551.573

SOME MONTHLY VALUES OF EVAPOTRANSPIRATION IN FINLAND COMPUTED FROM AEROLOGICAL DATA

by

D. Söderman and J. Wesanterä

Department of Meteorology, University of Helsinki

1. *Introduction*

The evapotranspiration is an important part of the water cycle, and the annual course of this quantity is therefore of considerable interest to both meteorologists and hydrologists. Computations of the evapotranspiration in Finland have usually been based on the hydrological water balance method or on direct measurements of the local evaporation. Investigations of this kind have been made by Sirén [6], who computed the mean monthly evapotranspiration in the Päijänne area in southern Finland for the years 1915—1935, and by Niinivaara [3], who used a somewhat modified hydrological method to determine evapotranspiration values for the years 1936—1947. A similar study has been made by the Swedish Meteorological and Hydrological Institute for the southernmost part of Sweden (Skåne). It should be stressed that the hydrological water balance method gives reliable results only if very long periods of time are considered.

On the other hand, the amounts of evaporation given by different instruments (e.g. the U. S. Weather Bureau »Class A» pan or the Popov lysimeter) do not correspond too well to the real evapotranspiration from the ground and the vegetation. This can also be said about the so called »Potential Evapotranspiration» (PET) method. This method was developed in the United States and has been used in Finland by Musto-

NEN [2], who pointed out that it gives too large values in spring and too small ones in autumn. This is due to the fact that the changes in the storage of heat in the ground are not considered.

In recent years a new method, based on the water budget of the atmosphere, has been developed. This method is in principle exact and gives the mean evapotranspiration from a relatively extensive area. The area must be bounded by a network of aerological stations, and the mean precipitation for the area must be known. This »aerological» method has earlier been used to determine the evapotranspiration in Finland by VÄISÄNEN [7] for the period August 9—16, 1959 and by NYBERG [4] for some months during the years 1956 and 1957.

The primary aim of this study was to get additional information regarding the evapotranspiration in Finland. For this purpose the aerological method was applied on the months March, June and September, 1964. This choice is based on the fact that the evaporation from land areas in middle latitudes reaches its maximum in early summer, while it is close to zero at wintertime. Thus a fairly good picture of the annual course of evapotranspiration should be attained.

In a study of the evaporation from the Baltic Sea PALMÉN and SÖDERMAN [5] obtained a value of 528 mm for the whole year if observed winds were used, while the use of geostrophic winds gave a corresponding value of 813 mm. This great difference indicates that the use of the geostrophic approximation may lead to erroneous conclusions. A comparison of this kind for a land area is of great interest as many authors (*e.g.* NYBERG, BENTON-ESTOQUE) exclusively used the geostrophic approximation, while many others (*e.g.* PALMÉN, VÄISÄNEN) used the observed wind values in their calculations of the moisture flux divergence. In the present study, where both methods have been used, we therefore have tried to analyze the reasons for the discrepancy between the methods.

2. *Computational procedure*

If we neglect the flux of water in its liquid and solid phase, the following expression can be derived for the water budget of the atmosphere (*cf.* PALMÉN-SÖDERMAN [5]):

$$E - P = \frac{1}{g} \int_0^{P_0} \frac{\partial q}{\partial t}\, dp + \frac{1}{gA} \int_0^{P_0} \oint (qv)_n \, dL dp \,. \tag{1}$$

This equation gives the difference between the mean areal evaporation (E) and precipitation (P) as the sum of the change in precipitable water (the first term on the right-hand side) and the vertically integrated moisture outflux from the area A (the last term.)

The region for the present computation is seen in Fig. 1. It is limited by the polygon formed by the following aerological stations: Sodankylä (02836), Jokioinen (02963), Sortavala (22802), Kem' Port (22522) and Kandalakša (22217). The area of this polygon is 2.47×10^5 km^2, and the length of the sides varies between 250 and 740 kilometers.

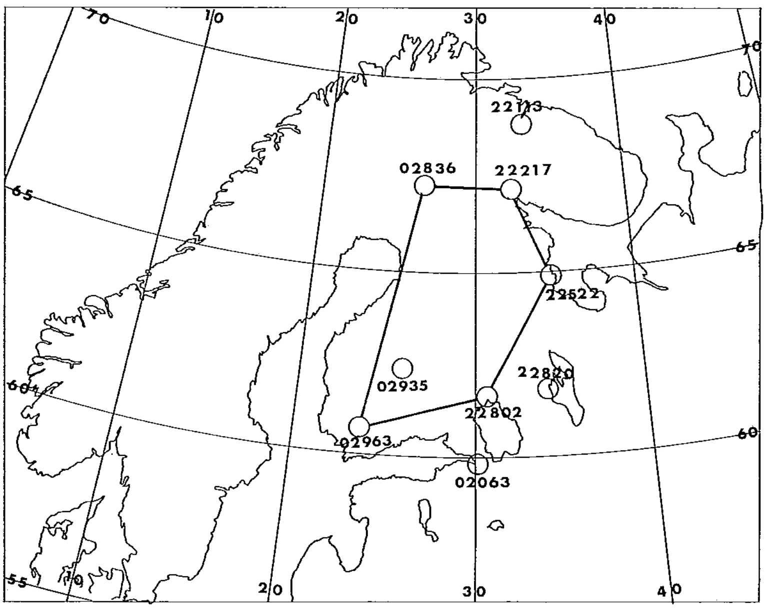

Fig. 1: The region for the computations.

For the numerical computations we made the assumptions:

a) that the mean humidity of the region can be defined as a weighted mean value of the humidity at the boundary;

b) that the wind and the humidity values vary linearly between two neighboring stations;

c) that the mean value of the ground level pressure at the five stations can be used as the lower boundary and the 400 mb surface as the upper boundary in the integration;

d) that the quantities to be integrated in Eq. (1) vary linearly between adjacent levels (the standard pressure surfaces 850, 700 and 500 millibars were used as intermediate levels);
e) that the time derivative of the humidity can be approximated as the change of humidity during the 24 hour period centered at the synoptic time in question, and
f) that the computed evaporation intensity is valid for the period starting 6 hours before and ending 6 hours after the synoptic time.

Assumptions b and d can be extremely dangerous for single synoptic situations, but the errors are of random nature and do not usually affect the computed mean evaporation for longer periods. Assumptions e and f were necessary as the aerological observations at the used stations are performed with 12 hour intervals (at midnight and noon Greenwich Mean Time), and as the available precipitation values cover the 12 hour periods ending at 6 and 18 hours GMT.

3. The computed values of evapotranspiration

The amount of precipitable water within the area during the months in question is seen as a function of time in Fig. 2. Since the changes especially in June and September are very rapid, and the corresponding changes in the moisture flux divergence probably are of the same order of magnitude, it is quite clear that it is not possible to get acceptable results for single synoptic situations. For longer periods of time, at least 5—10 days, errors of random nature are likely to cancel out and satisfactory evapotranspiration values can be achieved. We therefore have chosen to concentrate on periods of the length of 15 days.

If the moisture divergence term in Eq. (1) is denoted by D and the term representing the change in precipitable water by Q', the equation can be written:

$$E = P + Q' + D \,. \tag{2}$$

Of the quantities on the right hand side of Eq. (2) the mean areal precipitation P was determined as a weighted mean of the observed precipitation values within the area, while the terms Q' and D were computed from aerological data. These terms and the resulting evapotranspiration E for the six periods are seen in Table 1.

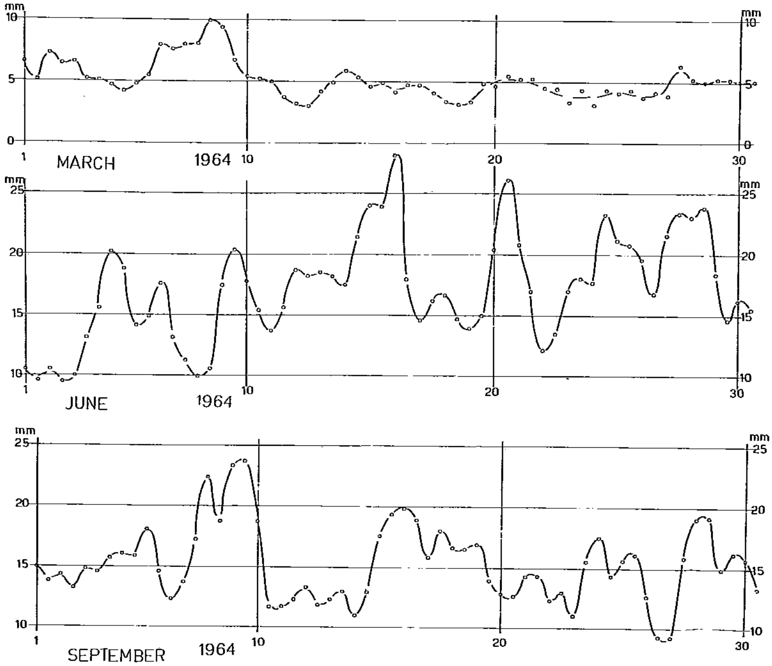

Fig. 2: The variation of the amounts of precipitable water during the months March, June and September 1964. Unit: mm

Table 1: The mean areal precipitation P, the change in precipitable water Q', the integrated moisture flux divergence D and the resulting evapotranspiration E in millimeters. Index »*o*» indicates that observed winds and index »*g*» that geostrophic winds have been used.

Period	P	Q'	D_0	D_g	E_0	E_g
March 1—15, 1964	6	-4	2	3	4	5
March 16—30, 1964	1	2	-3	-12	0	-9
June 1—15, 1964	30	15	13	8	58	53
June 16—30, 1964	16	-11	28	37	33	42
Sept. 1—15, 1964	29	2	32	19	63	50
Sept. 16—30, 1964	46	-5	-25	2	16	43

In Table 2 the computed values of the evapotranspiration in the selected region (E_0 and E_g) are compared with the following earlier estimates:

a) the evapotranspiration in southern Sweden computed by the Swedish Meteorological and Hydrological Institute (SMHI),

b)-c) the evapotranspiration in Finland determined hydrologically by Niinivaara and Sirén,
d) the potential evapotranspiration (PET) in Finland according to Mustonen, and
e) the evaporation in Finland measured with the »Class A» pan.
The first four estimates represent mean values for several years, while the pan observations were made during the actual year.

Table 2: The computed values of evapotranspiration (E_0 and E_g) compared with earlier estimates. Unit: mm.

Period	E_0	E_g	SMHI	Niinivaara	Sirén	Mustonen	Class A pan
March	4	-4	6	—	12	—	—
June	91	95	97	60	66	96	120
Sept.	79	93	50	40	22	22	29

The month of March 1964 was about 1.5 °C colder than normally, and the total precipitation during the month was only 7 mm. Thus a very small evaporation was to be expected. The computed E_0-value is therefore fully acceptable, whereas the negative E_g-value, which indicates a total net condensation of 4 millimeters of water vapor on the snow surface, probably is about 10 mm too low.

Both values for June (91 and 95 mm) seem reliable. They agree fairly well with the other estimates if it is remembered that the pan and the PET method usually give too large values in the springtime, and that the other estimates are mean values for several years.

The computed evapotranspiration values for September 1964 seem very questionable. Although especially the first half of this month was very favorable for evaporation because of a very strong insolation and a dominating westerly current with relatively dry air, there is no doubt that these values (79 and 93 mm) are too large. The synoptic situations during the period September 1—15, 1964 were therefore carefully studied, and we came to the conclusion that the linear approximation of the horizontal wind vector between adjacent stations is the main reason for the erroneous E_0-value.

We conclude, as a summary of the discussion of the results, that most of the computed values are fully acceptable. If frequent cases of unfavorable locations of frontal zones over the area occur during the period in question, errors in the mean values may be induced. These errors are primarily due to the invalidity of the horizontal linearity approximation, and are therefore correlated to the lengths of the sides of the polygon.

4. *A comparison of the results obtained with observed and geostrophic winds*

The vertical distribution of the water vapor flux divergence, computed with both observed and geostrophic winds, is seen in Fig. 3. A comparison of both sets of curves shows that the agreement is good for March 16—30 and June 16—30, fairly good for March 1—15, and bad for the remaining three periods. The great difference between the values at the surface level for all periods is explained by the invalidity of the geostrophic assumption in the lowest layer of the atmosphere.

We now focus our attention on the period September 16—30, 1964. This period, which is rather typical of the early autumn in Finland, was slightly colder than normally, and the total amount of precipitation was 46 mm. In order to make it possible to study the discrepancy between the two methods more carefully we write the last term in Eq. (1), by using Gauss' theorem, in the form

$$\frac{1}{gA}\int_0^{P_0}\oint (qv)_n \, dLdp = \frac{1}{g}\int_0^{P_0} \nabla \cdot q\boldsymbol{v} \, dp \, . \tag{3}$$

Here $\nabla \cdot q\boldsymbol{v}$ denotes the mean value of the isobaric moisture flux divergence for a fixed synoptic time over the whole area A. If a bar marks a time mean value for an extended period we can write

$$\overline{\nabla \cdot q\boldsymbol{v}} = \overline{q\nabla \cdot \boldsymbol{v}} + \overline{\boldsymbol{v} \cdot \nabla q} \, . \tag{4}$$

If we further denote the time fluctuations of q and $\nabla \cdot \boldsymbol{v}$ by q' and $\nabla \cdot \boldsymbol{v}'$, Eq. (4) can be transformed into:

$$\overline{\nabla \cdot q\boldsymbol{v}} = \bar{q}\,\overline{\nabla \cdot \boldsymbol{v}} + \overline{q'\nabla \cdot \boldsymbol{v}'} + \overline{\boldsymbol{v} \cdot \nabla q} \, . \tag{5}$$

The terms $\overline{\nabla \cdot q\boldsymbol{v}}$ and $\overline{q\nabla \cdot \boldsymbol{v}}$ in Eq. (4) were separately evaluated for the period September 16—30, 1964, or for 30 synoptic times. Hence also $\overline{\boldsymbol{v} \cdot \nabla q}$ was given as the difference between these quantities. Further the first right-hand term in Eq. (5) was computed separately. Combined with the previously evaluated terms of Eq. (4) this also determines the

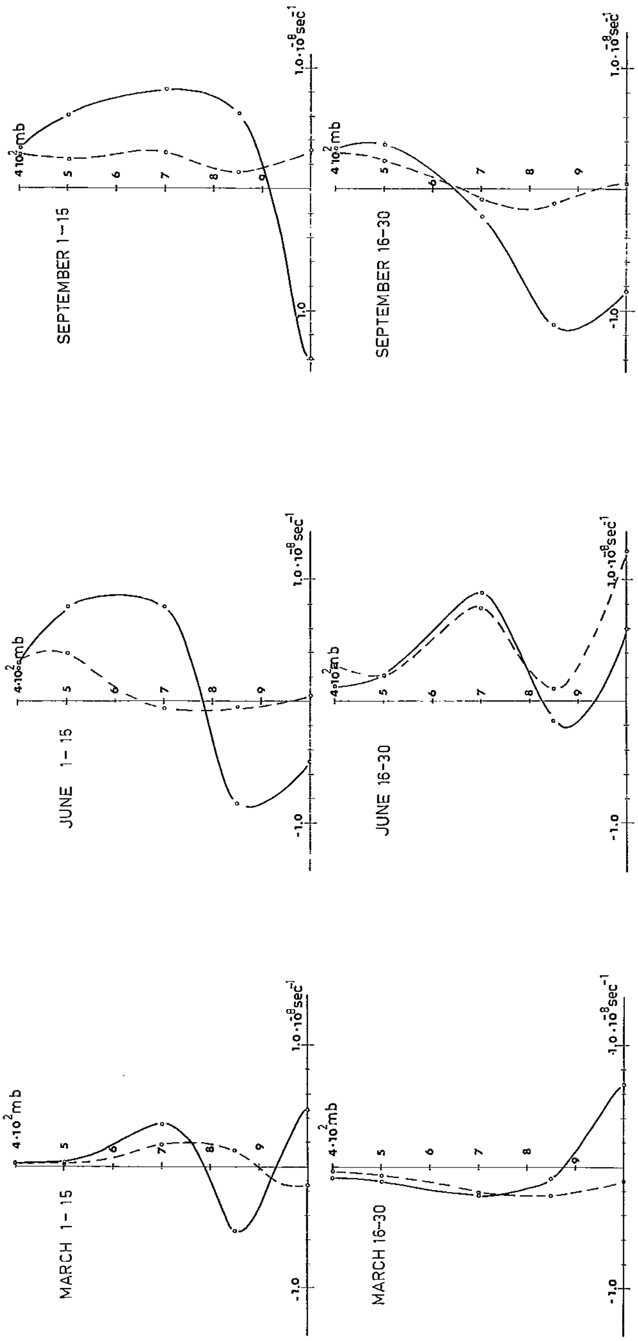

Fig. 3: The moisture flux divergence computed from observed winds (solid lines) and geostrophic winds (dashed lines). Unit: $10^{-8}sec^{-1}$.

term $\overline{q'\nabla \cdot \boldsymbol{v}'}$ in Eq. (5). The results of these computations are seen in Table 3.

Table 3. The different terms of Eq. (5) computed from observed humidity and wind values during the period September 16—30, 1964 compared with the corresponding moisture flux divergence obtained with the use of the geostrophic approximation. Unit: 10^{-8} sec^{-1}.

Level	$\overline{\nabla \cdot q\boldsymbol{v}_0}$	$\bar{q}\,\overline{\nabla \cdot \boldsymbol{v}_0}$	$\overline{q'\nabla \cdot \boldsymbol{v}'_0}$	$\overline{\boldsymbol{v}_0 \cdot \nabla q}$	$\overline{\nabla \cdot q\boldsymbol{v}_g}$
Surface	−0.84	−0.34	−0.46	−0.04	0.04
850 mb	−1.12	−0.64	0.00	−0.48	−0.11
700 mb	−0.22	0.25	−0.04	−0.43	−0.08
500 mb	0.37	0.27	0.03	0.07	0.23
400 mb	0.33	0.18	−0.07	0.22	0.30

If we neglect the presumably small errors induced by the use of a constant mean value of the Coriolis parameter at all stations, the geostrophic moisture flux divergence can be considered to be caused by advective effects only. It is therefore natural to compare this quantity with the advective term computed from the observed winds. A comparison of the two last columns of table 3 shows that the agreement generally, with the exception of the 850 mb values, is rather good.

The systematic difference between the methods is essentially determined by the two terms $\bar{q}\,\overline{\nabla \cdot \boldsymbol{v}_0}$ and $\overline{q'\nabla \cdot \boldsymbol{v}'}$. These terms are listed in the second and third columns of Table 3. The first of these terms is usually fairly well compensated in the vertical direction and approaches zero if long periods of time are considered. Therefore the second term is of the greatest interest. We note that there in this case, as presumably in all situations with dominating low level convergence and rather large precipitation values, is a high negative correlation between humidity and wind divergence. This leads to too large evapotranspiration values if the geostrophic approximation is used. It should be stressed that the above mentioned negative correlation exists even if we consider cases with low level divergence as the humidity values during such periods usually are rather low.

Thus the following conclusions can be made:

a) The geostrophic method may in cases with numerous frontal passages and an inadequate network of radiosonde stations give more reliable values than those achieved from observed winds if relatively short periods of time are considered.

b) The geostrophic method should not be used unless a more realistic approximation is introduced in the lowest layer.
c) The negative correlation between the humidity and the wind divergence in the lowest layers of the atmosphere leads to a systematic overestimation of the evapotranspiration computed with the aid of the geostrophic wind approximation.

Acknowledgments: We owe a great dept of gratitude to the late Dr. AIMO VÄISÄNEN, who initially was the leader of this project. The work has financially been sponsored by Suomen Luonnonvarain Tutkimussäätiö (The Finnish Research Foundation for Natural Resources).

REFERENCES

1. BENTON, G.S. and M.A. ESTOQUE, 1954: Water-vapor transfer over the North American continent. *J. Meteor.*, **11**, 462–477.
2. MUSTONEN, S.E., 1964: Potentiaalisen evapotranspiraation määrittämisestä. *Suomen Maataloustieteellisen Seuran Julkaisuja* 102.2 (Acta Agralia Fennica 102.2, English summary: Estimating Potential Evapotranspiration).
3. NIINIVAARA, K., 1954: Haihtumismääristä eri kuukausina. Maa- ja vesirakentaja 2. *Maa- ja vesirakennusinsinöörien vuosikirja* 1953–54. (English summary: On the amount of evaporation in the different months).
4. NYBERG, A., 1958: A determination of some monthly values of evapotranspiration in Finland and in a region in the Northeastern Atlantic. *Geophysica*, **6**, 377–387.
5. PALMÉN, E. and D. SÖDERMAN, 1966: Computation of the evaporation from the Baltic sea from the flux of water vapor in the atmosphere. *Ibid*, **8** 261–279.
6. SIRÉN, A., 1936: Niederschlag, Abfluss und Verdunstung des Päijänne- Gebiets. *V Hydrologische Konferenz der Baltischen Staaten*, Finnland, Juni 1936.
7. VÄISÄNEN, A., 1962: A computation of the evaporation over Finland during a rainless period based on the divergence of the water-vapor flux. *Geophysica*, **8**, 159–165.