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GUNNVALD BØYUM

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THE ENERGY EXCHANGE BETWEEN SEA AND ATMOSPHERE AT OCEAN WEATHER STATIONS M, I AND A

By Gunnvald Bøyum

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CONTENTS

Summary. An empirical formula giving the variation with height of the mean wind has been evaluated by means of observations from Ocean Weather Station M.

Following the general method adopted by Jacobs [5] and modified by Privett [8], monthly and annual values of the energy exchange between sea and atmosphere in the form of latent heat of evaporation, sensible heat, total energy and the Bowen ratio have been computed using observations from Ocean Weather Station M (66° N, 2° E) collected during a period of ten years. All the energy terms show a similar seasonal variation, with higher values in winter and lower in summer.

Consecutive annual values of the energy term have been examined and a considerable year-to-year variation is shown.

A certain indication of regional distribution of the energy exchange over the northern North Atlantic is obtained by comparing the energy values computed from observations collected at Stations A (62° N, 33° W), I (59° N, 19° W) and M. The results are compared with results previously obtained by Budyko [2 and 3] and Zaitzev [10] for the northern North Atlantic.

1. Introduction. It is well known that the full understanding of numerous oceanographical and meteorological processes requires information about the amounts of energy exchanged across the sea surface. This paper is concerned with some aspects of the important parts of this energy in the form of latent heat of evaporation and heat transferred from sea to atmosphere by conduction (sensible heat).

During recent years attempts have been made to portray the climatological distribution of evaporation and sensible heat exchange. Extensive investigations of this kind have been made by JACOBS [5], BUDYKO [2 and 3] and PRIVETT [8], who obtained estimates of seasonal values for the northern hemisphere, monthly values for the world's oceans, and seasonal values for the southern hemisphere, respectively.

A cursory inspection of these investigations will show that they do not agree in details. In fact it is only in the broad outlines of the distribution and in the order of magnitude for the energy processes that there is a general agreement.

In each investigation the same basic formula has been used to compute the energy transfer, but in each case with special modifications. The method of computation (see next chapter) involves the use of meteorological means of air/sea differences of humidity, temperature and wind speed, these elements being American data in JACOBS' investigations, British in PRIVETT's, whereas BUDYKO drew on a variety of sources.

As regards JACOBS' and BUDYKO's researches for instance, the transfer formulae used differ only slightly, and the discrepancies which may be considerable for many areas seem to be attributable to differences in the climatological mean values used. Since some years have elapsed between the different evaluations it is possible that the discrepancies at least partially may represent real time changes in the meteorological parametres.

A more probable cause for these discrepancies in the energy values may, however, be the different sets of data used, that may have been more or less insufficient to compute reliable climatological means for large areas of the oceans.

For certain locations this drawback has in recent years been greatly overcome by the regular data provided by the Weather-Ships Stations at which the observations are carried out every third hour throughout the day. In this paper monthly and annual values of the energy exchange have been computed by using such data collected during the decennial period from October 1948 to September 1958 at the Station M (66° N, 2° E).

After starting the work some newly published tables [7] came to my knowledge, the tables presenting climatological data from the Ocean Weather Stations in the North Atlantic over a period of ten years from 1951 to 1960.

For the purpose of acquiring a certain information about the regional variation of the energy transfer from the northern North Atlantic Ocean, the values of the energy exchanged at Ocean Weather Stations M (66° N, 2° E), I (59° N, 19° W) and A (62° N, 33° W) have been computed using data from these tables. Due to the reliability of the data from which the computations have been made, the results may to some extent serve as a check on already existing maps showing the regional distribution of evaporation and sensible heat flux from the area of the northern North Atlantic.

2. Procedure adopted.

The problem of evaporation from the oceans has usually been approached by two different methods: a) computations on the basis of available energy, and b) computations of vertical flux of water vapour.

a) During the year the oceans gain energy by short-wave radiation from the sun and sky, Q_s, and lose energy by longwave radiation to the atmosphere, Q_b, by evaporation, Q_e, and by conduction of heat to the atmosphere, Q_h. Compared with these, other sources of energy gains or losses such as conduction of heat from the interior of the earth, and energy changes related to chemical and biological processes are negligible. Under these conditions the heat budget of the ocean requires the following equation:

$$Q_s - Q_b - Q_e - Q_h = 0 \tag{1}$$

For particular parts of the sea and for short intervals of time it may also be necessary to take into consideration the heat carried by ocean currents or by mixing processes into or out of the oceanic region under consideration, and also the heat which over short periods of time causes changes in water temperature.

Introducing

$$R = \frac{Q_h}{Q_e} \tag{2}$$

and

$$E = \frac{Q_e}{L_t} \tag{3}$$

this gives

$$E = \frac{Q_s - Q_b}{L_t(1+R)} \tag{4}$$

where L_t is the latent heat of evaporation at the temperature L_t, E the evaporation expressed in centimetres of depth or in grammes per square centimetre.

The radiation surplus Q_s is determined from empirical relations. The value of the ratio, R, of vertical flux of heat to the ratio of latent heat can, as pointed out by Bowen [1], be computed from meteorological observations. Bowen's derivation leads to the formula

$$R = 0.65 \frac{t_s - t_a}{e_s - e_a} \tag{5}$$

where t_s and t_a denote the temperatures of water and air, and e_s is the saturation vapour pressure at temperatures t_s, and e_a is the actual vapour pressure in the air measured in mb.

From equation (4) the average annual evaporation between parallels of latitude has been computed by various authors. The energy equation cannot, however, render information as to seasonal and regional values of evaporation.

b) In order to approach this problem, formulae have been prepared showing the evaporation as a function of humidity and wind movement within the lower layer of the atmosphere. The basic equation from which such formulae have been derived may be written

$$E = -A\frac{dq}{dz} \tag{6}$$

where q is the specific humidity, z the altitude and A the coefficient of eddy diffusivity.

At some distance from the sea surface the eddy diffusivity and viscosity are assumed to be identical and then by indifferent stratification

$$A = \rho k_0 w_* z \tag{7}$$

where $k_0 = 0.4$ is von KARMAN's universial turbulent constant, and w_* is the "friction velocity" which can be determined from wind velocity at any level. Under stationary conditions E is constant and it follows that q must vary with the logarithm of height. MONTGOMERY [6] has therefore introduced an evaporation coefficient Γ whereby

$$E \approx \rho k_0 w_* \Gamma(q_a - q) \tag{8}$$

In this expression the evaporation coefficient is the unknown factor which has to be determined for hydrodynamically smooth and rough sea surface. According to ROSSBY the sea surface has the character of hydrodynamically smooth surface at wind velocities up to 6—7 m sec^{-1} as measured at a height of 8 m. At wind velocities exceeding 7—8 m sec^{-1} the surface appears to be hydrodynamically rough. This view is supported but also contradicted by other authors. Thus difficulties arise already at this stage.

A further difficulty arises because very close to the surface diffusivity and viscosity are not identical, and different assumptions as to the character of the diffusion close to the surface have led to widely diverging values of the evaporation coefficient.

Using vapour pressure instead of specific humidity, equation (8) may be written

$$E = K_a(e_s - e_a)V_a \tag{9}$$

where K_a is more or less complicated expression for the different theoretical models. V_a is the wind velocity.

In order to advance a step further it is, therefore, best to establish the evaporation factor K_a on a strictly empirical basis requiring that the evaporation computed from meteorological data shall agree with that obtained from energy considerations.

JACOBS followed this procedure. By applying the heat budget equation to four limited areas in the North Atlantic and North Pacific Oceans from which and to which little energy must be expected to be advected, he found when inserting American climatological data in equation (9)

$$K_a = 0.143$$

As suggested by SVERDRUP [9] the value 0.143 has no general significance because it applies to the specific data used by JACOBS and may not apply if other climatological data are used. More recently PRIVETT [8] determined a new value for the evaporation factor using data from British selected ships. The method employed was similar to JACOBS' and the same four areas were used. He found

$$K_a = 0.114$$

As shown by HAY [4] the agreement between the meteorological observations from the Weather-Ships Station J (52°30′ N, 20° W) and those from British selected ships in the same locality is good. It may be expected that the observations taken on board the different Weather-Ships are fairly homogeneous and the PRIVETT formula

$$E = 0.114(e_s - e_a)V_a \text{ mm day}^{-1} \tag{10}$$

has been adopted for computation of the evaporation at the Weather-Ship Stations M, I and A. The results have also been converted into their energy equivalents by using the relation

$$Q_e = \frac{EL_t}{10} \text{ g cal cm}^{-2} \text{ day}^{-1} \tag{11}$$

where L_t is the latent heat of evaporation at temperature t. The sensible heat lost to the atmosphere through turbulent heat exchange has been computed from

$$Q_h = RQ_e = 0.65 \frac{t_s - t_a}{e_s - e_a} Q_e \text{ g cal cm}^{-2} \text{ day}^{-1} \tag{12}$$

3. Height correction of wind speed. The PRIVETT formula provides the application of the mean wind speed at a standard height of 10 metres above sea level. During most of the period from October 1948 to September 1958 Station M has been served by two Norwegian vessels recording the wind speed at 10 metres above sea level, but during July—December 1954 and 1956 and July—October 1958 Station M has been occupied by two Dutch vessels which record the wind speed at 25 metres above sea level. Thus, a reduction of the mean wind data from the Dutch vessels is needed before using them in the computations.

A simple correction formula may be established on empirical basis by comparing the wind data collected by the two sets of Weather Ships. For this purpose the July—December wind data from the period 1949 to 1964 have been used except the July—December values from 1961 and 1963, which have been omitted because of a change in recording height on board one of the Norwegian vessels. Then in all 48 months of observations (from the years 49, 50, 51, 52, 53, 55, 57 and 59) made at the height of 10 metres and 36 months of observations (from the years 54, 56, 58, 60, 62 and 64) taken at 25 metres above sea level have been available. The mean wind determined from the data collected at the 10 and 25 metres amounts to 8.5 and 9.4 m/sec respectively.

The t-criterion for testing the difference of two means is given by

$$t = \frac{(\bar{x} - \bar{y}) - (m_x - m_y)}{\sqrt{n_x s_x^2 + n_y S_y^2}} \sqrt{\frac{n_x n_y (n_x + n_y - 2)}{n_x + n_y}} \tag{13}$$

where n_x (36) and n_y (48) are the sizes of random samples taken from normal populations with same variances σ^2 with means m_x and m_y. The symbols $\bar{x}$ (9.4) and $\bar{y}$ (8.5), S_x^2 (4.04) and S_y^2 (4.24) denote the sample means and variances. Introducing the values in the parenthesis and assuming $m_x = m_y$ one obtains

$$t = 1.95$$

This corresponds to a probability value of 0.051 which differs imperceptibly from the probability of 0.05 being used as the critical region for testing hypothesis. Although a more extensive material might be desirable the above test may indicate that there is a true difference between the two sets of wind data, which seems reasonable to interprete as attributed to the different recording heights.

A further indication that the difference of 0.9 m sec^{-1} between the means of the two sets of data may be due to a different recording height is the fact that when arranging the January—June wind data in the same manner as the July—December values, the two means obtained were equal, amounting to 9.6 m sec^{-1}. In this case both sets of the 48 and 36 months of observations have been collected from the same level of 10 metres by the Norwegian vessels.

The difference of 0.9 m sec^{-1} should only be used as a correction of mean wind velocities near 9.4 m sec^{-1}.

A formula which takes into account the wind velocity may be obtained by correlating the monthly values of wind speed measured by the Dutch vessels to corresponding differences between the two sets of wind data. Assuming as a first approximation the variation of the wind velocity between 10 and 25 metres height to be linear, the relation obtained may be written:

$$\Delta V = 6.3 \cdot 10^{-3} \cdot V_z (z - 10) \text{ m sec}^{-1} \tag{14}$$

where ΔV denotes wind correction and V_z is the wind speed at the altitude z.

This formula has been used for reducing monthly means of wind velocities observed by the Dutch vessels ($z = 25$) at Station M.

The formula should strictly speaking not be employed to data from other regions. The stability in the lower layer of the air which effects the wind profile is only implicitly given in the formula, and the stability condition may differ from location to location. It is assumed, however, that the formula may give approximate estimates of the wind variation with height within the area of the northern North-Atlantic and will also be used to data from Stations A and I, at which the wind speed mostly is recorded at a height of 18 metres above sea level.

4. Computation of the evaporation and sensible heat exchange. By means of equations 11 and 12 mean values of Q_e, Q_h and Q_a were computed for each month of the period from October 1948 to September 1958. These values are presented graphically in Fig. 1. The annual variation of the same quantities are illustrated in Fig. 2.

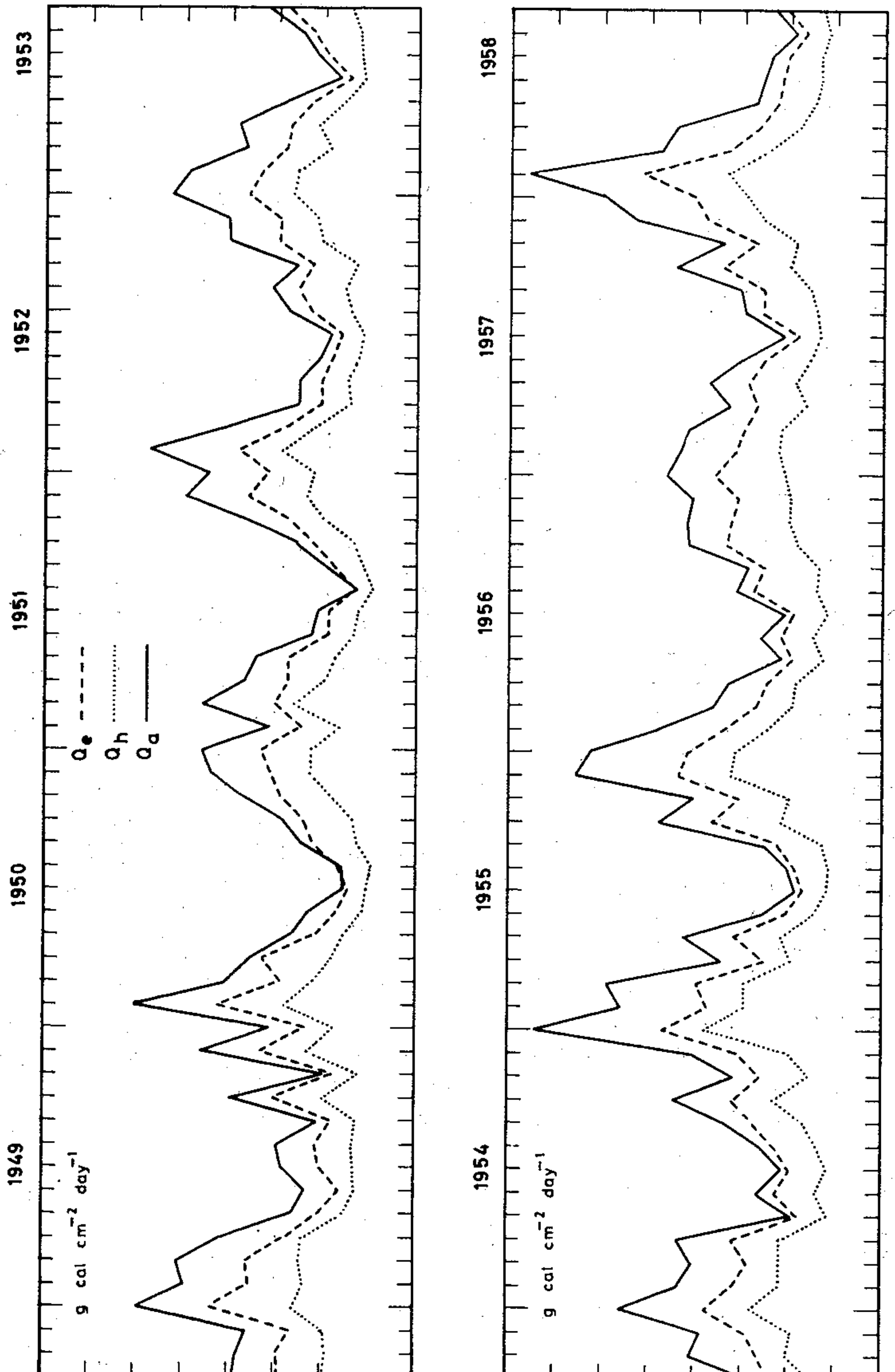

Fig. 1. Variation of monthly values of latent heat of evaporation Q_e, sensible heat Q_h and total heat Q_a at Ocean Weather Station M over the period October 1948 to September 1958.

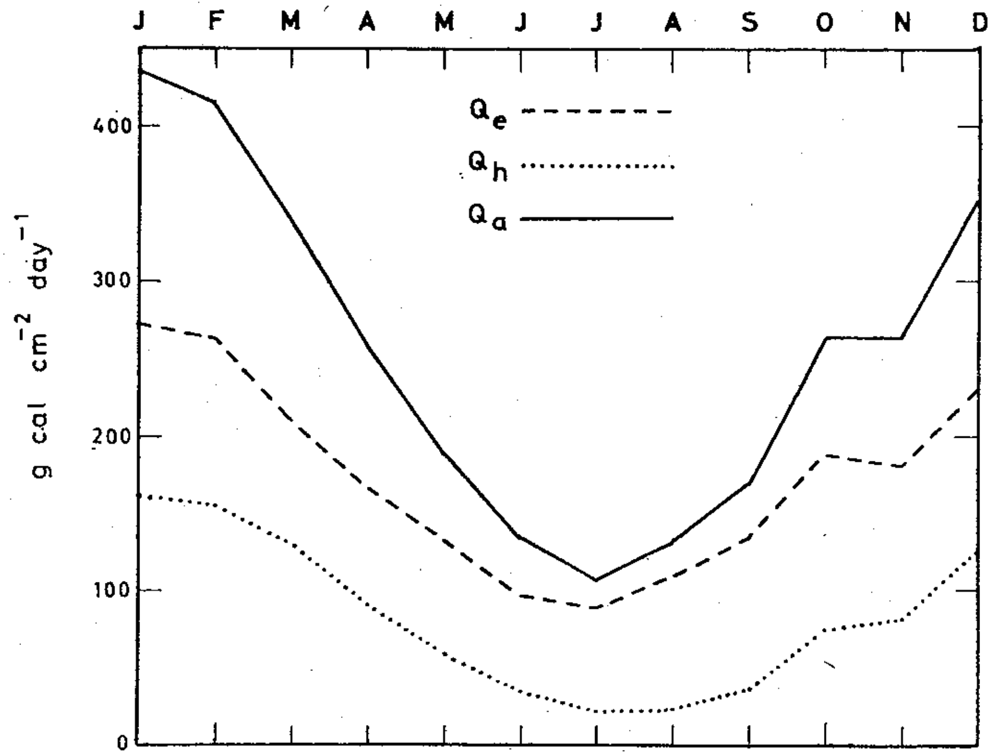

Fig. 2. Variation of mean monthly values of evaporation Q_e, sensible heat Q_h and total heat Q_a at Ocean Weather Station M (mean values for the period October 1948—September 1958).

a) *Energy used for evaporation* (Q_e).

As shown by the curve in Fig. 1 the water vapour transport is always from the sea surface to the atmosphere. A marked systematic annual variation of the evaporation is indicated, the greatest evaporation occurring in winter and the least in summer. The extreme monthly values were 419 g cal cm^{-2} day^{-1} in February 1958 and 33 g cal cm^{-2} day^{-1} in August 1951, corresponding to evaporation heights of 7.1 mm day^{-1} and 0.6 mm day^{-1}, respectively.

With the exception of a small irregularity in October, the mean monthly values of evaporation, as shown by Fig. 2, fall along a fairly smooth and regular curve.

The range of variation of the evaporation is between 84 g cal cm^{-2} day^{-1} in July and 271 g cal cm^{-2} day^{-1} in January. The corresponding heights of evaporation are 1.5 mm day^{-1} and 4.6 mm day^{-1}, that is, the evaporation in January is about three times that in July. The average annual amount of latent heat conveyed to the atmosphere is 60 900 g cal cm^{-2} which is equivalent to an evaporation height of 1030 mm year^{-1}.

An estimation of the magnitude of the evaporation at Station M may be made by comparing it with some of the results obtained by Budyko [3] and Jacobs [5]. Budyko's average annual value for the latitude range 60°—70° N, for instance, amounts to 550 mm year^{-1}. Jacobs' computations involve the areas to 60° N, and for the latitude range 50°—60° N there is a close agreement between Jacobs' and Budyko's values, amounting to about 650 mm year^{-1}. On the whole, for the latitude ranges north of 40° N, the average latitude evaporation values presented by the two investigators are lower than the evaporation value of 1030 mm year^{-1} obtained for the location of station M.

It ought to be emphasized that the value of the evaporation factor (equation 9) used by Budyko and Jacobs is respectively 20 and 25 per cent higher than in the Privett formula used in this investigation.

The above comparison suggests that the evaporation from the area of station M may be considerably higher than that from other northern ocean areas. (A more detailed comparison with Budyko's investigations will follow later).

Intensive evaporation may be expected from the location of Station M as a natural consequence of the special conditions prevailing in and around the Norwegian Sea. Station M is situated in the warm Norwegian Atlantic Current, flanked by extremely cold water masses to the west, and for a great part of the year by cold water masses to the east. Air masses originating from the cold ocean areas or from the snow- and ice-covered land surfaces surrounding the Norwegian Sea are characterized by low temperature and thus by low humidity content. These air masses, when reaching the warm water in the region of Station M will give rise to large values of the vapour pressure difference between sea and air; this in its turn favouring great evaporation.

b) *Sensible heat exchange between sea and atmosphere* (Q_h). The curve illustrating the monthly variation of the sensible heat exchange (Fig. 1) shows roughly the same course as shown for Q_e. The heat flux is positive except for the months of August 1950 and 1951, when a slight transfer of heat from the air to the sea occurs. The extreme values are 276 g cal cm^{-2} day^{-1} in January 1955 and —6 g cal cm^{-2} day^{-1} in August 1950. The maximum and minimum of the monthly mean values occur in January and July, amounting to 161 g cal cm^{-2} day^{-1} and 21 g cal cm^{-2} day^{-1}, respectively.

The annual value of the sensible heat flux amounts to 37000 g cal cm^{-2}. The Budyko average value for the latitude range 60°—70° N amounts to 16000 g cal cm^{-2} year^{-1}, which may indicate that from the region of Station M a rather intense heating of the air-masses takes place.

c) *Total energy exchanged between sea and atmosphere* (Q_a). The curve showing the total energy exchange Q_a, is of course in general configuration similar to the curves of Q_e and Q_h. The extreme monthly values were 657 g cal cm^{-2} day^{-1} in February 1958 and 28 g cal cm^{-2} day^{-1} in August 1951. The average monthly values range between 105 g cal cm^{-2} day^{-1} in July to 432 g cal cm^{-2} day^{-1} in January.

5. Year-to-year variations. In Fig. 3 are plotted consecutive annual mean values from 1948 to 1958 of each of the terms Q_e, Q_h and Q_a. The annual means have been computed from Tables 8, 9 and 10 over the year running from October to September.

As illustrated by the curves the different energy terms show quite appreciable changes

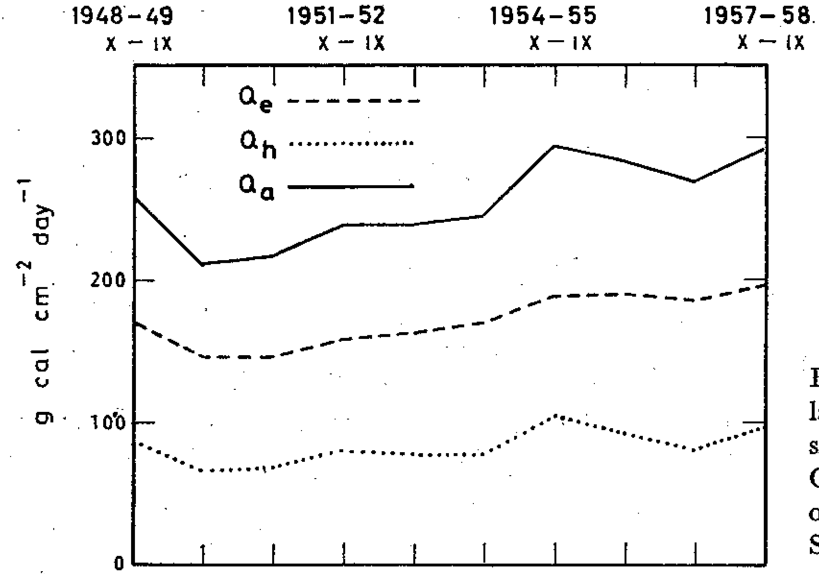

Fig. 3. Year to year variations of latent heat of evaporation Q_e, sensible heat Q_h and total heat Q_a at Ocean Weather Station M throughout the period October 1948 to September 1958.

throughout the period considered. The lowest evaporation, amounting to 147 g cal cm^{-2} day^{-1}, appears in the year October—September 1950—51. From this year on the evaporation increases gradually until the year 1954—55, whereafter a comparatively steady high rate of evaporation is found. The greatest evaporation occurs in the year 1957—58, and is computed to be 195 g cal cm^{-2} day^{-1}. The corresponding minimum and maximum values expressed in terms of evaporation heights are 2.5 and 3.3 mm day^{-1} respectively.

The mean annual variation of the sensible heat throughout the period is more irregular than that of evaporation, but on the whole the greatest heat flux occurs in the last part of the period. The annual values range between 66 g cal cm^{-2} day^{-1} in 1949—50 and 103 g cal cm^{-2} day^{-1} in 1954—55.

The total heat exchanged is at a minimum in 1949—50, amounting to 213 g cal cm^{-2} day^{-1}. In the following years the total energy exchanged increases somewhat irregularly and reaches its maximum value of 294 g cal cm^{-2} day^{-1} in 1954—55.

6. Variations in the Bowen ratio. In Fig. 4 the ratio R between mean monthly values of sensible heat and latent heat of evaporation is plotted.

The data presented show that the ratio R is a highly variable quantity. It is greatest in winter with a maximum value of 0.62 in March, and a minimum of 0.22 in August. This means that in March 38 per cent of the total energy exchanged is conveyed to the atmosphere as sensible heat, whereas in August only 18 per cent is used for direct heating of the air. The annual value of R is 0.48 which indicates a considerable northward increase of the ratio from the area of 55° N, where the value obtained by JACOBS amounts to 0.25.

Individual monthly values of the BOWEN ratio will of course vary over a wider range. Extreme values were 0.80 in April 1944 and —0.08 in August 1950.

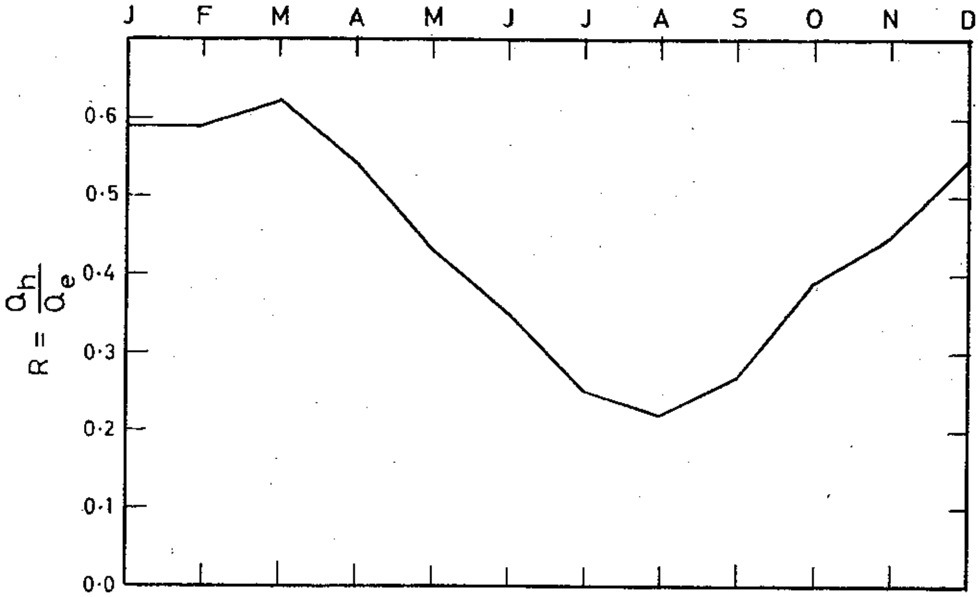

Fig. 4. Variation of the ratio R between mean monthly values of sensible heat Q_h and latent heat of evaporation Q_e at Ocean Weather Station M. (Q_h and Q_e are mean values for the period October 1948—September 1958).

7. A comparison of the energy exchanged at the Stations A, I and M. Certain information about the regional variation of mean monthly and annual values of the energy exchanged between sea and atmosphere over the northern north Atlantic may be obtained by comparing the energy values computed from observations collected at Stations M (66° N, 2° E), I (59° N, 19 °W) and A (62° N, 33° W). The data used for these computations have been taken from climatological tables [7] prepared from observations collected over the decennial period 1951—60. Accurate humidity values cannot be obtained from these climatological data as the differences $e_s - e_a$ must be established from means of surface and air temperatures and relative humidity. By using data from Station M a comparison between the mean humidity differences computed from single values of $e_s - e_a$ and those obtained from mean values of temperatures and relative humidity shows, however, that the errors introduced by following this procedure will be negligible.

In Fig. 5 are presented the mean monthly variations of latent heat of evaporation (the three uppermost curves) and the sensible heat flux (the three lowest curves) at Stations A, I and M.

These curves show all the same general configuration, the greatest energy exchange occurs in winter and the least in summer at all Stations. In all months of the year the evaporation at the location of Station I is appreciably higher than the evaporation at Stations M and A. From January to June the evaporation is greater at Station M than at Station A, while from July to December the evaporation differs only slightly at the two Stations.

The most marked differences in the heat flux at the three Stations occur in the period

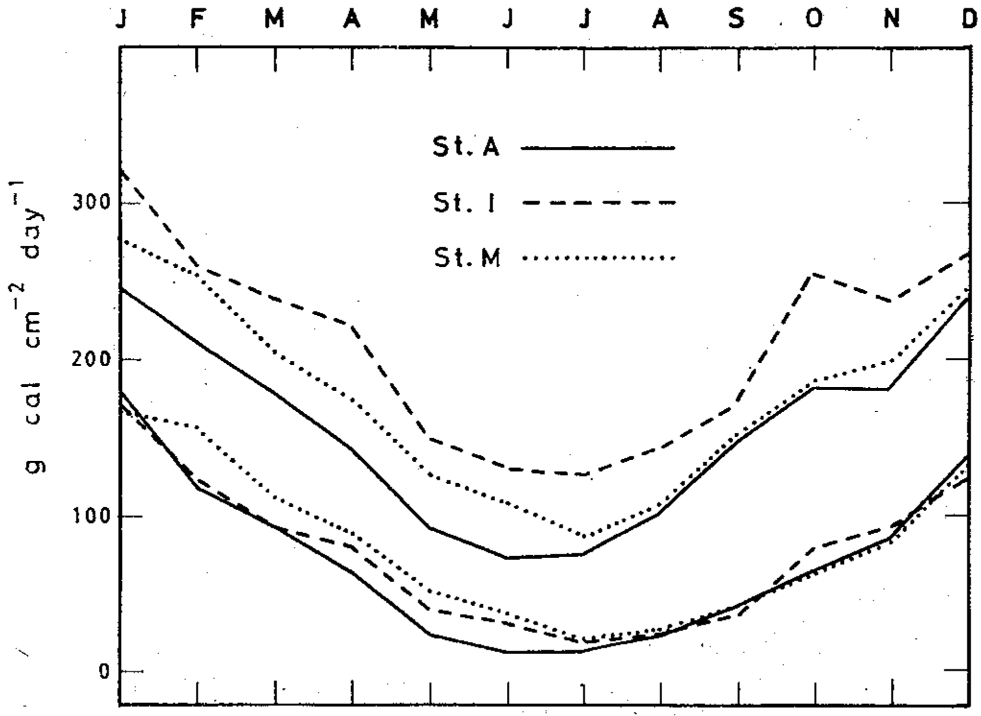

Fig. 5. Variation of mean monthly values of evaporation Q_e (the three upper curves) and sensible heat Q_h (the three lower curves) at Ocean Weather Stations M, I and A., (mean values for the period 1951—1960).

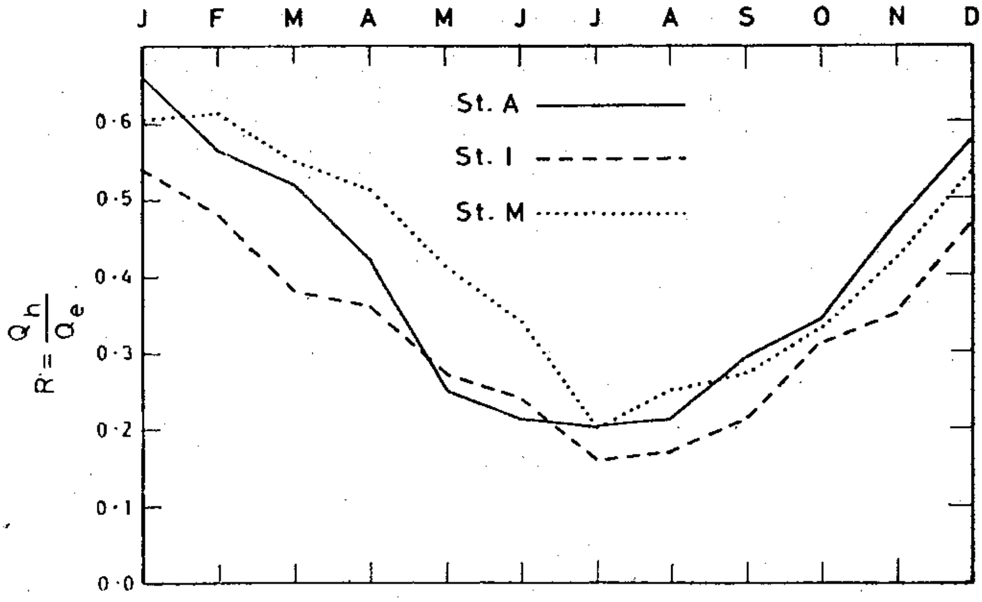

Fig. 6. Variation of the ratio R between mean monthly values of sensible heat Q_h and latent heat of evaporation Q_e at Ocean Weather Stations M, I and A. (Q_h and Q_e are mean values for the period 1951—1960).

February to June with greatest heating at Station M. From July to January the curves follow more or less the same trace indicating that in this period the regional variation of the heat flux may be small over large areas of the northern North-Atlantic.

In Fig. 6 are illustrated the variations of monthly values of the ratio (the Bowen ratio) between sensible and latent heat of evaporation. The ratio is highly variable throughout the year with highest values in winter and lowest in summer at all three Stations. That is, in winter a greater part of the total energy transferred to the atmosphere is in the form of sensible heat than it is in summer.

The curves clearly demonstrate the regional variations of the ratio, the regional differences being most pronounced in winter, spring and early summer. With the exception of the months of May and June, when the ratio at Station I is slightly higher than at Station A, a relatively smaller proportion of the total energy is transferred to the atmosphere as sensible heat at Station I than at the two more northerly Stations A and M.

In Table 1 are given the annual mean values of latent heat of evaporation, sensible heat, the BOWEN ratio, and evaporation in millimetres at the Stations A, I and M. In the same Table are shown corresponding values for the same positions from previous investigations. These are interpolated values from the BUDYKO maps [2] from 1955, the revised BUDYKO maps [3] from 1963 and the ZAITZEV map [10] of evaporation from 1961.

Table 1. *Mean annual values of evaporation, sensible heat and the ratio between sensible heat and latent heat of evaporation at Ocean Weather Stations M, I and A, with Budyko's and Zaitzev's values for comparison.*

		Q_e kcal cm^{-2} year^{-1}	Q_h kcal cm^{-2} year^{-1}	$R = \frac{Q_h}{Q_e}$	E mm year^{-1}
Weather Ships Values	St. A	56.8	25.4	0.45	970
	St. I	77.4	28.2	0.36	1320
	St. M	64.4	29.4	0.46	1080
Budyko's values from 1956	St. A	52	52	1.00	880
	St. I	50	37	0.74	850
	St. M	30	25	0.83	500
Budyko's values from 1963	St. A	50	22	0.44	840
	St. I	64	25	0.39	1090
	St. M	57	25	0.44	960
Zaitzev's values	St. A	29.5			500
	St. I	34.5			570
	St. M	42.0			710

As already indicated by the curves in Fig. 5 the greatest quantity of water vapour is supplied to the atmosphere at the location of Station I, whereas the heat transfer is greatest at Station M. The annual values of evaporation, as well as of sensible heat flux are least at Station A.

Striking disagreements between the Weather Ships values and the BUDYKO values from 1956 are shown in Table 1. These discrepancies relate both to the absolute values and the regional variation of the energy terms. In the revised Atlas of energy transfer from 1963 BUDYKO has drawn on the additional material of observations made available from the researches in the International Geophysical Year. Although the results obtained by BUDYKO in 1963 and those arrived at from the Weather Ships data show common features, certain deviations between the two sets of energy values may be pointed out.

The mean annual evaporation computed from the Weather Ships data is about 15 or 20 per cent higher than the interpolated values from BUDYKO's maps. The same percentage of deviations appears when comparing the two sets of sensible heat values. Here again it is appropriate to remind of the lower values of the leading coefficients in the transfer formulae for evaporation and heat flux used in this investigation.

The agreement between the two sets of the BOWEN ratio is good, and especially the agreement between the values from Station M and A is convincing.

As for the Weather Ships values BUDYKO found the greatest evaporation at the position of Station I and the smallest at Station A. The relative regional distribution of the annual sensible heat values seems also to be in good agreement.

As the isolines may be more or less spread, accurate interpolated values cannot be taken out from most of BUDYKO's monthly maps of energy exchange. However, a qualitative comparison between the sets of evaporation values, for instance, suggests, that in contrast to the annual distribution there are distinct differences as regards the regional distribution of the monthly evaporation values.

From February to May the BUDYKO maps indicate a slightly higher evaporation at Station M than at Station I. In January, June, July and September the evaporation seems to be nearly equal at the two Stations, whereas in the other months of the year the evaporation is considerably higher at Station M. This correlation between the monthly evaporation values for Station I and M is clearly contradicted by the Weather Ships values which show a markedly higher evaporation at Station I than at Station M throughout the year.

Except for December BUDYKO's maps show a lower evaporation at station A than at Station M, this being in accordance with the pattern shown by the Weather Ships values.

The annual evaporation values obtained by ZAITZEV [10] and those computed from the Weather Ships show a marked inconsistence. When computing the sensible heat flux, ZAITZEV obtained a value of 0.80 for the BOWEN ratio as a mean for the northern North Atlantic. This result is not supported by the Weather Ships values shown in Table 1., which only amount to about half of that obtained by ZAITZEV.

Acknowledgement. My most sincere thanks are due to Professor MOSBY for helpful comments and remarks during the preparation of this paper.

TABLES OF OBSERVED MEAN VALUES AND THE ENERGY EXCHANGE

Table 2. *Air temperatures.*

	J	F	M	A	M	J	J	A	S	O	N	D
1948......										6.1	5.1	5.4
1949......	4.0	4.2	3.6	3.3	5.4	7.7	9.6	9.8	10.0	6.8	7.4	4.4
1950......	4.6	3.3	3.5	4.9	5.6	8.4	10.8	13.1	10.6	8.4	5.7	3.3
1951......	3.8	4.1	2.5	3.1	5.4	6.7	9.5	10.8	10.1	8.5	4.6	4.3
1952......	3.0	2.5	3.0	5.3	6.0	7.7	9.4	9.6	7.8	7.5	4.8	3.8
1953......	2.9	2.6	4.4	3.1	5.4	9.0	12.0	12.7	10.5	8.9	6.3	5.9
1954......	3.6	4.5	3.5	4.4	7.7	8.1	10.8	11.2	9.1	6.5	6.2	4.8
1955......	1.6	2.4	2.6	3.4	4.3	6.9	9.9	11.0	10.5	6.4	5.8	2.4
1956......	2.9	2.5	4.3	3.6	6.6	6.8	10.0	10.6	9.5	7.4	5.9	4.9
1957......	4.8	3.3	3.7	5.4	5.2	7.2	9.3	10.3	9.5	7.2	5.9	4.1
1958......	2.9	1.6	2.2	4.6	5.4	6.9	9.8	11.0	10.8			
Mean.....	3.4	3.1	3.3	4.1	5.7	7.5	10.1	11.0	9.8	7.4	5.8	4.3

Table 3. *Sea-surface temperatures.*

	J	F	M	A	M	J	J	A	S	O	N	D
1948......										8.2	6.8	7.0
1949......	6.6	6.5	6.2	6.3	6.7	8.6	10.5	10.7	10.8	9.0	8.1	7.4
1950......	6.7	6.7	6.5	7.0	7.8	8.9	11.1	12.9	11.5	9.3	8.2	6.7
1951......	6.8	6.0	6.4	5.6	7.1	8.2	10.3	10.6	10.5	9.3	7.5	7.0
1952......	6.1	6.5	5.6	6.6	7.8	8.7	10.1	11.0	9.5	8.5	7.7	6.6
1953......	6.7	6.0	6.1	6.0	7.1	9.7	12.7	13.5	11.5	9.3	8.2	7.5
1954......	7.0	6.7	6.5	6.9	8.1	9.4	11.4	12.6	10.9	8.8	7.4	7.1
1955......	6.5	6.5	6.4	5.8	7.0	8.3	10.4	11.3	11.1	9.0	7.8	6.6
1956......	7.0	6.2	6.4	6.1	7.2	8.2	10.5	12.0	10.4	8.9	7.7	7.2
1957......	6.5	6.1	6.2	6.7	6.4	8.6	10.4	11.4	10.9	9.0	7.7	7.2
1958......	6.5	6.1	5.9	6.4	6.6	8.0	11.2	11.7	11.6			
Mean.....	6.6	6.3	6.2	6.3	7.3	8.7	10.7	11.8	10.9	8.9	7.7	7.0

Table 4. *Water vapour pressure differences in mb.*

	J	F	M	A	M	J	J	A	S	O	N	D
1948......										2.79	2.33	1.83
1949......	3.58	2.70	2.98	2.44	1.67	1.37	2.07	2.01	1.42	2.99	1.65	3.60
1950......	2.48	4.00	3.08	3.06	3.11	1.56	1.52	1.45	3.00	2.46	3.64	3.63
1951......	3.68	2.77	3.25	2.93	2.63	2.57	2.21	0.83	1.65	2.09	3.28	3.33
1952......	3.46	3.91	2.40	1.96	2.58	1.93	1.55	2.66	2.97	2.59	3.68	3.25
1953......	3.98	3.31	2.32	2.93	2.25	1.36	2.00	2.96	2.82	2.00	2.62	2.24
1954......	3.48	2.76	3.17	3.04	1.59	2.75	2.27	3.02	3.09	3.62	2.30	3.27
1955......	4.21	3.84	3.81	2.55	3.33	2.37	1.48	1.65	2.03	3.84	2.69	4.15
1956......	3.93	3.93	2.64	2.99	1.40	2.23	2.20	3.90	2.77	3.02	2.69	3.27
1957......	2.74	4.27	2.75	2.29	3.26	2.65	1.79	3.05	2.63	2.96	2.43	3.71
1958......	3.72	5.20	3.90	2.43	1.99	2.29	2.52	1.71	2.08			
Mean.....	3.53	3.57	3.03	2.66	2.38	2.11	1.96	2.32	2.45	2.84	2.73	3.23

Table 5. *Temperature difference between sea and air.*

	J	F	M	A	M	J	J	A	S	O	N	D
1948......										2.1	1.7	1.6
1949......	2.6	2.3	2.6	3.0	1.3	0.9	0.9	0.9	0.8	2.2	0.7	3.0
1950......	2.1	3.4	3.0	2.1	2.2	0.5	0.3	− 0.2	0.9	0.9	2.5	3.4
1951......	3.0	1.9	3.9	2.5	1.7	1.5	0.8	− 0.2	0.4	0.8	2.9	2.7
1952......	3.1	4.0	2.6	1.3	1.8	1.0	0.7	1.4	1.7	1.0	2.9	2.8
1953......	3.8	3.4	1.7	2.9	1.7	0.7	0.7	0.8	1.0	0.4	1.9	2.6
1954......	3.4	2.2	3.0	2.5	0.4	1.3	0.6	1.4	1.8	2.3	1.2	2.3
1955......	4.9	4.1	3.8	2.4	2.7	1.4	0.5	0.3	0.6	2.6	2.0	4.2
1956......	4.1	3.7	2.2	2.5	0.6	1.4	0.5	1.4	0.9	1.5	1.8	2.3
1957......	1.7	2.8	2.5	1.3	2.2	1.4	1.1	1.1	1.4	1.8	1.8	3.1
1958......	3.6	4.5	3.7	1.8	1.2	1.1	1.4	0.7	0.8			
Mean.....	3.2	3.2	2.9	2.2	1.6	1.1	0.8	0.8	1.0	1.6	1.9	2.8

Table 6. *Wind force in m sec*$^{-1}$.

	J	F	M	A	M	J	J	A	S	O	N	D
1948......										10.3	12.1	13.1
1949......	13.9	13.9	12.9	10.6	9.5	6.7	7.6	8.3	8.4	10.1	6.8	9.7
1950......	8.2	12.0	9.1	8.7	5.4	6.7	4.6	6.8	6.1	8.8	7.7	8.6
1951......	9.3	7.8	9.2	8.8	5.6	5.2	6.0	5.9	7.2	9.0	7.9	11.6
1952......	9.4	10.9	11.0	8.2	6.2	6.5	6.1	7.2	7.7	7.1	8.0	9.0
1953......	9.8	10.5	11.6	8.9	8.0	5.3	6.8	6.1	9.5	10.2	11.8	12.3
1954......	11.8	11.8	8.7	10.5	7.1	6.7	6.9	6.6	9.2	9.7	11.3	10.3
1955......	12.9	10.6	11.5	8.7	9.4	6.8	6.9	7.8	8.9	10.1	11.3	11.9
1956......	11.7	8.8	9.4	7.3	9.6	7.5	6.6	7.2	9.1	12.7	13.4	10.4
1957......	13.8	9.7	10.7	10.8	8.5	8.4	6.5	7.7	8.6	12.2	10.4	11.0
1958......	12.1	11.9	8.7	9.9	9.2	7.7	6.8	6.6	8.5			
Means ...	11.3	10.8	10.3	9.2	7.9	6.8	6.5	7.0	8.3	10.0	10.1	10.8

Table 7. *Evaporation in mm day*$^{-1}$.

	J	F	M	A	M	J	J	A	S	O	N	D
1948......										3.3	3.2	2.7
1949......	5.7	4.3	4.4	3.0	1.8	1.1	1.8	1.9	1.4	3.4	1.3	4.0
1950......	2.3	5.5	3.2	3.0	1.9	1.2	0.8	1.1	2.1	2.5	3.2	3.6
1951......	3.9	2.5	3.4	2.9	1.7	1.5	1.5	0.6	1.4	2.1	3.0	4.4
1952......	3.7	4.9	3.0	1.8	1.8	1.4	1.1	2.2	2.6	2.1	3.4	3.3
1953......	4.5	4.0	3.1	3.0	2.1	0.8	1.6	2.1	3.1	2.3	3.5	3.1
1954......	4.7	3.7	3.1	3.6	1.3	2.1	1.6	2.1	2.9	3.6	2.7	3.5
1955......	6.2	4.6	5.0	2.5	3.6	1.8	1.2	1.5	2.1	4.4	3.5	5.6
1956......	5.2	3.9	2.8	2.5	1.5	1.9	1.5	2.9	2.6	4.0	3.7	3.5
1957......	4.3	3.6	3.4	2.8	3.2	2.5	1.3	2.7	2.6	4.1	2.9	4.7
1958......	5.1	7.1	3.9	2.7	2.1	2.0	1.8	1.2	1.8			
Mean.....	4.6	4.4	3.5	2.8	2.1	1.6	1.5	1.8	2.3	3.2	3.0	3.8

Table 8. *Latent heat of evaporation in g cal* cm^{-2} *day.*

	J	F	M	A	M	J	J	A	S	O	N	D
1948......										194	191	162
1949......	337	254	260	175	107	62	106	112	80	203	76	236
1950......	138	325	190	180	113	71	47	66	124	146	190	211
1951......	231	146	203	175	174	90	89	33	80	127	175	261
1952......	220	289	179	109	108	85	64	129	155	124	199	198
1953......	264	235	182	176	122	49	92	122	180	138	209	186
1954......	278	220	186	216	77	124	96	122	174	216	160	207
1955......	367	275	296	150	212	109	69	87	122	262	206	334
1956......	311	234	168	148	91	113	89	172	155	235	222	209
1957......	256	215	199	167	187	151	79	158	153	244	171	276
1958......	305	419	230	163	124	119	105	69	108			
Mean.....	271	261	209	166	132	97	84	107	133	189	180	228

Table 9. *Sensible heat in g cal* cm^{-2} day^{-1}.

	J	F	M	A	M	J	J	A	S	O	N	D
1948......										95	90	92
1949......	158	140	148	140	55	27	30	33	29	97	20	127
1950......	76	179	120	79	52	15	6	− 6	25	35	85	129
1951......	123	66	158	96	73	34	21	− 5	13	32	100	138
1952......	130	190	125	47	50	29	19	44	57	31	102	111
1953......	164	158	86	113	60	16	21	22	41	46	98	89
1954......	178	115	116	114	12	39	16	36	61	125	55	95
1955......	276	193	193	92	112	41	15	10	24	115	99	221
1956......	211	143	91	81	25	46	14	39	33	78	97	96
1957......	105	120	117	62	82	51	31	36	52	98	82	152
1958......	192	239	142	78	48	37	37	18	27			
Mean.....	161	154	130	90	57	34	21	23	36	75	83	125

Table 10. *Total energy exchanged between sea and atmosphere in g cal* cm^{-2} day^{-1}.

	J	F	M	A	M	J	J	A	S	O	N	D
1948......										289	281	254
1949......	495	394	408	315	162	89	136	145	109	300	96	364
1950......	214	504	310	259	165	86	54	61	149	181	275	340
1951......	354	212	361	271	248	124	110	28	93	159	275	400
1952......	350	479	304	156	158	114	83	173	212	156	301	309
1953......	428	393	268	289	182	65	113	144	222	184	307	275
1954......	456	335	302	331	89	163	112	158	235	341	215	302
1955......	643	468	489	242	324	150	84	97	146	377	305	555
1956......	522	377	259	229	116	160	103	211	188	313	319	305
1957......	361	335	316	229	269	202	110	195	205	342	253	428
1958......	497	658	372	241	172	156	142	87	135			
Mean.....	432	415	339	256	189	131	105	130	169	264	263	353

Table 11. *Monthly values of the Bowen ratio.*

	J	F	M	A	M	J	J	A	S	O	N	D
1948......										0.49	0.47	0.57
1949......	0.47	0.55	0.57	0.80	0.51	0.43	0.28	0.29	0.36	0.48	0.27	0.54
1950......	0.55	0.55	0.63	0.44	0.46	0.21	0.13	−0.08	0.20	0.24	0.45	0.61
1951......	0.53	0.45	0.78	0.55	0.42	0.38	0.23	−0.16	0.16	0.25	0.57	0.53
1952......	0.59	0.66	0.70	0.43	0.46	0.34	0.29	0.34	0.37	0.25	0.51	0.56
1953......	0.62	0.67	0.47	0.64	0.49	0.33	0.23	0.18	0.23	0.33	0.47	0.46
1954......	0.64	0.52	0.62	0.53	0.16	0.31	0.17	0.30	0.38	0.42	0.34	0.46
1955......	0.75	0.70	0.65	0.61	0.53	0.38	0.22	0.12	0.20	0.44	0.48	0.66
1956......	0.68	0.61	0.54	0.55	0.28	0.41	0.15	0.23	0.21	0.33	0.44	0.46
1957......	0.41	0.56	0.59	0.37	0.44	0.34	0.40	0.23	0.34	0.40	0.48	0.55
1958......	0.63	0.57	0.62	0.48	0.39	0.31	0.36	0.27	0.25			

Table 12. *Annual and monthly means of observed wind speed, temperature and humidity differences between sea and air, and computed values of evaporation, sensible heat and the Bowen ratio at Ocean Weather Stations A, I and M based upon observations from 1951—1960.*

Station A

	J	F	M	A	M	J	J	A	S	O	N	D	Year
$t_s - t_a$ C°	3.1	2.4	1.9	1.4	0.6	0.5	0.5	0.7	1.1	1.4	1.8	2.7	1.5
$e_s - e_a$ mb	3.06	2.74	2.37	2.19	1.56	1.51	1.67	2.12	2.43	2.64	2.47	3.03	2.32
V_a m sec^{-1}	12.6	11.9	11.6	10.1	9.2	7.5	7.0	7.7	9.5	10.8	11.4	12.3	10.1
E mm day^{-1}	4.2	3.5	3.0	2.4	1.5	1.2	1.2	1.8	2.50	3.1	3.0	4.0	2.7
Q_e g cal cm^{-2} day^{-1}	247	210	177	142	92	72	75	104	148	183	181	240	156
Q_h g cal cm^{-2} day^{-1}	162	118	92	63	23	15	15	22	43	63	85	138	70
R	0.66	0.56	0.52	0.42	0.25	0.21	0.20	0.21	0.29	0.34	0.47	0.58	0.45

Station I

	J	F	M	A	M	J	J	A	S	O	N	D	Year
$t_s - t_a$ C°	3.3	2.5	1.8	1.7	1.0	0.9	0.6	0.7	0.9	1.6	1.7	2.7	1.6
$e_s - e_a$ mb	3.96	3.40	3.09	3.05	2.41	2.41	2.38	2.73	2.72	3.34	3.14	3.69	3.03
V_a m sec^{-1}	12.7	11.9	12.1	11.4	9.6	8.5	8.3	8.3	9.8	11.9	11.9	13.4	10.8
E mm day^{-1}	5.5	4.4	4.0	3.8	2.5	2.2	2.2	2.5	2.8	4.3	4.1	5.3	3.7
Q_e g cal cm^{-2} day^{-1}	322	259	239	222	148	131	126	144	170	255	239	317	214
Q_h g cal cm^{-2} day^{-1}	173	124	91	80	40	31	20	25	36	79	84	149	78
R	0.54	0.48	0.38	0.36	0.27	0.24	0.16	0.17	0.21	0.31	0.35	0.47	0.36

Station M

	J	F	M	A	M	J	J	A	S	O	N	D	Year
$t_s - t_a$ C°	3.4	3.2	2.5	2.1	1.5	1.2	0.6	0.9	1.1	1.5	1.8	2.8	1.9
$e_s - e_a$ mb	3.65	3.39	2.99	2.68	2.40	2.27	2.02	2.35	2.70	2.97	2.80	3.41	2.80
V_a m sec^{-1}	11.2	11.1	10.1	9.6	7.7	7.1	6.6	7.0	8.7	9.6	10.9	11.0	9.2
E mm day^{-1}	4.7	4.3	3.4	2.9	2.1	1.8	1.4	1.8	2.6	3.1	3.4	4.13	3.0
Q_e g cal cm^{-2} day^{-1}	277	255	204	174	125	109	87	107	152	185	199	245	177
Q_h g cal cm^{-2} day^{-1}	166	156	112	89	51	37	17	27	41	61	84	130	81
R	0.60	0.61	0.55	0.51	0.41	0.34	0.20	0.25	0.27	0.33	0.42	0.53	0.46

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LIST OF SYMBOLS

a	Altitude of observation above sea surface.
t_s	Sea surface temperature.
t_a	Air temperature at altitude a.
e_s	Saturation vapour pressure at sea surface.
e_a	Vapour pressure at altitude a.
q	Specific humidity.
V_a	Wind velocity at altitude a.
E	Height of evaporation.
L_t	Latent heat of evaporation at temperature t.
Q_s	Total solar radiation absorbed by the sea.
Q_b	Total back radiation from the sea surface.
Q_e	Energy used for evaporation.
Q_h	Sensible heat exchanged between sea and atmosphere through convection.
$Q_a = Q_e + Q_h$	Total heat exchanged between sea and atmosphere.
R	Bowen ratio $= \frac{Q_h}{Q_e}$

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