Spatial Heterogeneity of the Pre-foehnic Inn Valley Cold Air Pool and a Relationship to Froude Number

Observations from an Array of Temperature Loggers during PIANO

Master’s Thesis

in Atmospheric Sciences

Submitted to the Faculty of Geo- and Atmospheric Sciences of the University of Innsbruck

in Partial Fulfillment of the Requirements for the Degree of Master of Science

by

Thomas Muschinski

Advisor
Assoc. Prof. Dr. Alexander Gohm

Innsbruck, April 2019
Für Lars und Amelia

Every ending is a new beginning
Life is an endless unfoldment
Change your mind, and you change your relation to time
You can find the answer
The solution lies within the problem
The answer is in every question
Dig it?

George Clinton, Funkadelic
Abstract

The objective of the study was to investigate the structure and temporal evolution of pre-foehnic cold air pools (CAP) in the Inn Valley surrounding Innsbruck (Austria). Observations were taken from six Intensive Observation Periods (IOPs) of the Penetration and Interruption of Alpine Foehn (PIANO) campaign, conducted in fall and early winter 2017. Spatial inhomogeneities of the pre-foehnic CAP were analysed using an array of about 50 temperature and humidity loggers. In addition to a qualitative description of CAP inhomogeneity based upon valley bottom near-surface temperatures, the temperature measurements from four slope profiles provided information about spatial inhomogeneity in CAP depth.

During several IOPs, foehn flow first displaced or eroded the CAP to the east and northeast of Innsbruck and strong spatial heterogeneity in temperature was observed at the valley bottom. Locations further west, still well within the remaining CAP, had temperatures up to 10 K colder than in these foehn regions just a few kilometers away. During such periods, it also appeared that the northern profile was warmer at similar heights when compared to the southern profile.

To quantify the influence of southerly foehn flow exiting the Wipp Valley (S-N orientation) on the north-south CAP structure within the Inn Valley (E-W orientation), the differences in mean-profile potential temperature at the northern and southern profile were compared to Froude numbers. Using southerly wind component observations \( (U) \) from Patsch (in the Wipp Valley) and estimates of column integrated buoyancy \( (B) \) from the (Inn Valley) profiles below the height of Patsch, Froude numbers were calculated as the ratio of \( U \) to the square root of \( B \). It was found that for Froude numbers below approximately 1, the northern profile was colder than the southern profile. For larger Froude numbers, the northern profile was generally warmer than the southern profile. For low Froude numbers, the colder northern profile can be understood as a CAP tilt (deeper CAP towards the north), resulting from southerly wind stress aloft. For higher Froude numbers, other processes related to topographically induced flow deflection (at the E-W mountain range to the north of the Inn Valley) or growing shear instabilities (at the CAP-foehn interface) appear to dominate. For those cases, the result is often a warmer northern profile.
Furthermore, differences in profile-mean potential temperatures at the western and eastern profile were related to valley bottom pressure differences in the along-valley direction. A nearly linear relationship between potential temperature difference and valley bottom pressure difference was observed for all IOPs except IOP 7. The slope of the linear regression was slightly less than the theoretical value, which was derived under the assumption that valley bottom pressure differences are entirely caused by along-valley differences in potential temperature up to the height of the profiles (≈ 150 m above the valley floor). The conclusion was that, apart from perhaps IOP 7, the fractional contributions of CAP asymmetry and gravity wave asymmetry to measured valley bottom pressure differences remained quite constant.
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Chapter 1

Introduction

1.1 Motivation

Foehn is a downslope windstorm characterised by asymmetry with respect to the alpine crest and an accelerated flow on the leeward side, often resulting in very high wind speeds (Durran 1990). Due to the significant adiabatic descent, foehn is also characterised by relatively warm temperatures and its occurrence can result in strong temperature fluctuations in time at a given leeward location.

Naturally these characteristic phenomena of foehn can have a large influence on society. For one, such strong winds pose a danger to transportation and infrastructure, but may also help clear high concentrations of pollutants from a stagnant valley atmosphere (Schäfer et al. 2008). The timing of large temperature fluctuations can also affect the stability of mountain snow packs (DeWalle and Rango 2008) as well as the planning of crews tasked with keeping roads or landing strips free of snow and ice.

Downslope windstorms, foehn in particular, have been studied extensively and explained through theoretical frameworks of varying complexity (Smith 1987; Mayr et al. 2007; Drobinski et al. 2007). Most of these theories are based on the assumption of a stationary and fully established foehn flow and some will be shortly mentioned in the following subsection.

Even though there have been significant advances and investment in numerical weather prediction throughout the years, current numerical weather prediction models still do not have the necessary spatial and temporal resolutions to directly solve the Navier-Stokes Equations for boundary layer processes, but must rely on parametrisations (Bauer et al. 2015). These parametrisations are based on the more well established boundary layer theories derived and tested for homogeneous, flat and stationary conditions. It is then no surprise that with these limitations on grid resolution and insufficient research regarding the developmental and terminal foehn
stages, the predictive skill of foehn forecasts in a location such as Innsbruck still has significant room for improvement.

A field campaign by the name of 'Penetration and Interruption of Alpine Foehn' (PIANO) was conducted during the fall of 2017. The data collected during PIANO can hopefully be used to advance understanding in this area. More specifically, the large network of approximately 50 temperature and humidity loggers deployed during the significant observation period (SOP) and analysed in this Master’s Thesis will give an unprecedented spatial view of changing thermodynamic quantities at ground level in the hours surrounding foehn breakthrough and interruption.

1.2 State of Research

Much of the following subsection 'General Foehn Theory' is paraphrased from Seibert (2012). Please visit this reference for a more complete overview of the literary history regarding foehn.

1.2.1 General Foehn Theory

Foehn has been a subject of interest in the meteorological community since the mid 19th century. The first two European theories regarding the origin of these winds were developed by two Swiss naturalists, von der Linth and Desor, and the German meteorologist, Dove. The Swiss position was that foehn must originate in the Sahara due to its warmth and aridity. Dove, on the other hand, argued for a Caribbean origin due to frequent precipitation south of the alpine crest and deflection due to the Coriolis force. In 1866, Julius von Hann published an article applying thermodynamic theory to the atmosphere and explaining the warm and dry wind as a result of adiabatic compression of air during its descent from the mountains after latent release due to condensation on the windward side. In fact, the American meteorologist James P. Espy had used thermodynamic theory to explain the drier and warmer climate on leeward mountain sides many years earlier (Espy 1841). In Hann’s view, Espy was the originator of the ’correct foehn theory’.

Hann (1901) mentioned that precipitation is not necessary to explain the high leeward temperatures associated with foehn given typical atmospheric lapse rates, and that simple subsidence from the mountain ridge is sufficient. Ficker continued the research of Hann (Ficker 1910b,a), and one of his published figures even depicts upstream blocking in a foehn schematic. At some point in the 1940s though, there was a shift back to the theory which relied on latent heat release through condensation to explain the warmth of the wind. This explanation spread throughout meteorological textbooks and soon became well established.
More recent field campaigns in the Alps such as the Alpine Experiment (ALPEX) from 1981-1982 (Hoinka 1985) and Mesoscale Alpine Programme (MAP) in 1999 (Bougeault et al. 2001) reestablished blocking in the absence of precipitation as a significant cause of foehn (especially in Austria when compared to Switzerland). Additionally, due to advancements in remote sensing techniques, the effects of gravity waves and characteristics of the complex flow structure above the surface could be studied more.

Using air-mass trajectories derived from Consortium for Small-scale Modeling (COSMO) model simulations, Miltenberger et al. (2016) found that the transalpine flow pattern during foehn is much more complicated than generally assumed and the relative importance of adiabatic versus diabatic processes can differ depending on the air mass origin upstream. Those air parcels strongly heated by condensation can be found at higher levels on the leeward side compared to those parcels cooled through evaporation or sublimation, which are found nearer to the leeside valley bottom. These processes can cause a 'scrambling' of air masses, where lower parcels upstream end up higher in the lee of the mountain chain and higher parcels end up lower.

1.2.2 Factors influencing Foehn Breakthrough and Interruption

The occurrence of foehn is typically associated with a local increase in temperature. It is not immediately clear why the less dense foehn air should remove the cold (and denser) air preceding it. There are many processes which play a role in the development of foehn and the removal of such a cold air pool. Their relative importance may be dependent on the particular topography and synoptic scale atmospheric situation in question. Some of the potential mechanisms for foehn penetration are discussed below.

Differential Air Mass Advection

If there is a cold air pool (CAP) below a foehn layer, the density difference between the two layers determines the static stability of the arrangement. If the foehn flow cools and the CAP characteristics remain unchanged, the atmosphere becomes less stable and more prone to mixing, assuming the cross-boundary shear in horizontal wind remains constant (Lamb 1945).

Mayr and Armi (2008) found that shallow (restricted to the passes) and deep (cross-barrier flow up to and beyond crest level) foehns are mainly a response to the difference in air mass temperatures (and associated densities) between the upstream and downstream sides. A detailed case analysis of foehn on 30 October 1999 showed
that the 'maximum depth to where the air upstream was colder than downstream was also the top of the layer that descended and accelerated down the lee slopes of the Wipp Valley.' Even though the upstream air above this level had a stronger cross-barrier component, it did not descend due to its lower potential temperature compared with the same elevation downstream. If the entire upstream atmosphere cools, there is a larger potential for deep foehn as higher upstream layers are potentially cooler than those downstream.

Cold air advection downstream can also cause the interruption of foehn by the same mechanism. Gohm et al. (2010) examined the propagation of a cold front on 6 November 1999 based on observations collected during MAP. They found that the cold front approaching the Alps from the northwest was distorted and entered the Inn Valley via two passes, converging near Innsbruck before advancing towards the Brenner Pass via the Wipp Valley. This colder air (relative to the prefrontal foehn) acted as a density current and caused the foehn flow to lift. The presence of dynamical instabilities and turbulent wakes at the top of the density current were observed with a Doppler lidar in the Wipp Valley.

**Radiation**

Changes in air mass properties of the foehn flow or CAP need not be caused by advection alone; a radiative imbalance is another energy source or sink for the atmosphere. Due to the high absorptance and emissivity of the ground compared to the (cloud-free) atmosphere, the radiative balance of the boundary layer is often strongly influenced by that of the surface. Energy gained or lost at the surface is then distributed throughout the atmospheric boundary layer (ABL) via turbulent fluxes of sensible and latent heat.

The influence of radiation on CAP development and erosion is different for valleys and enclosed basins. Observations from small enclosed basins such as the Gstettner-Alm sinkhole in Austria (Sauberer and Dirmhirn 1954) and the Peter Sinks basin in Utah, USA (Clements et al. 2003) show the presence of extremely stable stratification with temperature inversions of more than 20 K in 100 m. In such enclosed basins and under weak wind conditions, advective processes or turbulent entrainment play a minor role and the nighttime energy loss through outgoing longwave radiation from the surface results in very low temperatures. In the case of unenclosed valleys, nighttime cooling due to radiative imbalance at the surface typically results in katabatic outflow. Potentially warmer air from upvalley descends as a result of mass conservation, reducing the cooling rate within the CAP and also the strength of katabatic winds (Clements et al. 2003). Despite this limit on radiatively induced CAP formation, persistent CAPs lasting several days can still form in open basins and valleys, especially during wintertime (Lareau et al. 2013).
Mayr et al. (2007) found, using a statistical analysis, a strong diurnal cycle in the frequency of foehn for Innsbruck. While the afternoon frequency maximum was 14%, the nighttime minimum was found to be just 1%. Nocturnal foehn breaks often occur, and it is natural to attribute them to the development of a stable near-surface stratification as a result of outgoing long-wave radiation and no incoming short wave radiation. The deepening of this stable nocturnal boundary could cause the foehn flow to rise until the next morning, when incoming solar radiation would cause an energy increase near the surface and subsequent destabilisation of the CAP.

Further complexity arises when considering radiative effects acting on other areas. While solar insolation can weaken a CAP in the Inn Valley, it may also simultaneously warm the foehn air in the Wipp Valley or destabilize the upstream air mass and lower stability. A less stable upstream atmosphere may result in less blocking and could change the characteristics of the large-scale foehn flow.

Leeside Pressure Field

Another influence on the persistence of a CAP and the development of a downslope windstorm is the pressure field to the lee of the mountain crest. Using a two-dimensional hydrostatic mesoscale model, Lee et al. (1989) found that in the case where the pressure gradient tends to force the CAP towards the mountain, the CAP is quite persistent and no large gravity waves form. In the opposite case, where the pressure decreases away from the mountain, a large downslope windstorm develops. The authors concluded that turbulent erosion is a rather ineffective mechanism for removing the cold air. Already in the early 1900s, Ficker (1910b) suggested that foehn breakthrough to the valley bottom results mainly from CAP drainage and the foehn descends into the valleys in order to replace the cold air removed by outflow.

In the case of south foehn in the Wipp and Inn Valleys, the problem is not two-dimensional as in Lee et al. (1989) and the induced pressure field is not symmetric with respect to the mean flow plane. Zängl (2003) explained the frequently observed gusty westerly winds near Innsbruck in advance of foehn (often called prefoehn westerlies) as a result of gravity wave asymmetry along the Inn Valley. A local pressure minimum was found in the lee of the Patscherkofel. His simulations with realistic topography and idealized atmospheric conditions showed sensitivity of the prefoehn strength to the initial presence of a cold pool and the timing of the synoptic scale situation with respect to the diurnal radiative cycle. Further analysis showed that the pressure difference was, for the most part, hydrostatic. He found strong spatial variations in temperature at 1000 m ASL over the Inn Valley.

Zängl and Gohm (2006) performed high resolution (Δx = 467 m) numerical simulations of two MAP foehn events in order to test the theory proposed by Flamant et al. (2002) that the higher wind speeds in the eastern part of the Wipp Valley
exit region are caused by interaction with outflow from tributary valleys such as the Stubai or Gschnitz Valley. They found that the asymmetry in the wind field remained even when altering the model topography so as to close the Stubai Valley. Furthermore, their simulations found that an easterly deflection of the foehn flow by the Nordkette in the Inn Valley caused a local minimum of the CAP depth over the eastern part of the city. In one case, the CAP depth to the east of Innsbruck was only 50-200 m compared to the 400-500 m to the west of Innsbruck. The hydrostatic pressure gradient associated with this temperature asymmetry resulted in increased surface winds.

**Dynamical Displacement**

In the case of Inn Valley CAPs, the cold air is partially bounded by topography. Due to the irregular wind stress at its top, internal gravity waves (IGWs) within the fluid are excited. In the special case of an (at least partially) bounded CAP, standing waves can be formed through the summation of two IGWs travelling in different directions (with opposite phase). Such a 'sloshing' of stable fluid in a basin has long been observed in bodies of water (Defant 1953) and more recently at the Arizona Meteor Crater during the Meteor Crater Experiment (METCRAX) in 2006 (Whiteman et al. 2008). High resolution numerical simulations of flow across the Meteor Crater show that sloshing of basin air over the crater rim is an efficient dynamic mechanism by which the CAP can be eroded during large-scale nocturnal katabatic flow situations (Fritts et al. 2010).

The Inn Valley is not a circular basin and is bounded by very large mountains. It is unlikely that the CAP would spill over the Nordkette, but it is possible that wave motions could cause temporal and spatial variability in the CAP depth or strength. In a field campaign to study persistent CAPs in the Salt Lake Valley, Lareau and Horel (2015a) found that the CAP depth increased in the direction of the prevailing wind by 200 m.

**Shear-induced Turbulence**

Petkovšek (1992) derived a theoretical model for CAP erosion due to shear induced turbulence with the assumption of K-closure. In order for turbulent mixing to occur, shear production of turbulent kinetic energy must be stronger than turbulence supressing effects due to negative buoyancy of the stable stratification at the CAP inversion. This necessary condition for turbulent erosion of the CAP is given by a subcritical Richardson Number, i.e., \( \text{Ri} < 0.25 \). Assuming a stably stratified CAP below a more stable inversion and constant free stream potential temperature above, a decrease in inversion height would increase the inversion stability. This increased
1.3 Goals and Outline

Shear-induced turbulent erosion of a CAP in the Inn Valley during foehn is most definitely not homogeneous. The wind field has been found to have high spatial variability as would be expected in a T-shaped valley (Zängl 2003; Gohm et al. 2010). As discussed, localized shear-induced turbulent erosion of the CAP or CAP stability would in turn require an increase in wind speed for continued erosion.

Rakovec et al. (2002) compared this theoretical model with measurements from the Ljubljana Basin and found a general agreement with the model. Zhong et al. (2003) expanded upon Petkovšek (1992) to examine the effect of turbulent erosion on an idealized basin given by the frustum of a cone with different slope angles, depths, and capping inversion strengths. They found that persistence of the CAP depends mostly on the wind speed above the inversion and the strength of the capping inversion layer (CIL). In concluding remarks they stated that a ‘shallow cold air pool of a few tens of meters with a weak inversion could be removed in less than a day if winds aloft were sufficiently strong, but it would take several days to break a CAP of a few hundred meters depth with a moderate inversion unless winds aloft were very strong or increased rapidly with time.’

Coherent Structures

The inherent assumption of the aforementioned CAP erosion studies is that the CIL strengthens with time due to the local nature of turbulent mixing, but turbulence in shear flow is not always adequately described by diffusion. Flows with subcritical Richardson numbers are not necessarily stable with respect to Kelvin Helmholtz instabilities at the shear interface. The breaking of such waves and formation of Kelvin-Helmholtz billows can cause large-scale vertical mixing. The presence of these phenomena would invalidate the assumption of K-closure (and only microscale turbulence) with respect to CAP dynamics in the Inn Valley during foehn.

While the aforementioned theoretical models (Petkovšek 1992; Zhong et al. 2003) suggest a limited influence of shear-induced turbulence on CAP removal, research conducted by Hazel (1972) and Lindzen and Rosenthal (1976) supports the idea that turbulent mixing could still be a significant process for CAP removal in the Inn Valley. They showed that the presence of lower boundaries can further destabilize stratified shear flow through the reflection of internal gravity waves and subsequent additional amplification at the interface. For the case of Inn Valley shear flow, gravity wave reflection could occur at the valley floor or lower slopes of bounding terrain still within the CAP. The resulting additional amplification could cause more turbulent erosion than suggested by Petkovšek (1992) and Zhong et al. (2003).
tilting (Lareau and Horel 2015a) due to shear stress from the free air stream can both induce compensating flows (Zängl 2003; Zängl and Gohm 2006) or excite wave motions including seiches (Fritts et al. 2010).

In the case of the Inn Valley, it is plausible to think that the persistence of the nocturnal CAP near Innsbruck is amplified by such compensating flows, which advect colder valley air from more sheltered upvalley areas that are less prone to strong winds, associated turbulent erosion and resulting (mainly hydrostatic) pressure drops. This advection may occur even in the absence of a large-scale downvalley flow, as evidenced by the local nature of the prefoehn westerly. The magnitude of this nocturnal cold air reservoir is determined in part by the radiative balance. But even in the situation with zero net radiation (where simulations by Zängl (2003) still show a prefoehn westerly) the cold pool volume upvalley could be quite large and in synoptic south foehn conditions in theory only limited by the next transalpine valley pass.

Clearly there should be some doubt over whether the theoretical models for shear induced mixing (Petkovšek 1992) apply to the Inn valley under foehn conditions. Their assumptions of micro scale turbulence and no advection of turbulent kinetic energy are most likely not appropriate for such a topographically complex location.

In general terms, the research questions surround understanding the characteristics of foehn breakthrough in the Inn Valley. To be more specific, three research questions are explicitly listed below:

1. Where in the vicinity of Innsbruck does foehn breakthrough occur first?
2. Are there spatial inhomogeneities in CAP strength or thickness during foehn events?
3. What are the time scales of periodic signals in temperature within the CAP and their potential causes?

In Chapter 2, the experimental setup of the PIANO campaign is partially explained and the most relevant stations introduced. The estimation of profile-mean potential temperatures, column integrated buoyancy and Froude number are presented. Chapter 3 begins with short qualitative case studies of the six south foehn IOPs before venturing into a quantitative relationship between Froude number and meridional CAP heterogeneity. The chapter finishes with an investigation of the relationship between along-valley CAP heterogeneity and valley bottom pressure differences. In Chapter 4, the results are discussed in the framework of existing research, speculations are made regarding the cause of observed fluctuations and ideas for future research are proposed. Concluding remarks can be found in Chapter 5.
Chapter 2

Data and Methods

2.1 Data

During the Penetration and Interruption of Alpine Foehn (PIANO) campaign in fall and early winter 2017, various instruments were deployed and operated in the Inn and Wipp Valley near Innsbruck to investigate processes responsible for foehn penetration into a stably stratified cold air pool (CAP). In this work, near surface observations were analysed on the basis of many small temperature and humidity loggers and several larger automatic weather stations measuring additional variables. A brief description of the data acquisition process follows below.

2.1.1 HOBO Temperature and Humidity Loggers

Fifty temperature and relative humidity (RH) monitors of type HOBO MX2302 (from now on called HOBO), manufactured by Onset, were deployed throughout the greater Innsbruck area to capture the characteristics of prefoehn surface temperature heterogeneity at a kilometer scale or less. Their spatial distribution can be seen in Fig. 2.1. Four slope profiles were created using the HOBOs in order to estimate the variability of cold pool depth and strength above the valley floor. The western and eastern profiles were shallower and reached to approximately 150 m above the valley floor. The southern profile reached to 300 m above the valley floor at Grillhof. The northern profile extended to the Nordkette ridge at Hafelekær (1700 m above valley floor), but for comparisons with the southern profile, the lowest 300 m were most useful.

The majority of HOBO sensors were deployed 4 m above ground level (AGL) on the northern side of street lamps. For this study, the most notable exceptions to the standardized installation height and location were at the southern profile (see H35, H34 and H37 in Fig. 2.1b and Table 2.1). At the Bergisel ski jump compound, H35 was installed on a metal structure 10-20 m above a steep slope and H34 was
installed on top of the tower, less than 1 m above the roof, but around 50 m above ground level (AGL). H37, the highest station of the southern profile, was located on top of a flagpole at more than 4 m height.

The Onset HOBO MX2302 measures temperature and RH externally with an accuracy of 0.2°C and 2.5% RH (between 10% and 90% RH), respectively. The temperature sensor has a resolution of 0.04°C and drifts less than 0.01°C per year. The RH sensor has a resolution of 0.05% and a drift of less than 1% per year. The temperature and RH sensor was protected from direct radiation by a radiation shield of the type RS3-B, also manufactured by Onset. The response times (to 90% change) of temperature and RH are 5 and 4 minutes, respectively, for air moving 1 m s$^{-1}$ and with the radiation shield mounted.

The HOBO logging rate, which can be specified between 1 second and 18 hours, was set to 1 minute. The reason for not choosing a faster sampling rate is primarily a result of the very limited logger memory (128 KB). Using the most minimal logging mode without statistics and just recording instantaneous values of temperature and RH every minute, the memory is full after 28 days. As the loggers must be readout before the memory is full to avoid losing data, increasing the sampling frequency or saving more statistics would greatly increase the logistical demands of HOBO readouts, while not adding much information due to the high pass filtering effect of the sensor housing and radiation shield (especially in low wind conditions). Furthermore, even with a less frequent sampling, readouts should still be performed regularly due to the random drift of the HOBOs internal clock. This time drift has a magnitude of 1 minute per month. At the time of readout, care must be taken to truly stop the logging process and readout the data before reconfiguring. The act of configuring synchronizes the logger clock with the smart phone.

Occasionally, there were either problems connecting to HOBO loggers via blue-tooth or mysterious logger malfunctions that could not be explained by the manufacturer. These readout difficulties required returning to the logger location with a vehicle and ladder to manually connect with the logger via button press. As a result of the readout delay, there were occasional data gaps, where the oldest data were deleted in favor of newer measurements (using the wrapping configuration). Sometimes, HOBOs stopped logging for no apparent reason and displayed the error message Logger Stopped (Power Reset) upon connecting. In rare cases HOBOs stopped working completely and needed to be returned to the manufacturer. These malfunction types resulted in additional unavoidable data gaps.

Before the measurement campaign, all HOBOs were mounted on the Institute roof for comparison measurements. Typical differences on the order of 0.2 K were observed. While the HOBO measurements were corrected for use in two Bachelor’s Theses investigating the effect of the urban heat island (UHI) in Innsbruck (Schmitt
2.1 Data

2018; Rzehak 2018), the measured temperature values were not corrected in this study for two reasons. Primarily, the temperature differences of interest observed during foehn are typically significantly larger than the effect of the UHI and it is not possible to separate the effects of micro-climates, also, for example, due to vegetation (Cantlon 1953), from CAP heterogeneity. Secondly, due to logger malfunction and replacement, not all HOBOs operated during the campaign have a correction value to apply.

2.1.2 MOMAA Automatic Weather Stations

Nine automatic weather stations were also installed. The Department of Atmospheric and Cryospheric Sciences had acquired these in 2005 through the project Mobiles Messnetz für alpine Atmosphärenforschung (MOMAA) and the stations (from here on called MOMAAs) were deployed to cover a greater area around Innsbruck than the HOBOs, but at a lower spatial resolution. They bridged the spatial gap to Teilautomatisches-Wetter-Erfassungs-System (TAWES), the Austrian state-run weather station network with a coarser spatial resolution. MOMAA stations measure air temperature, relative humidity, wind, radiation, precipitation, pressure and ground temperature using various sensors. The relevant sensor manufacturers and model types, as well as installed heights AGL can be found in Table 2.2. As observed by Brotzge and Duchon (2000), precipitation influences the net radiation measurement obtained from the NR-Lite sensor and can result in unphysical values. These faulty measurements are visible as sudden drops in net radiation on the order of 100 W m$^{-2}$ and are disregarded in the analysis.

2.1.3 Other Measurements

In addition to the MOMAAs, two flux stations measuring the three wind components, temperature, humidity, air pressure, radiation, precipitation, soil temperatures and ground heat flux were installed in the Inn Valley for the PIANO campaign. Measured pressures from the flux stations to the west (F01: Airport) and east of Innsbruck (F03: Thaur) (see Table 2.1) were used to investigate along-valley CAP heterogeneity due to the proximity of the flux stations to the eastern and western HOBO profiles. The location of the two flux stations with respect to the HOBO profiles can be seen in Fig. 2.1a. The pressure sensors were not calibrated and so the magnitude of the difference should be analysed with caution. In this study, the focus was more on observing changes in pressure difference between F01 and F03. Lack of calibration was therefore not a major hurdle. Despite the fact that the pressure sensor was located within a logger box, strong winds at one or both stations could have influenced the measurement (Straka et al. 1996). In order to
### Data and Methods

<table>
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<th>Station</th>
<th>Location</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
<th>Height (m MSL)</th>
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<td>11.398168</td>
<td>589.29</td>
</tr>
<tr>
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<td>11.399730</td>
<td>861.19</td>
</tr>
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<td>11.393317</td>
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</tr>
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<td>H17</td>
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<td>11.391630</td>
<td>751.53</td>
</tr>
<tr>
<td>H18</td>
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<td>47.276708</td>
<td>11.387454</td>
<td>701.79</td>
</tr>
<tr>
<td>H19</td>
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<td>47.275640</td>
<td>11.389442</td>
<td>644.59</td>
</tr>
<tr>
<td>H20</td>
<td>North</td>
<td>47.273292</td>
<td>11.390529</td>
<td>587.20</td>
</tr>
<tr>
<td>H32</td>
<td>East</td>
<td>47.277712</td>
<td>11.431982</td>
<td>567.51</td>
</tr>
<tr>
<td>H34</td>
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<td>11.399765</td>
<td>786.27</td>
</tr>
<tr>
<td>H35</td>
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<td>47.247971</td>
<td>11.399114</td>
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</tr>
<tr>
<td>H36</td>
<td>South</td>
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<td>11.398822</td>
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<tr>
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<td>11.406799</td>
<td>878.83</td>
</tr>
<tr>
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<td>11.427860</td>
<td>729.58</td>
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</tr>
<tr>
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<td>11.398600</td>
<td>725.85</td>
</tr>
<tr>
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<td>Patsch</td>
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<td>11.410511</td>
<td>982.79</td>
</tr>
<tr>
<td>M05</td>
<td>Oelberg</td>
<td>47.278424</td>
<td>11.390297</td>
<td>722.37</td>
</tr>
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</tr>
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</tr>
<tr>
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<td>Volders</td>
<td>47.293052</td>
<td>11.569799</td>
<td>551.98</td>
</tr>
<tr>
<td>M09</td>
<td>Unterperfuss</td>
<td>47.261521</td>
<td>11.260705</td>
<td>593.65</td>
</tr>
<tr>
<td>M10</td>
<td>Inzing</td>
<td>47.274402</td>
<td>11.214329</td>
<td>596.74</td>
</tr>
</tbody>
</table>

**Table 2.1:** Measured latitude, longitude and height above mean sea level for the two relevant flux stations, the HTL lidar, slope profile HOBOs and all nine MOMAAAs. Station designations beginning with F, H, L, and M are short for Flux, HOBO, Lidar and MOMAA, respectively. For HOBOs, the associated slope profil is given in the Location column. For all other stations, this column contains a short name to describe the station location.
Table 2.2: Manufacturer and model of selected MOMAA sensors and their installation heights above ground level.

<table>
<thead>
<tr>
<th>Measured Quantity</th>
<th>Instrument</th>
<th>Height AGL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature/ RH</td>
<td>Rotronic HC2A-S3 in RS12T enclosure</td>
<td>2 m</td>
</tr>
<tr>
<td>Horiz. Wind and Dir.</td>
<td>Gill Instruments WindSonic Option 1</td>
<td>3.5 m</td>
</tr>
<tr>
<td>Net Radiation</td>
<td>Kipp and Zonen Net Radiometer NR Lite 1</td>
<td>1.8 m</td>
</tr>
</tbody>
</table>

To quantify the influence of the wind, a true static pressure measurement would have been needed near the locations of F01 and F03, but was not available.

The TAWES at Patscherkofel was used as a wind and temperature reference due to its exposed nature during southerly foehn flow (Fig. 2.1a). Estimates of horizontal winds above Innsbruck were obtained from a Doppler wind lidar (Halo Photonics Stream Line) located on the HTL roof (L02: HTL, see Table 2.1 and Fig. 2.1b). Additional TAWES within and near the city were used to enhance the spatial coverage of potential temperature and wind used in the qualitative analysis of Chapter 3.1. Their position is denoted by black squares in Fig. 2.1a.

2.1.4 Geodesy

Using a differential GPS and the help of Assoc. Prof. Dr. Armin Heller at the Department of Geography, the station elevations were measured to a high accuracy (less than one meter). Care was used in converting the positioning data from the WGS84 ellipsoid to the Bessel Ellipsoid (BMN 28) and finally into the Austrian Gebrauchshöhe (the reference used in Austrian Cartography). The coordinates and heights of selected stations can be seen in Table 2.1. The stations are also shown in Fig. 2.1 to illustrate their position relative to the complex topography.

2.2 Methods

2.2.1 Calculation of Potential Temperature

For our analysis, the potential temperature of an air parcel at a given height is understood to mean the temperature the parcel would attain if raised or lowered dry adiabatically to a defined reference height. This formulation contrasts with the standard definition of potential temperature, where the air parcel is brought to a standard reference pressure, typically 1000 hPa (American Meteorological Society 2019). An adiabatic process is one in which energy is exchanged between the air parcel and its surroundings only in the form of work and not heat. The dry adiabatic
Figure 2.1: Topographic maps at a (a) larger and (b) smaller scale. HOBO locations are indicated by circles; purple, green, red and orange colors highlight profile stations. Western, northern, eastern and southern profiles are indicated by W, N, E and S, respectively, in (a). TAWES Patscherkofel is indicated by a white square and remaining TAWES are depicted by small black squares in (a). MOMAA (MXX), flux (FXX) and lidar (L02) locations are also included.
2.2 Methods

The lapse rate for the unsaturated atmosphere is given by \( \Gamma_d = \frac{g}{c_{pd}} \approx 9.8 \ \text{K km}^{-1} \), where \( g \) is the gravitational acceleration and \( c_{pd} \) is the specific heat capacity of dry air at constant pressure. A reference height of \( z_r = 550 \ \text{m MSL} \) was defined, to approximately match the elevation of the lowest PIANO station. The potential temperature, \( \theta^i \), at station \( i \) with observed temperature \( T^i \), is given by

\[
\theta^i = T^i + (z^i - 550 \ \text{m}) \cdot \Gamma_d.
\]  

Comparing the potential temperature between stations of different heights can be useful in estimating the atmospheric stability between them given several assumptions. A potential temperature difference of zero between two stations indicates neutral stratification. An increase of potential temperature with height occurs during stable stratification and the opposite occurs during unstable stratification, the latter leading to convection. Potential temperature differences between the Inn Valley bottom and locations within the foehn flow are used to diagnose the extent to which the valley CAP has been removed. Such an analysis assumes that the foehn flow descends into the Inn Valley adiabatically and the atmosphere is not saturated. Furthermore, when analysing the stability of the CAP using potential temperatures from the HOBO slope profiles, there is an implicit assumption that near surface potential temperatures from the slope can be used as a proxy for potential temperatures nearer the valley centerline and do not just represent the thermal characteristics of a thin slope layer. Under stable nocturnal conditions, this assumption may be fair (Whiteman et al. 2004).

**Estimation of Profile-Mean Potential Temperature**

Mean potential temperatures of the northern, southern, eastern and western profile were estimated using the irregular trapezoidal rule. Given \( n \) stations in profile \( A \) with ascending heights \( z^1 < z^i < z^n \), for \( 1 < i < n \), and potential temperatures \( \theta^1, ..., \theta^n \), the mean potential temperature of profile \( A \) was approximated by:

\[
\theta^A = \frac{1}{z^n - z^1} \int_{z^1}^{z^n} \theta(z) \, dz \approx \frac{1}{(z^n - z^1)} \sum_{i=1}^{n-1} \frac{1}{2} (\theta^{i+1} + \theta^i) (z^{i+1} - z^i). 
\]  

The difference in mean potential temperature at the northern and southern profile was defined to be \( \Delta \theta^{S,N} = \theta^S - \theta^N \). If \( \Delta \theta^{S,N} > 0 \), the northern profile was colder than the southern profile. Alternatively, if \( \Delta \theta^{S,N} < 0 \), the northern profile was warmer than the southern profile. Similarly, the difference between the profile-mean potential temperature at the eastern and western profile was defined to be \( \Delta \theta^{E,W} = \theta^E - \theta^W \).

For intercomparability of results between IOPs of varying stratification, a normalized measure of the difference between mean potential temperatures at the north-
ern and southern profiles was defined for all $\bar{\theta}^S, \bar{\theta}^N < \theta^P$ (where $\theta^P$ is the potential temperature at Patsch):

$$\Delta \bar{\theta}^{S,N} = \frac{\Delta \bar{\theta}^{S,N}}{\theta^P - \min(\bar{\theta}^S, \bar{\theta}^N)}.$$ (2.3)

Put in words, the difference in profile-mean potential temperatures was scaled to the difference between the potential temperature at Patsch and that of the colder profile. The reason for choosing such a scaling will become evident by the end of the following section. For now, let us be content to observe that $\Delta \bar{\theta}^{S,N}$ has the properties:

- $\Delta \bar{\theta}^{S,N} \in (-1, 1)$ for $\bar{\theta}^S, \bar{\theta}^N < \theta^P$
- $\Delta \bar{\theta}^{S,N} = 0$ for $\bar{\theta}^S = \bar{\theta}^N < \theta^P$
- $\lim_{\bar{\theta}^N \to \theta^P} \Delta \bar{\theta}^{S,N} = -1$ for given $\bar{\theta}^S < \theta^P$
- $\lim_{\bar{\theta}^S \to \theta^P} \Delta \bar{\theta}^{S,N} = 1$ for given $\bar{\theta}^N < \theta^P$

In short, $\Delta \bar{\theta}^{S,N}$ is always between $-1$ and $1$. It equals $0$ if the northern and southern profile have the same potential temperature. If the southern profile is entirely within the foehn flow, but some CAP remains in the north, it equals $1$. $\Delta \bar{\theta}^{S,N}$ becomes $-1$ if the opposite occurs: there is some CAP influence at the southern profile and a complete foehn breakthrough in the north.

### 2.2.2 Calculation of Froude Number

To investigate how CAP heterogeneity in the north-south direction, as expressed by $\Delta \bar{\theta}^{S,N}$ or $\Delta \bar{\theta}^{S,N}$ (Chapter 2.2.1), reacts to changing flow conditions, it is useful to introduce the Froude number. The Froude number (Fr) is calculated in different ways in the literature, depending on the simplifying atmospheric model used, but can express the tendency of foehn flow to overcome stable stratification within the CAP and dynamically force a CAP removal (Bell and Thompson 1980; Reinecke and Durran 2008; Lareau and Horel 2015b). Sufficiently large values of Fr result in foehn flow overcoming the stratification and a breakthrough to the valley bottom. In this study, an analysis was conducted of the relationship between Fr and the difference in profile-mean potential temperature at the northern and southern profile ($\Delta \bar{\theta}^{S,N}$). Estimates of atmospheric stability from potential temperature measurements were integrated with wind speed measurements to calculate the non-dimensional Froude number (Fr).
Column Integrated Buoyancy

For the calculation of Fr, it is necessary to quantify atmospheric stability within the CAP. Possible metrics could include the potential temperature difference between the foehn flow and CAP bottom or a layer-mean estimated Brunt-Väisälä Frequency (Reinecke and Durran 2008). The stability metric used in this study was column integrated buoyancy \( B \) as in Lareau and Horel (2015b). To estimate the column integrated buoyancy using the northern and southern profiles, a reference potential temperature was first defined. The location of the potential temperature reference should ideally be at the same elevation as the wind reference, or contained within the same neutrally mixed layer. Of the nine MOMAA stations, M04 in Patsch was the natural reference choice due its location within the Wipp Valley. The buoyancy at a height \( z \) with potential temperature \( \theta(z) \) was defined to be

\[
b(z) = g \frac{\theta^p - \theta(z)}{\theta^p}.
\]

(2.4)

The column integrated buoyancy,

\[
B = \int_{z_1}^{z_P} b(z) dz,
\]

(2.5)

was approximated by the irregular trapezoidal rule in a similar manner to \( \overline{\theta}^S \) and \( \overline{\theta}^N \) (Eq. 2.2), using stations from the southern and northern profile, to arrive at \( B^S \) and \( B^N \).

Wind Reference

In addition to a stability metric, the calculation of Fr requires quantification of a relevant horizontal wind forcing \( (U) \) above the CAP. Here, \( U \) was taken to be the southerly component of the in situ wind measurement at Patsch (M04) and denoted \( U^P \). Other, more complicated approaches were also tested, but each had significant drawbacks. For example, lidar estimation of the horizontal wind field above the valley center was used to find the height and magnitude of the maximum wind speed, but such an approach was highly sensitive to the height up to which measurements were available. Under low aerosol conditions, there were periods with insufficient backscatter to identify the foehn maximum. Although not explicitly used in the calculation of Froude number, the lidar-estimated southerly wind component above the Inn Valley center at L02 \( (U^{L02}) \), averaged over a 100 m thick layer centered at the height of M04 in Patsch, was compared with \( U^P \). While poor data availability makes lidar observations impractical for the calculation of Fr, radiosondes, on the other hand, would, in theory, grant excellent vertical resolution of wind and thermodynamic quantities. There the problem is a quite poor temporal resolution (one launch every three hours).
Froude Number

Following Lareau and Horel (2015b), Fr was defined to be:

\[ Fr = \frac{U}{\sqrt{B}}, \]  

(2.6)

with \( U = U^P \). Separate Froude numbers were calculated using column integrated buoyancies derived from the two slope profiles. \( Fr^N \) and \( Fr^S \) are the Froude numbers calculated using \( B^N \) and \( B^S \), respectively. The final Froude number, \( Fr \), used in the analysis was simply the mean, given by:

\[ Fr = \frac{Fr^N + Fr^S}{2}. \]  

(2.7)
Chapter 3

Results

3.1 Overview of Intensive Observation Periods

During fall and early winter 2017, seven Intensive Observation Periods (IOPs) were conducted to investigate CAP-foehn interaction near Innsbruck. The first IOP was a west foehn case and the remaining six were south foehn cases. General information about the seven IOPs can be found in Table 3.1. The focus of the study was CAP heterogeneity and foehn breakthrough characteristics during south foehn. Since there was no south foehn during IOP 1, it was disregarded. Further analysis and comparisons were confined to IOPs 2-7.

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Duration Patsch/ h</th>
<th>Duration Hilton/ h</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>IOP 1</td>
<td>29 Oct 2017</td>
<td>-</td>
<td>-</td>
<td>west foehn</td>
</tr>
<tr>
<td>IOP 2</td>
<td>4-5 Nov 2017</td>
<td>26</td>
<td>5</td>
<td>south foehn</td>
</tr>
<tr>
<td>IOP 3</td>
<td>12 Nov 2017</td>
<td>2.5</td>
<td>1.5</td>
<td>south foehn</td>
</tr>
<tr>
<td>IOP 4</td>
<td>25 Nov 2017</td>
<td>12</td>
<td>0</td>
<td>south foehn</td>
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<tr>
<td>IOP 5</td>
<td>27-28 Nov 2017</td>
<td>16.5</td>
<td>6</td>
<td>south foehn</td>
</tr>
<tr>
<td>IOP 6</td>
<td>7-8 Dec 2017</td>
<td>16</td>
<td>0</td>
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</tr>
<tr>
<td>IOP 7</td>
<td>10-11 Dec 2017</td>
<td>40</td>
<td>18</td>
<td>south foehn</td>
</tr>
</tbody>
</table>

Table 3.1: Table giving information on date, foehn type and south foehn duration at Hilton and Patsch for the seven IOPs.

3.1.1 IOP 2

Nighttime CAP Structure and Evolution from 3 to 4 Nov 2017

During the first night of IOP 2 (3-4 Nov 2017), both the Inn and Wipp Valley experienced katabatic outflow without strong foehn influence. Wind directions at
Völs and Patsch were constant from 270° and 200°, respectively (Fig. 3.1d). One would expect similar wind directions during immediate prefoehn conditions. Observed wind speeds of 5 m s\(^{-1}\) at Patsch in the Wipp Valley (Fig. 3.1c) are slightly higher than typical magnitudes observed during katabatic flow during radiatively induced outflow (Dreiseitl et al. 1980). On the other hand, potential temperature at Patsch increased by 2 K between 00 and 06 UTC while net radiation remained negative (Fig. 3.1a,b). This indicates that it was not a pure katabatic outflow in the Wipp Valley, but potentially warmer (foehn) air could have warmed the atmosphere at Patsch through sensible heat flux convergence and/or advection. Such warming was not observed in the Inn Valley at Völs or Saggen until after 6 UTC, but even there, surface potential temperatures did not cool despite negative net radiation (Fig. 3.1a,b).

Within the Inn Valley, there was some inhomogeneity in CAP strength between the four profiles. The eastern profile had colder potential temperatures than the western profile (Fig. 3.2). Similarly, the lowest 150 m of the northern profile were colder than the southern profile, yet this relationship reversed above 750 m MSL, where the vertical potential temperature gradient in the north was stronger (Fig. 3.3).

**Weak Afternoon Foehn Breakthrough in the Northwest on 4 Nov 2017**

After weakening of the CAP (Fig. 3.2, 3.3) due to solar insolation and a period of quiescent conditions (Fig. 3.1), south foehn developed in the Wipp Valley and there was evidence for localized foehn in northwest Innsbruck during the late afternoon of 4 Nov 2017. Beginning at 06 UTC 4 Nov 2017, there was positive net radiation due to solar insolation at Völs, Saggen and Patsch (Fig. 3.1b). While the potential temperature at Patsch was already slowly increasing during the night, the increasing net radiation during daytime exactly paralleled the potential temperature evolution at Völs and Saggen (Fig. 3.1a,b). The strongest potential temperature increase at Patsch (between 08 and 11 UTC) was accompanied by a transition from katabatic outflow to weak upvalley flow (Fig. 3.1a,c,d). Shortly before 12 UTC though, there was an abrupt transition to southerly foehn flow at Patsch (Fig. 3.1c,d). Southerly winds in Patsch fluctuated between 8 and 12 m s\(^{-1}\) during the afternoon hours. In this time, potential temperatures at Völs, Patsch and Saggen began to decrease. While the afternoon potential temperatures at Völs and Saggen were always less than in Patsch, nearly neutral stratification reached up quite far into the valley atmosphere at the western and northern profile (Fig. 3.2a, 3.3a). The stratification was entirely neutral up to Patsch at the western profile shortly after 16 UTC. At this time, net radiation had already been negative for approximately two hours (Fig. 3.1b) and potential temperatures at Saggen and Völs had cooled by 5 K from the
3.1 Overview of Intensive Observation Periods

Figure 3.1: Timeseries of (a) potential temperature (°C), (b) net radiation (W m$^{-2}$), (c) wind speed (m s$^{-1}$) and (d) wind direction (°) for selected stations on 4 and 5 Nov 2017 (IOP 2). Additionally included are the (e) difference of mean sea-level pressure (hPa) between Bolzano and Innsbruck. Identified foehn periods are indicated by shading for Patsch (light grey) and Hilton (dark grey).
Results

Figure 3.2: Potential temperature (°C) as color contours at the (a) western and (b) eastern profile on 4 Nov 2017 (IOP 2). Potential temperatures are estimated at different elevations (m MSL) through interpolation from HOBO measurements. Elevation of HOBO measurements (m MSL) used in the interpolation denoted by dashed white lines.

Early afternoon (Fig. 3.1a). At 1630 UTC there was a region of enhanced potential temperatures to the northwest of Innsbruck (Fig. 3.4). Towards the east, potential temperatures at the valley bottom gradually decreased to a minimum of 8 K at the foot of the Patscherkofel in southeast Innsbruck. West of the enhanced potential temperature region, towards Völs, potential temperatures fell more abruptly. Due to an absence of solar insolation so late in the afternoon, the neutral stratification reaching to the Inn Valley bottom in the northwest of Innsbruck was most likely forced by the ongoing south foehn in the Wipp Valley.
3.1 Overview of Intensive Observation Periods

Figure 3.3: As in Fig. 3.2, but for the (a) northern and (b) southern profile on 4 Nov 2017 (IOP 2).

Nighttime CAP Oscillations between 4 and 5 Nov 2017

During the second night of IOP 2, from 4 to 5 Nov 2017, there was continuous foehn in the Wipp Valley at Patsch (Fig. 3.1c,d) and increasing wind speeds resulted in growing CAP oscillations and spatial inhomogeniety (Fig. 3.5, 3.6) around Innsbruck as the night progressed. Between 15 UTC and 18 UTC 04 Nov 2017, potential temperatures at Völs, Saggen and Patsch decreased by 5 K due to negative net radiation, while the potential temperature drop in Patsch was much less pronounced at 2 K (Fig. 3.1a). This disparity was a result of warm air advection or turbulent downmixing of potentially warmer air in the Wipp Valley, where winds at Patsch were southerly between 7 and 12 m s$^{-1}$ (Fig. 3.1c,d). After 18 UTC there appeared to be
Figure 3.4: Map of potential temperature (θ) and wind measurements from HOBO, MOMAA and TAWES stations on 4 Nov 2017 (IOP 2). Values of θ are indicated by color scale. The numerical value of θ is rounded to the nearest integer and included for HOBO stations. Wind direction and speed (kts) indicated by wind barbs.

a regime shift as the cross-alpine pressure gradient strengthened (Fig. 3.1e). Winds at Patsch doubled to 15 m s\(^{-1}\) by 01 UTC 5 November, with gradually increasing potential temperature (Fig. 3.1a). Additionally, beginning at 18 UTC, the potential temperature at Saggen cooled much slower than in Völs and was characterised by periodic oscillations not seen in Völs. Oscillations and increasing spatial inhomogeneity can also be seen when comparing the west and east profiles (Fig. 3.5). While the CAP depth at both profiles fluctuated more than during the first night of IOP 2, the warm air intrusions tended to reach further into the CAP in the east, where potential temperatures were also generally warmer at every height. The strongest warm air intrusion in the eastern profile occured shortly after 04 UTC and removed nearly the entire CAP there (Fig. 3.5b). A less pronounced CAP thinning was synchronously observed at all three remaining profiles (Fig. 3.5a, 3.6). Saggen, located between the northern and eastern profiles, experienced enhanced wind speeds of 4 m s\(^{-1}\) during this time and also an abrupt potential temperature jump of 3 K (Fig. 3.1a,d), leading credence to the conjecture that foehn intrusions or associated enhanced vertical mixing influenced the lowest Inn Valley atmosphere. After the foehn intrusion at 04 UTC, the CAP at the eastern profile progressively eroded, while it remained unchanged (or even deepened slightly) at the other profiles. Beginning around this time, anticorrelated oscillations in potential temperature were observed at the northern and southern valley bottom (Fig. 3.7). Lower potential tempera-
tures were observed at the base of the northern profile (H14) simultaneously with a deepening of the CAP in the north. Overall, in contrast with the first night of IOP 2 (3-4 Nov 2017), the second night (4-5 Nov 2017) was characterised by foehn in the Wipp Valley and spreading foehn influence in the eastern regions of Innsbruck, as evidenced by increasing horizontal temperature gradients and growing temporal oscillations in CAP depth, temperature and wind speed.

Figure 3.5: As in Fig. 3.2 for 5 Nov 2017 (IOP 2).

Foehn Breakthrough Spreading from the Northeast during Morning of 5 Nov 2017

After a partial foehn breakthrough to the east of Innsbruck before sunrise, the spatial extent of the foehn flow at the surface grew throughout the morning hours due to
increasingly positive net radiation (Fig. 3.1b), eventually encompassing Völs and Volders at its maximal extent around 11 UTC. While net radiation was still negative (-50 W m$^{-2}$) at Völs and Saggen shortly before 06 UTC (Fig. 3.1b), the potential temperature of the easternmost HOBO stations at the valley bottom were well mixed with Patsch and the CAP there was temporarily removed (Fig. 3.8). After sunrise, net radiation became positive and potential temperature increased at Völs, Saggen and Patsch (Fig. 3.1a,b), yet wind speeds at Patsch decreased (Fig. 3.1c) and the eastern breakthrough ceased due to a CAP resurgence by 0730 UTC (Fig. 3.5b, 3.9). By 09 UTC, there was an established foehn flow from east of the city center past Volders downvalley (Fig. 3.10). Interestingly, at this time the northern profile was neutral, while the southern profile was still stably stratified (Fig. 3.6). Over the next two hours, the spatial extent of foehn flow at the Inn Valley bottom continued.
3.1 Overview of Intensive Observation Periods

Figure 3.7: Potential temperature ($\theta$) at the southern (H10) and northern (H14) valley bottom and for three stations in the northern profile (with increasing height: H18, H17 and H16) on 5 Nov 2017 (IOP 2). An anticorrelation can be observed between $\theta$ at H10 and H14. Low $\theta$ at H14 appear to be correlated with increasing CAP depth at the northern profile (drops in $\theta$ at H18 and H17). The highest northern profile station included (H16) is within the foehn flow.

- Figure 3.7: Potential temperature ($\theta$) at the southern (H10) and northern (H14) valley bottom and for three stations in the northern profile (with increasing height: H18, H17 and H16) on 5 Nov 2017 (IOP 2). An anticorrelation can be observed between $\theta$ at H10 and H14. Low $\theta$ at H14 appear to be correlated with increasing CAP depth at the northern profile (drops in $\theta$ at H18 and H17). The highest northern profile station included (H16) is within the foehn flow.

- to expand towards the west and south. Shortly before 11 UTC, the foehn flow in the Inn Valley reached its maximal extent (Fig. 3.11) and winds over the city center were northerly, an unexpected direction during south foehn. Further west and east, observed wind directions were more in line with expectations. The foehn flow was channeled by topography to approximately follow the valley axis. The northerly winds over the city center can be explained by flow deflection at the Nordkette or the presence of a lee wave rotor and, in turn, help one understand the delayed CAP removal at the southern profile. The foehn did not remove the CAP from the south (the wind direction within the Wipp Valley), but progressively eroded the stable valley stratification from the north and east as a deflected flow. Furthermore, there was an unexpected CAP resurgence east of the city after sunrise, although one would expect solar insolation to assist in removing the CAP and enabling foehn penetration to the valley bottom. These unexpected observations illustrate some of the potential complexity of CAP-foehn interactions in an alpine environment.
3.1.2 IOP 3

Deep CAP with Weak Stability from 11 to 12 Nov 2017

During the night between 11 and 12 Nov 2017, the Inn Valley CAP was deep, moist and weakly stratified, while the Wipp Valley at Patsch had southerly winds despite being within the CAP. Between 00 and 06 UTC, net radiation at Völs was approximately zero and potential temperatures remained constant between 6 and
3.1 Overview of Intensive Observation Periods

7°C (Fig. 3.12a,b). Potential temperatures at Patsch behaved similarly, although periods with slightly negative net radiation were observed there. Periods of negative net radiation at Patsch (03-07 UTC) occurred synchronously with marginally higher wind speeds of 6 compared to 4 m s$^{-1}$ during the period with a more balanced radiative budget near the surface (00-03 UTC) (Fig. 3.12b,c). During the period with more negative net radiation, the wind direction was southerly, while it was southwesterly during near zero radiation (Fig. 3.12b,d). It appears that for most

Figure 3.10: As in Fig. 3.4 for 5 Nov 2017 (IOP 2).

Figure 3.11: As in Fig. 3.4 for 5 Nov 2017 (IOP 2).
of the night, the Inn Valley CAP reached into the Wipp Valley at least as far south as Patsch, where the potential temperature was the same as the Inn Valley stations (Fig. 3.12a). The depth of the Inn Valley CAP can be estimated using the full northern HOBO profile to the Hafelekark. A nearly neutral stratification was observed to reach a height of around 1000 m AGL at 03 UTC (Fig. 3.13) and, since conditions were quite stationary (Fig. 3.12, 3.14), this snapshot in time was a good representation of the remaining night. In addition to temporal stationarity, the spatial homogeneity of potential temperature along the Inn Valley bottom is clearly evident (Fig. 3.13). In contrast to the two nights of IOP 2, the Inn Valley CAP during the night from 11 to 12 Nov 2017 was deeper, near saturation and less stable.

Prefoehn Westerlies over Innsbruck during Early Afternoon of 12 November

With increasingly positive net radiation after sunrise, the southerly flow in the Wipp Valley at Patsch weakened beginning at 07 UTC to eventually become stagnant by 12 UTC (Fig. 3.12b,c,d). During the stagnation period, the direction of the weak winds at Patsch were even northerly and the potential temperature there dropped by 2 K to become well mixed with the Hilton station in Innsbruck (Fig. 3.12a,c,d). The northerly wind direction and dropping potential temperatures suggest the Inn Valley CAP was spreading southward into the Wipp Valley. Above this growing and (necessarily deepening) CAP, the strength of the foehn flow at Patscherkofel increased. Between 11 and 14 UTC there were periods of enhanced prefoehn westerlies at Völs and Hilton despite weaker winds at Patsch than during the nighttime and morning hours, when there were no enhanced westerlies in the Inn Valley. Presumably, stronger wind speeds at Patscherkofel after 11 UTC resulted in enhanced gravity wave action in the Patscherkofel lee in the Inn Valley to the east of Innsbruck. During the prefoehn westerly winds, no spatial heterogeneity of potential temperature was observed at the Inn Valley bottom. Since the CAP near Innsbruck was nearly neutral in stratification (Fig. 3.14) during this time, it is possible that patterns of pressure anomalies caused by gravity waves were not visible in the potential temperature signal at the valley bottom. In any case, it appears that foehn penetration into the CAP to the elevation of Patsch was not a prerequisite for prefoehn westerlies in the Inn Valley.
3.1 Overview of Intensive Observation Periods

Figure 3.12: As in Fig. 3.1 for 12 Nov 2017 (IOP 3).

Foehn Breakthrough in Innsbruck from the South during Late Afternoon of 12 November

With a transition to negative net radiation, foehn broke through at Patsch around 15 UTC 12 Nov 2017 and at Hilton in Innsbruck one hour later. Beginning at 14
UTC, net radiation at Patsch and Völs turned negative, and southerly winds at Patsch doubled to 10 m s$^{-1}$ by 15 UTC (Fig. 3.12b,c). Although winds at Patsch strengthened so shortly after sunset, this appeared to be a case of south foehn as opposed to katabatic outflow since potential temperatures at Patsch increased simultaneously to 12.5°C (Fig. 3.12a,c). Until the cold front arrival at 1730 UTC, potential temperatures at Patsch remained nearly constant and were 2 K lower than at Patscherkofel (Fig. 3.12a). The Hilton rooftop in Innsbruck experienced a later foehn breakthrough than Patsch, with a 3 K potential temperature increase between 1500 and 1545 UTC. In the wind data, the breakthrough at Hilton is not so evident, and directions fluctuated between westerly and southerly. The potential temperature and wind map (Fig. 3.15) suggests that the southerly foehn flow from the Wipp Valley entered the Inn Valley from the south along the Wipp Valley extension and mainly influenced potential temperatures in the immediate city. As would be expected with a breakthrough in the Inn Valley from the south, the CAP in the south was eroded slightly earlier (Fig. 3.14). In fact, the CAP was never completely removed at the northern profile, even while the southern profile was neutrally stratified and in the foehn flow. This breakthrough from the south and associated warmer southern profile temperatures were in stark contrast to the foehn event during day two of IOP 2 (5 Nov 2017), where the northern profile experienced enhanced potential temperatures and foehn entered the city as a northerly wind near the surface.

Figure 3.13: As in Fig. 3.4 for 12 Nov 2017 (IOP 3).
3.1 Overview of Intensive Observation Periods

3.1.3 IOP 4

Periodicity in Nighttime Windfield at Patsch from 24 to 25 Nov 2017

Between 18 UTC 24 November and 01 UTC 25 November, Patsch was within the CAP and experienced fluctuating wind direction with a period on the order of an hour or two (Fig. 3.16a,d). During these seven hours, potential temperatures decreased at Patscherkofel, Patsch, Hilton and Völs with constant negative net radiation around -30 W m\(^{-2}\) (Fig. 3.16a,b). Although potential temperature was changing at all four stations, it dropped at nearly the same rate everywhere, preserving vertical static stability within the CAP. Wind speeds at Patscherkofel were also fairly constant between 14 and 18 m s\(^{-1}\) from the south (Fig. 3.16c,d). At Patsch, periods of southerly winds (before 1830 UTC, 2000-2030 UTC, 2130-2215 UTC,
2330 UTC, 0030-0100 UTC, and after 0130 UTC) alternated with northerly winds (1900-2000 UTC, 2045-2130 UTC, 2230-2330 UTC, 0015 UTC) (Fig. 3.17c). Maximal wind speeds ranged from 3.5 m s⁻¹ northerly (21 UTC) to 4.5 m s⁻¹ southerly (2145 UTC) (Fig. 3.17b). After 23 UTC though, wind perturbations appeared to decrease in magnitude. Before perturbations decreased after 23 UTC, there was a correlation between wind direction and potential temperature perturbations (Fig. 3.17a,c). During southerly winds, the potential temperature at Patsch was higher, as one would expect with increased penetration of foehn air. On the other hand, during northerly winds, the potential temperature was lower, indicating that the CAP was spreading southward near Patsch. If these perturbations in wind and potential temperature at Patsch were related to CAP oscillation, one would expect similar oscillations at other Wipp Valley stations near or within the CAP, with foehn at Wipp Valley locations nearer to the Brenner Pass.

At Bergisel, within the CAP near the Wipp Valley exit, there appear to have been similar fluctuations in potential temperature as in Patsch, while upvalley at Steinach am Brenner there was foehn with no clear oscillations in potential temperature or wind direction (Fig. 3.17a,c). As potential temperature dropped by 2 K at Patsch in the 10 to 15 minutes before 1840 and 2100 UTC, winds at Patsch turned from southerly to northerly, as described above. Interesting is that the completion of this 2 K drop at Patsch coincided perfectly with the beginning of a 2 K potential temperature increase at Bergisel. Winds at Bergisel were always below 2 m s⁻¹ in magnitude and tended to come from the north more often than at Patsch, yet were southerly during these two warming periods. Upvalley (to the south) of Patsch, at
Steinach am Brenner, there was a clear southerly flow around 4 to 6 m s$^{-1}$, with
no change in wind direction, suggesting that the station was within the foehn flow.
The automatic foehn classification according to Plavcan et al. (2014) also resulted in
nearly 100% foehn probability during the entire night at another Wipp Valley sta-
tion: Ellbögen (1080 m MSL). The largest wind perturbations appeared at Patsch,
while at Bergisel winds were weak. The relationship between the potential tem-
perature perturbations at Patsch and Bergisel suggests that they were not a microscale
phenomenon and may have been related to CAP dynamics resulting from forcing
by the foehn flow aloft.

**Increased Erosion of Inn Valley CAP from 02 to 07 UTC 25 Nov 2017**

After 02 UTC 25 November, strengthening winds at Patsch and Patscherkofel (Fig.
3.16c) led to a spatially heterogeneous weakening of the Inn Valley CAP (Fig. 3.18,
3.19). The increase in foehn strength can be seen as an increase in wind speed
at Patscherkofel after 02 UTC. Simultaneously, there was a foehn breakthrough at
Patsch and a doubling of the potential temperature difference to the Inn Valley
bottom at Hilton (Fig. 3.16a,c,d). While Inn Valley bottom temperatures at Hilton
and Patsch were steady between 03 and 06 UTC, the Inn Valley CAP warmed from
the top down due to turbulent erosion or displacement (Fig. 3.18) and individual
stations of the northern profile warmed by up to 7 K. The strongest CAP warming
occurred at the northern and eastern profiles (Fig. 3.18a, 3.19b) The growing het-
erogeneity in CAP depth between 03 and 06 UTC was accompanied by prefoehn
westerlies of 5 m s$^{-1}$ at Hilton (Fig. 3.16c,d). At 07 UTC, net radiation began to
increase due to solar insolation and valley bottom potential temperatures increased
at Hilton and Völs (Fig. 3.16). As a result of rising surface temperatures, the stabil-
ity of the Inn Valley CAP began to decrease and there was a nearly complete CAP
removal at the northern profile by 07 UTC (Fig. 3.18a). While the CAP thinning
at 07 UTC was most likely triggered by changing net radiation around sunrise, the
CAP thinning of the previous hours can be attributed to mechanical processes re-
sulting from increased foehn wind speed. Less than an hour after 07 UTC 25 Nov
2017, the CAP was entirely removed at the eastern profile and foehn reached to the
valley bottom (Fig. 3.19b).

**Long Duration Partial Breakthrough in Innsbruck during Morning of 25
Nov 2017**

Despite several hours of solar insolation and strong southerly winds at Patsch and
Patscherkofel (Fig. 3.16b,c,d), the CAP in Innsbruck was never completely removed
during 25 Nov 2017 (Fig. 3.16a). Foehn in the Inn Valley was confined to eastern
regions of Innsbruck (Fig. 3.20, 3.21, 3.22) with prefoehn westerly winds at Hilton (Fig. 3.16c,d) and decreasing potential temperatures towards the west. Since the Inn Valley CAP was already almost entirely removed at the northern and southern profile by 07 UTC (as described above), one would expect a complete CAP removal
3.1 Overview of Intensive Observation Periods

Figure 3.17: Time series of (a) potential temperature, (b) wind speed and (c) wind direction at Bergisel (M03), Patsch (M04) and the TAWES: Steinach am Brenner (1036 m MSL), for 18 UTC 24 Nov 17- 03 UTC 25 Nov 17 (IOP 4).

with the added energy input of solar insolation and increasing winds at Patscherkofel until 11 UTC (Fig. 3.16c). Instead, there were repeated CAP resurgences at the lowest 100 m of the southern and northern profiles after the thinning event at 07 UTC (Fig. 3.18). Upvalley, well within the CAP, the potential temperature at Völs increased smoothly due to positive net radiation and appears to have fluctuated less than potential temperature at Hilton (Fig. 3.16a,b), located closer to the CAP-foehn boundary. Similarly, the CAP resurgences were most visible at the northern and southern profile (Fig. 3.18), which lie near the boundary of foehn and CAP, while the western and eastern profiles exhibited less clear oscillations (Fig. 3.19). At 0745 UTC, potential temperatures were highest near the eastern profile and most
valley bottom stations were still within the CAP (Fig. 3.20). One hour later at 0845 UTC, the CAP appears to have been completely eroded in a thin swath from the lee of Patscherkofel in the south, towards the eastern profile in the north (Fig. 3.21). Potential temperatures within the foehn swath were 8 K warmer than within the CAP at Völs. By late morning, wind speeds at Patscherkofel reached a maximum of 25 m s\(^{-1}\) (Fig. 3.16c) and at 11 UTC the potential temperature at Hilton jumped by 5 K to 13°C (Fig. 3.16a). This potential temperature jump at Hilton resulted from a growing foehn region within in the Inn Valley. Despite the abrupt potential temperature jump, the potential temperature at Hilton was still 2 K less than the potential temperature of the foehn flow (Fig. 3.16a) and winds remained prefoehnic westerly (Fig. 3.16c,d). Foehn was well established to the north and east of the city center, but locations west of the airport were within the CAP (Fig. 3.22).
3.1 Overview of Intensive Observation Periods

Figure 3.19: As in Fig. 3.2 for 25 Nov 2017 (IOP 4).

Between the airport and the city center, the CAP was mostly, but not entirely removed and there was no true foehn breakthrough at Hilton (Fig. 3.16a). To the southeast of Innsbruck, in the lee of the Patscherkofel, there was occasional CAP influence with lower potential temperatures, but this was not a persistent feature. It is interesting that the Inn Valley CAP, already nearly removed at sunrise, remained well entrenched west of the city center despite strengthening winds and decreasing CAP stability for more than four hours.
### 3.1.4 IOP 5

**Shallow Foehn below Northwesterly Winds at Patscherkofel**

Between 12 UTC and 20 UTC 27 Nov 2017, a weak shallow southerly foehn developed at Patsch and Hilton despite northwesterly winds aloft (Fig. 3.23a,c,d). There were weak northwesterlies between 3 and 8 m s$^{-1}$ at Patscherkofel during this period, but also strengthening southerly winds at Patsch (7.5 m s$^{-1}$ by 19 UTC) (Fig.
3.23c,d). Since the southerly winds began with decreasing net radiation towards sunset, one could suspect they were of katabatic origin, yet potential temperatures were equal at Hilton and Patsch (Fig. 3.23a,b), and southerly winds of (5 m s\(^{-1}\)) also developed at Hilton (Fig. 3.23c,d). Winds at Patscherkofel abruptly turned southerly around 2030 UTC (Fig. 3.23d) and the potential temperature at Patsch increased (Fig. 3.23a). Wind speeds at Patsch and Hilton remained similar to before, but the wind direction at Hilton turned from south to west. Foehn at Hilton was replaced by prefoehn westerlies as stable stratification developed in the Inn Valley. Potential temperatures at Patscherkofel continued to increase until 02 UTC 28 Dec 2017 due to warm air advection (Fig. 3.23a). Due to stronger warm air advection with southerly winds at higher levels, the potential temperature at Patscherkofel increased faster than at Patsch and lower locations within the Inn Valley (Fig. 3.23a). Increasing stability resulted in a weak, but deeper and stratified southerly foehn at Patsch until 06 UTC 28 Nov 2017 (Fig. 3.23d). Weak foehn at Hilton in Innsbruck only occurred during a period of northwesterly winds and lower potential temperatures at Patscherkofel. After a shift to southerly winds at Patscherkofel, advection of potentially warmer air from the south resulted in increased stability of the Inn Valley CAP and an end to weak south foehn at Hilton.
Figure 3.23: As in Fig. 3.1 for 06 UTC 27 Nov - 18 UTC 28 Nov 2017 (IOP 5).
3.1 Overview of Intensive Observation Periods

3.1.5 IOP 6

Strengthening Foehn during Clear Night before 01 UTC 8 December

Between 15 UTC 7 December and 01 UTC 8 December, foehn strength increased at Patsch and prefoehn westerlies developed in the Inn Valley (Fig. 3.24c,d). Due to clear sky conditions, net radiation in the target area was clearly negative with $-60\ \text{W m}^{-2}$ between 15 UTC and 19 UTC 07 December, and potential temperatures at Patscherkofel, Hilton and Völs fell by approximately 2 K (Fig. 3.24a,b). At Patsch, on the other hand, potential temperatures increased by 1 K due to turbulent downmixing of potentially warmer air from the developing southerly flow, which strengthened to 5 m s$^{-1}$ by 19 UTC. During this time, the Inn Valley CAP was still well developed to a height of at least 300 m AGL, and the northern profile appears to have been slightly cooler than the southern one (Fig. 3.25). Shortly before 20 UTC though, there was a growing foehn intrusion above $\approx 700\ \text{m MSL}$ at the northern profile (Fig. 3.25a) at the same time that Patsch experienced a transition to more distinct foehn conditions, with increased wind speeds from 5 to 8 m s$^{-1}$, a slight change in wind direction, and a potential temperature increase of 2 K to 8°C (Fig. 3.24a,c,d). Between 2000 and 2230 UTC, the foehn strengthened not only at Patsch, but also at Patscherkofel. Additionally, clearly defined prefoehn westerlies began at Hilton and strengthened to 7 m s$^{-1}$ by 2230 UTC (Fig. 3.24c,d). The time of strongest westerlies at Hilton occurred simultaneously with a period of stronger winds at Patscherkofel (Fig. 3.24c) and enhanced foehn penetration at the eastern profile (Fig. 3.26b). Between 22 UTC 7 December and 00 UTC 8 December, there was also enhanced foehn penetration and CAP thinning at the northern and southern profiles (Fig. 3.25). As in previous IOPs, there once again appears to have been a correlation between the strength of prefoehn westerlies and CAP heterogeneity, potentially resulting from gravity wave asymmetry or a CAP tilt (Fig. 3.26) caused by flow deflection.

Overcast Conditions influence CAP Erosion after 01 UTC 8 December

A increase in cloud cover after 01 UTC 8 December 2017 resulted in decreased radiative energy loss within the CAP and facilitated a partial foehn breakthrough to the valley floor east of Innsbruck. Before 01 UTC 8 Dec 2017, clear skies had resulted in negative net radiation at the surface between $-60$ and $-70\ \text{W m}^{-2}$ (Fig. 3.24b) and a continuous energy loss for the near surface atmosphere within the CAP, as evidenced by decreasing potential temperatures at Völs (Fig. 3.24a). At Völs during this time, the CAP-stabilizing effect of radiative energy loss near the surface dominated CAP-weakening due to turbulent mixing, advection or other processes. At Hilton, the difference was not so apparent; potential temperature
already began to increase slightly after Patsch entered the foehn flow around 20 UTC 7 Dec 2017 (Fig. 3.24a), suggesting enhanced turbulent CAP warming over the city compared to further up the Inn Valley. The stabilizing effect of negative net radiation decreased in significance after 01 UTC, as net radiation increased to -20
3.1 Overview of Intensive Observation Periods

W m\(^{-2}\) due to enhanced cloudiness. As a result, energy brought to the surface layer through advection or vertical turbulent transport was not lost to radiative processes as rapidly and near surface temperatures began to increase at Völs, where they had been decreasing earlier in the night (Fig. 3.24a).

The observed impact of increased net radiation on CAP structure was largest at the western profile (Fig. 3.26a), where potential temperature at the lowest profile stations significantly increased. Perhaps, the effect of changing radiation was most visible here since the CAP structure at the eastern, southern and northern profile was more strongly influenced by changing wind speeds at Patsch and Patscherkofel (Fig. 3.24d, 3.25, 3.26b). At the eastern profile, there was a complete CAP removal between 00 UTC and 03 UTC (Fig. 3.26), but it is difficult to attribute this solely to the effect of changing radiative conditions, since winds at Patscherkofel

Figure 3.25: As in Fig. 3.3 for 15 UTC 7 Dec- 15 UTC 8 Dec 2017 (IOP 6).
also increased from 13 to 20 m s\(^{-1}\) during this time. While increased cloud cover during the night after 01 UTC resulted in less energy lost within the CAP, wind speeds at Patsch and Patscherkofel also began to decrease after 04 UTC (Fig. 3.24d), presumably resulting in less energy gain for the CAP due to turbulent mixing.

During daytime, the cloud cover strongly limited incoming solar insolation, resulting in low daytime net radiation around 60 W m\(^{-2}\) (Fig. 3.24b), compared to up to 200 W m\(^{-2}\) during other IOPs. Although net radiation at the surface was positive during daytime and an energy source for the CAP, resulted in less energy gain compared to typical clear daytime conditions. The energy input due to solar insolation was not very strong and weak foehn hindered a complete CAP removal. There was a continuous partial foehn breakthrough in the east, while western parts of the city remained within the CAP (Fig. 3.24a, 3.26). As expected with such
along-valley CAP heterogeneity, there were continual prefoehn westerlies of around 5 m s\(^{-1}\) at Hilton until 12 UTC 8 Dec (Fig. 3.24c,d).

Overcast conditions after 01 UTC decreased the diurnal variation of net radiation at the surface and, in this case, permitted a sustained period of prefoehn westerlies at Hilton and limited CAP erosion in the west after sunrise. Despite the decreased diurnal variation of net radiation, the boundary between CAP and foehn flow near the valley bottom did not remain stationary and was instead characterised by significant motion on time scales less than an hour (Fig. 3.27, 3.28). Spatio-temporal variations in foehn breakthrough were responsible for spikes in potential temperature of around 2-3 K at Hilton between 02 and 06 UTC, with weaker fluctuations visible during daytime as well (Fig. 3.24a). Similar oscillations are visible in CAP depth at all four profiles (Fig. 3.25, 3.26).

3.1.6 IOP 7

24 hours of Partial Foehn in the Inn Valley

Between 00 and 08 UTC 10 Dec 2017, the lowest \(\approx 300\) m of the Inn Valley CAP between Hilton and Patsch were neutrally stratified (Fig. 3.29a), but almost 10 K cooler than Patscherkofel. At Patscherkofel, winds increased from 10 to 20 m s\(^{-1}\) as a result of increasingly high pressure in Bolzano, south of the Brenner Pass, compared to Innsbruck (Fig. 3.29c,e). As in previous IOPs, fluctuations in wind direction were observed within the CAP (Fig. 3.29d), presumably due to increasing wind speeds aloft.

Due to CAP weakening by solar insolation after sunrise, and strengthening southerly flow at Patscherkofel, Patsch abruptly entered the foehn flow around 08 UTC 10 Dec 2017. Potential temperature at Patsch increased by 7 K and southerly winds of 15 m s\(^{-1}\) rapidly developed (Fig. 3.29). Shortly after 09 UTC, the weakly stratified CAP was removed at the eastern profile (Fig. 3.30b), but still more than 100 m deep at the western profile (Fig. 3.30a), while prefoehn westerlies developed at Hilton (Fig. 3.29c,d). As observed in previous IOPs, the prefoehn westerlies developed simultaneously with an increase in heterogeneity of CAP depth. Between 10 and 11 UTC, the Inn Valley CAP continued to weaken as the foehn region expanded westward.

As the foehn boundary approached Hilton, the potential temperature difference to Patsch decreased to just 1 K (Fig. 3.29a). Winds at Hilton turned south-southwesterly and increased to 10 m s\(^{-1}\) (Fig. 3.29c,d), indicating a southerly foehn over the city center as opposed to deflection by the Nordkette. A southerly foehn flow out of the Wipp Valley to the Inn Valley bottom can also be inferred from the warmer potential temperatures and neutral stratification at the southern profile.
around noon, when the northern profile was still within a weak CAP (Fig. 3.31). In the potential temperature map from 1230 UTC (Fig. 3.32), one sees that the CAP was restricted to regions west of the city center, while regions to the east were in the foehn flow, with slightly increasing potential temperatures. The potential temperature increase within the foehn flow towards the east may have been due to different air mass origins. Regions near Hall and Thaur may have been well mixed with the potentially warmer Patscherkofel summit, while regions further west were
well mixed with the potentially cooler Patsch. Southerly winds at Oelberg and neutral stratification to around 1600 m MSL with potential temperatures of 2°C (Fig. 3.32) suggest that the winds originating from the Wipp Valley may have reached the north profile and not winds descending from the potentially warmer Patscherkofel. With negative net radiation after 14 UTC 10 Dec, the CAP strengthened and grew in area. The foehn region at the valley bottom was then restricted to regions further east and prefoehn westerlies again developed at Hilton, ending the period of southerly foehn there.

Despite ongoing strong winds aloft during nighttime, the CAP strengthened as a result of warming foehn flow and negative net radiation near the surface. Potential temperatures at Patscherkofel and Patsch increased by around 7 K between 12 UTC 10 December and 06 UTC 11 December (Fig. 3.29a) due to advective processes. At the same time the potential temperature at Völs, in the more unperturbed CAP region, remained steady (Fig. 3.29a). This differential warming led to a potential temperature difference of 10 K between Völs and Patsch by 06 UTC 11 December (Fig. 3.29a). Despite such a strong potential temperature difference, the CAP was not deep at any of the four profiles (Fig. 3.33, 3.34). Between 03 and 06 UTC 11 December, the potential temperature difference between Völs and Patsch was largest, yet the northern profile is nearly well mixed above 650 m, with a potential temperature increase of 8 K in the lowest 50 m (Fig. 3.33). A similarly stable, yet slightly deeper CAP was also observed at the western profile (Fig. 3.34a). On the other hand, the eastern profile was strongly influenced by foehn throughout the night and only weak stratification developed at the lowest stations (Fig. 3.34b).

The Most Complete Event: Foehn at Völs after 10 UTC 11 December

After sunrise on 11 December, the Inn Valley CAP was rapidly eroded (Fig. 3.33, 3.34) and strong foehn conditions were observed throughout the observation area. At 07 UTC 11 December, net radiation at the surface began to increase (Fig. 3.29b) and there was a jump of 5 K in potential temperature at Hilton to equal the potential temperature at Patsch (Fig. 3.29a). Net radiation in the Inn Valley was increasing, but still negative at the time of the foehn breakthrough, suggesting that the dynamic forcing was enough to remove the CAP at Hilton without radiative energy input. The breakthrough at Hilton was not visible as a sudden increase in mean wind speed, but as oscillating winds, often from between northwest and northeast (Fig. 3.29c,d). The oscillating winds at Hilton can be attributed to the complex and turbulent nature of the breakthrough suggested by the chaotic potential temperature distribution at the Inn Valley bottom (Fig. 3.35). The rapid foehn breakthrough presumably resulted from a rapid removal of the thin CAP due to strong winds aloft coupled with energy input from solar insolation.
After the CAP was completely removed at the northern, southern and eastern profiles by 09 UTC (Fig. 3.33a, 3.34), winds at Hilton turned southerly and strengthened to over 10 m s\(^{-1}\) (Fig. 3.29c,d). Prefoehn westerlies were restricted to regions further west, where a thin CAP remained (Fig. 3.34a) and extreme horizon-
3.1 Overview of Intensive Observation Periods

tal potential temperature gradients of more than 5 K km\(^{-1}\) were observed near the foehn-CAP boundary (Fig. 3.36). The foehn region spread westward and reached Völs by 10 UTC as a northeasterly wind (Fig. 3.29a,c,d). Winds at Patscherkofel continued to strengthen until 11 UTC and reached 40 m s\(^{-1}\) (Fig. 3.29c,d) as the pressure difference between Bolzano and Innsbruck approached 15 hPa (Fig. 3.29e). Both quantities were the highest observed during the SOP. By 12 UTC, the entire greater Innsbruck area was well within the strong foehn flow (Fig. 3.37). Perhaps the unusually strong cross-alpine pressure difference during IOP 7 (when compared to the other IOPs), coupled with a thin pre-foehnic CAP on this day, contributed to the most complete observed foehn breakthrough of the PIANO SOP.

**Figure 3.30:** As in Fig. 3.2 for 10 Dec 2017 (IOP 7).
3.2 Quantifying CAP Heterogeneity between North and South

Mean-profile potential temperatures, column integrated buoyancy and Froude numbers were calculated for the northern and southern profiles as described in Chapter 2. The derived quantities were calculated based on 10 minute averaged wind and temperature measurements and analysed for the six south foehn IOPs presented in Chapter 3.1 to quantify CAP heterogeneity ($\Delta \theta^{S,N}$) between north and south and relate it to the magnitude of Fr.
3.2 Quantifying CAP Heterogeneity between North and South

3.2.1 IOP 2

During the first night of IOP 2 (3 Nov- 4 Nov 2017), the northern profile was colder than the southern profile ($\Delta \theta^{S,N} > 0$), while during the second night (4 Nov- 5 Nov 2017), Fr was larger and the northern profile became warmer than the southern profile (Fig. 3.38b,e). During the first night, there were katabatic winds at Patsch with weak foehn influence (Chapter 3.1.1) and positive $\Delta \theta^{S,N}$. Patsch was within the CAP and potential temperatures there increased due to a lowering of the foehn flow height (Chapter 3.1.1). As a result, column integrated buoyancy ($B$) increased from 00 to 06 UTC 4 November despite no significant decrease in $\theta^{S}$ or $\theta^{N}$ (Fig. 3.38a,c). Fr values were below 1.25 due to relatively weak southerly winds at Patsch of less than 7 m s$^{-1}$. During the second night, from 4 to 5 November, the flow situation was quite different. Although the strength of $B$ was comparable during the two nights, with values between 25 and 50 m$^2$ s$^{-2}$ (Fig. 3.38c), winds at Patsch were much stronger during the second night (Fig. 3.38d) as a result of clear foehn within the Wipp Valley (Section 3.1) and this resulted in Fr between 1.5 and 2 (Fig. 3.38e). During the second night with higher Fr, $\Delta \theta^{S,N} < 0$ (Fig. 3.38b) and there were larger temporal fluctuations in $\theta^{N}$ (Fig. 3.38a). Similar, but weaker, fluctuations in $\theta^{N}$ also occurred when Fr was largest (near 1.25) during the first night between 02 and 03 UTC 4 November (Fig. 3.38a). It appears that during IOP 2, higher values of Fr occurred with negative $\Delta \theta^{S,N}$ and stronger fluctuations in profile-mean potential temperature, especially in the north.

Froude numbers were largest during the daytime periods with foehn in the Inn.
Valley. On 4 November, Fr increased throughout the late morning and early afternoon due to weakening $B$ and increasing foehn strength at Patsch (Fig. 3.38c,d,e). The localized foehn breakthrough in the northwest of Innsbruck at 1630 UTC 4 November (Chapter 3.1) occurred shortly after Fr reached its maximum daily value and the northern profile was nearly well mixed with Patsch ($B^N \approx 0$) (Fig. 3.38c,e). During the complete and widespread foehn breakthrough in Innsbruck on 5 November (Chapter 3.1), both $B^N$ and $B^S$ were near zero (Fig. 3.38c). Occasionally, $B^N$ was even positive, resulting in imaginary Fr.
3.2 Quantifying CAP Heterogeneity between North and South

3.2.2 IOP 3

On 12 November, $\Delta \tilde{\theta}^{S,N}$ was nearly zero during nighttime and largest during the afternoon, when winds at Patsch were stronger due to foehn. Despite the deep nighttime CAP between 0030 and 0500 UTC 12 November (Chapter 3.1.2), winds of up to 5 m s$^{-1}$ at Patsch and $B < 10$ m$^2$s$^{-2}$ resulted in Fr between 1 and 2 (Fig. 3.39). At the same time, $\Delta \tilde{\theta}^{S,N}$ was near zero, but slightly negative. The potential temperature difference between north and south was restricted to small magnitudes since the CAP was almost neutrally stratified to 1000 m above the Inn Valley bottom (Chapter 3.1.2). During the partial breakthrough in Innsbruck during the late afternoon (Chapter 3.1.2), Fr was largest, with a value of approximately 3. As during both foehn episodes of IOP2, the most complete foehn penetration occurred

![Figure 3.34: As in Fig. 3.2 for 11 Dec 2017 (IOP 7).](image)
with largest Fr, but in IOP3 the sign of $\Delta \theta^{S,N}$ was different during this time. In contrast to both foehn events in IOP 2, the foehn breakthrough on 12 November occurred with near-surface southerly winds over Innsbruck and an incomplete CAP removal at the northern profile (Chapter 3.1.2). Interestingly, during the partial foehn breakthrough in the afternoon of 12 Nov (IOP 3), lidar estimated southerly wind speeds at the elevation of Patsch above the Inn Valley center ($U^{L02}$) were higher than measured southerly wind speeds at Patsch (Fig. 3.39d). During IOP 2
foehn, the wind speeds over the Inn Valley were lower than at Patsch (Fig. 3.38d). Although in both IOP 2 and IOP 3, foehn periods occurred simultaneously with large Fr values, there were differences in $\Delta \theta^{S,N}$ and $U^{L02}$ between these times.

### 3.2.3 IOP 4

During the first half of the night leading up to 02 UTC 25 November, $\Delta \theta^{S,N} > 0$ and Fr < 1 despite fluctuating $B$ and $U^P$. Between 15 and 18 UTC 24 November, winds at Patsch increased to maximally 8 m s$^{-1}$ (Fig. 3.40d), but Fr remained below 1 due to increased $B$ resulting from a simultaneous potential temperature increase at Patsch (Fig. 3.40a,c,e). After 18 UTC, southerly winds at Patsch were weaker on average and fluctuated between weak southerly foehn flow and northerly winds (Chapter 3.1.3). During this time, Fr was even lower, less than 0.5. During both periods, the northern profile was colder than the southern profile ($\Delta \theta^{S,N} > 0$) by 0.5 to 2 K. As during IOP 2, it appears that periods with low Fr tended to have $\Delta \theta^{S,N} > 0$.

After foehn began at Patsch around 02 UTC 25 November, Fr increased and $\Delta \theta^{S,N}$ became negative. Between 0130 and 0230 UTC 25 November, the potential temperature at Patsch increased by 3 K due to the foehn breakthrough (Chapter 3.1.3) and at this time $B^S$ and $B^N$ became strongest with 80 m$^2$ s$^{-2}$. At 0230 UTC, just when the CAP below Patsch was most stable, $\Delta \theta^{S,N}$ also switched sign from positive to negative. Potential temperatures at the northern profile began to increase more rapidly than at the southern profile as Fr increased past 1 (Fig.
Figure 3.38: Time series of (a) $\bar{\theta}^S$, $\bar{\theta}^N$ and $\theta^P$, (b) $\Delta\bar{\theta}^{S,N}$, (c) $B^S$ and $B^N$, (d) $U^P$ and $U^{L02}$ and (e) $Fr^S$, $Fr^N$ and $Fr$ for 18 UTC 3 Nov 2017-18 UTC 5 Nov 2017 (IOP 2). $U^{L02}$ is the southerly component of the estimated horizontal wind above the Inn Valley at L02, averaged over a thickness of 100 m, centered at the same elevation as Patsch, where $U^P$ is measured. For a discussion of the remaining variables, please see Chapter 2.2.2.
Figure 3.39: As in Fig. 3.38 for 12 Nov 2017 (IOP 3).
Results

3.40a,e), resulting in increasingly negative $\Delta \tilde{\theta}^{S,N}$ up to -2.5 K between 06 and 07 UTC (Fig. 3.40b). Similarly to the second night of IOP 2, $\tilde{\theta}^{N}$ exhibited stronger fluctuations than $\tilde{\theta}^{S}$ during the period with larger Fr, and again $\Delta \tilde{\theta}^{S,N}$ was negative.

With a near complete CAP removal after sunrise, $B$ weakened and Fr increased above 2 (Fig. 3.40c,e). For two hours following the abrupt CAP thinning after sunrise (Chapter 3.1.3), the northern profile was slightly colder than the southern profile ($\Delta \tilde{\theta}^{S,N} > 0$) (Fig. 3.40b). Then from 09 to 11 UTC, there was stronger warming in the north and $\Delta \tilde{\theta}^{S,N}$ became negative. For a half hour around 0730 UTC, within the period of $\Delta \tilde{\theta}^{S,N} > 0$, wind speeds over the Inn Valley were comparable to those in Patsch (Fig. 3.40d). On the other hand, when $\Delta \tilde{\theta}^{S,N} < 0$, winds at Patsch were generally much higher. This same pattern was observed in IOP 2 and IOP 3 during partial foehn breakthroughs. Perhaps the lower wind speeds over the Inn Valley compared to Patsch resulted from a hydraulic jump where the Wipp Valley foehn flow interacts with the remaining Inn Valley CAP near Bergisel. Such a hydraulic jump near the southern profile would explain the cold air surges observed there.

3.2.4 IOP 5

During the shallow foehn event before 21 UTC 27 November, Fr was large due to near zero $B$ (Fig. 3.41c,e), but the transition to a more deep foehn in the Wipp Valley resulted in increasing $B$, lower Fr and weakly positive $\Delta \tilde{\theta}^{S,N}$ (Fig. 3.41). Due to limited stratification below Patsch, $B$ fluctuated between -10 and +10 m$^2$s$^{-2}$ between 15 UTC and 18 UTC, and Fr was greater than 3 despite relatively weak winds of 5 to 7 m s$^{-1}$ at Patsch (Fig. 3.41). After 21 UTC, with increasing $\theta^p$ due to a flow transition to deep foehn in the Wipp Valley (Chapter 3.1.4), $B$ strengthened to 50 m$^2$s$^{-2}$ by 06 UTC 28 November (Fig. 3.41c), shortly before sunrise. During this time, Fr continuously decreased to a value of around 0.6 by 05 UTC and $\Delta \tilde{\theta}^{S,N}$ became more positive, although still less than 1 K (Fig. 3.41b,e).

3.2.5 IOP 6

Between 15 and 20 UTC 7 December, the northern profile was colder ($\Delta \tilde{\theta}^{S,N} > 0$) and $B$ became more negative, while Fr remained below 1. Winds at Patsch increased from 0 at 15 UTC to 5 m s$^{-1}$ by 1930 UTC (Fig. 3.42c), at which time $B^N$ reached its maximum of 80 m$^2$s$^{-2}$ and began to rapidly weaken (Fig. 3.42e). The largest potential temperature difference ($\Delta \tilde{\theta}^{S,N} \approx 1.5$ K) occurred at 1930 UTC and was followed immediately by a rapid decrease in $\Delta \tilde{\theta}^{S,N}$. Within approximately 30 minutes, $\Delta \tilde{\theta}^{S,N}$ became zero and Fr $\approx 1$. Interestingly, this transition in $\Delta \tilde{\theta}^{S,N}$ occurred simultaneously with strengthening winds over the Inn Valley (Fig. 3.42e).
3.2 Quantifying CAP Heterogeneity between North and South

Figure 3.40: As in Fig. 3.38 for 15 UTC 24 Nov- 15 UTC 25 Nov 2017 (IOP 4).
Figure 3.41: As in Fig. 3.38 for 12 UTC 27 Nov-18 UTC 28 Nov 2017 (IOP 5).
Before 20 UTC, southerly winds over the Inn Valley were weak compared to Patsch, but by around 22 UTC, $U^{L02}$ and $U^P$ were comparable. As observed in previous IOPs, once again $\Delta\bar{\theta}^{S,N} > 0$ while Fr < 1.

As Fr increased above 1 after 21 UTC, the Inn Valley CAP began to rapidly weaken as a result of shear-produced turbulence (Chapter 3.1.5) and $\Delta\bar{\theta}^{S,N}$ became negative. The most negative $\Delta\bar{\theta}^{S,N}$ occurred around 22 UTC (Fig. 3.42b), when Fr $\approx 1.5$ and $B^S$ increased most rapidly (Fig. 3.42c,e). After 2230 UTC, when winds at Patscherkofel and prefoehn westerlies at Hilton reached a maximum (Chapter 3.1), the northern profile began to cool and $\Delta\bar{\theta}^{S,N} > 0$ until 00 UTC 08 December (Fig. 3.42a,b). During this 90 minute period, Fr $\approx 2$ (Fig. 3.42) and $U^{L02}$ was less than half of $U^P$. After 00 UTC, the CAP was almost completely removed at the eastern profile (Chapter 3.1.5) and $\Delta\bar{\theta}^{S,N}$ became negative once again. Until 09 UTC, $B$ remained relatively constant, while $U^P$, $U^{L02}$, Fr and $\Delta\bar{\theta}^{S,N}$ all decreased (Fig. 3.42). During IOP 6 after 21 UTC 7 December, the same relationship between $\Delta\bar{\theta}^{S,N}$ and Fr was observed as in previous IOPs, except for the brief period between 2230 UTC 7 December and 00 UTC 8 December, where Fr $\approx 2$, yet $\Delta\bar{\theta}^{S,N} > 0$. During this period, $U^P$ was much greater than $U^{L02}$, but in contrast with IOP 4, where a hydraulic jump was proposed as an explanation for a cooler southern profile, the southern profile here was warmer.

### 3.2.6 IOP 7

The deep prefoehn CAP had weak stratification below Patsch, but weak winds at Patsch result in Fr $< 1$ and slightly positive $\Delta\bar{\theta}^{S,N}$ (Figure 3.43b,c,d,e). After the foehn flow abruptly established in Patsch around 08 UTC 10 December, there was a 2 hour period with rapid turbulent erosion of the Inn Valley CAP (Chapter 3.1) and strongly negative $\Delta\bar{\theta}^{S,N}$.

During the 24 hours of partial foehn discussed in Chapter 3.1.6, cold air surges at the southern profile ($\Delta\bar{\theta}^{S,N} < 0$) were found to coincide with lower values of Fr and weakened winds above the Inn Valley (Fig. 3.43a,b,d,e). While the wind speed at Patsch ($U^P$) remained quite constant between 15 and 20 m s$^{-1}$ from 12 UTC 10 December to 12 UTC 11 December, southerly wind speeds at the same height above the Inn Valley center ($U^{L02}$) fluctuated much more strongly (Fig. 3.43e). At 12 UTC 10 December, $U^P$, $U^{L02}$ $\approx 20$ m s$^{-1}$ and $\Delta\bar{\theta}^{S,N}$ was slightly positive. 18 hours later, at 06 UTC 11 December, $U^{L02}$ $\approx 0$ and $\Delta\bar{\theta}^{S,N}$ $\approx -3$ K (Fig. 3.43b,e). Other periods with $U^{L02}$ significantly less than $U^P$ were 14 UTC to 17 UTC 10 December, 02 UTC 11 December and 03 to 07 UTC 11 December (Fig. 3.43e). Although the effect of cold air surges at the southern profile were visible in lower values of Fr, it was mainly due to the increased strength of the southern CAP, not changes in wind...
Figure 3.42: As in Fig. 3.38 for 15 UTC 7 Dec-15 UTC 8 Dec 2017 (IOP 6).
speed at Patsch. On the other hand, changes in wind speed above the Inn Valley ($U_{L02}$) appear to have been more closely related with fluctuations in $B^S$. Here the relationship between $U^P - U_{L02}$ and $\Delta \theta^{S,N}$ was the same as in IOP 4 and could be explained by a hydraulic jump near the confluence of the Wipp and Inn Valley.

### 3.2.7 A Relationship between Fr and $\Delta \theta^{S,N}$

Examining the time series of Fr and $\Delta \theta^{S,N}$ discussed above for the six IOPs, it appears that, given a sufficiently intact CAP, there was a negative correlation between Fr and $\Delta \theta^{S,N}$. That is, for small Fr, $\Delta \theta^{S,N}$ appear to have been positive in general, while for larger Fr, $\Delta \theta^{S,N} < 0$. Based on a qualitative analysis, the threshold between small and large Fr is estimated to have been around 1.

To verify this hypothesis and quantify the relationship between these two variables, $(\text{Fr, } \Delta \theta^{S,N})$ pairs were selected for timesteps (with 10 minute resolution) that satisfy the criteria:

- $B^S, B^N > 20 \text{ m}^2\text{s}^{-2}$
- $U^P > 0.5 \text{ m s}^{-1}$

In an attempt to make the magnitudes of $\Delta \theta^{S,N}$ comparable between IOPs of differing stratification, $\Delta \theta^{S,N}$ was normalized to $\tilde{\Delta} \theta^{S,N}$, as described in Chapter 2.2.1 (Eq. 2.3). The resulting dimensionless pairs for each IOP were fit with a linear regression (Fig. 3.44). The Pearson correlation coefficient ($r$), $p$-value, slope and $x$-intercept were also calculated.

Overall there was a negative correlation between Fr and $\tilde{\Delta} \theta^{S,N}$ for all IOPs except IOP 3, but the correlation strength differs between the six IOPs. The weakest correlations were found for IOP 5 ($r = -0.27$) and IOP 3 ($r = 0.29$). The other IOPs, from strongest to weakest correlation were: IOP 2 ($r = -0.77$), IOP 6 ($r = -0.53$), IOP 7 ($r = -0.47$) and IOP 4 ($r = -0.37$). The $p$-values for all correlations except IOP 5 were less than 0.05, but this is no surprise due to the high number of data points and slowly changing atmospheric conditions. This metric may not be ideal to evaluate the significance of the correlations. For IOPs 2 and 6, with the strongest correlations, the $x$-intercepts, 0.98 and 1.14, respectively, were comparable with the threshold Fr value of 1, estimated from the time series analysis of the individual IOPs.

Perhaps IOP 5 and IOP 3 would show a similarly significant negative correlation as the other IOPS, but there were not many pairs (satisfying the buoyancy criteria) with Fr $> 2$ for these two IOPs, due to insufficient wind speeds at Patsch. Taken as a whole, there appears to have been a negative correlation between Fr and $\Delta \theta^{S,N}$. Whether this correlation was a result of a direct relationship between Fr and $\Delta \theta^{S,N}$,
Figure 3.43: As in Fig. 3.38 for 10 Dec-11 Dec 2017 (IOP 7).
or if simultaneous changes in both were caused by a third forcing, remains open to discussion.

3.3 Quantifying CAP Heterogeneity between East and West

As discussed in previous literature (Chapter 1) and observed during the six south foehn IOPs (Chapter 3.1), strong along-valley CAP heterogeneity have been known to occur in the Inn Valley during foehn. Along with CAP heterogeneity, prefoehn

Figure 3.44: Scatterplots of (Fr, \( \Delta \theta^{S,N} \)) pairs for (a) IOP 2, (b) IOP 3, (c) IOP 4, (d) IOP 5, (e) IOP 6 and (f) IOP 7, with regression lines (solid) plotted and fit parameters: Pearson correlation coefficient (r), p-value (p), x-intercept \((x_0)\) and slope \((\beta_1)\), included.

3.3 Quantifying CAP Heterogeneity between East and West
westerly winds have been observed over Innsbruck. The winds have been thought
to result from an along-valley pressure gradient related to a local surface pressure
minimum in the lee of the Patscherkofel due to enhanced gravity wave action. Using
the observations from the six PIANO IOPs, the along-valley CAP heterogeneity was
quantified as the difference in profile-mean potential temperatures between east and
west ($\Delta \bar{\theta}^{E,W}$). This quantity was compared to the uncalibrated (see Chapter 2.1.3)
difference in surface pressure $\Delta p^{W,E} = p^{F01} - p^{F03}$ between flux stations F01 and
F03. The hydrostatic pressure difference, at the valley bottom, resulting from $\Delta \bar{\theta}^{E,W}$
was estimated by

$$\Delta p_h^{W,E} \approx \bar{\rho} g h \Delta \bar{\theta}^{E,W} / \bar{\theta}, \quad (3.1)$$

where $g$ and $h$ are the gravitational constant and the height of the profiles ($\approx 150$ m),
respectively, and $\bar{\rho}$ and $\bar{\theta}$ are not true profile-mean values of air density and potential
temperature, but enter the equation through the application of the integral mean
value theorem. It is clear though, that they are not far from the true profile-mean
values and must be between the maximum and minimum non-averaged values for
all heights within the profile.

Equation 3.1 was derived under the assumption of no pressure difference be-
tween the top of the eastern and western profile. In that case, clearly

$$\Delta p_h^{W,E} \approx -gh \Delta \bar{\rho}^{E,W}, \quad (3.2)$$

where $\Delta \bar{\rho}^{E,W}$ is defined analogously to $\Delta \bar{\theta}^{E,W}$, by $\Delta \bar{\rho}^{E,W} = \bar{\rho}^E - \bar{\rho}^W$. Using
the ideal gas law and typical observed values of $\rho$, $\theta$, $p$, as well as along-valley differences
thereof, one finds that the normalized pressure differences are an order of magnitude
less than those of potential temperature and density. This justifies a simplification to

$$\frac{\Delta \bar{\rho}^{E,W}}{\bar{\rho}} \approx -\frac{\Delta \bar{\theta}^{E,W}}{\bar{\theta}}. \quad (3.3)$$

Equation 3.1 follows immediately from combining Eq. 3.2 and 3.3.

For reasons of simplicity, and due to the many assumptions already made, $\bar{\rho}$ and
$\bar{\theta}$ in Eq. 3.1 were assigned constant values of 1.15 kg m$^{-3}$ and 285 K, respectively.
The idealized line with slope

$$\alpha = \bar{\rho} g h / \bar{\theta}, \quad (3.4)$$

which represents a surface pressure difference entirely resulting from differences in
profile-mean potential temperature, was calculated and included in the scatterplots
of ($\Delta p_h^{W,E}$, $\Delta \bar{\theta}^{E,W}$) pairs for each IOP (Fig. 3.45).

Similarly to the regressions in Fig. 3.44, IOP 3 and IOP 5, again did not
have a large range of values. Therefore the linear regression in Fig. 3.45 was not
calculated for these two IOPs. Very strong correlations between $\Delta p_h^{W,E}$ and $\Delta \bar{\theta}^{E,W}$
were observed in IOPs 2, 4 and 6, with Pearson correlation coefficients of 0.87, 0.91
3.3 Quantifying CAP Heterogeneity between East and West

Figure 3.45: Scatterplots of $(\Delta p^{W,E}, \Delta \theta^{E,W})$ pairs for (a) IOP 2, (b) IOP 3, (c) IOP 4, (d) IOP 5, (e) IOP 6 and (f) IOP 7, with regression lines (solid) plotted and fit parameters: Pearson correlation coefficient ($r$), $p$-value ($p$), $y$-intercept ($\beta_0$) and slope ($\beta_1$), included. The slope of the dashed line is $\alpha$ in Eq. 3.4.

and 0.96, respectively. In IOPs 2 and 6, the regression slopes were quite close to the hydrostatic estimation, but a little more shallow. During IOP 4, the points were also well approximated by a linear regression, although $\beta_1$ was significantly smaller. For IOP 7 (Fig. 3.45f), the point distribution did not follow a linear relationship and therefore no regression was calculated. In IOP7 (Fig. 3.45f), for $\Delta p^{W,E} < 0$, a cluster of points was observed with $\Delta \theta^{E,W}$ larger than hydrostatically expected. For large $\Delta p^{W,E} \approx 2$ hPa, there were many observations with $\Delta \theta^{E,W}$ less than expected.

To locate the time periods during which $\Delta \theta^{E,W} \not\approx \alpha \cdot \Delta p^{W,E}$, the time series of $\Delta \theta^{E,W} - \alpha \cdot \Delta p^{W,E}$ was calculated for IOP 7 (Fig. 3.46). The time periods with
largest deviation in both directions from the hydrostatic approximation are indicated by grey shading. Around 11-15 UTC 10 Dec 17, $\Delta p_{W,E}$ was larger than expected hydrostatically given $\Delta \theta_{E,W}$. After 10 UTC 11 Dec 2017, $\Delta p_{W,E}$ was smaller than expected. These two periods both occurred during complete foehn breakthroughs at the northern and southern profiles (Fig. 3.43a). After 10 UTC 11 Dec, both the eastern and western profile were completely within the foehn flow (Fig. 3.34) and winds at Hilton (slightly) and Völs had an easterly component. The easterly wind component observed over the city makes sense given the decreasing surfaces pressure observed from Thaur towards the west, but does not fit with the hypothesis that enhanced gravity waves in the Patscherkofel lee would cause a local pressure minimum, as during prefoehn conditions. Perhaps the gravity wave asymmetry no longer plays a leading role after the CAP has been removed. In contrast to the period after 10 UTC 11 Dec, the period between 11 and 15 UTC 10 Dec 17, had larger $\Delta p_{W,E}$ than expected. These may have been due to potential temperature inhomogeneities between the CAP at the western profile, which was nearly entirely within the foehn flow, and the CAP above the pressure measurement at flux station F01, from which there were no observations.

Figure 3.46: Time series of $\Delta \theta_{E,W} - \alpha \cdot \Delta p_{W,E}$ for 10-11 Dec 2017 (IOP 7). Grey shading qualitatively indicates periods with large deviation from the approximation $\Delta p_{W,E} \approx \Delta p_{h,E}$ (Eq. 3.1).

In general, apart from IOP 7, for IOPs with sufficient along-valley heterogeneity, there was a clear relationship observed between $\Delta p_{W,E}$ and $\Delta \theta_{E,W}$. Furthermore, the observed nearly-linear relationship was compared to the assumption that surface pressure differences were solely the hydrostatic result of potential temperature differences in the lowest $\sim 150$ m of the Inn Valley atmosphere and that the pres-
sure differences at 150 m above the valley floor were zero. The values for $\Delta \theta^{E,W}$ derived under this assumption (Eq. 3.4) appear to represent an upper bound on the observed values. That is, there is most likely a dynamical component to the measured pressure gradient as well, and pressures at the eastern profile top are less than at the western profile top. Still, despite this potential pressure asymmetry aloft, the observed linear relationship suggests that the fraction of $\Delta p^{W,E}$ caused hydrostatically by $\Delta \theta^{E,W}$ remains quite constant.

The exception was IOP 7, where the strongest foehn occurred and the relationship between $\Delta p^{W,E}$ and $\Delta \theta^{E,W}$ was most non-linear. This is no surprise, since the hydrostatic assumption and assumption of zero horizontal pressure gradient above the surface were most likely not fulfilled for such strong dynamic forcing. Additionally, as discussed in Chapter 2.1.3, the pressure measurements at F01 and F03 may have been influenced by the wind directly and not represented the true static pressure (Straka et al. 1996). The magnitude of this effect is most likely less than 1 hPa, though, and does not explain most of the deviation, which presumably results from changing gravity wave asymmetry with time.
Chapter 4

Discussion

4.1 Initial Location and Characteristic of Foehn Breakthrough

Since only observations from six south foehn cases are available (IOPs 2-7), it is not possible to make any statements of statistical significance regarding typical initial south foehn breakthrough locations in the Inn Valley. Nevertheless, the cases observed during PIANO in fall and early winter 2017 can be compared and contrasted. We compare the location of initial foehn breakthrough. In some cases, the foehn region within the Inn Valley grows from the initial breakthrough location to encompass all of Innsbruck and surroundings. In other cases, the region of foehn at the valley bottom remains localized.

4.1.1 Northeastern Breakthrough

Based on potential temperatures obtained from the array of HOBO loggers, most of the observed foehn cases appeared to have had an initial breakthrough in the northeastern regions of the greater Innsbruck area. Typically, the eastern profile near Arzl entered the foehn flow first and the CAP to the south and west was subsequently eroded. During IOPs 3, 4, 6, and on the first day of IOP 7 (10 December), the spatial evolution of foehn, as inferred from the spatial potential temperature distribution, was quite similar. The CAP between the Innsbruck city center and the longitude of Arzl was eroded progressively from the north. During the second day of IOP 2 (5 November), there was also an initial eastern breakthrough, but further east in the region of Hall. In this case, the eastern Innsbruck city center was within the CAP and had prefoehnic westerlies. The surface potential temperature distribution suggests that the eastern displacement of initial breakthrough location on the second day of IOP 2 (5 November) when compared with the other northeastern breakthroughs
occurred with stronger CAP influence over the eastern city.

For most of the time during northeastern breakthrough days, foehn did not occur in the city center at Hilton and winds remained prefoehnic westerly there. Periods of foehn breakthrough at Hilton did occur during day two of IOP 2 (5 November), IOP 3 and day one of IOP 7 (10 December). The wind direction at Hilton after foehn breakthrough was not always southerly, but instead varied among the cases. During IOP 3, weak southerly winds of at most 5 m s\(^{-1}\) were observed at Hilton for half an hour around 16 UTC 12 November. Potential temperatures at Patsch and Hilton remained equal until 17 UTC, with calm winds at Hilton despite 10 m s\(^{-1}\) at Patsch. During the first day of IOP 7, from 10-14 UTC 10 December 2017, winds at Hilton were southerly with 10 m s\(^{-1}\) and potential temperatures just 1 K less than at Patsch.

### 4.1.2 Southeastern Breakthrough

A clear initial southeastern breakthrough in the Patscherkofel lee was only visible on day two of IOP 7 (11 December). Compared to the northeastern breakthroughs, here the initial foehn breakthrough occurred not at the eastern profile, but further south, yet still east of the Wipp Valley, where the northern slopes of the Patscherkofel reach to the Inn Valley bottom. Wind speeds at the Patscherkofel during day two of IOP 7 were stronger, at 35 m s\(^{-1}\), than during other IOPs. Based upon the potential temperature evolution, the foehn appears to have descended the lee of the Patscherkofel all the way to the valley bottom. The remaining CAP was pushed northward and soon destabilised, mixing into the foehn flow. The Inn Valley CAP was divided into two parts by the foehn flow and the remaining eastern CAP was quickly advected downvalley. The foehn also removed the CAP towards the west, albeit at a slower rate than towards the east.

An increase to foehn potential temperature at Hilton around 07 UTC 11 December was followed by 2 hours of fluctuating wind direction before a strong southerly wind with 10-15 m s\(^{-1}\) established. The two hour period of fluctuating wind direction despite foehn breakthrough, occurred simultaneously with the rapid removal of the Inn Valley CAP west of Hilton. Once net radiation became positive around 09 UTC, strong south-southeasterly winds developed at Hilton. The initially changing wind direction of the foehn flow at Hilton can be attributed to chaotic flow interaction between the foehn and destabilising CAP; once the CAP was completely removed near Hilton, a southerly foehn flow became established.
4.1.3 Western Breakthrough

The only initial foehn breakthrough west of the Innsbruck city center occurred on day one of IOP 2 (4 November). In that case, the western profile was neutrally stratified and well mixed with the potential temperature at Patsch, while the entire eastern profile was within the CAP. After noon on 4 November, cold air advection with the foehn flow resulted in cooling at higher levels, i.e., at Patscherkofel and Patsch. Potential temperature in the Inn Valley continued to slightly increase in the early afternoon due to solar insolation and, as a result, static stability decreased. Winds at the Patscherkofel were not very strong compared to the other cases, with only 15 m s\(^{-1}\). Enhanced gravity wave activity in the lee of the Patscherkofel did not appear to play a major role in the breakthrough. The CAP was not thinner in the east as in most other IOPs and no prefoehnic westerlies were observed over the city. Instead, weak easterlies developed within the CAP near the city center. During the period of easterlies, potential temperature was greater in the west, a reversal of the along-valley potential temperature gradient observed in most other cases.

4.1.4 Southern Breakthrough

During IOP 5, a weak shallow foehn flow occurred within the Wipp Valley and around Innsbruck, with northwesterly winds at Patscherkofel. The initial breakthrough location was not clearly defined, but winds over the city center were southerly. The fully developed foehn was restricted to Innsbruck and did not break through further east, as typically observed. Presumably, this is because winds at crest height were not southerly and did not result in enhanced downslope winds and CAP displacement or erosion in the Inn Valley east of Innsbruck. Once the wind direction at higher levels turned southerly, stability in the Wipp Valley increased due to warm air advection at higher levels above the mixed layer resulting from the shallow foehn. The weak south foehn in Innsbruck came to an end and westerlies developed at the valley floor within the CAP while the potential temperature at Patsch increased due to turbulent downmixing of potentially warmer air. The shallow foehn event has similarities to a gap wind (Flamant et al. 2002) and may be a reason for the atypical foehn breakthrough in the city.

4.2 CAP Heterogeneity in the Inn Valley

During foehn, flow interactions with the complex topography of the Wipp and Inn Valley and the stably stratified Inn Valley CAP result in spatial inhomogeneity of CAP characteristics. CAP inhomogeneity during foehn events was examined using the spatial distribution of valley bottom temperatures and differences in CAP depth.
as estimated from four slope profiles. CAP heterogeneity in the south-north direction was quantified by the difference in mean-profile potential temperature and related to Froude number. The along-valley CAP heterogeneity was also quantified by the difference in profile-mean potential temperature, but related to an along-valley pressure difference instead of Froude number. It was found that the relationship between differences in potential temperature and pressure was close to linear for all IOPs except IOP 7.

4.2.1 Cross-Valley Heterogeneity and Froude Number Regimes

A relationship was observed between Froude number and the difference between northern and southern profile-mean potential temperatures. These two profiles reached to a depth of between 250 and 300 m above the valley floor. The flow configuration was characterised by the Froude number defined as Fr = U/\sqrt{B}. For Fr \lesssim 1 it was found that generally the northern profile was colder than the southern profile. For larger Fr, the northern profile was typically warmer. A possible explanation for this relationship is introduced below and results are compared with the literature.

Small Froude Numbers: Fr \lesssim 1

During periods with smaller Fr \lesssim 1, the northern profile tended to be colder than the southern profile. This could be explained by CAP tilting (increasing CAP depth towards the north) due to southerly wind stress. For example, a CAP deepening of 200 m in the direction of upper level winds has been observed by Lareau and Horel (2015a). A more speculative theory is that the colder northern profile result from mesoscale pressure gradients aloft. In the case of south foehn, there are typically higher pressures in South Tirol than North Tirol, with pressure differences between Bolzano and Innsbruck on the order of 4 hPa. The distance between Bolzano and Innsbruck is approximately 80 km, so around 20 times the distance between the northern and southern profile (\approx 4 km). Assuming a constant pressure gradient, the pressure difference between the northern and southern profile due to this mesoscale gradient would be around 0.2 hPa. With a profile depth of 300 m, this pressure difference would hydrostatically cause an \approx 0.6 K difference in profile-mean potential temperatures (Eq. 3.1). Since the observed differences in profile-mean potential temperatures in cases with Fr \lesssim 1 are on the order of 0.5-2 K, this effect may be of importance when analysing cross-valley CAP heterogeneity.
Large Froude Numbers: \(1 \lesssim Fr \lesssim 3\)

At higher wind speeds, and when the CAP is shallow or weak (small \(B\)), \(Fr\) becomes greater than 1 and the northern profile generally becomes warmer than the southern profile. It is not apparent why the effects discussed above for \(Fr \lesssim 1\), that lead to a colder northern profile, should change for \(1 \lesssim Fr \lesssim 3\). Maybe they do not, in fact, change, but the northern profile warms due to growing influence from other forcings on the lowest \(\approx 300\) m of the Inn Valley atmosphere. Perhaps these atmospheric processes begin to gain importance as \(Fr\) increases and dominate the effects proposed for the case of \(Fr \lesssim 1\). Increased warming at the northern with respect to the southern profile could result, for example, from enhanced turbulent mixing in the north, flow deflection at the Nordkette, or gravity wave asymmetry.

One possible explanation for enhanced downmixing of foehn air at the northern profile is the growth of shear-instabilities (KHIs) as they propagate northward near the CAP top. Such behavior has been observed, for example, in numerical simulations of a CAP in the Arizona Meteor Crater (Fritts et al. 2010). For the case of foehn in the Wipp Valley, the southerly flow initially interacts with the Inn Valley CAP at its southern edge, often near Bergisel. The resulting sharp gradient in wind speed between the strong foehn flow and the more stagnant upper CAP may cause wave instabilities (Monin and Yaglom 1999). In that case, initially small wave amplitudes would grow as the waves propagate northwards along the CAP-foehn interface. As the waves break down into vortices and turbulence, they would mix potential temperature vertically: cooling regions within the foehn flow above the initial CAP boundary, while warming the upper CAP. The result of this widening shear zone is a weakening but deepening CAP and no change in the pressure difference between north and south at the valley bottom. Assuming that the profiles to be compared both reach to a height that is near the southern CAP boundary in this idealized case, then only the downmixing of warm air from the foehn flow into the profile measurement area influences the profile comparison. The cooling above the highest profile station in the north would not be taken into account when comparing to the southern profile-mean potential temperature in this hypothetical situation. Maybe for profiles with sufficient depth, such that the growing shear zone is entirely captured within the measurements, there would be less difference in profile-mean potential temperatures for such a purely-KHI situation.

Alternatively, warmer temperatures at the northern profile could be caused by flow deflection of the southerly foehn jet at the Nordkette. In this case, a profile-mean potential temperature difference would represent an actual difference in total CAP strength. Enhanced vertical motions are possible due to mass conservation where the foehn jet impinges upon the sloped topography of the Nordkette. To illustrate, imagine a jet flow impinging upon a vertical wall. The wind component
of the jet normal to the wall must become zero at the surface. This convergence in flow direction necessitates a divergence of the wind in the plane normal to flow direction in order to satisfy mass conservation. Most of the wind divergence in the normal plane is presumably horizontal, but there may be divergence in the vertical as well. This could result in enhanced vertical motions, CAP erosion or displacement and a warming of the northern profile with respect to the southern profile. In fact, flow deflection at the Nordkette has been observed by Zängl et al. (2004) in numerical simulations of a specific foehn event during MAP. The observed flow split into two branches at the Nordkette. The eastern branch entered the CAP from the north and caused a difference of more than 100 m in CAP thickness from east to west. It is conceivable that similar deflected flows occur during periods with Fr $\gtrsim 1$. Such flow deflection could have decreased CAP strength at the northern profile and resulted in negative $\Delta \bar{\theta}^{S,N}$, while $\Delta \bar{\theta}^{S,N}$ was positive for Fr $\lesssim 1$.

Finally, warmer northern profile potential temperatures could be caused by compensating flows below a cross-valley pressure gradient caused by gravity waves in the foehn flow above the CAP top (Vergeiner 1996). In Vergeiner’s model, the pressure above the valley floor increases towards the north. The colder and more dense air within the CAP must flow to below the southern pressure minimum aloft in order to balance the pressure near the valley bottom. The result would be a warmer northern profile, as observed for $1 \lesssim \text{Fr} \lesssim 3$.

Very Large Froude Numbers: Fr $\gtrsim 3$

Periods with Fr $\gtrsim 3$ occur only under weak CAP conditions, where foehn has broken into the lowest Inn Valley atmosphere. At this point, comparing the profiles becomes less meaningful as only isolated stations are within the CAP. By our definition of Fr, smaller $B$ result in larger Fr for constant $U$. It is important to remember though, that large Fr do not necessarily imply small $B$, assuming $U$ is large enough. In our observations though, there are no high Fr periods meeting the buoyancy criterion ($B > 20 \text{ m}^2 \text{ s}^{-2}$), except in IOP 7. This is no surprise, since winds during this IOP were strongest. Another reason for the unusual CAP persistence despite high Fr could be the influence of warm air advection aloft during IOP 7. The increase in foehn potential temperature effectively continually stabilizes the CAP. Such a trend is not taken into account in the formulation of Fr, which only includes information about the CAP stability at one time. During situations with high Fr, the CAP is warmed through strong turbulent heat flux convergence and would typically be rapidly eroded. Due to warming of the foehn flow, $B$ does not decrease as rapidly despite high Fr. The CAP persists for values of Fr $\gtrsim 3$, where $B$ would usually weaken below 20 m$^2$ s$^{-2}$.
Comparisons with the Literature

The observed characteristics of profile-mean potential temperature as related to Fr, can be understood from the literature. During higher Fr above 1, often mean-profile potential temperatures begin to increase (suggesting warming due to turbulent heat flux convergence). Additionally, the mean-profile potential temperature has stronger temporal fluctuations. Lareau and Horel (2015b) note that for Fr $\approx 1$, Kelvin-Helmholtz Waves (KHWs) begin in their numerical simulations. In the simulations, KHWs were found to increase in amplitude up to Fr $\approx 2$, at which point they reached to the valley surface. For Fr $> 2$, CAP erosion was found to occur and the situation was no longer steady state. In numerical and laboratory studies, Bell and Thompson (1980) observed valley ventilation, regardless of stratification, for Fr $> 1.3$. Rotunno and Lehner (2016) simulated stratified flow past a depression and found tilting isentropes (increasing in height towards flow direction) that fit with the PIANO observations for Fr $\lesssim 1$. Of course, a direct comparison to Fr thresholds from previous studies can generally not be made due to slight differences in the definition of Fr and, perhaps more importantly, major differences in model and real topography. For example, idealized two-dimensional simulations by Sheridan (2019) show increased wave breaking and decreased CAP persistence with a ‘double hill’ as opposed to ‘valley in plateau’ topography. Furthermore, smaller valleys were found to be ‘morphologically constrained’, while larger valleys exhibited more variability in the interactions between the external flow and CAP.

It is important to remember that the complex topography and flow characteristics around Innsbruck result in situations with extreme CAP heterogeneity, especially for large Fr. Further up the Inn Valley from Innsbruck, foehn is less frequent (Vergeiner 1996) and requires stronger forcing for a breakthrough to the valley bottom. Any CAP erosion or displacement by the foehn flow in the neighborhood of Innsbruck, would result in a pressure gradient at the surface to the west of the city and compensating flows from deeper CAP regions upvalley. The choice of profile location then becomes very influential in the estimation of Fr. Estimating $B$ from a profile further west would typically result in lower Fr than when using a profile from near Innsbruck. Out of scarcity, the northern and southern profile were used for buoyancy estimates, but perhaps a more sheltered upvalley profile to a higher depth, would also have yielded interesting results, especially if one is interested in forecasting time scales of complete breakthrough.

A theory of north-south CAP heterogeneity in Innsbruck was, in fact, developed by Vergeiner (1996) and already briefly mentioned above. His two layer idealized model consists of a foehn flow with constant speed, $U$, and two Brunt-Väisälä Frequency; $N$ for the foehn flow and $N_0$ for the CAP. The interaction between foehn and CAP is related to the values of two Froude numbers: one for the foehn flow and
one for the CAP. He proposes a gravity wave asymmetry in the north-south direction, with higher pressure in the north. The result is a compensating flow within the CAP and warmer air at the northern CAP. By setting the two Froude numbers equal, Vergeiner (1996) derives a critical Froude number $Fr_c$ between 1.6 and 1.7 for complete foehn penetration. His inclusion of a stability parameter for the foehn flow in the formulation of $Fr_c$, makes comparing magnitudes with this study difficult. Furthermore, he notes that the theoretical model may be suitable for numerical model verification or comparisons, but is not likely to be a good representation of the true atmospheric processes within the Inn Valley. Nevertheless, there are surely pressure differences in the north-south direction, above and within the CAP, that explain part of the spatial heterogeneity of potential temperature. Whether they are caused by gravity waves is another question all together. In order to compare observational results with Vergeiner’s model, it would be necessary to estimate the Brunt-Väisälä Frequency of the foehn flow. For this, one could use the difference in potential temperature at Patsch and Patscherkofel, for example. In the same vein, a foehn flow speed could be approximated as the average of the wind speed at Patsch and Patscherkofel.

4.2.2 Along-Valley Heterogeneity

Prefoehn Westerlies

The strength of prefoehn westerlies appears to be related to CAP heterogeneity in the along-valley direction. During IOPs 2, 4, 6 and 7, stronger prefoehnic westerlies were observed when a foehn breakthrough or shallow CAP at the eastern profile co-existed with a deeper CAP further west. Zängl and Gohm (2006) also observed CAP heterogeneity simultaneously with prefoehn westerlies in their numerical simulations of foehn. In the simulations, a shallow CAP of 50-200 m in the east was found to occur as a result of foehn flow deflection at the Nordkette, while the CAP further west had a depth of 400-500 m. In extreme cases during PIANO, the transition region between CAP and foehn at the valley bottom was very sharp. This foehn front resulted in near-surface along-valley potential temperature gradients around 10 K km$^{-1}$ and progressed slowly westward. Presumably there were also enhanced winds along the foehn front in the direction of the horizontal potential temperature gradient caused by a horizontal pressure gradient induced by rapidly varying CAP thickness in space. This explanation for the westerly winds was given by Zängl and Gohm (2006), who presented it as an addition to the already established theory of pressure gradients induced by gravity wave asymmetry (Zängl 2003).
A Relationship between Differences in Pressure and Potential Temperature

To investigate the relationship between along-valley heterogeneity of potential temperature and pressure, a more quantitative analysis of their correlation was performed. For the six IOPs, 10-minute averaged values of profile-mean potential temperature difference between east and west ($\Delta \theta^{E,W}$) were compared to the along-valley pressure difference between two flux stations: one near the airport in west Innsbruck and the other in Thaur ($\Delta p^{W,E}$). During IOPs 3 and 5, there was not a large range of $\Delta \theta^{E,W}$ or $\Delta p^{W,E}$ values due to the weak dynamical forcing. For IOPs 2, 4 and especially 6, the relationship was found to be nearly linear. During IOP 7, there were stronger deviations from the linear approximation.

To understand the meaning of such a linear relationship it is illustrative to imagine a hypothetical situation where there is constant pressure at 150 m above the valley floor (approximately the height of the eastern and western profile). Then using the hydrostatic assumption, pressure differences between two locations at the valley bottom are solely caused by differences in density of the lowest 150 m above the two locations. To a good approximation, this idealized relationship is linear and its slope can be calculated from theory. If the true relationship between the measured quantities is nearly linear and has a slope close to the theoretical value, it is plausible to think that horizontal pressure gradients above the valley bottom are small compared to the near surface horizontal gradients. If the relationship is linear, but the observed slope less than the theoretical prediction, the fraction of surface pressure difference caused by $\Delta \theta^{E,W}$ remains more or less constant. This was observed to be the case for all IOPs except IOP 7 and would support the theory that prefoehn westerlies and CAP heterogeneity are induced not only by gravity wave asymmetry in the foehn flow (Zängl 2003), but also by horizontal potential temperature gradients (Zängl and Gohm 2006).

It is possible, though, that the dynamical forcing was too weak for gravity wave asymmetry to dominate in IOPs 2-6, and that the enhanced foehn wind speeds and cross-alpine pressure gradient in IOP 7 caused a breakdown of the linear relationship observed between $\Delta \theta^{E,W}$ and $\Delta p^{W,E}$ for IOPs 2-6. During IOP 7, two distinct time periods were observed with strong deviations from the linear approximation. During these periods there were also high wind speeds at Patsch and Patscherkofel and widespread foehn breakthrough in Innsbruck. The two periods did not deviate in the same manner. On day one of IOP 7 (10 December 2017) $\Delta p^{W,E}$ was larger than expected, while on day two (11 December 2017) $\Delta p^{W,E}$ was smaller than expected. In fact, during the second period $\Delta p^{W,E}$ was even negative, with higher pressures in Thaur than at the airport. In this situation, there was a complete foehn breakthrough and the wind at Hilton, between the two pressure measurements, had
a slight easterly component, which makes sense given the measured pressure difference. In any case, it appears that, even during IOP 7 where the relationship was most nonlinear, the pressure at Thaur was not generally lower than would be hydrostatically expected. This indicates that it is not a general rule that gravity wave asymmetry causes lower pressures aloft in the east and perhaps the situation may be reversed under certain cases.

Of course, it is difficult to make definite claims regarding the pressure field aloft from less than ten temperature loggers and two surface pressure measurements. There are many problems with this approach. For one, the potential temperature measurements are not taken from the atmosphere above the pressure measurements in the valley center, but rather from the slopes to the north. Any difference in potential temperature between the atmosphere above the valley center and the near-surface slope is not taken into account. For high Fr, we presume there is strong CAP heterogeneity due to dynamical processes, but even for low Fr there may be a non-negligible and non constant difference; during daytime the near slope may be warmer than the valley center due to solar insolation, while at night the slope layer may be potentially cooler. These potential temperature gradients are responsible for the well known slope flows in mountaineous terrain (Doran and Horst 1983). While ignoring the effect of these winds directly may not pose a major problem, the theoretical linear relationship (and derived slope constant) rely on the hydrostatic assumption and, hence, no vertical accelerations. For very strong foehn, these vertical accelerations may make interpretation of the relationship difficult and could also be the cause of some deviation from the linear approximation observed in IOP 7. Furthermore, as mentioned more than once already, the pressure measurements may not represent the true static pressure and can additionally contain a dynamic pressure component due to direct wind influence at the sensor (Straka et al. 1996). Overall, it is surprising to find such a clear linear relationship between $\Delta \theta^{E,W}$ and $\Delta p^{W,E}$ for most of the IOPs. Even more astounding, given the extent of the assumptions discussed above, is that the slope constant estimated from the linear regression of measurements is not far from the theoretically expected value for some IOPs.

4.3 Speculation Regarding Potential Temperature Fluctuations

As noted throughout the results section, there were fluctuations with a wide range of periods in the observed potential temperature signals. Longer period oscillations, on the order of an hour or two, appeared to occur nearly in phase at several stations within the city. During at least one instance, shorter oscillations with periods on
the order of half an hour were observed. The oscillations appeared out of phase for HOBO stations to the north and south of the city, suggesting a seiche-like feature (Defant 1953; Arneborg and Liljebladh 2001). Furthermore, there were even shorter oscillations with periods of several minutes to tens of minutes, that occurred mainly near the CAP-foehn interface, especially at the northern profile. Smaller scale turbulent oscillations naturally occur as well, but were not captured by the HOBOs due to insufficient logging frequency (one measurement per minute) and the low-pass filtering effect of sensor housing and radiation shield. It is outside the scope of this paper to attempt a careful analysis of different wave types. In this section, some mechanisms that could result in the measured potential temperature fluctuations are discussed. The magnitude of their oscillation periods are estimated using simple theory or results from previous studies.

4.3.1 Gravity Waves

As discussed above, interactions between the foehn flow and the CAP can result in CAP displacement. If the foehn forcing of the CAP, i.e., due to wind stress or gravity wave asymmetry, changes, there is a force imbalance and the CAP has a tendency to flow back to its initial equilibrium position. To complicate matters, the CAP dynamics resulting from non-stationary forcing can, in turn, influence the wind field above the CAP in a coupled system (Porch et al. 1991; Mori and Kobayashi 1996). In general, the CAP imbalance need not be caused by dynamical forcing from the foehn flow, but could also result, for example, from spatial inhomogeneity of solar insolation at the valley bottom. The main flow direction above the CAP in the center of Innsbruck during south foehn is meridional, suggesting significant CAP oscillation in the meridional direction during non-stationary winds. Further west and east of the city, the foehn flow is presumably confined to flow along the valley axis. Upvalley of Innsbruck, the foehn manifests as an easterly wind, while downvalley it is more westerly. Hence, oscillations in the CAP are possible in the along-valley direction as well.

North-south oscillations of the CAP were inferred from comparing the potential temperature signals at the valley bottom in the south and north. On one occasion, while the valley bottom stations were within the CAP, the two potential temperature signals were out of phase, with a gradually changing period on the order of tens of minutes (Fig. 3.7). It is no surprise that the oscillation period is not constant due to the complex topography of the valley and two-dimensional wave propagation, but theoretical predictions of oscillation periods can still be made for idealized cases. An additional problem in observing seiches is that they dampen with time (Arneborg and Liljebladh 2001). In the atmosphere, non stationary flow conditions make a
spectral analysis of the fluctuations difficult.

Mathematically, north-south CAP oscillations can be described by two gravity waves with the same wavelength traveling in opposite directions. The relevant wavelength used to calculate the oscillation period of the first seiche mode, with one node at the valley center, is twice the distance between the bounding topography to the north and south (Defant 1953). To estimate the order of magnitude of the wave periods, a shallow water framework with step-like potential temperature inversion, no mean-wind, and vertical bounding walls is assumed. The phase speed of shallow water waves is given by \( c = \sqrt{g' h} \). For the case visualised in Fig. 3.7, reasonable values for CAP depth, \( h \), of 200 m and potential temperature inversion strength, 10 K, result in a reduced gravity of \( g' = g 10 \text{ K}/280 \text{ K} \approx 0.35 \text{ m s}^{-2} \), and a phase speed of \( c \approx 8 \text{ m s}^{-1} \). The period of the oscillation would then be given by \( T = 2L/c \), where \( L \) is the distance between the bounding topography in the north and south. If we choose \( L \) to be the distance between Hungerburg and Grillhof, \( L \approx 5000 \text{ m} \) and the period of oscillation, according to the Merian formula (Wilson 1972) is \( T \approx 10000 \text{ m}/8 \text{ m s}^{-1} = 1250 \text{ s} \approx 20 \text{ min} \). This calculated oscillation period is not far from the magnitude of periods observed in Fig. 3.7.

In contrast with the meridional oscillation, there are no clear boundaries blocking gravity waves in the CAP from advancing far up or down the Inn Valley. Around Oberperfuss, approximately 12.5 km to the west of Innsbruck, there is a bend in the Inn Valley to the north and a mountain range due west separates the Sellrain tributary valley to the south from the Inn Valley to the north. If this mountain chain acts as a partial barrier and allows some of the CAP to dam against it, or flow partially up the Sellrain Valley, a weakening easterly wind aloft could allow the deeper CAP to flow eastward towards the city center. In this case, the distance traveled would be approximately five times that of the meridional case and, assuming the same stratification, the period would be five times as large. A mean westerly flow within the CAP would decrease the speed of gravity waves propagating upvalley, while increasing their propagation speed downvalley.

Assuming such a partial wave reflection upvalley of Innsbruck, a disturbance travelling upvalley from Innsbruck should return to Innsbruck after 100 minutes, given the same assumptions of CAP depth and potential temperature inversion as for the meridional case above. So the oscillation period is on the order of an hour or two. This calculation assumes a reflecting boundary both upstream and near Innsbruck. In reality, any up valley propagation or damming of the CAP is also governed by the evolution of the wind stress above the CAP and difficult to estimate. Additionally, the lack of any clear boundaries and the long oscillation period would make observing multiple oscillations impossible. In any case, the order of magnitude fits quite well with periods of some observed fluctuations in CAP depth (well visible
4.3 Speculation Regarding Potential Temperature Fluctuations

in the Hovmoeller Diagrams), but this may be a coincidence. Along-valley wave propagation, even without true oscillation, could explain why some long period fluctuations appear to occur nearly in-phase at the northern and southern profile, for example, while shorter periods often exhibit larger phase differences between these two profiles. Of course, these fluctuations in CAP depth could also occur due to larger scale changes in the foehn flow and need not be a result of CAP-foehn interaction. This discussion is meant to foster ideas and should not be understood as a systematic analysis of potential temperature fluctuations in relation to the phase speed of gravity waves within the CAP.

Of course, there is no true step-like temperature inversion between the CAP and the foehn flow for the observed IOPs, the real topography is complex, and the wind field is spatially inhomogeneous and not zero-mean. A poor understanding of wave-wave interactions adds to the complexity of the problem (Sun et al. 2015). As a result, rigorously testing these hypotheses is not feasible and, in fact, they are meant not to perfectly describe the phenomenon. Perhaps, though, the physical mechanism of non-stationary wind stress may be partly responsible for slow and intermediate fluctuations seen in CAP depth. Given a sufficiently large dataset, a good first approach would be to analyse the spectra of CAP depth or mean-profile potential temperature. Perhaps distinct, case-dependent, frequency peaks in the spectra could be found. The frequency of these peaks could then be related to frequencies estimated from theory given measurements of CAP stability and depth.

4.3.2 Kelvin-Helmholtz Waves

In addition to the gravity-induced fluctuations discussed above, waves can also occur at the interface between CAP and foehn due to vertical shear in the horizontal wind field (Chapter 1). If vertical shear of the horizontal wind field is sufficiently strong compared to the static stability of the inversion, these waves can become unstable and grow without bounds. The ratio of buoyancy to shear effects is expressed by the Richardson number \((Ri)\) and for \(Ri \lesssim 0.25\) instabilities can occur (Miles 1961; Galperin et al. 2007). In unstable conditions, the shear-induced Kelvin-Helmholtz waves (KHWs) grow in amplitude and eventually break, mixing foehn air into the CAP, and colder air upwards into the foehn layer. The initially sharp temperature inversion is weakened due to a sensible heat flux divergence above and a sensible heat flux convergence below the interface. The resulting potential temperature fluctuations are especially visible at the northern profile for the large Froude number regime \((1 \lesssim Fr \lesssim 3)\).

In their numerical simulations, Lareau and Horel (2015b) observed KHWs at the CAP top with wavelengths around 1 km. Assuming similar wavelengths for our
cases and a translation speed that is the average between the lowest foehn flow speed (order of 10 m s$^{-1}$) and the southern wind component within the CAP (nearly 0 m s$^{-1}$), the time period of the oscillations measured at the northern profile would be on the order of several minutes. This estimate is comparable to observed periods around 5 minutes (Smith 1991) and 7 minutes (Belušić et al. 2007). In several foehn cases, Nater et al. (1979) also observed sine-like KHWs. They occurred just above the CAP, in the lower regions of the shear-zone, with 'peak to peak' amplitudes of 50 - 100 m and periods of around 300 - 400 s.

Again it is important to note, that shorter period fluctuations at the northern profile are not a result of pure KHWs. Nearly all quasi-periodic fluctuations in the temperature data during our foehn events would more appropriately be characterised as dirty waves (Sun et al. 2015). Especially, when looking at the potential temperature signal, wavelike phenomena must often be inferred from periodic spikes rather than clean sinusoids. One would expect surface pressure data to be more wavelike than potential temperature signals, due to the integrated effect of potential temperature (more accurately, density) differences above the sensor. Even though, there are waves of many different types, periods and phases. Separating all the influences without the assumption of stationarity or idealized terrain would most likely be impossible.

4.4 Further Research Ideas

A simple extension of the conducted research is possible using available data from the time of the PIANO SOP. Rather than just use the wind speed at Patsch, wind measurements from many points within the Wipp Valley, from Sattelberg and also Patscherkofel, could be integrated into the theoretical model. Given potential temperature at these locations, a multilayer model can be analysed in relation to CAP heterogeneity in both directions.

With a greater number of slope profiles reaching to several hundred meters above the valley floor, a more exhaustive investigation into CAP heterogeneity could be launched. Froude numbers could be calculated using wind speeds from various different heights, obtained either from in-situ measurements or lidar estimates of horizontal wind above the surface. A statistical analysis of the relationship between CAP heterogeneity and the wind field could be interesting, once the number of observed foehn cases becomes large enough and assuming adequate sensor density.

Simple idealized two dimensional simulations, similar to Rotunno and Lehner (2016), Sheridan (2019), or Lehner et al. (2016), could be useful to investigate the hypothesis of CAP-heterogeneity regimes based on Froude number. With simulations, one could quantify the effect of the different processes that influence the
profile potential temperatures and observe their evolution as Fr is increased. Three
dimensional numerical simulations, either idealized or not, would be needed to test
the influence of CAP oscillations in both the along-valley and cross-valley directions
and their interaction with the foehn flow.
Chapter 5

Conclusions

Observational data from six IOPs, conducted during fall and early winter 2017, are analysed to better understand spatial heterogeneity of the pre-foehnic Inn Valley cold air pool (CAP) and differences in initial foehn breakthrough location around Innsbruck. Potential temperature calculated from HOBO temperature measurements are used as a proxy for foehn influence at the valley bottom and along four slope profiles. Differences in the temperature characteristics at the northern and southern profiles for the lowest 300 m of the valley atmosphere are related to Froude numbers estimated using column integrated buoyancies (Lareau and Horel 2015b) and southerly wind speeds at Patsch (Wipp Valley). Additionally, along-valley (west-east) pressure differences are compared to differences in profile-mean potential temperature at the eastern and western profiles. The main findings of this analysis are:

- Most initial foehn breakthroughs in fall and early winter 2017 occurred to the northeast of Innsbruck with flow deflection at the Nordkette. One initial breakthrough in the western part of the city occurred during weak southerly winds aloft. A southeastern initial breakthrough occurred in the lee of the Patscherkofel during the strongest observed foehn event. An initial breakthrough in Innsbruck itself, with near-surface southerly winds, occurred only during a weak and shallow foehn event. Here winds were northwesterly at Patscherkofel, yet southerly at Patsch within the Wipp Valley.

- For cases with initial eastern foehn breakthroughs, winds within the CAP in Innsbruck tended to be westerly. These prefoehnic westerlies are explained as a compensating flow from regions with a deeper CAP to regions with a shallower CAP. Accordingly, prefoehnic westerlies were not observed during the weak event with an initial western breakthrough.

- A relationship was found between the difference in Froude number and profile-
mean potential temperature at the northern and southern profiles for the lowest \( \approx 300 \) m of the Inn Valley. The former is defined as the ratio of the near-surface wind speed in the Wipp Valley and the square root of the vertically integrated buoyancy within the Inn Valley CAP. Three flow regimes are identified based upon Froude number:

1. For \( \text{Fr} \lesssim 1 \), the northern profile is colder than the southern profile, suggesting a CAP tilt with increasing depth towards the north.

2. For \( 1 \lesssim \text{Fr} \lesssim 3 \), the northern profile is warmer than the southern profile and exhibits stronger temporal fluctuations than for \( \text{Fr} \lesssim 1 \). Meridional gravity wave asymmetry above the CAP (with higher pressure in the north), enhanced shear-induced vertical mixing in the northern CAP and flow deflection at the Nordkette are proposed as possible explanations for the warmer northern profile.

3. For \( \text{Fr} \gtrsim 3 \), the column-integrated buoyancy is weak and the CAP nearly entirely removed at the northern and southern profile. In such cases, foehn has established in large parts of Innsbruck and the difference in mean-profile potential temperature between the southern and northern profile is no longer a meaningful measure of CAP heterogeneity.

- For all IOPs except IOP 7, a nearly linear relationship is found between the difference in profile-mean potential temperature at the eastern and western profiles and the difference in pressure observed at the valley bottom in western Innsbruck, near the airport, and east of Innsbruck, in Thaur. The observed linear relationship appears to be slightly less steep than the theoretical linear relationship derived under the assumption that valley bottom pressure differences are entirely caused by differences in profile-mean potential temperature. Hence, the fraction of the surface pressure difference caused hydrostatically by CAP asymmetry remains quite constant for these cases. For IOP 7, the strongest foehn event, the linear relationship between pressure and potential temperature differences breaks down and large deviations from theory are observed. The reason for this may be an increased amplitude and non-stationarity of gravity wave asymmetry or a breakdown of the theoretical assumptions required for the linear relationship.

- CAP oscillations due to non-stationary dynamical forcing are proposed as causes of fluctuations in measured potential temperature with periods on the order of tens of minutes to more than an hour. Using shallow water theory and estimates of CAP depth and inversion strength from the early morning of 5 Nov
2017 (IOP 2), oscillation periods are estimated to be on the order of 20 minutes (meridional) and 100 minutes (along-valley). The theoretically estimated period for the meridional oscillation agrees reasonably well with observations. Kelvin-Helmholtz instabilities, growing during northward propagation at the foehn-CAP interface, may be the reason for large-amplitude shorter period fluctuations in potential temperature observed at the northern profile.
Bibliography


Acknowledgments

This work was supported by the Austrian Science Fund (FWF) and the Weiss Science Foundation under Grant P29746-N32. The PIANO field campaign was supported by KIT IMK-IFU, Austro Control GmbH, Zentralanstalt für Meteorologie und Geodynamik (ZAMG), Innsbrucker Kommunalbetriebe AG (IKB), Bergisel Betriebsgesellschaft m.b.H., Innsbrucker Nordkettenbahnen Betriebs GmbH, T-Mobile Austria GmbH, Unser Lagerhaus Warenhandelsgesellschaft, PEMA Immobilien GmbH, HTL Anichstrasse, Hilton Innsbruck, TINETZ-Tiroler Netze GmbH, Land Tirol, and the communities Patsch and Völs.

I would like to especially thank my advisor, Assoc. Prof. Dr. Alexander Gohm, for his helpful advice in structuring my thesis, as well as his thoroughness in proofreading and openness for discussion. Many thanks go to the remaining PIANO Team (Lukas Umek, Maren Haid, Helen Ward, Lukas Lehner) for the fruitful Tuesday meetings, and especially to Lukas Umek for his frequent assistance in saving HOBOs. Thanks to Assoc. Prof. Dr. Armin Heller for his instruction in differential GPS use, Maren Haid for helping with the GPS measurements, and to all the friends who offered emotional and technical support.
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