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BOUNDARY LAYER MOISTURE REGIMES IN SMALL CLOSED BASINS

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## 1. INTRODUCTION

The droplets of water referred to as 'dew' actually have several different physical origins. Single pendant droplets of water on the ends of blades of grass are usually produced by exudation of water from the moist ground under the action of root pressure in a biological or botanical process called *guttation*. Dew drops that are widely distributed over the surfaces of leaves or blades, on the other hand, are condensation products, with the condensation coming from two possible sources, the water vapor evaporating from the soil and the water vapor in the atmosphere (Monteith 1957). The process by which water vapor evaporates from the soil and condenses into dew has been referred to as *distillation*, while the process of condensation of atmospheric water vapor is termed *dewfall*. Distillation occurs on calm nights through a laminar sub-layer within the grass canopy with a transfer coefficient approaching the molecular value. Dewfall occurs when the leaves cool radiatively below the dewpoint temperature of the adjacent air and the water vapor condenses onto the surface. Additional water vapor is brought to the surface by turbulent diffusion. The downward flow of vapor from the atmosphere to the surface is indicated in atmospheric profiles by an increase of absolute humidity with height. The rate of condensation is increased by wind as this enhances turbulence and may even provide a source of new moisture. On windless nights, distillation is a relatively more important source of dew than is dewfall (Monteith 1957).

Because the rate of dew deposition is tied to the rate of heat release (through the latent heat of vaporization) the condensation of dew and the consequent release of latent heat reduce the total nocturnal cooling relative to a night with no dew. In the framework of the surface heat budget, the nocturnal longwave radiation loss is compensated not only by the upward flux of heat from the ground and the downward flux of heat from the atmosphere, but also by the release of latent heat at the surface.

A number of investigators have used nighttime sequences of atmospheric humidity soundings to estimate dewfall rates by observing the rate of nighttime loss of humidity from the lower atmosphere (Garratt and Segal 1988). Humidity advection during the night is not accounted for by this technique and, in open country, differential humidity advection (i.e., variation of humidity advection with height) often occurs, confounding the

analyses. A recent field experiment conducted in a completely enclosed limestone sinkhole in the Eastern Alps provides an opportunity to determine dewfall and its effects on the water and heat budgets of the sinkhole atmosphere in a situation where advection cannot be present.

## 2. BACKGROUND

Humidity balances in valleys and basins are affected by physical processes that differ from those over homogeneous terrain. The enclosed atmospheres of valleys and basins have higher ground-surface-area to air-volume ratios than an equivalent depth atmosphere over homogeneous terrain. The surface-to-volume ratio for a v-shaped valley having planar sidewalls, for example, is twice that of an air volume over a homogeneous plane surface having the same width and depth (Whiteman 2000). The actual valley or basin surface-to-volume ratio is further enhanced by small-scale irregularities that are often present on complex terrain surfaces. Further, the existence of thermally driven downslope and down-valley flows that form above the slopes provides a means to circulate (and re-circulate) air within the complex terrain volume allowing the moisture to come in contact more readily with the valley floor and sidewalls where dew can be deposited.

Two previous papers have dealt with atmospheric humidity budgets in valleys and basins. Hennemuth and Neureither (1985) reported the results of an investigation of the *daytime* humidity budget in Switzerland's Dischma Valley using radiosonde and aircraft observations. They found that the humidity decreased in the morning and increased in the afternoon. Whiteman et al.'s (1996) investigation of the Sinbad Basin found that the basin atmosphere dried during nighttime and moistened during daytime. As they noted, however, strong down-canyon flows drained this basin at night so that the basin atmosphere could not be considered isolated or closed off from its surroundings.

Despite the lack of published atmospheric humidity budgets, there are numerous published observations of sequences of valley humidity profiles during both night and day (Freytag 1985; Freytag and Hennemuth 1979, 1981, 1982, 1983; Reiter et al. 1984; Hennemuth and Neureither 1986), and a few investigators (e.g., Halbsguth et al. 1984; Hennemuth and Köhler 1984; Whiteman et al. 1989) have reported studies of surface energy budgets that include surface fluxes of latent heat at the floors of valleys or basins. Sequences of valley

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humidity profiles generally show a loss of water vapor in the valley atmosphere during nighttime and a gain of water vapor during daytime, but the effects of advection from outside the valley cause large variations from this general behavior on individual nights.

In this paper, we use series of tethersonde soundings collected on two nights in the lower, completely enclosed portion of Austria's Gruenloch basin to consider the effects of dewfall on the atmospheric moisture and latent heat budgets, specifically considering the effect of latent heat release on the cooling of the basin atmosphere. The enclosed basin greatly simplifies the budget estimates, which are more complicated in valley or open basin topography where along-valley circulations or flow intrusions advect air of different humidity into or out of the control volume.

### 3. EXPERIMENTAL DESIGN, SITES AND INSTRUMENTATION

A meteorological field experiment was conducted in the small enclosed Gruenloch sinkhole or *doline* in the eastern Alps in 2001-02 (Steinacker et al. 2002). As part of this experiment, a series of tethered balloon soundings were made from the floor of the sinkhole on the nights of 2-3 and 3-4 June 2002. Substantial dew and/or frost was noted on the ground and vegetation on both nights.

#### a. The Gruenloch basin

The Gruenloch, a small limestone sinkhole (Fig. 1) located on the Hetzkogel plateau 5 km south of Lunz, Austria, is about a kilometer in width and 150 m in

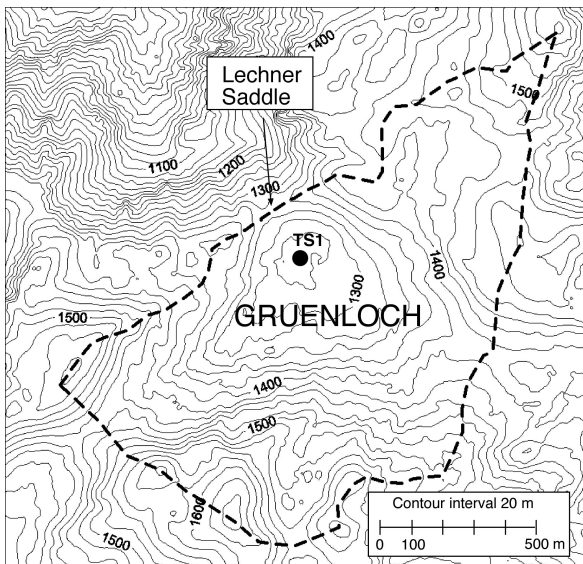


Fig. 1. Map of the Gruenloch Basin showing the location of the tethered balloon system (TS1) and the drainage boundaries (dashed line).

depth. The sinkhole is completely enclosed from the basin floor (1270 m MSL) up to the altitude of the lowest, or Lechner, saddle (1324 m MSL).

#### b. Synoptics

The night of 2-3 June was clear and undisturbed, while the night of 3-4 June was affected by strong winds and cirrus clouds that increased in the early evening to cover 4/8 to 7/8 of the sky between 1800 and 2200 CET. The winds died and the skies cleared by 2300 Central European (Standard) Time (CET). At sunrise, thin tendrils of fog were present here and there over the sidewalls and the entire floor of the doline was covered with rime. Whiteman et al. (2004) provide further information on the synoptic weather conditions for the two nights. Astronomical sunset occurred at 1946 and astronomical sunrise occurred at 0410 CET on these days

#### c. Experimental sites and equipment

The article by Steinacker et al. (2002) describes the instruments used in the Gruenloch experiments. In this article, we use selected data from tethered balloon ascents (Fig. 1). The TS-3A tethered balloon sounding system (Atmospheric Instrumentation Research, Inc., Boulder, Colorado) used aspirated dry and wet bulb thermistors to measure air temperature and to determine relative humidity and mixing ratio using standard formulas for saturation with respect to liquid water. On the two experimental nights, temperatures at the Gruenloch floor fell below freezing so that ascents and descents through the (rising) freezing level caused alternate freezing and thawing of the wet bulb wick and attendant data quality problems. These problems have been reduced by using only the tethersonde ascents (not the descents), since the wet bulb wick was equilibrated well at the ground before each ascent and the water phase of the wick is presumed known at the beginning of each ascent from the dry bulb temperature (liquid if the dry bulb temperature is above freezing and solid if below freezing). Individual soundings (where freezing/thawing appeared to have affected the humidity profiles (0345 and 0436 CET soundings on 4 June) were not used in the analyses.

### 4. RESULTS

Tethersonde soundings were made during two observational periods, 2-3 June 2002 and 3-4 June 2002.

#### A. 2-3 June 2002

The soundings on 2-3 June (Fig. 2a) show that a temperature inversion had already developed within the sinkhole by the time of the first sounding at 1957 CET, only a few minutes after astronomical sunset. The atmosphere continued to cool at all altitudes during the remainder of the night. Wind speeds became calm in

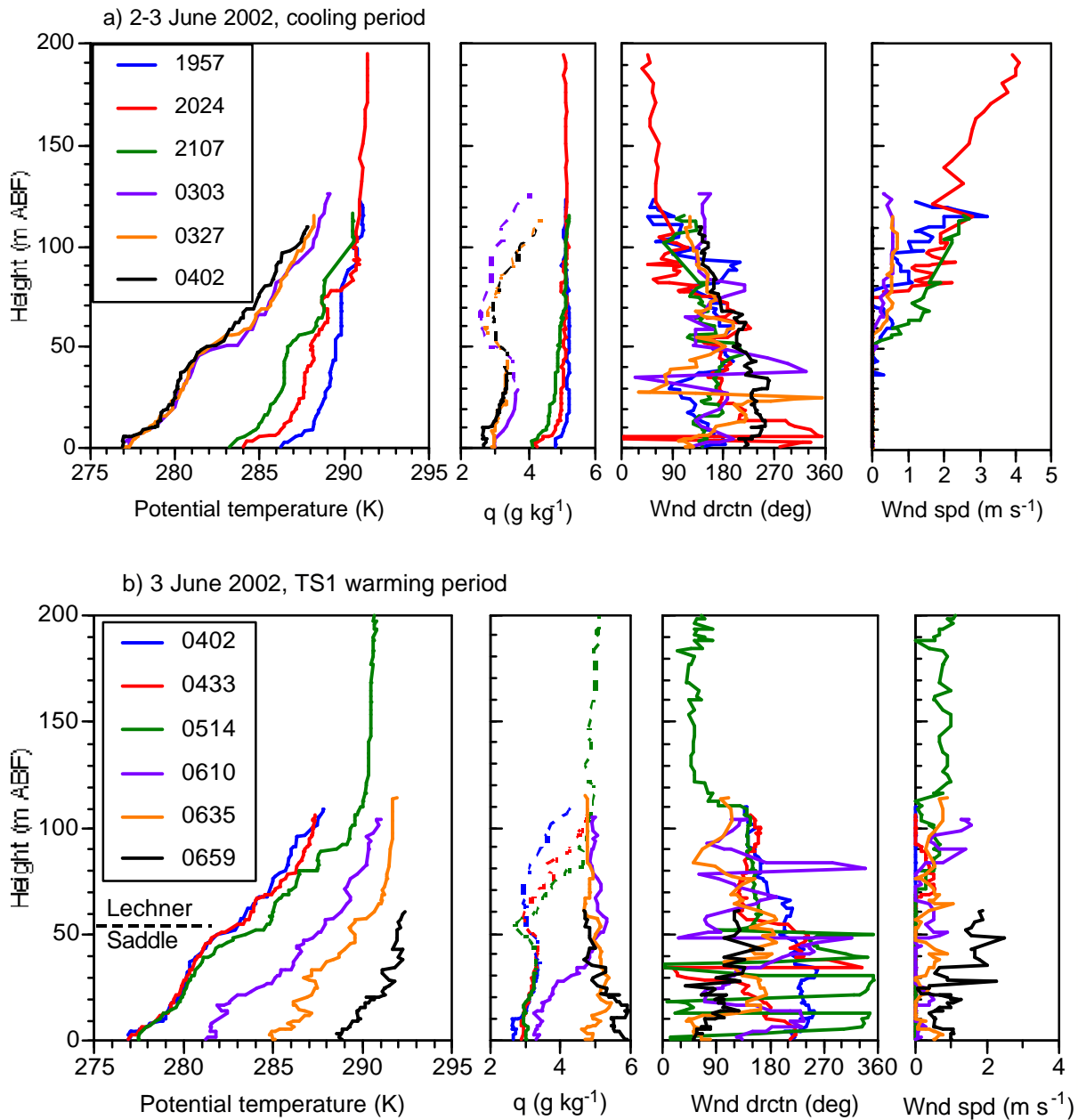


Figure 2. Series of tethered balloon soundings of temperature, mixing ratio  $q$ , wind direction and wind speed in the Gruenloch Basin on a) the night of 2-3 June and b) the morning of 3-4 June 2002. Dashed lines in the mixing ratio soundings indicate where it is unclear whether freezing or thawing might have affected the profiles. The legend indicates the sounding times in CET.

the lowest enclosed part of the sinkhole as the stability and the surrounding terrain isolated the basin from the stronger (but still weak) winds that occurred above the Lechner Saddle. The late afternoon mixing ratio was about  $5.2 \text{ g kg}^{-1}$  but, by the first sounding, the mixing ratio had already decreased in the lowest 20 m above the basin floor. During the night, the mixing ratios decreased in the enclosed lower portion of the basin. A

mixing ratio minimum occurred just above the Lechner Saddle outlet. The mixing ratio then increased with height to reach nighttime background values above the basin that were maintained at about  $5 \text{ g kg}^{-1}$ . After sunrise (Fig. 2b), mixing ratios increased in the basin as the higher mixing ratios from aloft descended into the basin and as evaporation increased from the ground. By 0659 CET, when the nocturnal inversion was nearly

Table 1. Values and units of parameters used in the calculations. Physical constants from Oke (1987).

parameter	value	units
$h$ = height of Lechner Saddle above basin floor	54	m
$A_h$ = drainage area at height $h$	$2.7 \times 10^5$	$m^2$
$V_h$ = air volume in basin below $h$	$6.05 \times 10^6$	$m^3$
$c_p$ = specific heat of air at constant pressure	1010	$J\ kg^{-1}\ K^{-1}$
$L_v$ = latent heat of vaporization	-2.5	$MJ\ kg^{-1}$
$L_s$ = latent heat of sublimation	-2.83	$MJ\ kg^{-1}$
$\rho_W$ = density of water	1000	$kg\ m^{-3}$

destroyed, the mixing ratio reached about  $6\ g\ kg^{-1}$  at the basin floor and decreased with height to the background values.

Estimates of the latent heat release in the lower enclosed basin and its effect on nighttime cooling can be made using the geometrical characteristics of the basin and the values of atmospheric constants listed in Table 1.

The latent heat released in the lower enclosed portion of the basin during the night is

$$H_L = \int_0^h L r(z) \Delta q(z) A(z) dz \quad (J), \quad (1)$$

where the increase in mixing ratio between sunset and sunrise  $\Delta q$ , the drainage area of the basin  $A$ , and the air density  $r$  are functions of height, and  $L$  is the latent heat (either latent heat of vaporization  $L_v$  or latent heat of sublimation  $L_s$ ), considered negative for condensation or vapor deposition.

The sensible heat loss from the lower basin is

$$H_S = - \int_0^h c_p r(z) \Delta T(z) A(z) dz \quad (J), \quad (2)$$

the mass of condensed liquid water is

$$M_W = - \int_0^h r(z) \Delta q(z) A(z) dz \quad (kg), \quad (3)$$

the dewfall volume is

$$V_W = M_W / \rho_W \quad (m^3), \quad (4)$$

and the dewfall depth is

$$D = \frac{V_W}{A_h} \quad (m). \quad (5)$$

The mixing ratio in the lower basin decreased by  $2-3\ g\ kg^{-1}$  between about 1900 CET 2 June (estimated  $q = 5.15\ g\ kg^{-1}$ , independent of height) and 0402 CET on 3 June. From equations (1) - (6), the latent heat release from condensation was 42 GJ, sensible heat loss was 90 GJ, the mass of condensed liquid water was 16,700 kg, dewfall volume was  $16.7\ m^3$  and dewfall depth was 61  $\mu m$ , and the ratio of latent heat release to sensible heat loss was  $42/90 = 0.47$ . For frost deposition, the latent heat release is 48 GJ and the ratio is 0.53. Thus, the latent heat released by dewfall or frostfall is quite a significant factor that reduces the sensible heat loss from the basin relative to the no-dew or no-frost case.

The sensible heat gains and mixing ratio losses in the lower basin during the post-sunrise morning transition period are roughly comparable to the nighttime values (but of opposite sign). Thus, much of the available energy during the post-sunrise period is used to evaporate water, slowing the inversion breakup in the basin compared to the no-dew case.

### B. 3-4 June 2002

The soundings on 3-4 June (Fig. 3a) were perturbed by moderately strong winds and cloudiness in the early evening. The two initial soundings exhibited a nearly constant potential temperature. A shallow inversion formed over the floor of the basin by the 2030 CET sounding, but it failed to grow further in depth or cool appreciably by the 2102 or 2131 CET soundings. Once the large-scale winds died and the clouds dissipated at 2300 CET, the basin went through a more typical cooling sequence. The mixing ratio profiles, also affected by the evening winds, oscillated about the well-mixed daytime value of  $6.1\ g\ kg^{-1}$  until after 2300 CET when the mixing ratios in the lower basin decreased and the drying progressed upwards in altitude. While the mixing ratio loss in the lower basin for the 2-3 June case was nearly independent of altitude, the 3-4 June loss decreased with altitude. Calculations show that the latent heat release for dewfall between sunset and 0114 CET was 29 GJ, the sensible heat loss was 87 GJ, the condensed liquid water was 11,750 kg, dewfall volume was  $11.8\ m^3$  and the dewfall depth was 44  $\mu m$ . For dewfall, the ratio of latent heat release to sensible heat loss was 0.33; for frostfall the latent heat release was 33 GJ and the ratio was 0.38.

Following sunrise, the moistening of the lower basin was accomplished through sinking of the higher mixing ratios from the upper basin and the evaporation of dew and frost from the surface. The post-sunrise sensible heat gains and latent heat losses were comparable to the nighttime values, although opposite in sign.

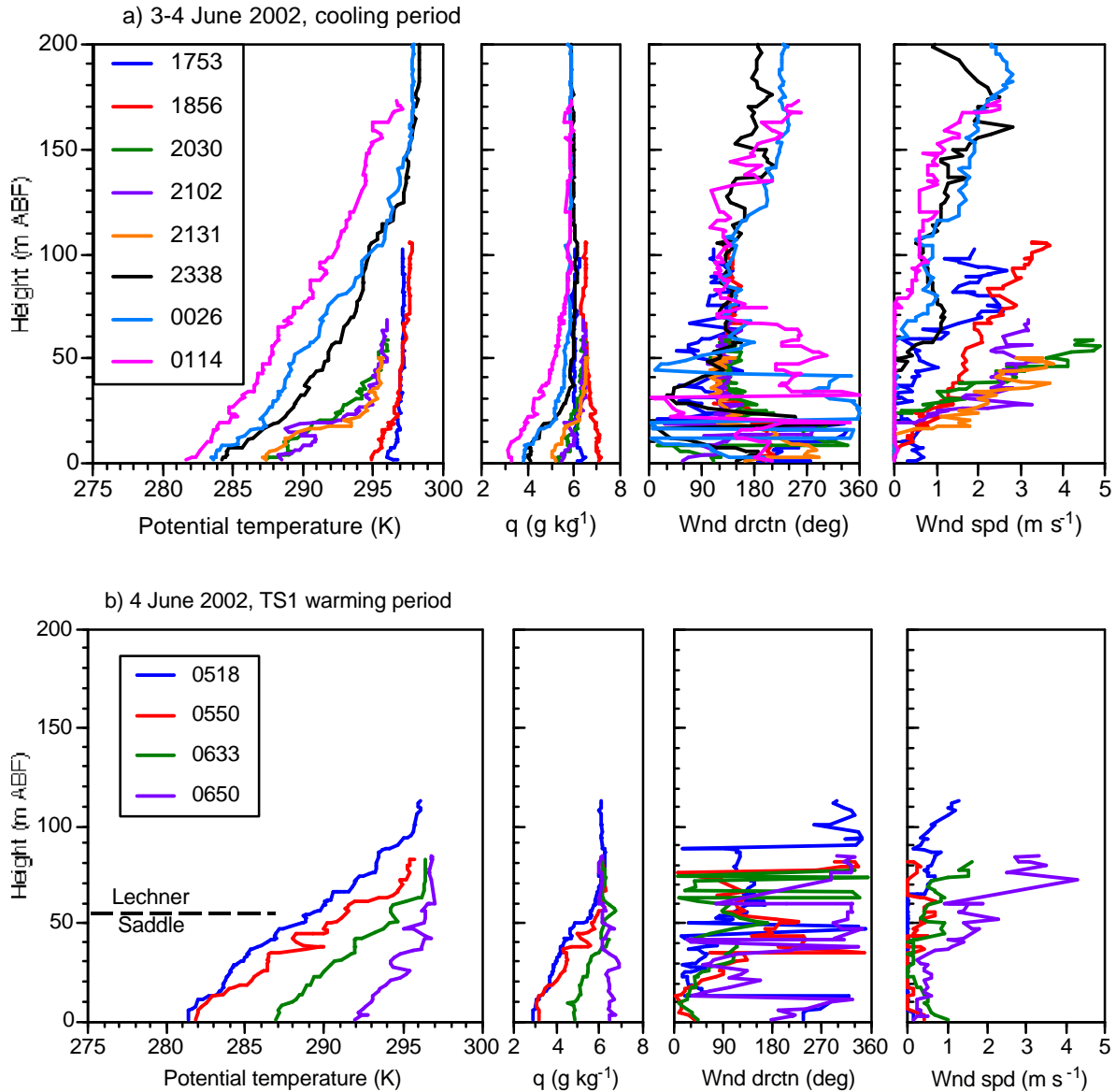


Figure 3. Same as 2, except for a) selected soundings on the night of 3-4 Jun 2002 and b) the morning of 4 Jun 2002.

## 5. DISCUSSION

Although fog tendrils were occasionally seen over the sidewalls on the morning of 4 June, the nighttime drying of the lower basin atmosphere was accomplished predominantly through dewfall and frostfall. As mentioned in the introduction, because water or ice on the ground can come from distillation or guttation, the observed frost or dew has other sources besides condensation from the atmosphere.

The Gruenloch sinkhole currently holds the minimum temperature record for central Europe,  $-52.6^{\circ}\text{C}$ , and is known to experience very cold temperatures in many winters. Geiger (1965) has stated

that such minima usually occur during cold, dry, synoptic weather incursions that result in clear nights following a fresh fall of new snow. Whiteman et al. (2004) reported that the diurnal temperature range on the floors of five sinkholes (including the Gruenloch) on Austria's Hetzkogel plateau on the clear night of 18-19 October 2001 ranged from  $22^{\circ}$  to  $28^{\circ}\text{C}$ , and that the Gruenloch temperature range on the clear night of 1-2 December 2001 following a fresh fall of snow reached  $19.7^{\circ}\text{C}$ . Such extreme diurnal temperature ranges, even with relatively dry air in the basin, will typically reduce air temperatures to the dew point. This has been illustrated recently by Zängl (2004), using numerical simulations (that include cloud microphysics) of sinkhole cooling

under extreme minimum conditions. Because radiative transfer is the key process removing heat from enclosed basins where stagnant air is trapped by the surrounding ridges, the removal of moisture from the basin atmosphere is critical to the attainment of these minima. To be maximally effective, the moisture should be removed without greatly decreasing the longwave radiative flux divergence in the sinkhole. It is interesting to speculate on the microphysical processes that could produce the drying. The flux of water vapor down the vapor gradient from the atmosphere to the surface or vegetation was responsible for the dewfall and frostfall observed in the June cases. In winter, the vapor flux could produce sublimation onto an existing snowpack. Other processes may play important roles in different circumstances. Deposition of cloud or fog droplets onto the ground or vegetation could occur through gravitational settling or through impaction onto surfaces as they are carried downslope in drainage flows. Nucleation of ice crystals in supercooled fog or cloud could cause ice crystals to form and fall, with the potential for additional moisture removal through riming, and drizzle could form in warm clouds. Some of these processes, while slow, could be important in a long-lived cloud that persisted all night.

The rate of release of latent heat in saturated air is smaller for the same temperature fall at colder ambient temperatures than at warmer ambient temperatures. Thus, the decrease in the rate of latent heat release in cold winter conditions could enhance the nighttime cooling in winter relative to warmer seasons.

## 6. CONCLUSIONS

The correspondence between temperature and moisture structure evolution in the small enclosed Gruenloch basin in the eastern Alps was investigated using series of tethered balloon soundings, with the goal of determining the diurnal evolution of moisture in the basin atmosphere, its effect on basin heat budgets and its relationship to boundary layer development. This investigation was motivated by the fact that heat budgets in closed basins are much easier to compute than heat budgets in valleys because of the closed volume in the basin and the consequent elimination of large-scale advective effects.

Data from the Gruenloch basin on two successive days showed that air confined inside the enclosed lower basin dried during the night as dewfall and frost formation occurred on the basin sidewalls and floor. The fall of frost or dew released latent heat. The latent heat released on these nights was a significant fraction of the sensible heat lost from the basin. If the air had been sufficiently dry that the nighttime temperature falls did not reach the dewpoint, no frostfall would have occurred and the nighttime cooling would have been substantially larger. This result was anticipated by Mahrt (1986) who stated that "the neglect of condensation in the surface energy budget can lead to significant overestimation of nocturnal cooling".

Diurnal temperature ranges are so large in this sinkhole on undisturbed clear nights that dewpoints will often be reached. To obtain the low temperature extremes that are characteristic of this basin, mechanisms must be available to dry the sinkhole atmosphere so that radiative processes can continue the cooling. In future research we plan to investigate whether microphysical processes in clouds or fogs that form within the sinkhole can provide alternative or more effective mechanisms for removing moisture from the sinkhole atmosphere.

While drying is the usual nighttime feature of the meteorology of this basin, moistening is the rule during daytime. Following sunrise, the moisture content increases in the basin as the elevated remnant of the nocturnal inversion descends into the basin, bringing down the higher moisture contents that remained above the basin during the night. Evaporation from the valley floor and sidewalls plays a role, as well, increasing the post-sunrise moisture contents. The evaporation will have an effect on the surface energy and atmospheric energy budgets, with much of the initial available energy going to evaporation rather than to sensible heat gain.

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