

Effect of Dewfall and Frostfall on Nighttime Cooling in a Small, Closed Basin

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ABSTRACT

Series of tethered balloon soundings of temperature and humidity in Austria's Gruenloch basin (floor elevation 1270 m MSL) on two June days showed that the water vapor mixing ratio fell by $2\text{--}3\text{ g kg}^{-1}$ overnight as dew or frost formed in the basin. After sunrise, the basin atmosphere remoistened as higher humidity was brought down into the basin from above and as evapotranspiration occurred from the basin floor and sidewalls. The latent heat released at night by the dewfall/frostfall was 33%–53% of the overall observed basin sensible heat loss, illustrating the important role of dew and frost formation on the nighttime heat budget of the basin atmosphere. An energy budget equation illustrates the decreasing importance of the latent heat release on the overall basin heat budget as ambient temperatures fall from summer to winter. Because the diurnal temperature range is frequently larger than the late-afternoon dewpoint depression, fog and clouds often form in this basin. The extreme temperature minima that have been previously observed in this basin are expected to be attained only if such cloud moisture is removed. Calculations show that several cloud moisture removal processes may be effective in removing this moisture.

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*. Dewdrops 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 sublayer 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, because this enhances turbulence and may even provide a source of new moisture. The increase with wind speed, however, occurs only for a limited range of wind speeds, because stronger winds can disrupt the nocturnal cooling. On windless nights, distillation is a

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relatively more important source of dew than 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.

Moisture condensation at the ground and the accompanying latent heat release has a number of practical implications. For example, they affect the forecasting of minimum temperatures, the moisture status and health of crops and ecosystems, and the postsunrise rate of growth of the unstable boundary layer. In addition, the formation of dew is closely coupled to the formation of fog, which may affect visibility, transportation systems, and other human activities.

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 (e.g., 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 from outside the sinkhole cannot be present.

2. Background

The humidity balance in valleys and basins is 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 equivalently deep 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 with 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 recirculate)

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 (1986) 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 in the valley decreased after sunrise as upslope flows carried humidity up the sidewalls, but increased in the afternoon as the up-valley wind advected higher humidity into the valley. 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., Halbguth 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 either valleys or basins. Sequences of valley humidity profiles generally show a loss of water vapor from 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 tethered balloon 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 nighttime 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 by the Department of Meteorology and Geophysics of the University of Vienna 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

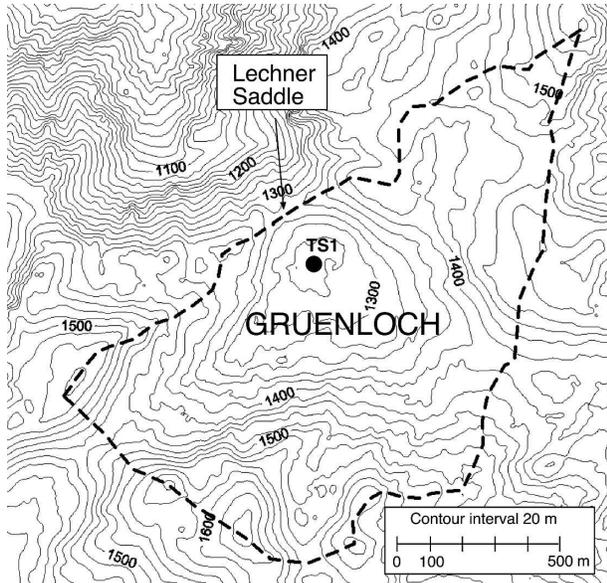


FIG. 1. Map of the Gruenloch basin showing the location of the tethered balloon system (TS1) and the drainage boundaries (dashed line).

of the sinkhole on the nights of 2–3 and 3–4 June 2002. Substantial dew and/or frost were noted on the ground and vegetation on both nights.

a. The Gruenloch basin

The Gruenloch (latitude: 47°49.22'N, longitude: 15°2.71'E), a small limestone sinkhole (Fig. 1) located on the Hetzkogel Plateau 5 km south of Lunz, Austria, is about 1 km in width and 150 m in 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). The Gruenloch is in a humid environment that receives approximately 2200 mm of precipitation per year. A deep humus layer occurs on the floor of the sinkhole with a small pond at the lowest elevation. The deep soil at the floor of the sinkhole decreases in depth with elevation, leaving patches of exposed limestone at the middle elevations of the sinkhole. Tall conifers grow on the higher-elevation slopes and ridges, while the lower elevations contain grasses and other subalpine herbaceous plants that can survive the extreme temperature minima experienced each winter at the floor of the sinkhole (Geiger 1965).

b. Synoptics

The night of 2–3 June was clear and undisturbed, whereas 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 central European standard time (CET). The winds decreased and the skies cleared by 2300 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 frost. Whiteman et al. (2004) provide further information on the synoptic weather conditions for the two nights. Astronomical sunset occurred at 1946 CET 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 (Figs. 2 and 3). The TS-3A tethered balloon sounding system (Atmospheric Instrumentation Research, Inc., Boulder, Colorado) used a small three-cup anemometer to measure wind speeds with an accuracy of 0.25 m s⁻¹ and a threshold starting speed of 0.5 m s⁻¹. Aspirated dry- and wet-bulb thermistors (accuracy ±0.5°C) were used to measure air temperature and determine the 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), because 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 it is 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. Equations

Estimates of the heat budget terms and dewfall quantities in an enclosed basin can be made from vertical soundings over the basin center by assuming horizontal homogeneity and using the geometrical characteristics of the basin and the values of atmospheric constants listed in Table 1.

The integrated latent heat gain (J) in an enclosed basin atmosphere is

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

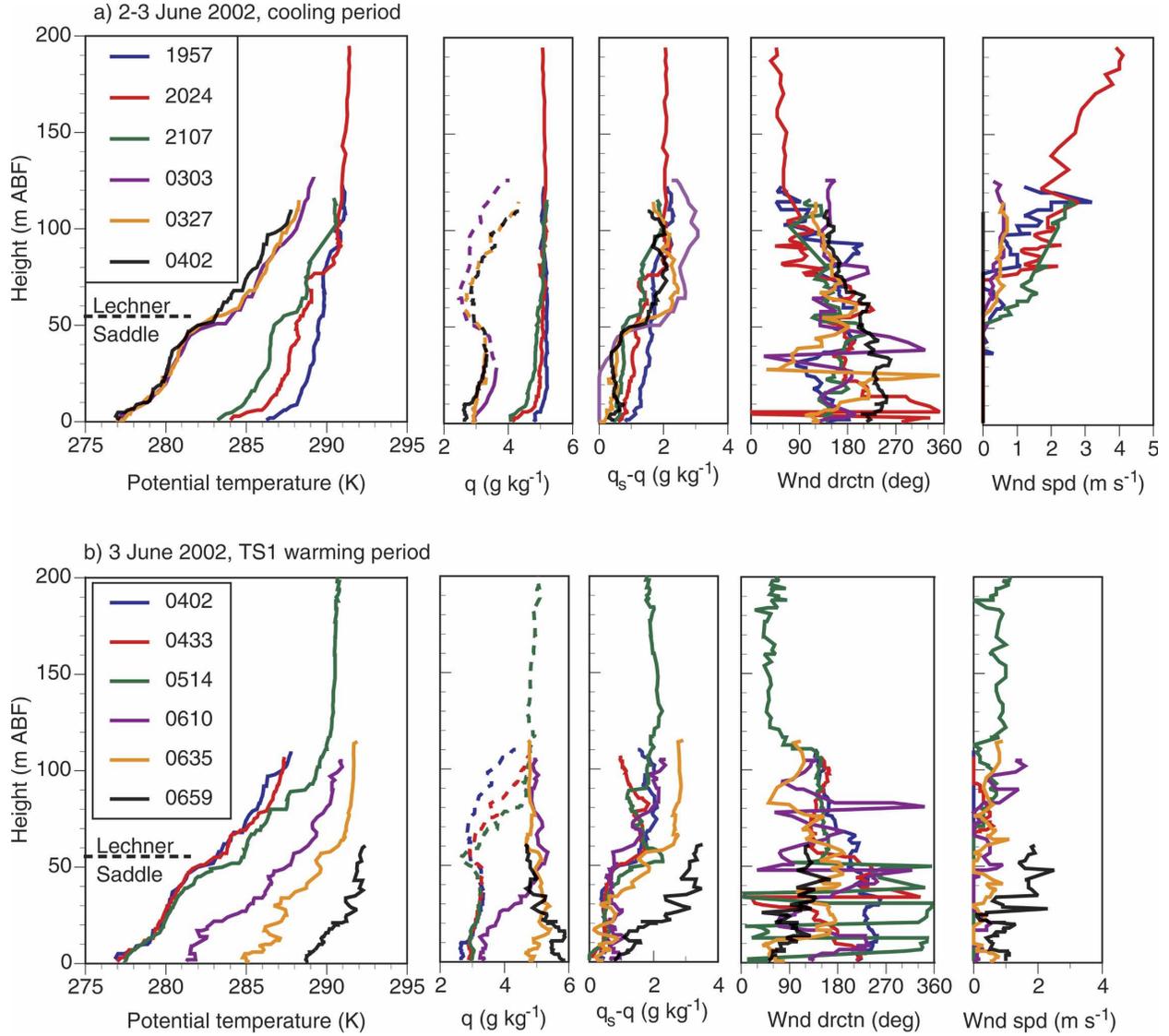


FIG. 2. Series of tethered balloon soundings of temperature, mixing ratio q , saturation mixing ratio deficit ($q_s - q$), wind direction, and wind speed in the Gruenloch basin on (a) the night of 2–3 Jun and (b) the morning of 3 Jun 2002. Heights are in m above the basin floor (ABF). Dashed lines in the mixing ratio soundings indicate where it is unclear whether freezing or thawing might have affected the profiles. The legend indicates the starting times of the balloon ascents in CET.

where Δq is the change in mixing ratio, A is the basin drainage area, ρ is air density, and L is the latent heat of condensation ($L_c = -2.5 \text{ MJ kg}^{-1}$) or deposition ($L_d = -2.83 \text{ MJ kg}^{-1}$).

The integrated sensible heat loss (J) from a basin is

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

the mass of condensed liquid water (kg) is

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

the dewfall volume (m^3) is

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

and the dewfall depth (m) over the drainage area of the basin is

$$D = V_W / A_h, \quad (5)$$

where A_h is the horizontal area at the height h of the top of the enclosed basin. These equations assume that the release of latent heat comes entirely from dew or frost formation, rather than from cloud or fog formation or from advection of moisture from outside the

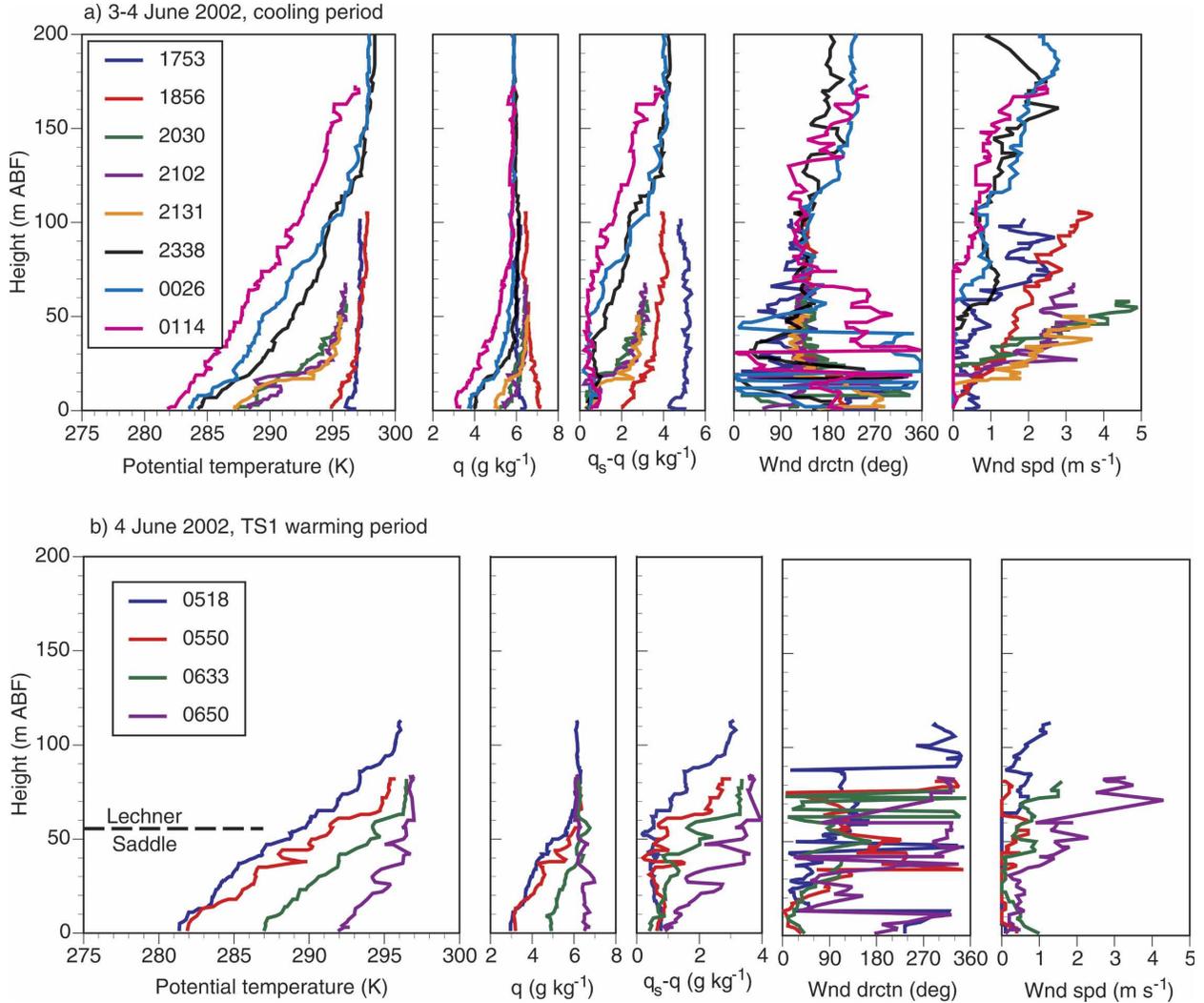


FIG. 3. Same as Fig. 2, but for (a) selected soundings on the night of 3–4 Jun 2002 and (b) the morning of 4 Jun 2002.

calculation volume. Distillation is not considered in these calculations; its effect would be to further enhance latent heat release in the basin.

5. Results

Tethered sondings (Figs. 2 and 3) were made during two observational periods of 2–3 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 first sounding at 1957 CET (times given are the starting times of the ascents), 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 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. Note that wind directions in Fig. 2a have little meaning in the lowest latitudes of the sinkhole where

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

Parameter	Value	Units
h = height of Lechner Saddle above basin floor	54	m
A_h = drainage area at height h	2.7×10^5	m ²
V_h = air volume in basin below h	6.05×10^6	m ³
c_p = specific heat of air at constant pressure	1010	J kg ⁻¹ K ⁻¹
ρ_w = density of water	1000	kg m ⁻³

wind speeds are below the threshold speed of the anemometer. The late-afternoon mixing ratio was about 5.2 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 to produce a double minimum—one at the basin floor and one just above the lower enclosed basin about 10–20 m above the Lechner Saddle. The relatively high values of mixing ratio between the two minima may have been produced by an inhibition of a moisture removal mechanism in the lower basin caused by the dying winds. Above the second minimum, the mixing ratio increased with height to reach nighttime background values above the basin that were maintained at about 5 g kg^{-1} . As temperatures fell during the night, the mixing ratios first approached their saturation values near the floor of the basin. The decreasing saturation mixing ratio deficits then moved progressively upward through the enclosed lower part of the basin. After sunrise (Fig. 2b), mixing ratios increased in the basin as the higher mixing ratios from aloft descended into the basin and as evapotranspiration increased. By 0659 CET, when the nocturnal inversion was nearly destroyed, the mixing ratio reached about 6 g kg^{-1} at the basin floor and decreased with height to the background values.

The mixing ratio in the lower basin decreased by 2–3 g kg^{-1} between about 1900 CET 2 June (estimated $q = 5.15 \text{ g kg}^{-1}$, independent of height) and 0402 CET 3 June. From Eqs. (1)–(5), as applied to the lower closed part of the Gruenloch sinkhole up to the height of the Lechner Saddle, 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 , dewfall depth was 0.061 mm, 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. As the calculations show, 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/no-frost case.

The sensible heat gain and latent heat loss in the lower basin during the postsunrise morning transition period are roughly comparable to the nighttime values (but of opposite sign). Thus, much of the available energy during the postsunrise period is used to evaporate water, slowing the inversion breakup in the basin in comparison with the no-dew case.

b. 3–4 June 2002

The soundings on 3–4 June (Figs. 3a and 3b) were perturbed by moderately strong winds and cloudiness in the early evening. The two initial soundings exhib-

ited 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 either 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 upward 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. The mixing ratios rapidly approached their saturation values as the cold air accumulated on the basin floor and as the cooling and drying progressed upward through the depth of the lower basin. Calculations using Eqs. (1)–(5) 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 0.044 mm. 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. To summarize, the nighttime drying of the lower-basin atmosphere was accomplished through dewfall and frostfall. The dew and frost observed on the ground and ground cover, as mentioned in the introduction, comes not only from condensation from the atmosphere, but also from distillation and guttation.

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. Similarly to the 2–3 June case, the postsunrise sensible heat gains and latent heat losses were comparable to the nighttime values, although opposite in sign.

6. Discussion

Further discussion will be focused on three issues. First, we will consider how the release of latent heat varies with ambient temperatures in the basin. The motivation for this is the knowledge that the Gruenloch experiences extremely low minimum temperatures in many winters (in fact it holds the minimum temperature record for central Europe, -52.6°C); there is thus an interest in latent heat release in the colder ambient conditions of winter. Second, we will compute the deposition velocity of water vapor for the two experimental nights. Third, we consider mechanisms other than dewfall and frostfall that could be responsible for night-

time drying of the Gruenloch atmosphere. The motivation for this is that the diurnal temperature range in the Gruenloch often exceeds the afternoon dewpoint depression, so that fog and clouds must often form in the Gruenloch with nighttime cooling when moisture removal by dewfall/frostfall or other mechanisms is not fast enough. Thus, an explanation of the low minimum temperatures that are often seen in the Gruenloch requires mechanisms that can remove fog and clouds that form in the basin or, at least, can decrease their optical depth to allow the nighttime radiative cooling to continue.

a. Release of latent heat within the Gruenloch

Consider an air parcel at a constant pressure p and temperature T that is saturated with water vapor at saturation mixing ratio q_s . The moist static energy H of the parcel is then $H = c_p T + Lq_s$, where c_p is the specific heat of air at constant pressure and L is the latent heat associated with the appropriate phase change of water vapor (L_c or L_d).

An energy increment (J kg^{-1}) extracted from the parcel

$$dH = c_p dT + Ldq_s \quad (6)$$

causes the parcel's temperature to fall by an increment $-dT$ and the parcel's water vapor content to decrease by an increment $-dq_s$. The decrease in water vapor content occurs through condensation, which produces liquid cloud droplets and releases an increment of latent heat that reduces the temperature fall that would have occurred if the air were unsaturated.

The saturation mixing ratio (kg kg^{-1}) is

$$q_s = 0.622e_s/(p - e_s), \quad (7)$$

where e_s is the saturation vapor pressure (hPa) as given by, say, the Magnus fit to the Clausius–Clapeyron equation

$$e_s(T) = a \exp\left(\frac{bT}{c + T}\right), \quad (8)$$

where the temperature is in degrees Celsius and the values of the coefficients a , b , and c vary depending on whether the saturation vapor pressure is computed over water ($a = 6.1078$, $b = 17.0809$, and $c = 234.175$), supercooled water ($a = 6.1078$, $b = 17.8436$, and $c = 245.425$), or ice ($a = 6.1071$, $b = 22.4429$, and $c = 272.440$). Plots of the mathematical relationship in Eq. (8) are shown in many introductory meteorology textbooks.

Because, at constant pressure, saturation mixing ratio is a function of T alone, the extraction of heat from a

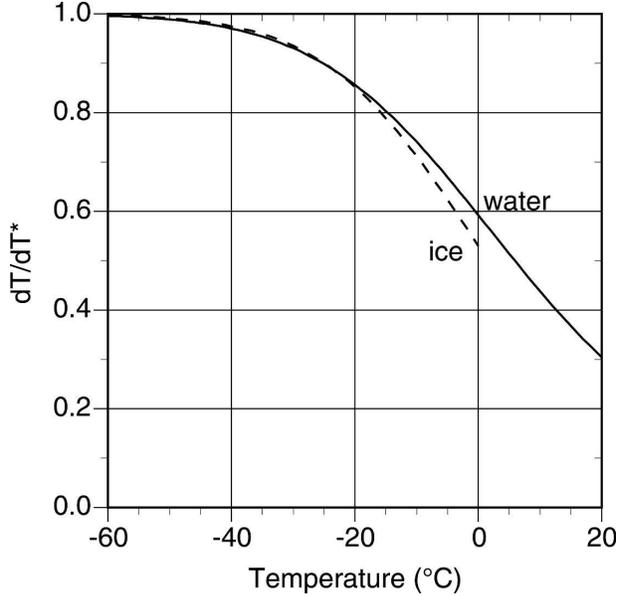


FIG. 4. Ratio of temperature changes with (dT) and without (dT^*) condensation as a function of temperature for water (solid curve) and ice (dashed curve).

saturated parcel is accompanied by a prescribed partitioning of the heat loss into the two terms on the right-hand side of Eq. (6).

To illustrate the reduced cooling in the presence of dewfall we determine the ratio of the temperature changes with (dT) and without (dT^*) condensation. From Eq. (6) it follows that

$$c_p dT^* = c_p dT + Ldq_s, \quad (9)$$

which gives for the cooling ratio

$$\frac{dT}{dT^*} = \frac{1}{1 + \frac{L dq_s}{c_p dT}}. \quad (10)$$

Figure 4 shows the cooling ratio according to Eq. (10) as a function of temperature for both saturation with respect to water and ice. At temperatures below -20°C sublimation effects reduce cooling by less than 15%. Around 0°C the effect reaches $\sim 45\%$, and at $+20^\circ\text{C}$ the cooling can be reduced by more than 65% in the presence of condensation.

The direct deposition of dew and/or frost in the Gruenloch on the June dates in question significantly decreased the nighttime cooling of the Gruenloch atmosphere through the release of latent heat. The formation of radiation fog or stratiform clouds in the Gruenloch, which must occur on occasion, would produce additional decreases in the cooling at the ground. Optically dense clouds lose radiation primarily from

their tops and the cold air generated there could overturn in the cloud and subcloud layers, decreasing the temperature fall at the basin floor relative to a clear-sky case. The extreme diurnal temperature ranges of 20°–30°C observed in the Gruenloch and in other basins are greater than the dewpoint depression usually observed in the late afternoon, suggesting that atmospheric moisture must be removed during the night if the basin is to continue the longwave loss that drives its cooling. Atmospheric moisture has an indirect radiative impact by producing additional downward longwave radiation and reducing the net longwave loss from the basin. In cases in which moisture condenses to form fog or cloud droplets, continued strong cooling of the basin atmosphere would require cloud droplet removal mechanisms so that the clouds could remain optically thin. In the next two sections, we briefly consider various mechanisms that may be responsible for removal of water vapor and cloud condensate from the basin atmosphere.

b. Direct deposition of water vapor

Clouds did not form in the Gruenloch on the night of 2–3 June 2002, and only a few wisps of fog were seen on the sidewalls on the morning of 4 June 2002. Thus, the removal of moisture from the Gruenloch atmosphere on these two nights was accomplished primarily by direct deposition of water vapor to the ground and vegetation to form dew or frost. In section 5, we estimated the equivalent depths of liquid water removed by deposition on these two nights to be 0.061 and 0.044 mm, respectively. On both nights, the mixing ratio gradients were of the correct sign to support this deposition, with mixing ratios increasing with height. The deposition velocity of the water vapor can be estimated using the equation

$$v_{\text{dep}} = M_w / (\rho q_{\text{sfc}} A_h \Delta t), \quad (11)$$

where M_w is the mass of water removed from the Gruenloch lower basin (section 4), ρ is air density, q_{sfc} is the near-surface mixing ratio, A_h is the drainage area of the lower basin, and Δt is the time interval over which the deposition occurs. For near-surface mixing ratios of 3 g kg⁻¹, and a 10-h night, deposition velocities are 0.0006 m s⁻¹ on 2 June and 0.0004 m s⁻¹ on 3 June.

c. Mechanisms for removal of cloud droplets from the Gruenloch atmosphere

There are many nights when fog or clouds form in the Gruenloch sinkhole (Geiger 1965). Whiteman et al. (2004) reported that the diurnal temperature ranges on the floor of the Gruenloch and four surrounding sink-

holes on the clear night of 18–19 October 2001 varied from 22° to 28°C. Such extreme diurnal temperature ranges, even with relatively dry air in the basins, will typically reduce air temperatures to the dewpoint. Zängl (2005) used numerical simulations of sinkhole cooling to show that the removal of moisture from the basin atmosphere is critical to the attainment of extreme temperature 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 in clouds and fog that could produce the drying 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. Additionally, drizzle could form in warm clouds although, if the clouds were dense enough or deep enough to form drizzle, it would be unlikely that extremely cold temperatures could form in the sinkhole. Some of these moisture removal processes, while slow, could be important in a long-lived cloud that persisted all night.

1) CIRCULATION INSIDE THE COLD POOL

Strong inversions that form in basins or sinkholes act as impediments to the development of nighttime drainage flows on the sidewalls. Observations in Peter Sinks, Utah, for example, found only weak air movements just above the sidewalls with depths of about 1 m and strengths of 0.3 m s⁻¹ (Clements et al. 2003). While no wind observations are available from the Gruenloch sidewalls, under similar nighttime stable conditions there are likely to be shallow drainage flows there, as well. They have also been observed by Mahrt et al. (2001) and others over lower-angled slopes. Whiteman et al.'s (2004) measurement of weak (<1°C) temperature deficits in the lowest 1–2 m above the Gruenloch sidewalls relative to the basin center support this conclusion. Assuming sidewall flows of 1-m depth H and strength $U = 0.2$ m s⁻¹, and using the Gruenloch circumference $S = 1300$ m at a height midway to the Lechner Saddle, the downslope volume flux would be

$$dV/dt = SUH = 1300 \times 0.2 \times 1 = 260 \text{ m}^3 \text{ s}^{-1}. \quad (12)$$

The Gruenloch volume below the Lechner Saddle is $V = 6.05 \times 10^6$ m³, and the turnover time of the air in the Gruenloch would be $\tau = V/(dV/dt) = 6.5$ h. It is

conceivable, then, that shallow, weak drainage flows on the sidewalls would recycle the air in the basin volume, continuously replenishing moisture that is lost to the sidewalls through deposition or to bring cloud droplets to the surface where they could be deposited on soil or vegetation. On the other hand, the development of dense fog or cloud might rapidly suppress the down-slope winds. With a volume flux of $260 \text{ m}^3 \text{ s}^{-1}$, cloud water of 0.1 g m^{-3} (Cotton and Anthes 1989), a horizontal drainage area of $2.7 \times 10^5 \text{ m}^2$, and a 10-h night, 3.5 g of water would be deposited per square meter for an equivalent depth of water of 0.0035 mm. This is much smaller than the equivalent depth of water produced by direct deposition on 2 and 3 June 2002.

2) SETTLING OF FOG OR CLOUD DROPLETS

The terminal velocity of fog droplets produced by condensation in the sinkhole is estimated from the Stokes law (Stull 2000) as

$$w \approx k_1 r^2, \quad (13)$$

where $k_1 = -1.19 \times 10^8 \text{ m}^{-1} \text{ s}^{-1}$, r is the radius of the droplet, and the negative sign indicates that the droplets are falling. Following this formula, droplets of $10\text{-}\mu\text{m}$ size have a terminal velocity of -0.012 m s^{-1} and would fall 43 m h^{-1} or 432 m in a 10-h night. The settling velocity of the fog droplets may thus be significant in the removal of fog droplets in the quiescent conditions of the nighttime cold-air pool. Assuming 0.1 g m^{-3} of cloud water, 432 g of water would be deposited per square meter by this process for an equivalent depth of water of 0.043 mm. This is similar in value to that removed by direct deposition on 2 and 3 June 2002.

3) SNOW OUT

Other cloud microphysical processes can more efficiently remove cloud or fog condensate from the sinkhole atmosphere, allowing the continuation of long-wave loss that would allow sinkhole temperatures to fall to extreme minima. The nucleation of ice crystals in supercooled fog or clouds that form in the sinkhole can result in vapor deposition on the crystals and their subsequent fall and, even, removal of additional supercooled cloud mass from the atmosphere by riming. The terminal velocities of single, unrimed, dry crystals (Fletcher 1966) are generally in the range from 0.25 to 0.60 m s^{-1} , depending somewhat on crystal type (plate, needle, dendrite, etc.). These fall speeds, except for needles, are nearly independent of crystal size. The terminal velocities of rimed crystals (Fletcher 1966) increase with crystal size, with typical speeds of 1 m s^{-1} . It would take only 120–480 s for crystals with terminal

velocities of $0.25\text{--}1 \text{ m s}^{-1}$ to fall through the entire 120-m depth of the sinkhole inversion. The equivalent depth of water removed by this process, assuming a 10-h night, would be 9–36 mm. This is much larger than the equivalent depth of water produced by direct deposition on 2 and 3 June 2002.

7. Conclusions

The correspondence between temperature and moisture structure evolution in the small, enclosed Gruenloch basin in the eastern Alps was investigated using a series of tethered balloon soundings, with the goals 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 easier to compute than heat budgets in valleys because of the closed volume of 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 frostfall occurred on the basin sidewalls and floor. This deposition of frost or dew releases latent heat. Calculations of the latent heat release show that the latent heat released on these nights was 33%–53% of the total 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 sensible 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.” The nighttime drying of the basin atmosphere is enhanced relative to that experienced over flat terrain by 1) the additional surface area that is in contact with the atmospheric volume of the basin, and 2) drainage flows over the sidewalls that can replenish water vapor or cloud droplets that are deposited on the vegetative or ground surfaces of the basin.

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.

Diurnal temperature ranges are so large in this sinkhole on undisturbed clear nights that the dewpoint temperature will often be reached, leading to the formation of fog or clouds. To obtain the low-temperature ex-

tremes that are characteristic of this basin, mechanisms must be available to remove cloud droplets from the sinkhole atmosphere so that radiative processes can continue the cooling. This paper discusses several cloud microphysical processes that could be responsible for the removal of cloud droplets. Weak, shallow downslope flows over the sidewalls could recirculate air within the closed basin and deposit cloud droplets on the basin vegetation and soil surfaces. This mechanism, for the strengths and depths of downslope flows assumed, results in moisture removal rates that are considerably below those observed by direct deposition of water vapor on the clear nights of 2 and 3 June 2002. Simple gravitational settling of the cloud droplets could remove moisture at about the same rate as observed on 2 and 3 June 2002. Moisture removal rates, however, can be much larger for snow out.

Although drying is the usual nighttime feature of the meteorological conditions 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 postsunrise 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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