PROJECT DESCRIPTION

Introduction

We propose a numerical study to investigate selected aspects of thermally driven flows and cold-air pool development, using as an example the Grünloch basin in Austria. The work will be performed in collaboration with and will complement the work done by Dr. Manfred Dorninger at the University of Vienna, who plans to conduct field experiments at the Grünloch. The Grünloch is located on the Hetzkogel Plateau in the eastern Alps near Lunz in Austria (Fig. 1). Several small sinkholes of various sizes have formed in the limestone of the 1300-m MSL high Hetzkogel Plateau due to subsurface solution of the rock and collapse of the ground. The Grünloch is the largest of these sinkholes with a diameter of approximately 1 km and a depth of about 150 m. The basin floor (47.8203°N, 15.0453°E) is at an elevation of 1270 m MSL and has a diameter of 60-100 m. Slope angles on the basin sidewalls vary between 15° and 20°, with somewhat steeper angles on the northeast sidewall than on the southwest sidewall. The enclosed Grünloch is surrounded by a continuous ridgeline, with the highest peak being the Hühnerkogel (1651 m MSL) to the south. Three major passes intersect the surrounding ridgeline, the Ybbstaler Saddle to the southwest, the Seekopfalm Saddle to the east-southeast, and the Lechner Saddle to the northwest. The Lechner Saddle is the lowest pass (1324 m MSL or 54 m above the basin floor) and leads down to the Lechner Gorge (Lechnergraben) toward the Ybbs Valley. The Grünloch and other sinkholes on the Hetzkogel Plateau are known for the formation of strong nocturnal temperature inversions with extreme minimum temperatures, with the Grünloch holding the minimum temperature record for central Europe with -52.6°C.



Fig. 1: (a) Location of the Grünloch in the Austrian Alps marked by a red x. (b) Topography of the Grünloch with contour lines every 25 m. GL (Grünloch basin floor), LG (Lechner Gorge), LGS (Lechner Gorge Saddle), SAS (Seekopfalm Saddle), and YTS (Ybbstaler Saddle). (c) Photograph of the Grünloch.

The proposed research will study the following aspects of thermal flows and cold-air pools, which are based on previous observations in the Grünloch basin:

- Daytime thermally driven cross-basin flows: (1) the interaction of the cross-basin circulation with ambient synoptic and mountain-induced winds; (2) the influence of heterogeneous vegetation and snow coverage.
- Nighttime cold-air pools: (1) the interaction of the cold-air pools in the Grünloch basin with the ambient atmosphere, particularly through flows into and out of the cold-air pool through passes in the surrounding ridge; (2) the effect of vegetation coverage on the inversion strength and minimum temperatures in the basin.

Present state of knowledge

Basin atmospheres

Many large basins, often sites of human habitation, have been subject to meteorological research, e.g., the Great Salt Lake basin (Doran et al. 2002; Lareau et al. 2013), the Colorado Plateau basin (Whiteman et al. 1999), and the Columbia River basin (Whiteman et al. 2001; Zhong et al. 2001) in the United States; the Ljubljana basin in Slovenia (Rakovec et al. 2002), the Palma basin in Majorca (Cuxart et al. 2007), and the Duero basin on the Iberian Peninsula (Martinez et al. 2010) in Europe; the Lake Tekapo basin in New Zealand (McGowan and Sturman 1996; Kossmann et al. 2002; Zawar-Reza et al. 2004); and several basins in Japan (Magono et al. 1982; Kondo et al. 1989; Maki et al. 1986; Mori and Kobayashi 1996). Many observational and numerical studies conducted in basins have investigated the formation and destruction of cold-air pools that commonly form in topographically sheltered terrain (e.g., Magono et al. 1982; Whiteman et al. 2001; Rakovec et al. 2002; Lareau et al. 2013). Several studies have also looked at thermally driven circulations (e.g., McGowan and Sturman 1996; Banta et al. 2004; Zawar-Reza et al. 2004) and daytime boundary-layer evolution (e.g., Kossmann et al. 2002). Numerical studies have also used idealized basin topographies to study, e.g., cold-air pools (Vrhovec and Hrabar 1996) and flow over and around a basin (Soontiens et al. 2013).

Few projects have studied the atmosphere in small basins or sinkholes, which, however, can be extensively instrumented due their small size. The Grünloch itself has been the location of several meteorological studies during the last century and again more recently (Steinacker et al. 2007). A large field campaign was conducted in the Meteor Crater, Arizona, in 2006 (Whiteman et al. 2008a) and a short field campaign was also conducted in the Peter Sinks basin, Utah (Clements et al. 2003). Both the Meteor Crater and the Peter Sinks are similar in size to the Grünloch. In Japan, Iijima and Shinoda (2000) studied the formation of cold-air pools in a small, elongated basin with a basin floor of about 50 x 200 m.

Numerical simulations for small basin topographies are challenging because of the relatively high computer resources necessary to resolve the topography and the phenomena occurring within the basins. These resources have become available only recently. Errors induced by terrain-following coordinates in combination with the steep terrain that often surrounds the basins or sinkholes pose an additional challenge. Based on the observations in the Grünloch and the Peter Sinks, Zängl (2005) ran MM5 simulations to further study the cold-air pool development in sinkholes, particularly the importance of moisture removal from the atmosphere on the formation of extreme minimum temperatures. To properly resolve the topography and the cold-air pool he had to increase the dimensions of the topography compared to the instrumented sinkholes. The study of the Meteor Crater has been the impetus for several numerical studies of small, idealized basins, including studies on the effect of small-scale terrain on turbulence (Katurji et al. 2013), daytime thermally driven flows (Lehner and Whiteman 2012, 2013), the effect of nocturnal cold-air inflows (Kiefer and Zhong (2011) performed two-dimensional simulations.

Previous observations in the Grünloch basin

Meteorological research has a long history in the Grünloch and its surroundings. In 1927, a network of 13 microclimatic stations was installed in the mountains south of Lunz (Schmidt et al. 1929; Schmidt 1930; Lauscher 1937). The extreme minimum temperatures recorded in the Grünloch basin led to the further deployment of minimum thermometers between the winters of 1928/1929 and 1941/1942. Temperatures below –50°C occurred during 8 of these 14 winters, including the minimum temperature record for central Europe of –52.6°C, which was measured with a minimum thermometer left there between 19 February and 4 March 1932 (Aigner 1952; Geiger 1965). A few years later, Sauberer and Dirmhirn (1954, 1956) flew tethered balloons and took temperature measurements to study the inversion structure in the Grünloch basin, and Litschauer (1962) compared temperatures in different sinkholes of the Hetzkogel Plateau from thermograph recordings.

For the past 12 years, the University of Vienna has taken continuous temperature measurements in the Grünloch. The measurements started with a field campaign that took place between October 2001 and June 2002 (Steinacker et al. 2007). During the field campaign surface temperature measurements were taken at the floor and the lowest saddle of five different sinkholes on the Hetzkogel Plateau, including the Grünloch basin, and along lines up the northwest, southeast, and southwest sidewalls of the Grünloch and down into the Lechner Gorge. In addition, three automatic weather stations were operated at the floor of the Grünloch, at the Lechner Saddle and at the peak of the Kleiner Hühnerkogel and tethersondes were flown during two nights in early June. Data from this experiment have been used to compare temperature measurements along the sidewalls with temperature profiles from the tethersondes (Whiteman et al.

2004c); to compare minimum temperatures and temperature inversion strengths in the five instrumented sinkholes from two nights, with and without snow cover (Whiteman et al. 2004b); to look at the effects of moisture on the development of the nocturnal inversions (Whiteman et al. 2007); and to calculate time scales for the development of the nocturnal boundary layer in different basins and valleys and over plains (De Wekker and Whiteman 2006). Whiteman et al. (2004a) compared the morning breakup of cold-air pools in the Peter Sinks and in the Grünloch and found that the time necessary for the complete breakup of the nocturnal inversion is shorter in both basins than in valleys or larger basins because of a smaller heat deficit. Because of the drier climate in Utah the observed temperature inversion in the Peter Sinks was much stronger than in the Grünloch but the equally stronger heat flux in the morning led to similar breakup times and to an inversion breakup by subsidence and convective-boundary layer growth from the surface, while the inversion in the Grünloch was destroyed by subsidence alone. The surface temperature measurements along the sidewalls were analyzed by Dorninger et al. (2011) to characterize the nocturnal cold-air pools by their temporal evolution depending on their interaction with ambient winds and turbulence.

Three additional short field campaigns were conducted by the University of Vienna in 2008, 2009, and 2011 as part of student classes. Surface temperature and wind measurements were taken during all three field campaigns. Tethersondes were flown in 2008 and 2011. During the last experiment, energy balance components were measured and a sodar was operated at the floor of the Grünloch. No numerical simulations, however, have ever been performed for the Grünloch.

Thermally driven cross-basin flows

Thermally driven cross-basin or cross-valley flows occur when one sidewall receives more solar irradiation than the opposite sidewall. The resulting temperature difference between the two sidewalls produces a horizontal pressure gradient, which then drives the cross-valley or cross-basin flow toward the more irradiated sidewall (Lehner et al. 2011; Lehner and Whiteman 2013). Cross-valley flows have been shown to affect air-pollution transport in valleys (Whiteman 1989). They are generally difficult to observe because of the relatively weak wind speeds [on the order of 1 m s⁻¹ in the Meteor Crater (Lehner et al. 2011) or 5 m s⁻¹ in the Dischma Valley, Switzerland (Hennemuth 1986)] compared to typical along-valley wind speeds. Sometimes cross-valley winds are only observed as a deflection of the upvalley flow toward the more irradiated sidewall (De Wekker et al. 2005). Hennemuth and Schmidt (1985) observed the most pronounced cross-valley flows during the morning transition period when along-valley winds are comparatively weak. In enclosed basins, cross-basin winds can develop in the absence of along-valley circulations and can thus be more easily studied. Lehner et al. (2011) showed the diurnal evolution of the cross-basin circulation in Arizona's Meteor Crater. Model simulations of the cross-basin circulation in

idealized basins showed that the strongest cross-basin flows occur in basins of a similar size to the Meteor Crater and that in wide but shallow basins the cross-basin pressure gradient becomes too weak to produce a persistent cross-basin flow (Lehner and Whiteman 2012).

The Grünloch is similar in size to the Meteor Crater so that the development of relatively strong crossbasin flows can be expected. Indications of cross-basin flows have already been observed during previous experiments in the basin during winter. Soundings taken in October, however, did not reveal a cross-basin circulation but rather a turbulent, well-mixed basin atmosphere. Simulations of the cross-basin flow for an idealized basin similar to the Meteor Crater also suggest that the cross-basin circulation is best developed in the morning under stable conditions and that particularly the flow above the surface layer is strongly influenced by convective eddies and by background winds above the basin, if present, once the basin atmosphere is completely mixed (Lehner and Whiteman 2012). Dr. Dorninger at the University of Vienna is planning a small field campaign in April 2014, specifically designed to investigate the occurrence of cross-basin circulations in the Grünloch. At this time of the year part of the basin is usually still covered by snow, while the snow has already melted on the more sun-exposed sidewalls. The partial snow cover is favorable for the formation of strong cross-basin irradiation and temperature differences.

Specific questions that will be addressed in this study:

- Simulations have shown that the interaction between the cross-basin circulation and background winds above the basin depends strongly on the angle between the cross-basin flow forcing (i.e., the cross-basin temperature or pressure gradient) and the direction of the background winds (Lehner and Whiteman 2012). The Grünloch is embedded into the complex topography of the northeastern Alps (Fig. 1), which can produce additional thermal circulations as well as modify synoptic winds. This allows an investigation of the possible interactions between the cross-basin circulation and other flows of different scales occurring in this area.
- In contrast to Arizona's Meteor Crater the vegetation in the Grünloch is strongly variable (Steinacker et al. 2007), with a small pond and grasses on the floor, dwarf pines on the lower slopes, and tall conifers on the higher slopes in addition to a likely inhomogeneous snow cover in spring. How does this complex distribution of surface characteristics impact the cross-basin circulation? Modeling studies by, e.g., Shapiro and Fedorovich (2007) and Lehner and Gohm (2010) have also shown that variations in the surface conditions with elevation can produce changes in the mass flux in the slope-wind layer and cross-valley flows due to mass conservation. What is the resulting cross-basin circulation if flows due to cross-basin temperature differences and due to heterogeneous surface conditions interact?

Cold-air pools and their response to flows through passes and saddles

Whiteman et al. (2001) define a cold-air pool as a "topographically confined stagnant layer of air that is colder than the air above" and distinguish between diurnal cold-air pools, which last only for one night, and persistent cold-air pools, which persist for more than one day. In inhabited valleys and basins cold-air pools, particularly persistent cold-air pools, can lead to the accumulation of air pollutants near the ground (e.g., Pataki et al. 2005; Malek et al. 2006; Silcox et al. 2012), which can affect visibility (Reddy et al. 1995) and human health. Additional orographic lifting produced by the presence of cold-air pools in valleys or basins can modify the distribution of precipitation in mountainous terrain (Hill 1993; Reeves and Lin 2006). Daly et al. (2010) have also shown that cold-air pools can affect the local impact of climate change.

The initiation and destruction of cold-air pools have received most attention in the literature. Nocturnal or diurnal cold-air pools form in the evening or late afternoon after sunset, when radiative and sensible heat flux divergence cool the atmosphere in topographic depressions (Clements et al. 2003; Hoch et al. 2011). While some studies attributed at least part of the cooling process to cold-air advection by the drainage flows along the sidewalls (e.g., Magono et al. 1982; Maki et al. 1986), Bodine et al. 2009 observed an upward-pointing along-slope temperature gradient, which would produce a warm-air advection by drainage flows. Sheltering by the surrounding topography reduces the heating from turbulent mixing (Vosper and Brown 2008; Sheridan et al. 2013; Vosper et al. 2013). Observations along a small slope in Oklahoma by Bodine et al. (2009) suggested that even vegetation can produce a similar sheltering effect. Persistent cold-air pools are often produced by warm-air advection above the surrounding topography, which can trap cold air near the surface thus producing a cold pool (Whiteman et al. 1999, 2001). Similarly, several mechanisms have been identified that can contribute to the weakening or destruction of cold-air pools, including diurnal heating (e.g., Vrhovec and Hrabar 1996; Whiteman et al. 1999, 2001; Zhong et al. 2001), cold-air advection above the cold-air pool (e.g., Vrhovec and Hrabar 1996; Whiteman et al. 1999, 2001; Zhong et al. 2001), warm-air advection at the surface (Whiteman et al. 2001), cold-air drainage from the cold pool (e.g., Whiteman et al. 1996; Zängl 2005) and turbulent erosion (e.g., Vrhovec and Hrabar 1996; Rakovec et al. 2002; Zhong et al. 2003).

Field campaigns designed to study various aspects of cold-air pools have been conducted in valleys and basins of different size. For example, in the Salt Lake Valley, Utah, the Persistent Cold-Air Pool Study (PCAPS) was conducted in winter 2010/2011, which focused on persistent cold-air pools (Lareau et al. 2013), and the Vertical Transport and Mixing (VTMX) program in 2000, which focused on mixing and transport mechanisms under stable conditions (Doran et al. 2002). On a smaller scale, the Meteor Crater Experiment (METCRAX) studied cold-air pools in a small crater basin in Arizona (Whiteman et al.

2008), while the Cold-Air Pooling Experiment (COLPEX) studied cold pools and associated fog formation in a small valley system in England (Price et al. 2011).

While many numerical studies have successfully simulated cold-air pools and have contributed to the current knowledge on cold-air pools (e.g., Vrhovec and Hrabar 1996; Rakovec et al. 2002; Zängl 2003, 2005; Vosper and Brown 2008; Katurji and Zhong 2012; Vosper et al. 2013), several studies have revealed the existing difficulties in correctly reproducing temperature inversions with numerical models, which often underestimate the strength of near-surface inversions (e.g. Fast et al. 1996). This underestimation of the inversion strength leads to errors in temperature forecasts in valleys, predicting too high temperatures during cold-pool episodes (Hart et al. 2004). Simulations of persistent cold-air pools in the Yampa Valley, Colorado, by Billings et al. (2006) pointed to the importance of horizontal resolution in properly resolving cold-air pools in narrow valleys. Hart et al. (2005), however, showed that an increase in horizontal resolution does not improve temperature forecasts in valleys if the model is not able to reproduce the cold pool. Another error source in simulating cold pools is the turbulent mixing parameterization. Zängl (2002) showed that horizontal diffusion along terrain-following model levels can produce errors in the simulation of temperature inversions and suggested that horizontal diffusion be calculated on truly horizontal surfaces.

Despite the extensive available literature on various aspects of cold-air pools and temperature inversions in complex terrain, there is little knowledge on the effect of small passes or saddles in the surrounding terrain, which allow an interaction of the cold-air pool air with the ambient atmosphere. Measurements taken in the Grünloch in 2001/2002 revealed the presence of a cold-air outflow through the Lechner saddle to the northwest (Pospichal et al. 2003). The Lechner saddle is the lowest pass in the relief surrounding the Grünloch, 54 m above the basin floor. Constant southeasterly winds with wind speeds of about 1 m s⁻¹ were observed at the saddle during clear-sky nights (Fig. 2). Soundings taken in the center of the basin also show southwesterly winds in a less stable layer above the strong temperature inversion, which forms below the height of the Lechner Saddle. The existing observations suggest that drainage flows forming on the basin sidewalls due to surface cooling do not have enough negative buoyancy to penetrate the extremely stable layer but are deflected away from the slope along the top of the inversion toward the northwest. In addition to the outflow over the Lechner saddle, an inflow of cold air over the Seekopfalm saddle into the Grünloch was also observed (Whiteman et al. 2004c). Simulations by Zängl (2005) showed the importance of cold-air outflow in removing valley cold-air pools for an Alpine valley system. Inflows of cold air into a basin, which affect the temperature structure within a cold-air pool, have also been observed at Arizona's Meteor Crater (Whiteman et al. 2010; Haiden et al. 2011). Clements et al. (2003), on the other hand, observed only a very weak flow through a gap that connects the two sub-basins

of the Peter Sinks.

While frequent minimum temperatures below -50°C were measured in observations during the first half of the last century, no similarly low minimum temperatures were recorded during the measurements of the past decade. One hypothesis is that this is caused by changes in vegetation in the Grünloch basin. While the slopes used to be only sparsely covered by trees, they are now more heavily forested. A parametric study is ideally suited to evaluate the effect of changes in vegetation cover on the strength of cold-air pools and minimum temperatures. Kiefer and Zhong (2013) studied the effect of forested valley sidewalls on drainage flows and the cold-air pool formation in large, idealized 2D valleys. They found that the cold-pool strength was diminished in the presence of forest cover, particularly if the forest covered the lower parts of the valley.



Specific questions to be addressed in this study with respect to flows out of and into the cold pool are:

- How deep is the outflow layer? Does its depth vary with time? When does the outflow start with respect to the evolution of the cold-air pool?
- What is the temperature difference across the saddle? Is the outflow driven by a pressure gradient, which is caused by a temperature difference, or do the drainage flows on the opposite side, which cannot penetrate into the strongly stable layer, simply flow over the top of the inversion as suggested by the existing observations?
- Does the outflow affect the basin inversion and, if so, how? Does the outflow limit the growth (depth and strength) of the inversion formed in the basin? If the outflow is produced by drainage flows from the sidewall running over the inversion, does the inversion remain unaffected or is there some detrainment/entrainment occurring at the top of the inversion that produces some erosion of the

inversion?

- If the outflow is produced by cold air from the inversion layer draining out of the basin similar to water flowing over the edge of a container, is there an equivalent inflow of air? Is the outflow identical to the total drainage flow coming down the sidewalls adding to the cold-air pool filling the basin? Does the energy associated with the inflow and the outflow balance or do these inflows and outflows contribute to the energy balance of the cold-air pool? What are the budgets of the different inflows/outflows?
- What is the effect of changes in vegetation cover on the strength of cold-air pools and minimum temperatures in the Grünloch?

Proposed research plan

We propose a numerical study, which will be performed in connection with a two-part field campaign in the Grünloch conducted by Dr. Manfred Dorninger at the University of Vienna. The first and smaller part of the field campaign in April 2014 will focus on the cross-basin circulation. The second and larger part of the field campaign will be conducted in winter 2014, part of which will focus on cold-air pools. Dr. Dorninger is currently writing a research proposal to the Austrian Science Fund to seek funding for this project. While the numerical study will strongly benefit from the measurements collected during this planned field campaign, it does not necessarily rely on the success of it since measurements from previous field campaigns at the Grünloch in 2002/2003 (Steinacker et al. 2007), 2008, 2009, and 2011 are available for model comparison.



Fig. 3: Initial model simulation for the Grünloch basin. Cross section of the eastwest wind component (color shading) and potential temperature (contour lines) through the Grünloch and the Lechner saddle to the left. The simulation shows a stable layer in the Grünloch and an outflow over the Lechner saddle on top of the stable layer.

The numerical simulations will be performed with the WRF (Weather Research and Forecasting; Skamarock et al. 2008; Skamarock and Klemp 2008) and the CM1 (Cloud Model 1; Bryan and Fritsch 2002) models. Both WRF and CM1 are non-hydrostatic models, which use terrain-following coordinates in the vertical. The model codes are written for parallel-computing platforms. Three compute clusters are

available for this research at the University of Utah's Center for High Performance Computing. WRF is ideally suited for case studies because it can be initialized from a large-scale model forecast or reanalysis and the model fields can be nudged towards the large-scale forecast or reanalysis at the lateral boundaries. Due to its nesting capabilities, a wide range of resolutions can be achieved within one model run. Multiple physics packages are available, which can be chosen depending on the application. WRF has been used by Dr. Lehner on a similar spatial scale for LES studies of thermally driven flows in Arizona's Meteor Crater (Lehner and Whiteman 2012, 2013) and its use in high-resolution simulations within complex terrain has also been documented by other investigators (e.g., Catalano and Cenedese 2010; Catalano and Moeng 2010). CM1 is ideally suited for idealized simulations, which focus on individual mechanisms. CM1 is currently used for simulations of the Meteor Crater (Lehner et al. 2013b) and we have performed initial simulations with CM1 for the nocturnal development in the Grünloch basin (Fig. 3).

The model simulations will be designed to answer the following questions, most of which have already been described in detail in the previous sections.

- Model performance: How well do the numerical models perform in simulating the extremely strong temperature inversions in this complex terrain? Our initial simulations have already indicated that this is an extreme situation that provides a challenging task for numerical models. We will compare the simulations with existing observations from the previous field measurements at the Grünloch and with the observations taken during the planned field campaign. Based on this comparison we will identify the numerical processes that are crucial to correctly simulating the cold pool.
- *Cross-basin flows*: What are the seasonal differences in cross-basin flows? Simulations for the month of April, when the field campaign is planned, will be compared with simulations for other months, for which no cross-basin flows have been observed so far. What are the interactions of the cross-basin circulation with circulations of different scales occurring in the complex terrain? The impact of relevant phenomena will be quantified through a series of well-designed parametric experiments in which different topographic or synoptic influences are turned on and off. How does the inhomogeneous vegetation and snow coverage affect the thermally driven cross-basin circulation?
- *Cold pools:* What is the effect of changed vegetation cover on the inversion strength and minimum temperatures in the Grünloch? A parametric study will be performed with modified vegetation coverage to evaluate the effect of the presence or absence of trees in and around the basin. The spatial and temporal extent of the inflows and outflows through the gaps surrounding the Grünloch and their effect on the cold pool will be determined. Detailed budgets of the outflows and inflows will be calculated, which will provide a higher spatial and temporal resolution than is possible from observations. Once all the contributing interactions with the ambient atmosphere are identified,

simulations with an idealized topography will be performed to reduce the terrain complexities and to focus on each of the interactions individually.

Personnel and schedule

Dr. Manuela Lehner, Postdoctoral Research Associate at the University of Utah, will be the Principal Investigator. Dr. Lehner has previous experience in high-resolution numerical modeling in complex terrain of a similar spatial scale as the Grünloch. Dr. C. David Whiteman, Research Professor at the University of Utah, will be a co-PI. Dr. Whiteman has extensive experience in the research of cold-air pools and thermally driven flows in complex terrain (e.g., Whiteman 2000, Whiteman et al. 2008a, Zardi and Whiteman 2012) and participated in the last field campaign in the Grünloch in 2002 (Whiteman et al. 2004a,b,c).

The first task of the numerical study will be to evaluate the model performance based on comparisons with the observational data from the field campaigns. Based on previous experience, this part will take about six months. In the second stage of the study, the production runs will be performed and analyzed and the results will be prepared for publication. We anticipate that two papers will be published from this work. We will have a meeting with our collaborators at the University of Vienna during the first year of this project and we will invite Dr. Dorninger to another meeting at the University of Utah during the second year.

Intellectual merit and broader impacts

Intellectual merit

The findings from this study will advance the present knowledge on cold-air pools and thermal flows in mountain basins and how they respond to variations in vegetation and snow coverage and how they interact with the ambient atmosphere, particularly through inflows and outflows through passes and saddles in the surrounding ridgeline. The availability of observational data for model comparison will allow the identification of important physical and numerical mechanisms for correctly modeling strongly stable layers in extremely complex terrain such as the Alps and the Rocky Mountains.

Broader impacts

Most basins, including inhabited basins, are surrounded by inhomogeneous terrain with several passes and outlets in the ridgeline. The results from this study will improve the understanding of basin atmospheres, specifically of thermally driven flows and cold-air pools in such extremely complex terrain. Thermally driven flows and cold-air pools are known to affect human populations in complex terrain through effects such as air pollution transport and dispersion and the creation of transportation hazards because of reduced visibility due to the presence of air pollutants or fog.

Results from the study will be made available through presentations at international conferences, publications in peer-reviewed journals, and invited seminar presentations and lectures. A website will be created to make results more accessible to the general public. Research results will be incorporated into graduate and undergraduate mountain meteorology classes taught by Dr. Whiteman at the University of Utah.

Investigator diversity is promoted by the gender and nationality of PI Manuela Lehner, who is an Austrian citizen.

Collaborations

The proposed study is based on an invitation from Dr. Manfred Dorninger, Assistant Professor at the University of Vienna, Austria, to collaborate on a meteorological study in the Grünloch. Dr. Dorninger is currently writing a research proposal to the Austrian Science Fund FWF to seek funding for a two-part field campaign at the Grünloch. He participated in a previous field campaign in the Grünloch in 2002 (Whiteman et al. 2004a, Steinacker et al. 2010, Dorninger et al. 2011) and has collected data continuously in the Grünloch since this field campaign. The two research groups at the University of Utah and the University of Vienna will work closely together to enhance the scientific outcome of the projects by combining the observational study and the modeling study. A letter from Dr. Dorninger is attached to this proposal.

Summary

We propose a numerical study to investigate thermally driven flows and cold-air pools in the small basin of the Grünloch in Austria. Thermally driven flows and cold-air pools in mountainous terrain affect, among others, air pollution transport and dispersion and fog formation, impacting human habitations in mountain valleys and basins. The proposed work will be conducted in collaboration with scientists at the University of Vienna, Austria, who have collected data in the Grünloch over the past 12 years and have extensive experience with the local meteorological conditions in the area. They are currently writing a proposal to the Austrian Science Fund to seek funding for another larger field campaign in the Grünloch. The co-PIs have the necessary knowledge in thermally driven flows, cold-air pools and numerical modeling in complex terrain to conduct this research and have adequate computer and other resources for this research. Several well-defined research questions have been formulated that can be answered by the planned model experiments during the 2-year project.

Results from prior NSF support

C. David Whiteman

(a) Award # AGS-0837870, \$616,846, 1 Jan 2009 - 31 Dec 2011. This award followed NSF award ATM-0444205 that funded the field program at Meteor Crater in 2006 and subsequent initial analyses and publications.

(b) "Collaborative research: The diurnal evolution of stable boundary layers in an enclosed basin"

(c) Scientific accomplishments include 1) discovery of near-continuous shallow cold air intrusions over the crater's rim (Whiteman et al. 2010). These intrusions produce unusual temperature profile evolution, including the development and nighttime maintenance of a near-isothermal temperature structure in the upper 75% of the crater atmosphere, 2) development of a mass-flux model that successfully explains the unusual temperature structure (Haiden et al. 2011). Co-PI Dr. Sharon Zhong at Michigan State University has extended this work by making numerical simulations with the ARPS model (Kiefer and Zhong 2011), 3) discovery of downslope-windstorm-type flow events that affect the upwind inner sidewall of the crater and produce warm air intrusions into the crater atmosphere (Adler et al. 2011), 4) determination (with ARO funding) of the role of longwave radiative flux divergence in nighttime atmosphere cooling in basins and valleys of different size, with a real-case simulation of Meteor Crater (Hoch et al. 2011), 5) determination of the physical processes leading to the evening transition between upslope and downslope flows on a Meteor Crater sidewall (Martinez et al. 2013), 6) assessment of the role of the Topographic Amplification Factor in basin cooling (Hahnenberger 2008), 7) study of the relationship between turbulence levels inside and outside the crater (Fu et al. 2010), 8) determination of the topographic effects on the surface radiation balance inside the crater (Hoch and Whiteman 2010), 9) assessment of regional scale drainage flows over the adjacent plain (Savage et al. 2008), and 10) determination of the causes and characteristics of thermally driven cross-basin flows (Lehner et al. 2011; Lehner and Whiteman 2012, 2013), 11) development of a radiation and surface energy budget model for Meteor Crater (Hull 2013). Additionally, with a German colleague, we modified a Monte Carlo radiative transfer model to improve performance in simulating radiative transfer in mountainous terrain (Mayer et al. 2010). We produced an overview of Meteor Crater meteorology for a general audience (Whiteman et al. 2008a) and have written a research article with Austrian scientists on meteorological events that affect basin temperature structure (Dorninger et al. 2011). We co-wrote a book chapter on thermally driven flows (Zardi and Whiteman 2012).

Broader impacts: We developed and maintained a METCRAX website for a general audience (www.inscc.utah.edu/~whiteman/METCRAX/), produced a poster displayed at the Meteor Crater Visitors

Center during the METCRAX 2006 experiment explaining the scientific goals of METCRAX and activities inside the crater, and we have prepared approximately 33 conference and seminar presentations. Through collaboration with a planetary geologist, we contributed a conference paper suggesting meteorological mechanisms that may be important for geological processes in Martian craters (Whiteman et al. 2008b). The field experiment itself and the resulting laboratory research activities have trained approximately 15 students in field and laboratory research. Several students have used the METCRAX datasets in class projects. Two master's degrees and one Ph.D. degree were completed using Meteor Crater datasets (Hahnenberger 2008, Lehner 2012, Hull 2013). We advised one post-doc, one Ph.D. candidate, several M.S. candidates and 3 visiting research scientists using the METCRAX datasets. We collaborated extensively with foreign scientists, and have hosted several scientists for extended stays at UU (Drs. Meinolf Kossmann, Thomas Haiden, Bernhard Mayer, Norbert Kalthoff, and Matthias Hornsteiner, as well as Mr. Dani Martinez, Ms. Bianca Adler, and Ms. Meike Zwanzger). We have also worked with foreign scientists hosted by co-PI Dr. Sharon Zhong, including Drs. Wenquing Yao and P. Fu. New meteorological research equipment purchased in connection with METCRAX, including a mini-SoDAR, is now being used by other research projects at UU. The MYSTIC Monte Carlo radiative transfer model, with our modifications for complex terrain simulations, is available as part of the libRadtran software package described by Mayer and Kylling (2005). Prof. Whiteman has made occasional presentations to NCAR COMET training courses, has produced a COMET Computer Based Learning Module, and has taught short courses featuring METCRAX results at the University of Vienna, the University of Trento and the University of Zagreb.

(d) Publications resulting from the two awards are indicated by asterisks in the reference list.

(e) METCRAX research findings are publicly available through journal publications and the project website. METCRAX data are available through the following NCAR and UU websites or by personal requests:

- http://www.eol.ucar.edu/deployment/field-deployments/field-projects/metcrax
- http://www.eol.ucar.edu/isf/projects/metcrax/iss/
- http://www.inscc.uta.edu/~whiteman/METCRAX/.

Manuela Lehner

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