Global solar radiation and potential evapotranspiration in Sweden

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ABSTRACT

By means of an established regression between monthly global solar radiation and monthly number of sunshine hours for eight stations in Sweden the global solar radiation has been calculated from values of sunshine hours for 35 Swedish stations for the period 1931–60. The distribution of global solar radiation in Sweden then has been mapped for the months April–September and the year.

Potential evapotranspiration from a grass-covered surface has been calculated for 27 stations in Sweden for 1931–60 making use of the Penman formula and applying the values obtained for the global solar radiation. The distribution of total potential evapotranspiration has been mapped for April–September and the year. Comparisons are made with values earlier obtained in Sweden for actual evapotranspiration and diagrams showing the annual development of the potential water balance conditions are given for some typical Swedish stations.

Introduction

For various applications—in particular to agriculture and forestry—it is essential to procure as good a knowledge as possible of the radiation energy and water-balance conditions available for plant development. The radiation energy available is not only important to know in itself, it is also required to determine the evapotranspiration which forms a basic factor in the water balance.

Throughout the years several investigations of the above-mentioned elements and their geographical distribution within the Swedish land area have been made. As early as in 1910 WESTMAN (1910) published a study of the distribution of insolation in Sweden where the insolation from sun and sky was calculated from basic measurements of the intensity of the sun's radiation on cloudless days at three different places in Europe and from cloudiness observations in Sweden. Although interesting from a theoretical point of view this study did not provide very accurate values of the radiation energy available at different places and various times of the year.

AURÉN (1939) published a study of the radiation climate in Scandinavia based on measurements of the global radiation at Stocksund (close to Stockholm) and cloudiness observations from a considerable number of Swedish stations. As this study was founded on global radiation measurements instead of on observations of direct radiation from the sun the results are probably more reliable than those of Westman.

Actual evapotranspiration in Sweden generally has been determined as a residual in the water-balance equation (A. WALLÉN, 1927, BERGSTEN, 1950). Very few direct observations of evaporation are available and they may not form a basis for a study of the area distribution. Actual evapotranspiration recently also has been calculated by TAMM (1956) for the Swedish land area from an empirical formula derived from values of evapotranspiration obtained for various catchments from the hydrological equation and values of the mean temperature of the air. No attempt to calculate potential evapotranspiration by means of the well-known formulas derived by Thornthwaite or Penman has so far been published.

The following study is a preliminary attempt to determine from measurements of the global radiation at some places in Sweden the area distribution of the radiation energy available at different times of the year. By means of the radiation values so obtained the potential evapotranspiration has been calculated by Penman's formula for stations in Sweden from which necessary climatological data are available. In both cases the data presented refer to the period 1931–60.

Global solar radiation

Since IGY 1957–58 a network of radiation stations has been operating in Sweden. For the actual study comparatively complete records of the global radiation were available for the period 1957–1963 from 8 stations, namely: Svalöv, Torslanda, Vixby, Karlstad, Stockholm, Erken, Frösön and Kiruna. Considerably longer records are available from Stockholm. Completing data from shorter records could be obtained from Studsvik, Sandviken, Teg and Luleå. Records of duration of sunshine were available from the first-mentioned 8 stations for the same period. Global radiation has been recorded with a Moll-Gorczynski solarimeter from Kipp and Zonen in Holland. Sunshine was recorded by Campbell-Stoke's autograph.

Thus it was possible to establish a relationship between duration of sunshine S and global radiation Q at those stations for which data are available.

ÅNGSTRÖM (1924) suggested an interpolation formula for this relationship:

$$Q = Q_0\left(\alpha_1 + (1-\alpha_2)\frac{S}{S_0}\right), \qquad (1)$$

where Q_0 is the global radiation with a perfectly clear sky and S_0 is the maximum possible duration of sunshine. BLACK, BONYTHON & PRESCOTT (1954) introduced instead of Q_0 the easily computed value Q_A corresponding to a perfectly transparent atmosphere and keeping the general form of the equation put

$$Q = Q_A\left(a + b\frac{S}{S_0}\right). \qquad (2)$$

ÅNGSTRÖM (1956) has discussed the interrelationship between the constants of the two expressions.

In view of the fact that it is easier to compute the latter expression it has been adopted in the present study. Later the expressions Q/Q_A and S/S_0 were computed for the above-mentioned 8 stations using monthly mean values of Q and S

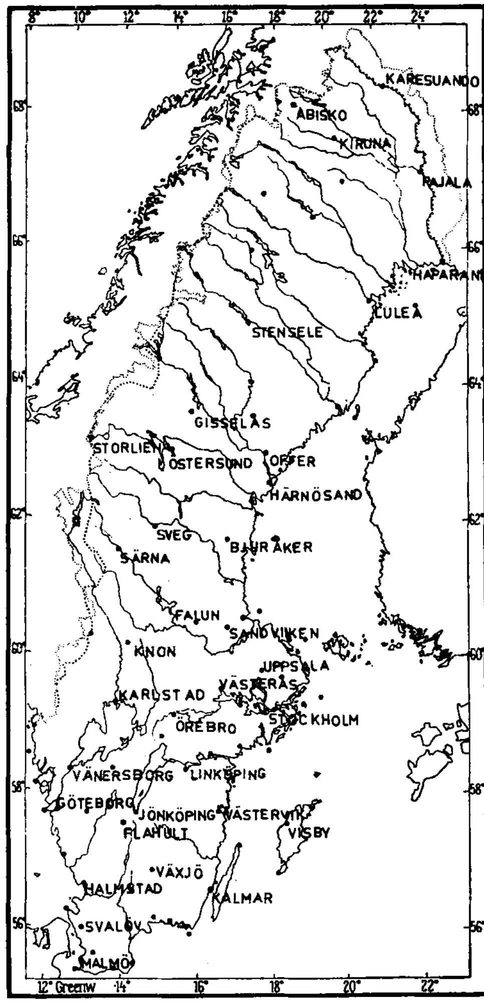

FIG. 1. Map of stations.

for the period 1957–63, and the obtained values were plotted in diagrams as shown in Fig. 2. It became obvious that the points representing various months could be connected with single straight lines only in the case of the southernmost stations: Svalöv and Torslanda. At other stations the winter months required a special line and at Kiruna a third line was necessary to introduce for spring and autumn. This of course indicates an annual variation of the constants in equation (2) which has been discussed by ÅNGSTRÖM (1956), who emphasizes that the calculation of the relation between radiation and sunshine preferably should be carried out for individual months using actual daily or

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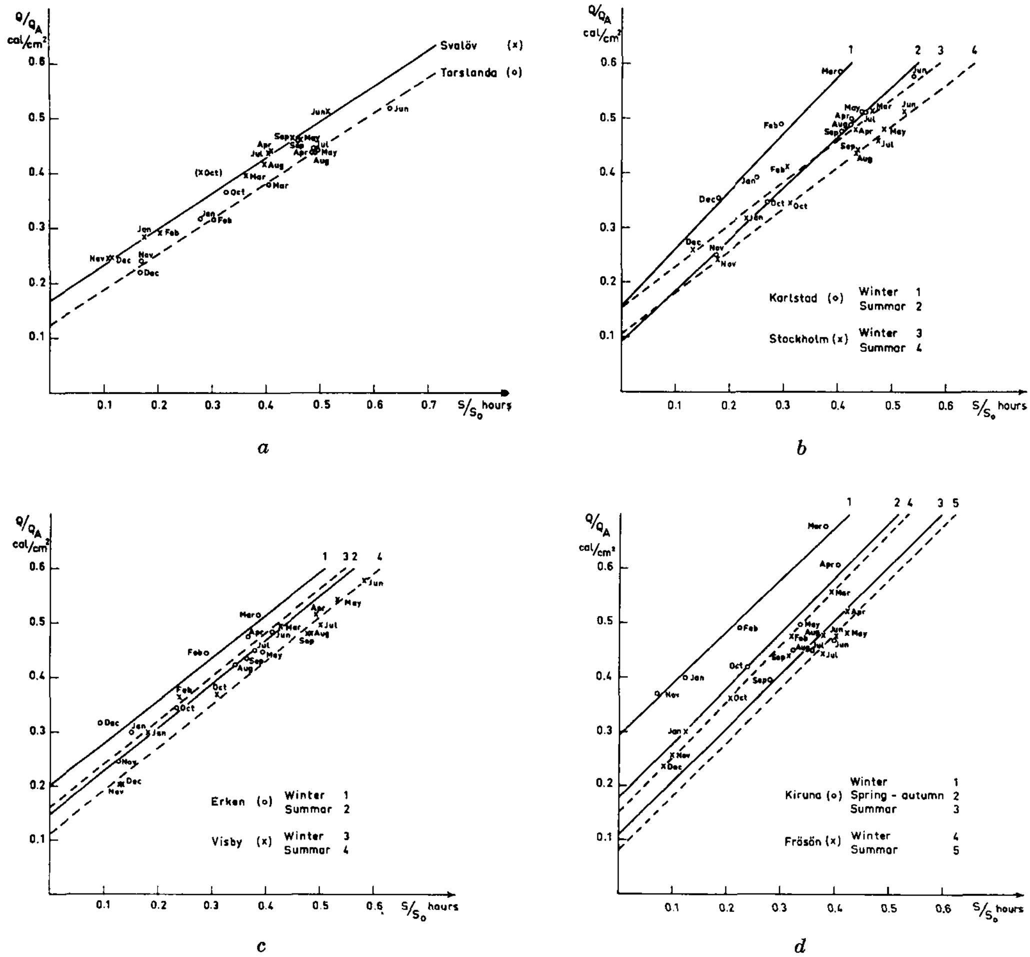

FIG. 2*a–d*. Linear relationships between monthly mean values of the relative global solar radiation (Q/Q_A) and of the relative number of sunshine hours (S/S_0) at selected stations in Sweden. In several cases different lines are obtained for winter, summer and spring–autumn months.

monthly values instead of mean values. This unfortunately was not possible in our case due to the shortness of the period from which data are available.

From the variation of the slope and situation of the lines in the diagrams it is clear that the constants of equation (2) also show typical variations with latitudes and other geographical conditions which the actual data are too scanty to investigate in detail. A few suggestions are, however, indicated. It is most likely that at all stations except Svalöv and Torslanda in southernmost Sweden the multiple reflexion in winter between the snow covered ground and the sky is of fundamental importance for rendering higher values of relative global radiation with a certain relative sunshine duration in winter than in summer. Multiple reflexion, however, cannot account for the total difference between winter and spring or autumn months on one hand and summer months on the other. A latitudinal effect indicating more rapid increase of global radiation with sunshine hours in the north than in the south is also obvious. It is likely that the turbidity of the air varying with the season in a different way along the Swedish west-coast than along the east-coast and in Norrland is also fundamental in creating for certain months a quite special relation between global radiation and sunshine duration.

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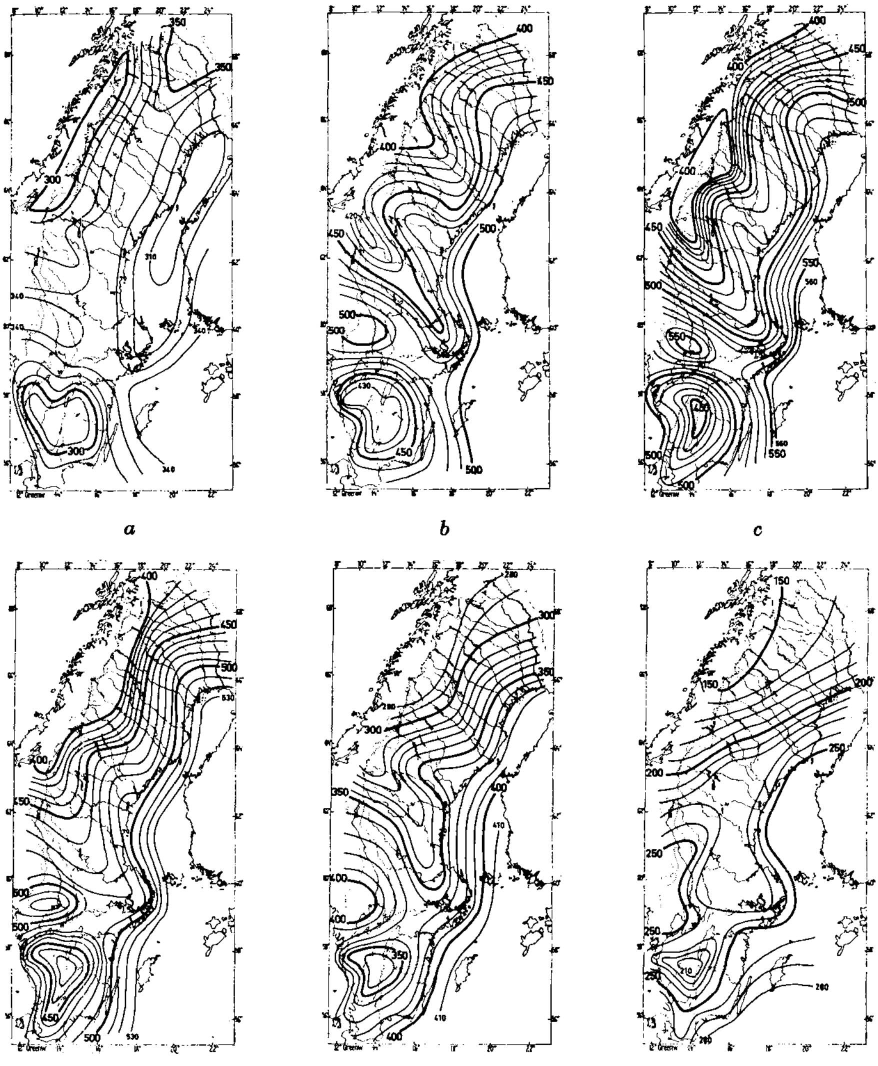

FIG. 3*a–f*. Distribution of global solar radiation in Sweden during each one of the months of April to September expressed in cal/cm^2 and day (ly/day).

This is seen from those cases in the diagrams where single points are situated quite out of the position where they should be placed according to the general line. A typical phenomenon worth noting is the slow increase of radiation with sunshine in Torslanda indicating high turbidity of the air due to both moisture and salt-particles from the sea and pollution from the city. A comparison between Stockholm and Erken gives a similar indication of the effects of the pollution from the city.

Assuming that the relationships obtained in the diagrams of Fig. 2 hold good approximately but in general they have been applied to calculate the global solar radiation for 35 Swedish stations where values of duration of sunshine are available for the period 1931–60 (Table 1). First the mean global radiation for this period was calculated for the basic 8 stations of the diagrams, later the diagrams were applied also to neighbouring stations having records of sunshine. Finally maps of the geographical distri-

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bution of global solar radiation in the period 1931–60 have been drawn for each month of the year and for the year itself. Maps showing the distribution of daily global radiation in each month April–September are shown in Fig. 3. Total global radiation April–September and for the whole year are given in kcal/cm² in Fig. 4.

The use of monthly mean values has obviously introduced a considerable approximation in our calculations of the relation between global radiation and sunshine duration. If the relation is determined graphically for seasons by means of monthly mean values for a certain period as in this case the constants in the equation (2) for winter and summer must differ from those which would be obtained for each month if actual monthly values were used and the complete annual variation of the constants thus considered. At this stage we can only regret that we have not sufficient data for such a more accurate computation. For mapping the global radiation in Sweden the method applied is therefore to be accepted only as approximate. The results still are likely to be more accurate than those presented by Westman and Aurén which in the first case seem to have been considerably too high in the latter considerably too low.

It must also be emphasized that the calculated values and the maps are preliminary and approximate also for other reasons. The basic network of radiation stations is small and the relationships between global radiation and sunshine that have been established are of course rather inaccurate also due to the shortness of the period which had to be used. Furthermore it is not absolutely sure that the regressions of Fig. 2 could be applied also to the period 1931–60, although it may be considered as a fair assumption.

Unfortunately it has not been possible to check the calculated values for Stockholm by comparing with recorded values for the period 1931–60. The records from Stockholm have been taken by different instruments during the first part of the period and in the latter. It cannot be accepted as homogeneous.

In spite of all these weaknesses these new maps of global solar radiation in Sweden present not only more probable values but also much more details than those earlier published and thus on the whole would imply a step forward in the development towards a better knowledge of our radiation climate. The new maps and the method to arrive at them also clearly indicate that global solar radiation is a more local phenomenon than one might presume, highly influenced as it is by local cloudiness and turbidity conditions.

The complete values given in Table 1 show that in all Sweden the global solar radiation in *November, December and January* is smaller than the outgoing radiation which in these months is close to 55 cal/cm² and day. Radiation in these months certainly does not contribute to any evaporation, a fact that is interesting to note for the following discussion of potential evapotranspiration. As early as in February the mean daily global radiation exceeds the outgoing south of latitude 65° N so that a small contribution for evaporation and warming is available during the latter part of the month in southern Sweden. *October* also is a transition month in which daily global solar radiation generally exceeds the outgoing during the first part of the month.

March is the first month of the year where global radiation gives a considerable contribution of energy for warming and evaporation. The daily mean value is at a maximum in the Vänern-area of central Sweden with 230 cal/cm² but as far north as in central Norrland at Kiruna the multiple reflexion from the snow cover helps to increase the total radiation to a value of 210 cal/cm² which is actually more than in Skåne at that time of the year. Along the east coast of northern Sweden the radiation is comparatively low probably due to high moisture of the air.

April again shows maximum values of daily insolation in central Sweden, in Gotland and in the continental parts of northernmost Norrland with 330–350 cal/cm². The south-Swedish highlands and the west coast receive only around 300 cal/cm² and day which is about the same as in the western mountains of Norrland.

In *May* the summer pattern of the distribution of insolation is established. A maximum of global solar radiation of 500 cal/cm² and day is obtained from north of Lake Vänern across central south Sweden to Gotland as well as all along the Swedish east coast. In the south-Swedish highlands and in the northern mountains the daily values drop to an average of 400–430 cal/cm². It is interesting to note the comparatively low values from Storlien and Östersund

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TABLE 1. *Global solar radiation.*

Station	cal./cm² and day												Total amount cal./cm²		
	J	F	M	A	M	J	J	A	S	O	N	D	Oct.–March	April–Sept.	Year
Malmö	40	100	200	320	465	485	465	380	265	110	45	25	15,775	72,710	88,485
Svalöv	45	100	195	310	465	480	455	365	260	105	45	25	15,620	71,335	86,955
Halmstad	35	80	190	305	455	480	470	360	250	100	40	20	14,135	70,885	85,020
Växjö	30	80	175	290	430	465	460	360	240	95	30	15	12,905	68,600	81,505
Kalmar	35	95	190	315	465	515	485	390	265	110	40	20	14,865	74,390	89,255
Visby	25	75	200	345	495	565	535	415	265	115	35	20	14,310	80,045	94,355
Göteborg-Torslanda	25	75	180	295	425	480	445	350	220	100	40	20	13,375	67,670	81,045
Jönköping	25	75	185	290	425	450	430	340	215	90	30	15	12,765	65,695	78,460
Flahult	25	75	190	295	425	450	430	340	210	90	30	20	13,075	65,695	78,770
Västervik	30	85	200	320	470	510	500	385	255	110	40	15	14,585	74,555	89,140
Vänersborg	25	90	205	300	440	490	470	380	245	110	45	20	15,030	71,040	86,070
Linköping	30	80	210	325	460	510	480	380	240	100	35	20	14,450	73,170	87,620
Örebro	35	80	220	335	490	525	490	370	230	90	30	15	14,300	74,550	88,850
Stockholm	25	75	195	320	475	530	485	375	225	100	30	15	13,385	73,635	87,020
Karlstad	35	90	230	330	495	550	535	400	240	100	35	15	15,350	77,930	93,280
Västerås	25	80	195	330	475	510	485	360	225	90	30	15	13,215	72,870	86,085
Uppsala	25	80	185	325	455	495	480	360	225	100	25	15	13,065	71,495	84,560
Sandviken	25	80	195	330	450	480	475	345	220	90	25	15	13,065	70,270	83,335
Knon	30	85	220	330	490	520	480	380	235	100	25	15	14,445	74,400	88,845
Falun	25	80	200	330	460	480	470	350	230	95	25	12	13,282	70,880	84,162
Särna	25	75	205	325	450	455	455	360	240	110	30	12	13,912	69,815	83,727
Bjuråker	25	75	200	330	465	475	475	340	230	95	25	12	13,142	70,730	83,872
Sveg	20	75	205	320	430	435	455	345	235	100	25	10	13,235	67,830	81,065
Härnösand	25	75	195	325	475	480	485	350	240	95	30	10	13,075	71,960	85,035
Offer	20	65	190	325	450	470	475	360	230	75	25	5	11,560	70,585	82,145
Östersund	20	70	195	330	465	470	450	330	220	90	25	8	12,413	69,195	81,608
Storlien	15	60	175	310	420	380	400	315	200	80	25	8	11,048	61,885	72,933
Gisselås	20	65	180	320	460	470	465	345	220	85	25	5	11,560	69,670	81,230
Stensele	10	60	185	330	425	460	430	300	180	60	15	5	10,190	64,905	75,095
Luleå	15	60	190	315	475	530	520	365	195	85	20	5	11,425	73,360	84,785
Haparanda	15	50	180	310	490	525	520	365	200	90	25	5	11,140	73,675	84,815
Pajala	5	50	190	330	450	480	470	310	165	65	15	0	9,910	67,380	77,290
Kiruna	5	50	210	350	420	450	440	295	160	65	10	0	10,380	64,605	74,985
Abisko	0	40	185	330	400	420	405	285	160	65	10	0	9,170	61,090	70,260
Karesuando	0	45	200	340	405	425	425	290	160	60	5	0	9,470	62,470	71,940

southeastwards indicating the influence of the comparatively high moisture content of the air having crossed the Storlien-pass of the mountain chain from the Atlantic.

June shows a similar picture as May with a maximum across central south-Sweden and in Gotland of 550–570 cal/cm² and day. A secondary maximum occurs in the coastal districts of northernmost Norrland. In the western parts of the south-Swedish highlands insolation is about 450 cal/cm² and day and in the northwestern mountains as low as around 400. The annual maximum of global radiation occurs at practically all places in this month. In *July* the distribution of global radiation is still similar to that of the months before. Maximums of around 530 cal/cm² and day are found north of Lake Vänern, in Gotland and in the coastal region of northern Norrland. Minimum values of around 400 cal/cm² and day are obtained in the northwestern mountains. Comparatively low values around 430 cal/cm² and day are obtained in the highlands of southwestern Sweden.

In *August* the decrease of radiation from south to north again starts to become an important feature of the distribution. Maximum still exists around Lake Vänern, in central south-Sweden and in Gotland with a daily amount of 400 cal/cm². In northernmost Sweden radiation has decreased to 290 cal/cm² and day while in

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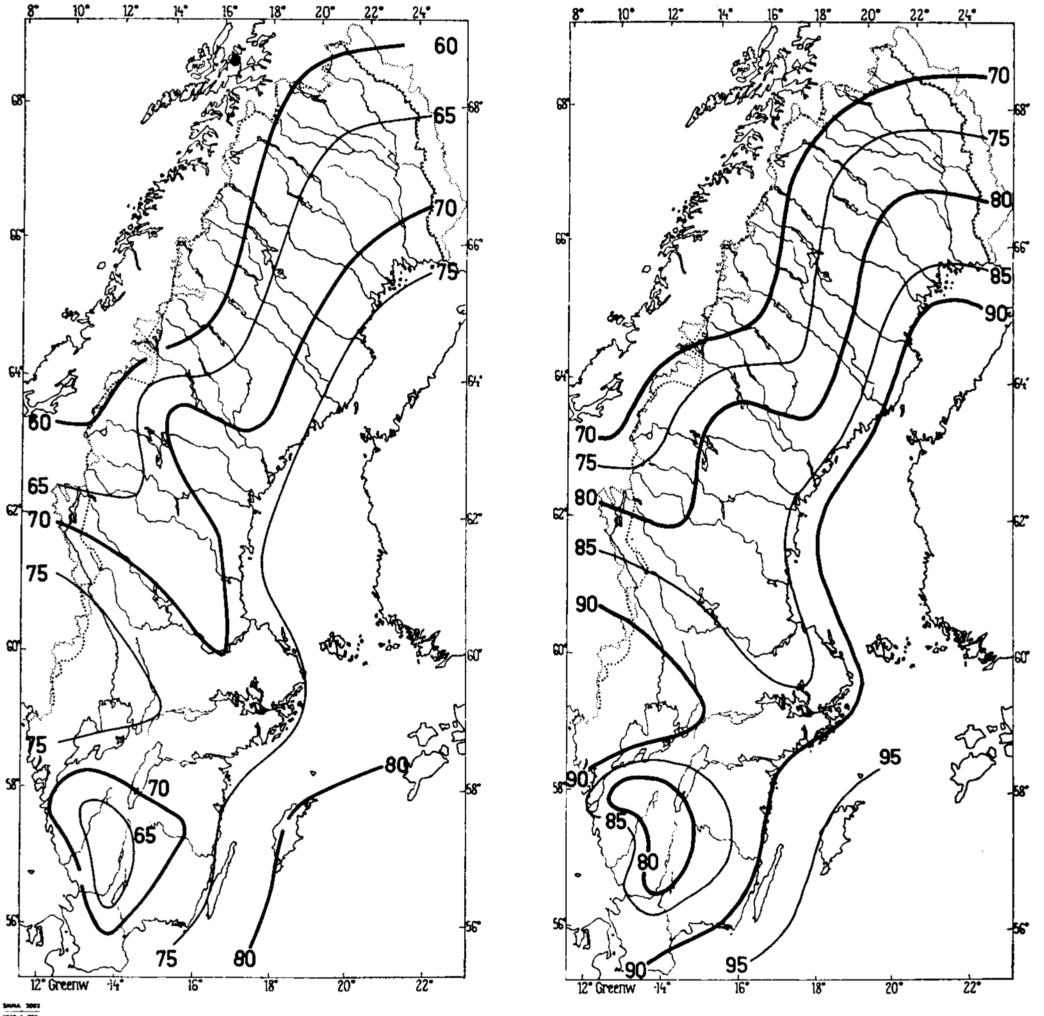

FIG. 4*a*–*b*. Distribution of global solar radiation in Sweden during the period April–September (*a*) and the whole year (*b*) expressed in kcal/cm².

the south Swedish highlands the average reaches a value of around 350 cal/cm² and day.

In *September* maximum of radiation income is found in southeast and in Gotland with values up to 280 cal/cm² and day. At the same time it is only around 150 cal/cm² and day in the northernmost part of the country. The Vänern area gets a secondary maximum value of about 240 cal/cm² and day.

The *annual amount of the global solar radiation in Sweden* is shown in Fig. 4*b* and given in kcal/cm². The overall distribution is quite similar to the one discussed for the summer months with maximums in central south Sweden, along the coasts and in Gotland. The highest annual value calculated is found for Gotland with about 93,000 cal/cm², the lowest is found for Abisko in Lappland with about 70,000 cal/cm².

A comparison with the annual values presented by WESTMAN (1910) indicates, as earlier mentioned, that his values were considerably higher. Westman presented for instance for Lund an annual value of 104.6 kcal/cm² while our calculations have rendered a value of about 88 kcal/cm². For Uppsala Westman has given 102 kcal/cm, while the recent value is 84. For

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Haparanda the corresponding values are 103 and 85 cal. Evidently Westman has obtained quite a good idea of the latitudinal variation of the global radiation in Sweden but his method based on direct solar radiation measurements seems to have led to values which are 15–20% too high. AURÉN (1939) on the other hand gives for Lund a value of 84 kcal/year, for Uppsala 72 and for Haparanda 63 kcal/year. The latitudinal decrease here seems to be exaggerated while the obtained values are practically the same as ours in the south but up to 25% lower in the north.

ÅNGSTRÖM (1924) presented for Stockholm a value of 76,600 kcal/cm² and year which is about 7% lower than the amount recorded at Stockholm for 1931–60. We have to remember here that this difference may be due to the fact that the period 1931–60 was a period of more sunshine than the earlier period used by Ångström and therefore is likely to give higher values also for the global radiation. This again may be one of the reasons for the low values obtained by Aurén.

The distribution of the global radiation over the Swedish land area given in Fig. 4 shows considerable similarities with the picture presented by AURÉN (1939).

Potential evapotranspiration

As mentioned in the introduction there are no values of potential evapotranspiration (potential transpiration) as defined by THORNTHWAITE and PENMAN[1] earlier presented for Sweden. There are various reasons why this parameter—mainly theoretical as it is—has not been introduced in Sweden. The basic reason is probably the fact that only small areas in this country show deficiency of water and few practical problems have so far arisen with regard to lack of water. However, as the water consumption is continuously increasing the theoretical and the practical water balance conditions in various parts of the country become of increasing interest. Moreover, as the potential evapotranspiration has been taken up for study in several neighbouring countries it has become a duty also for us to consider this parameter so as to allow for regional or global mapping of same. We shall return to the question of the relation between potential and actual evapotranspiration after the presentation of our results and then also compare them with those values earlier obtained for actual evaporation in Sweden by various authors.

In selecting among methods to calculate potential evapotranspiration from climatological data the one presented by Penman has been selected. Preliminary calculations with Thornthwaite's formula as well as comparisons between actual measurements and values obtained with his formula from Kristianstad, Skåne (HÖGSTRÖM, 1964) showed that it underestimates the potential evapotranspiration in all autumn and winter months in high latitudes.

As shown by, for instance, ASLYNG (1965) Penman's formula does not give absolutely true values of potential evapotranspiration either. Aslyng found in studies outside Copenhagen that the measured annual amount of water evaporated from a free water surface was about 10% lower than the value calculated by Penman's formula mainly due to the fact that the formula exaggerates the evaporation from water in spring and early summer. Late summer and autumn evaporation was correctly estimated by the formula. However, Aslyng's study seems to confirm, what several other recent investigations have shown, that this discrepancy is comparatively small and that Penman's formula is the best method that actually exists to calculate potential evapotranspiration from climatological data.

Penman himself and others have at various occasions presented modifications of the original formula presented by PENMAN (1948). In this study we have applied the following variant for calculation of potential evapotranspiration ETP:

$$\mathrm{ETP} = \frac{\Delta/\gamma \cdot H + E_a}{\Delta/\gamma + 1/SD}, \tag{3}$$

where

Δ = slope of the saturation vapour pressure curve at air temperature;

γ = psychrometer constant (0.66 mb);

$H = R_c(1-r) - R_B$, in which

R_c = global solar radiation energy expressed in mm of evaporated water per day;

r = reflexion coefficient of evaporating surface;

[1] PENMAN (1948): The amount of water lost through evaporation and transpiration by a surface completely covered by short green grass provided water is continuously available.

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$R_B = \sigma \cdot T_a^4 (0.56 - 0.09\sqrt{e_d})(1 - \alpha \cdot m)$, where
T_a = absolute temperature of the air;
e_d = vapour pressure in mb at air temperature;
m = mean cloudiness in tenths;
α = a constant given by Philips (1940) and varying with type of cloud;

and where

$E_a = 0.26(1 + 0.006\, u_2)(e_a - e_d)$, in which
u_2 = wind velocity in m/sec at 2 m height;
e_a = saturation vapour pressure in mb at air temperature.

Finally S and D are factors depending on vegetation and daylength. Originally Penman's formula was developed to determine the evaporation from a free water surface which was considered to represent potential evapotranspiration ETP_w. In this case $r = 0.95$ and of course S and D are not relevant so that the term $1/SD$ becomes equal to unity. Penman found empirically that potential evapotranspiration from a grass-covered surface ETP_g was well represented by $0.7 \cdot ETP_w$ but later developed his formula also to make possible a direct calculation of potential evapotranspiration from a grass surface. In this variant $r = 0.75$ and $1/SD$ becomes equal to 1.3 according to MILTHORPE (1960). Penman himself and other authors have put $1/SD = 1$ or differently but we have applied Milthorpe's value in this study as it seems to be based on sound assumptions regarding the importance of daylength and stomata conditions with grass.

Using the above-mentioned values in the formula the monthly and annual potential evapotranspiration has been calculated both for a free water surface and for a grass covered surface for stations in Sweden where suitable climatological data were available. Global solar radiation data, R_c, were taken from the maps shown earlier in this investigation, outgoing radiation R_B was calculated from Penman's expression and E_a was calculated applying available data for wind and humidity conditions. It should be emphasized that only in exceptions the wind data refer to the period 1931–60; in general they represent the conditions during the period 1949–58. As wind conditions are extremely local certain values from places where one had to suspect the measurements to be unrepresentative have been slightly corrected so that only in exceptional cases monthly mean values below 2 m/sec and above 5 m/sec have been accepted. The obtained values of ETP_g and ETP_w are given in Table 2 together with annual precipitation P and the potential water balance represented as the difference $(P - ETP_g)$.

As seen from the table Penman's formula strictly applied gives in most cases in our latitudes negative values for the winter months. This would imply that the moisture transport in those months is directed towards the surface instead of upwards, i.e., condensation takes place.

It is very doubtful whether this result from a strict application of the formula is correct. We have introduced the negative values in the table as the use of the formula actually result in them, but these values are due to be inaccurate as various investigations have shown that evapotranspiration actually takes place also in the winter months (ASLYNG, 1965; HÖGSTRÖM, 1965[1]).

The application of the formula in those months shows that the radiation term becomes negative while the aerodynamic term is not big enough to compensate for the negative radiation balance. Calculating for a whole month thus must lead to a negative value, which would imply condensation. However, the possibility of evaporation having occurred during certain periods of that month is not excluded although the overall monthly balance shows condensation to be dominant. It has not been possible to estimate the amount of this winter evaporation in any other way than to accept for southernmost Sweden those values given by Högström from measurements at Kristianstad. Högström gives a value of some 40 mm for these months as a reasonable value of the total evapotranspiration. On the other hand, as earlier mentioned, Penman's formula exaggerates the annual evapotranspiration from water by about 10% due to high spring values (ASLYNG, 1965). As an end result we therefore have accepted our values as fairly good considering the approximation involved in the method.

The negative monthly values for the winter given in Table 2 evidently must not be substracted from the evaporation values obtained for the rest of the year. If considered reliable as condensation amounts they should rather be

[1] Personal communication.

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TABLE 2. *Potential evapotranspiration and precipitation in Sweden 1931–60 in mm.*

		J	F	M	A	M	J	J	A	S	O	N	D	April.–Sept. ETP_g	Year	$\frac{ETP_g}{ETP_w}$	P-ETP_g year
Malmö	ETP_w	0	13	42	77	133	152	151	123	71	23	4	-8		789		
	ETP_g	-2	8	29	53	94	109	109	89	50	15	1	-7	504	557		
	P	48	36	30	32	38	45	65	62	52	54	44	44		550	0.71	-7
Svalöv	ETP_w	2	13	33	73	133	152	146	117	73	19	4	-7		765		
	ETP_g	0	7	21	50	94	108	106	85	51	12	2	-7	494	536		
	P	62	47	33	41	43	56	88	76	68	66	57	59		696	0.70	+160
Halmstad	ETP_w	-2	12	35	74	126	151	144	114	73	19	4	-5		752		
	ETP_g	-3	7	23	51	88	110	105	81	52	9	2	-5	487	528		
	P	55	46	34	36	47	62	108	97	76	63	55	57		736	0.70	+208
Växjö	ETP_w	-3	5	33	64	125	147	137	105	55	10	-5	-12		681		
	ETP_g	-4	2	21	43	87	103	98	74	36	6	-6	-11	441	470		
	P	50	38	32	36	40	54	75	91	64	60	49	55		644	0.69	+174
Kalmar	ETP_w	-3	11	34	75	125	160	155	121	71	21	2	-7		775		
	ETP_g	-4	7	23	51	88	111	112	93	49	13	0	-7	504	547		
	P	37	27	26	28	36	36	55	55	47	43	43	38		471	0.71	-76
Visby	ETP_w	3	14	40	78	129	171	172	132	89	28	9	-2		865		
	ETP_g	2	10	27	53	90	121	124	95	54	18	6	-2	537	600		
	P	53	42	29	31	30	32	52	56	51	52	48	53		529	0.70	-71
Göteborg-	ETP_w	-1	9	34	83	135	171	158	130	74	31	11	-2		836		
Torslanda	ETP_g	-1	5	23	60	98	126	121	95	54	22	8	-2	554	512		
	P	55	36	27	39	36	50	77	73	73	72	64	56		658	0.73	+46
Jönköping	ETP_w	-2	3	39	66	108	140	141	101	50	14	-2	-7		662		
	ETP_g	-3	1	27	45	75	107	97	73	32	9	-2	-7	429	466		
	P	34	24	24	31	40	55	71	68	57	49	41	42		536	0.71	+70
Västervik	ETP_w	-4	8	32	71	121	154	164	115	64	18	0	-10		747		
	ETP_g	-5	4	21	58	85	110	119	86	43	11	-1	-10	501	537		
	P	38	34	28	30	40	39	66	67	53	48	55	46		541	0.72	+4
Vänersborg	ETP_w	-5	6	33	64	114	147	145	118	64	18	2	-11		711		
	ETP_g	-5	3	21	43	79	105	109	84	44	11	-1	-10	464	499		
	P	66	42	37	44	39	57	80	79	81	80	76	68		749	0.70	+250
Linköping	ETP_w	-4	7	34	78	126	147	156	117	65	17	-2	-10		747		
	ETP_g	-4	4	21	54	88	104	113	83	45	8	-4	-9	487	520		
	P	38	31	25	31	38	46	67	69	54	42	47	40		528	0.70	+8
Örebro	ETP_w	0	3	29	68	132	160	151	105	51	8	-8	-11		707		
	ETP_g	-1	2	17	46	92	114	108	73	34	3	-8	-10	467	489		
	P	47	38	30	37	41	55	72	82	65	56	63	55		641	0.69	+152
Stockholm	ETP_w	-5	10	31	84	135	170	148	118	58	16	-1	-8		770		
	ETP_g	-5	6	20	58	96	122	117	85	40	9	-2	-8	518	553		
	P	43	30	26	31	34	45	61	76	60	48	53	48		555	0.72	+2
Karlstad	ETP_w	-3	5	34	72	133	166	171	122	63	16	0	-9		782		
	ETP_g	-3	2	21	49	95	118	123	87	43	10	-2	-8	515	548		
	P	40	25	22	39	35	48	60	78	68	62	67	50		594	0.70	+46
Västerås	ETP_w	-3	7	34	87	138	168	168	113	56	12	1	-8		784		
	ETP_g	-3	3	23	59	98	121	124	80	40	7	-1	-7	522	555		
	P	38	30	26	31	38	50	63	75	54	48	49	42		544	0.71	-11
Uppsala	ETP_w	-4	9	30	76	132	161	162	112	57	16	-1	-6		755		
	ETP_g	-4	6	19	53	94	118	118	81	42	10	-1	-6	506	541		
	P	41	27	26	33	34	49	64	75	56	54	51	44		554	0.72	+13
Knon	ETP_w	-3	9	34	74	152	167	154	110	58	12	-4	-7		770		
	ETP_g	-3	5	23	53	110	121	111	78	40	7	-4	-8	513	548		
	P	41	30	23	40	41	77	80	90	71	60	57	50		660	0.71	+112
Falun	ETP_w	-8	1	26	72	130	154	157	100	53	9	-8	-14		702		
	ETP_g	-7	-2	15	44	90	110	112	70	34	4	-8	-13	460	479		
	P	36	24	20	31	40	59	73	83	58	44	50	40		558	0.68	+79
Särna	ETP_w	-8	-2	22	59	108	138	137	93	49	11	-6	-6		617		
	ETP_g	-7	-4	9	39	74	99	98	68	32	6	-6	-5	410	425		

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Table 2 (*continued*)

		J	F	M	A	M	J	J	A	S	O	N	D	April.–Sept. ETP_g	Year	$\frac{ETP_g}{ETP_w}$	P-ETP_g year
	P	38	23	21	33	42	80	96	83	64	51	49	47		627	0.69	+202
Bjuråker	ETP_w	−6	−1	23	66	125	147	160	102	54	10	−7	−10		687		
	ETP_g	−5	−1	13	40	87	111	117	72	36	5	−7	−9	463	481		
	P	35	25	23	30	32	53	66	72	54	38	46	44		518	0.70	+37
Sveg	ETP_w	−5	0	21	67	118	134	145	94	61	13	−6	−9		653		
	ETP_g	−4	−1	12	45	83	98	104	65	42	9	−5	−8	437	458		
	P	34	21	21	30	36	69	94	80	58	39	40	36		558	0.70	+100
Härnösand	ETP_w	−5	4	25	65	123	150	156	106	61	11	1	−9		702		
	ETP_g	−5	2	15	42	88	105	113	76	42	5	−1	−8	466	488		
	P	62	37	32	46	34	52	58	78	68	63	87	80		696	0.70	+209
Storlien	ETP_w	−4	−1	16	47	85	102	115	84	43	3	−5	−9		495		
	ETP_g	−4	0	9	30	56	72	82	62	28	0	−5	−8	330	339		
	P	74	80	72	66	55	92	106	109	113	97	76	72		1012	0.68	+673
Östersund	ETP_w	−6	4	29	65	119	139	138	98	58	16	−2	−7		666		
	ETP_g	−5	1	19	44	82	100	99	70	38	9	−3	−6	433	462		
	P	34	23	23	29	31	69	77	74	51	43	42	36		532	0.69	+70
Stensele	ETP_w	−8	−3	18	52	101	131	124	79	32	−2	−10	−10		537		
	ETP_g	−7	−4	9	34	68	93	86	50	23	−2	−9	−8	354	363		
	P	30	23	21	25	33	57	80	67	47	37	38	36		494	0.68	+131
Haparanda	ETP_w	−8	−2	16	49	110	153	156	99	35	8	−7	−10		626		
	ETP_g	−7	−2	9	31	76	109	115	69	21	3	−7	−9	421	433		
	P	40	36	24	34	30	41	54	71	65	53	58	46		552	0.69	+119
Kiruna	ETP_w	−8	−4	17	49	89	116	122	72	24	−2	−10	−12		489		
	ETP_g	−7	−4	10	31	59	81	86	49	14	−4	−9	−10	320	330		
	P	23	24	21	33	37	64	86	74	57	36	30	28		513	0.68	+183
Karesuando	ETP_w	−6	−2	16	46	82	106	120	71	26	−4	−11	−11		467		
	ETP_g	−5	−3	8	28	55	72	84	48	16	−5	−9	−9	303	311		
	P	19	18	17	19	26	46	63	57	41	26	26	22		380	0.67	+69

added to the precipitation amounts to give a true picture of the water balance. However, due to the uncertainty of how to interpret those values given for the winter months this has not been done in this study; negative values thus have been treated as zero.

In the last column of the table the ratio ETP_g/ETP_w is given. As mentioned earlier Penman has found this to be 0.7. Our calculations confirm practically exactly this value in all cases which thus is a good check of the formula used to calculate ETP_g.

Distribution of the annual potential evapotranspiration from a grass surface in Sweden is given in Fig. 5. Maximum of potential evapotranspiration from a grass surface is obtained in Gotland with 600 mm. The value given for Gothenburg (612 mm) seems to be somewhat too high as taken from the airport in Torslanda and because of its situation not representative for the conditions in the agricultural regions outside of the city. Minimum of potential evapotranspiration is found in the western parts of the south-Swedish highlands around 450 mm and in northwestern Norrland (300 mm). For southern Sweden we may also compare our values with those measured by ASLYNG (1965). The annual potential evapotranspiration obtained by him as a mean value for the period 1955–64 was 512 mm which is about 8% lower than our value for Malmö. This seems reasonable, however, in view of the fact that the period 1955–64 includes a considerable number of cold summers. Generally speaking the agreement with Aslyng's value is acceptable.

In Fig. 6 the distribution of the potential water balance is demonstrated. Practically all the Swedish land-area shows a positive balance, only Gotland, Öland and a small part of southeast Sweden has an annual deficiency of water. The negative area in Södermanland and around Lake Mälaren is somewhat doubtful as caused by a negative value in Västerås, where the potential evapotranspiration seems to be slightly

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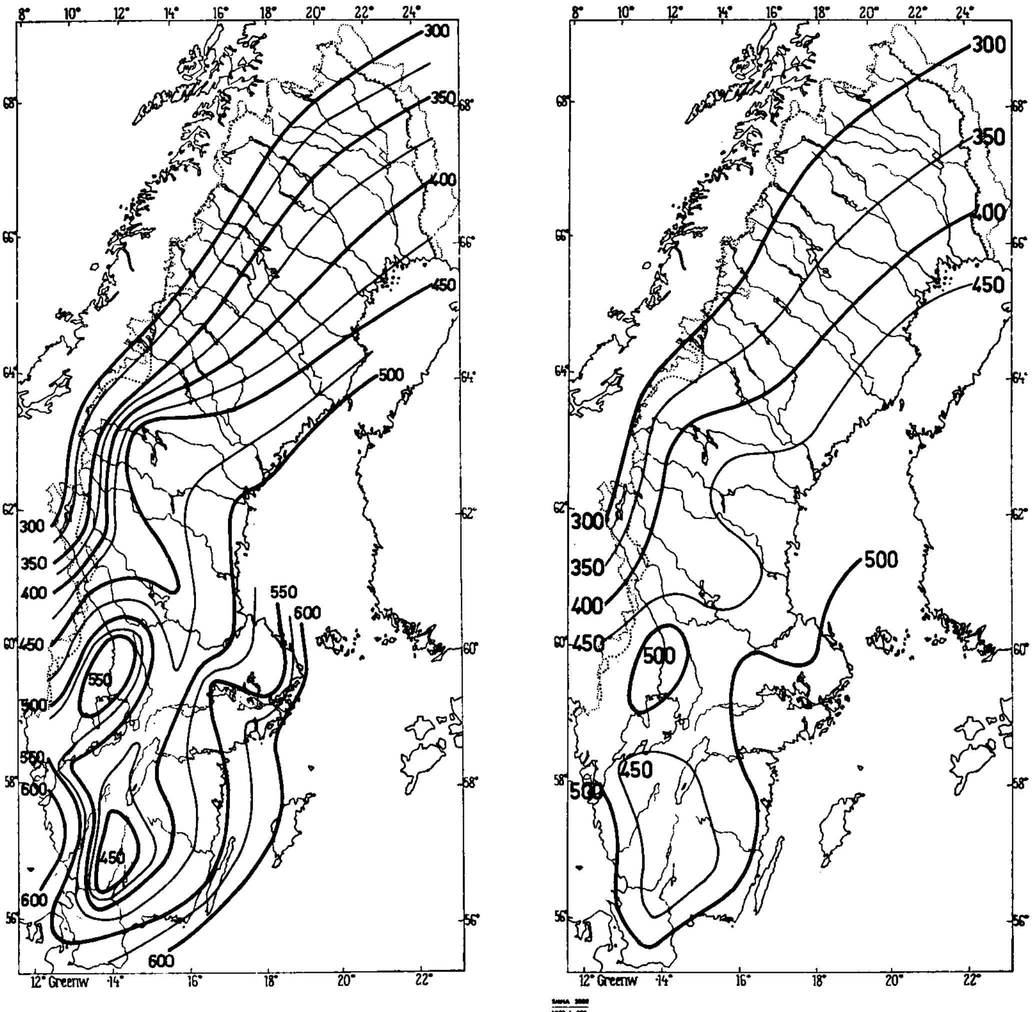

a *b*

FIG. 5*a*–*b*. Distribution of potential evapotranspiration in mm from a vegetative surface (acc. to Penman) in Sweden during the whole year (*a*) and the period April–September (*b*).

exaggerated due to a high value of wind velocity. The extremely high positive value at Härnösand seems to be due to extraordinarily high precipitation in the period 1931–60. Experience tells otherwise this picture to be approximately correct.

In order to get a true picture of the water balance which is of practical interest to agriculture and forestry it is necessary to estimate the actual evapotranspiration, ETA, from the potential. HÖGSTRÖM (1964) has during the three years 1961–63 measured the actual evapotranspiration in the Kristianstad area. He reached a mean value of 430 mm. If we compare this value with the one obtained from Fig. 5 for Kristianstad, namely 540 mm, we get a relation between ETA and ETP_g of 0.80. This seems to be a reasonable value to accept in view of many investigations carried out in other countries. ASLYNG (1965) has, for example, found 0.82 for Copenhagen. TAMM (1956) has calculated for Kristianstad an actual evapotranspiration of 439 mm which again is very close to the value given by Högström. This value renders ETA/ETP_g to be 0.81. The value of around 0.8 can, however, not be accepted to be constant for all

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the Swedish land area. Tamm, for instance, gives for Visby a value of ETA = 422 which divided with our ETP value of 600 mm gives a ratio of only 0.7. More values of the relation between Tamm's ETA value and our values of ETP are given in the following table:

	ETP (Wallén)	ETA (Tamm)	$\frac{\text{ETA}}{\text{ETP}}$
Kristianstad	540	439	0.81
Visby	600	422	0.70
Göteborg	612	445	0.73
Stockholm	553	393	0.71
Karlstad	548	393	0.72
Bjuråker	481	329	0.69
Östersund	462	291	0.63
Haparanda	433	251	0.58

The above table gives an indication of a general decrease of the relation between ETA and ETP_g with latitude, but in view of the uncertainty of the values both for ETA and ETP_g it is not acceptable to apply these values to calculate ETA from ETP_g for the whole land area at this preliminary stage.

It is also interesting to compare our results for the potential evapotranspiration with those values obtained by Nyberg (1965) for the actual evapotranspiration over south Sweden in 1957. The average potential evapotranspiration for all stations included in south Sweden (area corresponding to Nyberg's investigation) except Gothenburg which seems doubtful, is 511 mm/year. Nyberg (1965) gives for ETA for 1957 a value of 368 ± 50 mm, which related to our value gives $ETA/ETP_g = 0.72$. If we compare this value with the comparisons made above with Tamm's data we may conclude that we again reach a reasonable result.

We also wish to point out that the calculations of the ETP by Penman's formula confirm, what has been suspected for some time, that earlier estimated values of actual evapotranspiration in northern Norrland and the mountains, namely 150 mm (Bergsten 1950), are too low. Values around 250 mm seem to be more reasonable. In addition it should be pointed out that the values obtained for ETP by the Penman formula are quite reasonable as compared with the values for ETA given by Bergsten (1950) for certain catchments in other parts of the country.

From the point of view of agriculture the evapotranspiration during the vegetative season is of more practial interest than the annual

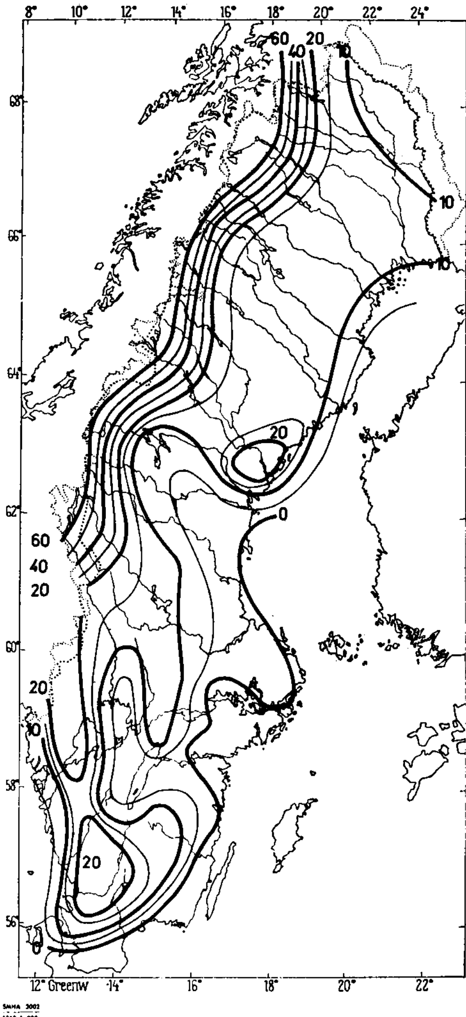

Fig. 6. Annual potential water balance in Sweden in mm calculated as the difference between annual precipitation and annual potential evapotranspiration.

values. In Fig. 5*a* the potential evapotranspiration during the period April–September is mapped.

Having confirmed the general accuracy of the annual values obtained by Penman's formula by comparisons with other measurements, we shall conclude by discussing somewhat the use of the monthly values obtained. The real advantage of the method to estimate evapotranspiration presented by Penman compared with, for instance, the hydrological method lies in the fact that monthly values are obtained

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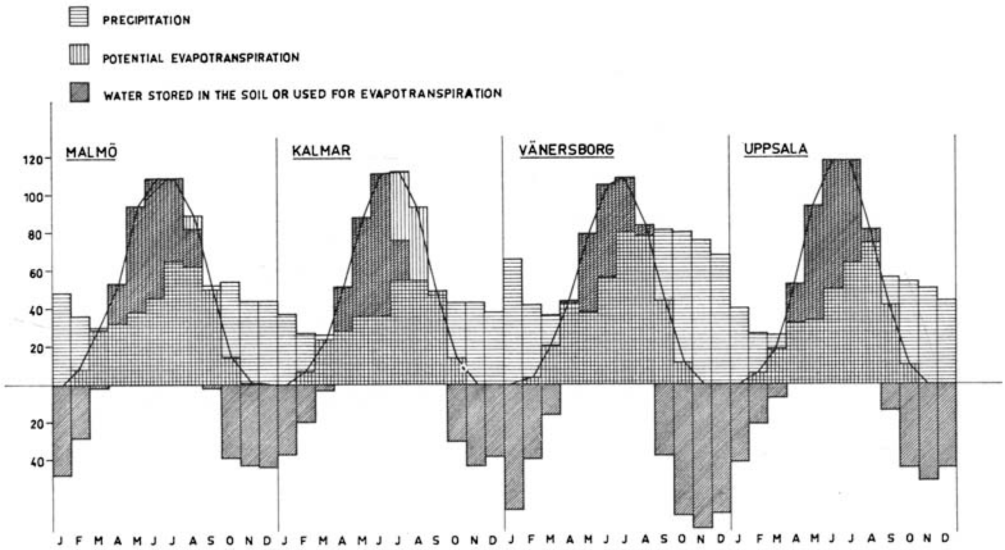

FIG. 7. Annual course of potential water balance shown as the relation between precipitation, potential evapotranspiration and water storage at selected stations in Sweden. *Malmö:* Potential water balance becomes negative in August = −7 mm. *Kalmar:* Potential water balance becomes negative in July = −77 mm. *Vänersborg:* Potential water balance positive = +250 mm. *Uppsala:* Potential water balance slightly positive = +13 mm.

making it possible to follow the annual variation of the water-balance conditions. For this purpose it may be advantageous to use a diagram of the type shown in Fig. 7.

When applied to potential evapotranspiration this diagram of course gives a very theoretical picture of the development of the water balance. In its simplest form it is based on the assumption that all precipitation received in a particular month and which is not used for evapotranspiration is stored in the ground and may be used during later months for evapotranspiration. We reach the theoretical point of water deficiency when evapotranspiration is higher than precipitation in a particular month and the amount of water earlier stored in the ground is used up. The year in this case of course should be counted as a hydrological year, i.e., begin in autumn, when precipitation starts to exceed evapotranspiration. For practically all Swedish stations there is no theoretical problem of water deficiency. Only in south-east Sweden and in Öland and Gotland the theoretical mean conditions show that in certain cases there is a definite risk of water deficiency as early as in July. In Kalmar, for instance, the theoretically stored amount of water is sufficient to balance potential evapotranspiration only until sometime around the middle of July as seen from Fig. 7. It is interesting to compare with Kalmar the typically positive water-balance conditions in south-west Sweden as indicated by Vänersborg. For more practical applications it is necessary to make further investigations of various assumptions regarding the relation between ETA and ETP_g and the annual variation of the relation. Furthermore we have to consider the true storage of water in the ground making determinations or assumptions regarding soil moisture conditions and surface run off. These problems are out of the scope of this preliminary investigation but will be taken up later.

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ПОЛНАЯ СОЛНЕЧНАЯ РАДИАЦИЯ И ПОТЕНЦИАЛЬНАЯ ЭВАПОТРАНСПИРАЦИЯ В ШВЕЦИИ

С помощью известного уравнения регрессии между ежемесячной солнечной радиацией и ежемесячными числами солнечных часов для восьми шведских станций была вычислена полная солнечная радиация при помощи величин солнечных часов для 35 шведских станций для периода 1931–60 гг. Были построены карты распределения полной солнечной радиации в Швеции для месяцев с апреля по сентябрь и годовая карта.

Затем для 27 шведских станций для периода 1931–60 гг. с помощью формулы Пенмана и с использованием полученных величин для полной солнечной радиации была рассчитана потенциальная эвапотранспирация от поверхности, покрытой травой. Были построены карты потенциальной эвапотранспирации для месяцев с апреля по сентябрь и годовая карта. Проведено сравнение с величинами действительной эвапотранспирации, полученными ранее для Швеции, и для некоторых типичных шведских станций построены диаграммы, показывающие годовой ход условий потенциального водного баланса.

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