HYDROLOGICAL PROCESSES
Hydrol. Process. **13**, 1589–1601 (1999)

Observation and estimation of daily actual evapotranspiration and evaporation on a glacierized watershed at the headwater of the Urumqi River, Tianshan, China

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Abstract:

In order to develop an effective approach to estimate evaporation and evapotranspiration (ET) in the glacierized watershed for hydrological process studies, the meteorological and energy budget data obtained in 1986 from a small watershed at the headwater of Urumqi River Basin, Tianshan, China were utilized. The field observation of ET and surface soil water content was briefly described. The performance of several existing approaches in estimating the daily actual ET and evaporation for the two kinds of predominant ground surface in the basin (i.e. the alpine tundra and glacier surface) was examined. The estimated daily ET from the alpine tundra for the summer season by Morton's equation correlates fairly well with the lysimeter-observed data, and the proposed wetness index by means of the principle of Morton's complementary relationship, provided reliable information of the surface soil wetness condition for the same period. For the other seasons, Kojima's equation was adopted for estimation of daily evaporation on both alpine tundra and the glacier surface when most parts of the watershed were snow covered. The daily evaporation on the glacier surface for the melting season was ultimately estimated by Ohno's equation for the non-melting season. The monthly mean evaporation estimated for the glacier surface was close to the field observation data obtained in 1987–1988. The annual evaporation obtained on both sites by this approach was in good agreement with that estimated with the water balance method for the same sites by Zhang *et al.* (1992). Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS daily evaporation; daily actual ET; lysimeter observation; surface soil water content

INTRODUCTION

In a surface hydrological model, two difficult problems still remain: one is linked to the notion of effective rainfall, and another to the correct estimation of actual evapotranspiration (ET) over a large area, such as a watershed of a principle river or its tributaries. With regard to the partitioning of the measured precipitation the supply can be divided into two parts, one giving the short-term runoff response to the rainfall, the other linked to a longer term response to the baseflow. It has been shown that one approach to deal with this problem is to take into account the soil hydrological state through a simple coefficient acting directly on the rainfall partition (Fukushima, 1988; Edijatno, 1989).

For the correct estimation of ET, many studies have been conducted on different underlying conditions to promote effective use of water resources and to introduce it into long-term rainfall–runoff models. Many approaches regarding different climatic or underlying conditions for estimating actual ET have been

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CCC 0885–6087/99/111589–13$17·50

Received 15 May 1998
Accepted 22 December 1998

proposed (Morton, 1978; Brutsaert and Stricker, 1979; Kojima, 1979; Otsuki *et al*., 1984). By comparing 20 different methods for estimating ET, Jensen *et al*. (1990) showed that Morton's complementary equation provides the most accurate estimate of monthly ET from well-watered grassland under varied climatic conditions. However, the applicability of the equations on different time and space scales has not yet been clearly understood. Only a few studies of evaporation have been conducted in cold alpine regions owing to the difficulties in measuring the necessary meteorological and energy budget parameters, especially in evaporation observation in such regions (Ohno *et al*., 1992; Zhang *et al*., 1992). Based on the multiple bulk method, in combination with the *in situ* observation of evaporation on the snow-covered surface, Kojima (1979) proposed a semi-empirical relationship to estimate the snow surface evaporation. Through the field observation of basic meteorological parameters, energy budget terms as well as evaporation on the glacier surface, Ohno *et al*. (1992) proposed an empirical expression which is very similar in form to Kojima's to estimate the evaporation on a glacier melting season in Chinese Tianshan areas.

In the summer seasons of 1986–1987, a joint project between Tianshan Glaciological Station of the Chinese Academy of Sciences (LIGG–CAS) and the Geography Institute of the Swiss Federal Institute of Technology (GI–ETH) was carried out at the headwater of the Urumqi River, Tianshan, China. The purpose of the project was to obtain the basic energy budget parameters on the glacier surface in the high altitude area as well as on the alpine tundra for a better understanding of the energy exchange process and its relationship to glacier melting. During the field seasons of the project, energy budget terms and conventional meterological parameters were observed on both experimental sites at 30 min intervals. The daily actual ET and surface water content were also measured on the alpine tundra of the basin (Zhang, 1987). This made it possible to examine the applicability of several proposed approaches to estimating the daily actual ET or evaporation in such a high altitude watershed. By means of the field data observed, the present study aimed to examine the possibility of developing an effective approach to estimate the daily actual ET and evaporation for the two kinds of underlying conditions, so as to contribute to hydrological modelling studies in alpine glacierized watershed. Since the field observation of evaporation or ET in alpine glacierized catchment is extremely difficult, this study is thus expected to provide a reliable reference for the future application of remote sensing techniques, as alternative tools for areal evaporation estimations in such water resource areas.

OBSERVATION SITES

The observation sites in the studied watershed are located in the source region (43°00′–44°07′N and 86°45′–87°56′E) of the Urumqi River, Tianshan, China (Figure 1). The catchment area of the watershed is about 28·9 km^2, including 5·74 km^2 covered by seven glaciers. Outflow from the watershed is regularly gauged by the total control hydrological station of the Glaciological Station of the Chinese Academy of Science. The altitude of the basin ranges from 3403 to 4479 m a.s.l, spanning an underlying surface of glaciers, bare rocks and moraines above 3600 m a.s.l. to alpine tundra below it. There are three hydrological stations and one standard meteorological station (Daxigou Meteorological Station) within the basin. According to observations conducted at the Daxigou Meteorological Station (3539 m a.s.l.), from 1959 to 1996 the mean annual precipitation was about 436·4 mm with a standard deviation of 51·2 mm. The mean annual air temperature was about −5·1° C. Most of the precipitation was concentrated in the warm season from June to August, accounting for 66% of the annual totals. Meanwhile, the glacier ablation was intense during these months since the air temperature is also high.

The 1986 summer observation sites in the basin were set up on two different underlying surfaces: one was at 3903 m a.s.l. on the surface of Glacier No. 1, and another at 3539 m a.s.l. on the alpine tundra near the Daxigou Meteorological Station (Figure 1). According to Zhang (1992), the snow-covered period at the headwater of the Urumqi River Basin is about 8 months per year, but the stable snow cover period is only about 3 months. Except for the alpine tundra below 3600 m a.s.l. (from June to August), the whole watershed is snow covered all year round with only short periods of discontinuities.

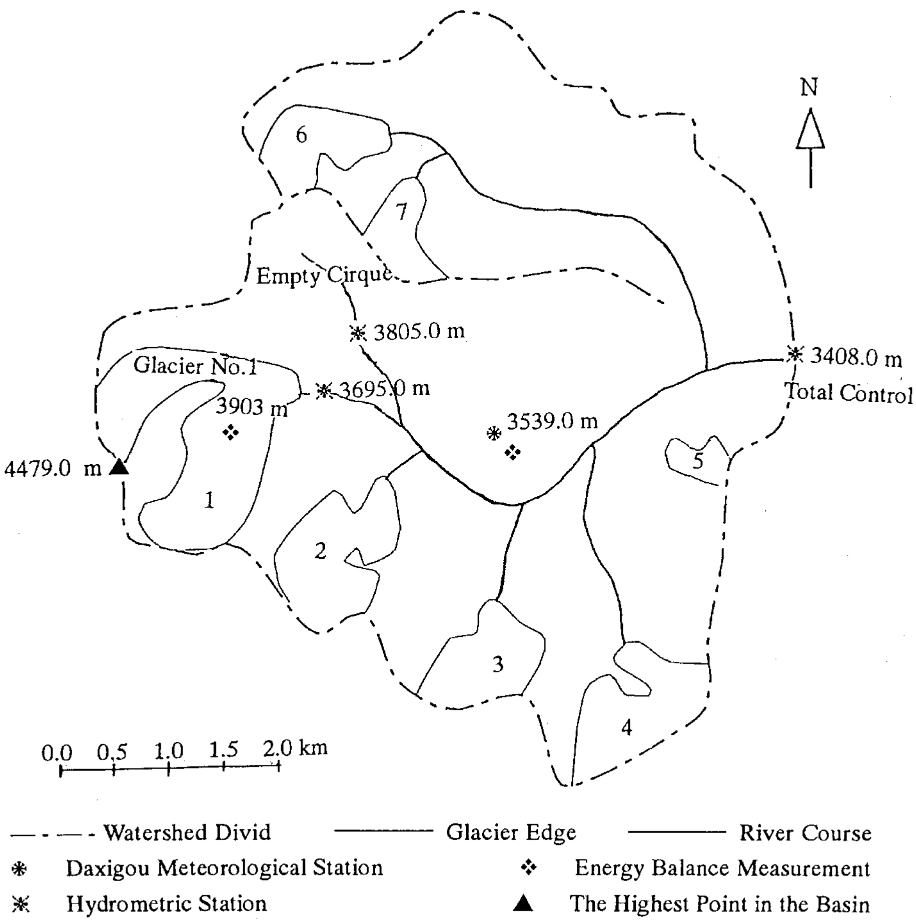

Figure 1. A schematic map of the source basin of Urumqi River showing locations of the experimental sites as well as the meteorological and hydrological stations installed. [Modified from Figure 1 of Kang *et al.* (1992)]

FIELD OBSERVATION AND DATA OBTAINED

During June–August 1986, a systematic observation on the energy budget and conventional meteorological parameters was conducted on both the glacier surface and alpine tundra by the Sino–Swiss Joint Project. The equipment utilized in the observation sites was an EKO model MR-21 reflectometer for measuring global solar radiation and reflected radiation; a Swissteco net radiometer; and a VAISALA automatic meteorological observation system installed on a 2 m step-ladder. In this meteorological observation system, air temperature, humidity and wind speed sensors were fixed at heights of 2, 1, 0·5 and 0·25 m. All the measurement data were automatically recorded and averaged for each 30-minute period in the corresponding dataloggers. For detailed information about the field settlement and relevant parameter observations, refer to Kang *et al.* (1992) and Zhang *et al.* (1992).

The daily meteorological data obtained at 3903 m a.s.l. on the surface of Glacier No. 1 for the summer season and daily meteorological data for the whole year of 1986 as well as energy budget data for the summer season observed at 3539 m a.s.l. on the alpine tundra near the Daxigou Meteorological Station, which will be used later in the evaporation estimation, are presented in Figures 2 and 3, respectively.

During the period of meteorological and energy budget observations on both the experimental sites of the basin, the measurements of daily ET and soil water content were also carried out on the alpine tundra near

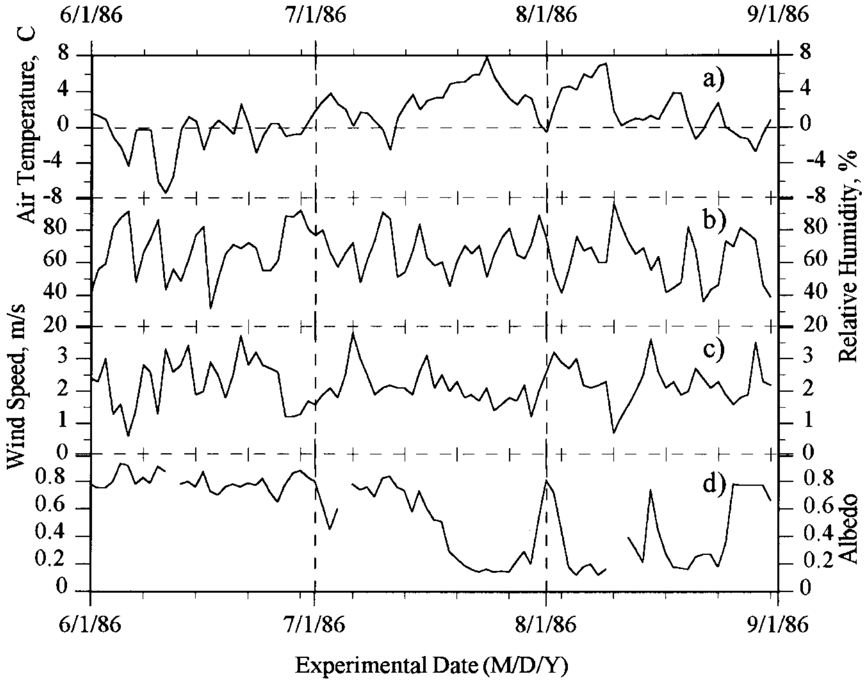

Figure 2. Temporal variation of daily mean (a) air temperature (°C) at 1 m height, (b) relative humidity (%), (c) wind speed (m s^{-1}) at 1 m height and (d) albedo measured at 3903 m a.s.l. on the surface of Glacier No. 1

the Daxigou Meteorological Station by one of the authors. The daily ET was observed by the weighing-lysimeter method, and the daily soil water content was measured by the dry-weighting method for monitoring the surface 5–10 cm soil samples. In order to obtain a precise measurement of ET and surface soil water content on the alpine tundra of the watershed, the observation site was arranged as shown in Figure 4. The lysimeter used in the observation was designed and settled as illustrated in Figure 5. A natural soil bulk of the same size and shape as the drum was set at the same level with the surrounding soil surface. A small hole at the centre of the drum's bottom allows the penetrating water released from the soil bulk to be collected by a bottle lying at the bottom centre of the tuff. The soil bulk in the drum was changed every 3–5 days according to climatic conditions. A rain gauge was installed on the ground surface near the lysimeter for measuring the amount of water received by the lysimeter. The weight changes of the soil bulk and penetrating water were measured at 8:00 p.m. every day, and thus the ET can be calculated by:

$$ET = \Delta W/S + Pr \tag{1}$$

where ΔW is the weight difference of soil bulk and penetrating water; Pr is precipitation observed at the ground surface, and S is the surface area of the natural soil bulk.

Figure 6 represents the daily actual ET (mm d^{-1}) and surface soil water content (% in weight) measured from June to August of 1986. The correlation analysis was made to understand the relationship between daily actual ET and surface soil water content θ on the alpine tundra of the basin. It was found that the actual ET is highly correlated with θ in an exponential function, as shown in Figure 7. In this area, however, the surface soils are frozen all year round except in the warm season (May–September). Thus, the calibration curves may not be applied in other seasons.

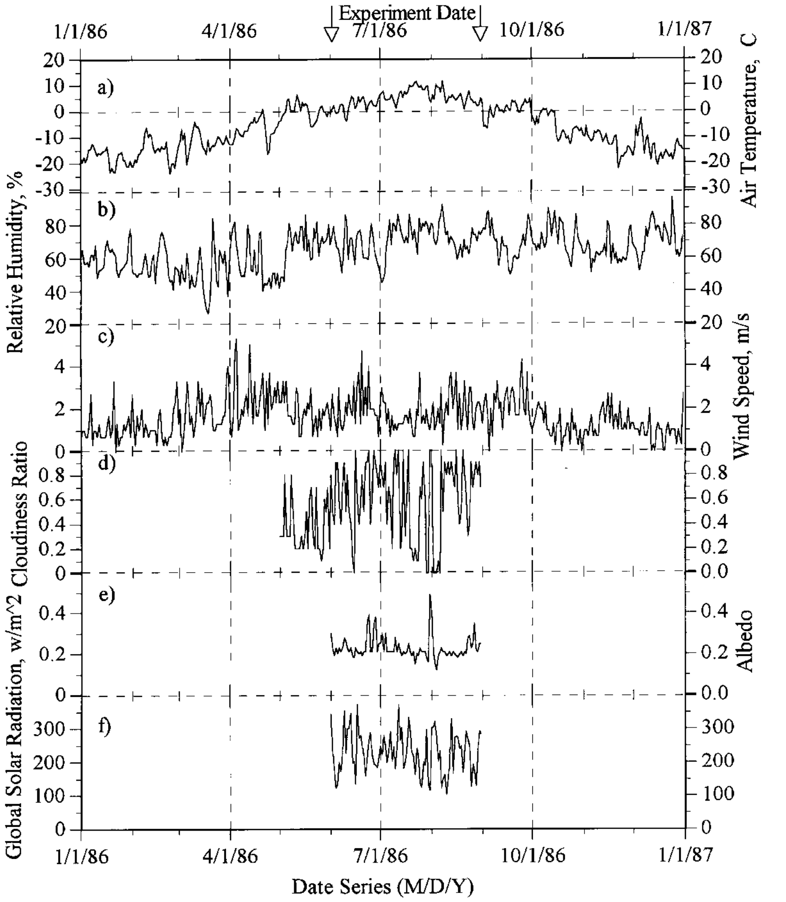

Figure 3. Temporal variation of daily mean (a) air temperature (°C), (b) relative humidity (%), (c) wind speed (m s^{-1}) at 1 m height, (d) cloudiness ratio, (e) albedo and (f) global solar radiation (W m^{-2}) measured at 3593 m a.s.l. on the alpine tundra near the Daxigou Meteorological Station

DAILY ACTUAL ET AND EVAPORATION ESTIMATION FOR ALPINE TUNDRA

For estimating actual ET, a complementary hypothesis was proposed by Bouchet (1963), and can be expressed mathematically as:

$$E_{pen} = 2E_{pt} - E_{ac} \tag{2}$$

where E_{pt} is the evaporation from an extensively saturated area, which would occur when the atmospheric conditions have adjusted to this evaporation rate (Brutsaert, 1984). The principle of the complementarity hypothesis is illustrated in Figure 8. It means that the potential ET, E_{pen}, responds in a complementary way to changes in the actual ET, E_{ac}, caused by changes in the availability of surface soil water. Theoretical analyses of the hypothesis have been presented by Sequin (1975) and McNaughton and Spriggs (1989), while several studies have evaluated field observations with regard to this hypothesis (Brustaert and Stricker, 1979; Morton, 1983; Lemeur and Zhang, 1990).

From Equation (2), it is easy to understand that the accurate estimate of E_{ac} depends considerably on the accurate estimate of E_{pt} and E_{pen}. Previous studies suggested that the modified Priestley–Taylor (1972) equation could provide a good estimate of E_{pt} (Culf, 1994). By comparing 20 different methods of estimating

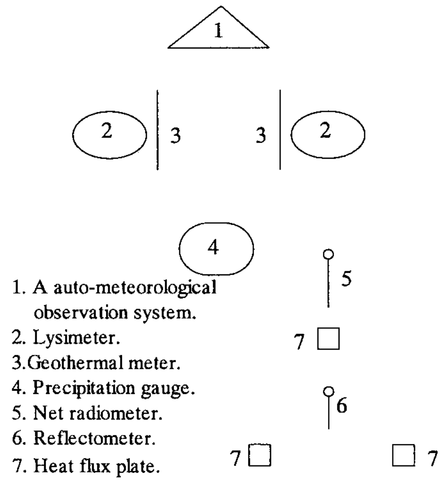

Figure 4. A schematic map showing the observation site settled on the alpine tundra near the Daxigou Meteorological Station. [Modified from Figure 1 of Zhang *et al.* (1992)]

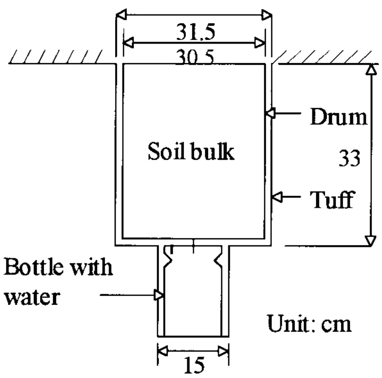

Figure 5. A schematic diagram illustrating the structure of the lysimeter and its settlement in the practical observations. [Modified from Figure 2 of Zhang *et al.* (1992)]

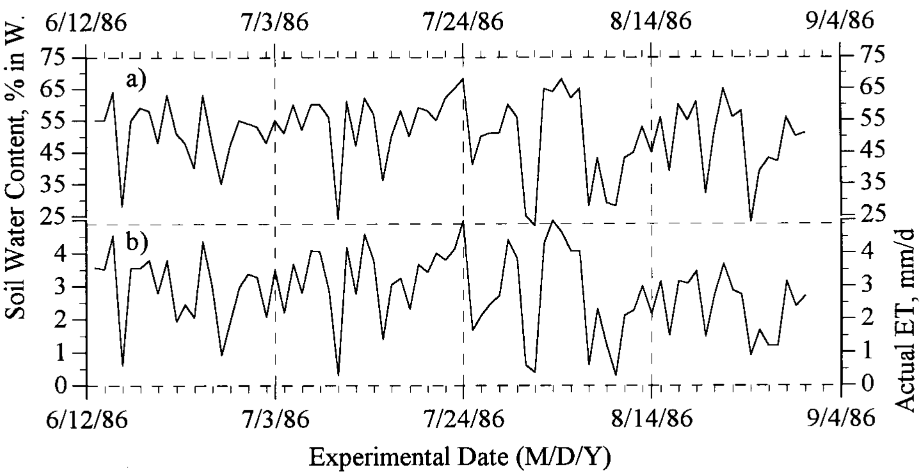

Figure 6. Daily mean variation of (a) surface soil water content (% in weight) and (b) actual ET (mm d^{-1}) measured for the summer season of 1986 at 3539 m a.s.l. on the alpine tundra near the Daxigou Meteorological Station

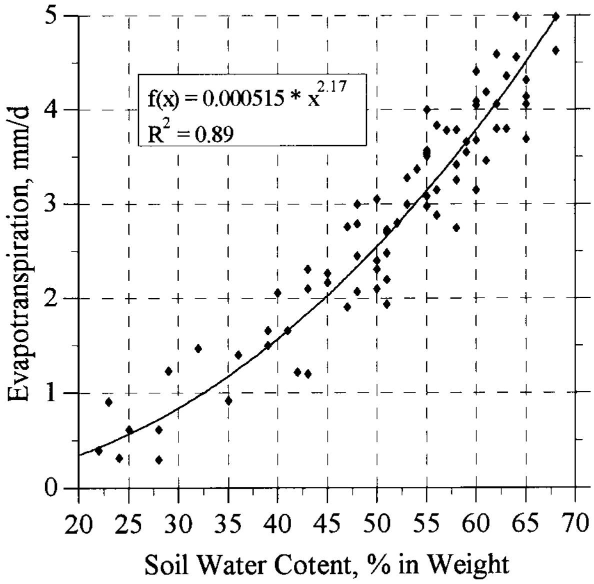

Figure 7. Relationship between the ET (mm/d) and the surface soil water content (% in weight) at 3539 m a.s.l. on the alpine tundra near the Daxigou Meteorological Station

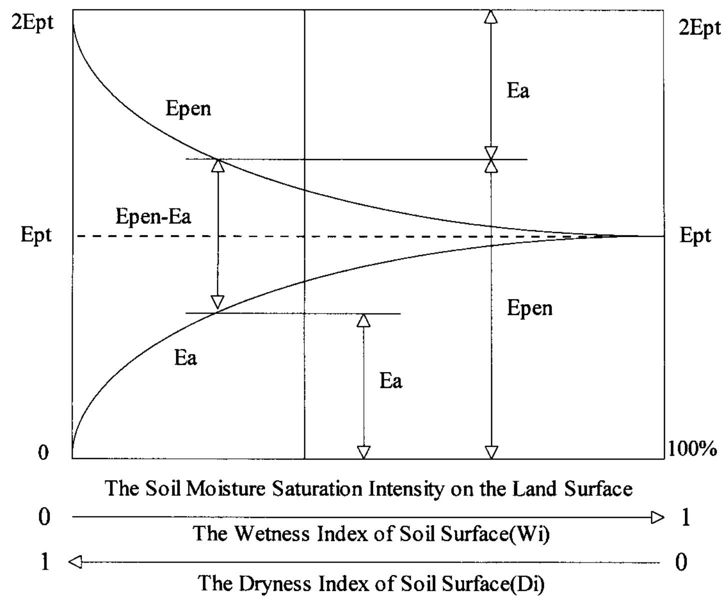

Figure 8. A schematic diagram showing the complementary relationship in estimated evapotranspiration, and the wetness index proposed

E_{pen}, Jensen *et al.* (1990) showed that the Penman–Monteith equation provided the best estimation of E_{pen} for well-watered grass under various climatic conditions.

For exploring an effective approach to the correct estimation of the summer dialy ET on the alpine tundra in the source region of the Urumqi River Basin, the applicability of Morton's equation (Morton, 1978), a kind of complementary relationship that employs the modified Priestley–Taylor equation for estimation of

E_{pt} and the Penman–Monteith equation for E_{pen} was examined. The Morton equation can be expressed mathematically in the following forms:

$$E_{ac} = 2\Psi(R_n + M)/L \times 86{\cdot}4 - [\Delta/(\Delta + \lambda) \times R_n/L + \lambda/(\Delta + \lambda) \times F/L \times (e_{sa} - e_a)] \times 86{\cdot}4 \quad (3)$$

$$R_n = (1 - \alpha)I_p - B \quad (4)$$

$$B = \varepsilon\sigma(T_a + 273)^4 \times [1 - \rho(0{\cdot}707 + e_a/158)] \quad (5)$$

$$\rho = 1 + [0{\cdot}25 - 0{\cdot}005 \times (e_{sa} - e_a)]C^2 \quad (\rho \geqslant 1) \quad (6)$$

$$M = 0{\cdot}66B - 0{\cdot}44R_n \quad (7)$$

$$\psi = [1 + (\lambda/\Delta) \times (0{\cdot}5 + 0{\cdot}5R_n + \lambda/\Delta)/(R_n + \lambda/\Delta]^{-1} + 0{\cdot}26 \quad (8)$$

$$\lambda = \gamma + 4\varepsilon\sigma(T_a + 273)^3/F \quad (9)$$

$$F = 22{\cdot}0/\xi \quad (T_a \geqslant 0) \quad (10)$$

$$\xi = [|e_{sa} - e_a|/6{\cdot}11]^{0{\cdot}12} \quad (11)$$

where E_{ac} is the actual ET (mm d^{-1}); R_n, the net radiation (W m^{-2}); α, the surface albedo; I_p, the global solar radiation (W m^{-2}); B, the net long-wave radiation loss (W m^{-2}); ε, the surface emissivity, according to Zhang *et al.* (1998), it is 0·97 on the studied region; σ, the Stefan–Boltzmann constant; T_a, the air temperature (°C); ρ, the ratio of average atmospheric radiation to clear sky atmospheric radiation; e_a, the vapour pressure (hPa); e_{sa}, the saturation vapour pressure at air temperature (hPa); C, the cloud cover ratio, 0–1; M, the advection energy (W m^{-2}); Ψ, the energy weighting factor; Δ, the rate of change of saturation vapour pressure with respect to air temperature (hPa °C^{-1}); γ, the psychrometric constant (hPa °C^{-1}); λ, the heat transfer coefficient (hPa °C^{-1}); ξ, the stability factor; L, the specific latent heat of vaporization (kJ kg^{-1}), equal to $2501 - 2{\cdot}4T_a$ for $T_a \geqslant 0$; and F, the vapour transfer coefficient (W m^{-2} hPa^{-1}).

Based on the principle of the complementary hypothesis explaining the relationship between the actual ET and the surface soil water content, the following two parameters were proposed to evaluate the hydrological state of the soils (Sado, 1996):

$$W_i = 2E_a/(E_{pen} + E_{ac}) \quad (12)$$

$$D_i = (E_{pen} - E_{ac})/(E_{pen} + E_{ac}) \quad (13)$$

where W_i represents surface soil wetness index and D_i is the dryness index. These two indices can be calculated from E_{ac} and E_{pen}, and the sum of them is 1.

Employing Morton's equation, the daily ET (mm d^{-1}) on the alpine tundra near the Daxigou Meteorological Station from 1 June to 31 August 1986 was calculated. The daily mean values of air temperature, relative humidity, surface albedo, global solar radiation and cloud cover ratio used in the calculation were all obtained from the 1986–1987 Sino–Swiss Joint Project in the source region of Urumqi River Basin. The e_{sa} and e_a are calculated by the following equations:

$$e_{sa} = 6{\cdot}11 \times 10^{[7{\cdot}5T_a/(237+T_a)]} \quad T_a \geqslant 0 \quad (14)$$

$$e_{sa} = 6{\cdot}11 \times 10^{[9{\cdot}5T_a(265+T_a)]} \quad T_{a<0} \quad (15)$$

$$e_{a_1} = e_{sa} \times R_h \quad (16)$$

where R_h is the relative humidity, (%).

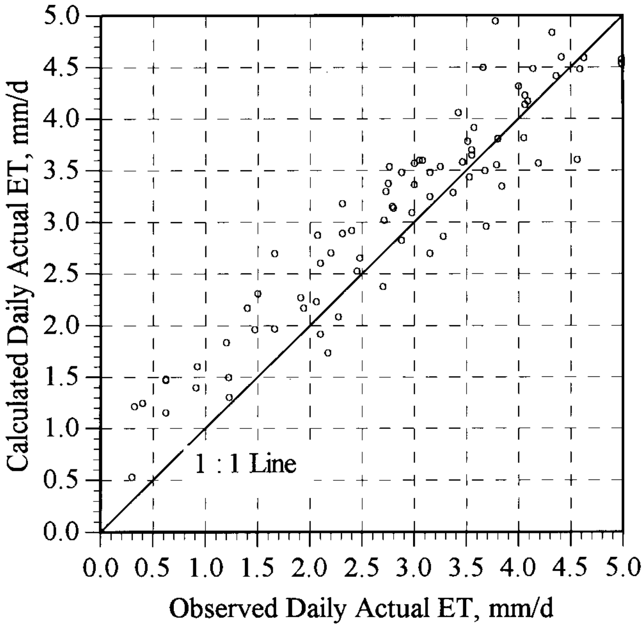

Figure 9. Scatter plot of the observed (lysimeter) and calculated daily actual ET for comparison. Statistics for evaluating the figure are given in Table I

The values of Δ and γ are approximated as:

$$\Delta = 1779{\cdot}75 \times \ln 10 \times e_{sa}/(237{\cdot}3 + T_a)^2 \quad (17)$$

$$\gamma = 1005 \times P/(0{\cdot}622L) \quad (18)$$

$$P = 1013{\cdot}25 - 0{\cdot}119861H + 5{\cdot}356 \times 10^6 H^2 \quad (19)$$

in which P and H are atmospheric pressure (hPa) and altitude (m), respectively.

The comparison between the calculated and field-measured daily ET (mm d^{-1}) is shown in Figure 9. It is clear that the calculated and measured results are very consistent with each other. The statistical analysis of the observed and calculated daily ET [lysimeter measurement (x) vs. calculated value (y)] for the alpine tundra for the calibration period is summarized in Table I. The mean absolute error (MAE) for all the estimated data is 0·20 mm d^{-1}, which is about 6% of the mean observed value. Thus, with respect to these lysimeter data, the error in the present calculations is not higher than 6%. The calculated daily ET values appear to be somewhat higher (*c.* 0·32 mm d^{-1}) than the observed ones at the low evaporation rate. The standard error of estimates (SEE) for the studied site is 0·25 mm d^{-1}, and the explained variances (γ^2) is 0·88.

Table I. Statistical analysis of the observed and calculated daily ET [lysimeter measurement (x) vs. calculated value (y)] for the alpine tundra near the Daxigou Meteorological Station*

Date set	γ^2	Intercept		Slope		SEE	MAE	IA
		OLS	LNS	OLS	LNS			
6/13–8/31(N = 80)	0·88	0·27	0·20	0·78	0·85	0·25	0·20	0·93

*The results given are total number of diary values (N), the explained variance (γ^2), the slope and the intercept calculated according to the ordinary least square (OLS) and least normal square (LNS) regression analysis, standard error of estimate (SEE), mean absolute error (MAE), and Wilmott's (1982) index of agreement (IA). Intercept, SEE and MAE are in units of mm/d.

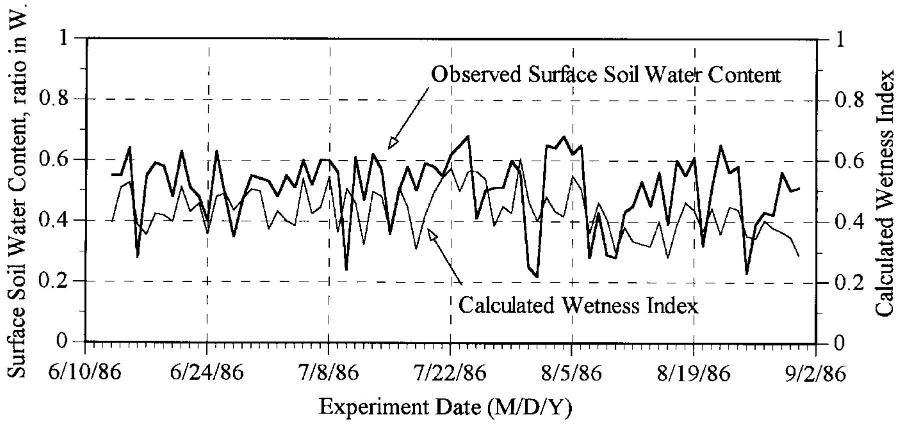

Figure 10. Comparison of the observed surface soil water content in ratio of weight with the calculated wetness index proposed on the basis of the complementary relationship for the summer season of 1986 at 3539 m a.s.l. on the alpine tundra near the Daxigou Meteorological Station

By using the wetness index shown in Equation (12), the daily variation of W_i on the grassy marshland of the basin was calculated. The calculated daily mean W_i compared with observed surface soil water content θ (ratios in weights) is given in Figure 10. It can be seen that the W_i generally varies with a similar pattern as that of the observed surface soil water content, but the value is lower by about 0·16 than the latter, on average.

Our final aim is to examine the possibility of obtaining the daily actual ET for the studied basin. It is not difficult to find that Morton's equation (Morton, 1978) is not suitable for use for evaporation estimation when the air temperature goes below 0 °C, especially for the seasons when the land surface is mostly covered with snow. In this case, Kojima's equation (Kojima, 1979), giving the evaporation from the snow surface, seems more suitable for estimating the evaporation from the snow-covered surface of alpine tundra for the other seasons calculating the climatic conditions in the studied area.

According to Kojima (1979), the snow surface evaporation could be estimated by the following equation assuming that the daily snow surface temperature was equal to the daily mean air temperature:

$$E'_{ac} = 1{\cdot}0 \times 10^{-3} u_1 (e_{sa} - e_{a_1}) \times 240 \tag{20}$$

where E'_{ac} is the evaporation on the snow surface (mm d^{-1}), u_1 and e_{a_1} are the wind speed (m s^{-1}) and the vapour pressure (hPa) at 1 m above the snow surface, respectively.

The seasonal actual daily evaporation on the alpine tundra of the basin estimated by Kojima's equation, together with the results from Morton's equation are shown in Figure 11. In this calculation, we used the meteorological data obtained from the Daxigou Meteorological Station. The annual evaporation in 1986 calculated by this method was 363·8 mm, which is about 100 mm higher than that estimated by Zhang *et al.* (1992), who assumed that the evaporation took place only in the warm season from June to September. However, this result is consistent with value of about 347 mm for 1986 estimated at the same site using the water balance method by Zhang *et al.* (1992).

DAILY EVAPORATION ESTIMATION ON THE GLACIER SURFACE

As the surface temperature and the surface-specific humidity are constant on a melting glacier, the evaporation on the glacier surface can be estimated by using the bulk transfer method dealing with a wide range of information about the temperature, humidity and wind speed in the atmospheric boundary layer. It is, however, impossible to apply this method for glaciers under non-melting conditions because surface

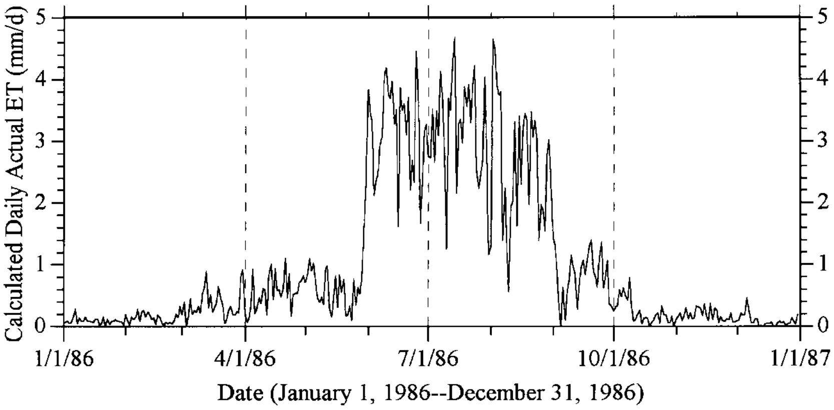

Figure 11. Daily mean actual ET estimated by Morton's equation for the summer season and by Kojima's equation for the other seasons in 1986 at 3539 m a.s.l. on the alpine tundra near the Daxigou Meteorological Station

elements vary considerably according to the surface heat balance condition. Therefore, we divide the year into two seasons for the convenience of evaporation estimation: the melting season in which the firn is melting during most of the day and the non-melting season during which melting never occurs. According to Ageta *et al.* (1980), when the air temperature exceeds −3 °C, a mountain glacier in Nepal Himalaya starts to melt. The air temperature on the glacier surface, as shown in Figure 2, was above −3 °C most days during the period from June to September. Therefore, a melting season from 1 June to 30 September 1986 and a non-melting season for other days are assumed in this study.

Between summer 1987 and spring 1988, Ohni *et al.* (1992) carried out a systematic study on annual evaporation of Glacier No. 1. Based on field observation data of evaporation obtained in the melting season, by examining the relationship between daily meteorological data derived at the Daxigou Meteorological Station, the following regression was established:

$$E'_{ac} = 1{\cdot}0 \times 10^{-3} u_1 (e_0 - e_{a_1}) \times 280 \tag{21}$$

where e_0 is the saturation vapour pressure of the melting ice (6·11 hPa). This expression, compared with Kojima's equation (20), suggests that the expression of both equations is basically the same. We, therefore, use Ohno's equation to estimate the daily evaporation of the glacier surface for the melting season, and Kojima's equation (Kojima, 1979) for the non-melting season. Since the meteorological parameters were measured only in the summer season from June to August of 1986 at 3903 m a.s.l. on the surface of Glacier No. 1, the meteorological parameters for other seasons were estimated from the data observed at the Daxigou Meteorological Station. It this process, the temperature on the glacier surface was calculated assuming the constant altitudinal gradient of −0·88 °C/100 m (Zhang *et al.*, 1998), and the saturation vapour pressure as a function of the temperature are calculated by Equations (14)–(16), respectively.

In this calculation, the R_h values were derived from the measurements on the glacier surface for the summer season, and from the Daxigou Meteorological Station for the other seasons, assuming that R_h is independent of altitude in such a small basin.

The wind speed at 1 m above the glacier surface for the non-melting season was estimated from observations at Daxigou Meteorological Station by means of a relationship proposed by Kang *et al.* (1992).

The daily evaporation estimated on the surface of Glacier No. 1 was thus obtained by the method described above. The results are shown in Figure 12. By summing the daily evaporation estimated, the annual evaporation for 1986 on the glacier surface was derived as 145·7 mm, which is close to the value of 164·9 mm estimated on the glacier surface for 1986 with the water balance method of Zhang *et al.* (1992). The calculated daily mean evaporation for spring (March–May), summer (June–August), autumn

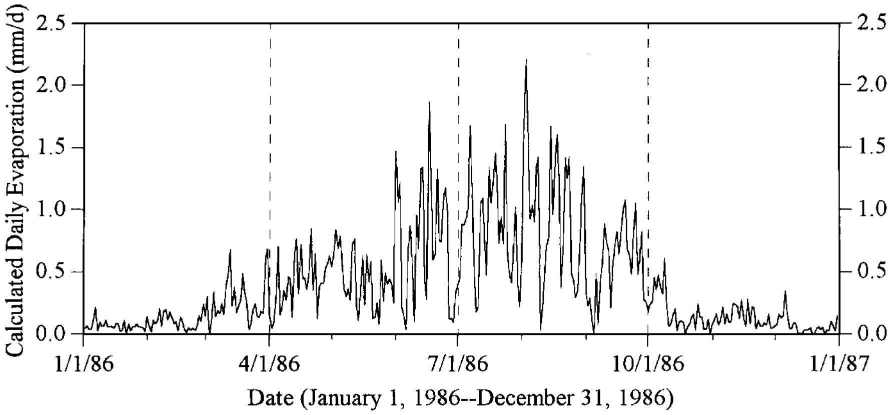

Figure 12. Daily evaporation estimated for 1986 by Ohno's expression for the melting season and by Kojima's equation for the non-melting season on the surface of Glacier No. 1, Tianshan, China

(September–November) and winter (December–February) was 0·35, 0·79, 0·31 and 0·13 mm d^{-1}, respectively. Zhang *et al.* (1992) reported that an experimental study was carried out to observe the evaporation at 4100 m a.s.l. on the surface of Glacier No. 1 for four seasons from 1987 to 1988. A few ten-day periods were selected for each season to measure the daily evaporation on the glacier surface. The seasonal daily mean evaporation on the glacier surface was 0·32 daily for spring, 0·7 for summer, 0·36 for autumn and 0·2 mm d^{-1} for winter, respectively.

DISCUSSION AND CONCLUSION

Meteorological and energy budget data obtained on the alpine tundra and glacier surface from the 1986 Joint Project of LIGG–CAS and GI–ETH were utilized to estimate the daily actual ET on the alpine tundra by using Morton's complementary relationship for the summer season, and the daily evaporation on the glacier surface by Ohno's expression for the melting season. The daily evaporation on both the alpine tundra and glacier surface for other seasons were estimated with Kojima's equation (Kojima, 1979) by using the meteorological data obtained at the nearby meteorological station. In this way, the daily evaporation and ET on both glacier surface and alpine tundra for 1986 were obtained. The results were compared with lysimeter measurements as well as with estimated results by the water balance method. It was found that the results estimated by a combined approach of Morton's, Ohno's and Kojima's equations were very consistent with the lysimeter observation data and estimated results by the water balance method. This suggests that the employed estimation method would be applicable for the correct estimation of daily ET and evaporation on alpine regions of western China.

It is difficult to assess the accuracy of the estimated daily evaporation values because of a lack of observed evaporation data on both the snow-covered alpine tundra and the glacier surface. However, the observed evaporation data of the selected periods of the four seasons from 1987 and 1988 on the glacier surface seem to suggest that the calculated results are reasonable. The calculated annual ET on the alpine tundra of the basin is about 363·8 mm, while the estimated annual evaporation on the glacier surface yields 145·7 mm. These results are fairly consistent with those estimated from the water balance method by Zhang *et al.* (1992). This study demonstrated the applicability of Morton's equation in providing reliable daily actual ET on the alpine tundra for the summer season, and Kojima's equation for the other seasons, when snow cover is predominantly at the source area of the Urumqi River Basin. Both daily actual ET on alpine tundra and daily evaporation on the glacier surface reach their maximums during the summer season while the temperature is relatively high, and the precipitation is concentrated. The daily actual ET measured on the alpine tundra was found to correlate closely with the surface soil moisture content, with an exponential relationship, in the summer season. The wetness index proposed on the basis of the principle of the complementary relationship is thought to be a reasonable parameter to indicate the surface soil moisture content in the studied basin.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the staff of Tianshan Glaciological Station, Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Science, for their logistic support in the field observations. We are indebted to Professor Y. Fukushima for constructive discussions and for his very useful and stimulating comments. This work was performed with a lot of encouragement from our colleagues.

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