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# Evapotranspiration at Two Mountain Sites During the Vegetation Period

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Hourly values of evapotranspiration (*ET*) for the months July to September 1976 and 1977 were calculated from energy balance measurements at two test sites near the village of Obergurgl in the Austrian Alps. One test site was situated at 1,960 m a.s.l. on a cultivated meadow near the timberline, the other test site at 2,580 m a.s.l. was covered with alpine sedges and grasses. Examples of the daily variations and daily sums of the energy fluxes are presented for clear and cloudy days. The mean daily courses of *ET* at the two test sites are shown for every month of the measurement periods; differences in *ET* between the two test sites are related to the decrease of transpirating leaf areas with altitude. Monthly sums of *ET* are presented in relation to net radiation and precipitation; on the average ET was about 30% lower at the higher elevated site. High correlations were found between the daily sums of net radiation and of *ET* at both sites. This relation can be used for calculating *ET* from radiation measurements.

## Introduction

The components of the surface energy balance and other meteorological parameters were measured at two test sites in the Austrian Alps in the months July, August, and September of the years 1976 to 1978. These measurements were a contribution to the Man and Biosphere (MaB) Project No. 6, Working Group Obergurgl (Moser 1977), which investigated ecological systems in the mountain region near the village of Obergurgl (1.930 m a.s.l., 11°2' E, 46°28 N) in the

Central Alps of Tyrol. The energy balance measurements were carried out at the two test sites Obergurgl Wiese-I (WI) and Hohe Mut (HM).

The test site WI was situated on a cultivated meadow in 1,960 m a.s.l. not far below the timberline, it was on a slope of about 10° inclination exposed toward WNW. Due to the location near the bottom of a narrow valley a certain percentage of solar radiation is lost in the morning through screening by mountain ridges. On clear summer days the loss of solar irradiance by screening amounts to about 10% of the daily sum.

The test site Hohe Mut (HM) was situated on a flat mountain ridge in 2,580 m a.s.l., about 3 km from the site WI. The ridge, extending from NW to SE, rises about 300 m between two narrow valleys, the loss of radiation due to screening by higher mountains is insignificant in summer. The surface at HM was covered with sparce vegetation, mainly alpine sedges and grasses.

The energy balance measurements were carried out in the years 1976 and 1977 from July 1 to September 30, and in 1978 from July 1 to September 15. This covered nearly the whole vegetation period at HM and the main part of it at WI, where winter snow cover disappears about middle of May. Periods with snowfall may occur at both sites during the whole summer. In July 1976, for example, snow cover was observed on 2 days at the site WI and on 7 days at HM, in September 1976 there were even 23 days with snow cover at HM.

In this paper data of hourly, daily, and monthly evapotranspiration (*ET*) calculated from the energy balance measurements are presented and the relations to other meteorological parameters are discussed. For a limited period in 1978 *ET*-measurements from small weighing lysimeters were available for comparisons.

## Instruments and Methods

Because of the rather long measurement periods and because power was available only from batteries, relatively simple instrumentation was used for the energy balance measurements with the same types of instruments at both stations. Two pyrradiometers and two pyranometers at each site measured the incoming and outgoing radiation fluxes. Dry and wet bulb temperatures were measured 25, 50, and 150 cm above the surface with aspirated 100-Ohm platin resistance thermometers. Soil temperature was acquired with resistance thermometers in 5, 10, and 25 cm depth, for some period additionally in 2 cm depth. Wind velocities were measured with miniature cup anemometers in 3 heights at the site HM and in 1 height at the site WI. Most of the data were recorded in 2-minutes intervals with batterypowered digital tape recorders. Additional meteorological observations and measurements were carried out by students who maintained the stations.

Among these observations were hourly notes on cloudiness and on weather events during the day, and precipitation measurements twice daily.

Hourly values of evapotranspiration were calculated from the surface energy balance

$$LE = -(R_n + G + H)$$

where *LE, H,* and *G* are the fluxes of latent, sensible, and soil heat respectively. The net radiation flux $R_n$ was obtained from the measured incoming and outgoing radiation fluxes (Staudinger 1978). The soil heat flux was calculated from the hourly changes of measured soil temperature in 3 depths and of soil surface temperature. Surface temperatures were obtained from radiometer measurements. Constant values of soil density and heat capacity were used for the calculation of *G* at each site (Rott 1979).

Latent and sensible heat fluxes were determined with the energy balance method, calculating the Bowen ratio $B = H/LE$ from the gradients of temperature and humidity, which were taken in most cases from the measurements in 25 cm and 150 cm. Though the terrain around the test sites did not ideally fulfill the requirements on horizontal homogeneity, possible horizontal advection was of minor importance, at least during the hours of significant heat exchange (Rott 1979). The measurements of wind speed were not used for the calculation of the energy fluxes, but were an aid for interpretation and for comparisons.

Estimates of the accuracy of *LE* show that errors are caused mainly by measurement errors of temperature and humidity gradients, which result in errors of the calculated Bowen ratios. The measurement accuracy of temperature difference is about 0.1°C and cannot be improved significantly by temporal averaging. Therefore relative errors are highest in hours with small temperature gradients and decrease for periods with significant evaporation.

The measurements with small weighing lysimeters, which were carried out at HM during 6 weeks in 1978, provided daily sums of *ET* for comparison with the energy balance data (Körner et al. 1980). Since the evaluations of the 1978 data are still going on, comparisons are available so far only for a few clear days. On these days *ET* from the lysimeter measurements was about 20% higher than *ET* calculated from the energy balance. These differences should be caused primarily by small scale spatial variations in *ET.* The profiles measured vertical gradients which were valid for an area of hundreds to thousands of square meters depending on wind velocity and stability. At HM surface was covered not only by sedges and grasses, but to some percentage by lichens and bare soil. The lysimeters for this comparison had a surface of about 0.4 $m^2$ and were set up with alpine grasses, they were located in some distance (25 m) from the profile measurements. These facts may contribute to differences in ET derived by the two methods, as may possible modifications of the soil water balance within the lysimeters. Further investigations of the comparative measurements will help to clarify these questions.

## Daily Sums and Daily Variations of Surface Energy Fluxes

The energy fluxes on clear days are good indicators for the microclimates at the two stations. Table 1 gives the mean sums of the energy fluxes for 8 clear days in July and August 1976 and 1977, separated in hours with positive net radiation and in hours with negative net radiation. Daily sums of incoming shortwave radiation and of net radiation are somewhat higher at the site HM, mainly due to the screening of the horizon at the site WI. The differences of the other energy balance components between the two stations are mainly related to the different plant cover. Dense vegetation and humid soil at the site WI reveal comparatively low values of soil and sensible heat fluxes. But also in the alpine grassland at the site HM sensible heat flux is clearly smaller than latent heat flux. Mean values of 3.5 mm for HM and of 3.9 mm for WI are calculated from Table 1 for the daytime. During the night the sensible heat flux clearly exceeds the latent heat flux.

Fig. 1 shows an example of the daily variations of the energy fluxes on a clear day: July 12, 1977, Fig. 2 gives the same diagram for a day with heavy cloudiness and some rain: July 14, 1977. The daily course of *LE, H,* and *G* is determined by the daily variation of net radiation. On a day with little cloudiness the course of the energy fluxes is nearly symmetrical to solar noon, however only few days like July 12 are observed during summer. Maximum hourly *ET* on this day amounted to 0.5 mm at *HM* and to 0.7 mm at *WI.* High percentages of cloudiness prevail during summer. An example is shown in Fig. 2. July 14, 1977,was a day with a mean cloudiness of 7 octal; some sunshine was recorded around noon, rain was observed in the afternoon and evening hours. During the hours of rain *H* and *LE* show different trends at the two stations, the mountain station HM was during this period temporarily within clouds.

The mean diurnal variations of *ET* for each of the months July, August, and September 1976 and 1977 are shown in Fig. 3. During the night evaporation occurs more often than condensation, the absolute amounts of these fluxes were small and could compensate only a part (20 to 40%) of the longwave radiative loss. The highest mean value of condensation was observed in September 1977,

Table 1 – Mean sums of energy fluxes for day and night at the stations HM (2.580 m) and WI (1.960 m) for 8 clear days in July and August. ($R_G$ = global radiation, $R_N$ = net radiation, $G$ = soil heat flux, $H$ = sensible heat flux, $LE$ = latent heat flux).

| | $R_G$ | $R_N$ | $G$ | $H$ | $LE$ | $H/LE$ |
|---|---|---|---|---|---|---|
| *Day* | | | | | | |
| HM | 28.5 | 16.1 | –2.2 | –5.3 | –8.6 MJ/m$^2$ | 0.62 |
| WI | 24.9 | 13.9 | –0.8 | –3.4 | –9.7 MJ/m$^2$ | 0.35 |
| *Night* | | | | | | |
| HM | | –2.8 | 1.1 | 1.3 | 0.4 MJ/m$^2$ | |
| WI | | –2.9 | 0.5 | 2.5 | –0.1 MJ/m$^2$ | |

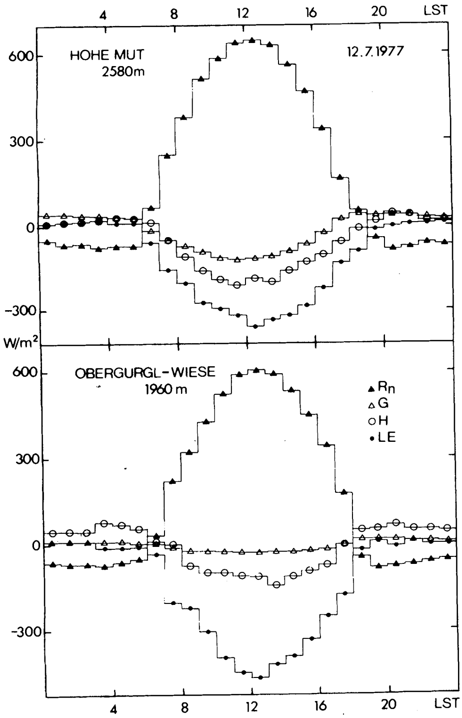


Fig. 1. Energy fluxes at the test sites Hohe Mut and Obergurgl – Wiese on July 12, 1977.

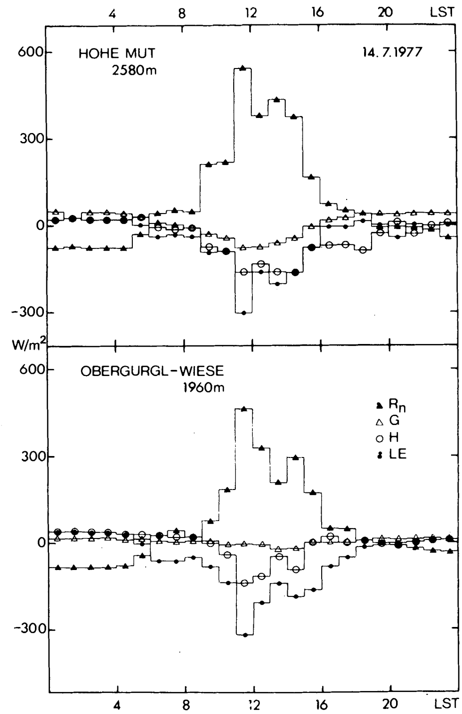


Fig. 2. Energy fluxes at the test sites Hohe Mut and Obergurgl – Wiese on July 14, 1977.

$R_N$ = net radiation
G ≡ ground heat flux,
H ≡ sensible heat flux
LE ≡ latent heat flux

where condensation in the nights prevailed, with an average sum of 0.3 mm at WI and 0.2 mm per night at HM.

During daytime *ET* followed the daily cycle of net radiation and showed some variability, which was related to the water supply and to the condition of the plant cover. Maximum *ET* occurred at noon or in the hour of minimum cloud cover before or after noon. In July the mean daily maximum was 0.45 mm per hour at WI and 0.32 mm/h (1976) and 0.34 mm/h (1977) at HM. These data indicate the decrease of plant transpiration due to decreasing leaf area with altitude. In September mean daily maximum of *ET* at WI was 0.27 mm/h in 1976 and 0.33 mm/h in 1977, the differences between the two years were caused by significant differences in monthly net radiation. At HM the mean daily maximum in September was 0.21 mm/h in 1976 and 0.22 mm/h in 1977. At WI soil moisture supply was

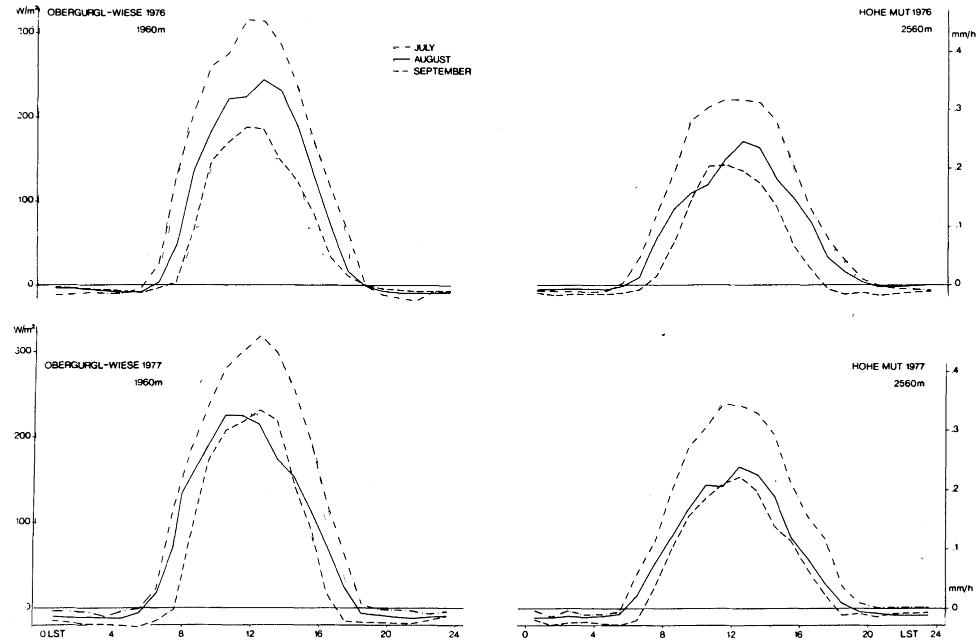


Fig. 3. Monthly averages of diurnal cycles of latent heat flux for July to September 1976 and 1977.

sufficient all over the vegetation period. At HM, where the contribution of evaporation from soil to *ET* is higher than at WI, decrease of *ET* during periods without rain indicate some limitation of *ET* by moisture of the uppermost soil layers.

## Evaporation During the Vegetation Periods in Relation to Other Parameters

The monthly sums of *ET* in summer 1976 and 1977 are listed in Table 2 for the two test sites together with the sums of net radiation and precipitation. The total sum of *ET* of the 3 months amounted to 221 mm at WI in 1976 and 222 mm in 1977, which exceeded *ET* at HM with 165 mm in 1976 by 33% and with 173 mm in 1977 by 27%.

The measurement period in 1976 had less sunshine and was slightly cooler (0.3 deg) than in 1977; the precipitation sum for this period at WI was by 23% higher in 1976 than in 1977, at HM it was by 32% higher in 1976 than in 1977. In 1976 incoming solar radiation was a limiting factor for *ET* at the site WI, the energy loss due to *ET* was in the order of 91% of net radiation. At HM this percentage was significantly smaller, the energy loss by *ET* amounted to 68% of net radiation, thus leaving a significant percentage of radiation for heating of soil and air. While

Table 2 – Monthly sums of radiation balance $R_N$, precipitation P, latent heat flux LE & percentage of LE on $R_N$, evaporation E & percentage of E on P.

| Wiese 1976 | $R_N$ MJ/m$^2$ | $P$ mm | $-LE$ MJ/m$^2$ | $E$ mm | Mut 1976 | $R_N$ MJ/m$^2$ | $P$ mm | $-LE$ MJ/»m$^2$ | $E$ mm |
|---|---|---|---|---|---|---|---|---|---|
| Jul | 270.1 | 110.0 | 251.4 | 100.6 | Jul | 278.9 | 114.2 | 200.9 | 80.4 |
| | | | 93% of $R_N$ | 91% ofP | | | | 72% of $R_N$ | 70% of P |
| Aug | 220.4 | 62.6 | 181.8 | 72.7 | Aug | 253.2 | 73.5 | 135.1 | 54.0 |
| | | | 82% | 116% | | | | 53% | 74% |
| Sep | 119.4 | 130.5 | 119.3 | 47.7 | Sep | 75.3 | 120.5 | 78.3 | 31.3 |
| | | | 100% | 37% | | | | 104% | 26% |
| Sum | 609.9 | 303.1 | 552.5 | 221.0 | Sum | 607.4 | 308.2 | 414.3 | 165.7 |
| | | | 91% | 73% | | | | 68% | 54% |

| Wiese 1977 | $R_N$ MJ/m$^2$ | $P$ mm | $-LE$ MJ/m$^2$ | $E$ mm | Mut 1977 | $R_N$ MJ/m$^2$ | $P$ mm | $-LE$ MJ/m$^2$ | $E$ mm |
|---|---|---|---|---|---|---|---|---|---|
| Jul | 334.9 | 83.2 | 262.2 | 104.9 | Jul | 353.6 | 70.7 | 220.6 | 88.2 |
| | | | 78% of $R_N$ | 126% of P | | | | 62% of $R_N$ | 125% of P |
| Aug | 225.7 | 120.9 | 167.7 | 67.1 | Aug | 239.1 | 146.1 | 122.3 | 48.9 |
| | | | 74% | 55% | | | | 51% | 33% |
| Sep | 162.4 | 25.0 | 124.0 | 49.6 | Sep | 203.4 | 31.1 | 90.6 | 36.3 |
| | | | 76% | 198% | | | | 45% | 117% |
| Sum | 723.0 | 229.1 | 553.9 | 221.6 | Sum | 796.1 | 247.9 | 433.5 | 173.4 |
| | | | 77% | 97% | | | | 54% | 70% |

net radiation at HM in summer usually exceeds net radiation at WI, in September 1976 at WI net radiation was significantly higher. This was caused by a period of 23 days with snow cover at HM, while the test site WI was snow covered only on 7 days. Consequently *ET* was low at HM in September 1976, on some days even condensation prevailed.

In summer 1977 *ET* at WI was the same amount as in 1976, at HM *ET* was slightly higher in 1977. During the measurement period 1977 precipitation imposed some limitations on *ET*, especially in September. At WI total *ET* of the test period was in the order of 97% of precipitation, at HM it was 70%. For shorter periods such as single months the ratio of precipitation to *ET* is highly variable, this should cause some variability in soil water content.

The ratio of daily sums of net radiation to the amount of evapotranspiration for a certain type of vegetation is comparatively constant, if moisture supply is sufficient. This relation is shown in Fig. 4 for the two test sites. Clear summer days in

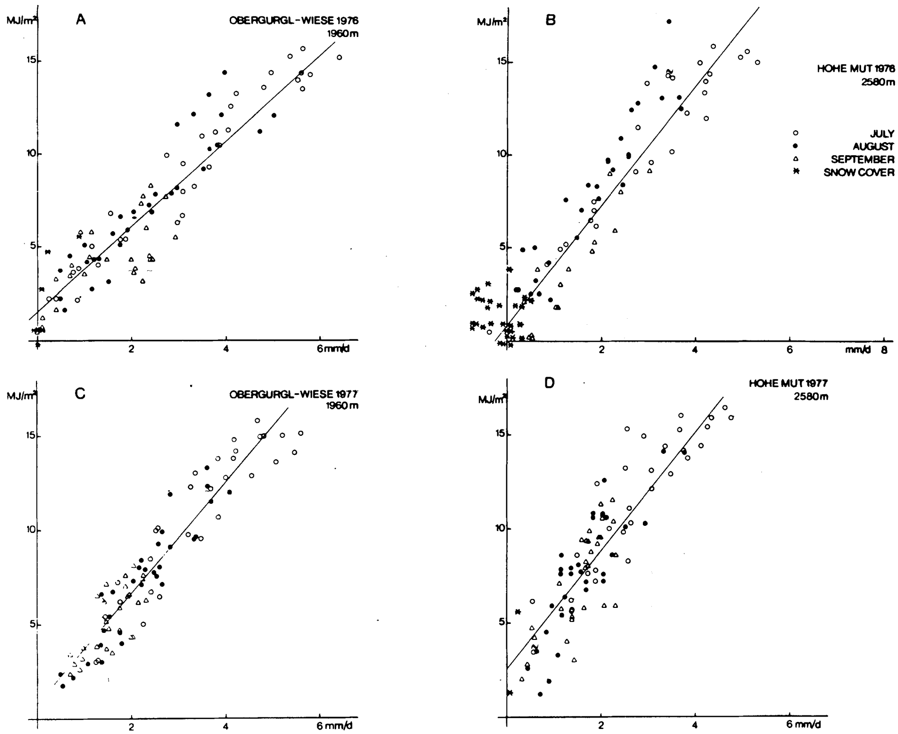


Fig. 4. Correlation between daily sum of net radiation and evaporation sum at the sites Wiese and Hohe Mut.

July yield sums of 15 $MJ/m^2$ of net radiation and between 5 and 6 mm of *ET* at the site WI. These values decrease to 12 $MJ/m^2$ and 4 mm in August. Some days at the end of clear weather periods show first signs of drying out, even with high radiation income they yield only about 3 mm of *ET*. In September the average sum of *ET* is around 2 mm with maximums of 3 mm on clear days with low relative humidity.

The drying out occurs sooner at the site HM, as Figs. 4B and D show. Single days in July and August with very high sums of net radiation fetch only little more than 2.5 mm of *ET* per day. Snow coverage in September results in condensation or evaporation of up to 0.3 mm per day, depending on air humidity.

The coefficients of the linear regressions show again the difference between the two stations and the two periods. At HM the regression lines are parallel shifted, this is due to the larger amount of precipitation in 1976 and corresponds in average to a 0.3 mm difference of evaporation per day.

Assuming a fairly constant level of soil moisture, estimates for the evapotranspiration can be made for a given vegetation type, if the radiation balance is

Table 3 – Coefficients for the linear regression lines
($E \equiv K \times R_N - d$ in mm/d ($E$) and MJ/M$^2$d ($R_N$)) and correlation coefficient $r$.

| | WIESE | | | HOHE MUT | | |
|---|---|---|---|---|---|---|
| | *K* | *d* | *r* | *K* | *d* | *r* |
| 1976 | .43 | .66 | .90 | .31 | .25 | .92 |
| 1977 | .34 | .28 | .93 | .32 | .86 | .86 |

known. The summer period 1978 (1, July to 15, Sep.), for which radiation data are available at the WI site, had similar to 1977 a sum of 616 MJ/m$^2$, but slightly less precipitation (181 mm) considered the shorter period. So 1978 was a little sunnier and dryer than 1977 and had the same temperature mean. It is therefore reasonable to take coefficients from Table 3 for the regression line of 1977. The sum of the daily evapotranspiration values calculated this way is 188 mm for the 77 day period.

## Conclusion

Evapotranspiration (*ET*) calculated from energy balance measurements at two Alpine test sites in 1,960 m and in 2,580 m a.s.l. clearly showed the decrease of *ET* with altitude.

The two test sites were covered with different types of grasses, which were representative for significant areas of the corresponding altitude. For the vegetation periods considered, *ET* was about 30% lower at the higher elevation, this can be related to the decrease of transpirating leaf areas and to the increasing percentage of evaporation from soil with altitude. At the lower site the amount of *ET* can reach the order of total precipitation during the vegetation period.

After snow melt soil is very wet at the beginning of the short vegetation period and long dry periods do not occur during summer, thus net radiation is the primary limiting factor for *ET* at these Alpine sites. Also the diurnal variations of *ET,* which followed the course of net radiation, indicated sufficient moisture supply. Reduced plant transpiration towards the end of the vegetation periods increased the variability of the relation between net radiation and *ET* to some degree and revealed some influence of precipitation on the amount of *ET.*

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