# A SINKHOLE FIELD EXPERIMENT IN THE EASTERN ALPS

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Observations from a high-altitude limestone sinkhole have helped improve understanding of temperature inversion formation and minimum temperatures in basins.

Over the last 25 years, a series of studies has investigated the diurnal formation and destruction cycle of temperature inversions in valleys and basins (for a review see, e.g., Whiteman 1990). In most of the valleys and basins that have been studied to date, advective influences produced by the well-known, diurnally reversing up- and down-valley wind systems have greatly complicated the analyses (e.g., Maki and Harimaya 1988; Mori and Kobayashi 1996). Thus, in recent years some investigators have attempted to find experimental locations in mountain areas with sloping terrain where inversion evolution occurs in the presence of up- and downslope wind systems, and in the absence of the larger-scale up- and down-valley wind systems. An ideal location for these studies would be a naturally confined basin without an outlet stream or river in which a constant-elevation ridgeline completely encircles the basin. Geomorphologic analogs for such an idealized experimental environment include open pit mines, meteor craters, and sinkholes. Sinkholes, which form in many types of terrain, are most frequently found in karst topography where solution of the underlying rock results in the collapse of underground caverns or drainage channels. Idealized small sinkholes or *dolines* are a natural laboratory for the study of the formation, maintenance, and dissipation of temperature inversions, especially during fair-weather conditions when the sinkholes are isolated from flows aloft by the surrounding mountains and high atmospheric stability. In such conditions, sinkholes and small basins are well known in many parts of the world for producing extreme minimum temperatures, and thus for forming intense inversions.

This paper gives an overview of a set of temperature inversion experiments conducted from October 2001 to early June 2002 in a set of limestone sinkholes of different sizes and shapes on Austria's Hetzkogel Plateau (see Fig. 1). It provides a review of previous and recent experimental studies on this plateau, providing information on the design of the recent

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experiments, the topography, the instrumentation used, the wintertime snow cover, the synoptic weather conditions, and the initial meteorological analyses. Separate papers have already been published by the experiment participants that extend the basic research findings reported here. The observational data with a spatial and temporal resolution never achieved before allow for a much-improved quantitative investigation of the thermodynamic and dynamic processes in and above the sinkhole and represent the ideal basis for the validation of very high resolution simulation models.

**REVIEW OF LITERATURE.** Because literature on temperature inversions and heat loss in small basins was reviewed recently by Clements et al. (2003), we will concentrate our survey on the history of measurements on the Hetzkogel Plateau. The basis for research on this plateau was established in 1906 when Carl Kupelwieser opened the Biological Station in Lunz, Austria, (Sauberer 1952), a station where regular meteorological observations had been taken since 1898. The primary goal of the Lunz Biological Station was to explore the rivers and lakes in the area, because there are three lakes of completely different types very close to Lunz. Shortly thereafter, biology and bioclimatology investigations were extended into the mountains south of Lunz, the so-called Dürrensteinstock, a limestone plateau with an altitude of about 1200–1878 m MSL. In 1927, Franz Ruttner, the long-time director of the Biological Station, started to build up a microclimatic observation network with thermographs. In cooperation with Wilhelm Schmidt and the Central Institute for Meteorology and Geodynamics [Zentralanstalt für Meteorologie und Geodynamik (ZAMG)] in Vienna, a measuring network containing 13 stations was installed in the mountainous area south of Lunz (Schmidt et al. 1929; Schmidt 1930, 1933; Lauscher 1937). These stations were equipped with thermohydrographs and a total of six air and ground extreme thermometers, which were mounted at different heights. The thermographs were serviced once a week either on foot or, under harsh winter conditions, by skis to change the paper charts. In a short time, many interesting results were found in this diverse area. Particularly surprising were the data from the Gruenloch Sinkhole where, in the first winter, –46°C was recorded by thermometers, mounted at the wall of a wooden shelter in the deepest part of the basin. Because the reliability of the instruments was called into question at these temperatures different types of alcohol thermometers were installed. These measured even lower temperatures in the following winter. In the following years, microclimatic stations were set up at other locations in the area, including at the top of the highest mountain, Mount Dürrenstein (1878 m MSL). Because of the interesting results, minimum thermometers were operated in the Gruenloch for 14 yr in total (from 1928/29 to 1941/42). Readings of the minimum temperature were taken every 2–4 weeks, depending on weather conditions. In 8 of these 14 winters, temperatures below –50°C were recorded, with the lowest value being –52.6°C, which occurred between 19 February and 4 March 1932 (Aigner 1952). This temperature still stands as the lowest certified temperature minimum in Central Europe. Such extremely low temperatures appear to occur only when snow cover is present, because this minimizes the upward flux of heat from the ground, which normally helps to counter a net longwave loss from the sinkhole surface.

Meteorological measurements were suspended in the Gruenloch during World War II, but, during this time, the German armed forces used the sinkhole for testing engines under extreme conditions, similar to those in Siberia. After the war, Sauberer and Dirmhirn (1954, 1956) conducted new measurements in the Gruenloch, following up on Aigner's research with the objective

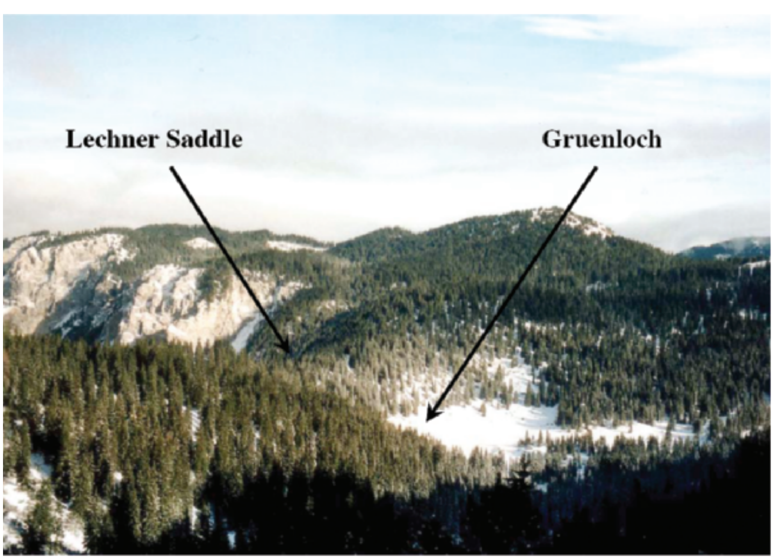

**Fig. 1. Photograph of the Hetzkogel Plateau taken from the Kleiner Huehnerkogel in November 2001 after the first snowfall of the season. View to the north-northeast.**

of investigating inversion structure in the Gruenloch with better instruments. Tethered balloons were used during two measuring campaigns in February/March 1953 and October 1954, and free-air measurements were compared with temperature measurements made on the basin's sidewalls. In addition, radiation balance measurements were taken and the wind distribution was studied using pilot balloons.

A few years later (1960/61), the Gruenloch area was again a target of meteorological research. Litschauer (1962) installed thermographs in several sinkholes of different sizes on the plateau and used the resulting temperature series as the basis for his dissertation on cold-air pools in alpine valleys and basins. His main goal was to compare basins and sinkholes with different geometries to determine the factors that lead to the buildup of extreme temperature inversions. He found relations between the depth, volume, and elevation of different sinkholes and minimum temperatures.

Meteorological research in the Lunz area diminished following Litschauer's work, because the research emphasis at the Biological Station changed to limnology. After 40 yr, a new era of research in this area has started, with cooperation between the landowner, Mr. P. Kupelwieser, the University of Vienna, and the Lunz Biological Station. The scientific aim was to use modern technology to collect a new dataset to be able to study still-open questions with regard to cold-pool formation and breakup. Since the winter season of 2001/02, temperature measurements have been taken continuously in the Gruenloch area. On a longer term the data will allow for an ideal comparison between historic and recent temperature minima in the light of global warming, because this location was, and still is, absolutely unaffected by human activity. Furthermore, it becomes possible with modern observation strategies to investigate the three-dimensional energy and mass budget within a sinkhole with a never-achieved accuracy. Is the turbulent erosion on top of the cold-air pool the most important factor that leads to an early nighttime temperature equilibrium, or are seiches with quasi-periodic swashing of air over the lowest saddle the way in which this is achieved? Are there slope winds still effective after inversion formation? Why is there hardly ever fog formation observed in the sinkhole despite a significant cooling below the evening dewpoint temperature? The instrumentation of sinkholes with different sizes and shapes, as well as the comparison to the results of field campaigns concerning sinkholes in other part of the world, promises a precise answer on how geometry, size, and climatic conditions determine the diurnal cycle of temperature. This is important to prove whether high-resolution numerical models are able to simulate the cooling and inversion breakup over complex terrain correctly.

**METHODOLOGY.** *The Gruenloch topography.* The study area (Fig. 2) is on the Hetzkogel Plateau, a limestone plateau in the eastern Alps approximately 5 km south of Lunz. The plateau contains many sinkholes,

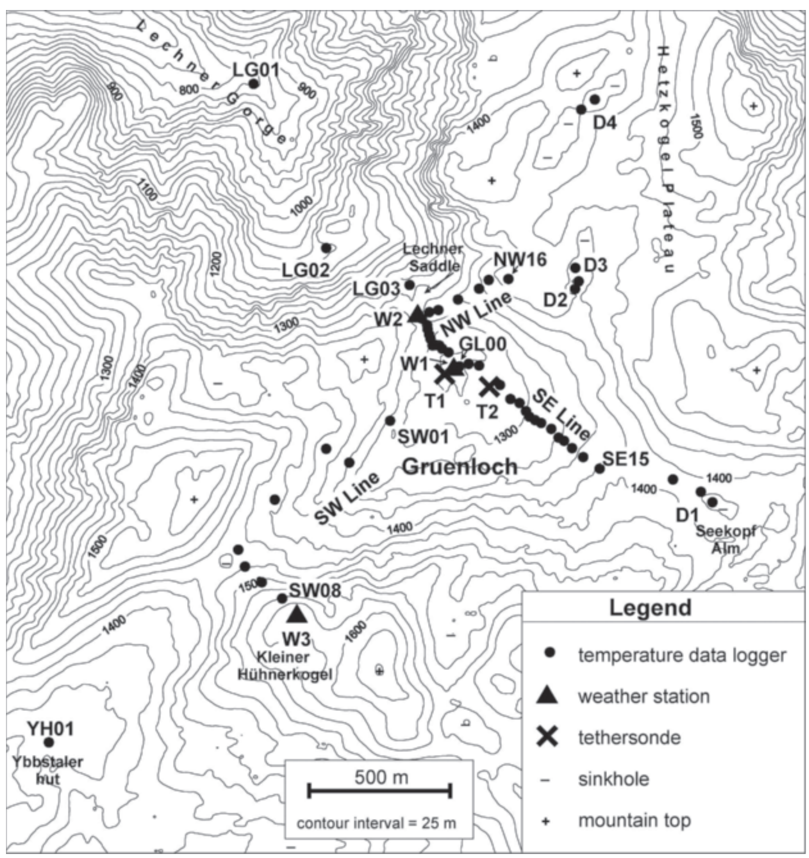


**Fig. 2. Topographic contour plot of a 2.5 km × 2.5 km area centered on the Gruenloch and showing the locations of the meteorological instruments used in the 17 Oct 2001–4 Jun 2002 experiments and in the 2–4 Jun 2002 intensive experiments. The minus signs indicate the centers of sinkholes; plus signs indicate peaks.**

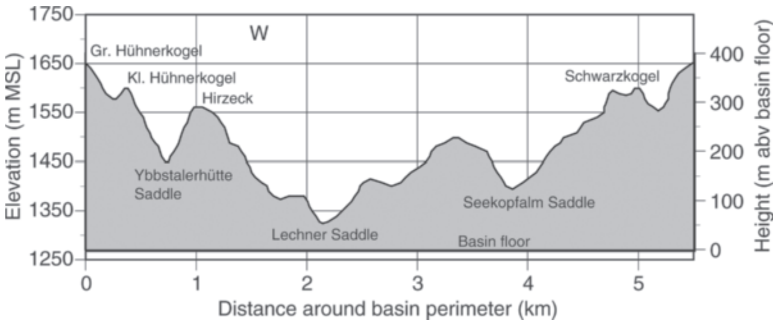


**Fig. 3. Ridge–crest elevation as a function of distance clockwise around the Gruenloch Sinkhole periphery.**

or *dolines,* of various sizes. The largest of the dolines is the Gruenloch (in previous literature this was called the Gstettner-Alm doline), a near-circular sinkhole of about 1-km diameter and approximately 150-m effective depth, with slope angles of 15°–20°. The ridgeline of this sinkhole (Fig. 3) is about 5.5 km in circumference. The lowest opening in the ridgeline, the Lechner Saddle (1324 m MSL), is 54 m above the floor (1270 m MSL) of the doline northwest of the basin center. On the far side of this saddle is the Lechnergraben [Lechner Gorge (LG)], which falls steeply into the adjacent Ybbs Valley, with a valley floor height of about 560 m MSL.

Other dolines of various sizes are found on the Hetzkogel Plateau (Table 1); in addition to the Gruenloch (D0), four of these (D1–D4) were instrumented. The next largest, the Seekopfalm, is located on a pass on the southeast edge of the Gruenloch. Two others (D2 and D3) are located side by side northeast of the Gruenloch, and a fourth doline (D4) is located north-northeast of the Gruenloch.

The plateau, a remote area inhabited by wildlife, is best known for its highest mountain, the Duerrenstein (1878 m MSL, some 3 km south of the Gruenloch). In summer, the pastures on the plateau are used for grazing cattle. No permanent habitations are found on the plateau, but a mountain hut [the Ybbstaler Hut (YH)], which is used mostly in summer, provides access to the Gruenloch via a 2-km hiking trail that crosses a saddle to the southwest of the sinkhole. Access to the Gruenloch in winter is either from the Ybbs Valley up a hiking trail through the Lechner Gorge, or up a road (winter trail) to the Ybbstaler Hut.

*The climate and vegetation of the Gruenloch.* The eastern Alps are in a temperate climate affected by both continental and maritime influences. The climate of the Hetzkogel Plateau is well known from extensive studies conducted over many years by the Lunz Biological Station (Lauscher 1937; Sauberer 1947, 1948). While the lowest elevations in the Ybbs Valley (e.g., Lunz) typically receive less than 1750 mm of precipitation annually, the average annual precipitation on the Hetzkogel Plateau is usually in the range from 2000 to 2750 mm (Sauberer 1947). Much of this falls as snow during the winter months. The average date of first snowfall at Lunz is 1 November, and continuous snow cover typically lasts there from 20 December through 3 March (Lauscher and Roller 1952). Continuous snow cover lasts considerably longer, approximately to mid-May, at the higher elevations of the Hetzkogel Plateau.

Because snowfall and snow cover are expected to provide important influences on the inversions that form in the sinkholes on the Hetzkogel Plateau, we have estimated (Fig. 4) the daily snow cover in the Gruenloch and at the passes in the Hetzkogel Plateau for the 17 October 2001 through 4 June 2002 experimental period from snow cover and snowfall data measured at Lunz and the surrounding mountaintop observatories (Rax and Feuerkogel; Table 2), considering wind direction, wind strength, and synoptic setting. The estimates were adjusted based on field experience from the monthly data-downloading visits to the Gruenloch.

**Table 1. Topographic characteristics of the five dolines.**

| Basin | Elevation of doline floor (m MSL) | Outflow depth h (m) | Diameter at h (m) | Drainage area below h (m²) | Volume below h (m³) | Total drainage area (m²) | Mean slope angle below h |
|---|---|---|---|---|---|---|---|
| D0: Gruenloch | 1270 | 54 | 600 | 295,000 | 7,000,000 | 2,120,000 | 11.7° |
| D1: Seekopfalm | 1368 | 26 | 250 | 51,000 | 550,000 | 245,000 | 12.5° |
| D2: Unnamed | 1393 | 7 | 45 | 1,600 | 2,700 | 313,000 | 12.2° |
| D3: Unnamed | 1381 | 19 | 75 | 4,440 | 19,300 | 313,000 | 29.5° |
| D4: Unnamed | 1372 | 22 | 76 | 4,560 | 41,000 | 334,500 | 32.3° |

The sinkholes on the Hetzkogel Plateau are formed in limestone bedrock. In the Gruenloch, where most of our experiments were performed, a deep humus layer is found on the basin floor, but bare limestone can be seen at places on the basin slopes. The low minimum temperatures at the sinkhole floor hinder the growth of trees. Only grasses and other subalpine herbaceous plants that can be covered by a well-insulating snow cover can survive such hostile conditions in winter. Despite the humid soil on the basin floor, which would otherwise be suitable for trees, tall conifers grow only on the crests of the basin and on the higher-elevation slopes. On the lower slopes, there is a sparse cover of dwarf pine trees, which one would normally find only at higher elevations at the same latitude. On the lowest point of the basin there is a small pond (less than 10 m in diameter) that contains water all year, but is snow covered in winter.

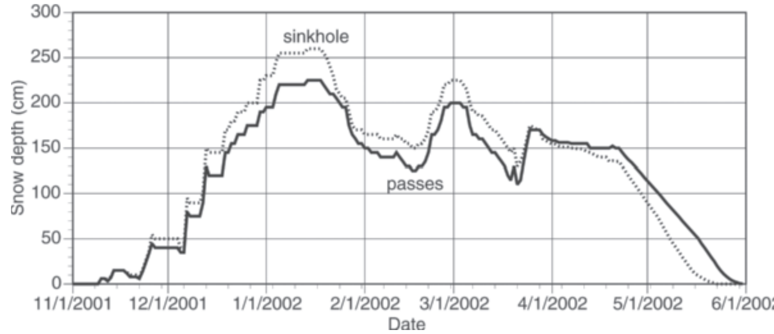


**Fig. 4. Mean snow depths (cm) in the bottom of the Gruenloch and on nearby passes for the winter of 2001–02, estimated from surrounding meteorological observatories.**

*Experimental design.* The experiments were designed to investigate the buildup and breakdown of tempera-

**Table 2. Instrument characteristics.**

| Instrument type | Manufacturer/model | Operating characteristics (from manufacturers) |
|---|---|---|
| Temperature dataloggers | Onset computer, Bourne, MA, Hobo H8 Pro series temp/ext temp | Thermistor, –40° to 100°C, accuracy: 0.7°C, resolution: 0.1°C, time constant: 2 min |
| Tethered balloon sounding systems | Atmospheric Instrumentation Research, Inc., Boulder, CO, TS3A | Dry-/wet-bulb thermistors, precision 0.5°C; relative humidity, precision ±5%; aneroid pressure, precision ±1 hPa; three-cup anemometer, precision ±0.25 m s$^{-1}$; wind direction, precision ±5° |
| Automatic weather stations | Vaisala Oyj, Helsinki, Finland, MAWS 201 | Three-cup anemometer, WMS302, threshold speed < 1.0 m s$^{-1}$, accuracy ±0.3 m s$^{-1}$ (< 10 m s$^{-1}$) or < 2% (>10 m s$^{-1}$), distance constant 2 m; wind vane, WMS302, 0°–360°, threshold < 1 m s$^{-1}$, accuracy ±3°; temp–RH, HMP45D probe, –40° to 60°C range, temp accuracy < ±0.3°C, RH accuracy ±2% (0%–90%RH) or ±3% (90%–100% RH); pressure, PMT16A, 600–1100 hPa, accuracy ±0.3 hPa; pyranometer, QMS101, 0.4–1.1 $\mu$m, nonstability < 2% yr$^{-1}$ nonlinearity < 1% to 1000 W m$^{-2}$, global radiation accuracy ±3% |
| Upward- and downward-looking pyrradiometers | Phillip Schenk, Vienna, Austria | Model 8111 pyrradiometer, 0.3–60 $\mu$m |
| Sonic anemometer | GILL WindMaster | Three-axis ultrasonic anomometer; wind speed: range 0–60 m s$^{-1}$, accuracy: 0–20 m s$^{-1}$, 1.5% rms, 20–35 m s$^{-1}$, 1.5%–3% rms; 30–60 m s$^{-1}$, 3% rms, resolution 0.01 m s$^{-1}$; direction: range 0°–360°; accuracy: < 25 m s$^{-1}$ ±2°, > 25 m s$^{-1}$ ±4°, resolution 1° |

ture inversions or cold-air pools in a confined topography where along-valley advection (a complicating factor) plays a minor or nonexistent role. Multiple dolines of different shapes and sizes were selected to determine the role of topography on cold-pool evolution. A dense network of meteorological instruments was used to monitor the diurnal inversion evolution over the October–June period to identify external events that affected the regular development of the inversion, including foehn winds, cloud cover, and frontal passages; and internal factors affecting the heat budget of the doline atmosphere, including soil moisture, snow cover, and fog. The spatial resolution was on the order of a few meters vertically along the slope of the dolines, with 5-min temporal resolution to detect sudden temperature changes. Special intensive observations were conducted on 2–4 June 2002 to investigate the detailed evolution of the vertical wind and temperature structure over the largest doline, to relate it to temperatures measured at the same time on the sidewalls, and to investigate the mechanisms leading to temperature inversion evolution.

*Instrumentation.* The meteorological instruments used in the sinkhole experiments and their operating characteristics are listed in Table 2. Locations of the instruments are shown in Fig. 2. The primary data came from a dense network of Hobo H8 Pro temperature dataloggers. These dataloggers (Hobos) are self-contained, battery-powered devices that use a thermistor sensor. Operational and laboratory tests for these dataloggers have been described by Whiteman et al. (2000). The datalogger locations and their periods of operation are shown in Table 3. Temperature dataloggers (Hobos) were installed primarily at the floors and lowest saddles of five dolines; on three main lines that ran up the sidewalls of the Gruenloch to the northwest (NW), southeast (SE), and southwest (SW) of the basin center; and on a line in the Lechner Gorge. The logger sites were named using two-digit identifiers (IDs) for the main lines (NW, SE, or SW), for shorter lines in either the LG or in smaller dolines (D1–D4), or for individual sites at the basin center (GL) or at the Ybbstaler Hut (YH). The two-digit ID is followed by a two-digit number running from the lowest to the highest site on each line. Where two instruments were at the same site but at different heights above ground a suffix indicates whether the instrument is in the upper (U) or lower (L) position. The Hobo thermistor sensors were exposed in RM Young six-plate radiation shields on wooden poles at heights of 1.4 m AGL. At several sites, however, additional Hobos (with a U suffix) were installed at 2.2-m height on the same poles. Data were sampled and stored at 5-min intervals. Heavy snowfall resulted in many of the Hobos being completely covered by snow for much of the winter, starting in mid-December, and some of the Hobos were buried so deeply that they could not be found for data downloading during the monthly visits to the sites. Hobos at sites SE01, NW06U, NW10U, SE14U, SW08, and YH01, because of their exposures or their placement at 2.2 m, were above the snow cover for most of the winter. By mid-April, most of the Hobos had emerged from the snowpack and almost all of the loggers were operational during the 2–4 June intensive observational period (IOP).

Additional measurements came from three automatic weather stations (W1, W2, and W3; see Fig. 2) that recorded temperature, relative humidity, wind speed, and wind direction at 1- or 5-min averaging intervals, depending on deployment date. The weather stations were located on the Gruenloch floor, on the Lechner Saddle, and on the Kleiner Hühnerkogel (a peak located high on the southwest sidewall of the Gruenloch). The operating characteristics of the automatic weather stations are given in Table 2. The three sites are identified in Table 4, along with the periods of record. Sensor heights were as follows: pressure at 1 m; temperature, humidity, and radiation at 1.5 m; and wind speed and direction at 2.5 m. A pyranometer was in use at one of the weather station sites. Heavy snow cover and cloudiness affected the operation of the weather stations occasionally when solar panels became covered with snow and could not recharge the station's batteries. Thus, the weather station data were intermittent throughout the winter, although they were operating well during the June IOP.

Tethersondes were operated in intensive experiments conducted on 2–4 June 2002. They recorded temperature, wet-bulb temperature, pressure, wind direction, and wind speed as the balloon ascended and descended through the basin atmosphere under operator control at speeds of typically 0.1–0.3 m $s^{-1}$. The operating characteristics are shown in Table 2. The locations and periods of record are provided in Table 4.

*The intensive observational period.* Observations during the intensive experimental period were primarily made during the nighttime periods of 2–3 and 3–4 June. The intensive observations in the Gruenloch during these nights supplemented the continuous measurements from the temperature datalogger and weather station networks. In these nighttime experi-

| **Table 3. Hobo locations and periods of record.** | | | | |
|---|---|---|---|---|
| **Site** | **Latitude** | **Longitude** | **Altitude (m MSL)** | **Periods of record (month/day)** |
| **Basin floor** | | | | |
| GL00D | 47°49'13.2" | 15°02'42.5" | 1270 | 10/17–06/04 |
| GL00U | 47°49'13.2" | 15°02'42.5" | 1270 | 10/17–11/16<br>05/21–06/04 |
| **Northwest line** | | | | |
| NW01 | 47°49'15.3" | 15°02'41.0" | 1275 | 10/17–06/04 |
| NW02 | 47°49'15.7" | 15°02'39.9" | 1282 | 10/17–04/04<br>04/18–06/04 |
| NW03 | 47°49'16.2" | 15°02'39.2" | 1287 | 10/17–06/04 |
| NW04 | 47°49'16.0" | 15°02'39.2" | 1294 | 10/17–01/30<br>05/21–06/04 |
| NW05 | 47°49'15.9" | 15°02'38.2" | 1299 | 10/17–06/04 |
| NW06D | 47°49'17.1" | 15°02'37.5" | 1304 | 10/17–06/04 |
| NW06U | 47°49'17.1" | 15°02'37.5" | 1304 | 10/17–06/04 |
| NW07 | 47°49'17.3" | 15°02'37.2" | 1309 | 10/17–06/04 |
| NW08 | 47°49'18.1" | 15°02'36.8" | 1315 | 10/17–06/04 |
| NW09 | 47°49'18.2" | 15°02'36.7" | 1320 | 10/17–06/04 |
| NW10D | 47°49'19.3" | 15°02'36.6" | 1324 | 10/17–01/30<br>05/01–06/04 |
| NW10U | 47°49'19.3" | 15°02'36.6" | 1324 | 10/17–06/04 |
| NW11 | 47°49'20.0" | 15°02'37.5" | 1332 | 10/17–03/09<br>03/29–06/04 |
| NW12 | 47°49'20.3" | 15°02'38.8" | 1337 | 10/17–03/09<br>04/18–06/04 |
| NW13 | 47°49'21.4" | 15°02'41.8" | 1350 | 10/17–03/09<br>04/18–06/04 |
| NW14 | 47°49'22.8" | 15°04'45.5" | 1370 | 10/17–03/09<br>05/21–06/04 |
| NW15 | 47°49'23.9" | 15°02'46.7" | 1392 | 10/17–03/09<br>04/18–06/04 |
| NW16 | 47°49'24.1" | 15°02'50.1" | 1412 | 10/17–03/09<br>04/18–06/04 |
| NW16G | 47°49'24.1" | 15°02'50.1" | 1412 | 10/17–02/08 |
| **Southeast line** | | | | |
| SE01 | 47°49'14.1" | 15°02'43.1" | 1275 | 10/17–06/04 |
| SE02 | 47°49'14.6" | 15°02'44.9" | 1280 | 10/17–01/30<br>03/29–06/04 |
| SE03 | 47°49'11.8" | 15°02'49.4" | 1285 | 10/17–06/04 |
| SE04 | 47°49'09.7" | 15°02'53.1" | 1291 | 10/17–04/04<br>04/18–06/04 |
| SE05 | 47°49'10.1" | 15°02'53.7" | 1296 | 10/17–06/04 |
| SE06 | 47°49'08.4" | 15°02'54.8" | 1300 | 10/17–04/04<br>05/21–06/04 |
| SE07 | 47°49'07.8" | 15°02'55.4" | 1305 | 10/17–06/04 |
| SE08 | 47°49'07.5" | 15°02'56.0" | 1310 | 10/17–06/04 |
| SE09 | 47°49'07.2" | 15°02'56.9" | 1315 | 10/17–06/04 |
| SE10 | 47°49'06.3" | 15°02'59.0" | 1320 | 10/17–06/04 |
| SE11 | 47°49'06.4" | 15°03'00.4" | 1325 | 10/17–06/04 |
| SE12 | 47°49'05.4" | 15°03'00.8" | 1331 | 10/17–11/16<br>12/12–01/30<br>03/29–04/18 |

| Table 3. Continued. | | | | |
|---|---|---|---|---|
| **Site** | **Latitude** | **Longitude** | **Altitude (m MSL)** | **Periods of record (month/day)** |
| SE13 | 47°49'05.0" | 15°03'01.4" | 1340 | 10/17–01/30<br>03/29–06/04 |
| SE14D | 47°49'03.8" | 15°03'02.1" | 1360 | 10/17–06/04 |
| SE14U | 47°49'03.8" | 15°03'02.1" | 1360 | 10/17–06/04 |
| SE15 | 47°49'02.2" | 15°03'07.0" | 1378 | 10/17–04/04<br>05/21–06/04 |
| SE16 (=D103) | 47°49'00.4" | 15°03'21.0" | 1394 | 10/17–01/30<br>04/18–06/04 |
| **Southwest line** | | | | |
| SW01 | 47°49'07.0" | 15°02'30.2" | 1311 | 10/29–03/09<br>06/02–06/04 |
| SW02 | 47°49'02.1" | 15°02'23.6" | 1352 | 10/29–05/22<br>06/02–06/04 |
| SW03 | 47°49'03.7" | 15°02'19.6" | 1390 | 10/29–03/09<br>05/20–06/04 |
| SW04 | 47°48'57.4" | 15°02'10.5" | 1433 | 10/29–03/09<br>05/20–06/04 |
| SW05 | 47°48'50.6" | 15°02'03.8" | 1458 | 10/29–03/09<br>05/21–06/04 |
| SW06 | 47°48'49.3" | 15°02'05.2" | 1472 | 10/29–03/09<br>05/21–06/04 |
| SW07 | 47°48'14.8" | 15°02'09.2" | 1513 | 10/29–06/04 |
| SW08 | 47°48'45.5" | 15°02'11.9" | 1550 | 10/29–03/09<br>05/21–06/04 |
| **Lechnergraben** | | | | |
| LG01 | 47°49'49.0" | 15°02'08.8" | 800 (820?) | 10/17–12/12 |
| LG02 | 47°49'27.8" | 15°02'27.8" | 1100 | 10/29–04/04<br>04/18–06/04 |
| LG03 | 47°49'25.3" | 15°02'37.0" | 1270 | 12/12–06/04 |
| **Other dolines** | | | | |
| D101 | 47°48'57.8" | 15°03'27.8" | 1368 | 10/17–03/09<br>05/21–06/04 |
| D102 | 47°48'59.3" | 15°03'25.7" | 1382 | 10/17–03/09<br>05/21–06/04 |
| D103=SE16 | 47°49'00.4" | 15°03'21.0" | 1394 | 10/17–01/30<br>04/18–06/04 |
| D201 | 47°49'23.0" | 15°03'01.9" | 1393 | 10/17–03/09<br>05/21–06/04 |
| D202 | 47°49'24.0" | 15°03'02.6" | 1400 | 10/17–03/09<br>04/18–06/04 |
| D301D | 47°49'25.2" | 15°03'02.1" | 1381 | 10/17–03/09 |
| D301U | 47°49'25.2" | 15°03'02.1" | 1381 | 10/17–03/09<br>05/21–06/04 |
| D302 | 47°49'24.0" | 15°03'02.6" | 1400 | 10/17–11/16<br>04/18–06/04 |
| D401D | 47°49'46.8" | 15°03'05.9" | 1372 | 10/17–03/09 |
| D401U | 47°49'46.8" | 15°03'05.9" | 1372 | 10/17–03/09<br>05/21–06/04 |
| D402 | 47°49'44.9" | 15°03'03.3" | 1400 | 10/17–03/09<br>05/21–06/04 |
| **Other sites** | | | | |
| YH01 | 47°48'28.2" | 15°01'31.2" | 1344 | 10/29–06/03 |

| Table 4. Other instrument locations and periods of record. | | | | |
|---|---|---|---|---|
| Site | Latitude | Longitude | Elevation (m MSL) | Periods of record (month/day)* |
| W1: Gruenloch (same site as GL00) | 47°49'13.2" | 15°02'42.5" | 1270 | 10/17–10/25<br>11/06–11/11<br>11/13<br>11/16–12/08<br>01/29–02/21<br>02/22–03/29<br>04/18–06/04 |
| W2: Lechner Saddle (same site as NW10) | 47°49'19.3" | 15°02'36.6" | 1323 | 10/17–10/24<br>10/29–11/10<br>11/16–11/23<br>01/29–03/28<br>04/18–06/02 |
| W3: Kleiner Hühnerkogel (peak) | 47°48'47" | 15°02'19.0" | 1601 | 10/17–10/25<br>10/29–11/12<br>11/16–11/20<br>01/30–03/21<br>04/18–06/04 |
| T1: Gruenloch (same site as GL00) | 47°49'13.2" | 15°02'42.5" | 1270 | 06/02–06/04 |
| T2 (same site as SE03) | 15°02'49.4" | 47°49'11.8" | 1286 | 06/03–06/04 |
| Rax (peak) | 47°43' | 15°47' | 1546 | Continuous hourly |
| Feuerkogel (peak) | 47°49' | 13°44' | 1618 | Continuous hourly |
| BS: Lunz Biological Station (Ybbs Valley) | 47°51' | 15°04' | 614 | Continuous hourly |
| SA01: Sonic anemometer | 47°49'03.2" | 15°02'42.5" | 1335 | 1700:00 06/02–1551:00 06/04 |
| R1 (=W1): Pyrradiometers | 47°49'13.2" | 15°02'42.5" | 1270 | 06/02–06/04 |
| R2 (=W3): Pyrradiometers | 47°48'47" | 15°02'19.0" | 1601 | 06/02–06/04 |

*Weather stations collected 1-min data through 13 November (11/13), with 5-min data thereafter; tethersondes made continuous ascents/descents at chosen times, mostly during nighttime; routine hourly data came from the Rax, Feuerkogel, and Lunz Biological Station sites.

ments, two tethered balloon sounding systems (T1 and T2; see Fig. 2), three pairs of pyrradiometers, sonic anemometers, and other special supporting equipment were operated. The tethersondes made frequent (2–4 times per hour) up and down soundings of the nocturnal inversions. On the first night, one tethersonde was operated at site T1, starting at about 1832 Central European Standard Time (CEST) and ending the next morning at 0617 CEST. On the following night, two tethersondes were operated at sites T1 and T2 starting at about 1750 CEST and ending the next morning at 0704 CEST. Other supporting instruments used during the IOP included upward- and downward-looking pairs of Schenk pyrradiometers at the basin floor, the Lechner Saddle, and the Kleiner Hühnerkogel.

Synoptic weather conditions were somewhat different for these two experimental nights. For the 2–3 June period, the Lunz area was under a dry high pressure ridge that extended southward into the Alps from southern Sweden. Scattered stratocumulus and cumulus dissipated early in the evening, and the remainder of the night was undisturbed, with clear skies and weak synoptic winds, providing an ideal night for studying an undisturbed inversion formation. In contrast, the 3–4 June experimental period was somewhat disturbed. Lunz was in an area of weak pressure gradients, but with a weak warm front and moister air approaching from the west. Cirrus increased in the early evening to cover 4/8 to 7/8 of the sky between 1800 and 2200 CEST. The onset of the cirrus clouds was accompanied by a strengthening of the synoptic-scale wind, which kept the inversion from building as quickly as on the previous night. During this time, however, cooling continued at the floor of the Gruenloch, wisps of fog formed,

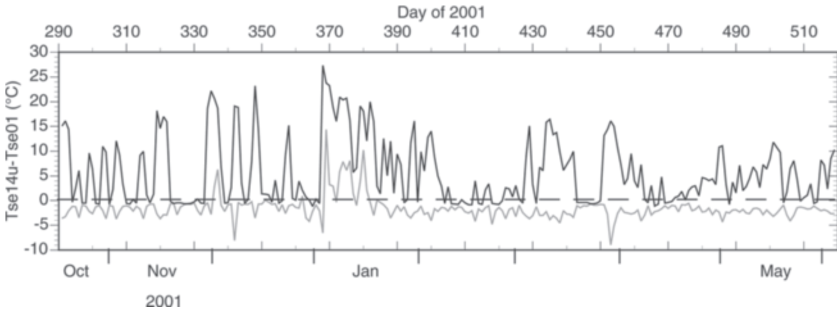


**Fig. 5. Time series of daily maximum (black line) and minimum (gray line) temperature differences of sites SE14U minus SE01 in the Gruenloch Sinkhole. Hobos at these sites were above the snow cover during the entire experimental period. SE01 is at an elevation of 1275 m MSL (5 m ABF), while SE14U is at an elevation of 1360 m MSL (90 m ABF).**

and the small pond began to steam. The cirrus band moved through, the winds in the Gruenloch weakened, and the cooling in the doline strengthened when the cirrus dissipated around 2200 CEST, leaving clear skies and light winds that persisted for the remainder of the night. At sunrise, the humidity in the cold pool was near saturation, patches of fog were present, and the entire floor of the doline was covered with rime. For reference, astronomical sunset occurred at 1946 CEST, while astronomical sunrise occurred at 0410 CEST.

**RESULTS.** In this section, we present a selection of basic results from analyses of the data.

*Minimum temperatures.* The extreme minimum temperature recorded during the winter deployment was −40.9°C at SE01, which was then 2.5 m above the snow-covered bottom of the sinkhole on 4 January 2002 following a fresh snowfall (Fig. 4). The total snow cover in the sinkhole was about 2.5 m deep. The minimum temperature probably would have been about 1°C lower at the lowest elevation station in the sinkhole (GL00), but it was buried under snow during this cold episode. The synoptic situation was governed by an intense high pressure cell over central Europe with weak winds in the eastern Alps region, which was built up after a frontal passage on 2 January 2002 with some fresh snow. The temperature in the free atmosphere on 4 January 2002 was not very low (approximately −20°C at 3000 m MSL), but was very dry (dewpoint temperatures at 3000 m were about −35°C).

*Inversion strengths.* Temperature inversions formed frequently in the Gruenloch throughout the experimental period and, even in midwinter, underwent regular daily buildup–breakup cycles. An indication of the relative strengths of the Gruenloch inversions throughout the experimental period is provided in Fig. 5, which shows the difference between the maximum and minimum temperatures, respectively, of sites SE14U minus SE01. These differences are the maximum and minimum differences determined from concurrent 5-min temperature values measured at the two sites between 1300 CEST on one day and 0900 CEST on the next. The two sites were separated by 85 m in the vertical and were above the snowpack all winter. Positive maximum values of temperature difference indicate that inversions formed on that day; negative minimum values on a given day indicate that the inversion was broken on that day.

Inversions formed in all seasons, but the highest frequency of formation in the experimental period was over snow-free ground in the fall and over fresh

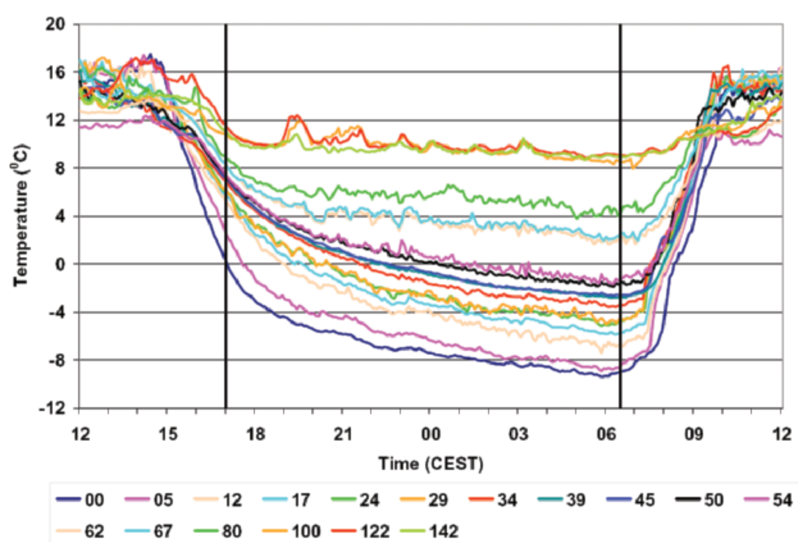


**Fig. 6. Temperature time series for 17 Hobos on the floor and sidewalls of the Gruenloch Sinkhole on 18–19 Oct 2001. The sites are at the floor (GL00D) and on the northwest line (NW01 through NW16). Elevations of the sites (m ABF) are shown in the legend. Vertical lines indicate the astronomical sunset (1704 CEST) and sunrise (0628 CEST).**

snow in the early winter. The strongest inversions generally produced temperature differences of 15°C or more over the 85-m elevation difference. The inversions were generally destroyed every day, except for multiday inversions that formed during a short period in early December and during a longer period in the early half of January. Fresh snow cover (Fig. 4) was present during these multiday events. In midwinter the bottom and the north-facing slopes of the sinkhole receive very little solar insolation, so that under a clear sky, fresh snow, and calm conditions there is insufficient energy flux to break up the inversion.

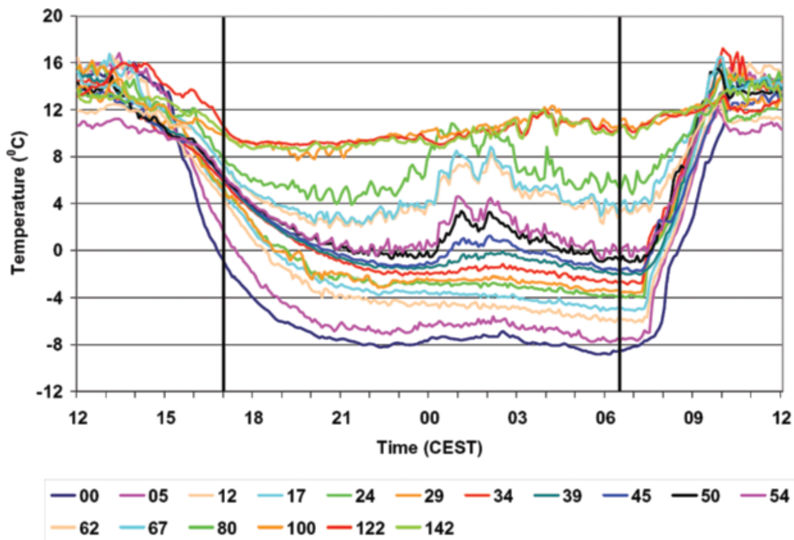


**Fig. 7. Same as Fig. 6, but for 19–20 Oct 2001.**

*Inversion buildup of 18–19 October (ideal night).* Temperature inversions built up in the Gruenloch and other sinkholes on many nights in all seasons. An example of inversion buildup in the Gruenloch during a clear, non-snow-covered period in the fall is shown in Fig. 6. Here, temperature time series are plotted for each of the Hobos from the NW line, as well as the Hobo on the basin floor at GL00D. On the floor of the sinkhole, temperatures dropped from 17°C in the midafternoon to –9°C by sunrise, for a diurnal temperature range of 26°C. The basin floor temperature fall, which was very rapid from 1500 to 1800 CEST, moderated after 1800 CEST. Temperatures at the upper altitudes of the sinkhole were isothermal and maintained a temperature of about 9°C through most of the night. Temperatures increased rather uniformly with altitude at about 0.15 K $m^{-1}$ between the floor and the upper altitudes of the Gruenloch. The very rapid breakup of the inversion after sunrise is indicated by the rapid warming at all sites and the homogenization of temperatures at all sites by about 0900 CEST. During the daytime, temperatures vary from site to site because of the varying exposures of the Hobos to sunlight and shadows from surrounding topography and trees. The basic diurnal temperature cycle in basins and sinkholes is known since 1921 when F. D. Young published his measurements from the Pomona Valley of California (Geiger et al. 2003). The high spatial and temporal resolution of the present experiments with extra measurements (Fig. 2) allows for additional insight into the microscale of the governing processes.

*Inversion disturbance of 19–20 October (upper disturbance).* The ideal case of an undisturbed night is relatively rare and could be observed in 8 out of 228 nights. An example for an upper disturbance is given in Fig. 7. The inversion buildup starts out quite similar to the previous night (Fig. 6); however, around midnight several temperature records show an increase of up to 6°C for about 3 h. This effect smoothes out for the lower-situated temperature probes, and finally at the basin floor the effect has almost disappeared. Also, the higher-elevated stations situated outside of the cold-air pool do not show any disturbances. We hypothesize that turbulent erosion resulting from increasing winds above the cold-air pool was responsible for this behavior.

*Inversion disturbance of 8–9 December (lower disturbance).* A different type of disturbance is presented in Fig. 8. On this date the area was snow covered. Around 1700 CEST the temperature at the basin floor started to rise by 5°C. The effect dampened out for higher elevations. This effect could be observed again around 0300 CEST, but was much weaker. Temporary cloud cover might be the reason for this behavior. Further investigations of the different possible types of disturbances are under way.

*Inversion breakup by subsidence, 4 June.* Nocturnal inversions in the sinkholes break up after sunrise showing patterns similar to those observed in deeper valleys (Whiteman 1982; Müller and Whiteman 1988), but the inversion breakup occurs over a shorter time period. The 4 June 2002 postsunrise breakup of the nocturnal temperature inversion

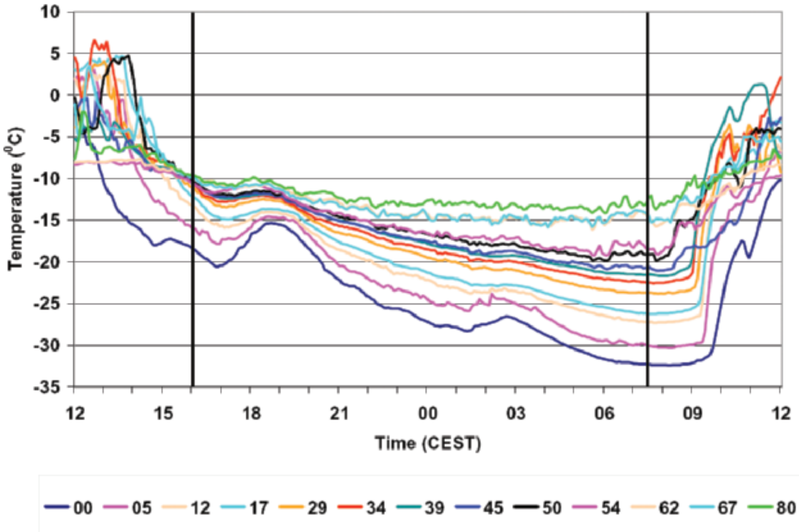


**Fig. 8. Same as Fig. 6, but for 8–9 Dec 2001. Vertical lines indicate the astronomical sunset (1607 CEST) and sunrise (0736 CEST). Note: Four Hobos have been snow covered.**

warming as a compensating response to slope wind circulations. Although the soundings were discontinued before the inversion was completely destroyed, the destruction was complete by about 0715 CEST. This pattern of inversion breakup was previously reported for deep Colorado valleys in winter when snow cover was present (Whiteman 1982). The very moist soil in the Gruenloch in June apparently reduces the rate of release of sensible heat flux so that the summertime pattern in the Gruenloch is similar to the wintertime pattern in the Colorado valleys.

in the Gruenloch is depicted in Fig. 9 from a series of tethersonde soundings. At about sunrise (0420 CEST), the nocturnal inversion had developed a linear temperature increase with elevation from −4°C at the floor of the sinkhole to +10°C at the top of the inversion 100 m above basin floor (ABF). The breakup was accomplished both by a descent at the top of the inversion and a more or less uniform rate of warming within it caused by subsidence

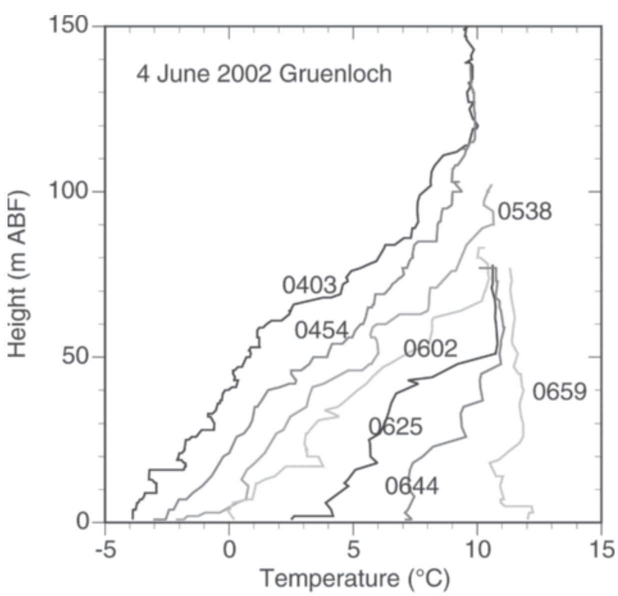


**Fig. 9. Tethersonde soundings from site T1 at the floor of the Gruenloch Sinkhole on the morning of 4 Jun 2002, illustrating the breakup of the nocturnal inversion. To reduce clutter in the figure only the tethersonde descents or down soundings are shown. The time of sunrise was at 0420 CEST.**

*Inversion breakup by turbulent erosion, 15–16 November.* A single episode of inversion destruction by turbulent erosion was observed in a shallow high-altitude sinkhole, but not in a nearby deeper sinkhole. The nocturnal inversion in the 26-m-deep Seekopfalm Sinkhole was destroyed by an episode of turbulent erosion during the night of 15–16 November 2001 (Fig. 10). Shown in the figure are temperature traces from Hobos located on the floors, midsidewalls, and lowest passes of both the Seekopfalm and Gruenloch Sinkholes. In the early evening the cooling rates were similar for the pairs of Hobos located on equivalent exposures of the two sinkholes. At about 2000 CEST, however, the temperature at the Seekopfalm Saddle stopped dropping relative to the Lechner Saddle as turbulent mixing produced by strong winds aloft coupled the temperatures at the Seekopfalm Saddle with those aloft. The increase of the upper-level winds were caused by a frontal wave that passed the Alps to the east. This mixing eroded slowly downward into the Seekopfalm temperature inversion, reaching the midslope station and causing a rapid rise in temperature at 2230 CEST, and, finally, reaching the Seekopfalm floor at 2330 CEST. Hobos in the adjacent, but deeper, Gruenloch Sinkhole showed no turbulent erosion during this event. While there were no indications of complete inversion destruction by turbulent erosion in the Gruenloch Sinkhole during the nearly 8-month experimental period, there were other isolated events in which the upper elevations at this sinkhole were subject to mixing events and warming episodes.

*Minimum temperatures in sinkholes of different size.* The five instrumented sinkholes covered a range of sizes and shapes (Table 1), but, surprisingly, two of the sinkholes at different elevations and with different drainage areas and volumes experienced nearly identical cooling curves and temperature minima on many nights. Figure 11 shows examples of this behavior for the Gruenloch and Seekopfalm Sinkholes for 18–19 October 2001. The similar temperatures in the two sinkholes are also seen in Fig. 10 for 15–16 November 2001. The reason for the similar cooling curves at these two sinkholes, and their differences from the other three sinkholes, are presently under investigation. Two of the hypotheses for the different behavior are the different sky-view factors and the whole-day shading of the small, steep sink holes during winter, which results in significantly different surface energy budgets.

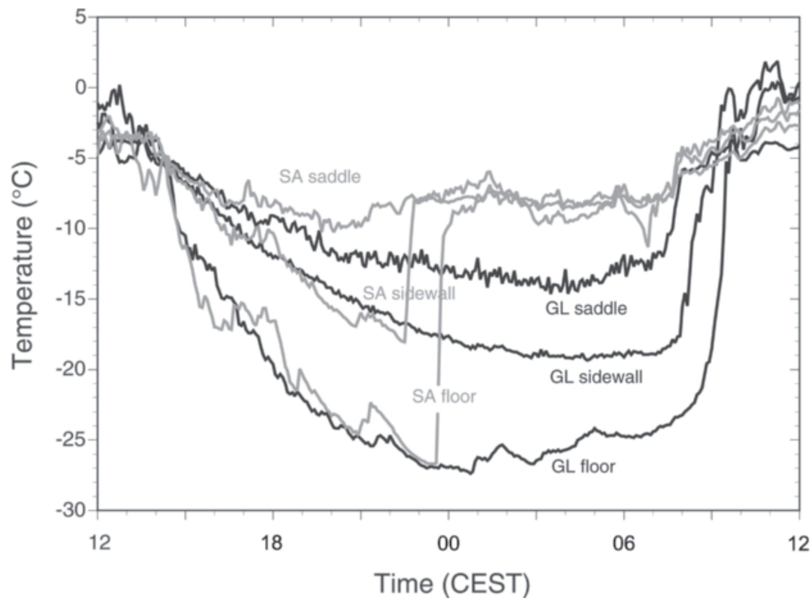


**Fig. 10. Turbulent erosion of the nocturnal inversion in the Seekopfalm (SA) Sinkhole on 15–16 Nov 2001. Shown are Hobo temperatures from the floors (D101, GL00D), midsidewalls (D102, NW10D), and lowest saddles (D103, NW05) of the Seekopfalm and Gruenloch Sinkholes.**

**SUMMARY AND OUTLOOK.** Meteorological experiments focused on gaining a better understanding of cold-air pools or inversions have been conducted in a set of five sinkholes of various sizes and shapes on the Hetzkogel Plateau south of Lunz, Austria. The largest sinkhole, the Gruenloch, some 100 m deep, 1 km in diameter, and at an elevation of 1300 m MSL, is the site where the lowest surface minimum temperature in Central Europe (–52.6°C) was recorded.

This paper provides an overview of the temperature inversion experiments run in the sinkholes from 17 October 2001 through 4 June 2002, reporting on the routine, continuous observations made in the sinkholes with temperature dataloggers and automatic weather stations, as well as on the special intensive experiments using free-air soundings in the Gruenloch with tethered balloon systems that were conducted on 2–4 June 2002. The previous meteorological research in the sinkholes and the present experimental design has been described, along with the topography and climate of the sinkholes and the synoptic weather situation during the intensive experiments. The types of instruments utilized, and their operating charac-

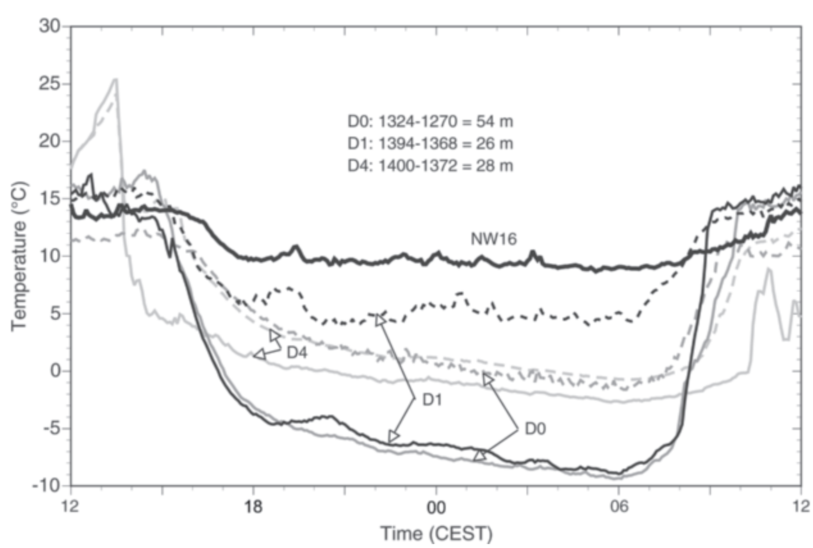


**Fig. 11. Temperature time series for three sinkholes of different sizes on 18–19 Oct 2001. Pairs of temperature time series (floors: solid lines; saddles: dashed lines) are shown for dolines D0, D1, and D4. Also shown, for comparison, is the temperature at NW16, a site 142 m above the Gruenloch floor. The floor and saddle elevations and elevation differences are shown for each of the dolines.**

teristics, locations, and periods of record, have been summarized in tables.

The extreme minimum temperature recorded in the Gruenloch during the experiments was −40.9°C. This occurred on a clear, windless night under dry atmospheric conditions 2 days after a fresh snowfall on 4 January 2002. Temperature inversion strengths in the Gruenloch during the experimental period varied from night to night, depending on the synoptic weather conditions. An indicator of inversion strength in the Gruenloch was the temperature difference between a station located 5 m above the basin floor and a station 90 m above the floor. Temperature differences between these stations exceeded 15°C on the strongest inversion nights, which occurred predominantly in fall and early winter. There were often sequences of nights with well-formed inversions. The nocturnal inversions broke up after sunrise on most days, but there were two periods in the winter following fresh snowfalls when the inversions persisted for multiple days. A fall case of inversion buildup in the Gruenloch showed the very rapid cooling of air in the sinkhole in the late afternoon, with the rate of cooling decreasing during the night to reach quasi equilibrium near sunrise. Inversion breakup after sunrise was investigated using a series of tethersonde soundings on 4 June 2002. The breakup was accomplished by a continuous descent of the top of the inversion and warming in the sinkhole through subsidence heating. This pattern of inversion destruction has been previously observed in other deeper valleys, but was previously seen only in snow-covered valleys in winter. The time required for inversion breakup was shorter in the sinkhole than previously observed in other valleys. An unusual inversion destruction event was documented in the shallow Seekopfalm Sinkhole on the night of 15–16 November when strong winds came in aloft. The nocturnal inversion on this night was destroyed by turbulent erosion, a process in which turbulence erodes the inversion from above, progressing deeper and deeper into the sinkhole until the inversion is completely destroyed. The process took 3.5 h to break the inversion in the 26-m-deep sinkhole. Finally, a comparison of temperatures at the floors of five sinkholes of different sizes and shapes revealed that the Gruenloch and Seekopfalm Sinkholes have similar cooling curves, even though they have quite different elevations, drainage areas, and volumes.

This paper has provided an overview of the Hetzkogel Plateau experiments and the initial results from analyses of the sinkhole data. The participants of the experiments have prepared additional papers focused on key phenomena, including temperature inversion breakups in the Gruenloch (Whiteman et al. 2004c), a comparison between temperatures on the sinkhole sidewalls and those measured over the basin center at the same time (Whiteman et al. 2004a), and a comparison of temperature inversions in sinkholes of different sizes and shapes (Whiteman et al. 2004b).

What new findings have been encountered so far? Because of tethersonde observations and smoke experiments it could be shown clearly that the air within the sinkhole is not completely decoupled from the air above. There is a shear layer on top of the inversion that is eroded continuously by winds aloft, assisted by seiche-like undulations of the cold-air pool. Despite extremely stable stratification, there are weakly pulsating downslope winds present during nighttime in the sinkhole. This means that a thermodynamic simulation of a strictly stagnant cold-air pool, for example, by an energy budget model, may lead to incorrect results. One of the big surprises was the finding that the breakup of the inversion is not being assisted by surface heating at the bottom of the sinkhole, but merely by subsiding motion as a response to upslope winds. The temporal change of the vertical temperature profile is strongly dependent on the shading and sky-view factor in accordance with the geometry of the sinkhole. A further new result was the observation that even a few clouds passing over the sinkhole during an otherwise clear night shows nearly instantaneously a significant temperature signal at the bottom; it reacts like an infrared thermometer.

Despite the basic understanding of inversion formation and breakup there remain several open questions that will be tackled by further experiments and a long-term observation strategy. What does the mass budget of the cold-air pool look like? There is evidence of an outflow from the doline through the Lechner Saddle. A quantification will help to transfer the findings of sinkholes to valley basins with narrow outflows. How does the mechanism of turbulent erosion on top of the cold-air pool work? Is there a penetration of slope winds above the sinkhole into the cold-air pool? Quantifying these slope flows will help to improve the knowledge on vertical exchange in valleys during highly stable stratified episodes. Is there an internal motion within the cold-air pool? Some recent smoke experiments showed clear indications of seiches. Why is there rarely fog formation observed in the sinkhole but intense dew or hoar frost deposits? How well do very high resolution models simulate the inversion formation and its breakup? What is the relation between weather types and inversion formation? Such relations could be used to improve temperature forecasts in other Alpine basins. Is the air mass (temperature–humidity regime) above the Alps and its characteristic downward radiative flux the determining factor for the minimum temperature? If so, the sinkhole could serve as a natural "thermometer," undisturbed by human activities. We could possibly find a signal of the changed greenhouse effect between the historic and recent observational data.

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## REFERENCES

Aigner, S., 1952: Die Temperaturminima im Gstettnerboden bei Lunz am See, Niederösterreich (The minimum temperatures in the Gstettner basin near Lunz, Lower Austria). *Wetter Leben,* Special Issue 1, 34–37.

Clements, C. B., C. D. Whiteman, and J. D. Horel, 2003: Cold air pool structure and evolution in a mountain basin: Peter Sinks, Utah. *J. Appl. Meteor.,* **42,** 752–768.

Geiger, R., R. H. Aron, and P. Todhunter, 2003: *The Climate near the Ground.* 6th ed. Rowman & Littlefield Publishers, 584 pp.

Lauscher, F., 1937: Grundlagen des Strahlungsklimas der Lunzer Kleinklimastationen (Fundamentals of the radiation climate of the Lunz microclimate stations). Jahrbuch der Zentralanstalt für Meteorologie u. Geodynamik, Beiheft 4, 1–24.

——, and M. Roller, 1952: Über die Struktur der Schneedeckenzeit in einem Alpental. Lunz am See (On the structure of snow cover duration in an alpine valley. Lunz am See). *Wetter Leben,* **4,** 15–20.

Litschauer, D., 1962: Untersuchung der Entwicklung von Kaltluftseen in Dolinen- und Beckenlagen (Investigation of the development of cool air pools in sinkholes and basins). Ph.D. dissertation, University of Vienna, 129 pp.

Maki, M., and T. Harimaya, 1988: The effect of advection and accumulation of downslope cold air on nocturnal cooling in basins. *J. Meteor. Soc. Japan,* **66,** 581–597.

Mori, M., and T. Kobayashi, 1996: Dynamic interaction between observed nocturnal drainage winds and a cold air lake. *J. Meteor. Soc. Japan,* **74,** 247–258.

Müller, H., and C. D. Whiteman, 1988: Breakup of a nocturnal temperature inversion in the Dischma Valley during DISKUS. *J. Climate Appl. Meteor.,* **27,** 188–194.

Sauberer, F., 1947: Kleinklimatische Niederschlagsuntersuchungen im Lunzer Gebiet (Microclimatic precipitation investigations in the Lunz area). *Die Umwelt,* **11,** 410–415.

——, 1948: Niederschlagsmessungen am Nordhang des Kleinen Hetzkogels (Precipitation measurements on the north slope of Kleiner Hetzkogel). *Wetter Leben,* **1,** 297–302.

——, 1952: Kleinklimatische und bioklimatische Arbeiten an der Biologischen Station Lunz (Microclimatic and bioclimatic studies at the Lunz Biological Station). *Wetter Leben,* **4,** 4–12.

——, and I. Dirmhirn, 1954: Über die Entstehung der extremen Temperaturminima in der Doline Gstettner-Alm (On the occurrence of extreme temperature minimums in the Gstettner-Alm Doline). *Arch. Meteor. Geophys. Bioclimatol.,* **5B,** 307–326.

——, and ——, 1956: Weitere Untersuchungen über die Kaltluftansammlungen in der Doline Gstettner-Alm bei Lunz in Niederösterreich (Further investigations of the cold air buildup in the Gstettner-Alm doline near Lunz in Lower Austria). *Wetter Leben,* **8,** 187–196.

Schmidt, W., 1930: Die tiefsten Minimumtemperaturen in Mitteleuropa (The lowest minimum temperatures in Central Europe). *Die Naturwissenschaften,* **18,** 367–369.

——, 1933: Kleinklimatische Beobachtungen in Österreich (Microclimate observations in Austria). *Geogr. Jahresbericht Österreich,* **16,** 53–59.

——, H. Gams, W. Kühnelt, J. Furlani, and H. Müller, 1929: Bioklimatische Untersuchungen im Lunzer Gebiet (Bioclimatic investigations in the Lunz region). *Die Naturwissenschaften,* **17,** 176–179.

Whiteman, C. D., 1982: Breakup of temperature inversions in deep mountain valleys. Part I: Observations. *J. Appl. Meteor.,* **21,** 270–289.

——, 1990: Observations of thermally developed wind systems in mountainous terrain. *Atmospheric Processes over Complex Terrain, Meteor. Monogr.,* No. 45, Amer. Meteor. Soc., 5–42.

——, J. M. Hubbe, and W. J. Shaw, 2000: Evaluation of an inexpensive temperature data logger for meteorological applications. *J. Atmos. Oceanic Technol.,* **17,** 77–81.

——, S. Eisenbach, B. Pospichal, and R. Steinacker, 2004a: Comparison of vertical soundings and sidewall air temeprature measurements in a small Alpine basin. *J. Appl. Meteor.,* **43,** 1635–1647.

——, T. Haiden, B. Pospichal, S. Eisenbach, and R. Steinacker, 2004b: Minimum temperatures, diurnal temperature ranges and temperature inversions in limestone sinkholes of different size and shape. *J. Appl. Meteor.,* **43,** 1224–1236.

——, B. Pospichal, S. Eisenbach, P. Weihs, C. B. Clements, R. Steinacker, E. Mursch-Radlgruber, and M. Dorninger, 2004c: Inversion breakup in small Rocky Mountain and Alpine basins. *J. Appl. Meteor.,* **43,** 1069–1082.