The Laseyer Rotor - Dynamics & Climatology
A detailed case study using large-eddy simulations and a climatological analysis of local weather station data

Master Thesis

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Publication date:
2009-09

Permanent link:
https://doi.org/10.3929/ethz-b-000630208

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The Laseyer Rotor - Dynamics & Climatology
A detailed case study using large-eddy simulations and a climatological analysis of local weather station data

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Statement of honesty

I hereby declare that this thesis is my own work and that it does not, to the best of my knowledge, contain any material previously published or substantially overlap with material submitted for the award of any other degree at any institution, except where due acknowledgement is made in the text.

Zürich, 30.9.2009

Lukas Egloff
In this thesis the phenomenon of the Laseyer winds - strong wind gusts in a narrow Alpine valley in North-East Switzerland - is examined by means of real-case numerical simulations with varying grid resolutions for the date of a train derailment in Wasserauen in January 2007. The hereby employed models are the COSMO-2 weather prediction model and the Advanced Regional Prediction System (ARPS). On a second track, measurements of local weather stations are analysed and compared to the model results, thus assessing the quality of the numerical simulation of the event. Additionally, several years of weather station measurements are objectively analysed for similar Laseyer winds and a simple climatological pattern is established. So far no study has looked into the formation of rotors of small spatial scale over highly complex topography as can be found in the narrow valley in the Alpstein mountain range.

The model simulations show the presence of an extended layer of stable air over the valley for the date of the accident. This stable layer may have facilitated high near surface wind speeds through constructive interference. High-resolution simulation runs exhibit north-westerly flow above the valley and strong vertical motion within, with areas of strong up- and downdrafts confined to the flanks of the down- and upstream ridgeline respectively. High horizontal wind velocities on the valley floor were modelled. The highest surface wind speeds of 38 m/s were found deep in the valley and lower maximum velocities around the location of the accident (24 m/s). The simulated flow was mainly directed towards the embouchure with hardly any cross-valley wind component. Trajectory analysis disclosed that air parcels can enter the valley from above near the valley head and in the following can generate down-valley flow on the valley floor.

The analysis of the weather stations measurements revealed that the strong winds causing the train accident were not excited by a typical Laseyer event characterised by strong cross-valley wind gusts. Instead, the observations showed strong flow into the valley on the whole morning, marking the event as rare but not unique. The observations further disclosed that strong wind gusts with an easterly component in the valley are most likely triggered by westerly winds aloft. The angle window for incident ambient wind favourable for the occurrence of strong easterly wind gusts in the valley is surprisingly narrow, it ranges from 265 to 295 degree azimuth. The measurements affirm the account of local residents stating that Laseyer episodes predominantly occur in the winter season; ambient westerly wind aloft going along with strong easterly wind gusts in the valley were recorded almost exclusively between November and March.

Neither the simulations nor the observations show strong wind components across the railway line in Wasserauen for the time of the accident and thus are inherently limited in their capability to explain the derailment. Further studies are desirable to detect additional key players for the formation of the strong wind gusts.
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1. Introduction

In January 2007 a control car of the Appenzeller Bahnen with a weight of approximately 20 tons was lifted of the tracks in a narrow valley in the Alpstein mountain range, which is indicative for extreme local wind maxima. These so-called Laseyer winds occur once or several times in most winters. According to observations of the local residents, the wind gusts come up in a quasi-oscillatory manner during a time period of several hours (Rueffimann, 2008). To date, no theory is able to explain the Laseyer winds.

It is assumed that the Laseyer winds belong to the class of atmospheric rotor winds, low-level vortices which form downstream of a mountain crest in association with large-scale mountain waves and feature a circulation axis oriented parallel to the mountain ridgeline. Rotor winds usually consist of high down-stream wind velocities near the surface which decelerate rapidly in the lee and give way to a weaker recirculating flow directed back toward the mountain (Doyle and Durran, 2007).

Several factors can influence the formation of rotors, as they are strongly coupled to the evolution and the structure of the overlying mountain waves as well as to the underlying boundary layer (Grubišić et al., 2008). Doyle and Durran (2002) have indicated the critical role of trapped lee waves in the formation of rotors and have shown that, given large enough wave amplitudes, the wave-induced adverse pressure gradient can cause flow separation and regions of recirculating flow beneath the wave crests. Furthermore they found that surface friction has a significant influence on whether flow separation is likely to occur in the first place. Jiang and Doyle (2008) observed that downslope winds and occurrences of rotors exhibited strong diurnal variations, indicating that boundary layer heating has a profound influence on the coupling of flow in the valley and the flow and waves above the mountain crest. The presence of sharp temperature inversions upwind can also significantly influence the formation of rotors (Vosper, 2004).

Even though rotors pose a substantial threat to aviation due to their high level of turbulence, the dynamics and structure of rotors are still relatively poorly understood and forecasted. Historically, this was mainly due to missing observational data and the lack of the necessary computational power to resolve the fine-scaled structure of rotors. Thus much of the current understanding is based on analytical and numerical studies of highly idealized conditions (e.g. Schaefer and Durran (1997)).

Observational data of rotor events have been lacking mainly because rotors are too small in spatial scale to be sampled by conventional observing networks and the hazardous nature of the turbulence prevented systematic in situ measurements (Grubišić and Billings, 2007). The first observations of rotors go back to the early 1950s, when the Sierra Wave Project and the subsequent Jet Stream Project were conducted in the Sierra Nevada mountain range (Grubišić and Lewis, 2004). With the exception of research aircraft observations and remote sensing lidar measurements, there were then surprisingly few direct observations of rotors until the 1990s.

Recently, more observational data have become available as rotors became the focus of new field campaigns. In the Sierra Rotors Project, which took place in spring 2004 in the Sierra Nevada, accelerated downslope flow along the lee slope together with reversed flow and rotors further downstream were observed (Jiang et al. (2005); Jiang and Doyle (2008)). Most recently the Terrain-induced Rotor Experiment (T-REX) investigated the structure and evolution of atmospheric rotors in an extensive field campaign in the Owens Valley also in the Sierra Nevada range in spring 2006 (Grubišić et al., 2008). One of the latest field campaigns in Europe observed the near-surface flows across and downwind of the Wickham mountain range on the Falkland Islands during a project aimed at improving the prediction of orographically induced turbulence (Mobbs et al., 2005).
1. Introduction

The necessary computation power to run 3D simulations with explicitly resolved eddy structures has only become available in recent times. A rotor under the crest of a lee wave can measure only 1-2 km in diameter, which requires a horizontal grid spacing of a few hundred meters (Doyle and Durran, 2002). Thus, until recently, simulations that made use of a high enough resolution to capture the internal structure of rotors had been limited to two dimensional models (e.g. Doyle and Durran (2002); Hertenstein and Kuettner (2005)). 2D Simulations are computationally efficient, however they may yield misleading results. Doyle and Durran (2007) conducted a series of high resolution, eddy-resolving simulations and found that the strength and evolution of subrotors and the internal structure of the main large-scale rotor are substantially different in 2D and 3D. Their results indicate that for flow over simple three dimensional terrain, subrotors can be intensified substantially by stretching and likely pose the greatest hazard to aviation. So far no study has looked into the formation of rotors of small spatial scale over highly complex topography as can be found in the narrow valley in the Alpstein mountain range.

In this thesis, the origins of the strong wind gusts are investigated by means of real-case numerical simulations with varying resolutions for the date of the accident in January 2007. On a second track, measurements of local weather stations are analysed and compared to the model results, thus assessing the quality of the numerical simulation of the event. Additionally, several years of measurements are objectively analysed for similar Laseyer winds and a simple climatological pattern is established. The key objective of this thesis is to detect critical ingredients for the formation of the strong winds and to put the incident in January 2007 into a broader climatological context.

The thesis is structured in the following way: Section 2 introduces the geographical setting of the Schwendetal and gives a short overview on the history of the Laseyer rotor as well as on theories and preliminary studies about its formation. The analysed weather data, the numerical models and the applied methodology are described in section 3. In section 4 the results of the numerical simulations and the analysed weather station measurements are discussed. Section 5 contains the conclusions and deals with open points and potential enhancements on the study.
2. Historical perspective, geographical setting and preliminary studies

In the night from January 18th to 19th 2007 the winter storm Kyrill swept over Switzerland. In the morning of January 19th at 9.20 UTC, a control car of the Appenzeller Bahnen was lifted of the tracks 200 m after leaving the station in Wasserauen in North-East Switzerland (Figures 2.1 and 2.2). The control car crashed to the west of the railway tracks onto the main road which runs alongside the railway line. The middle car got tilted while the rail car stayed on the tracks. There were two strange facts associated with the accident which made people take a closer look. Firstly, the ambient wind was seemingly flowing into the wrong direction: ambient incident flow was north-westerly over the whole morning. At first sight this didn’t look like being a good match to the train falling onto the western side of the railway line. Secondly, the wind in the area appeared to be too weak: weather services stated that the approximate weight of the control car of 20 tons implies wind velocities of at least 200 km/h to lift the coach of the railway line. Yet the observed maximum wind velocity on the nearby Säntis didn’t surpass 36 m/s. This comes all the more as a surprise given that, compared to the location of the accident in the narrow valley, the Säntis is directly exposed to the incident wind. Hence the flow had not only to turn around in the valley but also needed to intensify substantially in order to lift the train of its tracks.

According to the questioning of local residents by Ruettimann (2008), accidents in Wasserauen related to the wind gusts can be tracked back to the 1960’s. Local inhabitants report that the gusts lifted train cars of the tracks in at least 5 other occasions and also blew away kiosk-cots, hen-coops, rooftops and power poles in the past. The strong wind gusts are believed to originate from the Laseyer forest, which is also the namesake for the phenomenon, located on the western flank of the valley. The Laseyer episodes are said to occur once or several times in the winter season, preferably in the transition from autumn to winter or at the onset of spring. They usually come up in quasi-oscillatory manner for several hours and are accompanied by cold temperatures and precipitation. The strongest gusts on the valley floor occur in a range not wider than 1 km. The residents also distinguish between the real Laseyer, i.e. Laseyer episodes caused by north-westerly wind, and strong winds triggered by Föhn. If the latter is strong enough, the southerly wind may overcome the Alpstein mountain range and flow over the Alp Sigel and Bogarten into the Schwendetal.

Figures 2.2 and 2.3 show the topographical setting of the Schwendetal and its surroundings. In simple terms, there are two ridgelines which can potentially interfere with the incident flow. Given north-westerly flow, the upstream ridge extends over the Ebenalp to Bommen and has an altitude between 1200 and 1600 m a.s.l. in the critical region near Wasserauen. The downstream ridgeline near Wasserauen reaches higher up to elevations between 1500 and 1700 m a.s.l.

Several weather services came forward with theories about the formation of the wind gusts and most of them deal with either of the two ridgelines. The classic rotor theory focuses on the upstream mountain range and assumes that mountain induced waves and rotor turbulence with associated strong gusts form in the lee of the upstream ridge. As mentioned in the introduction, known rotor phenomena usually extend over a few kilometers. Since the valley of the Schwendetal has a diameter not exceeding 1.5 km, a potential Laseyer rotor would probably be on the scale of a few hundreds of meters and thus would

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2. Historical perspective, geographical setting and preliminary studies

Figure 2.1.: North-East Switzerland. The location of the six weather stations introduced in section 3.4 are marked with triangles.

Figure 2.2.: Close-up on the Schwendetal and its surroundings. The location of the weather stations on the Ebenalp and in Wasserauen are marked with triangles. The location of the train accident is marked with a circle.
represent quite an exceptional phenomenon. The theory involving the downstream ridgeline presumes that the north-westerly flow passes the upstream ridge unhampered but gets blocked at the opposing rock face near the Alp Siegel and is diverted downwards over the Laseyer forest into the valley. The effect may be amplified by an inversion layer over the valley. If the atmosphere is stably stratified just over the ridge, it may form a sealing cap which prevents the air from evading upwards. Instead, it is proposed that the air is accelerated downwards, passes the valley floor and rises on the upstream flank to be transported eastward again by the north-westerly flow on the upper level. In this way a closed circulation may establish which keeps the rotor going. Furthermore it is speculated that the rotor, triggered by north-westerly wind above the valley, may also be complemented and reinforced by southerly wind blowing towards the embouchure on the valley floor.

Sonderegger (2008) carried out idealised two-dimensional numerical experiments with the non-hydrostatic ARPS model for a setting similar to a cross section through the Schwendetal. He found that a steady state reversed flow can establish in the valley for uniform incident horizontal velocity with height and a given stratification of the atmosphere aloft. Sensitivity experiments further revealed the crucial role of the inversion height and strength in facilitating rotor formation. The generation of reversed flow is also found to be decisively influenced by the exact orography; a rotor didn’t form for altered mountain shapes and valley widths. The magnitude of the reversed flow was strongly dependant on the incident wind velocity. For an incident wind speed of 20 m/s, the simulations generated reversed flow of up to 13 m/s. Higher incoming wind velocities didn’t yield a steady state. Unaccounted three-dimensional effects like vortex stretching and tilting are presumed to have a profound influence on the strengthening of the rotor and may thus lead to higher velocities in three-dimensional simulations.
As mentioned above, in the aftermath of the train accident in January 2007, weather services pointed out that wind velocities of at least 200 km/h (~ 55 m/s) were required to cause the overturning of the control car. Richner (2009) calculated the necessary horizontal wind speed for the derailment of a cable car in an accident related to a Föhn event in the Jungfrau region in 1996. For a simplified setting with a wind vector perpendicular to the railway car, assuming constant, steady, laminar flow and neglecting acceleration forces, the critical wind speed was found to be in the range of 50 m/s. This assessment is further validated by wind tunnel experiments of the Jungfrau Bahnen, where the critical laminar horizontal wind velocity for the accident was determined to be around 45 m/s. The mass of the control car of the Appenzeller Bahnen is with roughly 20 tons less than half the weight of the motor coach of the Jungfrau Bahnen (52 tons) (Richner, 2008), implying that a steady wind speed considerably lower than the stated 200 km/h may have been sufficient to cause the accident (Hans Richner, personal communication). However, both incidents were probably at least partly caused by atmospheric turbulence and gustiness. Thus the critical velocities derived for laminar flow can be considered as a lower threshold for overturning. The velocities for derailment increase for transient gusts compared to a steady wind stream as additional inertial forces have to be overcome (Richner, 2009).

Taking this into account, we can set a conservative benchmark for cross-valley wind velocity at around 40 - 45 m/s which models should measure up to in order to explain the accident in Wasserauen.
3. Data and methodology

To examine the turbulence phenomenon and to detect key elements facilitating its formation, the atmospheric dynamics on January 19th 2007 were analysed by means of numerical simulations as well as observations of local weather stations. This section introduces the employed models, the analysed weather data and the applied methodology.

3.1. COSMO

In a first step, data of high resolution simulations of atmospheric flow around the Alpine mountain range for the date of the train accident was analysed. These simulations were performed with the COSMO-2 weather prediction model with a horizontal grid spacing of roughly 2.2 km and 60 vertical model layers. The COSMO-2 model is an implementation of the limited-area model developed within the framework of the Consortium for Small-Scale Modelling (COSMO) with the goal to conduct high-resolution weather forecasts (Steppeler et al., 2003).\(^4\) The model domain encompasses the alpine mountain range around Switzerland. It is nested into the computational domain of the regional COSMO-7 model, which features a horizontal grid spacing of approximately 6.6 km and provides the necessary boundary conditions to drive COSMO-2. COSMO-7 in turn is driven by the operational analysis of the European Centre for Medium-Range Weather Forecasts (ECMWF).

COSMO-2 is based on the primitive hydro-thermodynamical equations, which describe compressible non-hydrostatic flow in a moist atmosphere without any scale approximations. The model equations are solved numerically on a rotated latitude-longitude grid with terrain following coordinates in the vertical (Schaer et al., 2002), using an Eulerian finite difference method. The COSMO-2 model version became operational on 27\(^{th}\) of February 2008 and produces forecasts for the entire Alpine region eight times a day out to 24 hours in advance. The computational domain and the model topography of COSMO-2 is displayed in Figure 3.1.

To investigate the meteorological development which ultimately lead to the train accident, the operational analysis fields of COSMO-2 on January 19\(^{th}\) 2007 for the period between 6 UTC and 13 UTC were examined. In these analysis fields, the model forecast is complemented by measured data from various sources, which correct the forecast in order to better match reality. The data includes SYNOP and aircraft observations, radio soundings as well as surface measurements. The latter provides lots of data especially in Switzerland, due to a comparatively dense station network. The observations and the model forecast are combined by a data assimilation system which then supplies the hourly analysis fields for the initialization of the actual operational forecasts.

In section 4.5.1, the observed wind gusts are compared to the near-surface gusts computed by COSMO-2. The modelled maximum turbulent gusts 10 m above the ground are derived from the turbulence state in the atmospheric boundary layer, using the absolute speed of the mean wind on the lowest model level (~10 m above the surface) \(V_{10}\) and on 30 m above the ground \(V_{30}\):

\[
V_{10,\text{max}} = V_{30} + \alpha \, 2.4 \, \sqrt{C_D} \, V_{10}
\]

(3.1)

Where \(C_D\) is the drag coefficient for momentum and the parameter \(\alpha\) was set to \(\alpha = 3\) (Schulz, 2008).

More detailed information on the COSMO model can be found in the model documentation (Schattler et al., 2008).

\(^4\)http://www.cosmo-model.org/
3. Data and methodology

Figure 3.1.: Computational domain and orography of the COSMO-2 model.

3.2. ARPS

As the 2.2 km horizontal grid spacing of COSMO-2 is still too coarse to resolve the Schwendetal, a more highly resolved model is needed to simulate the flow in and around the valley. Thus, in a second phase, the output of the COSMO-2 model was coupled to the Advanced Regional Prediction System model (ARPS), which was run in large eddy simulation mode (LES).\(^5\)

The ARPS model is a three-dimensional, non-hydrostatic, compressible model formulated in generalized terrain-following coordinates with minimum approximations made to the original governing equations. The model applies a split-explicit scheme to integrate the sound-wave containing equations in order to remove the time step limitation due to the Courant-Friedrich Levy stability criterion. See Xue et al. (2000) for more information on the ARPS model.

An ARPS model-chain using a nested grid approach was then set up. Thereby the horizontal grid spacing was decreased stepwise from 2 km to 500 m to 150 m to 50 m. These ARPS simulations are hereafter referred to as ARPS-2km, ARPS-500m, ARPS-150m and ARPS-50m. Each simulation run on the coarser grid supplied the boundary conditions necessary to drive the simulation on the next higher resolved grid. The initial ARPS-2km run was driven by the boundary conditions provided by the COSMO-2 analysis. To keep computational costs in check, the model domain was reduced with increasing horizontal resolution; at last, the ARPS-150m and the ARPS-50m model run were applied only to the valley and its immediate surrounding. As the horizontal grid spacing is decreased, the vertical resolution is concurrently adjusted as well; Table 3.1 lists the settings made for the individual model runs. Note that although different surface roughness lengths are used for the specific simulations, they were uniform over the whole domain in all runs.

\(^5\)http://www.caps.ou.edu/ARPS/
Table 3.1.: ARPS model run specifications

<table>
<thead>
<tr>
<th>model version</th>
<th>ARPS-2km</th>
<th>ARPS-500m</th>
<th>ARPS-150m</th>
<th>ARPS-50m</th>
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</thead>
<tbody>
<tr>
<td>horizontal resolution [m]</td>
<td>2000</td>
<td>500</td>
<td>150</td>
<td>50</td>
</tr>
<tr>
<td>horizontal grid [nx x ny]</td>
<td>480 x 320</td>
<td>200 x 200</td>
<td>240 x 240</td>
<td>240 x 240</td>
</tr>
<tr>
<td>minimal vertical resolution [m]</td>
<td>40</td>
<td>40</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>average vertical resolution [m]</td>
<td>400</td>
<td>400</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>vertical model levels [-]</td>
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<td>60</td>
<td>119</td>
<td>179</td>
</tr>
<tr>
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<td>0.4</td>
<td>0.12</td>
</tr>
<tr>
<td>time step, short (sound waves) [s]</td>
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<td>0.2</td>
<td>0.1</td>
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<tr>
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</tr>
<tr>
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<td>yes</td>
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<tr>
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<tr>
<td>vegetation fraction [%]</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

3.3. Sub-grid scale turbulence

The treatment of subgrid-scale turbulent processes is of crucial importance for highly resolved large eddy simulations (LES). Unlike COSMO-2, ARPS uses a subgrid-scale turbulence parameterization, which retains a fully three-dimensional formulation at all scales. It offers three different subgrid-scale closure options for the turbulent mixing terms. In all of our simulations, the 1.5 order turbulent kinetic energy (TKE) scheme was used (Deardorff, 1980). COSMO-2 on the other hand employs a one-dimensional scheme, where subgrid-scale turbulence fluxes are considered solely in the vertical (Doms and Schattler, 2007). The underlying assumption is the so-called boundary layer approximation, i.e. horizontal homogeneity of variables and fluxes allow to neglect all horizontal turbulent fluxes. This supposition is usually fulfilled if the horizontal scales of motion outrange the vertical scale, as vertical transport dominates the contributions from horizontal turbulent fluxes. The boundary layer approximation can sensibly be applied to meso-B scale flow systems, i.e. to scales of 20-200 km. An option for a full three-dimensional treatment of turbulence in COSMO has been implemented lately and is under testing.

3.4. Observations

Complementary to the modelling studies, measurements at six local weather stations were analysed and compared to the model results. This allows to validate the numerical simulation of the event to a certain extent. In addition, measurements for the period from 1998 to 2006 for the weather stations Ebenalp and Wasserauen were analysed for similar Laseyer events and a simple climatology was established. The observations of the weather stations were provided by Meteomedia. The locations of the individual stations are displayed in Figure 2.1.

The analysed variables are limited to wind direction, mean wind, hourly wind gusts and temperature. Pressure measurements weren’t available for most of the stations, in particular for Ebenalp and Wasserauen. The hourly mean wind values consist of the average wind in the last 10 minutes before logging. Wind direction and temperature on the other hand are instantaneous values recorded at the time of the measurement. The wind gusts represent hourly peak velocities.

6http://www.meteomedia.ch
3. Data and methodology

3.5. Trajectory analysis

The trajectory calculations for the various ARPS runs were done with a Matlab-Code, which was developed based on LAGRANTO. LAGRANTO is a software tool to analyse Lagrangian aspects of atmospheric phenomena and is mainly applied for ECMWF analysis fields. See Wernli and Davies (1997) for a more in-depth description.

The procedure for the kinematic evaluation of the trajectories is based on a variant of Petterssen’s (1956) scheme. The trajectories are calculated with a predictor-corrector method. First, a provisional end position, \( r^{n+1} \), is calculated for the air parcel by applying a forward time-step with the velocity at the parcel’s original position, \( r^n \).

\[
r^{n+1} = r^n + v(r^n) \cdot \Delta t \tag{3.2}
\]

where \( r^n \) is the position vector of the trajectory at time \( t \).

Then, an iterative Euler step, a variant of Petterssen’s scheme, is performed with an adjusted mean wind \( v_m \):

\[
v_m = \frac{1}{2} \{ v(r^n) + v(r^{n+1}) \} \tag{3.3}
\]

where the number of iterations is set to three. The last derived mean wind allows to compute the definite starting position of the air parcel for the subsequent time step. Hereby necessary intergrid and intertemporal mean wind speed components are calculated by linear interpolation.

The trajectory calculations are prone to several sources of errors and uncertainties (Seibert (1993); Stohl (1998)). The tracks can be perturbed by the deviations between simulated and real wind fields and by errors arising from spatial and temporal interpolation. Moreover, they may be truncated by numerical errors, which may grow quickly if accuracy and time-step requirements are not met. While the uncertainties, due to the difference between the wind fields in analysis and reality, can not easily be dealt with, the numerical truncation errors can be reduced by choosing an appropriate time step. In general, if \( L \) denotes the typical length scale of the smallest pattern in the velocity field and \( U \) is the typical velocity, then the computational time step should be equal to or smaller than the typical time scale of the flow \( L/U \). In other words, the temporal resolution has to keep pace with the decreasing spatial discretization, otherwise smaller structures get neglected and cannot be represented in the trajectory path. Historically, trajectory calculations in atmospheric sciences were usually limited to the evaluation of results of comparatively coarse models with horizontal grid spacings in the order of a few kilometers. Thus, time steps of a couple of minutes up to a few hours were usually applied.

The trajectory calculations in this study are based on the wind fields of the ARPS-150m run. The horizontal grid spacing of 150 m and maximum horizontal velocities of 50 m/s implicate a time step of 3 seconds, which hence was used for all trajectory computations. Note that at this spatial and temporal scale, atmospheric turbulence becomes increasingly important and one of the underlying assumptions for trajectory analysis, the prevalence of laminar flow, may no longer hold. We are moving into the outer realms of where trajectory analysis is still a valid tool and provides meaningful results. The presented trajectory results should therefore be considered with care. To our knowledge there are no trajectory analyses applied to mountain flows at such a high horizontal resolution. A Lagrangian investigation of foehn flows in the Swiss and Austrian Alps was performed by Wuersch (2009), who ran backward trajectories from three Alpine foehn stations based upon the 7 km COSMO reanalysis (Jenkner et al., 2009). Engel (2009) uses trajectories based upon the 2 km COSMO forecast to investigate cirrus clouds by means of the match methodology (von der Gathen et al., 1995).

The complex orography of the region poses an additional challenge for the trajectory analysis, as we’re not only interested whether the air flows around or over the Alpstein mountain range, but rather if and how air parcels enter and move through the Schwendetal. The latter demand raises high accuracy requirements for the modelled wind field, the represented topography and the applied method for trajectory calculation. To avoid the early loss of too many trajectories due to their path running into the topography, the trajectories were elevated to 10 m above ground level, whenever they crossed the terrain.
4. Case study

4.1. Synoptic weather situation

In the night from January 18th to 19th 2007 the strong west storm Kyrill swept over large parts of Central Europe, devastating the landscape and claiming 47 lives. It was triggered by an extensive low pressure system, which moved rapidly over Northern Europe into the east. A pronounced pressure gradient, induced by the interaction of a strong high pressure system over southwest Europe and the depression over the north-western part of the continent, generated strong wind gusts over Middle Europe (Fink et al., 2009). Especially in middle and northern Germany, where the pressure rise associated with the passage of the cold front was able to amplify the wind gusts, the storm caused devastating damage. The cold front parted Middle Europe from the north-west to the south-east. Throughout the storm, Switzerland was located in the warm sector (Figure 4.1). Hence, the cold front presumably didn’t influence the flow around the Schwendetal. This is probably the reason why the wind speeds in Switzerland, although high, didn’t quite reach the velocities measured in Germany. While up to 140 km/h in lowland and nearly 200 km/h on mountain tops were measured in Germany, the weather station on the wind exposed Säntis recorded maximum wind speeds of 144.4 km/h. During the whole morning, the weather station on top of the Säntis recorded light to moderate precipitation.

![Figure 4.1](image-url)

Figure 4.1.: Synoptic weather situation on January 19th 2007 at 6.00 UTC when Kyrill was calming down. Plot of equivalent potential temperature on a 850 hPA surface in K (colours) and surface pressure in hPA (lines). GFS analysis chart from www.wetter3.de.

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7http://www.meteoschweiz.admin.ch/web/de/wetter/wetterereignisse/starker_weststurm.html
8ANETZ station data provided by MeteoSwiss
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4.2. COSMO analysis

In the following, the simulation results of COSMO and ARPS are shown for different points in time during the morning of January 19th. Although the train accident took place at 9.20 UTC, we don’t expect the models to replicate the atmospheric dynamics precisely and to turn out maximum turbulence at this exact moment. Rather, we try to account for model uncertainties like phase shifts by considering the whole simulation period. Thus, the following plots don’t exclusively show the model results around 9.20 UTC, but for points in simulation time which appear to be most significant in explaining key components for the formation of the Laseyer winds.

The following analysis of the COSMO-2 data is orientated on the work of Sonderegger (2008) and, in the main, backs up his findings based on the COSMO-7 model output. The hourly output of the COSMO-2 analysis of January 19th 2007 was examined for the period from 6 UTC to 13 UTC. During the whole period, Switzerland lay in a spacious oncoming flow from the north-west (Figure 4.2). The wind was diverted by the Alps and consequently turned with increasing altitude next to the mountain range; from westerly or south-westerly near the ground to north-westerly above 3000 m a.s.l.. Figure 4.3(a) shows the absolute wind velocity and wind direction 10 m above the ground at 9 UTC for the region around Wasserauen. As the storm travelled off into the east, the wind speed decreased from 6 UTC to 13 UTC, while the wind direction remained nearly constant. In the Mittelland, the wind blew from west or south-west, while over the Alps, the wind turned to north-westerly. In the region of Wasserauen, the wind was westerly throughout the morning. As Figure 4.3(b) shows, the wind in the north of the Alps turned with increasing altitude and was blowing from west-northwest on 2000 m a.s.l. during the studied period. However, above Wasserauen, the flow was still coming almost straight from the west. With the passing of the storm, the wind speeds decreased slightly from 38 m/s at 6 UTC to 32 m/s at 13 UTC, similar to the development in lower altitudes. Figure 4.3(c) shows a horizontal cross section on 3000 m a.s.l.. The wind was constantly blowing from the north-west over the Mittelland. During the studied period, the wind weakened slightly from 39 m/s at 6 UTC to 34 m/s at 13 UTC. Over the course of the morning, the wind in Wasserauen was westerly from the ground to an altitude of about 2000 m a.s.l. and then started to turn with increasing altitude to north-westerly at 3000 m a.s.l.. The velocity between 2000 m and 3000 m a.s.l. was almost constant, decreasing closer to the ground due to surface friction.

The COMSO-2 analysis backs up the statement in section 4.1, that there was no front passage over Wasserauen in the morning of January 19th 2007. Figure 4.4 shows that the front was displaced significantly to the north-west of Switzerland at 9 UTC. As noted in the introduction, vertically stratified air layers or inversions can decisively influence the airflow in lower altitudes and thus may facilitate rotor formation. In the following Figure 4.5, the stability of an air column is looked at by means of N², the Brunt-Väisälä frequency, where we define values of $N^2 > 2 \cdot 10^{-4} \text{ s}^{-2}$ as stable air layers and values of $N^2 > 3 \cdot 10^{-4} \text{ s}^{-2}$ as very stable air layers. At 6 UTC, a moderately stable layer ($2.5 \cdot 10^{-4} - 3 \cdot 10^{-4} \text{ s}^{-2}$) resided between 4000 and 5000 m a.s.l. over North-East Switzerland. Over the course of the morning, this air layer gradually descended, became more extended and more stably stratified. At 9 UTC, the air layer lay roughly at 3500 m a.s.l. and first patches of very stable air layers formed, although not directly above Wasserauen. At 13 UTC, the very stable air layer extended over a few hundred kilometers and reached down to 3000 m. Throughout the whole period, an almost neutral air layer ($N^2 < 1 \cdot 10^{-4} \text{ s}^{-2}$) was present in lower elevations below 1000 m a.s.l.. However, no statement can be made on the stratification in the Schwendetal itself, as the 2.2 km topography is not able to resolve the valley.

This stable air layer seems to have been transported into the region rather than to have developed by local modification. Figure 4.6 shows the maximum $N^2$ value and its height on the lowest 30 model levels north of the Alps, i.e. it depicts the altitude and relative magnitude of stability of the most stable layer in a vertical air column up to a height of roughly 6000 m a.s.l.. It’s apparent that an extended field of stable air approaches from the west and reaches the region of Wasserauen after 9 UTC. The stable air
4.2. COSMO analysis

Figure 4.2.: Horizontal wind direction (arrows) and velocity (colors, in m/s) of the COSMO-2 analysis on different elevations on January 19th at 9 UTC.
Figure 4.3: Close-up on horizontal wind direction (arrows) and velocity (colors, in m/s) of the COSMO-2 analysis on different elevations on January 19th at 9 UTC. The locations of Wasserauen and Säntis are marked with crosses.
The temperature profile above Wasserauen shows a descending of the stable air layer as well (Figure 4.7), the base of the inversion lay at roughly 4800 m a.s.l. at 8 UTC and dropped to 3200 m a.s.l. until 13 UTC. In this time, the stable layer deepened and the vertical temperature gradient gradually decreased until it finally got slightly negative at 12 UTC.
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Figure 4.5.: Vertical cross sections from north to south (left) and from west to east (right) of Brunt-Väisälä frequency (colours, in $s^{-2}$) and potential temperature (lines, in °C) of the Cosmo-2 analysis. The vertical line indicates the location of the Schwendetal. All plots for January 19th 2007. The course of the cross sections is depicted in Figure 4.4.
4.2. COSMO analysis

Figure 4.6: Maximum of Brunt-Väisälä frequency (colours, in s$^{-2}$) in lowest 30 model levels in the COSMO-2 analysis. The height of the maximum $N^2$ values is shown with lines [m a.s.l.]. All plots for January 19th 2007. The location of the Schwendetal is marked with a cross.
Figure 4.7.: SkewT/logP-plot of the temperature above Wasserauen in the COSMO-2 analysis from 6 UTC to 13 UTC on January 19th 2007.
4.3. Comparison ARPS - COSMO

Figure 4.8 is a vertical cross section of Brunt-Väisälä frequency and potential temperature, illustrating the strength and extension of the stably stratified air layer at 11 UTC in the COSMO-2 analysis and the different ARPS simulations. In both, the ARPS-2km and ARPS-500m simulations, the stable air layer ($N^2 > 2 \cdot 10^{-4} \text{ s}^{-2}$) forms later, is significantly weaker and not as continuous as in the COSMO-2 run. This can potentially influence the airflow in lower altitudes and thus may obscure the dynamics around Wasserauen in these ARPS simulations. Curiously, the inversion layer becomes stronger again in the ARPS-150m and ARPS-50m runs. The layer is still less stable and not as continuous as in COSMO, but it may very well affect the flow on lower elevations and act as a sealing cap over the valley. The formation of the stable layer in the ARPS-150m is discussed more extensively in section 4.4.1.

Additionally, vertical and horizontal velocity fields in the ARPS-2000m simulation and in the COSMO-2 analysis were compared (graphs are not shown). The general pattern of vertical velocity is similar; areas of up- and downdrafts match up reasonably. The ARPS-2000m run tends to simulate stronger vertical motion, i.e. it features higher peak velocities. The evaluation of the horizontal velocity fields yields similar findings; ARPS simulates slightly higher velocities but the general structure of the wind field remains comparable.
Figure 4.8: Vertical cross sections from north to south of Brunt-Väisälä frequency (colours, in $s^{-2}$) and potential temperature (lines, in $^\circ$C) at 11 UTC on January 19th 2007. From top to bottom: COSMO-2 analysis, ARPS-2 km, ARPS-500 m, ARPS-150 m and ARPS-50 m.
4.4. ARPS analysis

The analysis of the ARPS runs is focused on the two simulations with the highest resolutions, featuring horizontal grid spacings of 150 m and 50 m respectively. These resolutions should be able to fulfil the high requirements raised by the complex orography around the Schwendetal and ought to account for most of its topographical features.

4.4.1. ARPS - 150 m

In the following section, the results of the ARPS simulation on a grid with a horizontal spacing of 150 m are analysed. As can be seen in Figure 4.9, this resolution enables to depict the Schwendetal. Thus the simulation should at least in this regard potentially be able to reproduce the dynamics in the valley. The roughness length was set to 0.1 m, which is representative of a vegetation of low crops. The output time interval is set to 30 minutes and the first 3 hours of simulation from 3.00 UTC to 6.00 UTC were neglected to allow for sufficient spin-up time for the model.

![Figure 4.9](image)

**Figure 4.9:** Computational domain and orography (m a.s.l.) of the ARPS-150m simulation. The approximate location of the train accident is marked with a cross. The two black lines indicate the course of the vertical cross sections in Figure 4.14.

The wind direction stays essentially constant on all levels throughout the morning, whereas the velocity peaks at 6 UTC and then again from 10 UTC to 11.30 UTC with a calmer period in between. The flow velocity on the valley surface essentially follows the strength of the wind on the upstream ridge and hence the timing of maximum wind speeds inside the valley and above nearly coincides. The wind flows out of the valley during the whole morning with only small cross-valley components. At the place of the accident, the wind is flowing almost parallel to the railway line. At all times, the highest horizontal wind velocities on the valley floor are not found near the location of the accident but deeper inside the valley on a higher elevation. At the place of the accident, at 9.30 UTC, the wind blew with roughly 20 m/s and was directed alongside the railway line.
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Figure 4.10(a) shows the absolute velocity and the direction of the horizontal wind on the lowest model level at 10.30 UTC, when the highest velocities were simulated. The wind speed peaks at 24 m/s at the location of the accident, deeper in the valley maximum velocities reach 38 m/s. On the ridgeline, the velocities go up to 57 m/s. As we pass the upstream ridgeline, the wind turns from north-westerly on the crest to south-westerly on the valley floor forming a strong vertical gradient of horizontal velocity. This can be seen more clearly in Figures 4.10(b) - (d), which show the horizontal wind velocity on 1000, 1500 and 2000 m a.s.l. respectively. Figure 4.11 is a vertical cross section through the location of the accident depicting the change in velocity and direction of the horizontal wind with height. Note the local peak in velocity on the valley floor and how the wind first slightly weakens and then strengthens again with increasing altitude over the valley. Both phenomena can be observed deeper inside the valley as well.

Figures 4.12(a) - (d) show horizontal cross sections of vertical velocity at different elevations. The lifting of air masses by the upstream ridgeline leads to strong updrafts with velocities up to 12 m/s between 1250 m and 1750 m a.s.l. in the North-Western part of the valley. At the same time, strong downdrafts occur on the same elevation but over a more extended area in the South-Eastern part with local maxima reaching 20 m/s. Similar to the horizontal wind, the vertical motion is strongest deeper in the valley, while it’s comparatively calm in the air column above the location of the accident. Above 1750 m a.s.l. the vertical motion becomes significantly weaker over the whole valley outline. The vertical cross sections in Figure 4.13 disclose that the strong downdrafts extend down to the ground. Further inside the valley, around the Seealpsee, the downdrafts expand over almost the whole valley floor, while in the area of the accident, strong downward motion is confined to the southern flank of the valley.

As highlighted in section 4.3, the inversion layer becomes stronger again in the ARPS-150m run, after being relatively weak in the ARPS-500m and ARPS-2000m simulations. Figure 4.14 illustrates the evolution of the vertical stratification in the ARPS-150m simulation. At 8 UTC, a layer of stable air with a high vertical gradient of potential temperature has entered the model domain on the southern border and hovers at about 5000 m a.s.l. A band of moderately stable air ($N^2 > 2 \cdot 10^{-4} \, s^{-2}$) extends over the whole model domain at this altitude. At 11.30 UTC, this air layer descended to 3500 m a.s.l. and became more stably stratified over the whole area. In contrast to the COSMO-2 run, the most stable air masses are located in the south and the east and seem to enter the domain from these directions. This is a bit puzzling and may have a profound effect on the simulations. Note also the strong displacements of the potential temperature isolines on the southern border of the domain. However, this downstream boundary effect probably won’t affect the dynamics in the Schwendetal too much, as it doesn’t extend far into the domain. Even though the inversion layer doesn’t drop too far below 3500 m a.s.l. and thus hovers at least 1000 m above the ground at all times, it may still affect the dynamics on lower levels. The stable air layer can act as a cap, preventing air from flowing into higher altitudes and reflecting kinetic energy back towards the ground. Thereby constructive interference between surface and inversion layer may be induced, which in turn facilitates higher near surface wind speeds.

The strong gradient of vertical wind also leaves an imprint on the pressure field in the valley. Figure 4.15(a), showing the pressure distribution on 1500 m a.s.l., indicates that the location of local pressure maxima correspond to regions of strong downdrafts and vice versa. Figure 4.15(b) shows the surface pressure tendency from 6 UTC to 10.30 UTC. In this period, the pressure on the ground dropped in the whole region by 2 to 5 hPa, with no strong local deviations in pressure development within the valley. To interpret these pressure fields more meaningfully, a more comprehensive analysis of the different components which contribute to the acceleration of the air in the valley would be required.

To identify the origins of the air flowing in the valley, an extensive trajectory analysis for the 150m run was carried out. Figures 4.16(a) - (d) show forward trajectories, initiated at 9.00 UTC on different heights. For low initial altitudes, the flow paths are heavily influenced by the topography in general and here by the Alpstein mountain range in particular, whose impact diminishes with increasing height. Thus the flow pattern appears more uniform and streamlined on higher altitudes. The deflecting effect of the Alps on the wind field in lower elevations is again observable, as most of the trajectories starting on 1000 m a.s.l. move eastward with a small deviation to the north.
Figure 4.10: Horizontal wind direction (arrows) and velocity (colors, in m/s) of the ARPS-150m simulation on different elevations on January 19th at 10.30 UTC. The approximate location of the train accident is marked with a cross. The bold black line in Figure (d) indicates the course of the vertical cross section in Figure 4.11.
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Figure 4.11.: Vertical cross section from north to south of wind direction (colours, in degree azimuth) and velocity (lines, in m/s) of the ARPS-150m simulation for January 19th at 10.30 UTC. The cross sections runs through the location of the accident. The course of the cross section is depicted in Figure 4.10(d).

Figure 4.12.: Vertical wind velocity (colours, in m/s) of the ARPS-150m simulation for January 19th at 10.30 UTC on different elevations. The approximate location of the train accident is marked with a cross. The two blue lines in (a) indicate the course of the vertical cross sections in Figure 4.13.
4.4. ARPS analysis

Figure 4.13.: Vertical cross sections of vertical velocity (colours, in m/s) of the ARPS-150m simulation for January 19th at 10.30 UTC. The course of the cross sections is depicted in Figure 4.12(a).

(a) along valley: SW-NE

(b) cross valley: NW-SE

Figure 4.14.: Vertical cross sections from north to south (left) and from west to east (right) of Brunt-Väisälä frequency (colours, in s$^{-2}$) and potential temperature (lines, in °C) of the ARPS-150m simulation. The vertical line indicates the location of the train accident. All plots for January 19th 2007. The course of the cross sections is depicted in Figure 4.9.
Figure 4.15: Pressure distribution on 1500 m a.s.l at 10.30 UTC (a) and surface pressure tendency from 6 UTC to 10.30 UTC (b) of the ARPS-150m simulation on January 19th 2007. Pressure shown in hPa (lines), orography in m a.s.l. (colours).
Figure 4.16: 30 minute forward trajectories started at 9.00 UTC on January 19th 2007 for different initial elevations upstream of the Alpstein mountain range. The altitude (in m a.s.l.) is shown in color, the black dots indicate 5 minute time intervals. The location of Wasserauen and the Säntis are marked with crosses.
A backward trajectory run, which starts at 9.30 UTC in a vertical column above the location of the accident, is displayed in Figure 4.17. Most of the trajectories starting above 1500 m a.s.l. reached the valley straightly without being affected by the topography too much. They exhibit nicely how the wind is turning towards north-westerly with height. The air parcels at the six lowest starting points with initial elevations between 800 and 1400 m a.s.l. travelled quite a different path: They passed the upstream ridgeline more to the south-west to enter the valley in the back, where they lost elevation rapidly as they flew into the region with strong downdrafts. In the following, the parcels were blown down the valley and reached the accident location from a direction almost perpendicular to the air above, generating strong vertical wind shear. This split in the routing of lower and higher air parcels persists over the whole morning with the threshold altitude hovering between 1400 and 1500 m a.s.l.

A more detailed analysis of the flow over the upstream ridgeline was carried out to illuminate the development of the striking trajectories in Figure 4.17, which ended up running parallel to the railway tracks. These remarkable trajectory paths can be observed over most of the morning of the 19th of January 2007. Figure 4.18 shows a bird’s eye and a three dimensional view of forward trajectories with initial heights of 1500 m a.s.l starting at 11.00 UTC. While the flow arriving at the upstream ridgeline around Ebenalp does get excited into a small wavelike motion by the underlying foothill, it does smoothly flow over the valley. In contrast, the trajectories, reaching the ridgeline further to the west around the Altenalp Türm, lose altitude immediately after crossing the edge and are then diverted to the left by the rock face above the Seealpsee. Inside the valley, the air parcels further drop and eventually reach Wasserauen almost on ground level. Hence, these trajectories descended over 800 m over a short horizontal distance of no more than 3 km after crossing the ridge at about 1800 m a.s.l. Also to be noted again is the well observable strong vertical wind gradient above Wasserauen.
Figure 4.18: Forward trajectories initiated at 11.00 UTC on January 19th 2007 with a starting height of 1500 m upstream of the Alpstein mountain range. The altitude (in m a.s.l.) in Figure (a) is shown in color, the black dots indicate 1 minute time intervals. The location of Wasserauen and the Säntis are marked with crosses.
This section summarizes the results for the ARPS simulation carried out with a horizontal grid spacing of 50 m. Besides the higher resolution, the ARPS-50m run features a uniform, yet different, surface roughness compared to the ARPS-150m run. The surface roughness length was set to 1 m for the whole computational domain which approximates a mature forest canopy. A higher spatial resolution should be able to resolve turbulence of smaller spatial and shorter temporal nature. The output interval was shortened accordingly and is now set to 10 minutes. On the same note, the model domain was scaled down to keep the computational effort in check. The spin-up time from 3.00 UTC to 6.00 UTC was once again not analysed.

The results of the ARPS-50m run show a more turbulent flow in and around the valley. This is reflected in both, wind velocity and direction, which exhibit much stronger temporal and spatial variation than in the ARPS-150m run. Figures 4.19(a) - (f) show the velocity fields at 9.20 UTC on different heights. In general, the wind direction is similar to the ARPS-150m run throughout the simulation period, with south-westerly flow inside the valley and north-westerly wind above. However, the wind direction at a given location is less steady and can vary over shorter durations and smaller distances than in the ARPS-150m simulation, especially on middle levels inside the valley. At ground level, the wind direction and velocity don’t show strong temporal variability, possibly because of dampening due to surface friction.

The simulation on the 50m grid yields surprisingly high vertical wind velocities. Figures 4.20(a) - (c) display a bird’s eye view of vertical velocity on different heights, while Figures 4.21(a) - (b) show the vertical velocity in two vertical cross sections through the valley. Deep in the valley, the strongest downdrafts are found at the elevation of roughly 1700 m a.s.l. and feature maximum velocities of 34 m/s. As we move further towards the valley entrance, the vertical movement becomes less vigorous, but the up- and downdraft velocities still reach 20 m/s. The areas of strong up- and downdrafts occasionally reach down to ground level over the modelled period. In the back of the valley, a steady state configuration develops with the updrafts/downdraft regions found next to the upstream/downstream ridge respectively. Closer to the embouchure, this dipole schematic gets broken up. Instead, the vertical motion is slightly weaker and much more erratic over time. This can also easily be retraced by examining the horizontal cross section on 1500 m a.s.l. in Figure 4.20(b); the dipole structure doesn’t extend to the location of the accident but is confined to the deeper parts of the valley. Above 2000 m a.s.l., the topographical disturbance on the flow field decays fast and consequently, the vertical velocities reduce quickly.
Figure 4.19: Horizontal wind direction (arrows) and velocity (colors, in m/s) of the ARPS-50m simulation on different elevations on January 19th at 9.20 UTC. The approximate location of the train accident is marked with a cross.
Figure 4.20.: Vertical wind velocity (colours, in m/s) of the ARPS-50m simulation for January 19\textsuperscript{th} at 9.20 UTC on different elevations. The approximate location of the train accident is marked with a cross. The two blue lines in (a) indicate the course of the vertical cross sections in Figure 4.21.

Figure 4.21.: Vertical cross sections of vertical velocity (colours, in m/s) of the ARPS-50m simulation for January 19\textsuperscript{th} at 9.20 UTC. The course of the cross sections is depicted in Figure 4.20(a).
4.5. Analysis of observations

4.5.1. Weather station measurements

In the following section, measurements of the two weather stations at Ebenalp and at Wasserauen are analysed for the period from 1998-2006. The analysis is confined to this time span by two limitations: Firstly, the weather station on the Ebenalp records measurements only since 1998. Hence, no comparisons could be made which reach further back. Secondly, both, Ebenalp and Wasserauen, successively switched to an updated measurement and recording technology during the years of 2007 and 2008. This caused a prolonged period of frequent downtimes and dissimilar recording intervals, which would require more extensive pre-processing. An incorporation of this period into the analysis would certainly give more insight but for now remains outside of the scope of this thesis.

Likewise during the eight years of analysis, the equipment of both stations was changed, updated and repaired. As a result, especially the record of the Ebenalp station suffers from data gaps due to the occasional downtimes. To account for these gaps, the data was pre-processed to ensure that only observational records are compared where measurements had been logged at both stations. Thus, the eventually analysed dataset was shortened by 6589 hours compared to the actual observation period, which adds up to approximately 9 months of combined downtime.

The following graphs show wind direction, intensity and frequency at either Ebenalp or Wasserauen with different conditions for wind gust velocity and wind direction at one of the stations. As mentioned in section 3.4, the wind gusts are hourly maximum values, while the recorded direction is the current wind direction at the time of logging. The combination of conditions of hourly maximum values on one hand and regular hourly measurements on the other might prove problematic, i.e. the recorded wind direction doesn’t necessarily have to match the conditions at the time of peak wind gusts. Here, only the plots considering wind gusts are discussed - however, the findings can be backed up by accounting for the mean wind speed of the last 10 minutes before logging instead of the hourly gusts. The plots which are based on the mean wind are found in the Appendix; in essence they provide the same qualitative results. One might also argue that wind gust velocities in Wasserauen should be correlated with mean wind velocities on Ebenalp, as we’re trying to determine continuous ambient conditions, which cause the short-lived extreme events in the valley. The results of this analysis are also to be found in the Appendix and affirm the findings stated below.

Figures 4.22(a) - (d) show wind direction, intensity and frequency at Wasserauen for different gust velocity ranges. Plot (a) depicts that for wind gusts below 20 m/s, the wind flows mainly along the valley. For higher gust velocities, winds flowing from east to west across the valley get increasingly frequent. Between 20 and 30 m/s (Figure (b)), the flow pattern directed out of the valley is still the most prominent. Above 30 m/s (Figures (c) and (d)) the flow comes most likely across the valley from the east or south-east. In the following, we try to establish a possible connection between the emerging cross valley wind pattern for higher wind speeds in Wasserauen and the wind conditions on the Ebenalp.

Figures 4.23(a) - (d) show the wind distribution at Wasserauen for those times, where the wind on Ebenalp was blowing from an angle between 240 and 360 degree azimuth and for varying velocity ranges on the Ebenalp. The wind angle condition ensures the extraction of periods with incident flow from the north-west - a favourable flow pattern for the occurrence of Laseyer events (see section 2). Plot 4.23(a) shows the wind distribution in Wasserauen for times, where comparably slow wind gusts of up to 20 m/s were measured on the Ebenalp. Unsurprisingly, low wind speeds on the Ebenalp lead to small wind velocities in the valley. The wind flows predominantly along the valley, parallel to the railway tracks with a preference for flow directed out of the valley. For velocities between 20 and 30 m/s on Ebenalp (Figure (b)), the along valley winds in Wasserauen, although less frequent, still persist, but at the same time the wind blows more often from the south-east across the valley. This newly emerged wind pattern is causing most of the strong gusts with velocities above 25 m/s. The trend of less along valley winds and more and stronger winds from the east in Wasserauen continues for higher wind speeds on Ebenalp (Figures (c) and (d)). For wind gusts over 30 m/s on Ebenalp, easterly flow is occurring the
4. Case study

Figure 4.22: Recorded wind direction, intensity (colours) and frequency (percentage circles) of wind gusts at Wasserauen for different gust velocity ranges for the period 1998-2006. No wind direction requirements were imposed.
most frequent in Wasserauen with gusts above 30 m/s coming almost exclusively from this direction. In summary, Figures 4.23(a) - (d) show that strong north-westerly winds on Ebenalp trigger strong winds with an easterly component in Wasserauen. The mean wind velocity threshold at Ebenalp for the cross-valley wind pattern to set in lays around 10 m/s (Figures A.2 and A.3 in the Appendix), whereas the threshold for the wind gusts amounts to roughly 20 m/s (Figure 4.23(b)). Furthermore, the higher the wind gust velocity on Ebenalp, the more likely is the occurrence of strong gusts in the valley.

Figures 4.24(a) - (d) show the wind distribution on Ebenalp for the periods, where there was a wind with an easterly component in Wasserauen, i.e. the wind direction in Wasserauen is between 0 and 180 degree azimuth. In general, easterly winds in Wasserauen are likely to be triggered by westerly wind on Ebenalp. Again, stronger gusts in Wasserauen coincide with higher gust velocities on Ebenalp. To trigger strong gusts over 20 m/s with an eastward component in Wasserauen, high velocities in a very small angle range are required on Ebenalp. The narrowness of this angle window is remarkable; it ranges from 265 to 295 degrees azimuth. Over 90% of the time when easterly wind gusts in Wasserauen reached velocities above 30 m/s, they were accompanied by flow on the Ebenalp in this angle range. Over 60% of the time, those strong westward wind gusts went along with a wind direction between 275 and 285 degrees on the Ebenalp. These results back up the account of the local residents, after which the
Laseyer wind usually forms under westerly or north-westerly incident flow. They also disclose that the incident on the January 19th 2007 wasn’t a classic Laseyer event with strong cross-valley wind gusts. Instead, the westerly wind gusts of up to 37 m/s on Ebenalp together with the flow into the valley in Wasserauen with gusts peaking at 28 m/s make the event quite rare though not unique as can be inferred from Figure 4.23(c).

The local residents report that Laseyer events only come up in the winter season. To verify whether the observations are consistent with this statement, we define a Laseyer event as follows: In Wasserauen, we require wind gusts with velocities over 30 m/s and a wind direction between 0 and 180 degree azimuth, i.e. wind with an easterly component. On Ebenalp, we simply demand a wind direction between 180 and 360 degree azimuth, that is a wind with a westerly component. Table B.1 in the Appendix shows the dates where these conditions are satisfied. Over the eight years of measurements, 71 hours on 32 different days met the conditions. Only two of those hours were not between the beginning of November and the end of March. There were 10 independent events which lasted more than one hour, all of which took place between November and March. Again, even though we set a very lax direction criterion on Ebenalp, for the vast majority of the records, the wind angle on Ebenalp is between 270 and 290 degrees azimuth, thus emphasizing the point made above.
4.5. Analysis of observations

4.5.2. Comparison of observations and simulations

The observations of wind velocities and directions at the 6 local weather stations allow to validate the model results for duration of the case study. As the stations at Bächli-Hemberg, Schwägalp and Gäbris are outside of the model domain of the 50m-ARPS simulation, the model validation at these locations is limited to the COSMO run and the ARPS run on a 150 m grid. The observations are compared to the modelled surface wind velocities. The COSMO model explicitly computes the horizontal wind speeds 10 m above the ground, while for the ARPS model, the horizontal wind velocities on the lowest vertical layer were extracted.

The observational data as well as the model results plotted in Figure 4.25 represent instantaneous values of wind direction. At four of the six station locations, all model runs capture the wind direction reasonably well for the morning of the 19th of January. On Ebenalp, the ARPS-50m simulation consistently calculated more southerly flow. This comes as a bit of a surprise, considering that at the other stations both, the ARPS-50m run and COSMO-2, showed a tendency for more northerly flow than observed. The biggest departures of the models from the observed flow directions are found in Wasserauen. This is to be expected for the COSMO-2 model, where the resolution is simply too coarse to capture the valley and thus the modelled flow direction naturally deviates from the measurements. Conversely, both ARPS simulations feature a topography, which resolves the valley adequately and thus at least in theory should be able to predict wind direction in Wasserauen correctly. Yet this is not the case; both ARPS runs compute wind which flows out of the valley (see also sections 4.4.1 and 4.4.2). In contrast, the weather station recorded a flow which was directed the opposite way: into the valley. The recorded measurement by itself raises questions, which were discussed in greater detail in section 4.5.1.

A possible reason for the discrepancies can lay in the uniform roughness length in the ARPS simulations, which may not do justice to the heterogeneous surface in the valley and its surroundings and thus may have a critical influence on the flow behaviour. Moreover, a 50 m horizontal grid spacing might still be too coarse to replicate the small scale turbulences adequately. Note also, that the observation is a point measurement in space and time and thus is limited in its explanatory power regarding the flow behaviour in the whole valley cross-section, let alone in the entire valley. These issues merit attention in particular because highly turbulent dynamics on a small spatial and temporal scale are anticipated around Wasserauen. On the contrary, the model results, while being instantaneous values too, can be inspected over the whole domain and they do show a more or less uniform flow direction over the whole valley cross section (section 4.4).

Figure 4.26 shows the modelled and measured wind velocities at the identical six locations. The plotted observational data includes the average wind speed of the last 10 minutes as well as the hourly wind gusts. The COSMO-2 simulation, given that COSMO is the model with the crudest resolution, matches the observed wind velocities passably. As could be expected, the model results are closer to the observations in locations, where topographical influence on the flow is smaller. Hence the recorded values on the comparatively salient and wind-exposed Säntis, Gäbris, Schwägalp and Ebenalp are reproduced a bit better than those at Bächli-Hemberg and Wasserauen. As for the latter two, the lower resolution falls short of resolving the small scale features of the hilly landscape and thus, the narrow valleys simply don’t exist in the model. At Ebenalp and Gäbris the cause for the significant deviation is less obvious. The underestimation of the observations could be the implication of the coarser grid spacing, which smoothes the topography and scales down the peaks and ridgelines. For instance the elevation of the Säntis is reduced by over 600 m from 2490 m a.s.l. in reality to 1830 m a.s.l. in the model. The higher, more wind-exposed and salient location of the stations in reality goes hand in hand with higher wind speeds due to reduced surface friction. This could explain the underestimation of the measured wind speeds at Ebenalp and Gäbris and to a lesser extent also on the Säntis.

Beside the instantaneous wind velocity values, the COSMO model output includes hourly wind gusts as well. Here the COSMO model routinely overestimates the measured wind gusts, the only exception being the station on the Ebenalp, where the model results match the observations very well. The deviations at Wasserauen and Bächli-Hemberg can be attributed to topography related issues. Barring this, the
Figure 4.25.: Comparison of wind direction in the observations (blue line), COSMO-2 analysis (red dotted line), ARPS-150m run (green dash-dot line) and ARPS-50m (black dashed line) for January 19th 2009 at the location of the six weather stations.
COSMO model is known to systematically overestimate gusts in analysis and forecasts, which lead to a recent revision of the turbulent gust diagnostics in the model (Schulz, 2008). The way the hourly wind gusts are computed and measured certainly is important for the relative comparability. Furthermore, the formation of wind gusts are probably even more prone to small topographical and dynamical features than the average wind and thus the coarse resolution leads all the more to discrepancies if compared to point measurements. While ARPS doesn’t offer the option to compute wind gusts, the shorter output intervals of the two ARPS simulations partly compensate for the lack of hourly extreme values. The lowest vertical levels reach up to 20 m and 25 m above the ground in the ARPS-50m and ARPS-150m simulation respectively. As ARPS employs a staggered grid scheme, the velocities are computed for the middle of the grid box, so in this respect the extracted velocities should be fairly representative for the surface wind speed 10 m over the terrain. Recall that both runs weren’t able to reproduce the observed wind direction in Wasserauen correctly. This likely indicates that the models weren’t able to fully capture the dynamics in the valley and as such the wind speed comparisons for Wasserauen have to be considered with care. The results of the ARPS-150m run generally overestimate the observations and surprisingly don’t improve on the COSMO-2 results in most locations. On the Säntis, where both, the COSMO-2 run and the ARPS-50m run, yield satisfactory results, the ARPS-150m simulation overestimates the surface velocity by roughly 20 m/s. Although the results of the ARPS-50m run fluctuate stronger with time due to the shorter output interval and to the finer resolution, which also gives rise to increased turbulence, they match the hourly velocity observations passably. Considering that the ARPS-150m run was performing poorer than COSMO-2 in most locations and was providing the boundary conditions for the ARPS-50m run, this is a bit startling. Again, there is not an obvious explanation, however the surface velocities in both ARPS runs may be flawed considerably on account of the uniform roughness length. As mentioned in section 4.3, the presence of the stable air layer in the middle troposphere in the morning of the 19th of January may have had a strong influence on the atmospheric dynamics in lower elevations. Therefore, the ability of the models to reproduce the inversion layer is of particular importance. Figure 4.27 compare the modelled vertical temperature profiles ARPS-50m, ARPS-150m and COSMO-2 at 11 UTC in Wasserauen with the sounding of Payerne at 12 UTC and the composite temperature profile of the six weather stations introduced in section 3.4 at 11 UTC. For COSMO-2, the temperature profile above Payerne is plotted as well. The temporal discrepancy between the simulations and the sounding is due to the end of the simulated period being at 11 UTC in the ARPS-50m run. Figure 4.27(a) shows that models and observations agree reasonably well below 2500 m a.s.l.; the COSMO-2 analysis is slightly too cold in this range, while ARPS is a bit to warm below 1400 m a.s.l. Further up, the Payerne sounding depicts a sharp inversion at 3000 m a.s.l. (Figure 4.27(b)). The COSMO-2 analysis is able to reproduce the sudden temperature rise in the vertical column above Payerne in a satisfactory way. In Wasserauen, the analysis profile naturally looks a bit different, but it still features a strong increase of the vertical temperature gradient at this altitude. On the other hand, in both ARPS simulations the temperature decreases more rapidly, the inversion is significantly weaker and its lower base is roughly 500 m higher than in the COSMO-2 analysis. The shortcoming of ARPS to convincingly reproduce the inversion layer presumably does have an impact on the models ability to simulate the flow on lower levels. However, to be able to evaluate the actual impact of the lacking strong inversion layer on the model dynamics, a more advanced sensitivity study would be needed.
Figure 4.26: Comparison of wind velocity in the observations (blue lines, wind gusts with circles), COSMO-2 analysis (red dotted lines, wind gusts with squares), ARPS-150m run (green dash-dot line) and ARPS-50m (black dashed line) for January 19th 2009 at the location of the six weather stations.
Figure 4.27.: Comparison of measured and simulated vertical temperature profiles for January 19th for different elevation ranges: Sounding in Payerne at 12 UTC, composite profile of the six weather stations at 11 UTC, COSMO-2 analysis above Wasserauen and above Payerne, ARPS-150m and APRS-50m above Wasserauen. All model profiles for 11 UTC. The markers of the model profiles depict the altitude of the vertical model levels.
5. Conclusions and Outlook

In this study, the origins of the intense turbulence episodes in the Schwendetal were explored by means of real-case numerical simulations and weather station measurements. The following conclusions can be drawn from this analysis:

- The assessment of the COSMO-2 analysis fields for the morning of January 19\textsuperscript{th} 2007 demonstrates that spacious incident flow in North-East Switzerland turned from (south-)westerly near the ground to north-westerly above 3000 m a.s.l.

- In the COSMO-2 analysis, an extended layer of stable air was present over the Schwendetal in the late morning of January 19\textsuperscript{th} reaching down to 3000 m a.s.l.. The layer forms later and is less stable in the ARPS simulations, but nevertheless may have influenced the flow dynamics on lower elevations.

- The results of the ARPS run with 150 m horizontal grid spacing also showed north-westerly flow above the valley and strong vertical motion within, with areas of strong up- and downdrafts confined to the flanks of the down- and upstream ridgeline respectively. High horizontal wind velocities on the valley floor were modelled with highest surface wind speeds of 38 m/s found deep in the valley and lower maximum velocities around the location of the accident (24 m/s) at 10.30 UTC. The flow was mainly directed towards the embouchure with hardly any cross-valley component.

- Trajectory analysis of the ARPS-150m velocity fields disclosed that air parcels can enter the valley from above near the valley head and in the following can generate down-valley flow on the valley surface. Again, the entry location is further up-valley than the place of the accident. The predominant south-westerly flow in the valley combines with the north-westerly flow above to generate a strong vertical wind shear above Wasserauen.

- The results of the ARPS-50m simulation indicate a strong influence of the surface fields on the flow near the ground. Rotach and Zardi (2007) second this finding by emphasizing the importance to incorporate improved surface data for LES-type models with increased spatial resolutions. Uniform surface roughness does no longer justice to the heterogenous surface in the valley at this small spatial scale.

- The analysis of the observation at the weather stations on Ebenalp and in Wasserauen for the period 1998 - 2006 revealed that strong winds with an easterly component in the valley are almost exclusively accompanied and thus most likely triggered by westerly winds aloft. The angle window for incident wind favourable for the occurrence of strong easterly wind gusts in the valley is surprisingly narrow, it ranges from 265\textdegree to 295\textdegree azimuth.

- The measurements affirm the account of local residents stating that Laseyer episodes predominantly occur in the winter season. If a Laseyer event is defined as wind with a westerly component (i.e. 180\textdegree - 360\textdegree azimuth) on Ebenalp going along with wind gusts with an easterly component (0\textdegree - 180\textdegree azimuth) and velocities over 30 m/s in Wasserauen, then Laseyer episodes were recorded almost exclusively between November and March.

- It seems that the strong winds causing the accident on January 19\textsuperscript{th} 2007 weren’t excited by a typical Laseyer event characterised by strong cross-valley wind gusts. Instead, nearby observations showed strong flow into the valley during the whole morning, marking the event as rare but not unique.
5. Conclusions and Outlook

- Neither the simulations nor the observations show strong cross-valley wind components in Wassen- auen on the morning of January 19th and thus are inherently limited in their capability to explain the derailment.
- The observed wind gusts at the weather station on top of the valley station of the Ebenalpbahn were too slow to cause the accident. The measurement site is less than 200 m away from the place of the train accident indicating strong wind shear on a very small spatial scale. The observations at the weather station are thus most likely not representative for the dynamical conditions at the location of the accident.
- The small spatial extent of the phenomenon joint with its highly transient nature raises high demands on the models temporal and spatial resolution. Thus, even though the fine spatial resolution potentially enables the ARPS-50m simulation to reproduce the general flow pattern in the valley, the model may still not be capable to explain the formation of the wind gusts decisive for the train accident. The critical dynamics may hence still partly result from sub-grid scale processes, which places higher requirements on the treatment of the sub-grid scale fluxes and betokens their crucial importance in this setting.
- On a more general note, the model results also reflect the challenge of applying weather prediction models over complex terrain and thus adequately representing the interaction of atmospheric flow with steep topography. This matter is not limited to sub-grid scale turbulence parameterization but also includes the general difficulty of large-eddy simulations in near wall regions (Wood, 2000) and employing small slope boundary conditions in areas where the flat-boundary approximation no longer holds (Epifanio, 2007).

The following considerations may serve as starting points to expand on the present study and to detect additional key players in the development of the strong winds:

- To further pursuit the issue of putting the incident in January 2007 into the right context, the analysis of other identified Laseyer events could be highly instructive. It may also help in identifying further key ingredients for the formation of the wind gusts.
- Another advancement on the study at hand would be the inclusion of non-uniform surface fields into the ARPS model. This would allow to better account for the heterogeneous surface in the valley and would result in more realistic surface roughness lengths.
- After the derailment in January 2007, the Appenzeller Bahnen placed an anemometer next to the location of the accident to monitor the wind strength and if need be to suspend the train connection to Wasserauen. The wind data is on record since mid of 2008. A comparison between the observations at the Ebenalpbahn station and the newly installed measurement site could provide an indication of the representativeness of the wind measurements at the weather station for the location of the accident and thus could further delimit the scale of the wind shear in the valley.
- To clarify the importance of the inversion layer for the near-surface flow in general and the formation of strong wind gusts in the Schwendetal in particular, a sensitivity analysis would be of great interest. One could either look at more documented Laseyer events and examine soundings or reanalysis fields on the presence and strength of a potential inversion layer. Alternatively, the COSMO analysis of January 19th 2007 fields could be modified to create settings with stronger or weaker stratification of the upper levels.
A. Figures

Figure A.1.: Recorded wind direction, intensity (colours) and frequency (percentage circles) of mean wind at Wasserauen for different mean wind velocity ranges for the period 1998-2006. No wind direction requirements were imposed.
Figure A.2.: Recorded wind direction, intensity (colours) and frequency (percentage circles) of mean wind at Wasserauen for wind directions between 240 and 360 degree azimuth and different mean wind velocity ranges on Ebenalp. Analysed for the period 1998-2006.
(a) mean wind velocity range: 5-10 m/s

(b) mean wind velocity range: 10-15 m/s

(c) mean wind velocity range: 15-20 m/s

(d) mean wind velocity range: 20-25 m/s

Figure A.3.: Recorded wind direction, intensity (colours) and frequency (percentage circles) of wind gusts at Wasserauen for wind directions between 240 and 360 degree azimuth and different mean wind velocity ranges on Ebenalp. Analysed for the period 1998-2006.
Figure A.4.: Recorded wind direction, intensity (colours) and frequency (percentage circles) of mean wind on Ebenalp for wind directions between 0 and 180 degree azimuth and different mean wind velocity ranges at Wasserauen. Analysed for the period 1998-2006.
conditions are met on 1133 days for 3618 hours
wind speed [m/s]

conditions are met on 180 days for 423 hours
wind speed [m/s]

conditions are met on 31 days for 63 hours
wind speed [m/s]

conditions are met on 7 days for 11 hours
wind speed [m/s]

(a) gust velocity range: 10-20 m/s
(b) gust velocity range: 20-30 m/s
(c) gust velocity range: 30-40 m/s
(d) gust velocity range: 40-50 m/s

Figure A.5.: Recorded wind direction, intensity (colours) and frequency (percentage circles) of mean wind on Ebenalp for wind directions between 0 and 180 degree azimuth and different gust velocity ranges at Wasserauen. Analysed for the period 1998-2006.
B. Tables
Table B.1.: Laseyer event climatology for the period 1998-2006. The dates fulfill the following conditions: wind gust velocities over 30 m/s and a wind direction of 0-180° azimuth in Wasserauen as well as a wind direction of 180-360° azimuth on Ebenalp.

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Bibliography


Bibliography


Acknowledgements

I would like to express my gratitude to all the people and institutions who helped me with the realisation of this master thesis. My special thanks to

Dr. Jürg Schmidli and Dr. Michael Sprenger for your generous support in all kinds of problems, for the interesting discussions, for the helpful tips and explanations, for the constructive feedbacks, for your contagious enthusiasm, for the adventurous journey as well as for the review of this report.

MeteoMedia for providing the observational data. Especially to Joachim Schug for the helpful explanations.

MeteoSchweiz for providing the COSMO-2 reanalysis fields.

Dr. Daniel Lüthi and Dr. Urs Beyerle for your support when the computer didn’t want to behave as it should.

Professor Dr. Hans Richner for the time you took to answer my questions.

My fellow students up in the sky on CHN N floor and under the ground on D floor for your support and for all the reviving coffee breaks. Especially to Alessandro, Andreas, Chrigi, Franziska, Ines, Michael and Ruth.

Erich, Nadja and Yann for the review of this report and your helpful feedback.

Meiner Familie: Edith, Erich und Jonas.
Für euch Unterstützung, fürs a mich Glaube, fürs für mich do si.