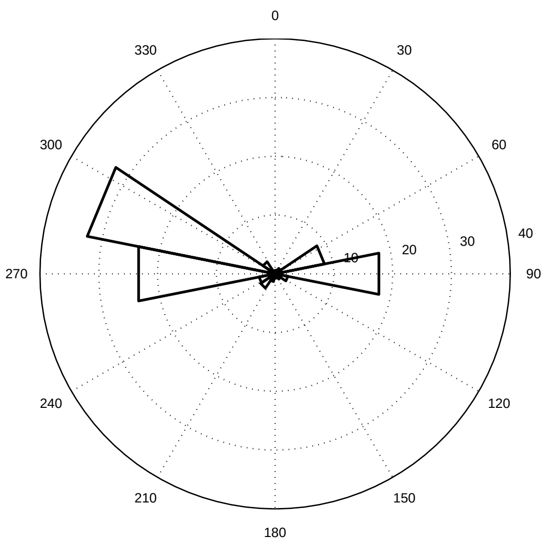


**Figure 4.2:** Same as fig.4.1, but for mountain station Galzig (#109368), westerly winds indicate downstream flow, easterly winds upstream flow

At Galzig (fig.4.2), the main wind directions are due to the west-east orientation of the Arlberg pass. Prevailing westerly winds likely arise from synoptic-scale westerly winds which are transported downward by vertical momentum flux.

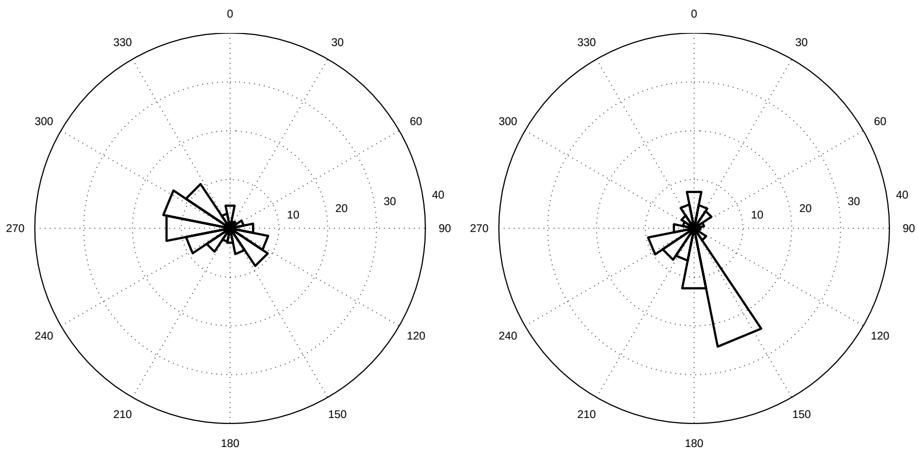


**Figure 4.3:** Frequencies of sectoral wind directions for the period 20071001-20091001 and ff larger 0.5 m/s at (left) Bludenz (# 71327) with down-valley winds SE and up-valley winds NW and (right) Landeck (# 97045), with down-valley winds SSE and up-valley winds NE

At Bludenz (fig.4.3,left), the frequency of directions well reflects the NW-SE orientation of the valley axis, with a large majority of up-valley winds (west to northwest) and a clear minority of down-valley winds (southeast). Remembering the location of the weather station in fig.3.1 more towards the southern side of the valley, it can be seen that the down-valley winds of the Kloster Valley will be deflected by the mountains south of Bludenz and merge with the down-valley winds of the Montafon southeast of Bludenz.

At Landeck (fig.4.3,right), down-valley winds (south to southeast) also outweigh the up-valley winds (northeasterly winds), and a third component (southwest) stems from the Sanna Valley southwest of Landeck (see fig.3.3).

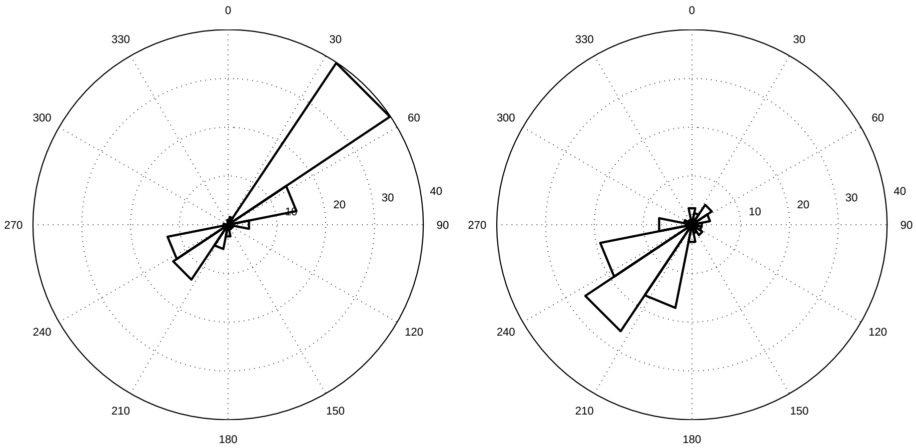


**Figure 4.4:** Frequencies of sectoral wind directions for the period 20071001-20091001 and ff larger 0.5 m/s at (left) Langen (# 101297) with down-valley winds NE and up-valley winds SW and (right) St.Anton (# 89156), with down-valley winds SW and up-valley winds NE-SE

In remarkable contrast, Langen (fig.4.4,left) has a great majority of down-valley winds (northeast) originating from the Arlberg pass region, and comparatively few up-valley winds. A distribution similar to Langen can be observed at St. Anton (fig.4.4,right) where the down-valley winds (southwest) clearly outweight the up-valley winds, but with higher frequency than at Langen which may serve as a hint that an additional wind regime may be superimposed on the normal valley wind system.

## 4.3 Wind rose plots of the limited period

The subperiod for which both ZAMG and ÖBB data are available ranges from 01. December 2008 to 15. September 2009. Situations with high pressure and calm winds, respectively, account for about 15% for this period (given wind speed averages of 4 m/s and below at the mountain stations Zugspitze and Säntis), and low-pressure systems often affect the area of interest (verified by GFS analysis maps from Wetter3, not shown). In the case of wind speeds lower than 2 m/s, most of the ÖBB data show "false" north winds. As a result, weaker winds than 2 m/s were excluded in the following wind rose plots. Overall, very weak winds occur more often in the Stanzer than in the Kloster Valley, which may be the consequence of the location of the weather station with respect to the topography, the steepness of the valley floor in the lower part of the Stanzer Valley (enhanced friction), the anemometer height and also differences in the strength of the valley wind system.

### 4.3.1 Without precipitation

The next plot set contains only wind directions when **precipitation is zero** and the **average wind speed of at least 0.5 m/s**. This will exclude calm winds and "false" wind directions as well as low-pressure environments with frontal passages when synoptic-scale winds dominate. Trace precipitation is not ruled out as observers are not present at the stations. Without precipitation, the wind rose plot of Bludenz (fig.4.5,right) exhibits solely wind directions along the valley axis and slightly more up-valley winds than down-valley winds. The picture of Landeck (4.6,right) shows a vast majority of down-valley winds, comparatively few up-valley winds and a third branch of down-valley winds originating from the Sanna Valley (SW). Galzig (fig.4.7,right) has slightly decreasing westerly winds compared with the plot without preconditions, possibly a hint for less synoptic-scale influence and more *self-made* winds.

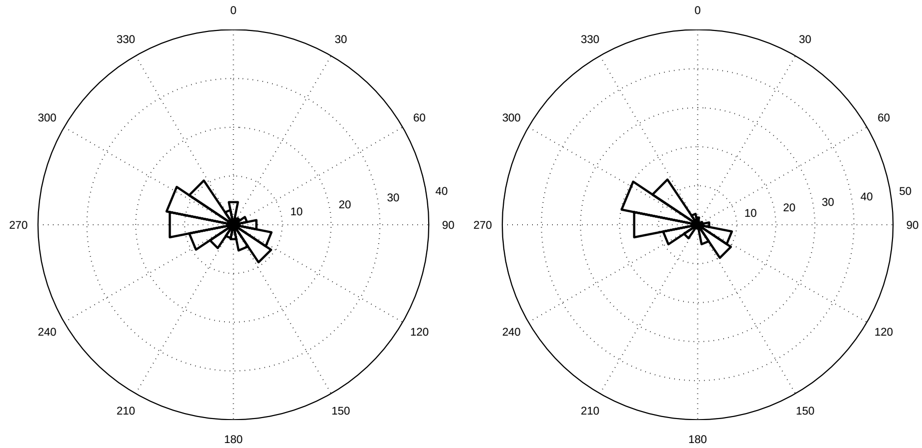


**Figure 4.5:** Frequencies of sectoral wind directions for the period 20081201-20090915, ff larger 0.5 m/s at Bludenz (left) without precondition and (right) without precipitation (# 25174)

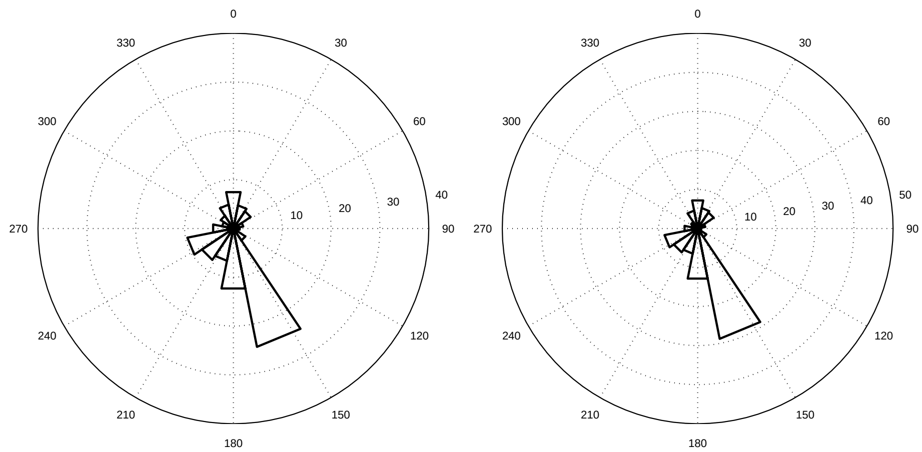


**Figure 4.6:** Frequencies of sectoral wind directions for the period 20081201-20090915, ff larger 0.5 m/s at Landeck (left) without precondition and (right) without precipitation (# 34322)

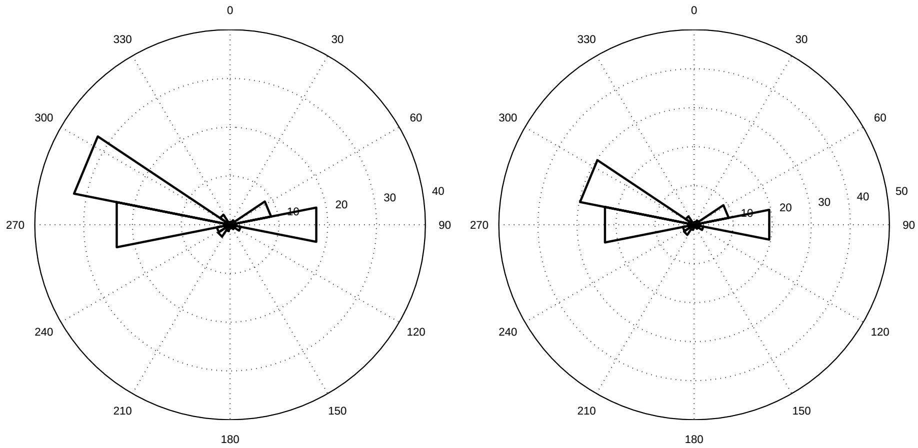


**Figure 4.7:** Frequencies of sectoral wind directions for the period 20081201-20090915, ff larger 0.5 m/s at Galzig (left) without precondition and (right) without precipitation (# 35746)

While the valley wind systems unfolds at Bludenz (fig. 4.5,right), the winds at Langen (fig.4.8,right) blow more often from the pass than from the lower part of the valley. St. Anton (fig.4.9b) shows a strong loss of up-valley winds in the absence of precipitation which seems to contradict the expectations of an idealized valley wind system as being observed at Bludenz.

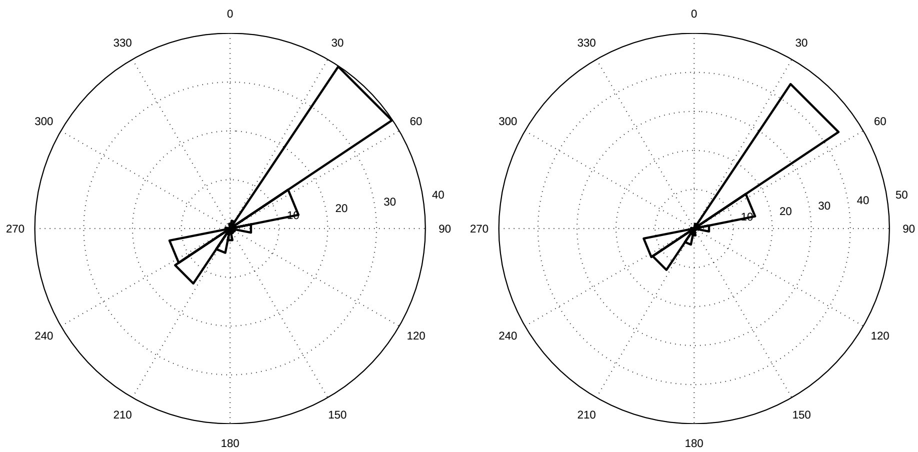


**Figure 4.8:** Frequencies of sectoral wind directions for the period 20081201-20090915, ff larger 0.5 m/s at Langen (left) without precondition and (right) without precipitation (# 33596)

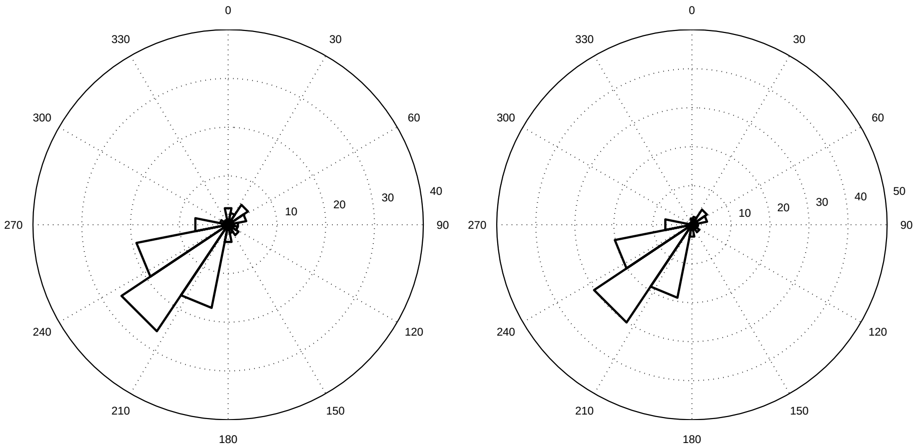


**Figure 4.9:** Frequencies of sectoral wind directions for the period 20081201-20090915, ff larger 0.5 m/s at St.Anton (left) without precondition and (right) without precipitation (# 31520)

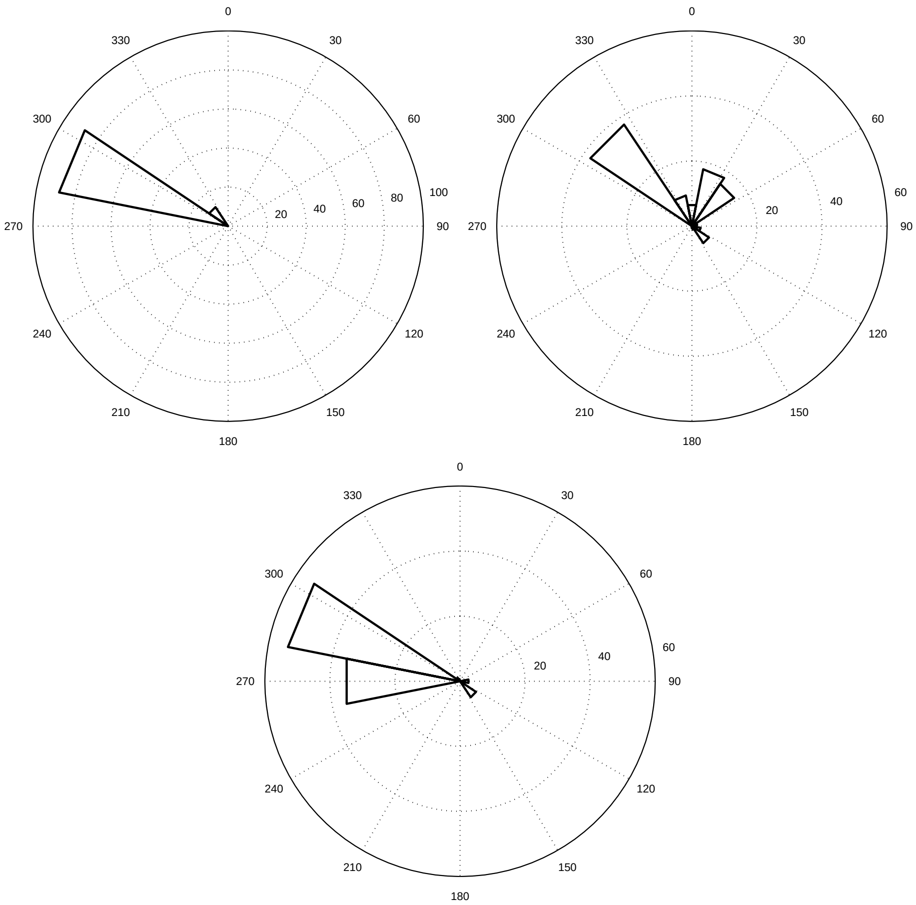


**Figure 4.10:** Frequencies of sectoral wind directions for the period 20081201-20090915, ff larger 2 m/s and without precipitation at (left) Wolfsgrubentunnel (#265), (right) Flirsch (# 365) and (bottom) Strengen (#152), with down-valley winds generally NW and up-valley winds SE

Flirsch (fig.4.10,right) still has dominant down-valley winds and only a small portion of up-valley winds. The northeasterly winds do not match the orientation of the valley, they may be slope winds. In the case of Wolfsgrubentunnel (fig.4.10,left), down-valley winds are always present without precipitation. However, the quite low number of winds of at least 2 m/s (¡ 5 %) in general should be taken into account. For Strengen (fig.4.10,bottom), down-valley winds also hold the majority, but at least a small portion is due to up-valley winds.

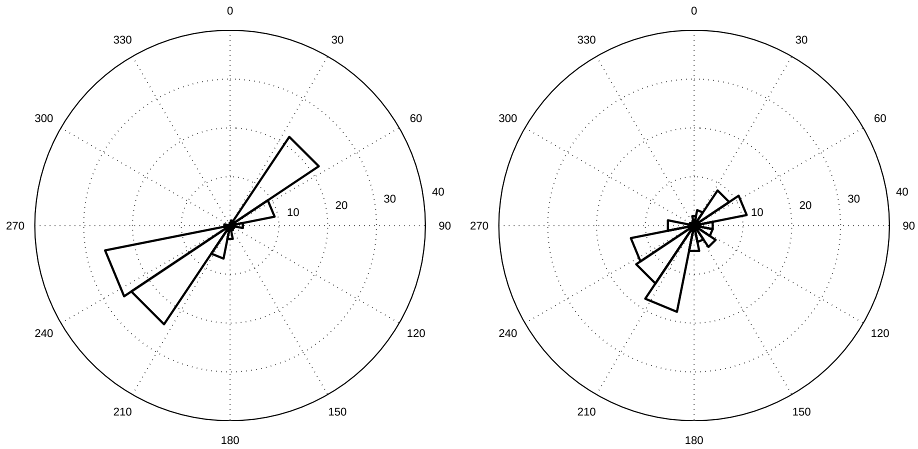


**Figure 4.11:** Frequencies of sectoral wind directions for the period 20081201-20090915 without precipitation and when ff is larger than 0.5 m/s, for (left) Langen when Bludenz has up-valley winds $(240 - 330°)$ and (right) for St.Anton when Landeck has up-valley winds $(0 - 60°)$

Taking **only** up-valley winds at Bludenz and at Landeck into account, one obtain different frequencies for the valley winds at Langen (fig.4.11,left) and at St. Anton (fig.4.11,right), respectively. While Langen still has an ordinary valley wind system with similar frequencies of up- and down-valley winds, St. Anton shows more down-valley winds than up-valley winds.

In conclusion, the lack of precipitation suggests the presence of a valley wind system. Bludenz has a textbook valley wind system where up-valley winds reach a similar frequency as down-valley winds. The other weather stations all detect a vast majority of down-valley winds. At Langen the adjacency to the pass region may play a prominent role in determining the direction of the valley winds (synoptic-scale winds, foehn winds, catabatic winds) whereas Landeck experiences enhanced down-valley winds due to south foehn (Strobl 2009). With up-valley winds at the mouth of the Kloster and Stanzer Valley, respectively, the majority of down-valley winds in the Stanzer Valley is better visible.

### 4.3.2 With Sunshine

The next plots of Langen, Galzig, St. Anton and Landeck address to the valley wind regime associated with sunshine duration. The wind roses were plotted for wind directions of periods with 10 minutes sunshine per 10 min interval (full sunshine duration) and the wind average of least 0.5 m/s. Sunshine duration is not available at the ÖBB stations and at Bludenz.

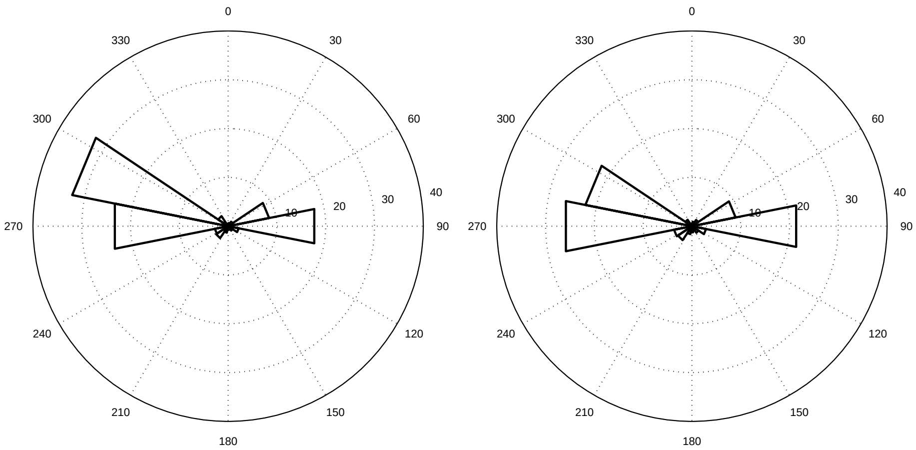


**Figure 4.12:** Frequencies of sectoral wind directions for the period 20081201-20090915, ff larger 0.5 m/s at Galzig (left) without precondition and (right) during full sunshine duration (# 5460)

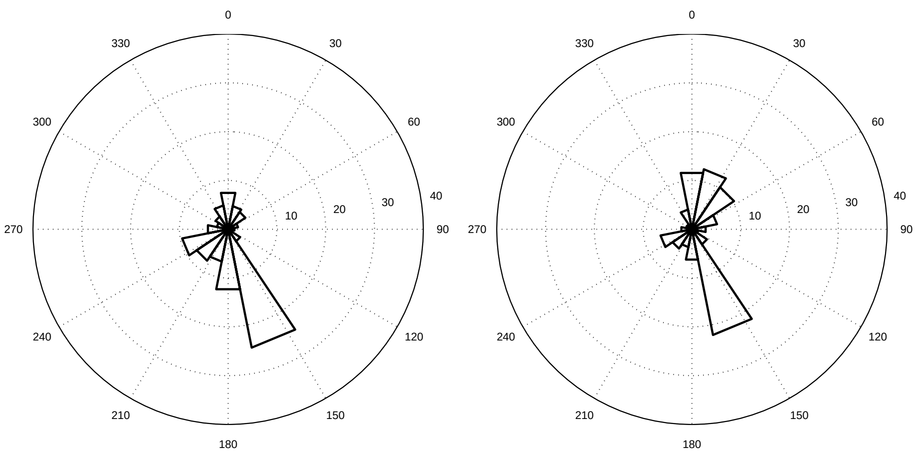


**Figure 4.13:** Frequencies of sectoral wind directions for the period 20081201-20090915, ff larger 0.5 m/s at Landeck (left) without precondition and (right) during full sunshine duration (# 5460)

At Galzig (fig.4.12,right), westerly winds are slightly more frequent than easterly winds. There are different possibilities for the nearly balanced frequencies during sunshine: strong westerly winds could be associated with strong synoptical westerly winds, and strong easterly winds could be the result of southerly winds being deflected by the mountain range to the north of Galzig when strong southerly flows are present, e.g. during a south foehn period in December 2008:

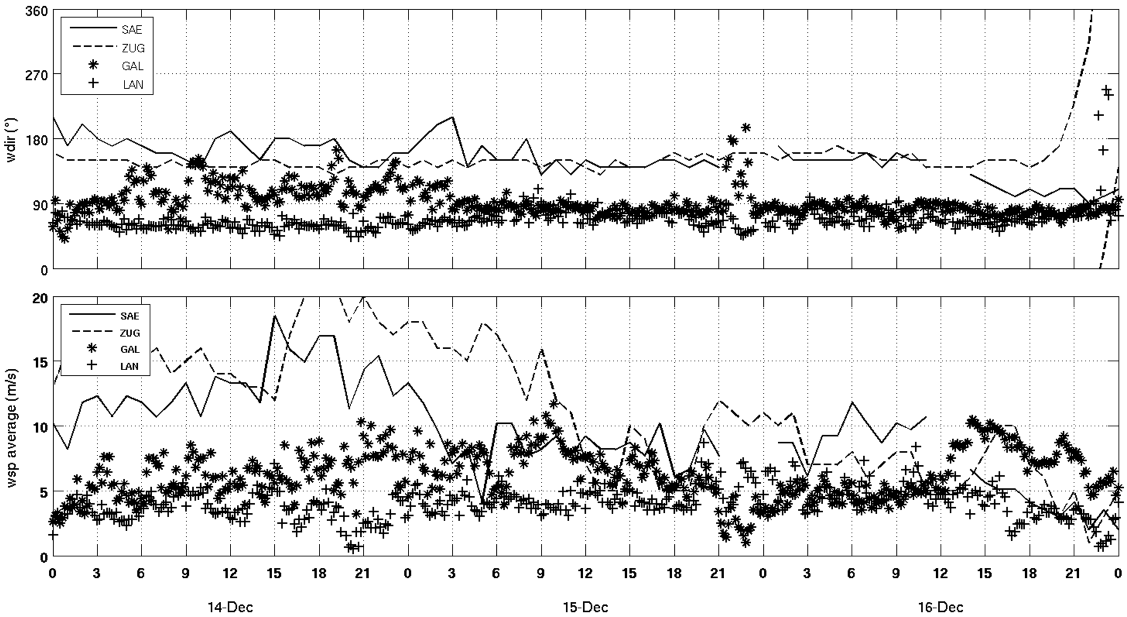


**Figure 4.14:** South foehn event 14-16th December 2008: Wind direction and average at the mountain stations Säntis (solid), Zugspitze (dashed) and Galzig (stars) as well as Langen (crosses)

Figure 4.14) shows persistent southerly winds at Säntis and Zugspitze while Galzig has easterly winds in exceed of 5 m/s simultaneously. So it is hard to separate synoptic-scale influence from local-scale influence at Galzig without using average wind thresholds at the mountain stations. An anomaly of valley winds also exists at Landeck (fig.4.13,right): for a higher threshold, the relative frequency is nearly 100 % for down-valley winds (see fig.4.15). They may arise from the pass farther southsoutheast at the Alpine main crest which induces south foehn winds with synoptic-scale southerly winds (Strobl 2009).

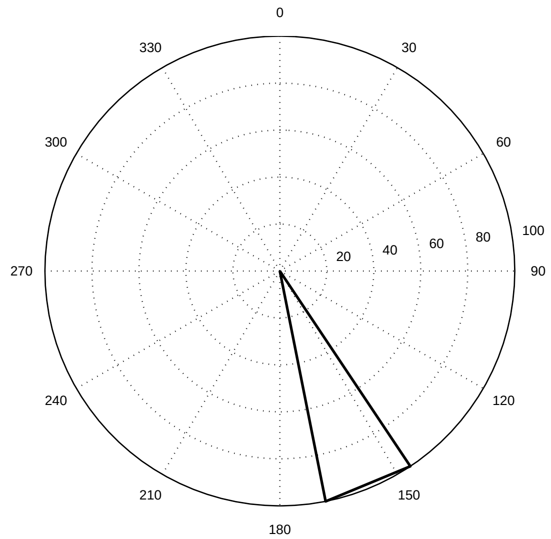


**Figure 4.15:** Same as fig.4.12, but for Landeck and with wind averages above 7 m/s

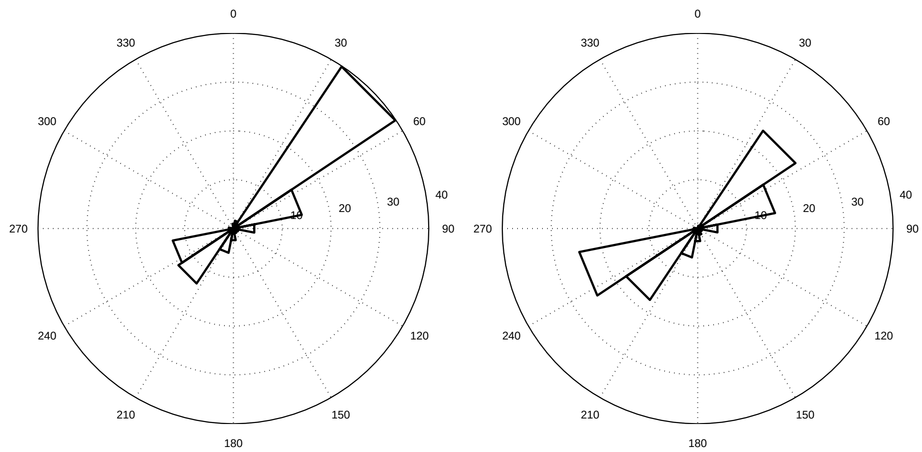


**Figure 4.16:** Frequencies of sectoral wind directions for the period 20081201-20090915, ff larger 0.5 m/s at Langen (left) without precondition and (right) during full sunshine duration (# 5460)

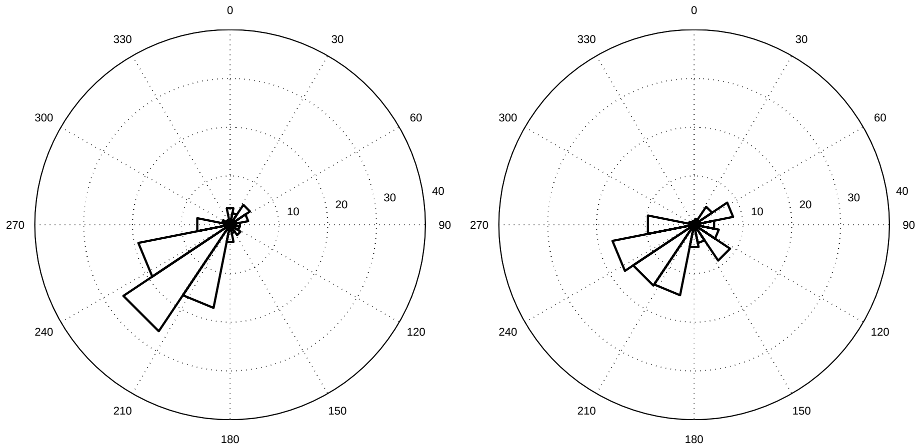


**Figure 4.17:** Frequencies of sectoral wind directions for the period 20081201-20090915, ff larger 0.5 m/s at St.Anton (left) without precondition and (right) during full sunshine duration (# 5460)

At Langen (fig.4.16,right), up-valley winds are slightly more frequent than down-valley winds. Despite sunshine, a considerable amount of down-valley winds is present. They could occur when solar input is not sufficient to erode the cold air pool produced by radiative cooling (additionally supported by snow cover), or from foehn winds which are deflected north of the Arlberg pass. The latter possibility is supported by the case study illustrated above (fig.4.14) for which Langen has easterly winds with above 3 m/s (sometimes higher) in the same direction and magnitude as Galzig.

At St.Anton (fig.4.17,right),down-valley winds dominate during sunny periods - another signal for reverse valley winds in the Stanzer Valley. At St. Anton, average winds larger than 7 m/s do not exist within the limited period.

## 4.4 Averaged daily course of winds in case of reverse valley winds

To examine in more detail the presence of reverse valley winds at St. Anton and Galzig, summary case studies were performed by searching days of reversal winds (up-valley winds in the before noon and down-valley winds in the afternoon) manually. As a result, there are 149 days (see table A.1 in the Appendix within the period 10/2007 -10/2009 where reverse valley winds could be observed, partly affected by precipitation. Most of days stem from April to September, and only few days from October to March indicating that the phenomenon is related to solar elevation. Each date in the high-resolution data set (10 min) was averaged and the respective mean and standard deviation as well as the 10%, 25%, 50%, 75% and 90% percentile for the wind direction and average were calculated The plots in subsections 4.4.1 refer to these 149 days, the plots in subsection 4.4.2 refer to the remaining days without reverse winds. Langen, Bludenz and Landeck serve as reference plots of the adjacent valleys.

### 4.4.1 Mean, standard deviation and percentiles

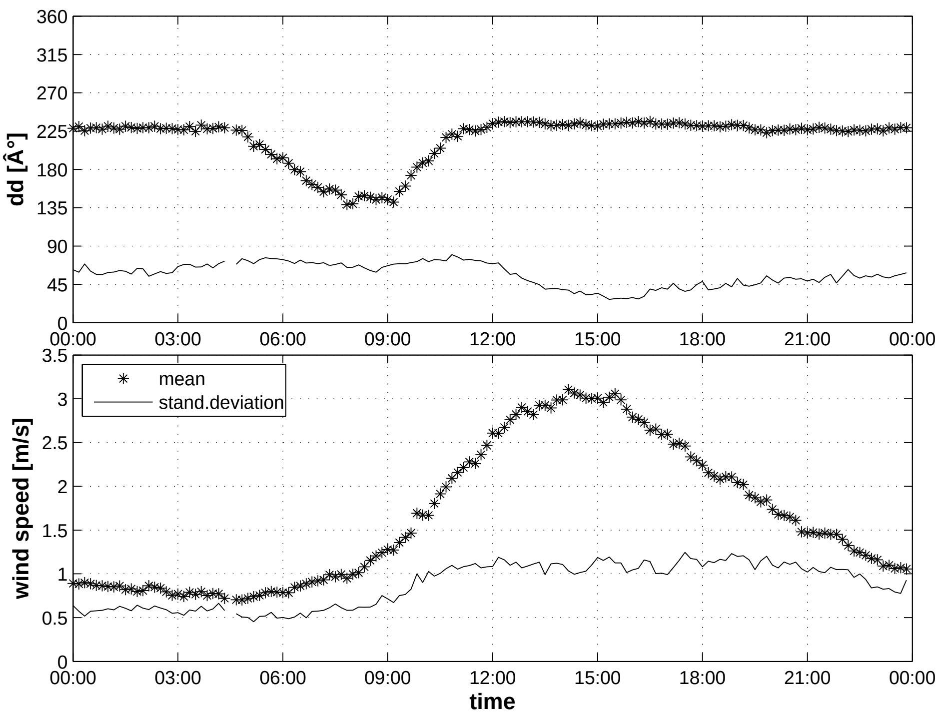


**Figure 4.18:** Mean diurnal winds (stars) and standard deviation (solid line) at St. Anton, valid for 149 days with manually identified reverse winds at St. Anton, down-valley winds: SW, up-valley winds: NE-SE

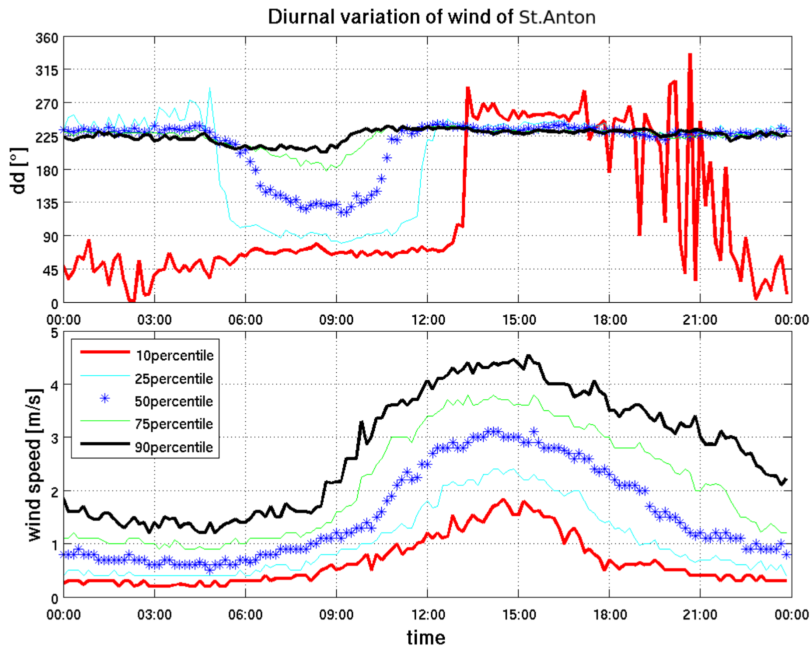


**Figure 4.19:** St. Anton. Same as in section 4.4.1, but with percentiles. Red: 10th percentile, black: 90th percentile, turquoise: 25th percentile, green: 75th percentile, blue stars: 50th percentile (= median)

The mean diurnal course of winds at St. Anton (fig.4.18) on days with reverse winds exhibits three phases: weak down-valley winds from 00 UTC to 07 UTC, slightly increasing up-valley winds from 07 UTC to 11 UTC and finally change to increased down-valley winds from 11 UTC to 00 UTC. The corresponding standard deviation suggests that the first wind change from down-valley to up-valley winds ranges from early morning to before noon. However, the phase of enhanced down-valley winds in the afternoon is linked to a decrease of standard deviation below 40 degrees, that is, afternoon down-valley winds almost always exist. The down-valley winds in the afternoon are opposite to the classical valley wind regime.

The plot of the percentiles (fig. 4.19) depicts in all cases a phase of down-valley winds in the afternoon hours, with increasing winds during the transition time and maxima when down-valley winds become etablished. The transition point varies with the wind speed. The larger the speed, the less pronounced and earlier the change into down-valley winds.

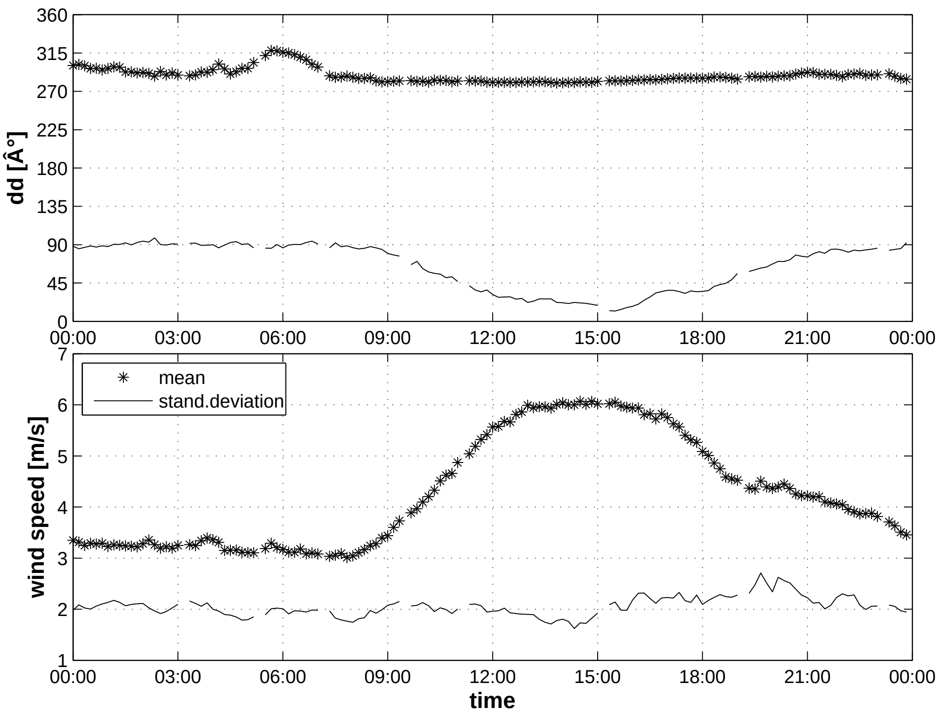


**Figure 4.20:** Same as fig.4.18, but for Galzig

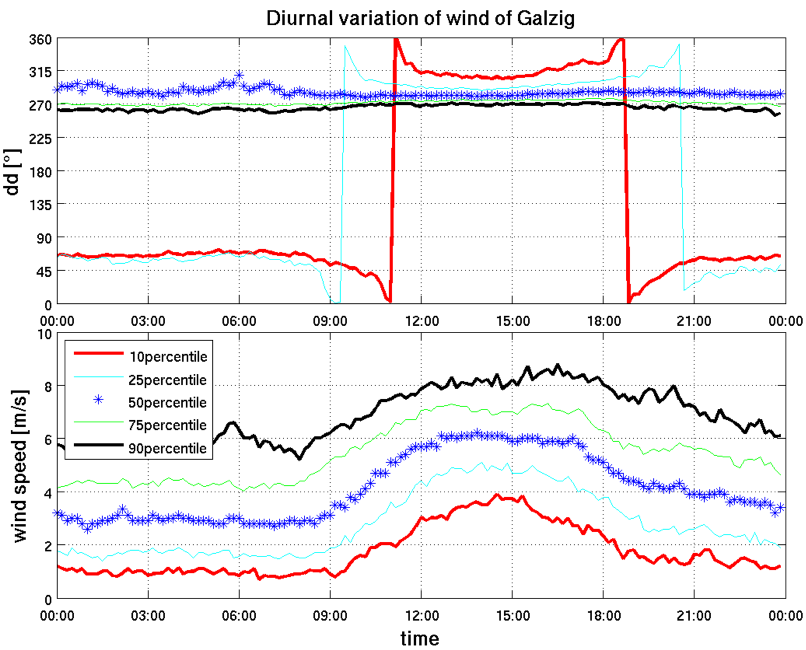


**Figure 4.21:** Galzig. Same as fig. 4.19

On days with reverse winds at St. Anton, Galzig (fig.4.20) has westerly winds throughout day and night. Wind directions vary least in the afternoon at the time

of reversed winds at St. Anton. Wind speeds at Galzig are about 2-3 m/s higher than at St.Anton. Large standard deviations before 09 UTC and after 21 UTC of about 90 degrees indicate that the wind direction varies between northerly winds (occurring rather infrequently - checked manually) and southerly winds, but with weaker velocities.
Galzig (fig. 4.21) reveals changing wind directions in the lower percentiles like St. Anton, with two transition points and corresponding low wind speeds. In the case of stronger winds (¿ 3 m/s), the phenomenon does not exist and synoptic-scale westerly winds dominate throughout the day.

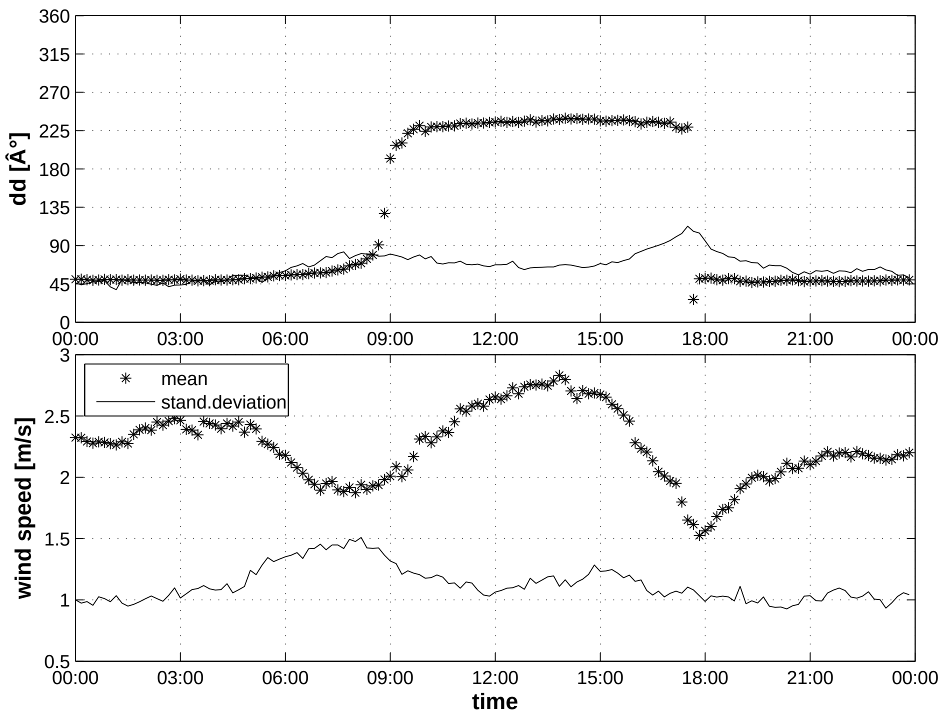


**Figure 4.22:** Same as fig.4.18, but for Langen, down-valley winds: NE, up-valley winds: SW

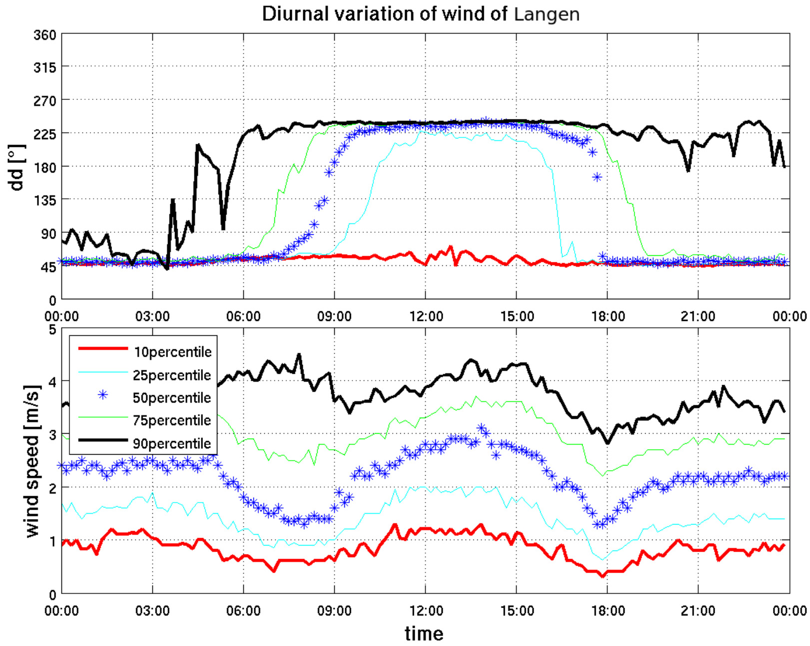


**Figure 4.23:** Langen. Same as fig. 4.19

Langen (fig.4.22) west of the Arlberg pass shows a classical diurnal wind regime with up-valley winds between 09 UTC and 18 UTC and abrupt direction changes. Compared with the other valley stations, the mean wind speed stays relatively high during the down-valley wind phases. It might be caused by the persistent downward-mixing of slightly larger wind speeds of Galzig as already mentioned by Ekhart (1937).

The percentiles (fig. 4.23) show a more complex picture with two extrema: persistent down-valley winds throughout the entire period (10th percentile) which may originate from foehn winds as already seen in fig. 4.14 in section 4.3.2, and one-transition-point with the 90th percentile when up-valley winds blow from early morning until midnight with strongest wind speeds (in exceed of 3 m/s) as it could be the case when strong synoptic-scale winds are superimposed. Otherwise, the up-valley wind phase becomes established - similar to St. Anton - the stronger the wind, the earlier the transition which means that enhanced vertical momentum flux could favour the onset of up-valley winds at Langen.

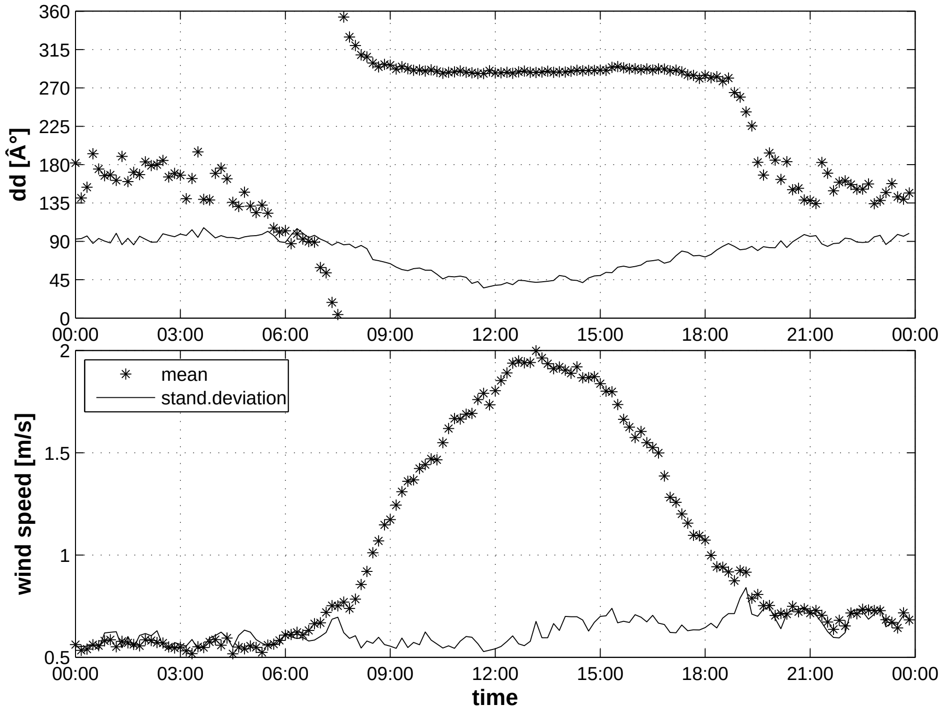


**Figure 4.24:** Same as fig.4.18, but for Bludenz, down-valley winds: SE, up-valley winds: NW

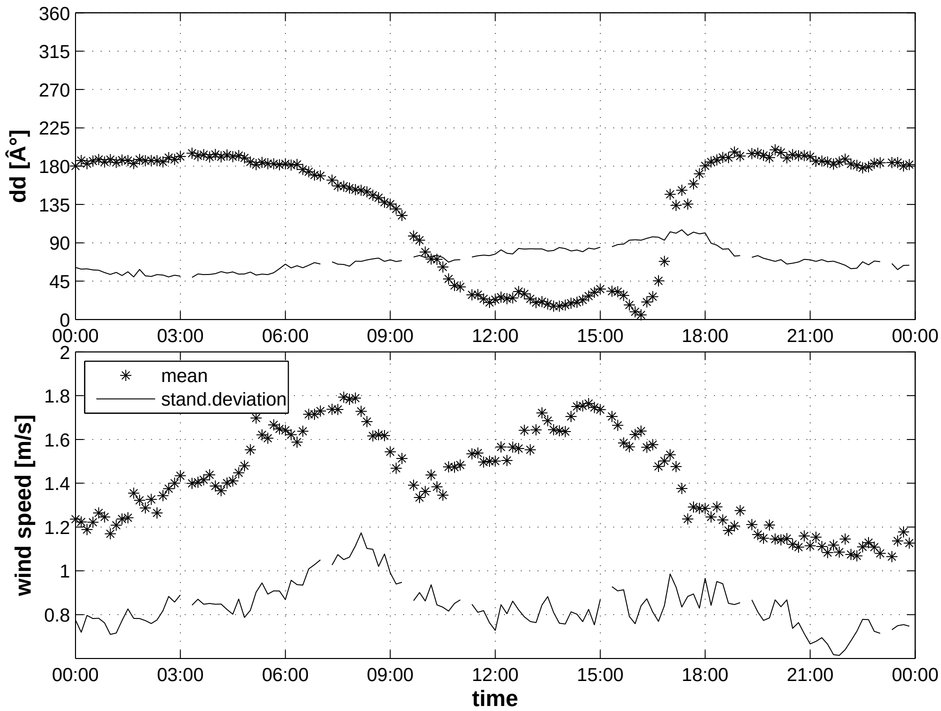


**Figure 4.25:** Same as fig.4.18, but for Landeck, down-valley winds: SSE, up-valley winds: NE

Now let us take a look at Bludenz (fig. 4.24) where a textbook-like course of winds is present. The mean wind direction changes from down-valley winds during the night and the early morning to up-valley winds by 08 UTC and ends with about 19 UTC. The phase of up-valley winds is accompanied by weak, but noteworthy winds with low standard deviation. Besides this period, generally weak winds prevail and down-valley winds with large deviation of the mean direction exist.

Landeck (fig. 4.25) has a normal valley wind system as well as the wind changes in the forenoon hours from southeasterly (down-valley) to northeasterly (up-valley) winds, and back to down-valley winds in the evening. Standard deviations are higher than at the other stations, especially during the transition point in the evening. Velocites are below 2 m/s, with about 0,5 m/s increase towards the first transition point and a second one during peak-time of the sun/up-valley winds.

### 4.4.2 Percentiles outside the period of reverse winds

Finally, plots were performed for all days outside the special period.

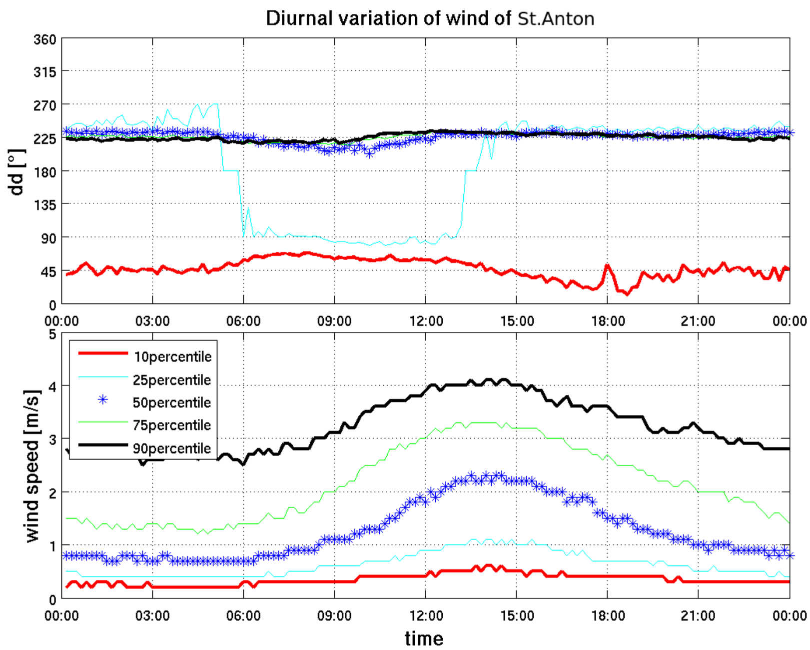


**Figure 4.26:** St. Anton. Same as in section 4.4.1, but with percentiles. Red: 10th percentile, black: 90th percentile, turquoise: 25th percentile, green: 75th percentile, blue stars: 50th percentile (= median), only valid outside the period of 149 days

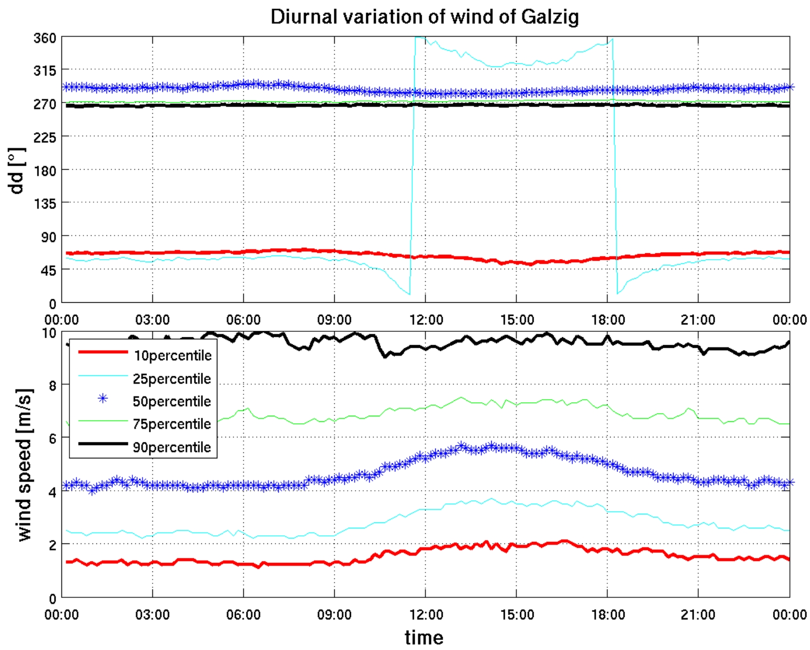


**Figure 4.27:** Galzig. Same as fig. 4.26

Exluding the period of manually detected reverse winds, the plot of St.Anton (fig. 4.26) confirms that reverse winds still occur in 25% of the days of the remaining period . Persistent up-valley winds solely exist with low-end average winds.

The same picture at Galzig (fig. 4.27), where three regimes can be found: switching wind directions similar to St. Anton, persistent westerly winds when synoptic-scale westerly winds are strong, and persistent easterly winds when synoptic-scale easterly winds are strong and south foehn winds exist (cf. fig.4.14), respectively. The connection of synoptic-scale winds with persistent wind direction at Galzig becomes especially visible with the case studies in chapter 6 considering turbulent mixing.

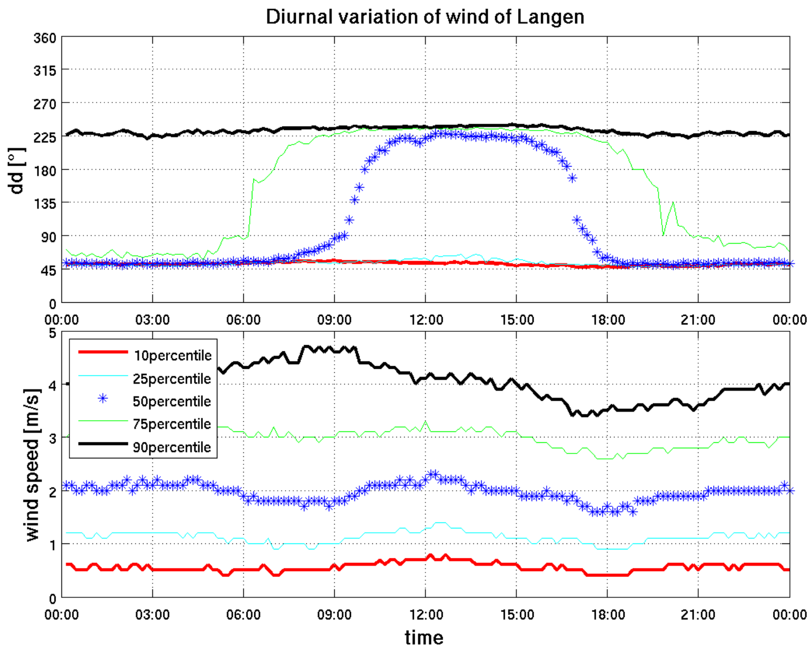


**Figure 4.28:** Langen. Same as fig. 4.26

The same holds for Langen (fig. 4.28), but with reverse sign. Weak down-valley winds and strong up-valley winds throughout the entire period, moderate winds when a valley wind system can evolve.

## 4.5 Summary

In the case of weak pass winds at Galzig, the valley wind systems of Langen and St. Anton are most pronounced. St. Anton possess the mentioned reversal of the valley winds with a short period of up-valley winds before noon and a longer period of enhanced down-valley winds in the afternoon passing into weak down-valley winds in the evening and first half of the night when radiative cooling brings the *usual* down-valley wind back.

When (westerly) pass winds are stronger, the respective valley wind systems are less pronounced, but still present in both valleys. Up-valley wind periods tend to be shorter at St. Anton (where the westerly wind counteracts the easterly up-valley wind) and tend to be longer at Langen (where the up-valley and synoptic-scale wind have the same direction). One may consider it as a hybrid case when an ill-defined valley wind system and weakly turbulent downward-mixing of synoptic-scale winds coincide.

The third situation evolves when dominant westerlies aloft are always stronger so that up-valley (= westerly) winds and down-valley (= westerly) winds at St. Anton prevail most of the day, probably due to the vertical momentum transport. The latter may act as a classic "west foehn" with decreasing relative humidity, increasing temperatures and increasing wind speed. As the vast majority of winds at St. Anton originates from the pass region, there is no sudden change of the wind direction when foehn winds are observed.

Furthermore, it is important to note that - with reverse winds at St. Anton - Galzig develops a valley wind system, too. It does not happen simultaneously but slightly shifted, with down-valley winds about two hours earlier at Galzig. Another difference is that Galzig has a second transition point (down-valley to up-valley winds) within the period where enhanced down-valley winds at St. Anton still exist.

Bludenz and Landeck possess usually pronounced valley wind systems on days with reversal valley winds at St. Anton indicating that the generation of the reversal valley winds in the Stanzer Valley (and Arlberg pass region) is favoured when weak synoptic winds are present. The next section (5) set up theories to explain the processes leading to the reversal of the winds in the Stanzer Valley.

# Chapter 5

# Hypotheses to explain reverse winds in the Stanzer Valley

The results of section 4 raise the question through which process the reversal of the Stanzer Valley winds is generated. To clarify this point, four hypotheses basing on earlier hypotheses and recent ideas of myself and others will be posed.

The first hypothesis is related to the asymmetries of the valley geometry of both the Kloster and Stanzer Valley (Wagner 1932b; Ekhart 1937) suggesting differential heating in both valleys is responsible for the reversal of the valley winds in the Stanzer Valley by "encroaching" valley winds from the Kloster Valleys across the Arlberg pass into the Stanzer Valley. Due to missing area-height results for the valleys, that matter cannot be followed up in the case studies in section 6.
The second hypothesis is based upon findings from Klainguti-Schaumann (1937) and Georgii et al. (1974) supposing the Maloja wind (see sec. 2.4) is enhanced with a superimposed flow in the down-valley direction and inhibited with a flow in the up-valley direction. Since the Arlberg pass region seems to have similar prerequisites compared with the Maloja pass region (e.g. the differently sloped terrain beyond the pass), that theory was transferred to the area of examination. The third hypothesis is linked to studies in the Karwendel mountains (Hornsteiner 2005) and close to Trento (De Franceschi et al. 2002) where local-scale gap flows are observed. Under the assumption of horizontal potential temperature differences beyond the Arlberg pass, gap flow dynamics may be responsible for the observed "encroaching" valley winds. The last hypothesis was expressed by Ralph Rickli, meteorologist, in personal communication, likewise addressing the Maloja winds, assuming differential heating alongside the valley axis of the Upper Engadin. Subsequently, stronger heating in the lower parts of the valley causes a stronger pressure fall and downward directed gradient winds.
The different hypotheses shoud not be considered in a separate manner but they

can be linked together if one or more prerequisites are present.

## 5.1 Asymmetries of the valley geometries beyond the Arlberg pass

According to the first hypothesis, reverse winds result from asymmetries of the valley geometry. Fig. 5.1 shows the slope of the terrain starting with Bludenz to the west and ending with Landeck to the east. It reveals that the Kloster Valley is sharply sloped throughout the entire valley except upstream of Langen. In contrast, the Verwall Valley and upper Stanzer Valley up to Wolfsgrubentunnel are less sloped, with increasing inclination up to the mouth into the Sanna Valley and Landeck. Thus, it is difficult to simplify the asymmetries to a steep Kloster Valley and a flat Stanzer Valley bottom as the Stanzer Valley itself consists of two differently sloped parts.

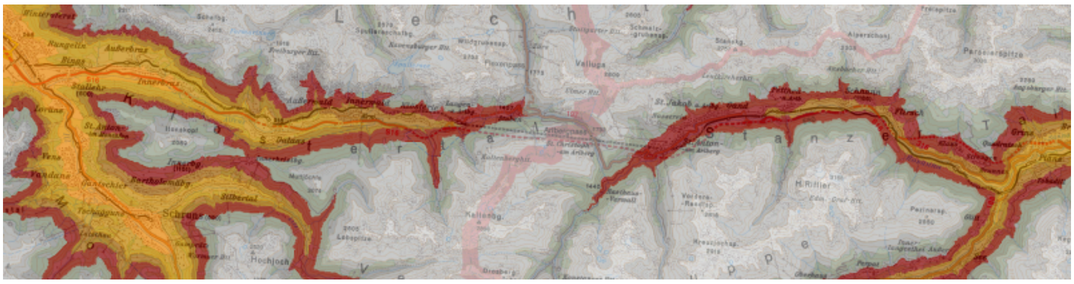

**Figure 5.1:** Slope angle of the topography (coloured) of the Kloster and Stanzer Valley on a scale of 1:50000, ranging qualitatively vom flat terrain (red) to sharply inclined terrain (yellow). ©BEV 2010 - reproduction with courtesy of BEV - **B**undesamt für **E**ich- und **V**ermessungswesen in Vienna, T2010/66937

Due to the lack of area-height distributions in both valleys, it is not possible for me to quantify the influence of the valley geometry on the daily heating rate and the TAF, respectively. However, considering the slope angles of the topography one would assume larger heating rates in the Kloster Valley than in the Stanzer Valley which is in contrast to the argumentation of Ekhart (1936) who found larger daily temperature amplitudes (by means of barometric mean temperatures) at St.Anton than at Langen.

For better examinations, area-height distributions should be calculated to quantify the potential heating rates in different layers of the valleys. Moreover, the influence of TAFs is confined to below-crest level inversions which was not taken into account by Ekhart.

## 5.2 Turbulent downward mixing

The second hypothesis is based upon Klainguti-Schaumann (1937) and Georgii et al. (1974) assuming the Maloja wind is enhanced with a superimposed flow in the down-valley direction and inhibited with a superimposed flow in the up-valley direction. In addition to that, Li et al. (2008) considering the Owens valley states that " WRF simulations show that for synoptic westerly days the detected westerly wind at the valley bottom in the afternoon may be caused by the *intrusion of the ridge-top wind* but may be also the result of the modified valley circulation, depending on wind strength and valley stability."

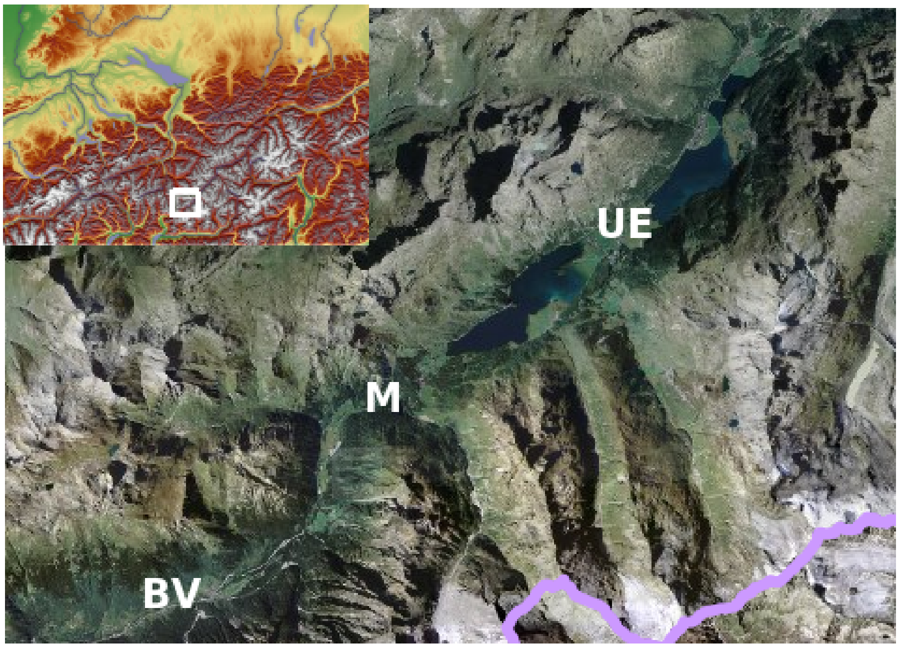


**Figure 5.2:** Maloja pass region in the southern central Alps. BV = Bergell Valley, M = Maloja pass, UE = Upper Engadine. ©Swisstopo (aerial photograph), situation of the photograph: Wikipedia

The Maloja pass region (see section 2.4 for geographic description) in fig.5.2 consists of a "ramp" with the steeply inclined Bergell Valley southwest of the pass and a quite flat and elongate valley bottom of the Upper Engadine northeast of the pass- The situation in the Arlberg region looks similar, with the steep Kloster Valley to the west of the Arlberg pass and the comparatively flat upper Stanzer Valley to the east of the Arlberg pass (neglecting that the terrain between Arlberg pass and upper Stanzer Valley is stronger sloped). Therefore, the theory is translated to the reversal of the valley winds in the Stanzer Valley. Under the assumption of superimposed westerly winds, one would expect down-valley winds east of the Arlberg as a result of vertical momentum transport.

**Test method:** On days with reverse winds, the wind directions and potential temperatures of St. Anton, Galzig (affected by valley winds) as well as Säntis and Zugspitze (mountain stations close to the free atmosphere) were plotted.

**Check:**

(a) valley winds stronger than winds aloft at Zugspitze or Säntis

(b) wind direction of winds aloft (Säntis, Zugspitze, Galzig) are not westerly

(c) stable stratification: $\Delta\Theta > 3$ Kelvin

## 5.3 Gap flow

A few years ago, Hornsteiner (2005) examined local wind systems in the Karwendel mountains between the Upper Inn Valley and the Bavarian Alpine Foreland where he revealed small-scale foehn winds (denoted as *Miniföhn*) in the Isar Valley close to Mittenwald caused by horizontal temperature differences between the foothills of the Alps and its interior.

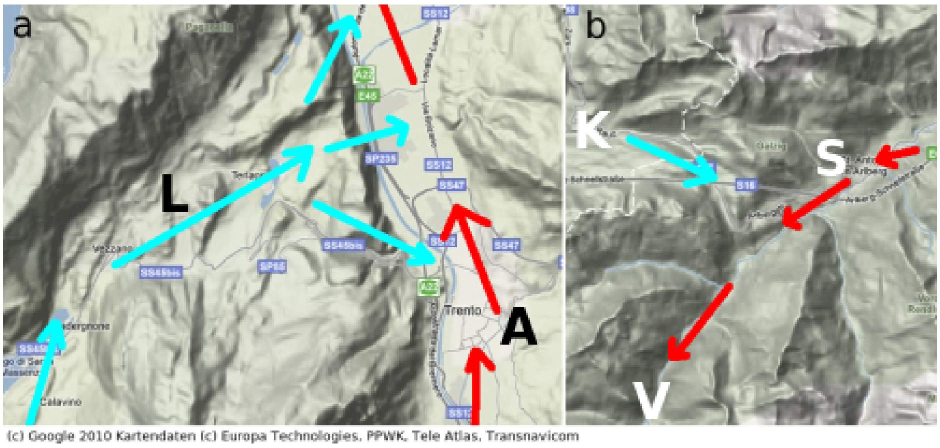


**Figure 5.3:** Comparison of (a) the Laghi Valley (L) -Adige Valley with (b) Arlberg pass region with Kloster Valley (K), Verwall Valley (V) and Stanzer Valley (S), produced by Google Maps. Red arrows indicate up-valley winds and blue arrows indicate down-valley winds.

In Trentino-Alto Adige close to Trento, De Franceschi et al. (2002) showed that the potentially cooler "Ora del Garda" (the up-valley wind blowing from the Garda Lake) acts as a gap flow blowing through the Laghi Valley over an elevated saddle into the Adige Valley. Considering the topographic situation of both the Arlberg region and the Laghi Valley (fig. 5.3), the similarity appears to be much greater than between Arlberg and Maloja pass. In both regions a pass separates two valleys, possibly with protuding potentially cooler air masses, analog to the Isar Valley in a very local scale.

**Test method:** Comparison of upstream (Langen), pass (Galzig) and downstream (St.Anton) potential temperatures, with aid of wind direction, wind average and mixing ratio.

**Check:**

(a) $\Theta_{Galzig} - \Theta_{St.Anton} \geq 5$ K

(b) $r_{Galzig} > r_{St.Anton}$

(c) $dd_{Galzig}$ not westerly

## 5.4 Differential heating alongside the Stanzer Valley

Ralph Rickli, forecaster in Switzerland and giving lectures in Aviation Meteorology and Mountain Meteorology at the University of Bern, told me of another possibility to form winds of the Maloja wind type (2009).

He suggested "the Maloja wind is not a pure valley wind but a gravity current as it blows down the valley. The down-valley winds are triggered by thermal heating at Samedan (downstream) leading to a rapid bulge of geopotential and subsequent upper-level divergence. In lower levels, equivalent potentially cooler air pushes over the Maloja pass into the Upper Engadine. Given sufficient moisture, this happens in the shape of a Maloja serpent. The Maloja wind "looses" downstream of Zernez" (situated between Upper and Lower Engadine), that is the Maloja wind gradually weakens and the valley wind system of the Lower Engadine becomes increasingly dominant. Regarding the slope of the terrain (fig. 5.1), the inclination within the Stanzer Valley varies from a relative flat valley floor in the upper part and a steep floor in the lower part. Given diurnal heating, the lower part will be warmed faster than the upper part due to the favourable area-height distribution (the lower part is steeper and less volume close to the surface has to be warmed) and a horizontal pressure gradient can arise. As a result, down-valley winds develop during the day. During nighttime, the lower valley cools faster than the upper valley and a reverse valley wind comes up, possibly supported by the early onset of up-slope winds in the pass region where solar radiation takes place first.

For the purpose of computing differential heating rates alongside the valley, the hypsometric difference between Galzig and the valley stations is computed from the hydrostatic equation using temperature and pressure measurements. However, the ÖBB data do not show reliable pressure data (which are obtained already as reduced pressure) to perform these computations. As the ÖBB stations are decisive for the development of down-valley pressure gradients, this hypothesis could not be further pursued.

# Chapter 6

# Testing hypotheses in case studies

In this chapter, three case studies will be performed to test the hypotheses for reverse valley winds in the Stanzer Valley posed in chapter 5.To cover most of the season and use all the available stations (with ÖBB data and rare METAR observations of Alpe Rauz), the limited period from May 2009 to September 2009 was chosen. The first case of May 2009 is representative for spring-time, August 2009 is representative for the late summer and finally, the first decade of September 2009 for early fall. The respective case studies start with a short introduction of the weather sitation (see Appendix for the figures) and a temporal overview of wind, sunshine and precipitation at the valley stations. The ÖBB data have lower temporal resolution and less useful wind measurements, and should be considered more qualitatively. Thereafter, each hypothesis will be tested by means of time series and falsification of the checklist set up in 5.

# 6.1 Phase of reverse winds: 11-19 May 2009

## 6.1.1 Weather situation

The weather situation of the first phase of reverse winds at St. Anton ranging from 11th to 19th May 2009, illustrated in figure A.1 , is characterized by southwesterly upper- and mid-level flows.

The period begins with a warm front and corresponding shortwave trough crossing the area of interest from southwest. Thereafter, the Arlberg region lies within a relative warm air mass before another trough approaches from the Gulf of Bisyaca on 14 May. It brushes past on 16 May, temporarily lowering temperatures and causing precipitation. The same day already brings warm air advection before the situation becomes more diffluent in upper-levels and the southwesterly flow strengthens towards the end of the period. Moreover, deep-moist convection was initiated ahead of the next cold front trailing west of the Alpine region. The resulting precipitation is also reflected in the plotted time series below.

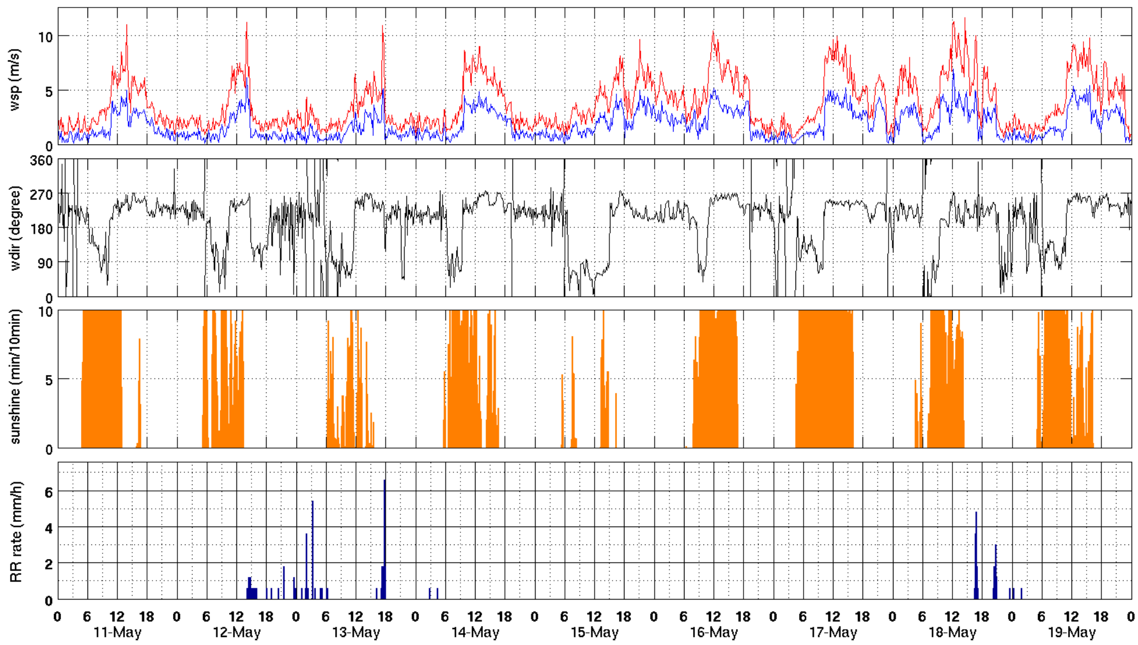


**Figure 6.1:** First phase of reverse winds in St.Anton ranging from 11 to 19th May 2009, time in UTC. First panel: wind average (blue) and maximum average within 10 min (red) in m/s, second panel: wind direction (°), third panel: sunshine duration in min/10min, fourth panel: precipitation rate within 10 min in mm/h

The time series in fig. 6.1 depicts the course of winds, sunshine and precipitation of St. Anton. The up-valley wind phases are strongly related to sunrise and occur each day with different longevity, but similar onset at about 6 UTC. Down-valley winds follow at 12 UTC (+/- 2h) with enhanced wind speed and pass into weak down-valley winds after sunset (possibly thermally driven), except for 12th May when precipitation led to a sudden change into up-valley winds in the early afternoon.

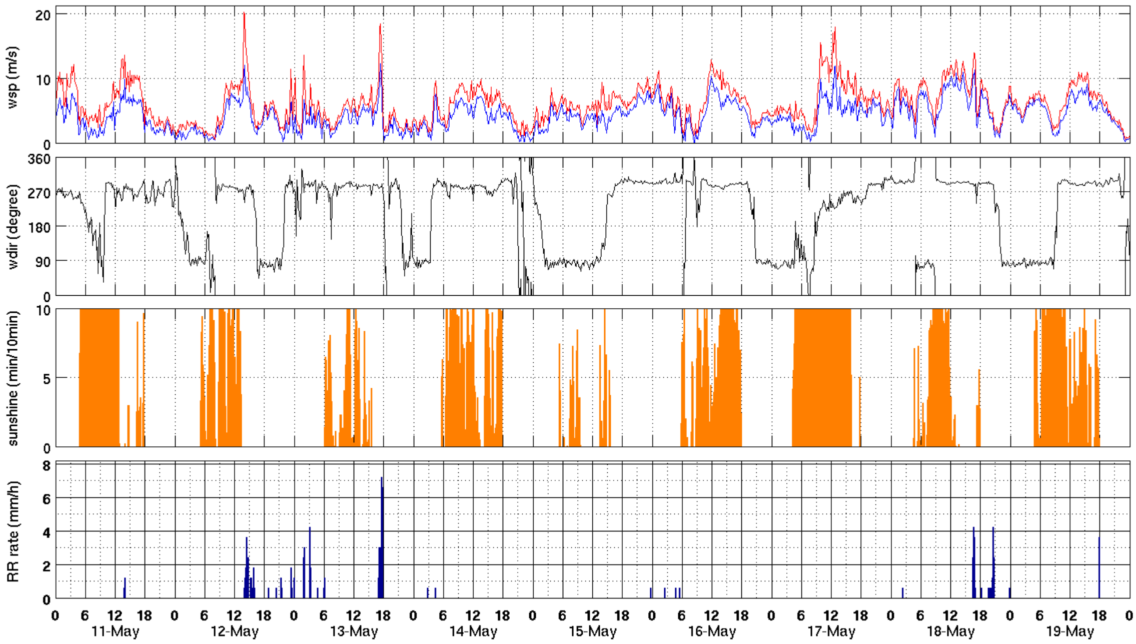


**Figure 6.2:** Same as fig. 6.1, but for Galzig.

For Galzig (fig. 6.2), valley winds also become established in the period of reverse winds at St. Anton. However, down-valley winds (= westerly) start earlier than at St. Anton. Interestingly, up-valley (easterly) winds mainly set up without sunshine periods.

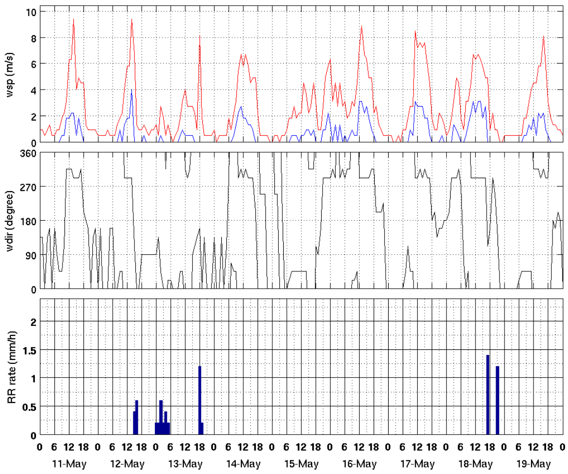


**Figure 6.3:** Same as fig. 6.1, but for Wolfsgrubentunnel (hourly) and without sunshine

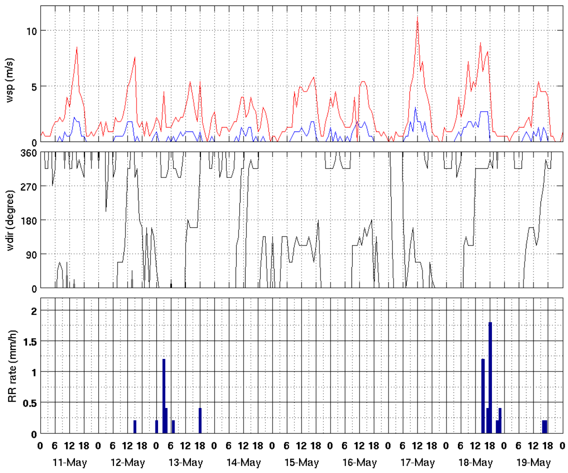


**Figure 6.4:** Same as fig. 6.1, but for Flirsch (hourly) and without sunshine

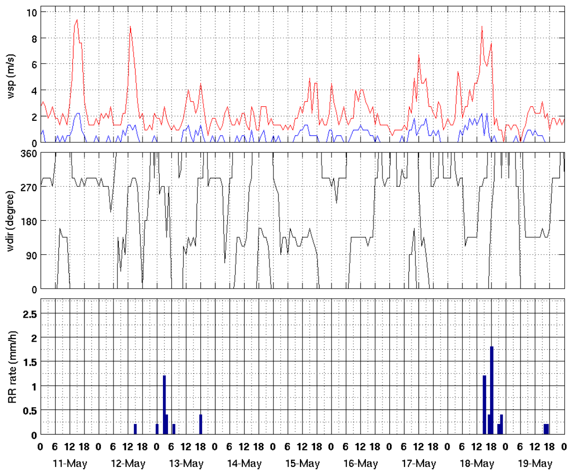


**Figure 6.5:** Same as fig. 6.1, but for Strengen (hourly) and without sunshine

The ÖBB data (6.3,6.4and 6.5) reveal quite week average winds caused by the low anemometer height. Nevertheless, peak winds are clearly visible being confined to down-valley winds (west to northwest at all stations) indicating the extension of reverse winds to the lower part of the Stanzer Valley.

Additional METAR data from Alpe Rauz just upstream of Galzig show down-valley winds on 11th, 13th and 14th May throughout the day, and up-valley wind phases on 12th, 18th and 19th May before noon, with different transition points (+/- 2 hours).

### 6.1.2 Turbulent downward mixing hypothesis

According to section 5.2, several conditions need to be fulfilled to have synoptic-scale winds turbulently mixed downward: valley winds at St. Anton have to be weaker than at mountain stations aloft, the wind directions of all stations have to be uniform (easterly winds with up-valley winds and westerly winds with down-valley winds) and the valley atmosphere has to be neutrally and unstable, respectively, stratified.

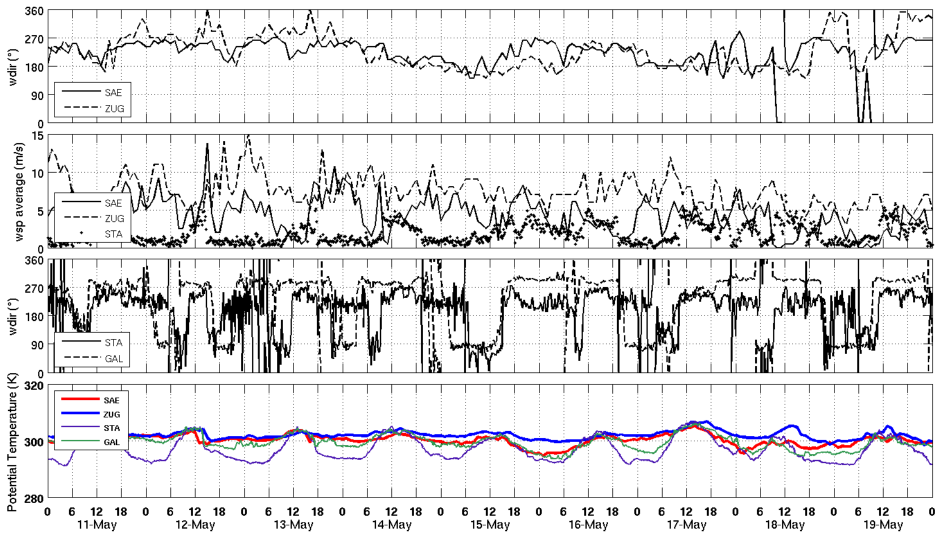


**Figure 6.6:** Reverse valley wind phase, 11-19th May 2009. (top panel) Wind direction (°) and (second panel) speed (m/s) of Säntis (solid), Zugspitze (dashed) as well as wind speed of St.Anton (crosses), (third panel) wind direction of St. Anton (solid) and Galzig (dashed) and (fourth panel) potential temperature (K) of Säntis (red), Zugspitze (blue), St.Anton (purple) and Galzig (green)

Figure 6.6 exhibits that firstly, winds in St. Anton are always clearly weaker than at the mountain stations Säntis and Zugspitze implicating that vertical wind shear exists to excite winds turbulently mixed downward. Secondly, the mountain stations have westerly winds during the first half of the period, even when St. Anton has up-valley winds, and southerly to southwesterly winds in the second half of the period when reverse valley winds still occur at St. Anton and also at Galzig. Thirdly, the potential temperature at St. Anton is significantly lower (about 5K) than the mountain stations, including Galzig, during the night, and match the values of the mountain stations only during daytime indicating that solar heating leads to deeply mixed boundary layers and radiative cooling produces a decoupled valley atmosphere from the free atmosphere above.

As a result, the necessary criteria to have turbulent downward mixing durch reverse valley wind phases are not entirely fulfilled as wind directions and potential temperature are different during the up-valley wind phases and only match, additional to the vertical wind shear in the down-valley wind phases.

### 6.1.3 Gap flow hypothesis

The detection of a gap flow in the Arlberg region suffers from the poor density of weather stations in the pass region, especially in the lower part of the pass (St. Christoph) and just downstream in the Rosanna Canyon. Taking these limitations into consideration, the next figure attemps to illustrate whether the prerequisites for gap flows were fulfilled during the Arlberg wind phase: wind directions of both Galzig and St. Anton have to be equal, $\Theta_{Galzig}$ has to be equal or slightly lower than $\Theta_{St.Anton}$ and mixing ratios at St. Anton have equal or higher than at Galzig.

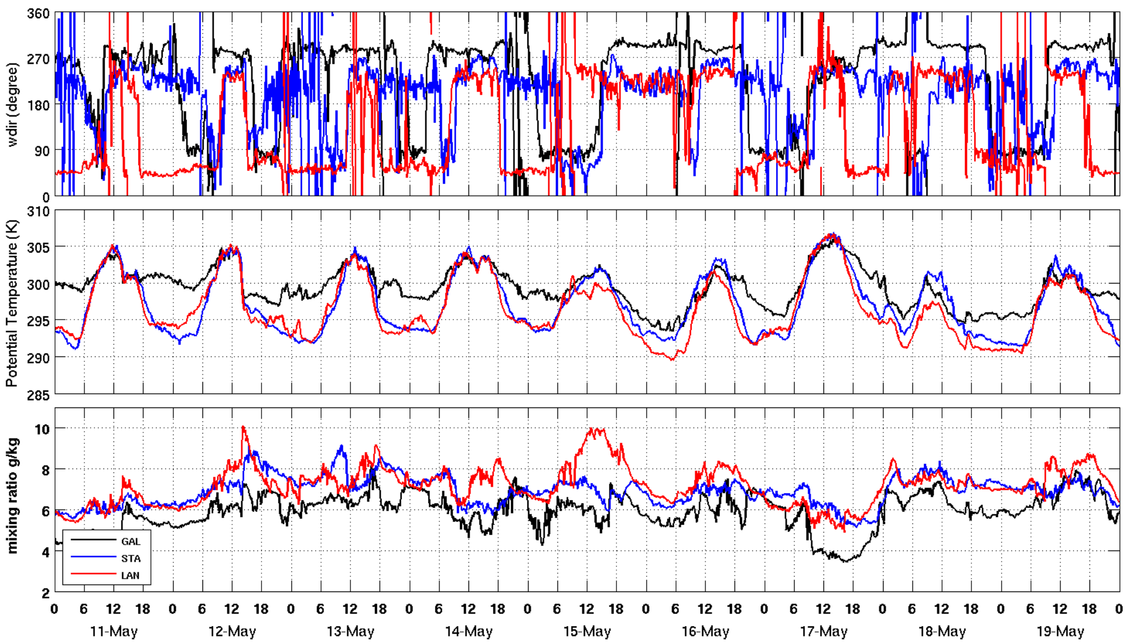


**Figure 6.7:** Reverse wind phase, 11-19th May 2009.(Top panel) Wind direction (°), (middle panel) Potential Temperature (K) and (lower panel) mixing ratio (g/kg) of Galzig (black), St. Anton (blue) and Langen (red).

Figure 6.1.3 reveals that the wind directions at St. Anton and Galzig are different during phases of up-valley winds at St. Anton (e.g. on 11th May, 13th May, 16th May and 18th May) with shifted transition points (later or earlier onset at one of both locations) of up-and down-valley winds. So the phases of up- and down-valley winds (easterly and westerly winds, respectively, at Galzig) do not coincide regarding the transition points. The same holds for Langen. Furthermore, the potential temperature at St. Anton is equal to Langen during up- and down-valley winds and slightly lower (about 2-3 K) than at Galzig during up-valley winds, and equal also to Galzig when the wind directions are identic. Mixing ratios at St. Anton are always higher than at Galzig.

As a result, neglecting the different transition points there may exist phases where gap flows are present as the mixing ratios, potential temperature and wind direction are equal and slightly differ within the range of tolerance, respectively.

## 6.2 Phase of reverse winds: 14-19 August 2009

### 6.2.1 Weather situation

The weather maps (fig.A.2) display weakly anticyclonic conditions prevailing throughout the period although quite high $\Theta_e$ values point to potential instability leading to convective precipitation on the first two days.

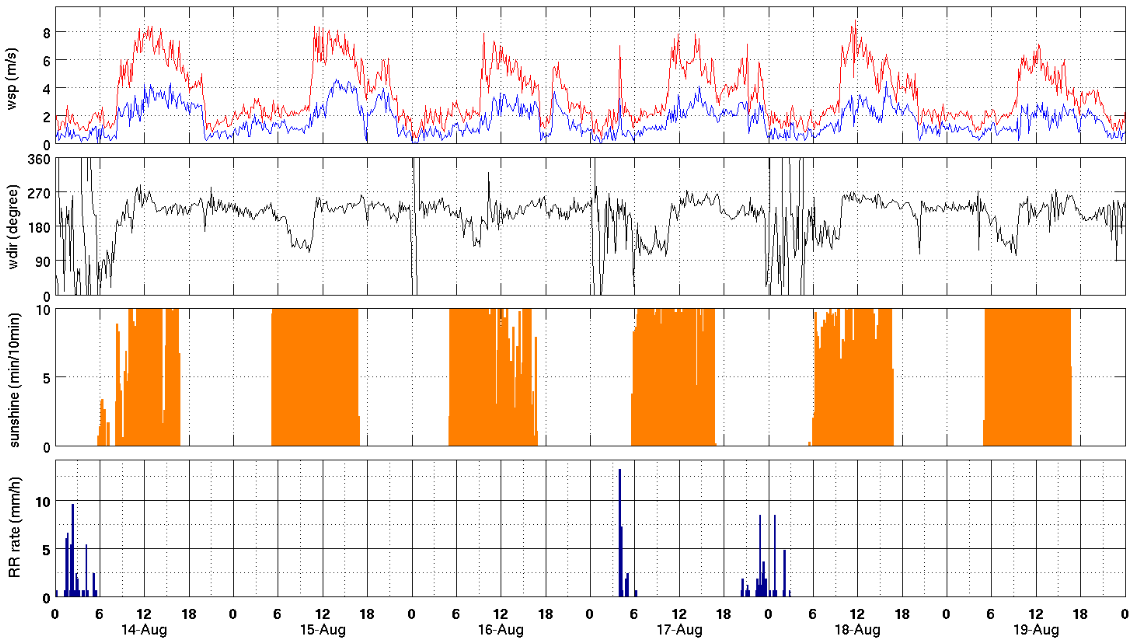


**Figure 6.8:** Second phase of Arlberg winds in St.Anton ranging from 14 to 19 Aug 2009, time in UTC.

In midsommer, the reverse wind system is most pronounced at St. Anton (fig. 6.8), with up- and down-valley wind phases each day in the respective period, even on days with precipitation, e.g. on 14th, 16th and 17th August. Similar to May 2009, the up-valley winds start with sunrise, and the period of enhanced down-valley winds ends with sunset.

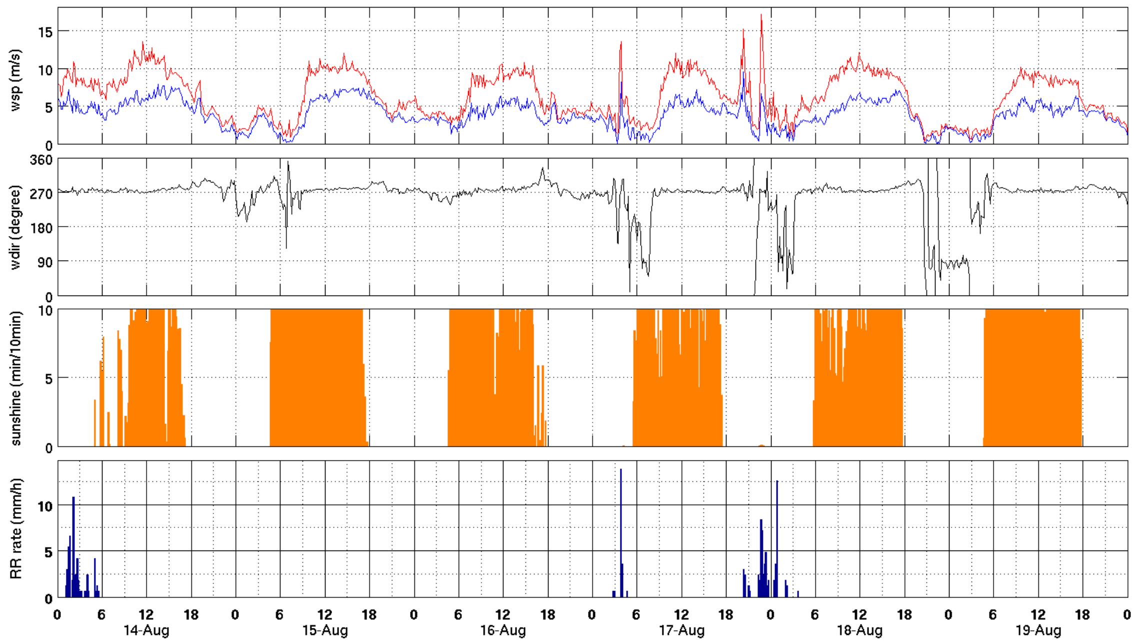


**Figure 6.9:** Same as fig. 6.8, but for Galzig.

The main difference to the May period is the lack of a well-defined valley wind system at Galzig (fig. 6.9) where down-valley winds (westerly) prevail during the first half of the period (until 17th August) and just short periods of up-valley winds (easterly) are present in the second part, not directly related to sunset (compare 17th, 18th and 19th August). Despite that, the down-valley winds reveal a clear diurnal course by becoming stronger in the afternoon.

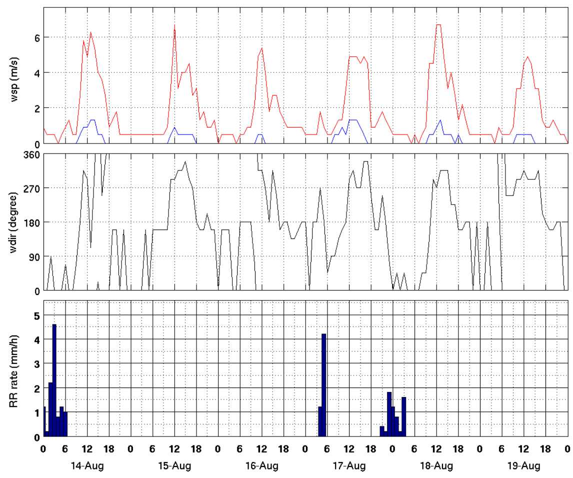


**Figure 6.10:** Same as fig. 6.1, but for Wolfsgrubentunnel (hourly) and without sunshine

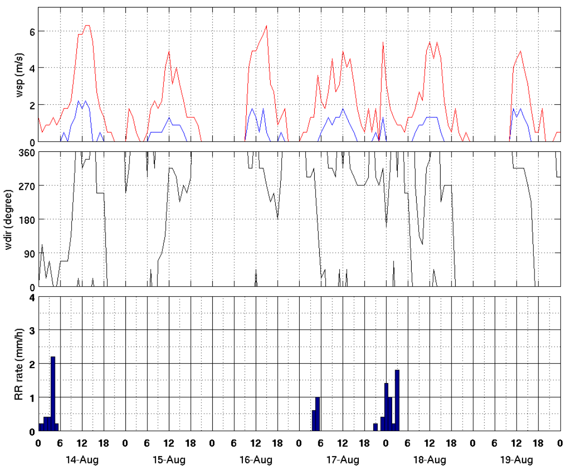


**Figure 6.11:** Same as fig. 6.1, but for Flirsch (hourly) and without sunshine

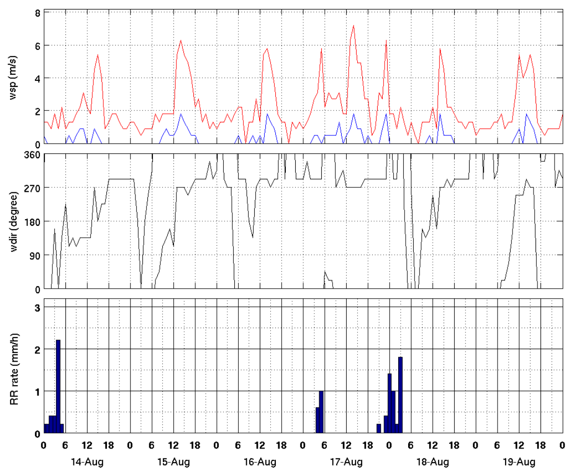


**Figure 6.12:** Same as fig. 6.1, but for Strengen (hourly) and without sunshine

Considering the valley stations farther downstream (6.10,6.11and 6.12), the down-valley winds extend up to Strengen during the day, with temporary up-valley winds at Wolfsgrubentunnel adjacent to St. Anton. Intensifying down-valley winds occur each day at each station albeit the wind speeds are rather low given the mentioned limitations.

METAR data of Alpe Rauz are not available in this period.

### 6.2.2 Turbulent downward mixing hypothesis

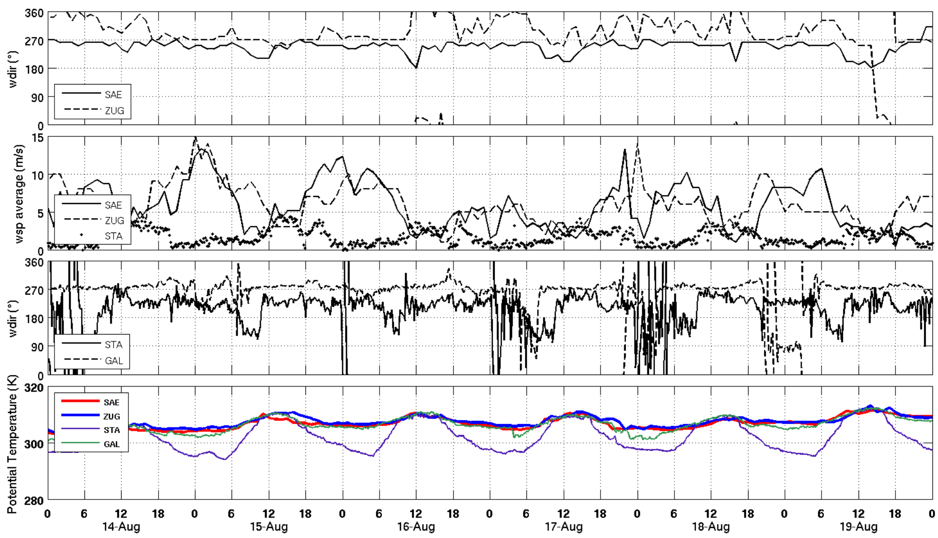


**Figure 6.13:** Reverse wind phase, 14-19th August 2009. Legend as fig. 6.6

The second extended phase of reverse valley winds at St.Anton is characterized by persistently higher wind speeds at the mountain stations than at St.Anton. However, westerlies prevail at Säntis, Zugspitze and Galzig even when St. Anton has up-valley (easterly) winds. Similar to May 2009, equal potential temperature solely exist from early noon to late afternoon and potential temperature of St.Anton is clearly lower (above 5K) outside this period.
Due to the different wind directions in the up-valley phase at St.Anton, turbulent mixing fails to explain the reverse valley winds in this case.

### 6.2.3 Gap flow hypothesis

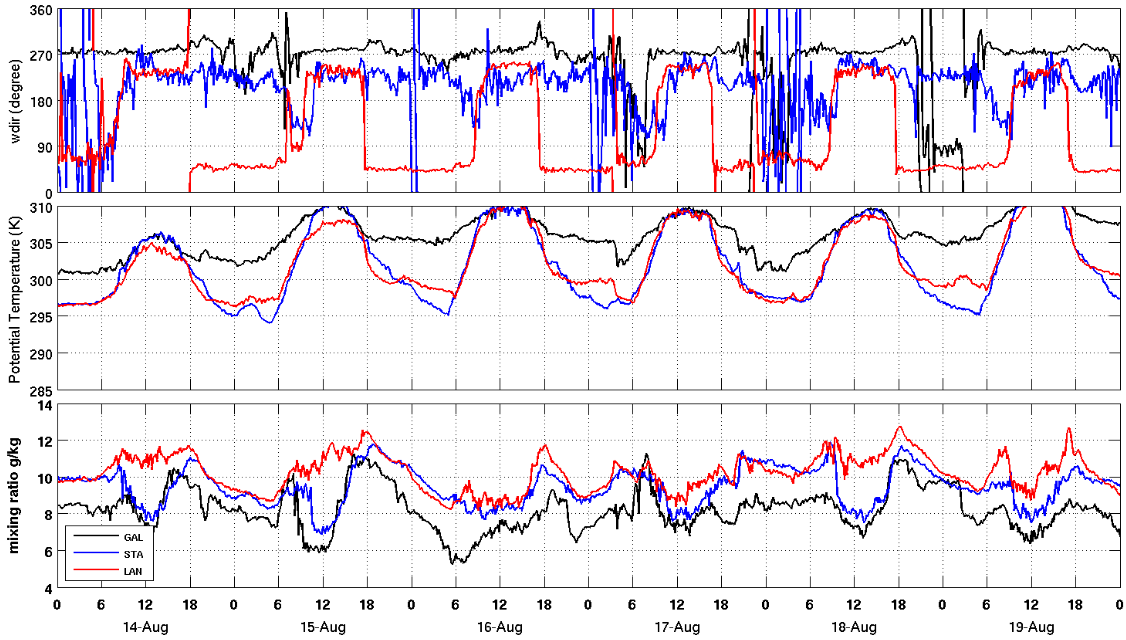


**Figure 6.14:** Reverse wind phase, 14-19th August 2009. Legend as fig.6.1.3

The same holds for the gap flow hypothesis concerning the different wind directions. Potential temperature differences between Galzig and St.Anton during down-valley winds at St.Anton are within the range of tolerance (below 5 K) at all days save 15th August, but do not match with up-valley winds. Finally, mixing ratios at St. Anton are equal or higher than at Galzig suggesting well-mixed valley atmospheres. As a result, gap flow hypothesis may explain down-valley winds at St. Anton during the afternoon, but still fail to explain up-valley winds before noon.

## 6.3 Phase of reverse winds: 1-9 September 2009

### 6.3.1 Weather situation

The beginning of september can be divided in two periods. The first period consisted of strong westerly flows (see fig.A.3), initially with a ridge over the Alps at the beginning. Afterwards a pronounced trough approached crossing on 5th September with temporarily decreasing $\Theta_e$ values. Again, the second period starts with the passage of a ridge, but the downstream trough propagated southwestward and finally cut off over Italy. As a result, easterly winds become established in wide parts of the Alpine region.

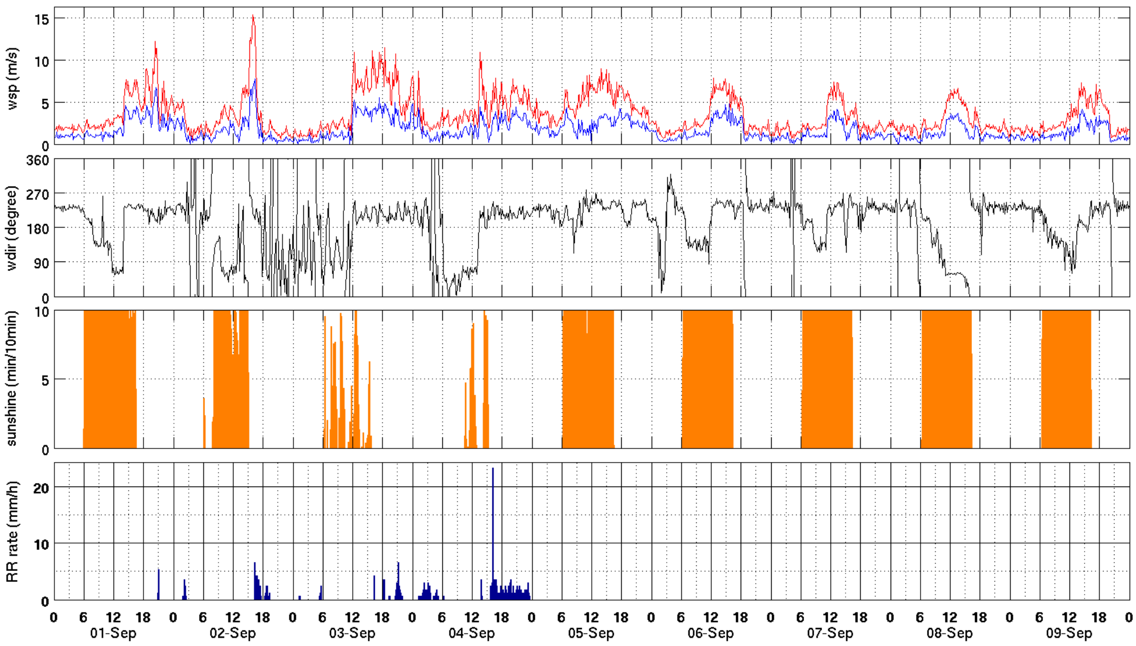


**Figure 6.15:** Third phase of reverse winds in St.Anton ranging from 1 to 9 September 2009, time in UTC. First panel: wind average (blue) and maximum average within 10 min (red) in m/s, second panel: wind direction (°), third panel: sunshine duration in min/10min, fourth panel: precipitation rate within 10 min in mm/h

During the third period in St. Anton (fig. 6.15), best pronounced reverse winds appear at 1st, 3nd, 4rd (despite precipitation), 6th, 7th and 9th September. Otherwise, varying winds (2th) , enduring down-valley winds (5th) and up-valley winds (8th) are present. The correlation to sunshine duration still exists on days with reverse winds, but full sunhine is also available on 5th and 8th September when it did not happen.

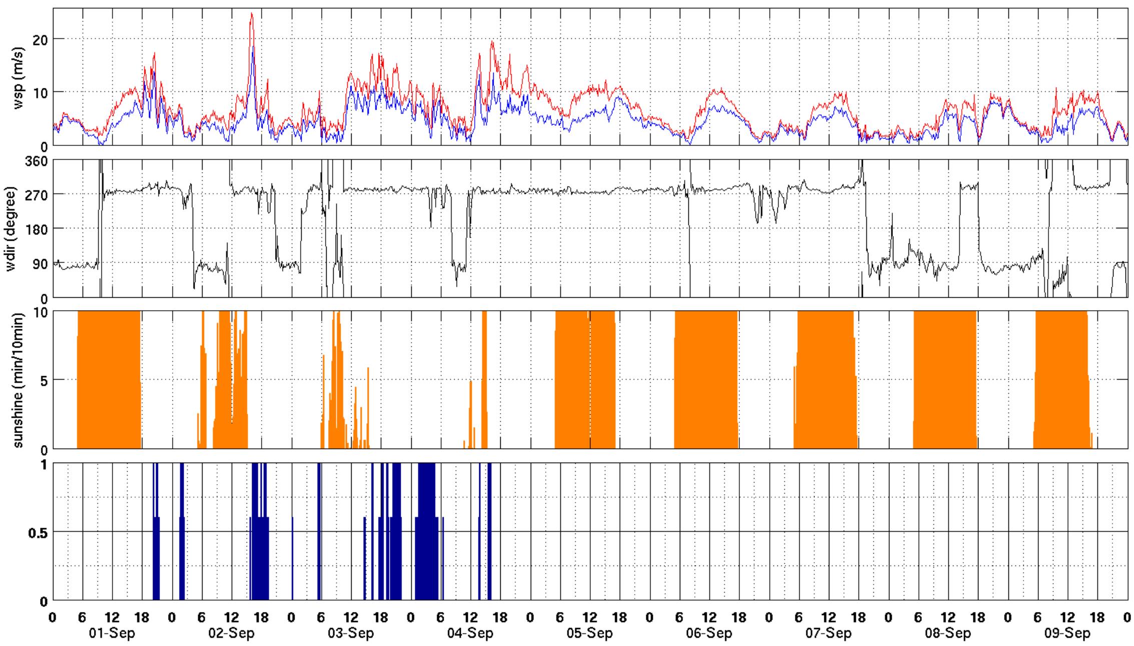


**Figure 6.16:** Same as fig.6.15, but for Galzig.

For Galzig (fig.6.16), the picture seems to be indifferent, with beginnings of valley wind circulations at 2th, 3th and by 7th September, but also with persistent westerly winds during full sunshine (5th and 6th september)

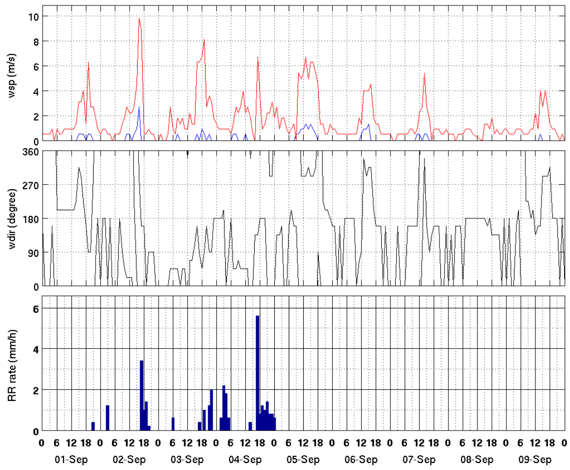


**Figure 6.17:** Same as fig. 6.1, but for Wolfsgrubentunnel (hourly) and without sunshine

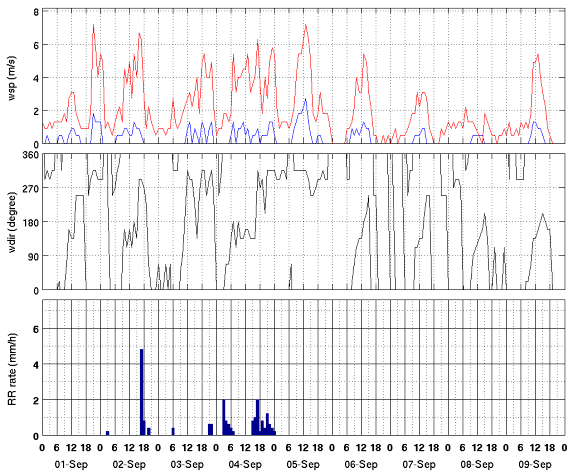


**Figure 6.18:** Same as fig. 6.1, but for Flirsch (hourly) and without sunshine

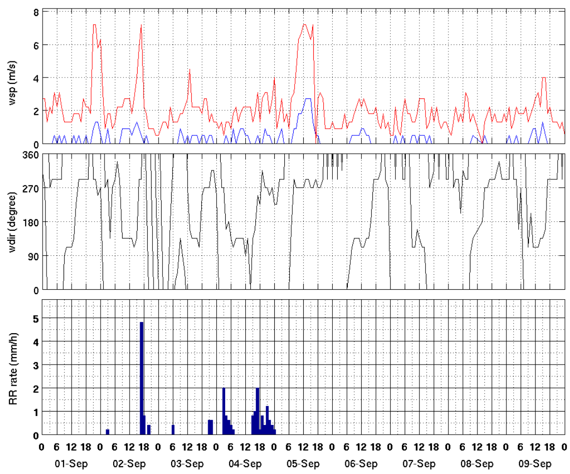


**Figure 6.19:** Same as fig. 6.1, but for Strengen (hourly) and without sunshine

In contrast to earlier cases, the ÖBB data do not contain a uniform picture anymore. Wolfsgrubentunnel (6.17) reveals increasing winds during the afternoon hours, with down-valley components except for the precipitation-loaded days and for 8th September. In case of Flirsch (6.18) and Strengen (6.19), the wind directions often vary, still with dominant down-valley winds, but reduced strength in Strengen. Subsequently, the reverse winds temporarily extend to the lower part of the Stanzer Valley, but lose intensity simultaneously.

METAR data of Alpe Rauz are available for 1-3 and 7-9 September disclosing up-valley winds before noon, again with different transition points ranging from 7 UTC (9th September) to 11 UTC (2th September).

## 6.3.2 Turbulent downward mixing hypothesis

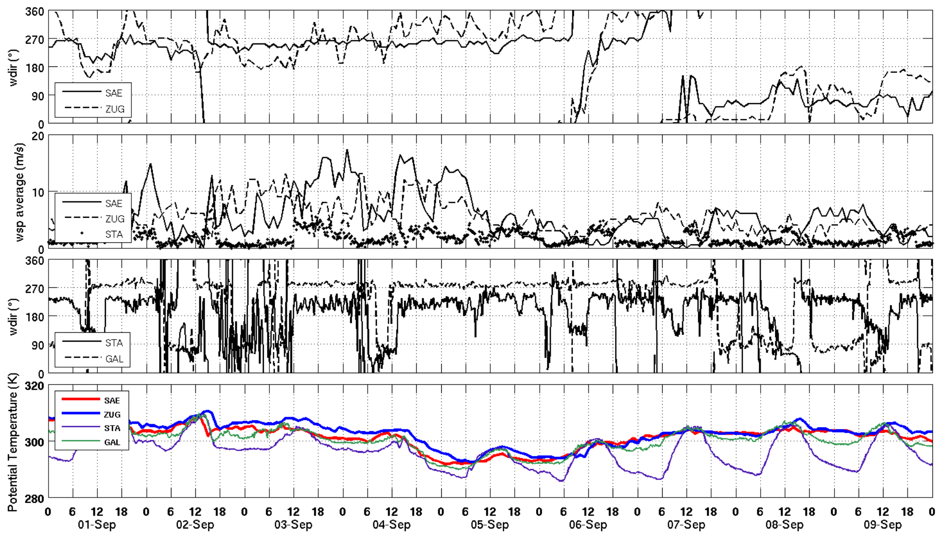


**Figure 6.20:** Reverse wind phase, 1-9 September 2009.

The third period of observed reverse winds can be divided into two phases, one from 1st to 5th September and the other one from 6th to 9th September. In both phases, the first condition for turbulently downward mixed winds are fulfilled as St.Anton has always weaker winds than the mountain stations. Besides the wind speed, the wind regime at Säntis and Zugspitze varies from westerly to northwesterly winds (with higher speed) in the first phase and from northeasterly to southeasterly winds (with lower speed) in the second phase. Moreover, Galzig has westerly winds, even with up-valley (easterly) winds at St.Anton (e.g. 6th and 7th September), and opposite winds towards the end period when the wind regime has changed. The last two days also exhibit opposite winds between Säntis/Zugspitze and St. Anton. Obviously, the presence of superimposed easterly winds cannot inhibit the develop-

ment of reverse winds at St.Anton (and at Galzig, respectively). Finally, the phase between 1st and 5th September is characterized by densely packed isentropes suggesting well-mixed lower atmospheres (partly affected by precipitation), in contrast the phase between 5th and 9th September shows gradually increasing isentropic differences between sunset and sunrise suggesting stabilization (larger diurnal amplitudes) with increasingly anticyclonic conditions.
Overall, turbulent mixing solely affects the wind circulation at Galzig, but influence diminishs in the Stanzer Valley, save 5th September when all conditions for turbulently downward mixing exist (vertical wind shear, uniform wind direction and quasi-equal potential temperature), but reverse valley wind do not exist.

### 6.3.3 Gap flow hypothesis

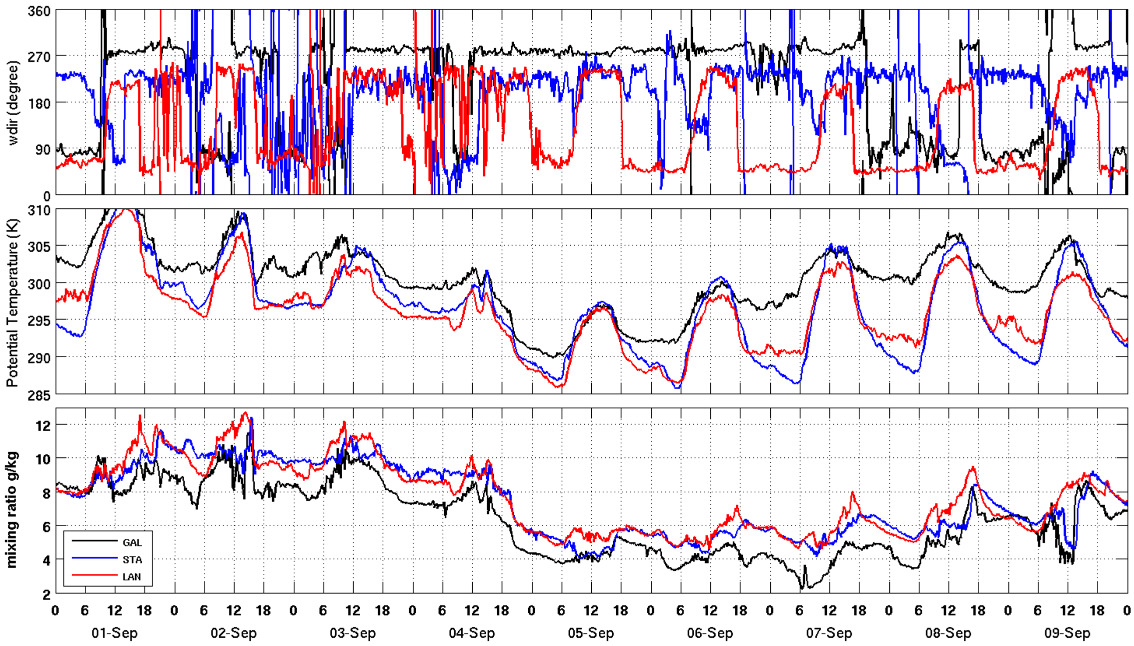


**Figure 6.21:** Reverse wind phase, 1-9 September 2009

As seen in the figures above, the wind directions predominantly differ, and only the potential temperatures at St.Anton and Galzig are close together during noon and afternoon. Mixing ratios at Galzig always stay much lower than at St.Anton.
Altogether, the lack of uniform wind directions during up- and down-valley winds at St. Anton fail to be a sign of existing gap flows within that period.

## 6.4 Summary

Three periods with reverse winds were considered in this chapter to examine the processes generating up-valley winds in the forenoon and down-valley winds in the afternoon in the Stanzer Valley.

Overall, turbulent mixing may only explain a part of the reverse valley winds at St. Anton as up-valley winds are not necessarily associated with easterly upper winds. Moreover, the valley atmosphere is stabilized by radiative cooling during the night and early morning which results into decoupled flow regimes (isolated valley atmosphere versus free atmosphere).

Gap flow theory fails in the case of September 2009 and fits well with May and August 2009, possibly due to the relative quiescent weather conditions in the case of the latter ones. One can constate differently (potentially) tempered air masses beyond the pass region during the night when radiative cooling leads to a strong temperature drop at St. Anton and to a less pronounced drop at Langen where turbulent mixing with enhanced down-slope winds is present. The wind directions of all three stations sometimes correlate, but not throughout every day with reverse winds, probably because Galzig is located too high above the pass (only 300 metres, but that may be enough with very shallow circulations).

Both gap flow and turbulent mixing theory show limited significance as they cannot explain up-valley winds and conditions are sometimes not fulfilled for the afternoon down-valley winds.

# Chapter 7

# Conclusions and Outlook

The results of the wind climatology in chapter 4 suggest that reverse winds actually exist in the Stanzer Valley but testing the hypotheses in chapter 6 could not clarify how the reversal of the valley winds is generated. According to the wind rose plots for the limited period, down-valley winds prevail from St. Anton to Strengen in absence of precipitation and with sunshine. That is, reverse winds mainly occur with fair weather conditions extending from the upper to the lower part of the Stanzer Valley. Westerly winds are also observed at the pass station Galzig, which is in line with wind measurements carried out in August 1985 (Karl Gabl, personal communication) and also mentioned by Ekhart (1937) in the framework of aerological measurements. To get more significant results, a larger time series should be considered as the results only based upon two years (full period) and nine months (limited period) with the full data set, respectively.

After taking 149 days with manually diagnosed reversal of valley winds at St. Anton into account, statistical examinations clarify that reverse winds consist of short up-valley wind phases before noon and longer down-valley wind phases in the afternoon hours. The diurnal wind regime consists of 3 phases:

At first,in the night radiative cooling produces ordinary thermally induced down-valley winds with low wind speeds. In the early morning the wind direction changes to up-valley (southeast) and increases until the second transition takes place with down-valley winds (westerly) by noon. That period continues until the evening and ends with the transition to (again) ordinary thermal winds simply indicated by diminishing wind speeds.

The occurrence of reverse winds is favoured by weak synoptic winds (i.e. weak winds at Galzig) while strong westerly winds at Galzig lead to an earlier onset of up-valley winds in Langen and down-valley winds in St. Anton, respectively, with shortened up-valley wind phase in St. Anton. That relation may result from enhanced turbulent downward mixing associated with stronger synoptic-scale winds. Thus, the valley wind system in the Stanzer Valley can be "overpowered" by west foehn winds given strong west winds at Galzig. Both west foehn and reverse valley winds exhibit a diurnal cycle of wind speed, so the lack of up-valley winds before noon with foehn winds allows for separating both wind systems . The diurnal cycle of winds regarding median and percentiles at the stations further away from the pass (e.g. Bludenz) moreover underlines that reverse winds are most likely when a thermal valley wind system there. The cross-check with days without reverse winds shows that reverse winds take place rather infrequently when the valley wind system of Langen is less pronounced and Galzig has west winds throughout the day.

Different hypotheses have been set up to explain the reversal of the valley winds whereupon turbulent downward mixing was already mentioned by Klainguti-Schaumann (1937) and Georgii et al. (1974) linked to Maloja winds. The performed case studies highlight that turbulent mixing seems to be unlikely to be the crucial mechanism for reverse winds as it is not able to give account of how the up-valley winds are generated. Furthermore, the theory of gap flow can be partly applied to the up- and down valley winds in St. Anton and Langen, but east wind components sometimes lack at Galzig. Either the gap flow theory fails under this conditions or the transition flow is too shallow to affect Galzig which is 300 metres above the pass. Similar potential temperatures at Langen and St. Anton during reverse wind phases suggest that gap flows may exist. This assumption is corrobated by observations of fog patches upstream of the pass on days with fair weather conditions. Two further conditions for gap flows are fulfilled: the temperature increases during the transition phase and the wind speed increases when the wind direction changes. However, to clarify whether gap flows are certainly present with reverse winds, further weather stations should be installed at the pass (e.g. St. Christoph) as they already existed while Ekhart undertook his field studies in late summer 1934 (Ekhart 1937). The third hypothesis aims to differences of valley geometry *alongside* the Stanzer valley. This is on contrast to former theories (as proposed in section 5.1) suggesting that differences of the valley geometries of *both* Stanzer and Kloster valley beyond the pass would be decisive. Unfortunately, both hypotheses could not be pursued farther due to the lack of calculations and reliable measurements, respectively.

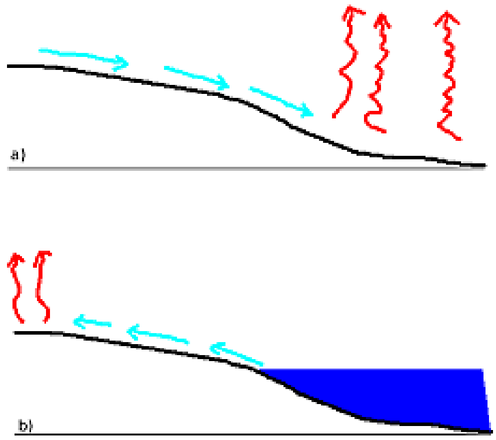


**Figure 7.1:** Sketch of processes which could lead to down-valley winds (a) and up-valley winds (b) in the Stanzer Valley

Figure 7.1 illustrates the third hypothesis and attempts to sketch how different heating rates might trigger the valley wind system in the Stanzer Valley. Diurnal heating warms the lower valley (to the right) stronger generating ascending air flow (thermals) and subsequently low pressure at the valley floor. In the late evening, radiative cooling let the anomalous down-valley wind pass into the thermal down-valley wind. Then, it remains still uncertain what happens just above the surface layer of down-valley winds. Ekhart (1936, 1937) elucidated by means of tethered soundings that up-valley winds still exist during the night, but decoupled from the surface layer with nighttime cooling. The up-valley component may arise from the larger cooling rates down the valley and earlier sunrise in the upper part of the valley. Consequently, the upper part initially warms faster which leads to the up-valley wind phase, but then the strong heating in the lower part gets in the lead. Unfortunately, the ÖBB stations do not measure the sunshine duration. Besides that, Langen shows a smaller decline of the potential temperature during the night than at St.Anton (see e.g. fig.6.2.3).which may arise due to the frequent occurrence of strong down-slope winds during the night hours reducing the nighttime cooling. From a current point of view, it remains unclear whether this fact has influence on the observed up-valley winds in the Stanzer Valley. So far, the existence of a fog snake upstream of the pass ("Maiennebel") similar to the "Maloja serpent" was neglected in this work. It arises when up-valley winds in the upper part of the Kloster Valley result in moist-diabatic cooling and subsequently condensation (starting somewhere between Langen and Alpe Rauz), and manifesting as fog serpent which encroaches the pass up to Galzig and some distance farther downward. Inhabitants interpret that cloud phenomen as "Schönwetterzeichen" (sign for fair weather) as reported by Ekhart

(1937). Aside from the Arlberg and Maloja pass, that cloud phenomenon also exists at the Grimsel Pass in Central Switzerland (where the cloud serpent moves downstream of the Hasli Valley into the Wallis up to Oberwald [1]. The "Gotthard serpent" in the Gotthard pass region linking the Urseren Valley and the Leventina Valley is also mentioned in glider reports. Strictly speaken, the presence of low fog with shallow south foehn in the Wipp Valley may be also conceived as a cloud serpent [2]. Future studies could focus on cloud serpents associated with pass regions and reverse valley winds.
Another interesting aspect which was not considered is the meso-scale distribution of air masses beyond the passes. On 28 June 2010, for example, calm weather conditions with almost no upper winds and strong solar radiation could realize. Despite the seemingly perfect conditions for the onset of reverse winds at both Maloja and Arlberg, observations showed that down-valley winds did <u>not</u> occur in the afternoon . The influence of the different air masses, with the equivalent potentially cooler (and drier) air masses north of the main crest may have played a prominent role by inhibiting the establishment of necessarily warmer air masses on the downstream side of the pass. Subsequently, the air masses in the Upper Engadine north of the Maloja pass and in the Stanzer Valley east of the Arlberg pass, respectively, stayed too cool to induce a down-valley pressure gradient. Further case studies should take the role of air masses in the surroundings into account.

[1] http://pwc.fly-aletsch.net/CMS_e/index.php?page=361455191&f=1&i=1454684329&s=361455191

[2] see e.g. http://www.wetteran.de/wissenswertes/flowphenomena171109.pdf

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# Appendix A

# Appendix

The appendix contains the synoptic maps used in chapter 6 to describe the respective weather situation during the three phases of reverse valley winds, and a table of 149 days on which reverse winds are detected manually used in section 4.4 in the framework of statistical analysis.

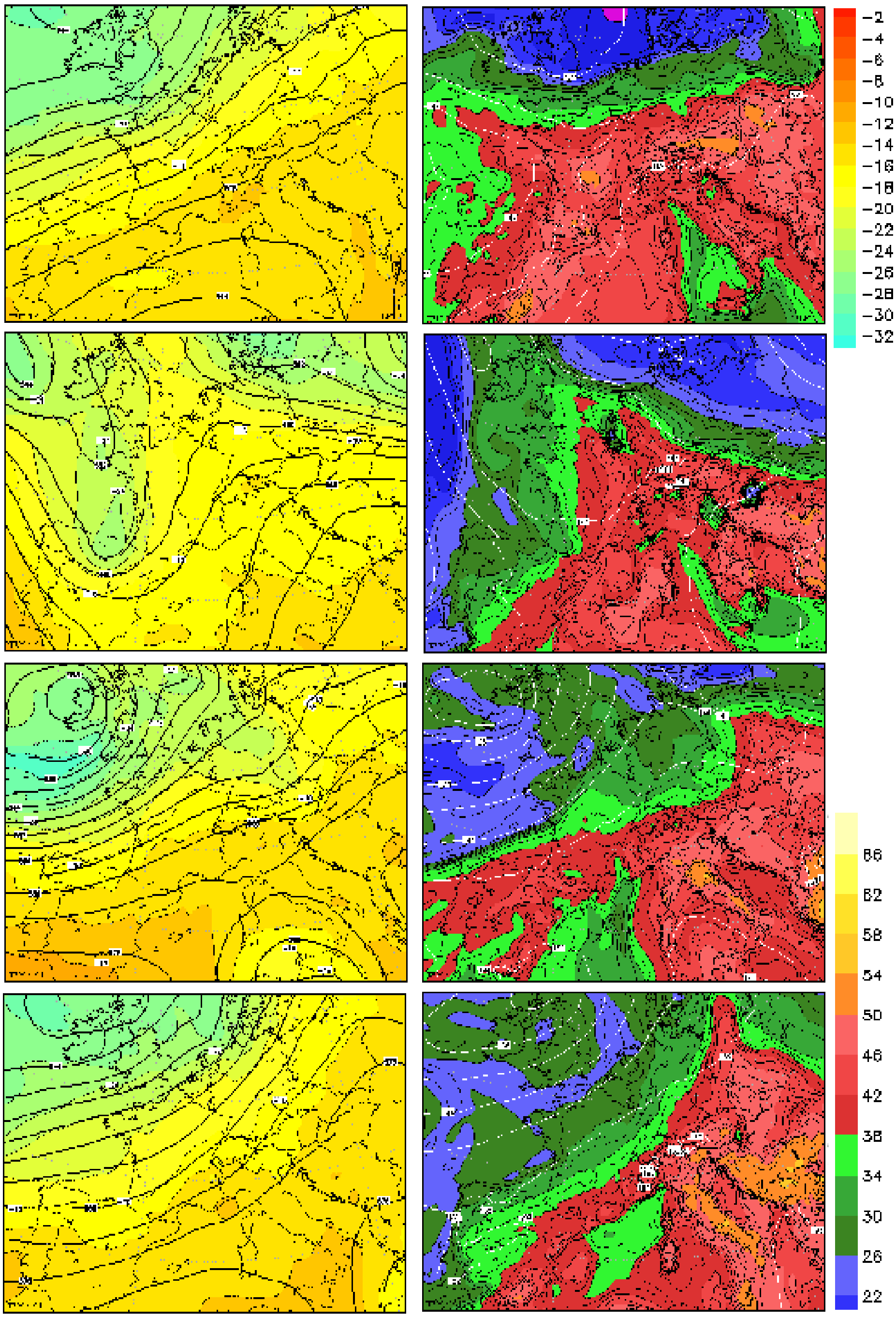


**Figure A.1:** ECMWF Analysis 12 UTC for section 6.1: 500 hPa geopotential heights [10m], temperature [C] at 500 hPa (left) and equivalent potential temperature [C], geopotential height [10m] at 850 hPa (right), valid for 11 May (top), 14 May (second), 16 May (third) and 18 May 2009 (bottom). Legend for 500 hPa temperature is at the top , legend for 850 hPa $\Theta_e$ at the bottom.

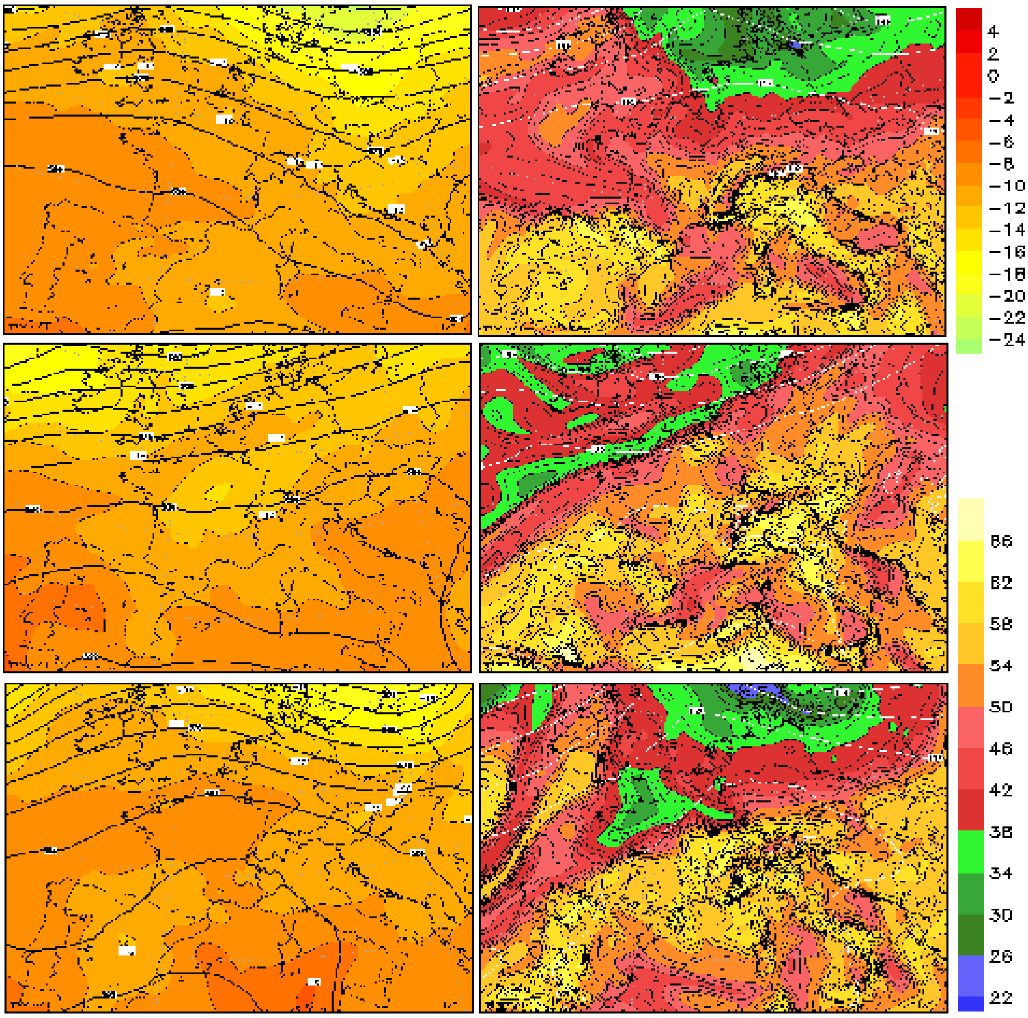


**Figure A.2:** ECMWF Analysis 12 UTC for section 6.2: 500 hPa geopotential heights [10m], temperature [C] at 500 hPa (left) and equivalent potential temperature [C], geopotential height [10m] at 850 hPa (right), valid for 14 August (top), 16 August (middle), 18 August (bottom) 2009. Legend for 500 hPa temperature is at the top , legend for 850 hPa $\Theta_e$ at the bottom

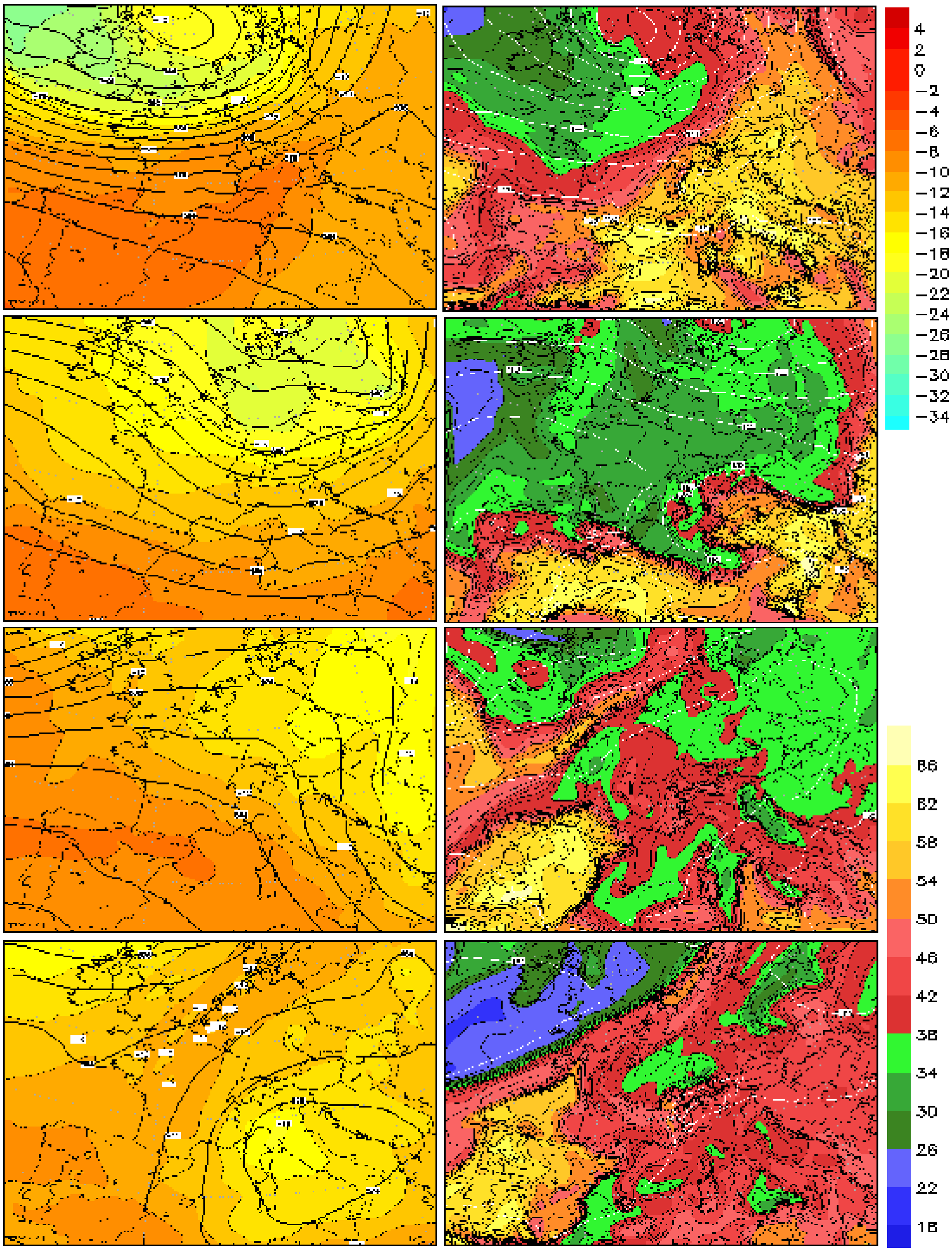


**Figure A.3:** ECMWF Analysis 12 UTC for section 6.3: 500 hPa geopotential heights [10m], temperature [C] at 500 hPa (left) and equivalent potential temperature [C], geopotential height [10m] at 850 hPa (right), valid for 3 September (top), 5 September (second), 7 September (third) and 9 September 2009 (bottom). Legend for 500 hPa temperature is at the top , legend for 850 hPa $\Theta_e$ at the bottom

**Table of Arlberg winds used for the statistical analysis in chapter 4.4**

| | | | |
|---|---|---|---|
| 20080322 | 20080719 | 20081125 | 20090705 |
| 20080405 | 20080725 | 20090219 | 20090713 |
| 20080413 | 20080728 | 20090302 | 20090716 |
| 20080426 | 20080802 | 20090319 | 20090719 |
| 20080427 | 20080806 | 20090327 | 20090721 |
| 20080428 | 20080807 | 20090408 | 20090722 |
| 20080502 | 20080814 | 20090409 | 20090723 |
| 20080503 | 20080817 | 20090415 | 20090726 |
| 20080504 | 20080819 | 20090418 | 20090727 |
| 20080506 | 20080822 | 20090428 | 20090728 |
| 20080507 | 20080824 | 20090503 | 20090729 |
| 20080508 | 20080825 | 20090507 | 20090801 |
| 20080509 | 20080826 | 20090508 | 20090806 |
| 20080513 | 20080827 | 20090509 | 20090807 |
| 20080514 | 20080828 | 20090511 | 20090811 |
| 20080515 | 20080829 | 20090512 | 20090812 |
| 20080516 | 20080830 | 20090513 | 20090814 |
| 20080523 | 20080913 | 20090514 | 20090815 |
| 20080524 | 20080914 | 20090515 | 20090816 |
| 20080614 | 20080915 | 20090516 | 20090817 |
| 20080615 | 20080916 | 20090517 | 20090818 |
| 20080619 | 20080917 | 20090518 | 20090819 |
| 20080621 | 20080923 | 20090519 | 20090822 |
| 20080622 | 20080924 | 20090521 | 20090824 |
| 20080623 | 20080928 | 20090522 | 20090827 |
| 20080624 | 20080929 | 20090523 | 20090830 |
| 20080625 | 20081001 | 20090524 | 20090901 |
| 20080626 | 20081006 | 20090525 | 20090902 |
| 20080627 | 20081007 | 20090526 | 20090906 |
| 20080628 | 20081009 | 20090527 | 20090907 |
| 20080629 | 20081011 | 20090605 | 20090909 |
| 20080704 | 20081012 | 20090614 | 20090913 |
| 20080705 | 20081013 | 20090617 | 20090919 |
| 20080707 | 20081015 | 20090618 | 20090922 |
| 20080711 | 20081022 | 20090702 | 20090923 |
| 20080715 | 20081024 | 20090703 | 20090924 |
| 20080716 | 20081026 | 20090704 | 20090925 |
| - | - | - | 20090928 |

**Table A.1:** Table of the 149 days with manually diagnosed reverse winds. Precipitation and foehn winds, respectively, also occurred on some of these days.

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# Curriculum Vitae

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6020 Innsbruck
Born on 31 August 1983 in Hardheim, Germany

Education and Professional training:

| | |
|---|---|
| 2009–2010 | Diploma thesis under the guidance of Ao. Prof. Dr. Mayr, Institute of Meteorology and Geophysics, University of Innsbruck: *"Arlberg winds in the Stanzer valley - reverse valley winds"*. |
| 2004–2010 | Diploma study at the University of Innsbruck. *Master of Natural Science (Magister rerum naturalium)* in Meteorology. |
| 2003–2004 | Diploma study Meteorology at the University of Mainz. *Master of Natural Science (Magister rerum naturalium)* in Meteorology. |
| 1994–2003 | Johannes-Butzbach-Gymnasium, Miltenberg. *Matura.* |

Teaching experience:

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|---|---|
| 2009–2010 | Tutor for "Wetterbesprechung" (Bachelor and Master degree course Atmospheric science) |

Practical Experience:

| | |
|---|---|
| since July 2009 | regular Alpine weather forecasts for http://www.gipfeltreffen.at |
| since July 2007 | regular severe convective storm forecasts for http://www.skywarn.at |
| 2007–2008 | regular synoptic forecasts on www.inntranetz.at with focus on Innsbruck and Austria |
| August 2008 | Practical training with AustroControl Innsbruck (Performing three case studies to thunderstorms) |
| Summer 2007 | Forecasts for "Red Bull X-Alps", an international competition for paragliders under supervision of Stefan Hörmann, owner of a weather service for gliders |

Further skills:

| | |
|---|---|
| Programming | HTML, LaTeX, Matlab (basics) |
| Languages | French (intensive course in school), English |
| Websites | http:www.wetteran.de (since 2002) and www.inntranetz.at (since 2006) |