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Solar and net radiation, available energy and its influence on evapotranspiration from grass[1]

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SYMBOIS USED *

e_d , e_d	saturation vapor pressure and mean saturation vapor pressure respectively at dew point temperature of the air, 2 m height	mm Hg
E_{ac} , E_{max}, E_{po}	actual, maximum and potential evapotranspiration	mm 24 hrs-1
E_o , E_o'	evaporation from an open thin waterlayer	mm 24 hrs-1
$_{nt}H$	net radiant flux density at earth surface	cal cm-2 24 hrs-1
H_{adv}	advective heat flux density	cal cm-2 24 hrs-1
H_{at}	radiant flux density from the atmosphere	cal cm-2 24 hrs-1
H_{ai} , H_{ai}	sensible heat flux density to or from the air	cal cm-2 24 hrs-1
H_{ea} , $_{nt}H_{ea}$ $_{nt}H^{\circ}_{ea}$	radiant flux density and net radiant flux density from the earth surface. ° = cloudless sky	cal cm-2 24 hrs-1
H_{ev}	latent heat flux density for evapotranspiration	cal cm-2 24 hrs-1
H_{so}	sensible heat flux density to or from the soil	cal cm-2 24 hrs-1
H_{su} , $_{nt}H_{su}$	radiant flux density (total global radiation) and net radiant flux density from sun and sky on a horizontal surface on earth	cal cm-2 24 hrs-1
$_{dr}H_{su}$, $_{df}H_{su}$	direct and diffuse short wave radiation of sun and sky. $_{dr}H_{su} + {}_{df}H_{su} = H_{su}$	cal cm-2 24 hrs-1
L_T	latent heat of vaporization at T °K	cal gr-1
m_d , m_n , m_{24}	mean fraction of the sky covered by clouds during daytime, night and 24 hrs. ($0 \leq \mathrm{m}_t \leq 1$)	
n , N	actual and possible duration of sunshine	hr
r_{su}	reflectivity of the evaporating surface for total global radiation	
T_{ai} , T_{ea} , T_{at}	temperature; ai = air; ea = radiating surface of the earth; at = atmosphere	°K, °C
U_{200}	windspeed at 200 cm height	m sec-1
u	photosynthetic energy conversion factor	
ε_{ea} , ε_{at}	emissivity for long wave radiation; ea = earth surface; at = atmosphere	
ν	cloud factor dependent on properties of clouds ($0.9 \geq \nu \geq 0.2$)	
ϱ_w	density of water	gr cm-3
σ	Stefan-Boltzmann constant for black-body radiation	cal cm-2 min-1 °K-4
$\downarrow$, $\uparrow$	indication of direction	

* The symbols H_{ai} , H_{so} , H_{ev} , H_{su} etc. for the dimension of sensible, latent or radiant heat flux density (cal 1-2 t-1) were introduced by Prof. Dr. W. R. VAN WIJK, Laboratory of Physics and Meteorology, Agricultural University, Wageningen, the Netherlands and by Prof. Dr. D. A. DE VRIES, Technological University, Eindhoven, the Netherlands.

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Summary

From studies on radiation and energy balance in the Netherlands it is concluded that reliable values for the net radiation over 24 hour periods can be obtained by computation, if differences in weather conditions during daytime and night are taken into account. A comparison of measured net radiation above short grass with net radiation computed from air temperature, water vapor pressure in the air and sunshine duration is given. Variations in nature of a cropped surface, as a consequence of variations in conditions of such a surface, may have influence on the radiation and energy balance. However, if soil moisture becomes less available for plant roots, moisture content is much more important for the distribution of the available energy over heating the soil, the air and over evapotranspiration than the type and nature of the soil cover.

For daily and 24 hour periods with similar atmospheric conditions, a linear relation between total global radiation and net radiation can be expected.

The ratio evapotranspiration from short grass under optimal water supply over the evaporation from a wet surface (or thin water layer) varied greatly for short periods of time under different conditions of radiation and temperature. These variations could be due to plant or weather factors influencing the aperture of the stomates, although variations in stability of the lower air layers may have had some influence.

Some differences between the evapotranspiration from grass under radiant and under "advective heat" supplies are discussed. Variations in intensity of potential and of maximum evapotranspiration rates and differences in the diurnal variations, as compared with the diurnal variation of net radiation, are shown.

A decrease of actual evapotranspiration from crops as soil moisture becomes less available and, of course, the potential evapotranspiration rate strongly depend on the net radiation gain.

1. Introduction

Neglecting the heat flux density from dewfall and the heat storage in and between the crop volume for periods of 24 hrs, we may write for the actual evapotranspiration from horizontal cropped surfaces [14]:

$$E_{ac} = 10\, \varrho_w^{-1}\, L_T^{-1}\, ({}_{nt}H + H_{adv} - H_{so} - H_{ai})\ mmt^{-1} \qquad (1)$$

$$(t = p \times 24 \text{ hrs};\ p = 1, 2, 3 \text{ etc.})$$

The actual evapotranspiration is the evapotranspiration from each cropped surface under the prevailing conditions, of weather, crop and soil moisture [14; 15; 16].
Writing $E_{ac} = A \times B$ [20], B now equals the evaporation from the wet surface of a body with the same dimensions, shape and nature as the cropped surface under consideration and exposed to the same meteorological conditions as that cropped surface. In the case of crops completely shading the ground, the evaporating surface mainly consists of plant leaves and the correction factor A ($0 \leqslant A \leqslant A_{max}$) now also reduces the total surface of the leaves to the effective transpiring surface of the stomates. Assuming, for the time being, max. A-values (primarily determined by the resistance of the stomates against water vapor diffusion) under conditions of not short of water, $B \times A_{max}$ may be equal to E_{po} if $H_{adv} = 0$, or may be equal to E_{max} if $H_{adv} > 0$ [14; 15; 16]. Under field conditions, however, there are sometimes sufficient reasons to expect E_{ac} to be greater or smaller than E_{po}, or E_{max} [15; 16].
In this paper attention will be given to the energy, ${}_{nt}H$ and H_{adv}, available at evapo-

rating surface under various weather conditions, the influence of the evaporating surface, and the influence of available energy on actual, potential and maximum evapotranspiration rate from grass.

2. Radiation

From the radiation balance on a horizontal surface on earth:

$$ {}_{nt}H = {}_{nt}H_{su} - {}_{nt}H_{ea} \quad \text{cal cm}^{-2}\ \text{t}^{-1}, \tag{2} $$

with:

$$ {}_{nt}H_{su} = ({}_{dr}H_{su} + {}_{df}H_{su})\,(1 - r_{su} - u) \quad \text{cal cm}^{-2}\ \text{t}^{-1}, \tag{3} $$

and:

$$ {}_{nt}H_{ea} = \left\{ \varepsilon_{ea}\,\sigma\,(T_{ea})_t^4 - \varepsilon_{ea}\,\sigma\,(T_{ai})_t^4\, f(\mathrm{e}_d)_t \right\} \left\{ f(\mathrm{m}_t) \right\} \quad \text{cal cm}^{-2}\ \text{t}^{-1}, \tag{4} $$

in which the function of cloudiness, $f(\mathrm{m}_t)$, can be replaced during daytime by a function of sunshine duration, $f(n/N)$ *, it becomes clear that ${}_{nt}H$ only depends on weather conditions if r_{su} , ε_{ea} , u and $H_{ea} = \varepsilon_{ea}\ \sigma\ (T_{ea})_t^4$ do not vary for different crop surfaces under similar meteorological conditions. For many green crops, completely shading the ground, r_{su} , ε_{ea} and u will not vary much (although there are of course variations with time), but T_{ea} and therefore H_{ea} may depend on crop height [14]. The temperature and the location of the "effective radiating surface" in case of a crop can not yet be determined in an easy way. However, it follows from temperature variations in various crop volumes [4], that the location of this surface will depend on length and density of the crop and the position of the leaves. High "surface" temperatures will occur in case of thin crops, incompletely shading the ground, strongly decreasing the air movements close to the ground and with shortage of water. With increasing crop heights one may expect decreasing temperatures of the effective radiating surfaces (since a greater volume for heat absorption is available), decreasing values of ${}_{nt}H_{ea}$ and, as a consequence, increasing values of ${}_{nt}H$ (TABLE 1). Apart from a possible decrease of H_{so} and H_{ai} under such conditions, this may result in increasing evapotranspiration rates under non limiting water supply to the roots**. If we consider relatively small areas, the influence of T_{ea} on $H_{at} = \varepsilon_{at}\,\sigma\ T_{at}^4$ can be ignored.

In energy balance computations for bare as well as for cropped soil surfaces, one may not assume, specially not under clear skies, that air temperature at 2 m height always equals T_{ea}. For mean daily values of T_{ai} and T_{ea} and more likely for mean monthly calues, the assumption $T_{ai} \sim T_{ea}$ may be right. From eq. (4) ${}_{nt}H_{ea}$ then can be computed from available meteorological data.

In case of $T_{ea} = T_{ai} + \Delta T$, TABLE 1 gives the difference in net back radiation, ${}_{nt}H^{\circ}_{ea}$, under clear skies ($f(\mathrm{m}_t) = 1$) for some values of T_{ai} and ΔT.

* During daytime the percentage of actual sunshine (n/N) is a fairly accurate measure for atmospheric conditions. Determining this percentage from the records of the Campbell-Stokes instrumentation, the intensity of sunshine is taken into account. As a consequence, variations in cloud thickness and in the nature of the clouds at each instant are taken into account, even if the fraction of the sky covered by clouds remains constant. Estimations of m_d are carried out only 2 or 3 times a day, while a continuous record is obtained from the Campbell-Stokes instrumentation.

** In case of crops short of water, the amount of available energy used for evapotranspiration, strongly depends on the extent of water availability [14; 15; 16]. Under such conditions moisture availability is much more important for the distribution of available energy over heating the soil, the air and over evapotranspiration, than the nature of the soil cover.

TABLE 1. The difference in ${}_{nt}H^{\circ}_{ea}$ computed with $T_{ea} = T_{ai} + \Delta T$ and ${}_{nt}H^{\circ}_{ea}$ computed with $T_{ea} = T_{ai}$ for some values of T_{ai} and ΔT. The difference in the net long wave back radiation expressed in cal cm^{-2} 24 hrs^{-1}.

ΔT (°C) =	1	3	5	10
T_{ai} = 10 °C = 283 °K	10.3	31.4	52.8	108.1
T_{ai} = 15 °C = 288 °K	11.3	34.4	57.9	118.1
T_{ai} = 20 °C = 293 °K	11.5	41.5	58.5	119.8
T_{ai} = 30 °C = 303 °K	13.6	43.6	64.5	124.1

With temperature differences of 1 to 5° C and T_{ai} = 10 to 20° C, the back radiation increases ($+\Delta T$) *or decreases* ($-\Delta T$), and the net radiation then decreases or increases respectively, with 10 to 65 cal cm^{-2} 24 hrs^{-1}.

To obtain more accurate values of net radiation for shorter periods of time, net radiometers must be used of course *. However, if the total global radiation, H_{su}, is measured and differences in weather conditions during daytime and night are taken into account, very reliable values for the net radiation for 24 hrs. periods were obtained in the Netherlands by computation [14] (FIG. 1).

Periods of 24 hrs. should be too short for application of formula (4). However, good values for ${}_{nt}H$ under overcast sky conditions during daytime and night ($m_d = m_n = 0.6 - 1.0$) were obtained with:

$$f(e_d)_{24} = 0.59 + 0.049 \sqrt{(e_d)}_{24} \quad \text{and:} \quad f(n/N) = 0.24 + 0.76\, n/N,$$

according to GEIGER [4], and with:

$$f(e_d)_{24} = 0.61 + 0.058 \sqrt{(e_d)}_{24} \quad \text{and:} \quad f(m_{24}) = 1 - 0.72\, (m_{24})^2,$$

according to BUDIKO [1] for 52° N.L. Of course the errors in $f(e_d)_{24}$ and in the assumption $(T_{ea})_{24} = (T_{ai})_{24}$ were of minor importance on such days.

Under clear sky conditions during daytime and night ($m_d = m_n = 0.3 - 0$), the best results were obtained with:

$$f(e_d)_{24} = 0.53 + 0.077 \sqrt{(e_d)}_{24} \quad \text{and:} \quad f(n/N) = 0.20 + 0.80\, n/N.$$

On July 25, August 27 and September 6, the sky was clear during the day ($m_d = 0 - 0.3$) but there was a complete nocturnal cloud cover ($m_n = 0.7 - 1$ and $\nu = 0.8 - 0.9$) decreasing the back radiation from the grass surface, as compared under clear skies, with about 60, 30 and 30 cal cm^{-2} night^{-1} respectively (TABLE 2) **.

The nocturnal cloudiness could be established and estimated from the continuous net radiation recordings and from air and soil temperature variations. An "intensified green house effect" is clearly shown on these days. Since $f(m_{24})$ in eq. (4) was com-

* During some radiation experiments at Wageningen *Suomi* and *Kuhn's* "economical net radiometer" was used. From a critical consideration [14] of this radiometer it was concluded that the temperature of the surrounding air may not be neglected in the computation of ${}_{nt}H$ from the temperatures of the blackened surfaces. As a consequence the work formules become more complicated. Continuous records of the instrument were obtained with thermo-couples at the black surfaces. The radiometer gave somewhat too high values for ${}_{nt}H$ at noon on clear, warm days. However, good results were obtained for 24 hrs. periods and during the night.

** In The Netherlands ($m_d + n/N$) ≈ 1 holds [12; 19]. Thus ($m_{24} + n/N$) ≈ 1 if $m_d = m_n$ and ($m_{24} + n/N$) $\neq 1$ if $m_d \lesseqgtr m_n$.

FIG. 1. Measured and computed net radiation on single days with different cloud conditions. The discrepancies on 7/25/'58, 8/27/'58 and 9/6/'58 are caused by differences in cloud conditions during daytime and night ($m_n > m_d$). From observations above short grass (grass length 2—4 cm) at Wageningen, the Netherlands [14].

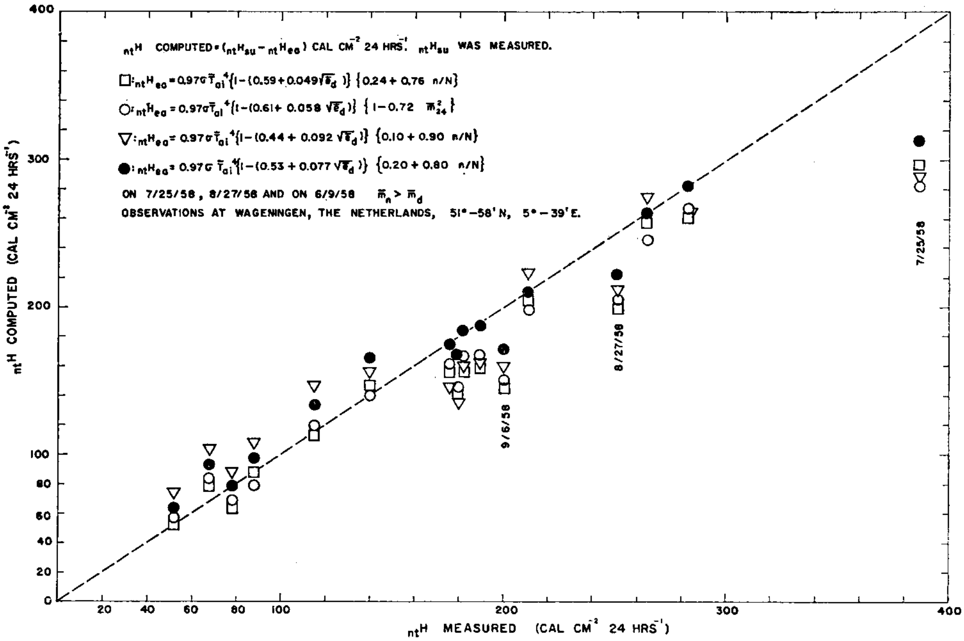


TABLE 2. Net radiation (cal cm^{-2} t^{-1}) measured at 2 m height above short grass by day, at night and for 24 hrs. and the computed net radiation for 24 hrs. on some days under equal cloud conditions during daytime and night ($m_d = m_n$) and on days with different cloud conditions by day and night ($m_d < m_n$). From observations at Wageningen, The Netherlands [14].

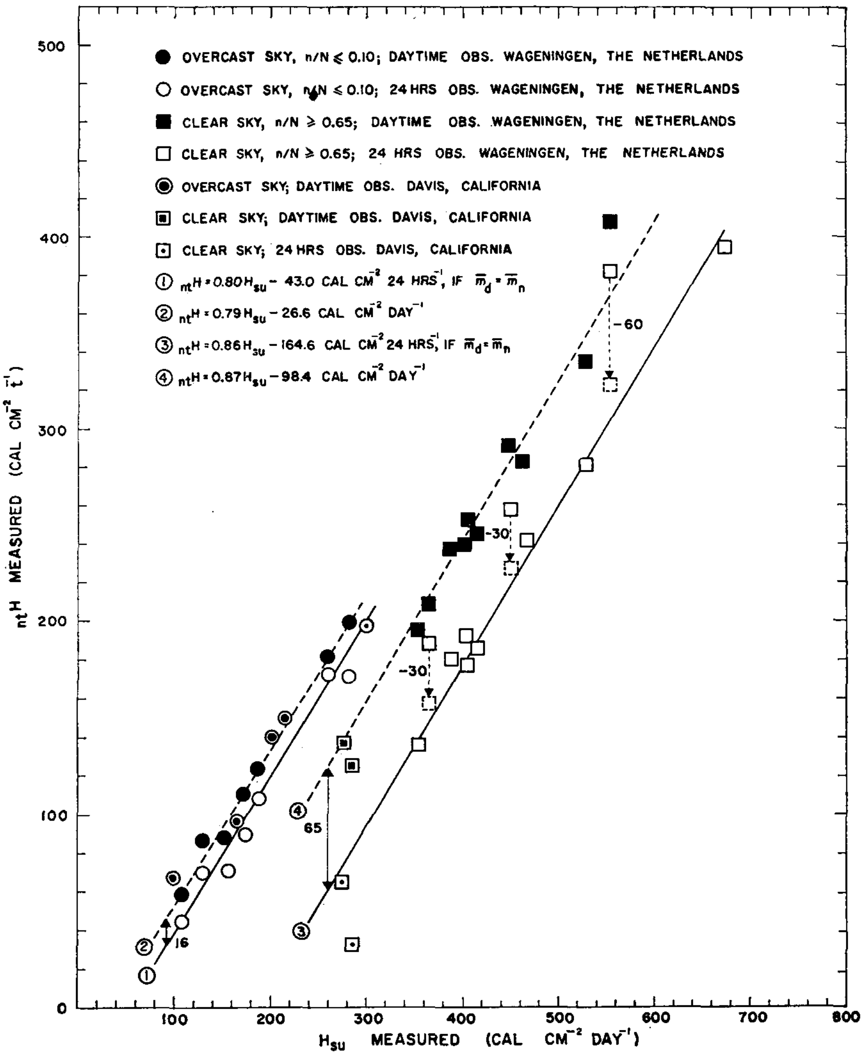
		$m_d < m_n$ or $(m_{24} + n/N) \neq 1$			$m_d = m_n$ or $(m_{24} + n/N) \approx 1$				
		7/25/58	8/27/58	9/6/58	8/5/58	7/20/58	9/2/58	9/1/58	9/3/58
$n/N = 1 - m_d$		0.70	0.66	0.68	0-0.1	0.3	0.74	0.75	0.77
m_n		0.9-1.0	0.6	0.7-0.8	0.9	0.7	0.3	0.2	0.2
$_{nt}H$	daytime	407	288	231	124	240	248	244	246
	night	10	37	30	15	32	64	65	70
	24 hrs.	397	251	201	109	208	184	179	176
	computed 24 hrs.	300	225	163	111	207	188	181	173

puted, as usually, from the measured sunshine duration (the Campbell-Stokes instrumentation was used), one obtains under such conditions ($m_d < m_n$) too great values for the net back radiation and, as a consequence, too small values for the net radiation. Discrepancies between the measured and computed net radiation are often due to errors in $f(\mathrm{m})$.

$$\text{With:} \quad f(\mathrm{m}_{24}) = N/24\ (a + b\ n/N) + (1 - N/24)\ (1 - \nu\ \mathrm{m}_n\ ), \qquad (5)$$

better results from eq. (4) will be obtained for shorter periods of time, in spite of possible errors in $f(\mathrm{e}_d)$ and in an assumption $T_{ea} = T_{ai}$.

FIG. 2. Linear relation between net radiation measured above grass and measured total global radiation, under clear and overcast sky conditions. Regression equations obtained from observations at Wageningen, the Netherlands, 51°58′ N, 5°39′ E [14]. Equations 1 and 3 hold only if m_d equals m_n.



From a consideration of the radiation balance [14] it follows, that $_{nt}H$ and H_{su} for daytime or 24 hrs. periods are lineairly related if the net long wave length radiation of the earth is constant. Since H_{su} and $_{nt}H_{ea}$ both depend on atmospheric conditions (they both decrease or increase with increasing or decreasing cloudiness respectively) there will be a relation between H_{su} and $_{nt}H_{ea}$ during periods with clear, broken and overcast skies. It was shown [14] that this relation for short periods (24 hrs.) in the Netherlands was mainly due to the term $f(m_{24})$ in the expression for $_{nt}H_{ea}$ (eq. (4)) and that the term including the law of STEFAN-BOLTZMANN was of minor importance. * For periods in which the cloudiness varies considerably

$$_{nt}H = (1 - r_{su} - u)\, H_{su} - F(H_{su}) \qquad \text{cal cm}^{-2}\ 24\ \text{hrs}^{-1}, \qquad (6)$$

in which $F(H_{su})$ depends on the time of the year. $F(H_{su})$ becomes nearly a constant on days with similar cloud conditions. Linear relations obtained between H_{su} and $_{nt}H$ above short grass at Wageningen, 51°58′N 5°39′E, [14] were in good agreement with results obtained at Ames, Iowa, 42°00′N 93°39′W [17] ** (FIG. 2). However, the net radiometer used gave probably somewhat too high values for $_{nt}H$ at noon on clear, warm days [14]. As a consequence, r_{su} of about 14 % on the clear days is somewhat low (apparent reflectivety) as compared with about 20 % under overcast sky conditions. More comprehensive discussions on the radiation balance and experimental results are given in the original paper [14].

3. Available energy and evapotranspiration

Under humid evapotranspiration conditions the total amount of available energy, primarily used for heating the soil and air and for evapotranspiration, comes from radiation. It was found in the Netherlands that for monthly or longer periods in summer often 75—85 % of the net radiation gain is used for evapotranspiration from grass not short of water [5; 14]. Then 15—25 % of the net radiation gain is used for heating the soil and air.

Potential evapotranspiration [15; 16] from short grass over short periods of time seemed linearly related with the measured net radiation (FIG. 3). Evapotranspiration was determined from an accurate water balance in the root zone. Moisture contents in the root zone were obtained from thermal conductivity measurements [18; 3; 14].

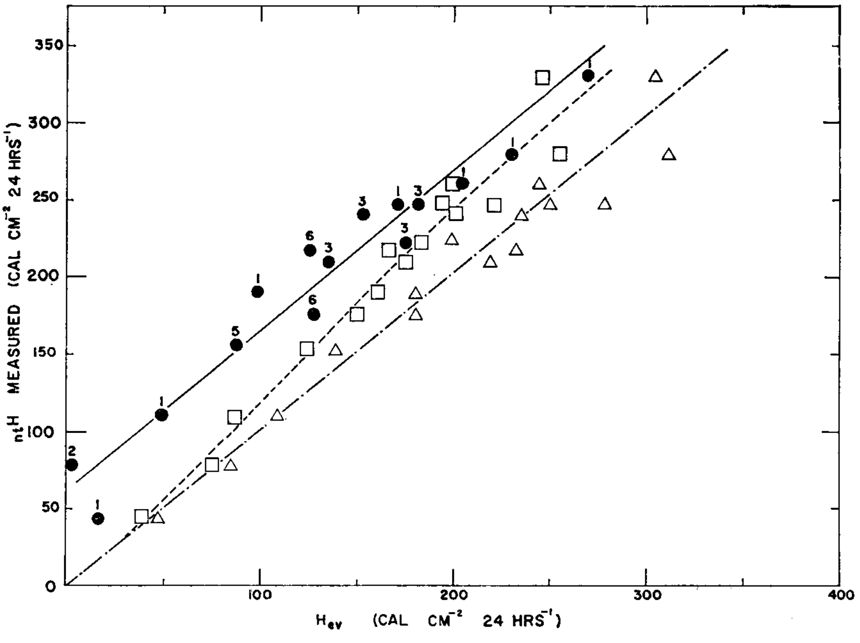
During these summer periods in the Netherlands, in which $_{nt}H$ above the grass varied from 330 to 70 cal cm^{-2} 24 hrs^{-1}, the ratio $(H_{so} + H_{ai})\, H_{ev}^{-1}$ varied from about 0.2 to 3.0. For an average net radiation gain of 200—240 cal cm^{-2} 24 hrs^{-1} this ratio became 0.3.

Assuming E'_o, computed from the energy balance above short grass, equivalent with the B-factor mentioned before, it should follow that $A_{max}(= E_{po}/B)$ comes close to unity on clear days during the observation period and decreases if the radiant

* The term last mentioned can be of importance if one compares the net radiation above different (low and hight) crops, since in that case T_{ea} may vary.

** Since the interval $0 \leq n/N \leq 0.75$ is somewhat great for the assumption $F(H_{su}) =$ constant. *Shaw* [17] obtained a rather great variation in his data for "cloudy days". In October and November the points for these days fit well on curves according to eq. (6), and 0.25 can be an apparent reflectivety of grass for short wave length radiation.

FIG. 3. Short period relation between net radiation measured above short grass and latent heat flux density of evapotranspiration (H_{ev}). ● = measured potential evapotranspiration from grass (E_{po}); △ = evaporation from an open thin water layer (E_o); □ = evaporation from a thin water layer computed from the net radiation gains above grass (E_o'). 1, 2, 3, etc. indicate the number of days in each observation period. From observations during summer months at Wageningen, the Netherlands [14].



heat flux density decreases (FIG. 3). For the short periods of 1 to 6 days also great variations in the ratio factor $f = E_{po}/E_o$ were found under different conditions of radiation and temperature (FIG. 4). If cloudiness increases or the radiant heat flux density decreases, the values of A and f should decrease. Over short intervals of time plant or weather factors (which influence the aperture of the stomates) and/or an increased stability of the lower air layers may have great influence under these conditions (errors in E_o and E'_o). However, if radiation gains and losses were measured and no correlation formules were used, PENMAN's formula for E_o [9; 10; 6; 7] gave very reliable values, even for shorter periods, in the Netherlands [14]. It was also found that the evaporation E_o from a thin water layer (expressed in cal cm^{-2} 24 hrs^{-1}) comes close to the net radiation (2 m height) above short grass (FIG. 3).

Under arid evapotranspiration conditions considerable amounts of energy, available for vaporization, may come from advective heat supplies. Some data of evapotranspiration from grass (grass length 6—8 cm), obtained with a giant weighable lysimeter at Davis, California [11], together with some radiation data are given in TABLE 3. *

January 15—19 were rainless days during the wet season in this part of the Sacramento Valley. January 15 and 16 were clear and windy days. Due to clear skies the

* During some months in 1960, author was a Research Associate in the Department of Irrigation, University of California, Davis, California.

FIG. 4. Net radiation measured above short grass and ratio factor $f = E_{po}/E_o$. 1, 2, 3, etc. indicate the number of days in each observation period. From observations during summer months at Wageningen, the Netherlands [14].

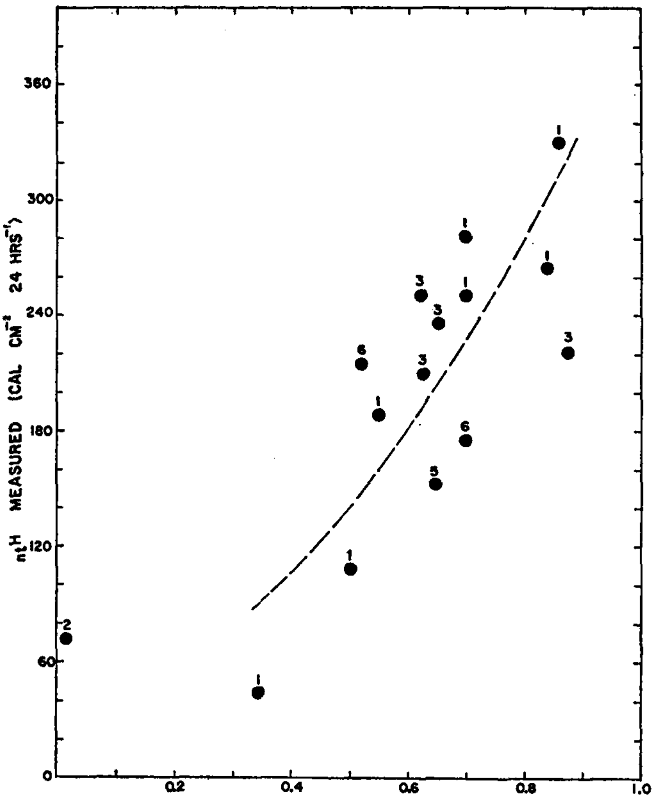


TABLE 3. Evapotranspiration and radiation on some rainless days at Davis, Calif. The evapotranspiration from grass (H_{ev}) under high moisture contents in the root zone. Grass length 6—8 cm. $_{nt}H$ was determined with a Beckman and Whitley net radiometer. H_{su} was measured with an Eppley pyrheliometer. During the nights no water loss from the lysimeter was observed.

38°32′N, 121°45′W	1/15/60	1/16/60	1/17/60	1/18/60	1/19/60
H_{ev} (cal cm-2 24 hrs-1)	76.9	76.0	36.2	24.4	45.3
E_o (U.S.W.B. pan, cal cm-2 24 hrs-1) .	129.8	106.2	23.6	29.5	35.4
H_{su} (cal cm-2 day-1)	284.0	279.0	218.0	100.0	202.0
$_{nt}H$ (cal cm-2 day-1)	121.0	128.2	123.2	72.8	117.6
$_{nt}H$ (cal cm-2 night-1)	—90.0	—64.0	—30.2	—1.6	—17.0
$_{nt}H$ (cal cm-2 24 hrs-1)	31.0	64.2	93.0	71.2	100.6

back radiation during the nights on these days was many times greater than on the following three days. As a result, the net radiation over 24 hrs. on these days was considerably smaller as compared with the net radiation gains on the 17th, 18th and

19th, although the total global radiation was greatest on the first two days. On January 15 and 16 the energy used for evapotranspiration over 24 hrs., probably under nearly optimal water supply to the roots, however, was considerably greater than the net radiation gain and was 2 to 3 times greater than energy used for evapotranspiration on the other days. (Compare TABLE 2 with TABLE 3 for the "intensified green house effect").

One could not conclude from soil temperature data that there was any considerable amount of net heat flow upward to the soil surface over the 24 hrs. periods. Probably the high amounts of evapotranspiration on these two days were due to "advective heat" supplies (net heat flow out of the overblowing air to the evaporating surface). On the calm days January 17, 18 and 19 the diurnal variation of (potential) evapotranspiration was in phase with the net radiation (FIG. 5 A). This in close agreement with earlier statements [20; 21]. There is nu reason to expect that this would not be true on January 15 and 16 under similar weather conditions. However, on these days the diurnal variation of (maximum) evapotranspiration was in phase with the north wind (and temperature) variation (FIG. 5 B) *. The evapotranspiration rate was still high when the net radiation had decreased considerably. January 16 showed the same phenomenon but in a less measure, probably as a consequence of decreasing wind velocities.

Neglecting the heat flux in soil for these 24 hrs. periods, the energy balance (in cal cm^{-2} 24 hrs^{-1}) becomes:

$$_{nt}H + H_{adv} = H_{ai} + H_{ev}\,.$$

Considering H_{adv} as a downward flux of heat, $\mathbf{H}_{ai}\downarrow$, out of the air to the evaporating surface, we may write:

$$_{nt}H = {}_{nt}H_{ai} + H_{ev}\,,$$

in which

$$_{nt}H_{ai} = H_{ai}(\downarrow,\uparrow) - \mathbf{H}_{ai}\downarrow\,.$$

Assuming no advection on January 17, 18 and 19, and neglecting H_{so} , the energy gains and losses (in cal cm^{-2} 24 hrs^{-1}) at this evaporating surface can be summarized as follows:

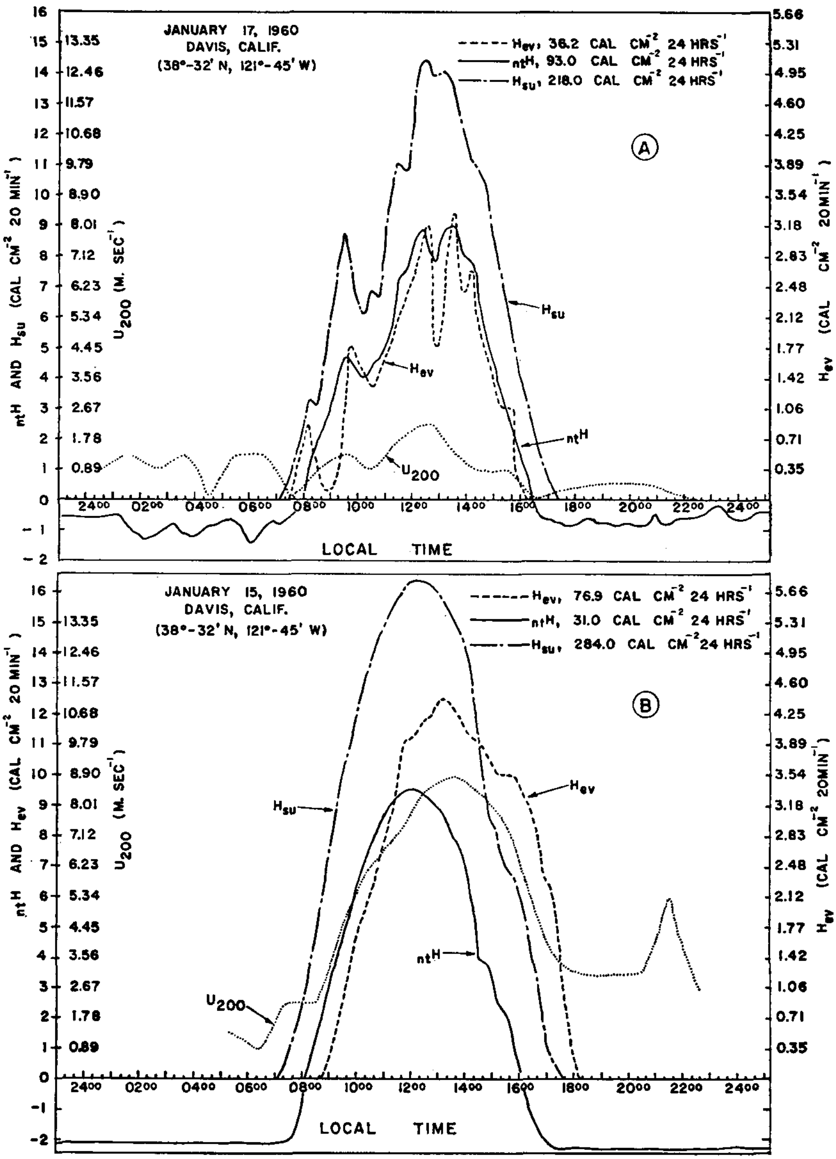
	$_{nt}H$ (↓)	H_{ev} (↑)	H_{ai} (↑)	$_{nt}H_{ai}$ (↓)
1/15/60	31.0	76.9	—	45.9
1/16/60	64.2	76.0	—	12.0
1/17/60	93.0	36.2	56.8	—
1/18/60	71.2	24.4	46.8	—
1/19/60	100.6	45.3	55.3	—

(↓) = heat flux density to the evaporating surface.

(↑) = heat flux density from the evaporating surface.

* Increasing wind may result in increasing evapotranspiration rates. Without advective heat supply, however, the energy used for evapotranspiration over 24 hrs. will not exceed the net radiation gain over 24 hrs. if $(-H_{so})_{24} \approx 0$.

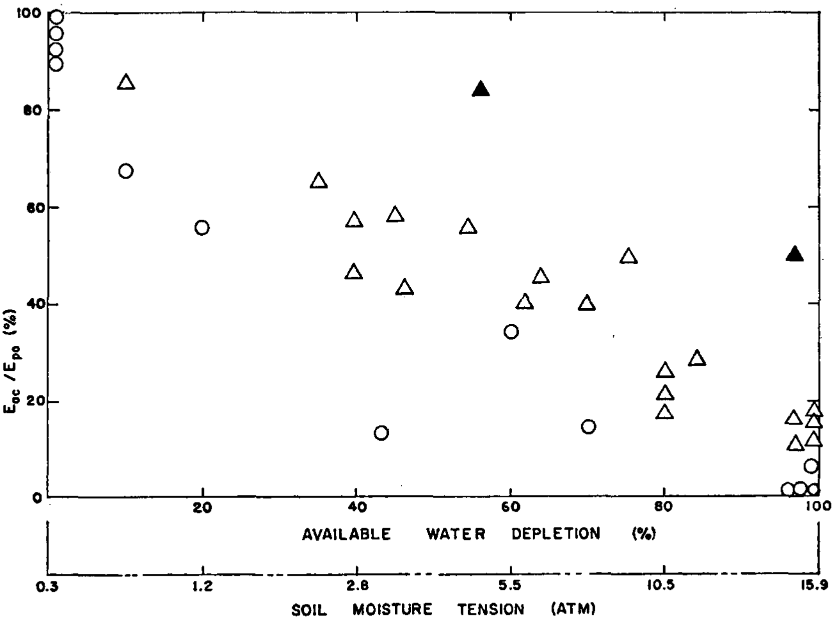
FIG. 5. Diurnal variation of total global radiation (H_{su}), net radiation ($_{nt}H$) and evapotranspiration (H_{ev}) from grass at Davis, California. Wind speed U measured at 200 cm height. Grass length 6—8 cm.



A: January 17, 1960. (potential) evapotranspiration in phase with radiation (note different scales). $(_{nt}H)_{24} = 93.0$ cal cm-2, $(H_{ev})_{24} = 36.2$ cal cm-2, $(H_{so})_{24} \approx 0$ cal cm-2, $(H_{ai} \curlywedge)_{24} \approx 56.8$ cal cm-2.

B: January 15, 1960. (maximum) evapotranspiration not in phase with radiation. $(_{nt}H)_{24} = 31.0$ cal cm-2, $(H_{ev})_{24} = 76.9$ cal cm-2, $(H_{so})_{24} \approx 0$ cal cm-2, $(H_{adv} \curlyvee - H_{ai} \curlywedge)_{24} \approx 45.9$ cal cm-2.

FIG. 6. Relative daily actual evapotranspiration rate from short grass, grown on a fine sandy soil, as a function of moisture depletion from the root zone and soil moisture tension averaged over the total root depth. ▲ = at $_{nt}H < 90$ cal cm-2 24 hrs-1; △ = at $150 \leq {}_{nt}H \leq 250$ cal cm-2 24 hrs-1; o = at $_{nt}H > 300$ cal cm-2 24 hrs-1. From observations at Wageningen, the Netherlands [14].



The influence of available energy on a decrease of evapotranspiration as soil moisture becomes less available for plant roots is clearly shown in FIG. 6 [14]. Under low net radiation gains, a decrease of evapotranspiration is less pronounced than it is under high net radiation gains. The same will hold for crop yields. The results obtained, that actual evapotranspiration from crops can be a function of soil moisture tension and of available energy (or potential evapotranspiration in the Netherlands) is in good agreement with earlier statements [8]. Similar results were recently obtained at Ames, Iowa *.

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