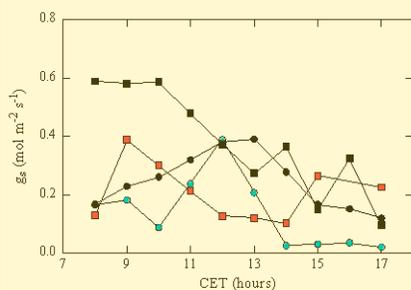


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Independent measurements of grassland evapotranspiration (ET) are compared against the eddy covariance (EC) method and used for inferring how to best close the energy imbalance commonly encountered with this method. To force energy balance closure, and thereby correct EC estimates of ET, adjustment with the average energy balance ratio is recommended.

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Insights from Independent Evapotranspiration Estimates for Closing the Energy Balance: A Grassland Case Study

When using the eddy covariance (EC) method for measuring the ecosystem–atmosphere exchange of sensible and latent heat, it is not uncommon to find that these two energy fluxes fall short of the available energy by 20 to 30%. As the causes for the energy imbalance are still under discussion, it is currently not clear how the energy balance should be closed. The objective of this study was to use independent measurements of evapotranspiration (ET) for empirically devising how to best close the energy balance. To this end, the ET of a temperate mountain grassland was quantified during two measurement campaigns using both an open- and a closed-path EC system, lysimeters, and an approach scaling up leaf-level stomatal conductance to canopy-level transpiration. Our study showed that both EC systems underestimated ET measured independently by lysimeters and the upscaling approach. The best correspondence with independently measured ET was achieved by assigning the entire energy imbalance to ET and by adjusting the ET according to the average energy balance ratio during the first and second measurement campaigns, respectively. Due to a large spatial variability in ET during the first measurement campaign and given large differences in spatial scale between the EC and the independent methods, we are more confident with the comparison of approaches during the second measurement campaign and thus recommend forcing energy balance closure by adjusting for the average energy balance ratio.

Abbreviations: CP, closed path; EC, eddy covariance; ET, evapotranspiration; IRGA, infrared gas analyzer; OP, open path; PAI plant area index.

The energy imbalance, that is the widespread shortfall of measured sensible (H) and latent (λE) heat fluxes with respect to available energy on the order of 20 to 30% (Wilson et al., 2002; Foken, 2008), is the thorn in the side of EC flux measurements (Baldocchi et al., 1988; Aubinet et al., 2000). Mathematically, the energy imbalance may be expressed as

$$\text{Res} = R_n - \lambda E - H - G \quad [1]$$

where Res is the residual energy or energy imbalance, R_n is the net radiation, and G is the soil heat flux. We note that Eq. [1] neglects other forms of heat fluxes such as biomass storage or metabolic reactions (Meyers and Hollinger, 2004; Oncley et al., 2007; Jacobs et al., 2008).

Because the causes of the energy imbalance are still under discussion (for a recent synthesis, see Foken, 2008), EC measurements of ET must be suspected of being biased low—in the most extreme case, the entire energy imbalance may be attributed to the latent heat flux (Wohlfahrt et al., 2009). The resulting uncertainty not only may be prohibitive for using EC ET measurements for practical applications such as irrigation scheduling (Twine et al., 2000) but poses problems if models, which assume the energy balance to be closed, are to be calibrated with EC flux data (Williams et al., 2009). Along this line, Wohlfahrt et al. (2009) recently showed that surface conductance estimates derived by inverting the Penman–Monteith combination equation (Campbell and Norman, 1998) may differ widely depending on how energy balance closure is forced.

Clearly, elucidating the causes for the energy imbalance should be one of the prime micrometeorologic research goals in the near future, also because the energy imbalance, if due to a systematic underestimation of the latent or sensible heat flux, may have implications for EC flux measurements of other trace gases (Twine et al., 2000; assuming scalar similarity with heat fluxes). In the meantime, alternative methods of quantifying ET may be used for comparison with ET measured by means of the EC method as a practical approach for correcting for the energy imbalance (Chavez et al., 2009).

The objective of this study was to use the EC and two alternative, independent methods to quantify ET of a temperate mountain grassland in Austria and to infer from a comparison of these how to best force energy balance closure with the EC flux data. To this end, two measurement campaigns were conducted during which, in addition to both an open-path and closed-path EC system (Haslwanter et al., 2009), ET was measured by weighing lysimeters (Wieser et al., 2008) and an approach by which measurements of leaf-level stomatal conductance were scaled up to canopy-level transpiration.

Materials and Methods

Study Site and Conditions during Measurement Campaigns

The study site was located in a meadow in the vicinity of the village of Neustift (47°7' N, 11°19' E) in the Stubai Valley (Austria) at an elevation of 970 m above sea level in the middle of the flat valley bottom. The fetch is homogenous up to 300 m to the east and 900 m to the west of the instrument tower, the dominant day- and nighttime wind directions, respectively. The average annual temperature is 6.5°C, and the average annual precipitation amounts to 852 mm. Further details on the soil, vegetation, and climate may be found in Hammerle et al. (2008) and Wohlfahrt et al. (2008).

Two measurement campaigns were conducted in June 2009 for determining the grassland ET by means of lysimeters and upscaling under conditions of contrasting canopy cover. The first campaign took place on 4 June, which was a relatively cool day (daytime average air temperature of 13.5°C) with little evaporative demand (daytime average vapor pressure deficit [VPD] of 0.7 kPa) and alternating periods of sunshine and clouds. The canopy was about 1 m tall and the plant area index (total amount of plant area per ground area) amounted to 8.6 m² m⁻² (96% of which were green leaves and stems). The second campaign took place on 18 June, after the meadow had been cut for the first time that year. This was a sunny (some thin clouds in the afternoon) and warm (daytime average air temperature of 21.3°C) day with a relatively high evaporative demand (daytime average VPD of 1.5 kPa). The canopy height was 0.15 m and the plant area index amounted to around 2.1 m² m⁻² (90% of which were green leaves and stems).

Eddy Covariance

Evapotranspiration, which may be converted to the flux of latent heat by multiplication with the latent heat of vaporization, and sensible heat fluxes were measured using the EC method (Baldocchi et al., 1988; Aubinet et al., 2000) as part of long-term flux measurements at this site since 2001 (Hammerle et al., 2008; Wohlfahrt et al., 2008; Haslwanter et al., 2009). The three wind components and the speed of sound were measured by a three-dimensional sonic anemometer (R3IA, Gill Instruments, Lymington, UK), H₂O mole densities or fractions by open-path (OP) (Li-7500, Li-Cor, Lincoln, NE) and closed-path (CP) (Li-7000, Li-Cor) infrared gas analyzers (IRGAs). In the CP system, air was sucked

from the inlet, displaced 0.1 m laterally and 0.1 m below the center of the sensor volume of the sonic anemometer mounted at 2.5 m above the ground, through a 10-m heated (to 35°C) Teflon tube of 0.004-m inner diameter through a filter (Acro 50, Gelman Sciences, Ann Arbor, MI) to the CP IRGA at a flow rate of 9 L min⁻¹ (N035ANE, KNF Neuberger, Freiburg, Germany). The CP IRGA was operated in the absolute mode, flushing the reference cell with dry N₂ from a gas cylinder at 0.1 L min⁻¹. The OP IRGA was displaced 0.3 m laterally and 0.2 m below the center of the sensor volume of the sonic anemometer and was tilted at an angle of 45° toward north. Both the CP and OP IRGAs were arranged approximately at right angles to the main daytime and nighttime wind direction thereby minimizing longitudinal sensor separation to the sonic anemometer. Raw voltage signals of the H₂O mole fractions or densities from both IRGAs were input at 10 Hz by the analog input of the sonic anemometer, where they were synchronized with the sonic signals, which were output at 20 Hz. All raw data were saved to the hard disk of a personal computer using the EdiSol software (School of Geosciences, Univ. of Edinburgh, Edinburgh, UK).

Half-hourly mean eddy fluxes of latent and sensible heat were calculated as the covariance between the turbulent departures from the mean of the vertical wind speed and the H₂O mixing ratios and sonic temperature, respectively, using the post-processing software EdiRe (School of Geosciences, Univ. of Edinburgh). Means and corresponding turbulent departures were calculated by Reynolds (block) averaging. The tube-induced time delay of the H₂O (0.9-s) signals was determined by optimizing the correlation coefficient with the vertical wind velocity (McMillen, 1988) within a given time window. A fixed lag of 0.3 s was imposed on the OP data through the IRGA software and removed. A three-axis coordinate rotation was performed, aligning the coordinate system's vector basis with the mean wind streamlines (Kaimal and Finnigan, 1994). Frequency response corrections were applied to the raw eddy fluxes, accounting for high-pass (block averaging) and low-pass (lateral sensor separation, dynamic frequency response, scalar and vector path averaging, frequency response mismatch, and in the case of the CP IRGA, the attenuation of concentration fluctuations down the sampling tube) filtering following Moore (1986), Massman (1991), and Aubinet et al. (2000). To this end, a site-specific model cospectrum, described in Wohlfahrt et al. (2005), was used. Finally, the sensible heat flux was corrected for the effects of air humidity following Schotanus et al. (1983) and density corrections were applied to both CP and OP latent heat fluxes based on Webb et al. (1980). For the CP fluxes, only the water vapor effect was corrected for because temperature fluctuations were assumed to have been dampened out by the time air arrived in the IRGA (Aubinet et al., 2000). Corrections for the effect of self-heating of the OP IRGA (Burba et al., 2008) were not applied because a previous comparison between fluxes measured by the OP and CP IRGAs found that this correction decreased the correspondence between the two EC systems (Haslwanter et al., 2009).

Evapotranspiration and sensible heat fluxes were calculated as the sum of the corrected vertical eddy term and the storage fluxes, the latter being estimated from the time-rate-of-change of the H₂O density and air temperature at the reference height, which in a previous comparison with a profiling system was found to be sufficiently accurate. Negative fluxes represent transport from the atmosphere toward the surface, positive ones the reverse.

Half-hourly flux data were quality controlled by the removal of time periods with (i) the H₂O signal outside a physically plausible range, (ii) the coefficient of variation for H₂O concentration and, in the case of the CP IRGA, internal pressure outside a specific range, (iii) the third rotation angle exceeding $\pm 10^\circ$ (McMillen, 1988), (iv) the stationarity test for the latent and sensible heat flux exceeding 60% (Foken and Wichura, 1996), (v) the deviation of the integral similarity characteristics >60% (Foken and Wichura, 1996), and (vi) the maximum of the footprint function (Hsieh et al., 2000) outside the boundaries of the meadow (cf. Novick et al., 2004).

Similar to Wohlfahrt et al. (2009), we used five scenarios for correcting ET measured by means of the EC method for any energy imbalance:

1. ET_orig: ET as measured by the EC method is assumed correct, i.e., the energy balance is closed each half-hourly period by attributing the residual energy to H or the available energy (i.e., $R_n - G$).
2. ET_resid: the energy balance is closed each half-hourly period by attributing all the residual energy to λE .
3. ET_β: the energy balance is closed each half-hourly period by attributing the residual energy to both H and λE according to (and thus preserving) the Bowen ratio ($\beta = H/\lambda E$).
4. ET_debc: the energy balance is closed on a daily basis by dividing the measured half-hourly H and λE by the daily energy balance ratio, which implies that β is conserved but also that during each half-hourly period the energy balance may not necessarily be closed.
5. ET_ltebc: the same as Scenario 4, but the energy balance is closed on a long-term basis (the entire month of June 2009 in the present case).

Lysimeter

The lysimeters (six replicates) consisted of 0.19-m-deep plastic cylinders with a diameter of 0.2 m (0.006-m³ volume and 0.03-m² area) that were filled with intact vegetated soil monoliths (Wieser et al., 2008) carefully excavated at the site 2 wk before the first measurement campaign. Care was taken to select excavated monoliths containing vegetation typical for the study site—this was achieved by comparing species composition, canopy height, and density. Previous experience (Wieser et al., 2008) indicated that lysimeters do function properly during extended time periods as long as the soil water is replenished at regular intervals. Between the excavation of the soil monoliths and the second measurement campaign, a total of 114 mm of precipitation was recorded, which is somewhat above the long-term average for this time of the year; on average, it rained every second day. The lysimeters were weighed at hourly (4 June 2009) and half-hourly (18 June 2009) intervals,

each measurement lasting <30 s. In between the measurements, the lysimeters were placed back into another set of cylinders with a slightly larger diameter that were sunk into the ground so that the upper edge of the lysimeters was level with the soil surface and exposed to an unaltered microclimate by the surrounding, undisturbed canopy (Wieser et al., 2008). The ET (mm h⁻¹) was calculated as the (half-)hourly mass difference (kg) divided by the area of the lysimeters (m²), the time difference between samplings (h), and water density ($\sim 1 \text{ kg m}^{-3}$).

Porometer-Based Upscaling

Transpiration of a dry plant canopy (T , mm h⁻¹) was estimated by upscaling leaf-level stomatal conductance to canopy-level transpiration using the following equation:

$$T = 3600M_w \times \sum_{p=1}^n \sum_{z=0}^h A(p, z) g_1(p, z) \frac{e_s(p, z) - e_a(z)}{P} \quad [2]$$

where M_w is the molecular mass of water (0.018 kg mol⁻¹), A is the plant area index (PAI, m² green plant area m⁻² ground area), g_1 is the leaf conductance to water vapor (mol m⁻² s⁻¹), e_s and e_a are the saturation and actual water vapor partial pressures (kPa), respectively, and P is the atmospheric pressure (kPa). The indices p and z refer to the plant species and canopy layer number (i.e., height above the ground) across which the summation occurs in Eq. [2]. The PAI was determined in a destructive fashion by stratified clipping of a representative square plot of 0.25 m² (Wohlfahrt et al., 2001). The thickness of the harvested layers ranged between 0.1 and 0.2 m, depending on the plant area density (higher resolution in the lower canopy). The harvested plant material was separated into leaves, (green) stems, reproductive organs, dead plant matter, and cryptogams. The latter three groups contributed <4% to the total plant area and their ET was neglected in Eq. [2]. Leaves and stems were further separated into the dominant herbaceous species (*Ranunculus acris* L., *Taraxacum officinale* F.H. Wigg. aggr., and *Trifolium* sp.), while the leaves and stems of all remaining forbs and grasses were pooled. The one-sided plant area was determined with an area meter (Li-3100, Li-Cor, Lincoln, NE).

The leaf conductance to water vapor was calculated according to the following equation, which makes the reasonable assumption of stomata being distributed just on one (the lower) leaf side:

$$g_1(p, z) = \frac{g_s(p, z) g_b(p, z)}{g_s(p, z) + g_b(p, z)} \quad [3]$$

where g_s is the stomatal conductance to water vapor (mol m⁻² s⁻¹), which was measured at hourly intervals (three replicates) under the prevailing environmental conditions on one grass (*Dactylis glomerata* L.) and three herbaceous (*R. acris*, *T. officinale*, and *Trifolium* sp.) species at various levels (species specific) within the canopy using a portable leaf porometer (Decagon Devices, Pullman,

WA), and g_b is the leaf boundary layer conductance to water vapor ($\text{mol m}^{-2} \text{s}^{-1}$), which was calculated according to Campbell and Norman (1998):

$$g_b(p, z) = 0.147 \sqrt{\frac{u(z)}{d(p, z)}} \quad [4]$$

where u is the mean horizontal wind velocity (m s^{-1}) measured at three levels (0.09, 0.35, and 0.90 m) within the canopy by means of hot-wire anemometers (ThermoAir2, Schildknecht Messtechnik, Gossau, Switzerland), and d is the leaf width (m), which was measured with a ruler.

The saturation water vapor partial pressure (e_s , kPa) was calculated as a function of leaf temperature (Campbell and Norman, 1998), which was measured by means of thermocouples (SA1-T, Omega Engineering, Stamford, CT) on seven leaves of three species (*D. glomerata*, *T. officinale*, and *Trifolium* sp.) at two to three heights (0.06–0.62 m) within the plant canopy. The actual water vapor partial pressure (e_a , kPa) was measured at three heights within or above the canopy (0.09, 0.35, and 2.0 m) with ventilated air temperature and humidity sensors (RFT-2, UMS, Munich, Germany). The atmospheric pressure (P , kPa) was measured with a barometer (CS100 Setra 278, Campbell Scientific, Logan, UT). All of these data except for the stomatal conductance data, which were saved on the leaf porometer, were logged on a datalogger (CR3000, Campbell Scientific, Logan, UT) and saved as half-hourly averages.

To apply Eq. [2], the measured leaf temperatures, actual water vapor partial pressures, wind speeds and stomatal conductances were linearly interpolated (close to the soil surface and toward the canopy top, in some cases they were also extrapolated) vertically to the grid of the plant area measurements (to the midpoint of each layer). Equation [2] neglects soil evaporation—this is not likely to cause a large systematic bias when the canopy is tall (see Wieser et al., 2008, and references therein), as during the first measurement campaign (4 June 2009). During the second measurement campaign on 18 June 2009, after the first cut, soil evaporation may, however, have contributed a sizeable fraction of the total ecosystem ET (Hammerle et al., 2008) and therefore we did not conduct the upscaling experiment during the second measurement campaign.

Ancillary Measurements

Supporting meteorologic measurements of relevance to this study included total photosynthetically active radiation (BF3H, Delta-T Devices, Cambridge, UK), air temperature and relative humidity at 2-m height, and soil temperature averaged across 0 to 0.05 m and at the 0.05-m depth, measured by the means of a combined temperature and humidity sensor (RFT-2, UMS, Munich, Germany) and averaging thermocouples (TCAV, Campbell Scientific, Logan, UT), respectively, soil heat flux (G) measured by the means of heat flux plates (three replicates at 0.05-m depth; HFP01, Hukseflux Thermal Sensors, Delft, the Netherlands) corrected for the change in heat storage above that depth using the calorimetric method

(Sauer and Horton, 2005), volumetric soil water content at the 0.05-m depth (ML2x, Delta-T Devices, Cambridge, UK), and precipitation (52202, R.M. Young, Traverse City, MI). Net radiation was measured with a four-component net radiometer (CNR-1, Kipp & Zonen, Delft, the Netherlands) with a quoted accuracy of daily sums of 10% for each radiation component. The calibration of the net radiometer was done at the factory and is traceable to the World Radiometric Reference in the case of the two pyranometers (CM3), while no primary standard exists for the pyrgeometers (CG3), which were calibrated against a reference that has been calibrated against a cold blackbody radiation source. All data were saved as half-hourly averages by a datalogger (CR10X, Campbell Scientific, Logan, UT).

Results

Using all the available data from June 2009, the (long-term) energy balance closure amounted to 84 and 85% with the CP and OP EC systems, respectively (linear regressions not significantly different; Fig. 1). Energy balance closure during the two measurement campaigns was very similar to the long-term closure for both systems (linear regressions not significantly different; Fig. 1).

As shown as an example in Fig. 2a, stomatal conductance was generally lower close to the soil surface and increased toward the canopy top. Stomatal conductance did not follow a general diurnal trend across species and canopy layers—in some cases, maximum conductances were reached around 1200 h, while in other cases conductances tended to be higher in the morning (and afternoon), and in some cases hardly any diurnal variation was observed (Fig. 2b). Plant area density was greatest in the lowermost canopy layer (<0.1 m) due to a large contribution by grasses, fairly constant to about 0.4 m, and from there quickly declined toward the canopy top (Fig. 2c). The vertical distribution of transpiration (Fig. 2d) reflected both the vertical distribution of the transpiring plant area (Fig. 2c) and the vertical gradient in transpiration per unit plant area (Fig. 2a).

On 4 June, i.e., before the cut, ET measured by both EC systems fell short of both the ET measured by the lysimeters and the upscaling approach by 24 to 34 and 29 to 39%, respectively (Fig. 3). The upscaled ET was within one standard deviation of the lysimeter ET (up to 0.2 mm h^{-1}), except for between 1100 and 1200 h (Fig. 3). The best qualitative and quantitative correspondence to the independent ET measurements was achieved when assigning the entire energy imbalance to ET (ET_resid; Table 1). In the case of the lysimeter measurements, the slopes and y intercepts of the linear regressions with ET measured by the EC method were not statistically significantly different from 1 and 0, respectively (Table 1). On 18 June, both EC systems underestimated the lysimeter ET by 18 to 19% (Fig. 3). Because the variability in lysimeter ET (up to 0.09 mm h^{-1} standard deviation) was much lower than the first measurement campaign, ET measured by the EC method was generally

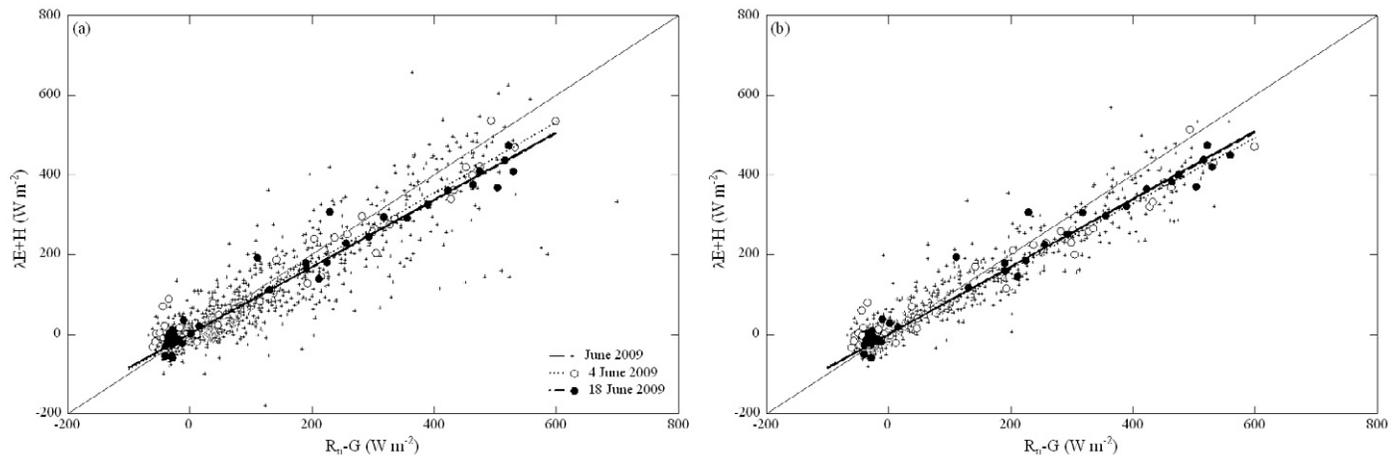


Fig. 1. Energy balance closure as latent (λE) plus sensible heat (H) vs. net radiation (R_n) minus soil heat flux (G) for the (a) closed-path and (b) open-path eddy covariance system from all of June 2009 compared with 4 and 18 June 2009. Linear regressions forced through the origin yielded the following coefficients: closed-path eddy covariance system: 0.84 (all of June), 0.89 (4 June), 0.84 (18 June); open-path eddy covariance system: 0.85 (all of June), 0.82 (4 June), 0.84 (18 June). The thin solid line (1:1 line) indicates perfect energy balance closure.

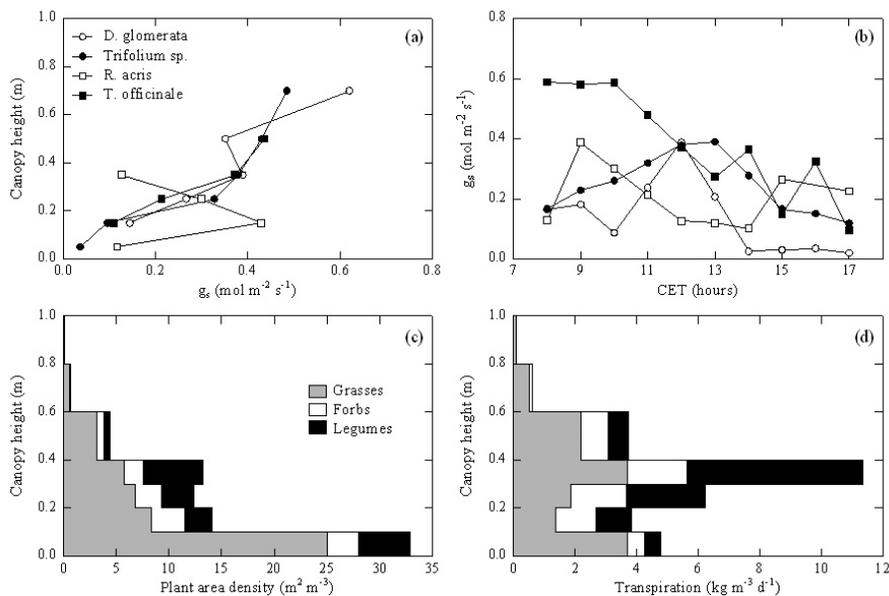


Fig. 2. Key results of the upscaling approach: (a) vertical profile of midday leaf-level stomatal conductance (g_s) for *Dactylis glomerata*, *Ranunculus acris*, *Taraxacum officinale*, and *Trifolium sp.*, (b) diurnal course of leaf-level stomatal conductance in the 0.3- to 0.4-m canopy layer, (c) vertical profile of plant area density, and (d) vertical profile of modeled transpiration. The various plant species have been pooled into three functional groups in (c) and (d).

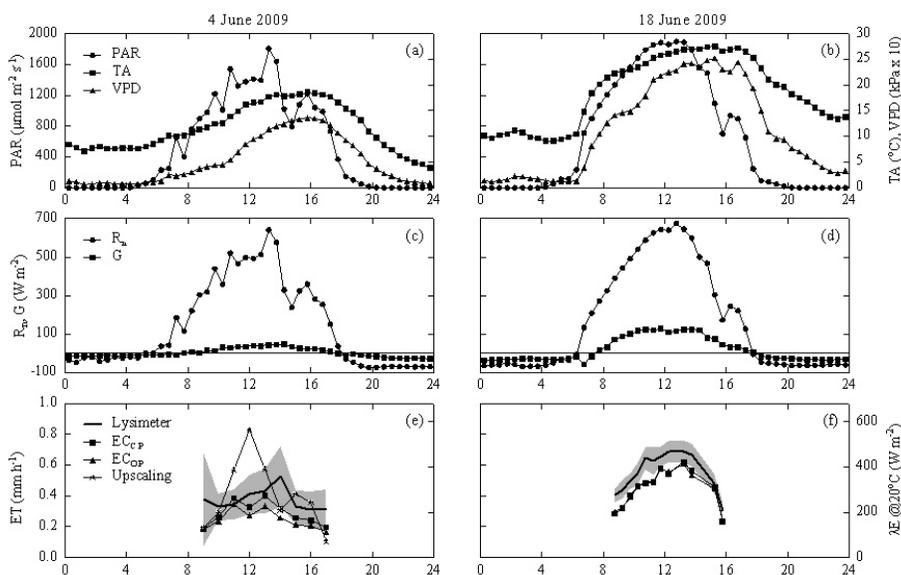


Fig. 3. Diurnal courses of (a and b) photosynthetically active radiation (PAR), air temperature (TA), and vapor pressure deficit (VPD), (c and d) net radiation (R_n) and soil heat flux (G), and (e and f) evapotranspiration (ET). The gray shaded area indicates one standard deviation ($n = 6$) around the mean of evapotranspiration measured by lysimeters; ET in energy units (λE , assuming an air temperature of 20°C) is shown on the secondary y axis of the two lowermost panels for reference.

Table 1. Linear regression statistics of evapotranspiration measured by means of eddy covariance (closed path [CP] or open path [OP]) vs. independently measured evapotranspiration (by lysimeters or upscaling).†

Approach	4 June 2009 (<i>n</i> = 9)								18 June 2009 (<i>n</i> = 12)			
	Lysimeter				Upscaling				Lysimeter			
	<i>k</i>	<i>d</i>	<i>r</i> ²	RMSE	<i>k</i>	<i>d</i>	<i>r</i> ²	RMSE	<i>k</i>	<i>d</i>	<i>r</i> ²	RMSE
	mm h ⁻¹			mm h ⁻¹	mm h ⁻¹			mm h ⁻¹	mm h ⁻¹			mm h ⁻¹
Closed path												
ET _{CP-orig}	<i>0.50</i> (0.75)	<i>0.10</i>	0.22	0.11	0.26	0.18	0.57	0.20	<i>0.91</i> (0.82)	<i>-0.05</i>	0.80	0.11
ET _{CP-resid}	<i>0.69</i> (0.88)	<i>0.07</i>	0.26	0.09	0.31	0.21	0.51	0.17	1.27	<i>-0.16</i>	0.93	0.06
ET _{CP-β}	<i>0.59</i> (0.89)	<i>0.09</i>	0.25	0.10	0.29	0.19	0.56	0.18	<i>1.23</i>	<i>-0.16</i>	0.94	0.06
ET _{CP-debc}	<i>0.56</i> (0.85)	<i>0.11</i>	0.22	0.09	0.29	0.20	0.57	0.18	<i>1.08</i> (0.98)	<i>-0.06</i>	0.80	0.05
ET _{CP-ltebc}	<i>0.59</i> (0.82)	<i>0.12</i>	0.22	0.09	0.31	0.21	0.57	0.17	<i>1.08</i> (0.98)	<i>-0.06</i>	0.80	0.05
Open path												
ET _{OP-orig}	<i>0.34</i> (0.65)	<i>0.12</i>	0.16	0.15	0.21	0.16	0.54	0.23	<i>0.88</i> (0.82)	<i>-0.04</i>	0.93	0.11
ET _{OP-resid}	<i>0.68</i> (0.87)	<i>0.08</i>	0.26	0.09	0.31	0.20	0.51	0.17	<i>1.25</i>	<i>-0.16</i>	0.92	0.06
ET _{OP-β}	<i>0.49</i> (0.77)	<i>0.11</i>	0.21	0.11	0.26	0.19	0.54	0.20	<i>1.21</i>	<i>-0.15</i>	0.93	0.06
ET _{OP-debc}	<i>0.41</i> (0.79)	<i>0.14</i>	0.16	0.11	0.25	0.20	0.54	0.20	<i>1.04</i> (0.97)	<i>-0.04</i>	0.93	0.04
ET _{OP-ltebc}	<i>0.40</i> (0.76)	<i>0.14</i>	0.16	0.11	0.24	0.19	0.54	0.20	<i>1.04</i> (0.96)	<i>-0.04</i>	0.93	0.04

† Five approaches have been used to close the energy imbalance associated with the eddy covariance method: ET_{CP-orig} and ET_{OP-orig}, evapotranspiration without corrections for energy imbalance; ET_{CP-resid} and ET_{OP-resid}, evapotranspiration adjusted by attributing the energy imbalance exclusively to evapotranspiration; ET_{CP-β} and ET_{OP-β}, evapotranspiration adjusted according to half-hourly Bowen ratio; ET_{CP-debc} and ET_{OP-debc}, evapotranspiration adjusted according to the daily energy imbalance ratio; and ET_{CP-ltebc} and ET_{OP-ltebc}, evapotranspiration adjusted according to the long-term energy imbalance ratio. The statistics include the slope (*k*) and *y* intercept (*d*) of the linear regression, the coefficient of determination (*r*²), and the root mean squared error (RMSE). Italic numbers that indicate the slope and *y* intercept are not statistically significantly different from 1 and 0, respectively. Slopes for regressions forced through the origin when *y* intercepts were not statistically significantly different from zero are in parentheses.

below one standard deviation (Fig. 3). The best qualitative and quantitative correspondence with lysimeter ET was achieved by adjusting ET according to the daily or long-term energy imbalance (EC_debc, EC_ltebc; Table 1). The slopes and *y* intercepts of the linear regressions with ET_debc and ET_ltebc were not statistically significantly different from 1 and 0, respectively (Table 1).

Discussion

When using the EC method for measuring the ecosystem-atmosphere exchange of sensible and latent heat, it is not uncommon to find that these two energy fluxes fall short of the available energy by 20 to 30% (Wilson et al., 2002; Foken, 2008). As the causes for the energy imbalance are still under discussion (Foken, 2008), it is currently not clear how the energy balance should be closed (Wohlfahrt et al., 2009). Closure is required if the measured sensible and latent heat fluxes are assimilated into or used to validate models that assume the energy balance to be closed (Williams et al., 2009; Wohlfahrt et al., 2009). The objective of this study was to use independent measurements of ET for empirically devising how to best close the energy balance. To this end, the ET of a temperate mountain grassland was quantified during two measurement campaigns in June 2009 using EC, lysimeters, and an approach scaling leaf-level stomatal conductance up to canopy-level transpiration.

To compare ET measurement systems, we first assessed the differences between the three methods (EC, lysimeters, and upscaling) in terms of their spatial and temporal scale and which water vapor

flux they actually quantify (Table 2). The footprint of the EC method is on the order of several hundreds of meters and varies with wind direction and atmospheric conditions (wind speed and atmospheric stability; Schmid, 1997). The source area of the lysimeter measurements amounts to less than a square meter and is, in contrast to the EC method, well defined and constant. The spatial scale of the upscaling approach ranges from millimeters, the size of the area of the leaf temperature measurements, through centimeters, the size of the leaf area enclosed in the porometer, up to 1 m, roughly the spatial scale of the canopy structure measurements. Eddy covariance measurements are made at 20 Hz, from which 30-min averages are calculated. The lysimeter ET represents an integral water loss during 30 to 60 min, while the temporal scale of the upscaling approach ranges from 30 s, the duration of the leaf conductance measurement, up to 30 to 60 min, the averaging interval of the driving forces. The EC method and lysimeters quantify both ecosystem evaporation and transpiration, while the upscaling approach neglects evaporation from the soil surface and any canopy surface water stores.

Table 2. Conceptual comparison of methods used to quantify grassland evapotranspiration.

Method	Spatial scale	Temporal scale	Vapor flux
	m		
Eddy covariance	100	50 ms, 30-min avg.	evapotranspiration
Lysimeter	0.1–1	30–60-min integral	evapotranspiration
Upscaling	0.01–1	30 s, 60-min avg.	transpiration

Several causes have been invoked for the observed energy imbalance (for a recent synthesis, we refer to Foken, 2008) and the scenarios proposed here for closing the energy balance reflect these.

Assuming that the ET as measured by the EC method is correct (Scenario 1: ET_orig), amounts to assigning the entire energy imbalance to the other terms of the energy balance (Eq. [1]). Indeed, several researchers have shown that improving the measurement or calculation of some of the nonturbulent energy balance components, e.g., the net radiation (Kohsiek et al., 2007), the soil heat flux (Heusinkveld et al., 2004), the storage term (Meyers and Hollinger, 2004), or including commonly neglected terms into the energy balance, e.g., energy flux into photosynthesis (Jacobs et al., 2008), may in some cases greatly reduce the energy imbalance without any adjustment in measured ET. Our study, in accordance with the results obtained by Chavez et al. (2009) for cotton (*Gossypium hirsutum* L.), showed that the EC method underestimated ET measured by the lysimeters and the upscaling approach during both measurement campaigns by 18 to 39% (Table 1; Fig. 3) and thus does not support Scenario 1.

Only minor differences between the OP and CP EC were found, in contrast to Haslwanter et al. (2009), who reported the CP system at our site to yield an 84 mm lower annual ET than the OP system. This difference may be explained by the fact that, during our study, the intake line of the CP system was heated to 35°C to reduce water vapor interactions with the tube walls (sorption and desorption; Massman and Ibrom, 2008). This measure was taken because Ibrom et al. (2007) have shown that the underestimation of ET by CP systems scales positively with the relative humidity in the intake line. The difference between the CP and OP systems reported by Haslwanter et al. (2009) may, however, also relate to the fact that their study was based on year-round data, while here we have used data from June only when the more favorable environmental conditions may improve the performance of the OP IRGA and thus the correspondence between the two systems.

If underestimated or neglected nonturbulent terms in the energy balance contribute significantly to the energy imbalance, one might expect the energy imbalance to differ between the two measurement campaigns, i.e., before and after the cut, because of changes in the contribution of these terms to the energy balance. After the cut, the midday G/R_n ratio increased from 0.07 before the cut to 0.18 (Fig. 3; Hammerle et al., 2008)—any error that scales with the measured soil heat flux may thus be expected to be larger after than before the cut. Conversely, errors arising from neglecting heat storage in the biomass may be expected to be quantitatively more important before the cut when the PAI was much higher. Likewise, the error caused by not accounting for the heat flux into photosynthesis must be assumed to be much larger before the cut when gross photosynthesis was up to $40 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ (i.e., $\sim 20 \text{ W m}^{-2}$), while only a few micromoles of CO_2 per square meter per second were fixed after the cut (Wohlfahrt et al., 2008).

As the energy imbalance hardly differed before and after the cut (Fig. 1), this may indicate that either the above-mentioned energy balance components have been quantified correctly or that the changes in the errors in opposite directions actually cancelled out.

Due to the latter possibility and the general uncertainties in quantifying the nonturbulent terms in the energy balance, Scenario 2, i.e., assigning the entire energy imbalance to ET (ET_resid), may be considered not very likely as well, as shown by Chavez et al. (2009). This is particularly true if the error in the ET measurement is due to some general shortcoming of the EC method, which would also apply to the sensible heat flux (see also discussion below). Nevertheless, on 4 June 2009 the discrepancy between the EC method and the two independent ET estimates was so large that assigning the entire energy imbalance to ET turned out to represent the best closure option (Table 1). Both quantitatively and qualitatively, however, the correspondence was much lower than the best closure approach for the second measurement campaign (Table 1).

At this point the issue of spatial scale, which is much smaller for the independent methods than for the EC technique (Table 2), and the heterogeneity within the footprint of the EC measurements, need to be discussed. The standard deviation of the lysimeter ET measurements on 4 June 2009 was up to 0.2 mm h^{-1} , which (assuming an air temperature of 20°C) translates into a latent heat flux of $\sim 135 \text{ W m}^{-2}$. This value is larger than the maximum average energy imbalance, which at 1200 h amounts to around 100 W m^{-2} (Fig. 1). While the footprint of our EC flux system appears homogeneous to the observer, there obviously is some small-scale variability in ET present, as evident from the spread in lysimeter measurements (Fig. 3e). If the vegetation patches that are characterized by lower than average ET rates (from lysimeter measurements) make up a significant fraction of the footprint, then the arithmetic-average lysimeter ET will be biased high. Ideally, the lysimeter ET would be calculated as the average weighted according to the contribution of the various patches to the EC footprint—at present, however, we lack the small-scale (<1-m) spatial information that would be necessary to this end. No error bounds have been provided for the upscaled canopy transpiration because the sources of errors associated with this approach are difficult to quantify. Possible errors relate again to the spatial scale of the measurements (Table 2) as opposed to the small-scale heterogeneity of the site, the limited number of replicates, errors in the measurements per se (e.g., the accuracy with which leaf stomatal conductance can be quantified), as well as errors arising from the need to interpolate measurements in both space and time and to integrate measurements over discrete canopy layers.

Because of the multitude of error sources, even if most of them are independent (Moncrieff et al., 1996), it is likely that the uncertainty of the upscaled canopy transpiration is larger than the statistical uncertainty of the lysimeter ET, as indicated by the almost twice as high canopy transpiration around 1200 h (up

to 600 W m^{-2}), which even exceeds net radiation (Fig. 3). The upscaled canopy transpiration estimates should thus rather be viewed as a conceptual test of our process understanding of canopy transpiration than a practical means for independently corroborating ET estimates measured with the EC method. Finally, we would like to mention that Scenarios 1 and 2, even if not the most likely ones, are nevertheless useful because they encompass the potential range of possible energy balance closure options and may thus serve as extreme scenarios for any study dealing with the problem of closing the energy imbalance (Twine et al., 2000; Wilson et al., 2001, 2002; Falge et al., 2005; Wohlfahrt et al., 2009).

Both experimental studies using area-averaging approaches (e.g., scintillometers; Meijninger et al., 2006) and modeling studies using the large eddy simulation technique (e.g., Kanda et al., 2004) suggest the energy imbalance to result from a significant energy flux contribution by large eddies, generated by larger scale heterogeneities, which are missed by the usual 30-min averaging periods used at most EC sites (Finnigan et al., 2003). According to Panin et al. (1998), Foken (2008), and Foken et al. (2010), it is this scale problem to which the majority of the energy imbalance has to be attributed. As an engineering-type solution (Foken, 2008), which assumes that the Bowen ratio of the energy fluxes carried by these large eddies equals the one measured by the EC method, the energy balance may be closed by assigning the energy imbalance to the sensible and latent heat flux according to the local Bowen ratio (Scenario 3: ET_β). On a regional scale such as the entire Stubai Valley, cutting of grasslands usually occurs within a time window of 2 to 3 wk, causing the landscape to become more heterogeneous (i.e., a mix of cut and uncut areas) once cutting has started. If the energy imbalance is indeed to be attributed to large eddies caused by the heterogeneity at the landscape scale (Foken, 2008), we would thus expect Scenario 3 to perform better after the cut. In the present study, however, Scenario 3 yielded the poorest correspondence with the independently measured ET during both measurement campaigns (Table 1). Possibly, the additional landscape heterogeneity initiated by the onset of the farmers' cutting activities, despite fundamentally altering the energy flux partitioning (Hammerle et al., 2008), is not enough to affect the generation of larger eddies, which depend more on roughness changes at forest–non-forest or urban–non-forest transitions, which can be considered static at this time scale. The poor performance of Scenario 3 may also have to do with the fact that, depending on the size and sign of λE and H , forcing closure according to the Bowen ratio may change ET by unrealistically large amounts (Wohlfahrt et al., 2009).

Another option for closing the energy balance is to use the average energy balance ratio directly for correcting sensible and latent heat fluxes (Twine et al., 2000). This approach likewise conserves the Bowen ratio, but it is conceptually different from Scenario 3 because during any averaging period, the energy balance may not necessarily be closed due to the spread of the half-hourly measurements around the average (Fig. 1). While this approach has been

applied in a few studies (e.g., Twine et al., 2000; Morgenstern et al., 2004), it is not yet clear which time frame should be used to determine the average energy balance ratio (Wohlfahrt et al., 2009), which is an issue if it varies temporally. Chavez et al. (2009) have used the average midday Bowen ratio to close the energy balance. In our study, we analyzed two averaging time frames—daily (Scenario 4: ET_{debc}) and longer term (i.e., monthly, Scenario 5: ET_{ltebc}), which in the present case yielded similar results because the daily and monthly energy balance ratios differed only slightly (Fig. 1). Note that the year-round (2001–2006) energy balance closure at this site is lower, amounting to 0.76 and 0.78 for the CP and OP systems, respectively (Haslwanter et al., 2009). After the cut, on 18 June 2009, adjusting ET for either the daily and long-term energy imbalance resulted in the best correspondence with the lysimeter ET (Table 1). In contrast to the first measurement campaign on 4 June 2009, the variability in lysimeter ET was much smaller (standard deviation of $\sim 0.09 \text{ mm h}^{-1}$ or its λE equivalent of 60 W m^{-2}), indicating that cutting may have reduced the spatial heterogeneity in ET. Due to the differing spatial scales of the lysimeter and EC measurements (Table 2), we are thus more confident in the comparison between lysimeter and EC ET for the second measurement campaign and thus, in accordance with Chavez et al. (2009), tend to favor Scenarios 4 and 5 for forcing the energy balance closure. These two scenarios have the advantage of reducing the random flux uncertainty, which is on the order of 10 to 40% for half-hourly energy flux measurements (Richardson et al., 2006). We have to stress, though, as mentioned above, that these two scenarios may be associated with a residual energy during any half-hourly period that needs to be considered to fully close the energy balance. To this end, Scenarios 1 or 3 may be used.

Conclusions

Our study showed that both the OP and CP EC systems underestimated ET measured independently by lysimeters and an approach by which leaf-level stomatal conductance is upscaled to canopy-level transpiration. During two measurement campaigns, however, no single best approach for forcing the energy balance closure could be identified. During the first campaign, assigning the entire energy imbalance to ET resulted in the best correspondence to independently measured ET, while during the second campaign the best correspondence with the lysimeter ET was achieved by adjusting the EC ET according to the average energy balance ratio. Due to large differences in spatial scale between the EC and the independent methods and a seemingly large spatial variability in ET during the first measurement campaign, we are more confident in the comparison of the approaches during the second measurement campaign and thus conclude that for the present data set, forcing the energy balance closure by adjusting for the average energy imbalance ratio provided the best correspondence with independently measured ET. But clearly, there is a need for further comparisons between ET measured by the EC method and independent approaches for a wider range of ecosystems to

corroborate our results, also because our measurements were limited to two short campaigns due to the time-consuming nature of the measurements.

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