ESTIMATION OF REGIONAL EVAPOTRANSPIRATION USING REMOTELY SENSED LAND SURFACE TEMPERATURE

K. Kotada, S. Nakagawa, K. Kai, M. M. Yoshino

Environmental Research Center
University of Tsukuba
Sakuramura, Ibaraki, Japan

K. Takeda and K. Seki

National Institute of Resources
Science and Technology Agency
Chiyoda-ku, Tokyo, Japan

ABSTRACT

In order to study the distribution of evapotranspiration in the humid region through the remote sensing technology, first, in the Part I of this paper, the parameter (α) in the Priestley-Taylor model was determined. The daily means of the parameter $\alpha=1.14$ can be available from summer to autumn and $\alpha=1.5\sim2.0$ in winter. Secondly, in Part II of the present paper, the results of the satellite and the airborne sensing done on 21st and 22nd January, 1983, were described. Using the vegetation distribution in the Tsukuba Academic New town, the radiation temperature obtained by the remote sensing and the radiation data observed at the ground surface, the evapotranspiration was calculated for each vegetation type by the Priestley-Taylor method. The daily mean evapotranspiration on 22nd January, 1983, was approximately 0.4 mm/day. The differences of evapotranspiration between the vegetation types were not detectable, because the magnitude of evapotranspiration is very little in winter.

PART I
Measurement of Evapotranspiration at the Environmental Research Center, University of Tsukuba

and

Determination of Priestley-Taylor Parameter

K. Kotoda, S. Nakagawa, K. Kai and M. M. Yoshino

Environmental Research Center
University of Tsukuba
Sakuramura, Ibaraki, Japan

INTRODUCTION

Evaporation is the physical process by which a substance is converted from a liquid or solid state into a vapor state. In natural environment, evaporation of water is one of the main components of the hydrological cycle. Water, entering into an evaporation phase in the hydrological cycle, becomes unavailable for further use by plants and human activities. Therefore, accurate knowledge of evaporation is indispensable for the planning and management of water resources.

Direct measurement of evapotranspiration over long time period is difficult because of the lack of routinely usable instruments. Moreover, evaluation of regional evapotranspiration is very difficult owing to the complex land properties. Therefore, many estimation methods for evapotranspiration have been developed and several concepts of evapotranspiration have been proposed.

The "potential evaporation", proposed by Priestley and Taylor (1972), is one of these concepts. They took the "equilibrium evaporation", presented by Slatyer and McIlroy (1961), as the basis for the estimation of potential evaporation. Potential evaporation, which is represented by Eq. (1), is defined as the evapotranspiration from a horizontally uniform saturated surface with a minimal advection

$$\lambda Ep = \alpha \frac{\Delta}{\Delta + \gamma} (Rn - G) = \alpha \lambda Eeq \tag{1}$$

where λ is the latent heat for vaporization, Ep the potential evaporation, α the parameter, Rn the net radiation, G the soil heat flux, Δ the slope of the saturation vapor pressure curve, γ the psychrometric constant, Eeq the equilibrium evaporation. As the method proposed by Priestley and Taylor was very simple and physically sound, many applications have been made over a variety of surfaces.

The equation presented by Priestley and Taylor only needs climatological parameters so that it seems a promising tool for the estimation of evapotranspiration by a remote sensing approach. The value of α in Eq. (1), however, have been found to vary widely from crop to crop even under wet soil conditions. In this paper, the proposed values of α are reviewed first. After that, the representative value of α for pasture under wet soil conditions and the factors affecting the seasonal variations of α are discussed.

PARAMETER OF THE PRIESTLEY-TAYLOR MODEL

The applicability of the Priestley and Taylor model (hereafter referred to as P-T model), which is represented by Eq. (1), for the estimation of evapotranspiration from various surfaces has been examined in many places.

(1) Open water

For open water, the value of $\alpha=1.26$ is supported by Stewart and Rouse (1976, 1977) for shallow lakes and ponds, de Bruin and Keijman (1979) for Lake Flevo over the summer and early autumn.

(2) Bare soil surface

Priestley and Taylor (1972) found that $\alpha=1.08$ for bare soil surface on a day after a heavy rainfall by analysing the data obtained by Dyer and Hicks (1970). Barton (1979) obtained $\alpha=1.05$ for a bare soil in a burnt area under potential conditions. However, Jackson et al. (1976) studied evaporation from clay loam soil to obtain $\alpha=1.37$ under wet soil conditions by using daytime Rn and assuming G to be negligible.

(3) Land surface with short vegetation

In cases of land surfaces covered with fairly short vegetation, the data obtained by Stewart and Rouse (1977) for sedge meadow, Williams et al. (1978) for wheat, Nakayma and Nakamura (1982) for radish supported the value of $\alpha=1.26$. Davies and Allen (1973) obtained the value of $\alpha=1.27$ for well watered perennial ryegrass, Jury and Tanner (1975) $\alpha=1.28$ for potatoes and Mukammal et al. (1977) $\alpha=1.29$ for grass. However, Jury and Tanner (1975) obtained $\alpha=1.42$ for alfalfa, Kanemasu et al. (1976) $\alpha=1.43$ for soybean and Heilman et al. (1976) $\alpha=1.35$ for winter wheat. These values of α are greater than 1.26. The fact that the values of α are greater than 1.26 may suggest the existence of remarkable advection.

(4) Land surface with tall vegatation

For tall vegetation, like forests, McNaughton and Black (1973) found $\alpha=1.18$ for young Douglas fir forest (8 m high) on a day after rain had fallen and $\alpha=1.05$ from the data of well supplied with water but not wet condition. Spittlehouse and Black (1981) obtained $\alpha=1.1$ for Douglas fir and Stewart and Thom (1973) $\alpha=0.6\sim0.7$ for pine trees. Shuttleworth and Calder (1979) compared equilibrium evaporation (Eeq) with long-term evaporation (Ea) for a spruce forest in Plylimon, Wales, and with a Scot Pine forest in Thetford, Norfolk, and proposed the relationship of

$$Ea = (0.72\pm0.07)\Delta(Rn\text{-}G)/[\lambda(\Delta+\gamma)] + (0.27\pm0.08)P \qquad (2)$$

They suggested that the possibility of significant variability in evapotranspiration from forest vegetation in response to precipitation input P.

EXPERIMENTAL METHOD

Experimental site

The study was conducted at the heat and water balance experimental field of the Environmental Research Center (ERC), University of Tsukuba, Ibaraki Pref., Japan (36°05′N, 140°06′E). University of Tsukuba is located in the core of the Tsukuba Academic New Town about 60 km northeast of Tokyo (Fig. 3-1).

The experimental field is a circular plot with a radius of 80 m and has a 30-m meteorological tower at its center. The vegetation of the field consists of mixed pasture. The pasture approaches maturity in summer and mowing is done in early winter. The surroundings of the field are not completely homogeneous due to some buildings and pine trees. To the north of the field, there exists a large and long building which contains a large experimental flume, 188-m long and 9.5-m high. Pine trees with a height of about 10 m exist to the northwest and the southeast of the field.

Instrumentation

Research on the evapotranspiration is facilitated by a grass covered experimental field 80 m in radius (over 20,000 m^2) and the 30-m meteorological tower. In the field and on the tower are a number of instruments including: sonic anemometer-thermometers (at 30.5, 29.5, 12.3 and 1.6 m), resistance thermometers (at 29.5, 12.3 and 1.6 m), dew-point hygrometers (at 29.5, 12.3 and 1.6 m), resistance thermometers (at −2, −10, −50 and −100 cm), heat flux plates (at −2 and −10 cm), ground water level gauges (at −2, −10 and −20 m), a pryheliometer, a total hemispherical radiometer, a net radiometer, a weighing lysimeter, an evaporation pan, a rainfall intensity recorder, a rainfall gauge, and a discharge meter (for measuring runoff from the experimental field). Table 3-1 shows the observations items and instruments, and Fig. 3-2 shows the locations of the instruments in the field.

In addition to the 30-m tower there is also an 8-m observation pole. Psychrometers and 3-cup anemometers at heights of 0.5, 1.0, 2.0, 4.0 and 8.0 m provide data on wind speeds and wet and dry air temperatures. Periodic measurements are made of area and height of the grass growing in the experimental field.

Data collection

All of the instruments on the tower and in the field are tied into a terminal box that leads to a computer-controlled data acquisition system (Oriental Electronics Inc., Model A2270) and eventually to a printout form. The system consists of an analog-to-digital converter, a multiplexor for multichannel analysis, a microcomputer for system control, a cassette magnetic tape unit and a dot printer. The system records and prints out hourly and daily mean values of the observation items automatically.

DEVELOPMENT OF EQUILIBRIUM EVAPORATION MODEL

Determination of actual evapotranspiration

To obtain detailed information on evapotranspiration (E), intensive field observations were carried out from July 20 to August 31, 1980 at ERC experimental field. At the time of observation, the experimental field was covered with 40-cm tall pasture. During this period, 2-m high poles for the determinations of the profiles for air temperature, vapor pressure and wind speed were installed. Air temperatures and vapor pressures were observed at heights of 0.1, 0.2, 0.4, 0.8 and 1.6 m by ventilated psychrometers with C-C thermocouples. Wind speeds were observed at heights of 0.4, 0.8, 1.2, 1.6 and 2 m by three-cup anemometers.

For a short time period such as 1-hr, the use of a weighing lysimeter for the determination of actual evapotranspiration is very difficult, because of measurement errors caused mainly by wind. Therefore, an energy budget-Bowen ratio (EBBR) method was used for the determination of hourly evapotranspiration. As mentioned, temperature and vapor pressure were measured at three levels above the crop surface, namely 0.8, 1.2 and 1.6 m. The combinations of 1.2 with 1.6 m or 0.8 with 1.6 m were used for the calculation of Bowen ratio. The EBBR method, however, could not be used occasionally at either sunrise or sunset. Also on occasions there might be a drying of a wet-bulb. The energy budget with wind and scalar profile (EBWSP) method (Brutsaert, 1982) was used, when the EBBR method could not be applied. Temperatures and wind speeds measured at heights of 0.8 and 1.6 m were used in the EBWSP method.

Daily evapotranspiration was obtained by a weighing lysimeter.

Relationship between actual evapotranspiration and equilibrium evaporation

The method proposed by Priestley and Taylor (1972) has been applied to a variety of surfaces owing to its simple and reasonable form. The value of $\alpha=1.26$ was universally obtained for evaporation from open water surfaces. It has been reported, however, that the value of α is not necessarily equal to 1.26 over bare soil or vegetated surfaces even under wet soil conditions and that it varies depending on surface properties.

Analyses were made to determine the representative value of α for pasture. The pF values of soil water matric potential were below the critical value when soil water limits the evapotranspiration.

Figure 4-1 shows the hourly variations of α obtained from hourly values of actual evapotranspiration and equilibrium evaporation. Although the hourly variations of α differ from day to day, it can be seen as a general pattern that α takes maxima early in the morning and late in the afternoon, and that a minimum occurs near midday with few exceptions (e.g., August 12, 13 and 29). Except for these days, α values are between 0.95 to 1.4. The diurnal variations of α obtained here differ from the previous results for a grass by Yap and Oke (1974) and for a lake by de Bruin and Keijman (1979). They observed the diurnal variations of α with a midday minimum followed by a rise to mid-to-late afternoon. It is worth noting that the diurnal patterns of α obtained in this analysis differ from the previous observational results described above. That is, large values of α occur not only in the afternoon but also early in the morning. In addition, the value of α early in the morning tends to be larger than that in the late afternoon.

To consider the reason of the large values of α in the early morning, the amount of nighttime dewfall and the duration of dew evaporation were calculated. The amount of nighttime dewfall was calculated by summing up negative E values obtained by the EBWSP method. The duration of dew evaporation was obtained as follows: firstly, dew evaporation was considered to start when positive E occurred. Secondly, dew evaporation was considered to stop when the accumulated positive E became larger than the amount of dewfall. By comparing the durations of dew evaporation with the value of α, the large value of α in the early morning proved to be caused by the fact that an evaporating surface acts as a completely saturated surface due to the evaporation of dew. The gradual drops of α observed late in the afternoon on August 12 and 13 may be attributed to an increase in the aridity of air.

Figure 4-2 shows the relationship between actual evapotranspiration (E) and equilibrium evaporation (Eeq). It can be seen in Fig. 4-2 that, on the whole, actual evapotranspiration falls in the range between the equilibrium evaporation ($\alpha=1$) and the potential evaporation ($\alpha=1.26$). From Figs. 4-1 and 4-2, it is obtained that the value of α early in the morning is usually near 1.26 but for the rest of the day α tends to be smaller than 1.26. The average value of α during the evaporation of dew proves to be 1.25 ± 0.02, which is very close to the value of $\alpha=1.26$ for saturated surfaces. The $\pm$ notation is used to denote the standard error of the mean. On the other hand, actual evapotranspiration is nearly equal to the equilibrium evaporation only very humid days (i.e., August 29 and 30). The overall mean of α is taken as 1.16 ± 0.01, which is smaller than the value of α for completely wetted surface.

From the above discussion, it becomes clear that the upper limit of evapotranspiration is represented by the potential evaporation and the lower limit by the equilibrium evaporation for actively growing pasture with no shortage of water. Actual evapotranspiration, however, is usually smaller than the potential evaporation even if there is no shortage of soil water for evapotranspiration. Actual evapotranspiration becomes equal to the potential evaporation when the evaporating surface acts as a completely saturated surface during the evaporation of dew.

Figure 4-3 shows the relationship between the daily actual evapotranspiration (Ely) and the daily equilibrium evaporation (Eeq). As shown in Fig. 4-2 α ranges from 1.0 to 1.26. However, the scatters of data are smaller than those in Fig. 4-2. The average value of α is found to be 1.14 ± 0.03, which is almost the same average value of α obtained from the analysis of hourly data but it is smaller than 1.26 for completely wetted surfaces.

Validity of the equilibrium evaporation model

As stated above, daily evapotranspiration from actively growing pasture under a non-limiting soil water condition can be expressed as

$$E = \alpha Eeq \tag{3}$$

where α is a constant equal to 1.14. Hereafter, the estimation method of evapotranspiration with equilibrium evaporation as a basis is referred to as "equilibrium evaporation model" (E-E model), which is expressed by Eq. (3).

The test of $\alpha=1.14$ in the E-E model is made for the whole observation period in the summer of 1980 (from July 20 to August 31). Figure 4-4 shows the daily variations of actual evapotranspiration (Ely) measured by a weighing lysimeter and estimated evapotranspiration (Ees) from the E-E model with $\alpha=1.14$. The plot for August 5 is missing because of lack of data. Evapotranspiration was zero on August 3 due to an all-day rain. As can be seen in Fig. 4-4, the daily variations of Ees and Ely are closely related.

The summer of 1980 was a season of unusual weather because of low rainfall, low sunshine and low temperature (Murakami, 1981). Hence, it is questionable whether the value of α obtained in 1980 is valid for other years. To investigate this question, the E-E model was tested again using summer data of 1978. The summer of 1978 was hot, in contrast to the summer of 1980. In 1978, net radiation and soil heat flux measurements were only available from August 4 to 24. Figure 4-5 shows the daily patterns of Ely and Ees for 1978. Similar to the results for 1980, there exist close relationships between Ely and Ees, which confirms the validity of $\alpha=1.14$ in the E-E model.

Table 4-1 shows the totals of Ely, Eeq and Ees for both observation periods. It can be seen in Table 4-1 that evapotranspiration from actively growing pasture with no soil water shortage can be estimated with an accuracy of about 5% by the E-E model with $\alpha=1.14$

APPLICATION OF EQUILIBRIUM EVAPORATION MODEL TO SEASONAL EVAPOTRANSPIRATION

Seasonal Variations of α

Net radiation, soil heat flux, air temperature and evapotranspiration had been measured continuously until April 17, 1981 after intensive observations during the summer in 1980. The applicabilities of the equilibrium evaporation model (E-E model), especially the variations of the proportional constant α in Eq. (3) were investigated using the data obtained from September to April.

The day-to-day variations of daily values of α in the E-E model shows very complex features (Fig. 5-1). Moreover, the values of α become very large especially in winter months and in some cases they exceed the value of $\alpha=1.26$ for completely saturated surface.

Factors affecting the seasonal variations of α

Seasonal variations of α have been reported by Jackson et al. (1976), McNaughton et al. (1979), de Bruin and Keijman (1979) and Nakayama and Nakamura (1982) for bare soil, pasture, shallow lake and radish, respectively. All of them found an increase in α in cool season but seasonal variations of α from winter to spring have not been reported yet. It has been pointed out that large value of α is obtained when daily energy balance terms are used rather than daytime ones (Yap and Oke, 1974; Kanemasu et al., 1976; Tanner and Jury, 1976).

To evaluate the factors affecting the seasonal variation of α, an analysis based on daytime data was conducted.

In this analysis, the daytime period was considered as the period during which available energy (Rn-G) $\geq \mu 0$. The day-to-day variations of α, obtained from daytime data, show small fluctations and the value of α do not exceed 1.14, which was obtained from the summer data (Fig. 5-2). Furthermore, the march of α shows a distinctive seasonal trend.

Figure 5-3 shows seasonal variations of monthly mean values of α. Daily α and daytime α are almost equal in August but daily α is consistently greater than daytime after September. Month-to-month variations of daily α show a complicated pattern. On the contrary, daytime α shows a distinctive month-to-month variation pattern which may reflect the physiological nature of pasture.

To examine the effect of nighttime radiative cooling on the differences in α with different averaging time, the degree of nighttime decrease rate of available energy (R') was calculated from

$$R' = \frac{\overline{(Rn - G)} - (Rn - G)_d}{(Rn - G)_d} \tag{4}$$

where the bar and the subscript d represent daily values and daytime values, respectively. Figure 5-4 shows the seasonal trend of R'. By comparing Fig. 5-4 with Fig. 5-3, it may be found that the variations in R' and those in the difference between daytime α and daily α have similar seasonal patterns. To investigate the relationship between them, the rate of increase in $\alpha(\alpha')$ was calculated by

$$\alpha' = \frac{\overline{\alpha} - \alpha_d}{\alpha_d} \tag{5}$$

where the meanings of bar and subscript d are the same as those in Eq. (4). Figure 5-5 shows the relationship between α' and R' calculated from monthly means values. As can be seen in Fig. 5-5, there exists an almost linear relationship between α' and R', which implies that the differences between daily α and daytime α are caused by the nighttime decrease in available energy.

As described above, α in the E-E model proves to be an effective parameters showing distinctive seasonal variations which may reflect the activity of pasture. Special attention, however, should be paid to the application of the E-E model to periods with strong nighttime radiative cooling.

Monthly evapotranspiration estimate with equilibrium evaporation model

To apply the E-E model to the annual evapotranspiration estimate, the values of α for May and June must be included. The daily integrated radiation data by the routine measuring system became available from August 1981. Therefore, the values of α for May and June were calculated from the routine data in 1982. Since data of soil heat flux (G) were not available in May and June in 1982, G was estimated from the regression equation between Rn and G observed from September, 1980 to April, 1981. As a result, $\alpha=1.15$ for May and $\alpha=1.12$ for June were obtained. The monthly mean values of daily α are summarized in Table 5-1. It is noticeable in Table 5-1 that α takes nearly the same value from May to August, during which pasture grows actively and the effects of nighttime radiative cooling on daily available energy are considered slight.

The estimation of monthly evapotranspiration by the E-E model with α listed in Table 5-1 was carried out for the periods from 1980 to 1982. The results are shown in Fig. 5-6. It is clear from Fig. 5-6 that there exists close agreement between estimated and measured monthly evapotranspiration. In addition, annual evapotranspiration can be estimated within 10% accuracy by the E-E model.

PROBLEMS OF ADVECTION

Advection due to incomplete adjustment of atmospheric variables to a surface may affect the components of heat balance and then estimated values of evapotranspiration.

To evaluate the magnitude of the advection effect, the following calculation was done. The heat balance equation for a vegetated surface may be given by

$$Rn = \lambda E + H + G + \Delta M \tag{6}$$

$$\Delta M = Av + \mu Fp + B \tag{7}$$

where Av is the advective energy, μ the thermal conversion factor for fixation of carbon dioxide, Fp the specific flux of CO_2, B the rate of energy stored per unit area in the layer. The exact nature of each term depends on the type of layer. However, for many practical purposes, some of the terms can be negligible. If Fp and B are negligibly small compared with other terms, such as G, the substance of ΔM may be representative of advection.

In this study, Rn, λE, H and G were measured independently. Therefore, ΔM can be estimated from day to day and from season to season. The result is shown in Fig. 6-1. As shown in the figure, the values of ΔM are remarkable in winter (from December to February) and April. However, from summer to autumn except August, ΔM are negligibly small compared with Rn. It means that, if we consider the daily amount of evapotranspiration, α in the E-E model can be fixed as a constant during summer and autumn seasons. However, in winter and early spring it may be necessary to consider the effect of advection on α.

Table 6-1 shows the result of the measured monthly evapotranspiration rate and the relevant components of heat balance for a grass land.

CONCLUSION

The hydrologic cycle of evaporation is one of an integral part of water balance and heat balance of the earth's surface. Recently, the development of remote-sensing techniques by using satellites can enable to take a huge amount of data from the earth's surface and numerous attempts have been made to overcome the difficulties of estimating the regional evaporation.

The parameterization of equilibrium evaporation model proposed by Priestley and Taylor is one of them. However, studies in humid region are scarce and suitable parameterization for the humid regions has yet to be developed.

The applicabilities of the equilibrium evaporation model to estimate the regional evapotranspiration were studied by using the remotely sensed measurements.

The results are summarized as follows:

(1) The potential evapotranspiration, defined by a vapor-saturated surface condition, tends to overestimate the evapotranspiration from actively growing pasture grass with ample soil water.

(2) Hourly variations of α for a pasture grass land falls into the range of 0.95 to 1.4 during summer season.

(3) The daily actual evapotranspiration from pasture, without a serious soil water shortage in summer, falls in the range between Eeq ($\alpha = 1$) and the potential evaporation Epe ($\alpha = 1.26$).

(4) The average value of $\alpha = 1.14 \pm 0.03$ was induced by using the data of Ely and Eeq for pasture grass. It was found that evapotranspiration from actively growing pasture with no soil water shortage can be estimated with an accuracy of about 5% by the equilibrium evaporation model.

(5) The applicabilities of the equilibrium evaporation model (E-E model), especially the vibrations of the proportional constant α in $E = \alpha Eeq$, were investigated. The day-to-day variations of daily values of α and daytime values of α are shown in the figures accompanied, respectively. As the result of investigation, it was found that the differences of α between daily α and daytime α are caused by the nighttime decrease in available energy.

(6) The monthly mean values of daily α are nearly the same value from May to August, during which the pasture grows actively and the effects of nighttime radiative cooling on daily available energy are considered slight. It was found that the estimation of monthly evapotranspiration by the E-E model can be estimated within 10% accuracy.

(7) Seasonal variation of advective effects on heat balance terms was evaluated. The results showed that the value of α can be fixed as a constant during the season of summer and autumn. However, it was found that the more suitable value of the α-parameter is necessary to estimate the evapotranspiration in winter and early spring.

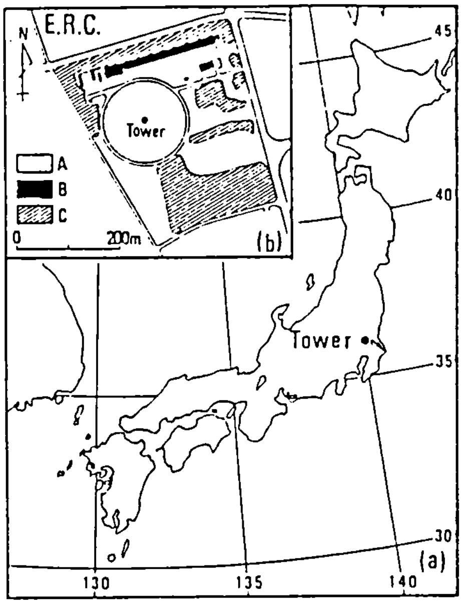

Figure 3-1. Location of the experimental site.
A = Grass field, B-Buildings, C-Pine trees

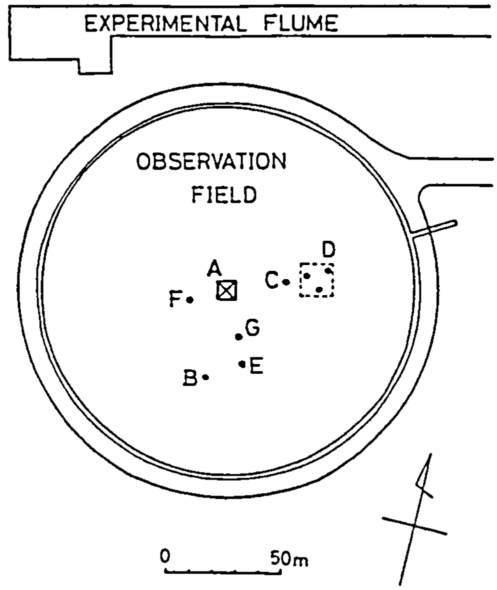

Figure 3-2. Location of instruments in the experimental field. A-G show observation points.

Table 3-1
Observation items and instruments.

番号 No	観測項目 Item	記号 Symbol	高さ Height	観測場所 Site	測器名 Instrument	製作会社名 Maker	型式 Model
1	wind direction	D	30.5m	ERC Tower, A	sonic anemometer	Kaijo Denki	SA-200
2	wind speed 1	U-1	1.6	〃	sonic anemometer-thermometer	〃	PAT-311
3	〃 2	U-2	12.3	〃	〃	〃	〃
4	〃 3	U-3	29.5	〃	〃	〃	〃
5	momentum flux 1	UW-1	1.6	〃	〃	〃	〃
6	〃 2	UW-2	12.3	〃	〃	〃	〃
7	〃 3	UW-3	29.5	〃	〃	〃	〃
8	sensible heat flux 1	WT-1	1.6	〃	〃	〃	〃
9	〃 2	WT-2	12.3	〃	〃	〃	〃
10	〃 3	WT-3	29.5	〃	〃	〃	〃
11	short-wave radiation	I	1.5	ERC Field, B	pyranometer (Gorcynski type)	Eiko Seiki	MS-43F
12	net radiation	RN	1.5	〃	net radiometer (Middlton type)	〃	CN-11
13	soil heat flux	G1	-0.02	ERC Field, C	soil heat flux meter	〃	CN-81
14	air temperature 1	T-1	1.6	ERC Tower, A	Pt resistance thermometer (with ventilater)	Nakaasa	E-731
15	〃 2	T-2	12.3	〃	〃	〃	〃
16	〃 3	T-3	29.5	〃	〃	〃	〃
17	soil temperature 1	ST-1	-0.02	ERC Field, C	Pt resistance thermometer	〃	E-751
18	〃 2	ST-2	-0.10	〃	〃	〃	〃
19	〃 3	ST-3	-0.50	〃	〃	〃	〃
20	〃 4	ST-4	-1.00	〃	〃	〃	〃
21	groundwater level 1	GW-1	depth	ERC Field, D	water level gauge (float type)	〃	W-131
22	〃 2	GW-2	from the	〃	〃	〃	〃
23	〃 3	GW-3	S. Level	〃	〃	〃	〃
24	dewpoint temperature 1	TD-1	1.6	ERC Tower, A	dew-point hygrometer (LiCl dew cell)	〃	E-771
25	〃 2	TD-2	12.3	〃	〃	〃	〃
26	〃 3	TD-3	29.5	〃	〃	〃	〃
27	evaporation	E	+0.20	ERC Field, G	evaporation pan	〃	Class A (D-211)
28	precipitation	P	+0.30	ERC Field, E	rain gauge (tipping bucket type)	〃	B-011-00
29	evapotranspiration	ET	0.00	ERC Field, F	weighing lysimeter (2mφ, 2m depth)	Shimazu	RL-15TFA
30	atmospheric pressure	AP	+5.00	ERC Building		Nakaasa	F-401

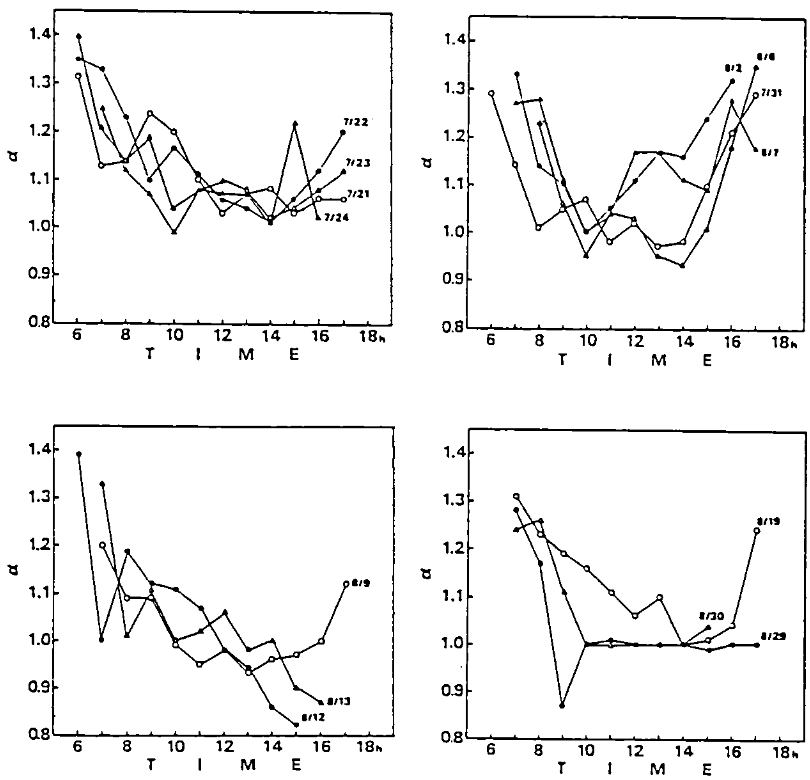

Figure 4-1. Hourly variations of α.

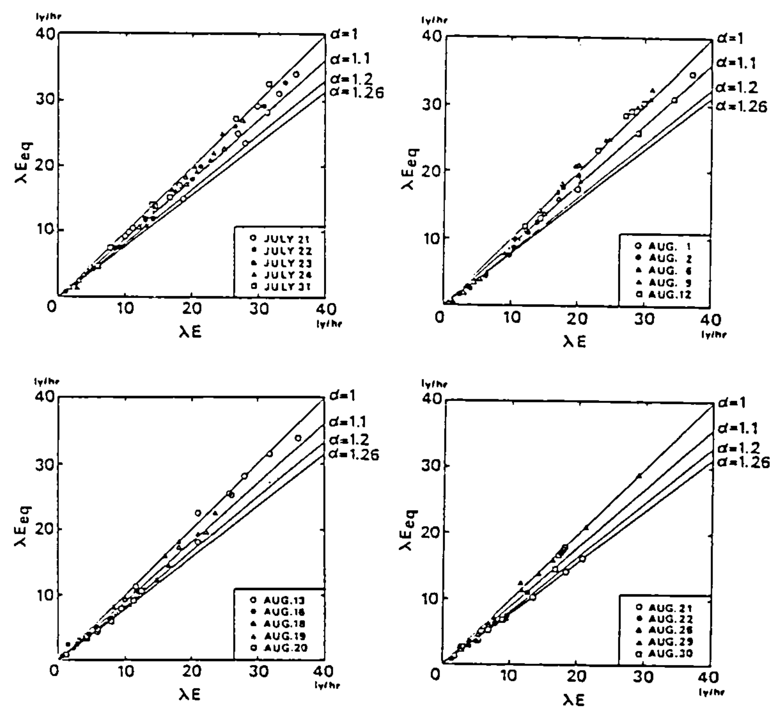

Figure 4-2. Relationship between hourly actual latent heat flux (λE) and hourly equilibrium latent heat flux (λEeq).

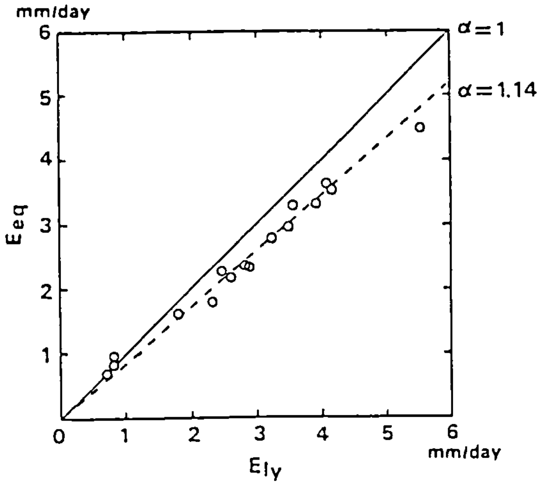

Figure 4-3. Relationship between daily actual evapotranspiration (Ely) and equilibrium evaporation (Eeq).

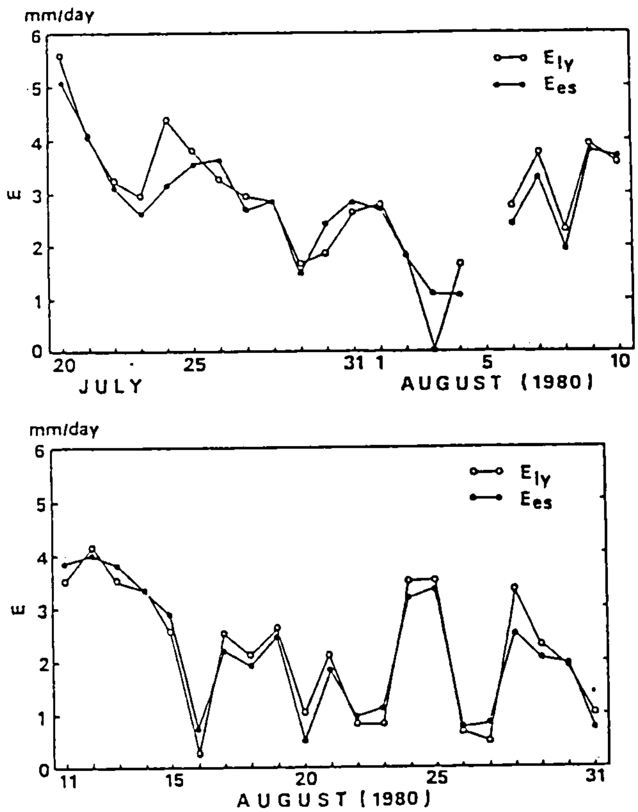

Figure 4-4. Day-to-day variations of actual evapotranspiration (Ely) and estimated evapotranspiration (Ees) in 1980.

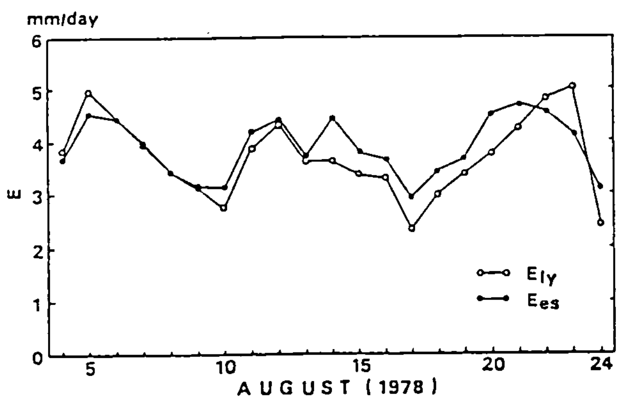

Figure 4-5. Day-to-day variations of actual evapotranspiration (Ely) and estimated evapotranspiration (Ees) in 1978.

Table 4-1
Comparison of estimated evapotranspiration with actual evapotranspiration.

	E_{eq}	E_{es}	E_{ly}
1978 Aug. 4 ∿ Aug. 24	71.4	81.4	77.0
1980 July 20 ∿ Aug. 31	91.5	104.3	108.1

(unit : mm)

E_{eq} : equilibrium evaporation

E_{es} : estimated evapotranspiration by the equilibrium evaporation model with $\alpha = 1.14$

E_{ly} : actual evapotranspiration by a weighing lysimeter

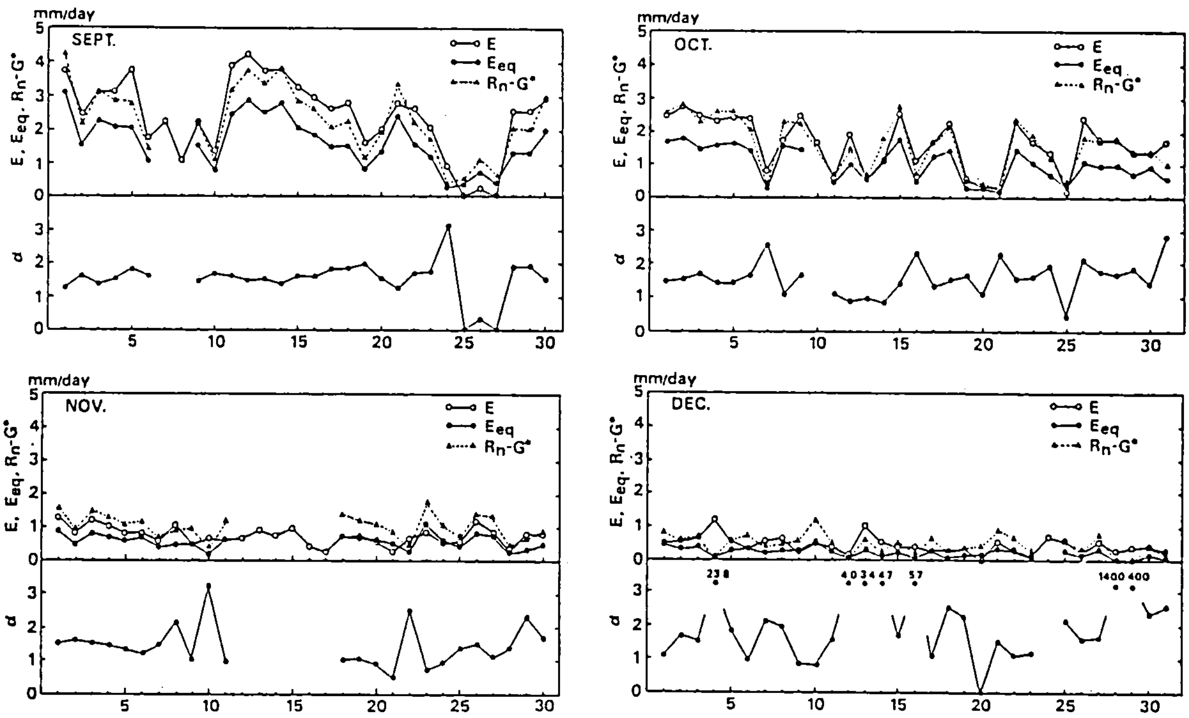

Figure 5-1. Day-to-day variations of daily evapotranspiration (E), equilibrium evaporation (Eeq), available energy in evaporation equivalence (Rn – G*), and the parameter α in the equilibrium evaporation model. Figures in α represent the value of α.

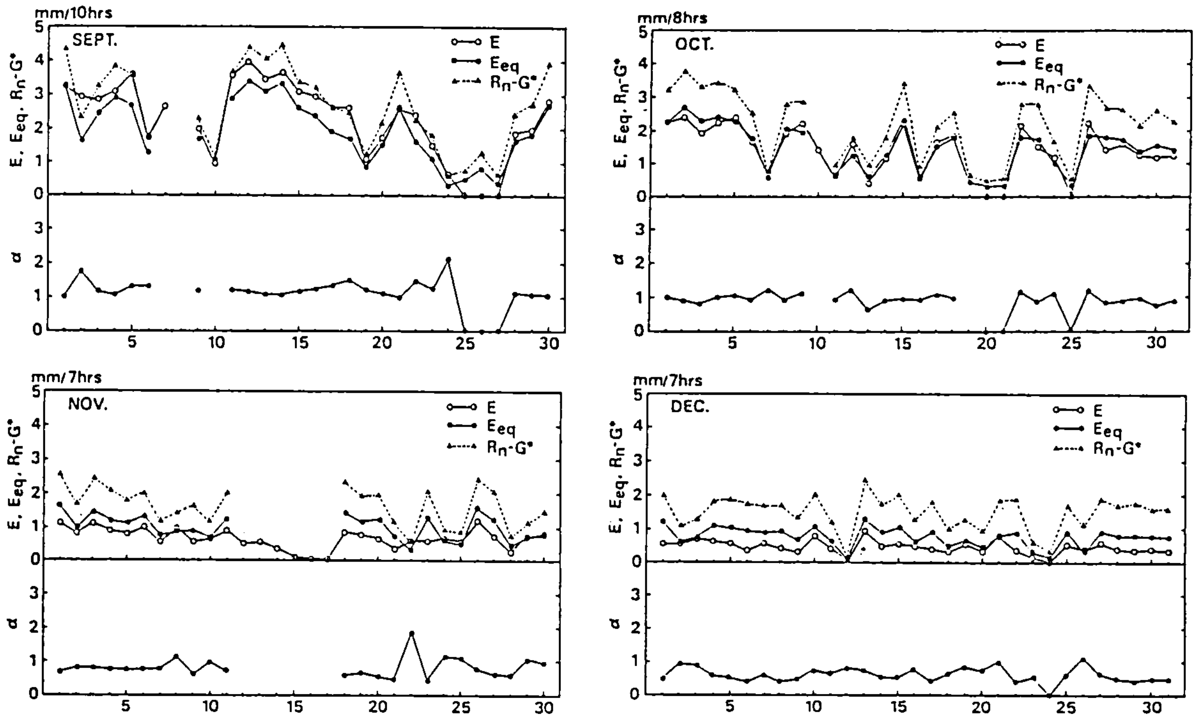

Figure 5-2. Day-to-day variations of daytime evapotranspiration (E), equilibrium evaporation (Eeq), available energy in evaporation equibalance (Rn – G*), and the parameter α in the equilibrium evaporation model.

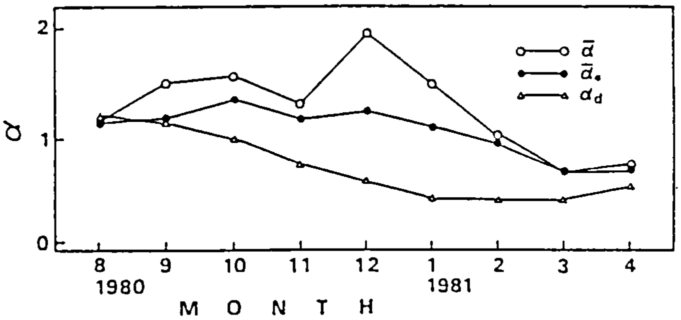

Figure 5-3. Seasonal variations of monthly mean α.

$\overline{\alpha}$: daily value

$\overline{\alpha^*}$: daily value in the case $\lambda E < R_n - G$

α_d : daytime value

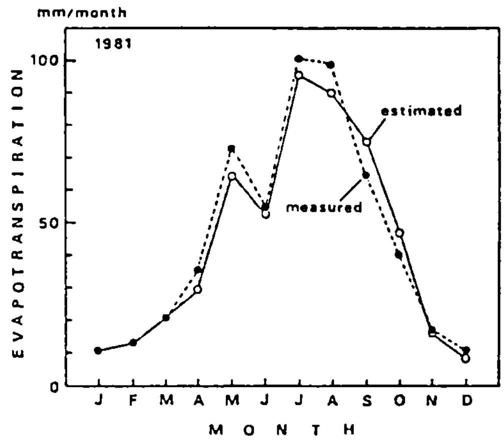

Figure 5-6. Comparison of estimated monthly evapotranspiration by the equilibrium evaporation model with actual evapotranspiration.

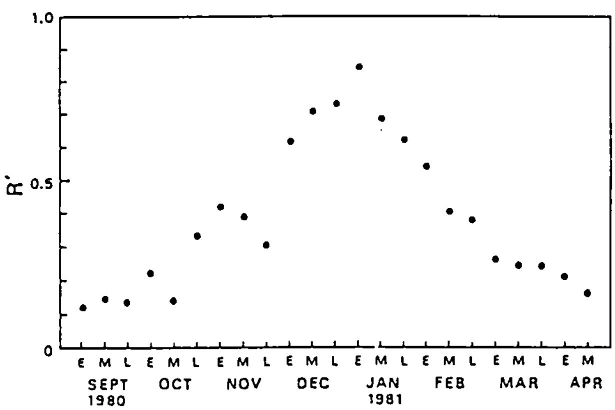

Figure 5-4. Seasonal variations of 10-day mean values of the rate of decrease in daily available energy (R′) due to nighttime radiative cooling.

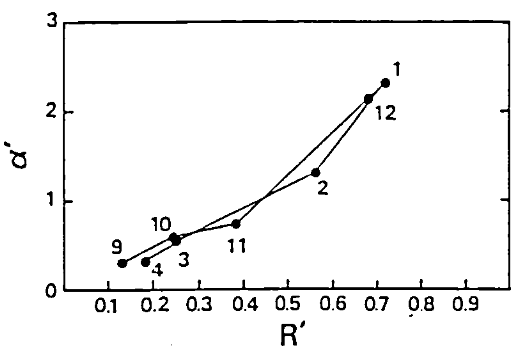

Figure 5-5. Relationship between the rate of increase in α (α') and the rate of decrease in available energy (R′). Figures represent month.

Table 5-1. Monthly mean values of the proportional constant (α) in the equilibrium evaporation model.

	α
Jan.	1.50
Feb.	1.03
Mar.	0.70
Apr.	0.75
May	1.15
June	1.12
July	1.14
Aug.	1.14
Sept.	1.50
Oct.	1.56
Nov.	1.31
Dec.	1.95

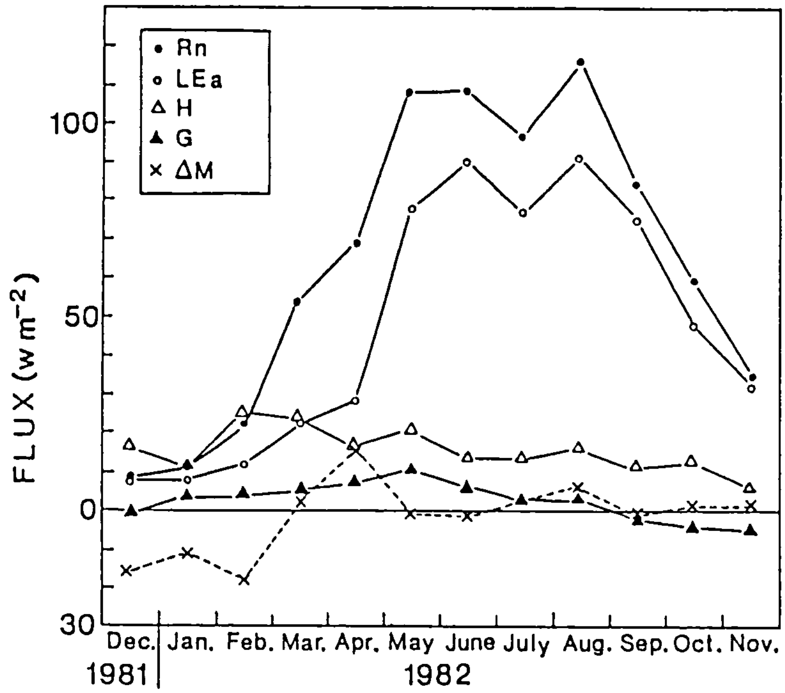

Figure 6-1. Monthly variations of heat balance and its residual term (ΔM) for a grass land.

Table 6-1. Monthly variations of heat balance and its residual term (ΔM) for a grass land.
$r = [\Delta M / (Rn - G)] \times 100$ (%)

	NO.	Rn	G	Rn-G	LEa	Ea	H	ΔM	r
	days	W / M²				mm/day	W / M²		%
Dec. 1981	14	8.19	-0.88	9.07	8.44	0.29	17.42	-16.80	-185.3
Jan. 1982	12	11.51	3.50	8.00	7.86	0.27	11.87	-11.72	-146.4
Feb.	12	22.76	3.64	19.12	11.66	0.40	25.55	-18.09	-94.6
Mar.	12	54.35	5.02	49.32	22.58	0.79	23.80	2.94	6.0
Apr.	14	69.65	7.21	62.44	28.41	0.99	17.40	16.64	26.6
May	23	108.11	10.65	97.46	77.76	2.74	20.94	-1.24	-1.3
June	13	109.02	5.93	103.09	90.40	3.19	14.60	-1.92	-1.9
July	13	97.70	2.87	94.82	77.77	2.74	14.06	3.00	3.2
Aug.	19	116.11	2.70	113.41	91.13	3.23	15.96	6.32	5.6
Sep.	13	84.96	-2.37	87.33	75.37	2.66	12.84	-0.88	-1.0
Oct.	12	59.07	-4.15	63.22	48.47	1.70	13.52	1.23	2.0
Nov.	7	34.99	-4.76	39.74	32.45	1.13	5.84	1.45	3.7
MEAN		64.70	2.45	62.25	47.69	1.68	16.15	-1.59	-32.0

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