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Authors: Wieser, Gerhard, Hammerle, Albin, and Wohlfahrt, Georg

Source: Arctic, Antarctic, and Alpine Research, 40(2) : 439-445

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1523-0430(07-039)[WIESER]2.0.CO;2

Arctic, Antarctic, and Alpine Research, Vol. 40, No. 2, 2008, pp. 439–445

The Water Balance of Grassland Ecosystems in the Austrian Alps

*Gerhard Wieser**
Albin Hammerle† and
Georg Wohlfahrt†

*Corresponding author: Department of Alpine Timberline Ecophysiology, Federal Research and Training Centre for Forests, Natural Hazards and Landscape, Rennweg 1, 6020 Innsbruck, Austria
Gerhard.Wieser@uibk.ac.at
†Institute of Ecology, University of Innsbruck, Sternwartestraße 15, 6020 Innsbruck, Austria

Abstract

The altitudinal variation of precipitation, evapotranspiration, and runoff was quantified at 16 different grassland sites between 580 and 2550 m a.s.l. in the Austrian Alps. Along this altitudinal transect annual evapotranspiration decreased from roughly 690 mm at low elevation sites to 210–220 mm at the upper limit of the alpine grassland belt. A detailed analysis of the data showed that the observed reduction in the annual sum of evapotranspiration could be mainly explained by the altitudinal decline of the length of the snow-free period (i.e. the vegetation period). Daily mean sums of evapotranspiration showed no altitudinal trend and averaged 2.2 mm d^{-1} independent of elevation, although the leaf area index, growing season mean air temperature, and vapor pressure deficit declined with increasing altitude. As precipitation increased with elevation, evapotranspiration seems to be of secondary importance when compared to runoff. Inter-annual variability of evapotranspiration was fairly low across contrasting dry and wet years (coefficient of variation = 7%), indicating that even during dry years water availability was not limiting evapotranspiration.

DOI: 10.1657/1523-0430(07-039)[WIESER]2.0.CO;2

Introduction

Grasslands are one of the most widespread vegetation types and cover approximately one-fifth of the earth's land surface (Hall and Scurlock, 1991). In the Austrian Alps a variety of grassland ecosystems such as meadows, pastures, alpine grass, and sedge mats cover approximately 40 to 45% of the total land area and extend from the valley floor to the upper limit of the alpine grassland belt at approximately 2600 m a.s.l. (Schiechtl and Stern, 1974; Laboratoire des Ecosystèmes Alpines, 1995). Altitudinal alterations in climate (Schröter, 1926; Steinhauser et al., 1960; Ellenberg, 1996; Franz, 1979; Baumgartner 1980, Fliri, 1975, Veit 2002), edaphic parameters (Franz, 1979), and land use (Cernusca et al., 1999) cause significant changes in species composition, biomass production, and canopy structure of grassland ecosystems in the Austrian Alps (Cernusca and Seeber, 1981).

The water balance of montane, subalpine, and alpine (*sensu* Ellenberg, 1996) grassland ecosystems is an important feature, especially in the Austrian Alps where precipitation exceeds the water use of vegetation and the storage capacity of soils. Vegetation is an important factor influencing the annual ecosystem water balance, which is determined by the water input through precipitation (P) which falls as rain, snow, or fog. Some of the P adheres on the above-ground vegetation and evaporates before reaching the ground—the so-called interception (I). The remaining P reaching the ground runs off (R_S, surface runoff), infiltrates into the soil, and percolates through to the water table (R_D, deep seepage), finally leaving the system as base flow. The amount of water which is held against gravitational forces within the soil matrix can be taken up by the plant roots and is finally transpired through the stomata of the leaves into the atmosphere (T, transpiration) and evaporates from the soil surface (E). So, over short periods, there are also changes in the soil water content (ΔW). All the components involved are given in mm (= kg m^{-2} of slope parallel ground) and the complete water balance equation of an ecosystem reads:

$$P = E + T + I + R_D + R_S + \Delta W. \quad (1)$$

In view of the fact that it is frequently very difficult to measure all the terms of Eq. 1 and taking into account that over long periods (an entire growing season or year) ΔW may be assumed to approach zero, the water balance equation (Eq. 1) can be simplified to:

$$P = ET + R, \quad (2)$$

where ET is the sum of all water vapor fluxes from the system to the atmosphere ($E + T + I$), and R is the sum of deep seepage and surface runoff.

Earlier estimations of the annual water balance at different altitudes for the European Alps (Baumgartner, 1980) included estimations of ET based on meteorological data (Müller, 1965; Kern, 1975) or estimations of total R from catchment stream flow data (Steinhäusser, 1952, 1970). Since the mid 1980s, lysimeter studies (Körner et al., 1978; Guggenberger, 1980; Wieser ,1983; Scott et al., 2002), the Bowen-ratio method (Cernusca and Seeber, 1981; Staudinger and Rott, 1981; Rosset et al., 2001), and the eddy covariance technique (Wohlfahrt, 2004; Hammerle et al., 2007) have also been used to measure ET for calculating the water balance of grassland ecosystems at various sites within the Austrian Alps.

The objective of this paper is to compile what is presently known about the water balance of grassland ecosystems in the Austrian Alps. We first examine the inter-annual and seasonal variability and the driving forces of ET using data from a long-term mountain grassland study in the Stubai valley. The following section deals with the altitudinal variation of ET, and finally we focus on how the overall water balance of grassland ecosystems changes with elevation.

1523-0430/08 $7.00

TABLE 1

General overview of the study sites.

Location and Station number	Station name	Latitude, Longitude	Elevation (m)	Aspect	Inclination (°)	Vegetation period (weeks)	Observation period	Experiment	References
Southern outer rim									
1	Sagritz	46°58′N, 12°55′E	1085	SSW	10	28–30	1978–1979	L	1
2	Heiligenblut	47°03′N, 12°51′E	1300	N	0	27	1978–1979	L	1
3	Seppenbauer	47°03′N, 12°52′E	1612	S	25	25–26	1978–1980	L	1
4	Guttal	47°04′N, 12°49′E	1912	S	15–20	20–22	1978–1980	L	1
5	Wallackhaus	47°04′N, 12°51′E	2300	S	15–20	14–20	1978–1980	L	1
6	Wehr	47°04′N, 12°51′E	2430	S	5	13–14	1978–1980	L	1
7	Hochtor	47°05′N, 12°51′E	2528	S	10–15	13–14	1978–1980	L	1
8	Stubner Alm	47°07′N, 13°07′E	1815	NE	19	18	1977	L	2
Inner Alpine region									
9	Obergurgl	46°52′N, 11°02′E	1980	WSW	10	13–19	1976–1979	L, B	1, 3
10	Hohe Mut	46°51′N, 11°02′E	2550	S	5	9–13	1976–1978	L, B	1, 3
11	Haggen	47°13′N, 11°06′E	1805	S	35	22–25	1979–1981	L	4
12	Neustift	47°06′N, 11°19′E	970	—	0	33–40	2001–2006	EC	5
13	Patscherkofel	47°12′N, 11°27′E	2175	SW	5	18	1976	L	6
Northern limestone Alps									
14	Innsbruck	47°16′N, 11°21′E	580	—	0	44	1979–1980	L	1
15	Seegrube	47°18′N, 11°23′E	1960	S	5–10	18	1980	L	1
16	Hafelekar	47°19′N, 11°23′E	2330	S	15–20	18	1980	L	1

L = Lysimeter; B = Bowen ratio; EC = eddy covariance.

References: 1—Wieser (1983); 2—Körner et al. (1978); 3—Staudinger and Rott (1981); 4—Kronfuss (1997); 5—Wohlfahrt (2004); 6—Guggenberger (1980).

Study Sites and Methods

To characterize the effects of altitude on the various components of the water balance of grassland ecosystems we compare experimental data from 16 sites in the Austrian Alps between 580 and 2550 m a.s.l. The selected sites differ with respect to geographic location, altitude, exposition, and inclination (Table 1) and include montane and subalpine meadows and pastures below the timberline and alpine grassland ecosystems above the alpine timberline, respectively. Eight sites (stations 1 to 8) were located in the Hohe Tauern mountain range in the southern part of the Austrian Alps. Five stations were in the inner Alpine sector, namely in the Ötztaler Alpen (station 9 and 10), the Stubaier Alpen (station 11 and 12), and the Tuxer Voralpen (station 13).In addition, there were also three stations situated along an altitudinal transect in the Northern limestone Alps (stations 14 to 16). Figure 1 shows the location of the 16 sites.

A common set of precipitation, *ET* and runoff measurements was acquired at each site. Precipitation was estimated with Hellmann rain gauges installed 2 m above ground and throughout the growing season also with rain gauges installed slope parallel close to the soil surface (Henning, 1974). The latter are suggested to be more representative for *P* when focusing on the water availability of canopies during the snow-free period (Stigter, 1974). On average, growing season sums of *P* estimated slope parallel close to the soil surface were 6-11% higher than *P* values obtained by Hellmann rain gauges at 2 m above ground.

At all stations (see Table 1) except station 12 (Neustift), *ET* and total runoff were measured by means of weighting and non-weighting "monolithic" lysimeters (Courtin and Bliss, 1971; Körner et al., 1978; Wieser, 1983; Scott et al., 2002) sunk into the ground. The soil within the lysimeters was undisturbed, pores at the bottom of the lysimeter allowed drainage and forced all runoff into seepage. Evaporation from the snow surface was calculated using Sverdrup's formula of the sublimation of snow (Müller, 1965). At the two sites in the Ötztaler Alpen and at Neustift, *ET* was quantified using micrometeorological methods (Table 1): At the two sites in the Ötztaler Alpen (station 9 and 10) the Bowen-ratio method (Staudinger and Rott, 1981) was applied in addition to lysimeters; at the study site Neustift, (station 12) the eddy covariance technique was used for determining *ET* as described in Wohlfahrt (2004) and Hammerle et al. (2007). At Neustift, which is representative for the lower elevation grasslands of the investigated transects, *ET* has been measured since 2001 and this six-year data set will be used to analyze the inter-annual and seasonal variability, as well as the controls on daily *ET*.

Results and Discussion

INTER-ANNUAL VARIABILITY, SEASONAL TRENDS, AND DRIVING FORCES OF EVAPOTRANSPIRATION

As shown in Figure 2, daily *ET* at the low-elevation site Neustift was generally very small from January through March (0.05-0.15 mm d^{-1}), when snow usually covers the ground. After snowmelt, evaporation rates quickly increased, reaching peak values of 4-5 mm d^{-1} during the period May-October, after which *ET* gradually declined back to wintertime values (Fig. 2). These peak evaporation rates are in good agreement with other studies on well-watered grassland ecosystems (e.g. Meyers, 2001; Rosset et al., 2001; Tasser et al., 2001; Wever et al., 2002).

During 2001-2006, annual *ET* ranged from 446 mm (2005) to 527 mm (2006) (Fig. 2), or 53% (2002) to 91% (2006) of annual *P*, with coefficients of variation of 7 and 20%, respectively. The potential driving forces considered (global and net radiation, air and soil temperature, vapor pressure deficit, soil water content, and precipitation) explained little of this variability, the best predictor being air temperature, which in a linear regression explained 35% of the variability in annual *ET* ($p = 0.11$). Restricting the analysis to the vegetation period, where the majority of *ET* occurs (Fig. 2), improved regression statistics only slightly (data not shown). Once *ET* was normalized with precipitation, a statistically significant non-linear relationship was found with precipitation, shown in Figure 3. There it can be seen that the fraction of precipitation

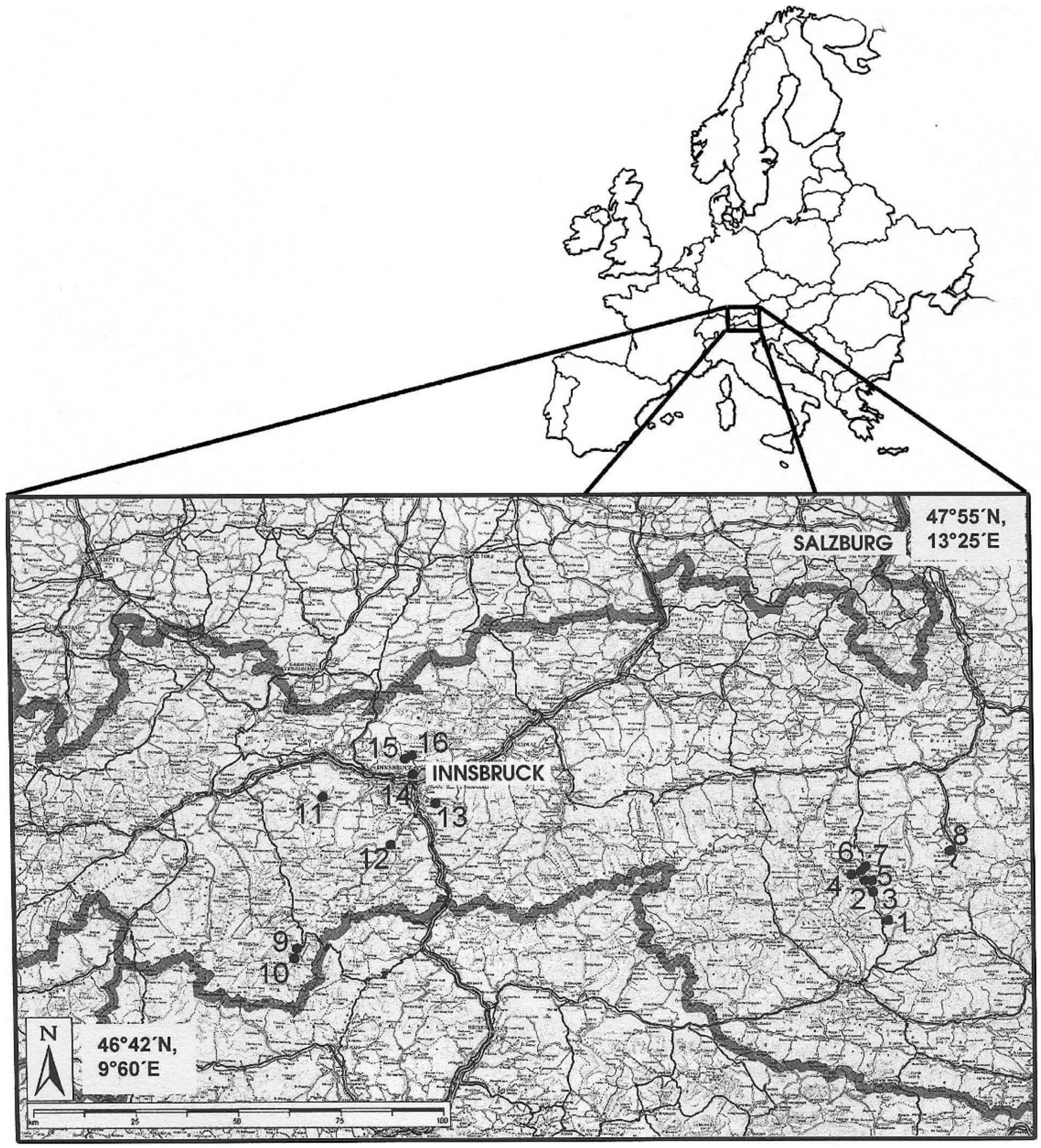

FIGURE 1. Map showing the location of the study sites. Refer to Table 1 for station numbers.

evaporated to the atmosphere increased with decreasing precipitation and that this increase was asymmetric, i.e. *ET* increased disproportionately during years with little precipitation. We interpret this behavior as to indicate that even during dry years, when up to 90% of the precipitation is evaporated, no water stress occurs in these systems, but that in contrast, environmental conditions (higher evaporative demand, higher radiation input) lead to increased evaporation rates.

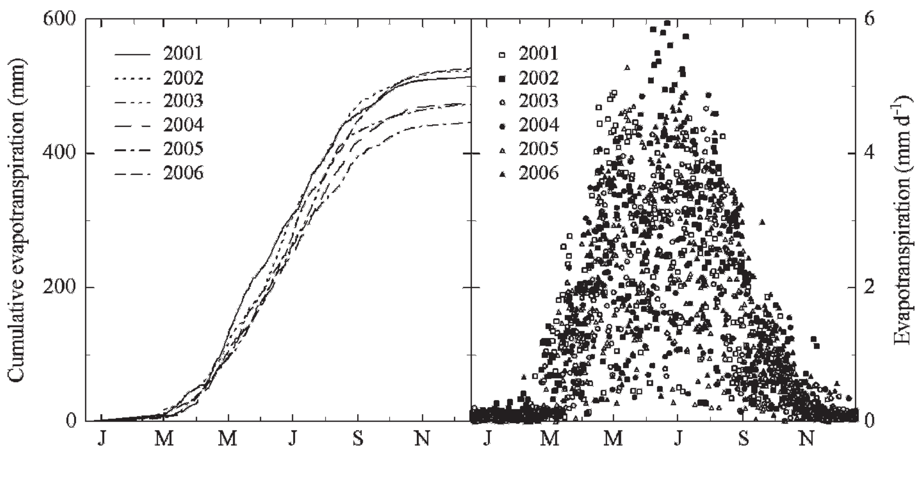

FIGURE 2. Inter-annual variability of cumulative evapotranspiration (left) and daily evapotranspiration (right) of a low-elevation mountain grassland (study site Neustift, 970 m a.s.l.).

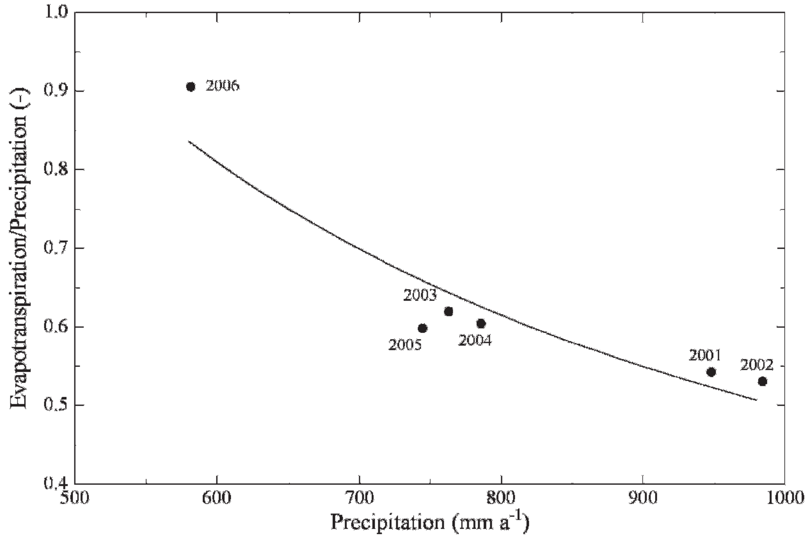

FIGURE 3. Annual evapotranspiration normalized with precipitation against precipitation for a low-elevation mountain grassland (study site Neustift, 970 m a.s.l.).

The largest fraction of variability in daily *ET* (excluding periods of snow cover) was explained by the amount of incident photosynthetically active radiation (Fig. 4; $r^2 = 0.74$, $p = 0.00$), followed by net radiation (data not shown; $r^2 = 0.70$, $p = 0.00$), which were though strongly correlated ($r^2 = 0.92$, $p = 0.00$). Similar correlations have also been observed for the two sites in the Ötztaler Alpen by Staudinger and Rott (1981). This reflects the energy demand for the evaporation of water (Campbell and Norman, 1998), as well as photosynthesis, which is linked to transpiration by stomatal conductance (Larcher, 2001). The good predictive power of these two radiation forcings again indicates that limitations of transpiration by stomatal closure due to low soil water availability and/or dry air played a minor role at this site. This is corroborated by the dependency of daily *ET* on the vapor pressure deficit (Fig. 4; $r^2 = 0.61$, $p = 0.00$), whose slope tended to decrease only at very high vapor pressure deficits, as also observed for the sites Seppenbauer, Guttal, and Wallackhaus at the south rim of the Hohen Tauern by Wieser (1983). A step-wise linear regression analysis included incident photosynthetically active radiation and the vapor pressure deficit, the combined linear model explaining 77% of the observed variability in *ET* ($p = 0.00$).

EVAPOTRANSPIRATION WITH RESPECT TO ALTITUDE

For assessing the altitudinal variation in annual *ET* we compiled data from all 16 investigated grassland ecosystems (Table 1). These data clearly show that the annual *ET* declined from 690 mm in an inner alpine valley floor (580 m a.s.l.; station 14) to 210–220 mm at the upper limit of the alpine grassland belt in the inner Alpine sector (2550 m a.s.l.; station 16) and in the southern part of the Austrian Alps (2528 m a.s.l.; station 7), respectively (Fig. 5). There were no differences in the vertical gradient of *ET* between stations located in inner alpine sectors (stations 9 to 13) and in the southern (stations 1 to 8) and northern outer ranges (stations 14 to 16) of the central Austrian Alps (Fig. 5). The observed reduction in *ET* of 210 mm per 1000 m increase in altitude (Fig. 5; $r^2 = 0.86$, $p = 0.00$) is within the range of earlier estimations for other parts of the central Alps based on catchment stream flow analysis (170 mm km^{-1}, Steinhäußer, 1970; 185 mm km^{-1}, Koehl, 1971; 356 mm km^{-1}, Steinhäußer, 1952) or meteorological calculations (160 mm km^{-1}, Müller, 1965; 180 mm km^{-1}, Kern, 1975). Snow sublimation during the winter months was only a minor fraction of annual *ET* and varied between 13 mm at the valley floor and 45 mm at the upper limit of the alpine grassland belt (Fig. 5).

The observed linear altitudinal decline in the annual *ET* (Fig. 5) can be completely explained by the altitudinal reduction of the vegetation period (Wieser, 1983; Wieser et al., 1984; Menzel et al., 1998; Körner, 2003). When the growing season water loss was divided by the number of snow-free days (see Table 1), the altitudinal gradient disappeared and the daily mean of grassland *ET* during the growing season ranged from 1.9 to 2.6 mm d^{-1} and

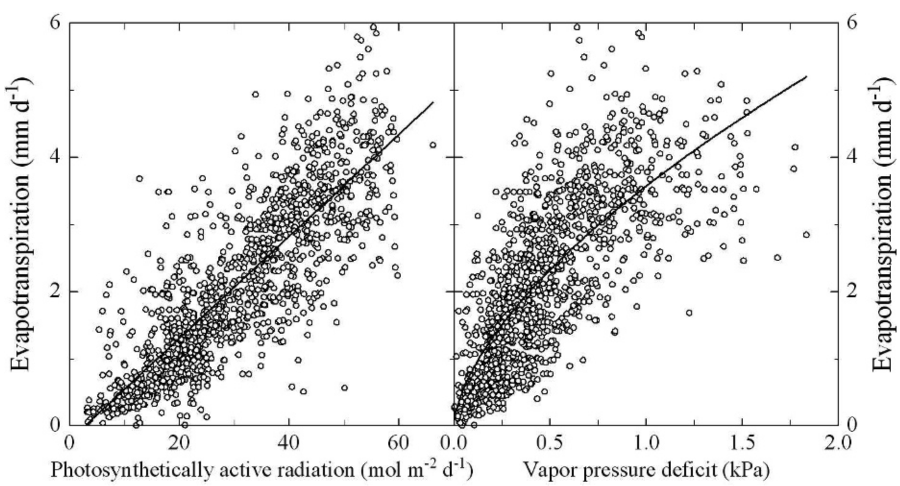

FIGURE 4. Daily evapotranspiration of a low-elevation mountain grassland (study site Neustift, 970 m a.s.l.) as a function of incident daily photosynthetically active radiation (left) and the air vapor pressure deficit (right). Solid lines show best fits to data using linear ($r^2 = 0.74$, $p = 0.00$, left) and logarithmic ($r^2 = 0.61$, $p = 0.00$, right) models, respectively.

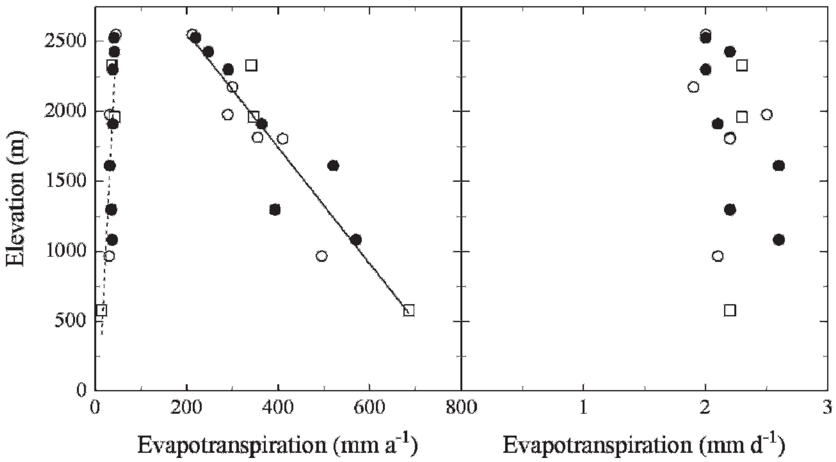

FIGURE 5. Total annual evapotranspiration ($r^2 = 0.86$, $p = 0.00$, solid line, left) and snow sublimation ($r^2 = 0.62$, $p = 0.00$, dotted line, left) and daily mean evapotranspiration (right) of grassland ecosystems located on the southern outer rim of the Austrian Alps (●), the inner Alpine region (○), and the Northern limestone Alps (□) between 580 and 2550 m a.s.l. (after Wieser, 1983, and Wieser et al., 1984).

averaged 2.2 mm d^{-1} (Fig. 5; Wieser, 1983; Wieser et al., 1984). The growing season mean *ET* of the grasslands under study is similar to the value of 2.0 mm d^{-1} obtained for mixed forest stands in the Alps between 490 and 1950 m a.s.l. (Matyssek et al., personal communication).

The leaf area index of grassland ecosystems declines from peak values of 6-8 in the valley floor (Körner and Mayr, 1981; Wohlfahrt et al., 2001) to less than 2 in the alpine grassland belt (Cernusca and Seeber, 1981). As a consequence of the declining leaf area index, wind velocity (Wohlfahrt and Cernusca, 2002) and aerodynamic conductance were found to be significantly higher in the alpine grassland belt as compared to pastures and meadows at lower elevations (Cernusca and Seeber, 1981). Due to the altitudinal decline in leaf area, evaporation from the soil surface below the vegetation cover increases from 10% of total *ET* in the valley floor (Rutter, 1975) up to approximately 25% in the alpine sedge belt (Körner, 1977; Körner et al., 1980). Moreover, due to heat accumulation in the canopy (Körner, 2003), low stature alpine grasslands often heat up to a larger extent causing the driving forces for *ET* to increase (Cernusca and Seeber, 1981). Consequently, high elevation plants display higher leaf conductances (Körner and Mayr, 1981) and higher stomatal densities (Körner et al., 1989) than comparable plants at lower elevations. Periodic soil water shortage at low elevation sites with soil water potentials close to the wilting point cause stomatal restrictions much more often as compared to plants growing above the timberline (Körner and Mayr, 1981), where soil water potentials seldom drop below critical values (Neuwinger-Raschendorfer, 1961; Neuwinger, 1970, 1980; Gunsch ,1972; Wieser et al., 1989), even during the Central Europe–wide extremely dry summer of 2003 (Rebetez et al., 2006; Wieser and Tausz, 2007). This may be attributed to the higher amount of precipitation (Fig. 6) and to the fact that rain is observed every third or fourth day on average above the timberline (Frei and Schär, 1998).

THE ANNUAL WATER BALANCE WITH RESPECT TO ALTITUDE

Annual evapotranspiration normalized with precipitation (*E*/*P* ratio) decreased with increasing altitude (Fig. 6 left; all data pooled $r^2 = 0.83$, $p = 0.00$); conversely runoff normalized with precipitation (*R*/*P* value) increased with increasing altitude and equaled *E*/*P* at approximately 1300 m a.s.l. Theses trends were much more pronounced on the southern outer rim as compared to the inner Alpine region and the Northern limestone Alps. This results from the fact that there is no unique relation between altitude and precipitation in the Alps (Schröter, 1926; Steinhauser et al., 1960; Ellenberg, 1996; Franz, 1979; Baumgartner, 1980; Fliri, 1975; Veit, 2002). On average, annual precipitation increased by approximately 75 mm per 100 m of altitude and by less than 15 mm per 100 m of altitude in the southern outer rims and the Northern limestone Alps, respectively (Fig. 6, right). In the inner Alpine region, by contrast, precipitation did not change significantly with altitude and averaged 980 mm irrespective of height above sea level (Fig. 6, right).

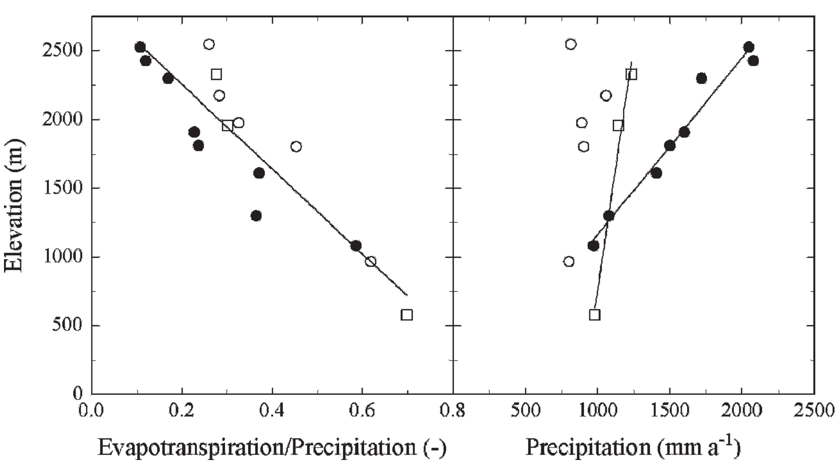

FIGURE 6. Annual evapotranspiration normalized with precipitation (left) and precipitation (right) with respect to elevation of grassland ecosystems located on the southern outer rim of the Austrian Alps (●), the inner Alpine region(○), and the Northern limestone Alps (□) between 580 and 2550 m a.s.l. Solid lines show best fits to data using linear models (left: all data pooled; $r^2 = 0.83$, $p = 0.00$; right: southern outer rim of the Austrian Alps: $r^2 = 0.97$, $p = 0.00$, Northern limestone Alps: $r^2 = 0.98$, $p = 0.04$).

Conclusions

Our compilation of studies on the water balance of grassland ecosystems in the Austrian Alps leads to the following conclusions: (1) even during dry years grassland ecosystems in the Austrian Alps seem not to suffer from water stress; (2) the observed linear altitudinal decline in annual *ET* can be explained by the altitudinal shortening of the snow-free period; and (3) with increasing altitude runoff, at the expense of *ET*, dominates the water balance.

The major part of studies contained in this compilation was conducted in the late 1970s. Given recent evidence of climate change impacts on mountain ecosystems, in particular the accelerated warming rates at high altitudes (Kromp-Kolb and Formayer, 2005), it may thus be timely to repeat those measurements in order to detect and quantify possible effects of climate change on the water balance of Austrian Alpine grassland ecosystems.

Acknowledgments

Part of this study was financially supported by the EU FP 5 project CARBOMONT (EVK2-CT2001-00125), the Austrian National Science Fund (P17560), and the Tyrolean Science Fund (Uni-404/33). The Hofer family (Neustift, Austria) is thanked for granting us access to the Neustift study site.

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Ms accepted September 2007