Comparison of Vertical Soundings and Sidewall Air Temperature Measurements in a Small Alpine Basin

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ABSTRACT

Tethered balloon soundings from two sites on the floor of a 1-km-diameter limestone sinkhole in the eastern Alps are compared with pseudovertical temperature ‘‘soundings’’ from three lines of temperature dataloggers on the basin’s northwest, southwest, and southeast sidewalls. Under stable nighttime conditions with low background winds, the pseudovertical profiles from all three lines were good proxies for free air temperature soundings over the basin center, with a mean nighttime cold temperature bias of about 0.4°C and a standard deviation of 0.4°C. Cold biases were highest in the upper basin where relatively warm air subsides to replace air that spills out of the basin through the lowest-altitude saddle. On a windy night, standard deviations increased to 1°–2°C. After sunrise, the varying exposures of the dataloggers to sunlight made the pseudovertical profiles less useful as proxies for free air soundings. The good correspondence between sidewall and free air temperatures during high-static-stability conditions suggests that sidewall soundings can be used to monitor temperatures, temperature gradients, and temperature inversion evolution in the sinkhole. Sidewall soundings can produce more frequent profiles at lower cost than can tethersondes or rawinsondes, and extension of these findings to other enclosed or semienclosed topographies may enhance future basic meteorological research or support applications studies in agriculture, forestry, air pollution, and land use planning.

1. Introduction

In the past, temperature data have been collected along mountainsides 1) to determine whether mountainside temperatures were useful proxies for free atmosphere temperatures in the air surrounding or upwind of mountain areas and 2) to compare local microclimates on mountainsides having different orientations.

The first kind of study provided one of the original justifications for establishing mountain observatories in the Alps, because they provided air temperature measurements that were used to determine the then-unknown vertical temperature structure of the earth’s lower atmosphere. Early experience (Barry 1992) showed that mountainside measurements provided useful proxies for nearby free air soundings if the surface stations were sited well so as to remove microclimatic influences. Mountaintop temperatures were generally cooler than concurrently measured temperatures in the nearby free atmosphere at the same elevation, with the temperature difference depending on cloud amount. On clear, undisturbed days, mountaintop temperatures tended to be warmer during daytime and cooler during nighttime than the nearby free atmosphere. For isolated mountains in strong winds, the lifting of the air up the mountainside produces relatively cold temperatures at the mountain summit relative to the surrounding air at the same height because of the dry isentropic or adiabatic temperature decrease produced as the air is lifted up the slopes.

The second kind of study has focused on the microclimates of slopes. Near-surface air temperatures can be inhomogeneous in complex mountainous terrain when wide spatial variations occur in the energy budgets of the underlying surfaces. For example, inhomogeneous patterns occur during daytime when solar radiation falls with different intensity on slopes of different aspect and inclination angles. McCutchan and Fox (1986) analyzed weather station data from the peak and from northeast, southeast, and northwest exposures at the base and midslopes of an isolated conical mountain in New Mexico. They showed that the average 0000 mountain daylight time range of temperature differences among the stations at the same altitudes during a July–August period was 1.5°–2°C, with the largest range at the mountain base. The average daytime range of temperature differ-

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ences among the stations over the same period was 1°–3°C, with the largest differences occurring at both the midslope and mountain-base elevations when background winds were light (≤ 5 m s^{-1}).

The study presented here has a somewhat different focus from the two kinds of studies mentioned above. Our objective is to determine under what conditions air temperature measurements from sidewalls can provide useful proxies to atmospheric soundings in the free air over the center of enclosed basins. This objective is met by comparing pseudovertical temperature profiles obtained from three lines of temperature dataloggers on the sidewalls of a small enclosed basin with concurrent tethered balloon soundings in the free air over the basin center. Such studies support the broader goal of investigating the evolution of atmospheric temperature structure within various types of mountainous terrain. Demonstration of the utility of temperature datalogger lines for studies of temperature structure evolution in enclosed and semienclosed topographies could advance meteorological research and lead to improvements in understanding of the effects of the changing atmospheric structure on biological communities and on applications in agriculture, forestry, air pollution dispersion, and land use planning. Surface-based instruments greatly reduce costs as compared with rawinsondes or other in situ or remote sensing equipment and would produce a higher frequency of ‘‘soundings’’ that would support detailed boundary layer and micrometeorological studies within complex topography areas.

2. Method

a. Experimental design

The experiment was designed to determine under what conditions pseudovertical temperature profiles obtained from surface stations on the sidewalls would provide useful proxies for vertical soundings in the free air over the basin center. Free air soundings were made with tethersondes while pseudovertical profiles were made with three lines of surface-based temperature dataloggers on the sidewalls. Concurrent observations were made during two experimental periods that began in the later afternoon and continued until late morning the next day. The first period had clear skies and weak upper-level winds, and the second period had an evening episode of strong upper-level winds and cirrus clouds. During this second period, two tethersondes were flown at different locations on the basin floor to ascertain whether the free atmosphere of the basin was horizontally homogeneous. During both experimental periods, the temperature datalogger lines were used to ascertain if basin sidewall exposure affected the comparisons. Weather stations were used to measure other atmospheric variables (in addition to temperature) both inside and above the basin.

b. Topography, instruments, and instrument locations

Experiments were conducted on 2–3 and 3–4 June 2002 in the Gruenloch basin, a small enclosed basin on an elevated sloping plateau in the eastern Alps. A contour map showing the measurement sites in the basin is provided in Fig. 1. A summary of the meteorological experiments (Steinacker et al. 2002) is presently being extended into a detailed journal article, so that a short summary will suffice here.

The Gruenloch (also called the Gstettneralm) is a 1-km-diameter limestone sinkhole or *doline* formed in karst topography on the Hetzkogel plateau 5 km south of Lunz, Austria. The climate is humid, with the Gruenloch receiving about 2100 mm of precipitation per year (Sauberer 1947). The Gruenloch has recorded some of the coldest minimum temperatures in central Europe (Sauberer and Dirmhirn 1954, 1956). Over the period from 1928 through 1942, minimum thermometers left in the Gruenloch were read 73 times. Twenty-seven readings were below −40°C, with the lowest reading at −52.6°C (Geiger 1965). Because of these temperature extremes, distinctive vegetative patterns are found in the doline. The floor of the basin at 1270 m MSL is subject to the most extreme temperatures and is covered only with grasses that can survive the winter under a snow cover; a 5-m-diameter pond is present at the lowest point of the basin. Dwarf firs are found on the lower- and midelevation sidewalls, with stately firs and tall woods at the upper elevations (Geiger 1965). A thin layer (∼20 cm) of grass-covered soil covers limestone bedrock over much of the doline, so that it is possible only with effort to find suitable locations on the sidewalls to install the wooden posts on which the temperature dataloggers were exposed; a deep layer of soil was found only at the lowest elevations of the basin floor. No snow was present in the basin during the June experiments.

Three lines of temperature dataloggers (HOBO Pro Temp/External Temp dataloggers, Onset Computer Corporation, Bourne, Massachusetts) were placed on the northwest, southeast, and southwest sidewalls of the basin. Whiteman et al. (2000) recently reported on laboratory and operational tests of these dataloggers, their operating characteristics, and their suitability for meteorological investigations. The loggers were placed on the northwest and southeast lines at varying altitude intervals—5 m at the lowest elevations, changing to 10 and 20 m at the higher elevations. On the southwest line, which extended to higher altitudes than the other lines, HOBOS were separated by 14–44-m intervals. The datalogger thermistors were exposed at 1.3 m AGL in six-plate radiation shields (R. M. Young Company, Traverse City, Michigan) mounted on wooden posts. At selected sites, a second HOBO was placed on the post at a height of 2.0 m AGL. The HOBOS stored instantaneous temperature samples every 5 min using a sensor with a 2-min time constant. The temperature accuracy

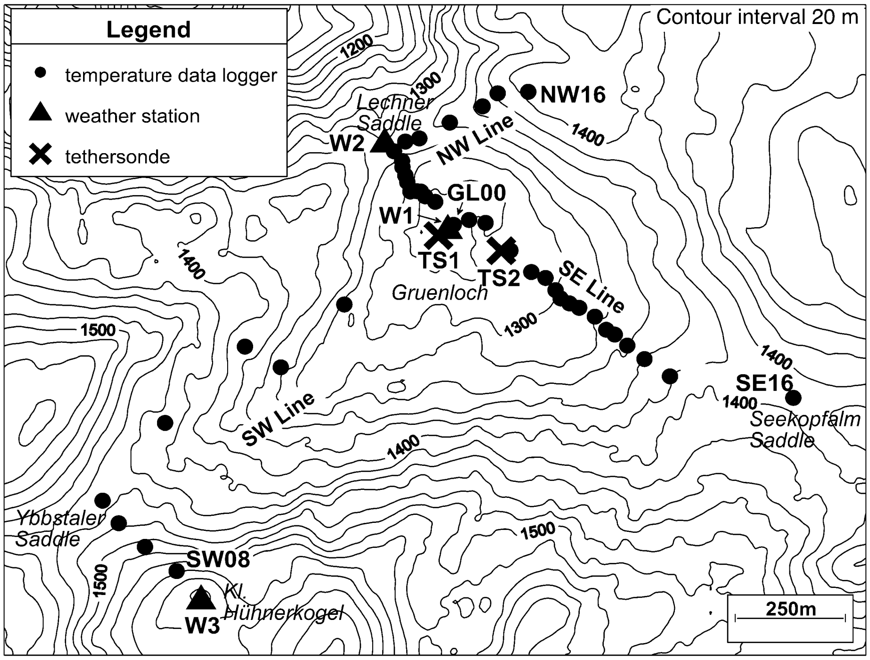

FIG. 1. Topographic map of the Gruenloch and surroundings, showing the locations of the temperature dataloggers (black dots), automatic weather stations (W1–W3, black triangles), and tethersondes (TS1 and TS2, ×). The dataloggers were placed on lines running to the northwest (NW), southeast (SE), and southwest (SW) of the doline center. HOBOs on these lines are above the lowest logger on the doline floor (GL00) and are numbered NW01–NW16, SE01–SE16, and SW01–SW08.

of the HOBO is ±0.4°C over the range from −10° to 50°C, with a resolution of better than 0.1°C over the range from 0° to 40°C. Whiteman et al.'s (2000) calibrations show that the HOBOS have an increasingly negative bias with rising temperatures. Because temperatures increase with height in the basin, there would be a slight tendency for the HOBO line to underestimate vertical temperature gradients in the basin.

The northwest line, on the steepest sidewall of the basin, was closest to the main tethered balloon sounding site, TS1. The first 10 HOBOS on this line ran up the sidewall of the enclosed lower basin to the Lechner saddle. This saddle is the lowest saddle in the basin and is the only opening in the basin below an altitude of 120 m above the basin floor (ABF), the typical height of temperature inversions in the Gruenloch. The remaining six HOBOS on this line ran up the ridgeline of the basin from the saddle. The southeast line was placed on a longer, lower-angle slope. The highest-altitude HOBO on this line, SE16 (see Fig. 1), was placed in the Seekopfalm saddle, the saddle separating the Gruenloch from a smaller, higher-altitude doline (the Seekopfalm). The southwest line extended to higher altitudes than the other lines. The first four of the HOBOS on this line were placed on a steep southeast-facing slope. The fifth HOBO was placed in the Ybbstaler saddle, with the remaining three HOBOS running up the ridgeline from the saddle toward the weather station on the Kleiner Hühnerkogel.

Two TS-3A tethered balloon sounding systems manufactured by Atmospheric Instrumentation, Inc. (now part of Vaisala, Inc.), of Boulder, Colorado, were used to make a series of continuous up and down soundings of temperature, humidity, pressure, wind direction, and wind speed from the floor of the basin to altitudes of approximately 200 m AGL at the locations shown in Fig. 1. Single up and down soundings were completed over periods of about 20 min. Only the TS1 tethered balloon system was flown on the first night; the TS1 and TS2 tethered balloon systems were both flown on the second night. Six soundings were made at TS1 on the first night, and 11 were made on the second night. The accuracy of the tethersonde temperature sensor is ±0.5°C.

Three automatic weather stations (MAWS 201, Vaisala, Inc., Helsinki, Finland) were operated on the floor of the Gruenloch, in the Lechner saddle northwest of the basin center, and on the top of the Kleiner Hühnerkogel (1601 m MSL), a peak above the southwest sidewall. The weather stations recorded average temperature, relative humidity, wind direction, and wind speed at 5-min intervals. The temperature accuracy of the weather stations is ±0.3°C.

c. Analysis limitations

There are several limitations of the analysis. Tethersonde temperature data come from a fast-response thermistor that makes instantaneous samples at approximately 10-s intervals while performing continuous up and down soundings through the basin atmosphere, whereas the HOBOS take instantaneous samples at fixed locations on the sidewalls at 5-min intervals. The comparisons are made between tethersonde temperatures that are interpolated to the fixed altitudes of the HOBOS and HOBO temperatures that are closest in time to the interpolated tethersonde temperatures. Thus, the HOBO–tethersonde temperature comparisons are always within 2.5 min of each other. Only tethersonde *ascents* (i.e., up soundings) during the period of nighttime cooling were used for these comparisons.

The HOBO sites on the sidewalls were chosen to avoid nonrepresentative microclimates, within the practical limitations imposed by the necessity to separate adjacent HOBOS by selected vertical altitude intervals. We were generally able to place the HOBOS on open slopes with widely spaced trees rather than in confined drainage channels or in thick forests. Sites NW11 and NW12 were exceptions. NW11 was located on a ridgeline under a closed forest canopy, and NW12 was located close to an outcropping of limestone.

d. Synoptic conditions during the two nights

Synoptic weather conditions were somewhat different for the two experimental nights. For the 2–3 June experimental 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. The night of 2–3 June was, thus, 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 from 4/8 to 7/8 of the sky between 1800 and 2200 central European standard time (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, 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, patchy wisps of fog were present here and there on the sidewalls, and the entire floor of the doline was covered with rime. For reference, astronomical sunset occurred at 1946 CEST and astronomical sunrise occurred at 0410 CEST.

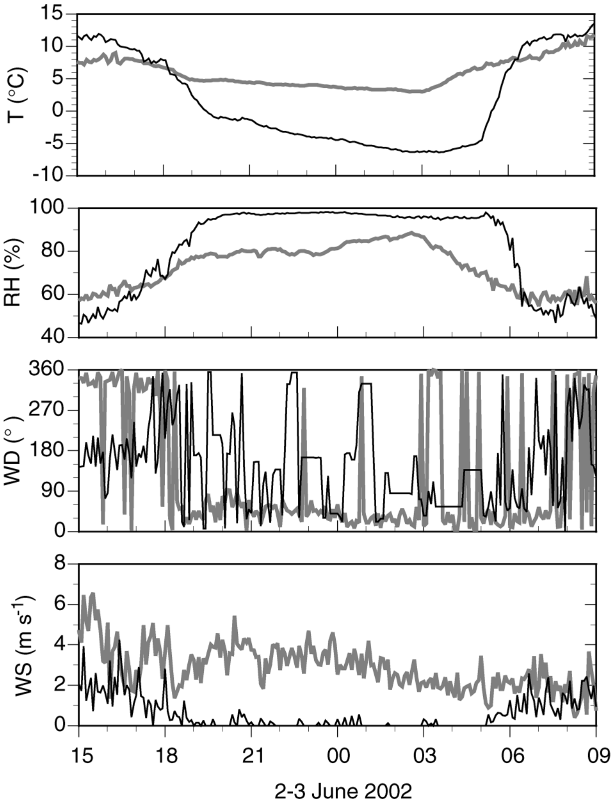

FIG. 2. Meteorograms for 2–3 Jun 2002 from weather stations W1 and W3, located at the floor of the Gruenloch (black line) and on the nearby summit of the Kleiner Hühnerkogel (gray line). Shown are time series of temperature, relative humidity, wind direction, and wind speed.

3. Analysis of data

a. 2–3 June 2002

Figure 2 presents time series of meteorological variables observed at weather stations on the floor of the Gruenloch and at the summit of the Kleiner Hühnerkogel from midafternoon on 2 June through midmorning on 3 June. Pressure decreased slowly throughout this experimental period (not shown). Temperatures near 12°C on the floor of the Gruenloch fell to -7°C by sunrise, with the most rapid fall in the early evening. A much weaker diurnal temperature oscillation was seen on the nearby summit of the Kleiner Hühnerkogel. Daytime relative humidities of 50%–60% increased during the night to over 90% at the Gruenloch floor and 80%–90% on the nearby summit of the Kleiner Hühnerkogel. Winds on the floor of the Gruenloch were light and variable in direction during the night, while northeasterly winds of 2–4 m s^{-1} prevailed on the Kleiner Hühnerkogel.

Figure 3a presents data from a series of six tethered balloon soundings on the night of 2–3 June. Soundings were unavailable between 2200 and 0300 CEST. The basin cooled continuously and the vertical temperature gradient in the basin strengthened during the night. A persistent stepwise increase in temperature occurred in all soundings near 54 m ABF, the level of the Lechner saddle. The winds within the lower, closed basin became calm. Humidity in this nearly stagnant pool was maintained at 80%–90% and the mixing ratio decreased throughout the night (not shown) as moisture was removed at the surface through deposition and condensation. An outflow of basin air occurred just above the height of the Lechner saddle, where southeast winds were observed with wind speeds below 2 m s^{-1} up to an altitude of 80 m ABF.

A time–height plot of hour-average temperatures on 2–3 June 2002 for the northwest line of HOBOS is shown in Fig. 4. The horizontal temperature differences between the HOBOS on the sidewalls and the tethered balloon over the center of the basin varied throughout the night on the three lines and are shown as a function of height for the northwest and southeast lines in Fig. 5. The absolute temperature differences on the northwest line (Fig. 5a) were less than about 2°C throughout the night. These differences are somewhat larger than the uncertainty due to the accuracies of the two instrument systems (section 2b). There was a tendency for HOBOS within the enclosed lower altitudes of the basin to agree better with tethered balloon temperatures, indicating that temperatures were more horizontally homogeneous within the enclosed cold-air pool than for sites above the Lechner saddle outflow. The lowest HOBO on the basin floor was typically about 1°C colder than the tethersonde during the entire night. HOBOS just above the floor at 1275–1294 m MSL had a tendency to be slightly warmer (by several tenths of a degree) than the air over the basin center, while the HOBOS above the Lechner saddle were 1°–2°C colder than the free air. A similar analysis on the southeast line (Fig. 5b) supports the finding of relatively cold HOBO temperatures on the basin floor. In contrast to the northwest line, however, relatively warm HOBO temperatures generally occurred on the southeast line above the saddle except at and just below the Seekopfalm saddle, where cold air overtopped the Seekopfalm doline and ran down into the Gruenloch. The site on the saddle (SE16) had temperatures that were as much as 6°C colder than at the same height over the basin center. Following sunrise (0410 CEST), HOBO–tethersonde temperature differences became much more variable. By 0700 CEST, individuals HOBOS deviated by +3° to −4°C from the free air values, depending on the exposure of the HOBOS and their surroundings to insolation (not shown).

The mean nighttime differences between the HOBO temperatures and the concurrent tethered balloon temperatures at the same heights and times, and the confidence intervals for the mean for the six evening and nighttime (1957–0402 CEST) soundings of 2–3 June are summarized for the northwest, southwest, and southeast lines of HOBOS in Fig. 6a. On all three HOBO lines, the nighttime-averaged HOBO temperatures were lower than the concurrent free air temperatures over the basin center. In some cases, however, the temperature differences were less than the likely measurement errors (section 2b). These cold temperature biases were largest at the highest altitudes and smallest within the topographically enclosed lower basin where stability was stronger. On the northwest line, mean nighttime HOBO temperatures were within 1.2°C of the free air values at all altitudes. The nighttime temperature differences below 1380 m averaged −0.40°C with a standard deviation of 0.42°C. Below the Lechner saddle, the nighttime temperature differences averaged −0.42°C with a standard deviation of 0.26°C. In a similar way, on the southeast line below 1350 m MSL the mean difference was −0.31°C with a standard deviation of 0.41°C. On the southwest line below 1400 m MSL, corresponding values were −0.45° and 0.37°C. The tethersonde reached above 1400 m on only one of the six nighttime soundings, so that the values above 1400 m have little statistical significance. Another characteristic of the temperature differences is the relatively cool HOBO temperature at the basin floor. This difference is attributed partly to the differing measurement heights—the HOBO at 1.3 m AGL and the balloon sonde, because of rigging limitations, at about 2 m AGL. In individual temperature profile comparisons, the temperature differences at the uppermost HOBO sites were often larger than temperature differences at lower altitudes (this is also seen in the averages shown in Fig. 6a). These larger temperature differences are produced by the intrusion of upper winds into the higher altitudes of the doline. In addition to the warm- or cold-air advection associated with these intrusions, their deflection up and down the slopes produces temperature changes caused by isentropic expansion and compression, respectively.

b. 3–4 June 2002

Figure 7 shows the time series of meteorological variables observed at weather stations on the floor of the Gruenloch and at the summit of the Kleiner Hühnerkogel from midafternoon on 3 June through midmorning on 4 June. Atmospheric pressure was steady (not shown). Temperatures on the floor of the Gruenloch fell from 16°C in the afternoon to −5°C by sunrise. Temperatures at the summit fell from a daytime maximum of about 14°C to a sunrise minimum of about 7°C. The temperature difference between the summit and the basin floor increased throughout the night as the basin inversion strengthened. Relative humidity rose from 50% during afternoon to nearly 100% during the night on the basin floor and rose from 60% in the afternoon to 75% in the night on the Kleiner Hühnerkogel. At the summit, winds veered from east-southeasterly to west-

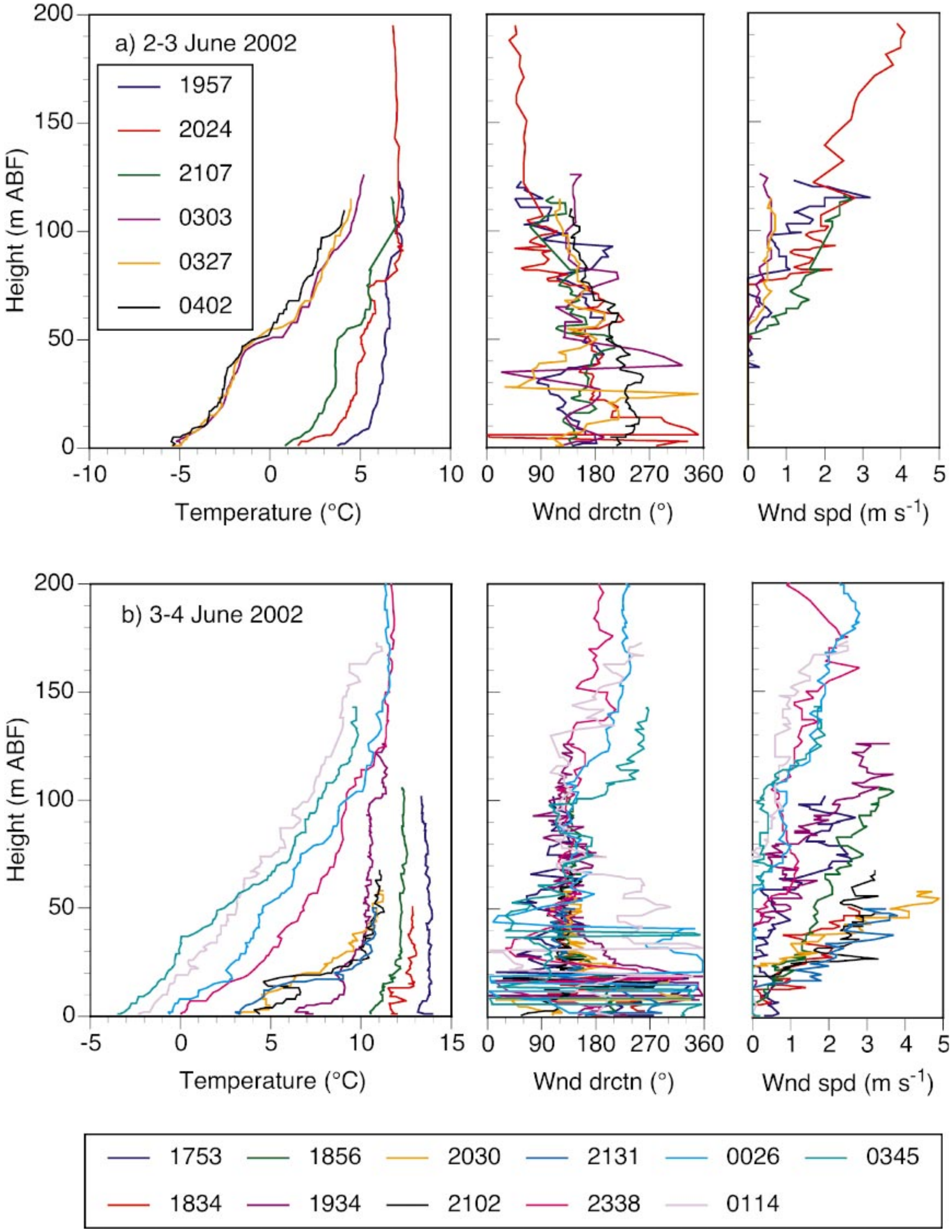

FIG. 3. Tethersonde TS1 up soundings of temperature, wind direction, and wind speed during the cooling periods of (a) 2–3 Jun and (b) 3–4 Jun. The starting times of the up soundings (CEST) are indicated in the legends.

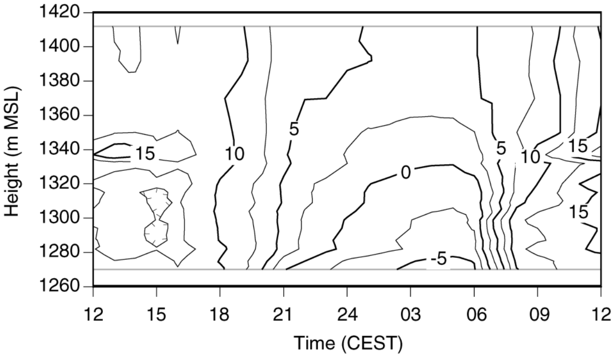

FIG. 4. Time–height plot of hour-averaged temperatures (°C) in the Gruenloch basin on 2–3 Jun 2002 as determined from the northwest line of HOBOs.

erly during the night, with wind speeds generally in the range from 1 to 4 m s^{-1}, but with a period of stronger winds reaching 10 m s^{-1} between 1900 and 2100 CEST. Despite the stronger winds on the Kleiner Hühnerkogel, the basin floor was shielded by the surrounding terrain from the stronger winds aloft and winds remained below 1 m s^{-1} during most of the experimental period at the basin floor weather station, with variable wind directions.

Figure 3b shows the sequence of 11 tethersonde soundings on 3–4 June. The generally stronger, but variable, wind speeds in the early evening of this night (relative to 2–3 June, Fig. 3a) affected the development of the temperature profiles. In the first sounding, winds were below 1 m s^{-1} to a height of 60 m, with stronger winds aloft. These stronger winds intruded into the lowest altitudes of the sinkhole in the second and third soundings, mixing the atmosphere and keeping the temperature profiles near isothermal. Additional cooling occurred in the lowest 40 m of the fourth sounding (1934 CEST) as winds dropped below 1 m s^{-1} in the lowest 80 m. A temperature jump that appeared at the 100-m level in this sounding, like the jump at the 80-m level on the 2024 sounding of the previous evening, appeared at a height corresponding to the base of the stronger

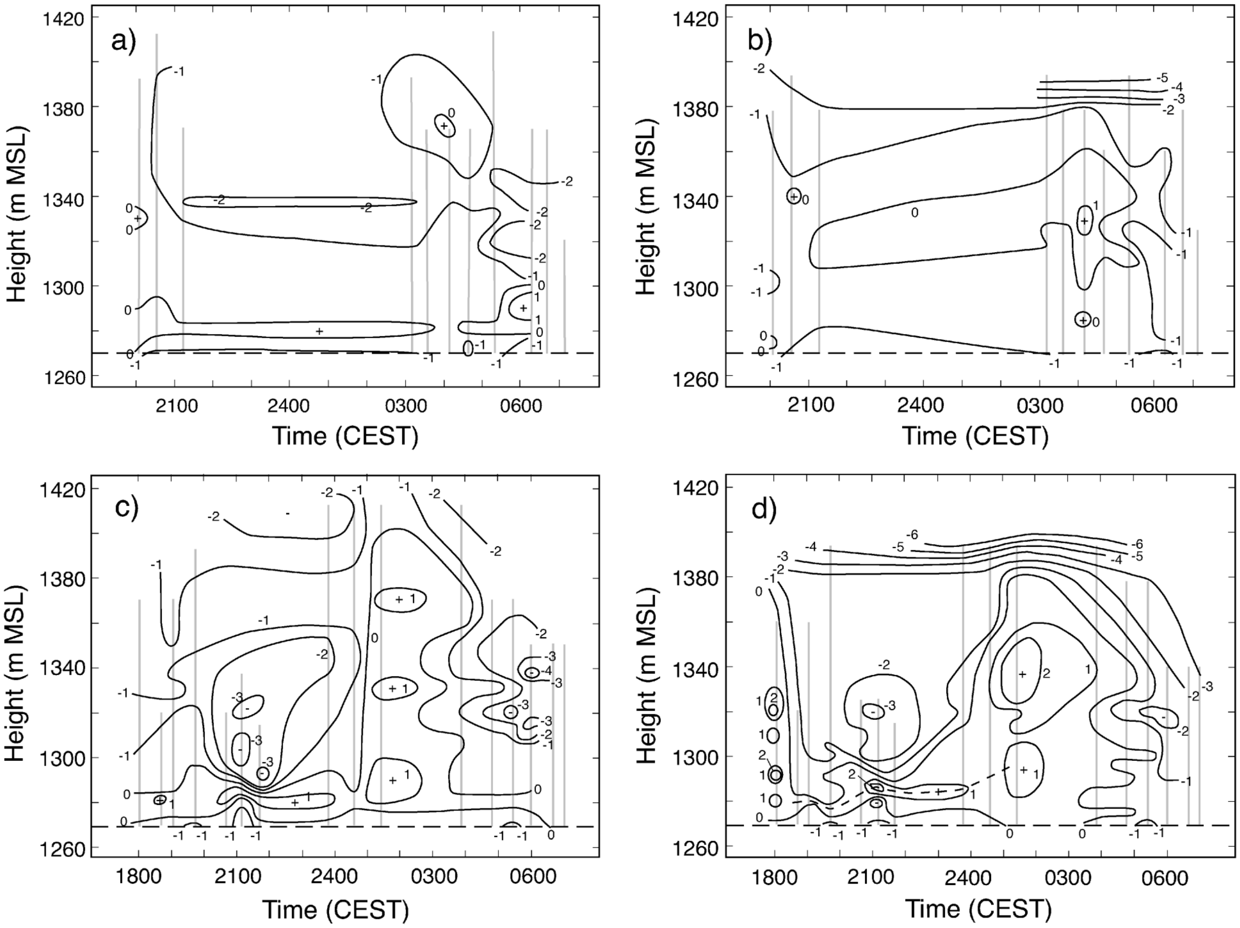

FIG. 5. HOBO–tethersonde temperature differences on the (a) northwest and (b) southeast lines for 2–3 Jun 2002 and on the (c) northwest and (d) southeast lines for 3–4 Jun 2002. The dashed horizontal line is the height of the basin floor. The thin gray lines indicate the times and heights for which data comparisons were available for drawing the contours. Note the 6-h period of missing data during the middle of the night in (a) and (b).

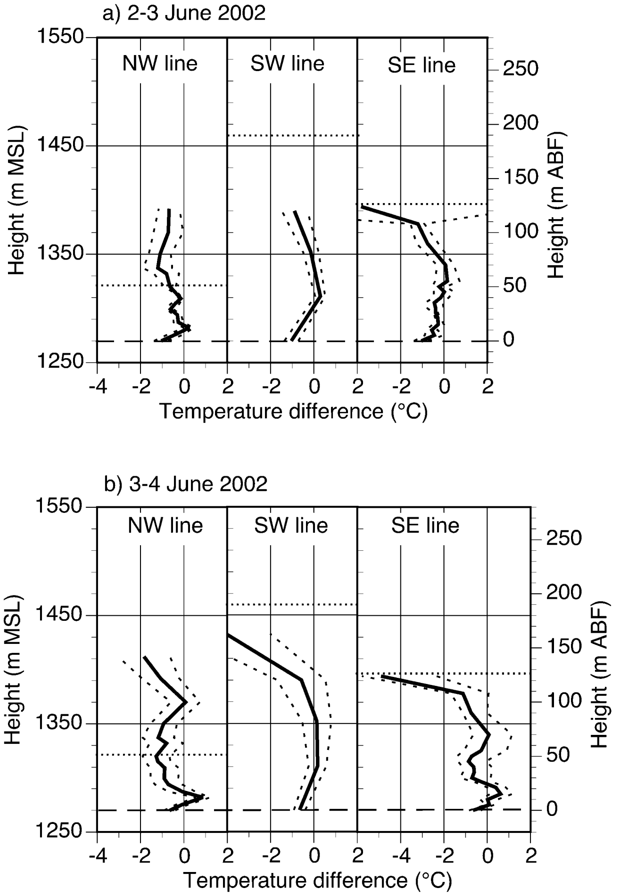

FIG. 6. Mean temperature differences between HOBOs and TS1 tethersonde soundings (solid lines) and their 90% confidence intervals (dashed lines) as a function of height for (a) 2–3 Jun and (b) 3–4 Jun 2002 for each of the HOBO lines (NW, SW, and SE). The means and confidence intervals are computed over the nighttime soundings from early evening until sunrise for all heights at which three or more HOBO–tethersonde comparisons were available. The horizontal dashed line indicates the elevation of the basin floor. The horizontal dotted lines show, from left to right, the heights of the Lechner, Ybbstaler and Seekopfalm saddles, respectively.

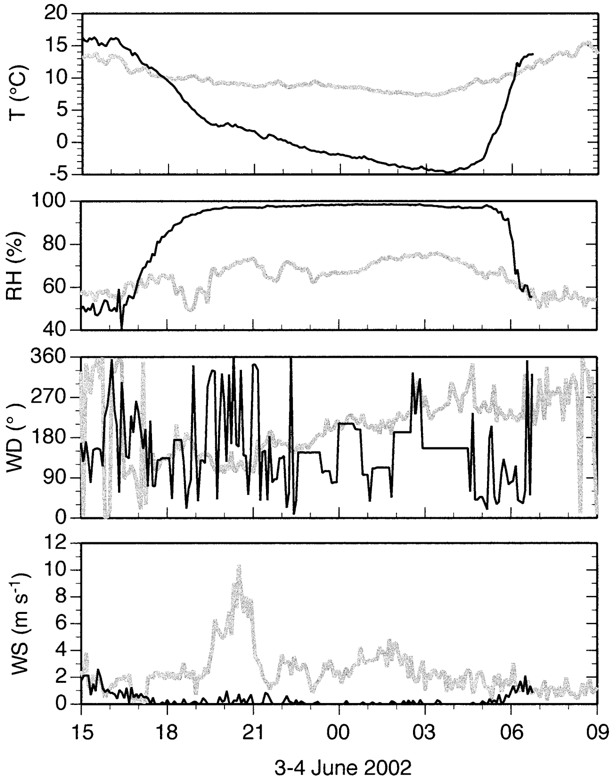

FIG. 7. Same as Fig. 2, but for 3–4 Jun 2002.

winds aloft. The fifth, sixth, and seventh soundings (2030–2131 CEST) were made as strong winds again intruded into the lower altitudes of the doline, with the effect of confining the strongest cooling to a shallow layer at the doline floor. Winds weakened in the late evening and remained light for the rest of the night, allowing the inversion to grow more normally, as for the previous night. The inversion deepened throughout the remainder of the night, with cooling being distributed mostly evenly with height. The mixing ratio within the doline decreased throughout the night (not shown), as noted for the previous night.

The temperature differences between the sidewall pseudoprofiles obtained from the northwest and southeast lines and the tethered balloon ascents are shown in Figs. 5c and 5d, respectively. The strong horizontal winds that descended into the basin in the early evening caused a warming in the basin center relative to the sidewalls, presumably caused by a circulation in which air descended over the basin center and reascended at the slopes. The sinking motions in the stable air over the basin center produced warming, while the compensatory ascending air over the slopes produced relative cooling. The relative cooling was somewhat stronger over the northwest line because the prevailing winds were generally from the southeast. Downward turbulent fluxes at the sidewalls, promoted by the shear generation of turbulence, probably also played a role in local cooling adjacent to the slope. Both before and after the introduction of the strong winds, the temperature differences approximated those observed on the previous, undisturbed night, with horizontal temperature differences of ±1°C. These differences, as before, should be compared with the measurement errors stated in section 2b.

The 0114 CEST sounding sampled an event for which the HOBO lines were relatively warm as compared with the basin center. The amount and vertical distribution of the warming varied between the northwest and southeast lines. The relative warming locally reached as high as 1.5°C on the northwest line and 2.6°C on the southeast line. We could not determine the length of the event, because the relative warming was seen in only one sounding. The event occurred at a time when a 40-m-deep stagnant layer was present at the bottom of the sinkhole. Above this layer, southeast winds varied in speed with height. The higher stability in the basin at this time and the lower wind speeds suggest that this event, in contrast to the earlier event in which substantial vertical motions were present in the basin, involved horizontal eddies (i.e., eddies with a vertical axis).

Figure 6b summarizes the mean temperature differences between the three lines of HOBOs and the tethersondes for the night of 3–4 June. Also shown are the confidence intervals for the mean, as averaged over the 10 nighttime soundings. Like the previous night, HOBO temperatures tended to be colder than free air temperatures at the same altitudes, although a band of relatively warm temperatures persisted all night on the lower sidewalls inside the enclosed lower basin. As compared with the previous night, temperature differences were unsteady on this windier night. The relatively high standard deviations about the mean on this night, which produced wider confidence intervals in comparison with 2–3 June were caused by alternating periods during the night when HOBO–tethersonde temperature differences changed sign within the basin. On the northwest line, standard deviations of temperature differences between the HOBOs and tethersonde soundings were about 0.5°C at the lowest three HOBOs and around 1°C at the higher HOBOs. On the southeast line, the standard deviation increased from 0.5°C at the basin floor to 1.9°C just above the Lechner saddle, with a decrease back to 1°C above that. The southeast line was in sunlight during the first sounding of the afternoon (1753 CEST), producing elevated temperatures at some of the HOBOs relative to the tethersondes. A period of relatively cold HOBO temperatures in the range from −1 to −3°C was first seen on the southeast line above 1296 m MSL in the 1856 CEST sounding. The relatively cold HOBO temperatures were later noted on the northwest line after the 1934 CEST sounding. They persisted through the 2131 CEST sounding on both lines. The 0114 CEST sounding, by contrast, found HOBO temperatures at nearly all elevations on both sidewalls to be warmer (by as much as 2.6°C) than the tethersonde sounding. Again, like the 2–3 June case, very cold sidewall temperatures were found below the Seekopfalm on the southeast line, indicating a flow of cold air out of the Seekopfalm basin. Last, on the southwest line, the HOBOs that extended to higher altitudes experienced relatively cold sidewall temperatures, especially just below the Ybbstal saddle where one of the HOBOs was poorly exposed in a minor tributary.

Another interesting feature of the HOBO–tethersonde temperature differences, most apparent on the northwest line, was the warmer (i.e., relative to the tethersonde ascents) HOBO temperatures that persisted all night at elevations 5–20 m above the basin floor. A similar HOBO temperature excess on the southeast line was first noted 5 m above the basin floor in the early evening. The axis of maximum temperature excess grew during the night to reach 1305 m MSL by sunrise.

A second tethersonde (TS2; Fig. 1) was operated on the night of 3–4 June on the same schedule as the first tethersonde. This tethersonde was operated southeast of the basin center at a base altitude of 16 m ABF, with somewhat smaller depth soundings than at TS1. Our analysis (not shown) of the temperature differences between the HOBO lines and the TS2 tethersondes is in broad agreement with the findings at TS1. On average, the HOBOs were 0°–1°C colder than the tethersonde on the northwest and southeast lines, with a standard deviation of 1°–2°C. The shorter soundings and larger altitudinal differences between HOBOs on the southwest line allowed comparisons to be made for only three HOBOs. The mean standard deviations were, again, 1°–2°C, but the mean temperature differences were close to zero on this line, except at the intermediate site, where the HOBO was nearly 1°C warmer than the tethersonde.

c. *Comparison of vertical profiles from three HOBO lines*

If lines of surface-based temperature dataloggers on a sidewall are used as proxies for free air temperature soundings in a basin, will the proxies differ depending on which sidewall is chosen for the line? This question is investigated in Fig. 8, where hour-averaged pseudoprofiles from the three lines of HOBOs are compared at 3-h intervals for 2–3 June 2002. During daytime (0800, 1100, and 1400 CEST), noticeable temperature excursions occur not only between lines, but also between HOBOs on the same line. In the lower basin, temperatures tend to be generally higher on the northwest line in the morning and early afternoon because of its southeast- and south-facing aspect, which is favorable for receipt of solar radiation. The temperature differences between HOBOs on a given line, on the other hand, are affected by the nonuniform exposure of the HOBOs to shadows that propagate across the terrain from the surrounding topography and, especially, from nearby trees. At night, the temperature profiles from the lines of dataloggers are in much better agreement than during the daytime. Nonetheless, there are some systematic differences between the sidewall lines. The southeast line is warmer than the northwest line through a 50-m-deep layer above the Lechner saddle. This is, no doubt, caused by the outflow of cooled air through the saddle, a phenomenon discussed further by Pospichal et al. (2003). The line of HOBOs on the saddle and the adjacent ridgeline are exposed to this cool flow of air, and the HOBOs on the southeast line may also experience some warming associated with descending air on the southeast sidewall that supports the flow through the saddle.

Poorly exposed HOBOs can be clearly identified from sequences of pseudovertical temperature profiles as shown in Fig. 8. The poor exposure of the uppermost

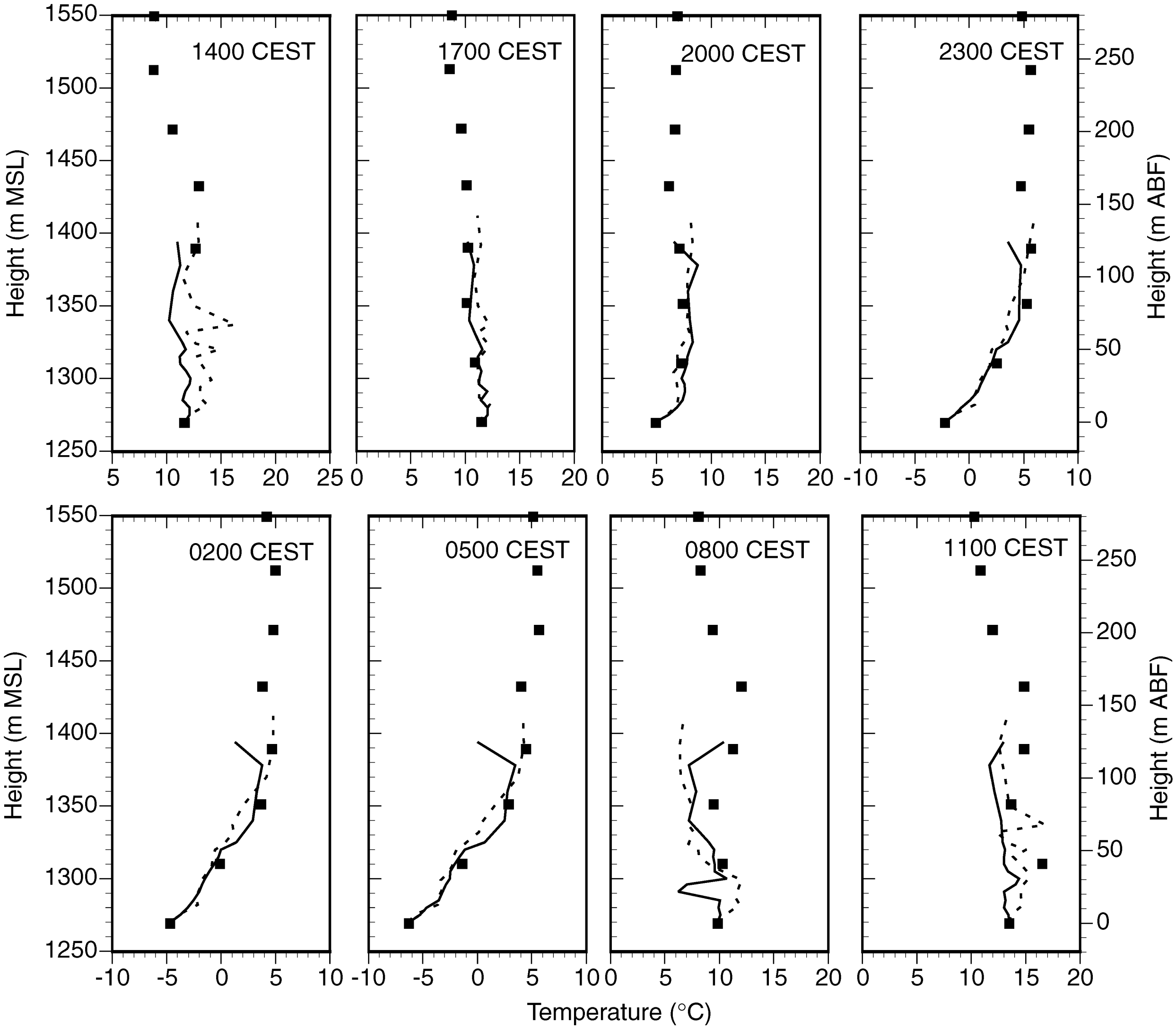

FIG. 8. Comparison of pseudovertical soundings from the three HOBO lines on 2–3 Jun 2002. The black line is the southeast line, the dashed line is the northwest line, and the solid squares are on the southwest line.

HOBO on the southeast line (SE16) is readily apparent in the figure. This HOBO's temperature (plotted at the top of each of the solid curves) is affected by cold-air outflow from the Seekopfalm at night, as mentioned in section 3a.

The quantitative comparisons between tethersonde and HOBO profiles, and between different lines of HOBOs, show that errors in the pseudoprofiles are small relative to the inversion strength. Thus, the pseudovertical profiles are suitable for detecting the formation of inversions in the doline, as well as for making useful measurements of inversion strengths, depths, and vertical temperature gradients. Although it is clear that some accuracy is lost relative to vertical profiles over the basin center, gains are made in terms of the higher frequency and lower cost of the surface-based temperature profiles.

4. Discussion

In this section, we provide an explanation for the observed temperature differences between sidewalls and the free air and provide guidance on extending the Gruenloch results to other topographic situations.

a. Temperature differences

In undisturbed conditions, nighttime temperature differences between the slopes and the basin center can be caused by two main processes. The first is the well-known development of shallow temperature deficits above a slope caused by the net loss of longwave radiation from the slope and the (partially) compensating downward turbulent flux of sensible heat from the overlying atmosphere, which cools the layer of atmosphere above the slope. This nighttime temperature deficit over a slope relative to air at the same elevation adjacent to the slope drives the well-known downslope flows that develop over sloping surfaces (Whiteman 2000). These flows are usually strongest in the early evening before the basin inversion builds up over the slopes, and it is typical for the downslope flows to weaken or die in basins and for the air to become stagnant once the inversion builds up within the basin (see, e.g., Clements et al. 2003). The second process, important in drained valleys or basins, is the sinking of potentially warmer air into a valley to compensate for the cooled air that drains out of the valley in down-valley flows. Enclosed basins generally attain much lower nighttime temperatures than do drained valleys or basins, because this source of warm air is eliminated in topography that is not drained by down-valley flows (Whiteman 2000). These two processes maintain the temperature difference between the slope and the basin center in the Gruenloch. In the lower basin, the temperature difference is maintained solely by the first process. In the basin above the Lechner saddle, both processes are at work, producing larger temperature differences that are maintained all night, especially on the low-angle, high-elevation slopes.

In a similar way, the development of a warm layer over the slope when it is illuminated after sunrise drives up-slope flows (Whiteman 2000). The net radiant input onto the slopes during daytime is much larger than the net nighttime loss, and thus variations in soil type, albedo, vegetation, and other factors that affect the receipt and disposition of net radiation into sensible heat flux through the surface radiation budget become important in producing thermals and spatial variations in temperature over the slopes.

b. Extending the Gruenloch results

The suitability of pseudovertical profiles from surface-based dataloggers as proxies for free air profiles over valleys and basins depends on many factors, some of which have been investigated in this paper. Key considerations include the following:

- Pseudovertical profiles will usually have a mean temperature deficit (i.e., a cold bias) at nighttime relative to the air at the same level away from the slope because a shallow temperature deficit forms over the slope.
- For useful profiles, dataloggers must be installed in appropriate exposures outside of localized microclimates. Several general principles for the exposure of these instruments can be given. If possible, instruments should be exposed on open hillsides with homogeneous soil or vegetation where the complicating influences of inhomogeneous forest canopies are absent. Tributary valleys, gullies, or other smaller channels for shallow drainage flows should be avoided; small ridges projecting from an open slope will provide a somewhat more representative exposure to the free basin atmosphere. Other more subtle exposure problems may be present, as represented by Gruenloch site SE16 where cold-air flows into the doline from an adjacent doline. Poorly chosen sites can often be detected by inspecting the time evolution of pseudovertical temperature profiles obtained from large numbers of dataloggers on an altitudinal cross section. Experimental and instrumental errors of various types (e.g., datalogger elevation errors, temperature offsets, and radiation shield problems) can be determined by inspecting pseudovertical profiles on days on which the basin atmosphere is expected to be well mixed (cloudy, windy periods). During such periods, the pseudovertical temperature gradients should be approximately isentropic (Whiteman et al. 2000), with temperature decreasing smoothly with height at the rate of 9.8°C km^{-1}.
- The Gruenloch analyses show that under nighttime conditions of strong stability with weak winds aloft and with properly exposed dataloggers, the suitability of proxy soundings does not depend sensitively on the locations of the sidewall data lines. In strong inversions, buoyancy tends to maintain horizontal isotherms, and strong inversions tend to reduce the influence of winds aloft. The pseudovertical profiles are, thus, expected to be most useful in strong inversion conditions. Perfectly horizontal isotherms within the basin will cause the pseudovertical temperature profiles from different sidewalls to become coincident. They can also become coincident if the isotherms are horizontal in the bulk of the basin cross section at a time when equal temperature deficits form over all of the slopes.
- Pseudovertical profiles can be expected to be much more representative of the free atmosphere during nighttime than during daytime, because, when the atmosphere becomes stable, buoyancy or gravitational effects tend to produce horizontal isotherms. Pseudovertical profiles may also provide useful proxies for free air soundings during the daytime in winter, especially when a uniform snow cover maintains nighttime stability and reduces the temperature contrasts usually associated with radiation receipt on different-aspect slopes and different types of ground cover.
- Meteorological disturbances tend to perturb the isotherms or isentropes. For example, strong winds above an inversion may cause waves to form at the inversion top that may perturb the sidewall temperatures for some distance below the inversion top. This, however, is usually strongly damped with distance downward into the basin (Whiteman et al. 2001). Also, strong

flows carried up the outside slopes of a basin or valley can produce cold temperatures at the basin or valley ridgeline because the air carried up the slope will cool adiabatically at the rate of 9.8°C km^{-1}. This continuous source of cold air at the ridgeline may be colder than the air in the basin or valley below and could be transported in gravity flows down the inner sidewall, as Bossert and Cotton (1994a,b) have previously documented and simulated for Colorado topography.

- Because differences between pseudovertical and free air temperature profiles are enhanced by the intrusion of strong winds from aloft, the openness of a basin or valley to wind intrusions will have an important effect. Pseudovertical profiles can, therefore, be expected to be most suitable as proxies for free air soundings when a basin or valley is enclosed by surrounding sheltering topography. Larger-diameter basins are likely to provide less shelter from strong background winds, and the upper sidewalls are expected to be more exposed to strong wind influences than are the lower sidewalls.

5. Conclusions

Tethered balloon soundings in a limestone sinkhole in the eastern Alps on a clear, undisturbed night were compared with pseudovertical temperature soundings from three lines of temperature dataloggers exposed at 1.3-m height on the basin's northwest, southwest, and southeast sidewalls. Under stable nighttime conditions, the pseudovertical profiles from all three lines were good proxies for free air temperature soundings over the basin center. The HOBO–tethersonde temperature differences were frequently within the measurement error expected from the reported accuracies of the HOBO and tethersonde temperature sensors. The pseudovertical profiles had a mean cold temperature bias of about 0.4°C as compared with free air soundings within the basin, with a standard deviation of about 0.4°C. Because the sidewall temperature errors are small relative to inversion strengths within the sinkhole, the sidewall soundings are expected to be useful in estimating free air temperatures and temperature gradients within the sinkhole. The best correspondence between the pseudovertical and free air profiles was in the confined cold-air pool in the lowest 54 m of the sinkhole where atmospheric stability was highest. Above the confined cold-air pool, there was a tendency for the sidewall temperatures to be a little cooler, presumably because warmer air sinks into the center of the basin to replace air that is cooled on the slopes and flows out of the basin at altitudes above the lowest pass. The mean temperature bias and the nighttime standard deviation of the temperature bias varied little from line to line, suggesting that the orientation and inclination angles at the sidewall lines are relatively unimportant in these high-stability, low–wind speed conditions.

On a second night with higher synoptic winds, a similar cold temperature bias was again observed on the sidewalls, but the nighttime standard deviation of the biases was much higher (1°–2°C) because of the time-varying exposure of the sidewalls to wind intrusions from aloft.

In the experiments described, the locations of the dataloggers on the sidewalls were carefully chosen to avoid nonrepresentative or localized microclimates. Nonetheless, one site (SE16) had an extreme local microclimate that was over 6°C colder than the free air over the basin center at the same altitude, caused by inflow into the basin from an adjacent higher-altitude basin. After sunrise, the differing microclimates of the individual surface sites, especially their exposure to sunlight or shade, make the pseudovertical profiles less useful as proxies for free air soundings.

The good correspondence between the sidewall and free air temperatures in the basin suggests that the sidewall soundings will prove to be useful in monitoring temperatures and vertical temperature gradients over the basin during clear, nighttime, stable conditions with weak winds aloft. Because sidewall soundings can be made more frequently and extended over many nights at lower cost than free air soundings with tethersondes and rawinsondes, they provide valuable advantages for some types of meteorological analyses. For example, HOBO profiles in the Gruenloch basin (Eisenbach et al. 2003) have been used to classify different types of cold pool disturbances, including foehn intrusions, mixing events caused by wind shear, turbulent erosion episodes, frontal passages, and cloud formation/dissipation. An extended analysis of these classifications for an 8-month period using hourly averaged pseudovertical profiles from the Gruenloch is now being prepared for publication.

Extensions of the results in this paper to larger basins, to open basins that are better exposed to synoptic wind influences, and to stable wintertime soundings in snow-covered terrain are left to future investigations. The alternative approach of using ground-based remote sounding systems, such as radio acoustic sounding systems or microwave radiometers, to make proxy temperature soundings of valley and basin atmospheres has, so far, not been investigated.

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