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Lake Erie Terrestrial Radiation

Jan A. Derecki

National Oceanic and Atmospheric Administration, Great Lakes Environmental Research Laboratory
Ann Arbor, Michigan 48104

Terrestrial or long-wave radiation over a body of water consists of the atmospheric radiation, with incident and reflected components, and the radiation emitted by the water body. These three radiation components produce a net back radiation, an energy loss from the water to the atmosphere. Basic required data (air temperature, humidity, solar radiation, and water surface temperature) were derived, and long-term (17 years) average monthly radiation values were calculated for the Lake Erie incident and reflected atmospheric radiation and the radiation emitted by the water body. The net result or the effective net back radiation averaged 100 Ly/d from 1952 to 1968.

Terrestrial radiation is required for a variety of studies dealing with the Great Lakes heat budget, such as those on evaporation and ice or snowmelt. In a recently completed long-term Lake Erie evaporation study [*Derecki,* 1975] the energy budget method was one of the approaches used to compute monthly evaporation. Since long-wave radiation components constitute the principal heat transfer processes affecting the lake, determination of the terrestrial radiation was required. This paper describes the derivation of the terrestrial radiation components and presents results obtained in that study. The period of record for the energy budget computations covered 17 years, 1952–1968. Because of limitations of the required data, determination of the energy budget factors, including radiation, was restricted to average monthly values. The Lake Erie basin and pertinent locations are shown in Figure 1.

Terrestrial or long-wave radiation over a body of water consists of the incident and reflected atmospheric radiation components and the radiation emitted by the water body. The net result of long-wave radiation is an effective back radiation, an energy loss from the water to the atmosphere. The net back radiation may be determined from total radiation measurements (long-wave plus short-wave during daylight hours), but there is no regular network for such measurements; total radiation measurements are limited to periodic observations at research installations. Net back radiation from the lakes is usually calculated from related climatic elements; it is a function of the air temperature, humidity, and cloud cover, which control atmospheric radiation, and of the temperature of the water surface, which governs emitted radiation.

Basic Data

Basic climatological and water temperature data used to compute terrestrial radiation were obtained from land and water intake stations located around the lake. Such lake perimeter data are not representative of the open-lake conditions, but over-water measurements on the Great Lakes are not available for any appreciable period of time.

Meteorological data. Meteorological data (air temperature and humidity) for the lake were determined from four first-order weather stations located on opposite ends of Lake Erie to give a good approximation of average conditions around the lake. Average values for air temperature and humidity were obtained by averaging monthly records from Buffalo, New York; Cleveland and Toledo, Ohio; and London, Ontario. The station at London, location some 40 km from the lake, is not a perimeter station but is the only suitable station north of the lake with a long-term record of required data.

The average perimeter air temperature for Lake Erie is given in Table 1. The 17-year average annual temperature was 8.8°C. The average monthly temperatures varied from −4.4°C in January to 21.7°C in July. Monthly temperatures are based on daily means determined by averaging maximum and minimum temperatures, a standard procedure for determining air temperature at the weather stations.

Humidity data were used to derive the air vapor pressure, which is a function of air temperature and relative humidity. Published humidity records consist of observations at 4 synoptic hours (0130, 0730, 1330, and 1930 EST), from which mean daily values were derived. The average perimeter humidity for the period of study is given in Table 1. Annual humidity around Lake Erie had the average value of 74%. The average monthly humidity varied from 68% in May to 79% in December.

Solar radiation. Solar or short-wave radiation data were used to indicate the degree of cloudiness. The incoming solar radiation is reduced by the atmosphere before reaching the earth and is a good indicator of cloudiness during daylight hours. Attentuation of the extraterrestrial solar radiation by the atmosphere is caused by scattering, reflection, and absorption by gas molecules, water vapor, clouds, and suspended dust particles. Since these factors may differ considerably over land and large water areas, radiation measurements should be made over the lake. However, the only measurements of solar radiation in the Lake Erie basin with a substantial period of record are those made at Cleveland, Ohio. Cleveland records were used in the present study, without adjustments to over-water conditions. They indicate that average incident solar radiation for the 1952–1968 period varied from 198 Ly/d in December to 558 Ly/d in June, with an annual average of 327 Ly/d (Table 1).

Because of the lake effect, listed solar radiation values are potentially too low during summer and too high during winter months. Preliminary investigations of solar radiation on the Great Lakes, based on limited data from synoptic surveys, confirm the physical concepts of the lake effect. Results of a preliminary study conducted by *Richards and Loewen* [1965] indicate that solar radiation over the lakes is greater than that recorded on adjacent land stations during summer and smaller than that recorded during winter. Their study is based on 4 years of limited data (1960–1963) during the April through December period and shows that over-water radiation at the beginning and end of the period amounts to 90% of the over-

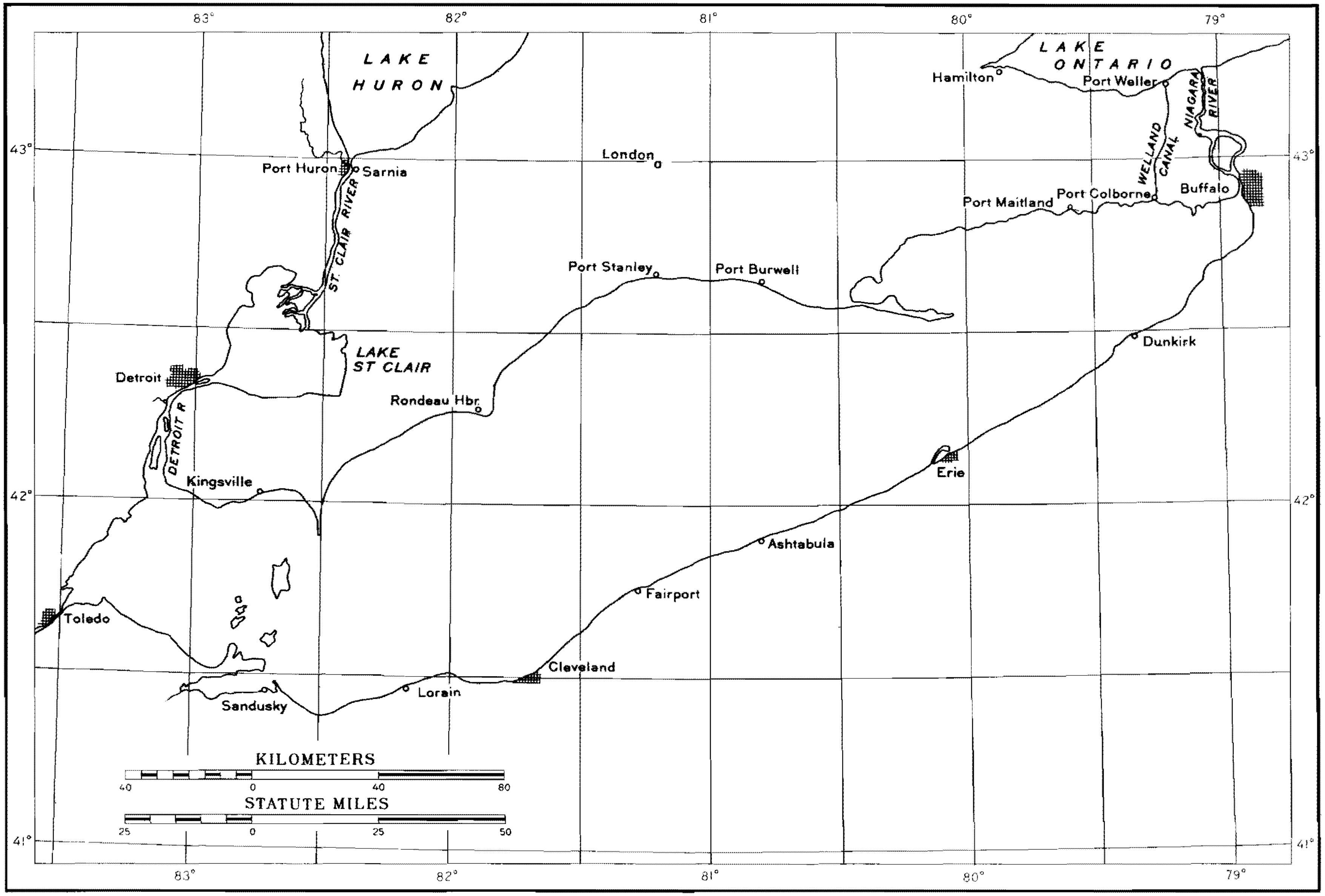

Fig. 1. Lake Erie basin.

TABLE 1. Average Basic Data Values For Lake Erie During 1952–1968

Period	Air Temperature T_a, °C	Relative Humidity H, %	Solar Radiation Q_s, Ly/d	Water Temperature T_w, °C
January	−4.4	78	129	0.2
February	−3.4	77	189	0.1
March	0.9	76	290	0.5
April	8.3	70	381	3.2
May	13.7	68	507	9.1
June	19.6	69	558	15.9
July	21.7	70	537	20.3
August	20.8	74	465	21.9
September	17.1	74	369	19.4
October	11.1	73	257	15.1
November	4.7	77	139	10.1
December	−1.8	79	109	3.1
Annual	8.8	74	327	9.9

land radiation. The over-water radiation increases gradually during spring and summer to an average high of about 135% of the overland radiation in the late summer and then decreases rapidly in the fall. These results may be modified by a more comprehensive study; they include bias toward fair weather conditions, especially during months with frequent seasonal storms.

Water surface temperature. The only sources of water surface temperature data in the Great Lakes with long periods of record are the municipal water intakes. Water temperature at the intake stations is obtained in the coastal waters, a few hundred to a few thousand meters offshore, at some depth below the surface. These data do not represent water surface temperatures in the open lake and require adjustments.

Water surface temperatures used in the present study were obtained by adjusting values derived from water intakes at Erie, Pennsylvania, and Avon Lake, Ohio, to open-lake conditions. The average temperature from these two stations was considered to be sufficiently representative of the whole lake by *Powers et al.* [1959]. The required adjustments were determined from the lake surface temperatures presented by *Millar* [1952] and simultaneous records from the water intake stations. The temperature adjustments consist of average monthly differences between these temperatures. The surface temperatures from Millar and the water intakes and the corresponding adjustment terms are shown in Table 2. Because of insufficient data during winter months, Millar excluded winter temperatures, and they had to be estimated. Adjustments to the average monthly shore temperatures vary from −3.1°C in April to +0.6°C in November, with an annual average of −1.6°C. These values are based on a relatively short period of record (1937–1941) and may be modified by temperature relationships for longer periods.

The Lake Erie water surface temperature for the period of study is given in Table 1. Annual temperatures during the 1952–1968 period had an average value of 9.9°C. The average monthly temperatures varied from a low of 0.1°C in February to a high of 21.9°C in August. Derived water temperatures agree reasonably with those presented for a comparable period, 1950–1968, by *Richards and Irbe* [1969], which are also based on partial estimates. Their average temperatures indicate similar monthly variation (0.6°C to 22.2°C), with an annual value of 10.3°C. The monthly differences in the two sets of water surface temperatures are within 0.5°C during most months, with extreme differences of approximately 1°C.

ATMOSPHERIC RADIATION

Incident radiation. Atmospheric radiation may be computed by several equations that utilize various radiation indexes (temperature, percent of sunshine or cloud cover, and vapor pressure). The equation used in this study was that proposed by *Anderson and Baker* [1967], who present a method for computing incident long-wave radiation under all atmospheric conditions from observations of surface air temperature, vapor pressure, and incoming solar radiation. Their approach consists of determining typical clear sky atmospheric radiation Q_{act}, adjusted for a particular location A and degree of cloudiness Q_s/Q_{sc}, as expressed by the following equation:

$$Q_a = \sigma T_a^4 - \{228.0 + 11.16[(e_{sa})^{1/2} - (e_a)^{1/2}] - A\} \times (Q_s/Q_{sc})^n \quad (1)$$

where

Q_a	incident atmospheric radiation under all conditions, langleys per day;
σ	Stefan-Boltzmann constant (11.71 × 10^{-8} Ly/d/°K^4);
T_a	surface air temperature, degrees Kelvin;
e_{sa}	saturation vapor pressure at T_a, millibars;
e_a	surface vapor pressure at T_a, millibars;
A	station adjustment term, langleys per day;
Q_s	incident solar radiation, langleys per day;
Q_{sc}	clear sky solar radiation, langleys per day;
n	exponent of ratio for degree of cloudiness (2.0).

The station adjustment term is a function of the long-term relationship between air temperature at the surface and at an upper level (50–200 mbar above the surface). *Anderson and Baker* [1967] determined the adjustment term by plotting the atmospheric radiation difference between typical and actual profiles versus the temperature difference between the two profiles at the surface and at a given level. A linear relationship being assumed, the values of A for the upper level of 150 mbar above the surface are given by the equation

$$A = 5.0(T_{ua} - T_{ut}) \quad (2)$$

where T_{ua} is the difference between actual upper-air and surface temperature from a long-term relationship in degrees Celsius and T_{ut} is the same difference for a typical temperature profile in degrees Celsius (−9.3°C for 150 mbar).

Equation (1), terminating with the station adjustment term,

TABLE 2. Lake Erie Water Surface Temperature Analysis for the Period 1937–1941

Period	Water Temperatures, °C Open Lake*	 Water Intake†	Adjustments,‡ °C
January	0.6§	2.5	−1.9
February	0.0§	2.3	−2.3
March	0.6§	2.7	−2.1
April	3.3¶	6.4	−3.1
May	10.0	12.8	−2.8
June	17.2	18.7	−1.5
July	21.1	22.6	−1.5
August	22.8	23.9	−1.1
September	19.4	20.7	−1.3
October	15.0	15.5	−0.5
November	9.4	8.8	+0.6
December	3.3¶	4.4	−1.1
Annual	10.2§	11.8	−1.6

*Surface temperatures are from *Millar* [1952].

†Water intake stations are located at Avon Lake, Ohio, and Erie, Pennsylvania.

‡The temperature adjutments consist of average monthly differences between open-lake and water intake temperatures.

§Estimated values.

¶Values extrapolated from Millar's partial records.

gives clear sky atmospheric radiation for any station or locality. To calculate atmospheric radiation during cloudy conditions, further adjustment of the clear sky atmospheric radiation is required. The extent of cloudiness may be determined from observations of cloud cover or percent of sunshine or from the ratio of observed to clear sky solar radiation. Each of these approaches has its advantages and disadvantages. Cloud cover can be observed throughout the day but lacks consistency (visual observations); percent of sunshine may have the same objection and applies only to daylight hours. The ratio of incident to clear sky solar radiation is a good index of cloudiness but is also limited to daylight hours.

Selection of the solar radiation ratio as the index of the degree of cloudiness requires determination of the clear sky solar radiation. A convenient method of computing clear sky solar radiation, used in the present study, is presented by *Bolsenga* [1964]. A simplified expression for the total clear sky solar radiation (direct and diffuse) is given by the equation

$$Q_{sc} = Q_{se}(a + 0.5s) \qquad (3)$$

where

Q_{sc}	clear sky solar radiation, langleys per day;
Q_{se}	extraterrestrial solar radiation, langleys per day;
a	total transmission coefficient (including moisture absorption and molecular scattering);
s	total depletion by atmospheric scattering and diffuse reflection.

Values for the major components required to compute atmospheric radiation and the resulting incident atmospheric radiation are shown in Table 3. Average incoming atmospheric radiation for the 1952–1968 period varied from the winter low of 570 Ly/d (January) to the midsummer high of 737 Ly/d (August), with an annual average of 650 Ly/d. These values are based on perimeter data and contain inherent land bias in the input parameters (air temperature, humidity, and solar radiation). For the average monthly values the extreme errors should not exceed 1°C for air temperature (T_a), 5% for relative humidity (H), and 50 Ly/d for solar radiation (Q_s). The sensitivity of these parameters on computed atmospheric radiation (Q_a) for the above differences is as follows: (1) a 1°C increase in T_a produces a 8-Ly/d increase in Q_a, (2) a 5% increase in H produces an insignificant (0.5-Ly/d) decrease in Q_a, and (3) a 50-Ly/d increase in Q_s produces a 30-Ly/d decrease in Q_a.

Reflected radiation. The reflectivity of a water surface for atmospheric radiation has been determined by *Anderson* [1954] to be 3%. The resulting heat loss from Lake Erie through reflected radiation is shown in Table 4. The reflected atmospheric radiation is relatively small and nearly constant throughout the year, with the average annual value of 20 Ly/d. The average monthly values vary from 17 Ly/d in the winter to 22 Ly/d during summer. Since the input data for computing atmospheric radiation are based on the perimeter measurements, the resulting atmospheric radiation contains some land surface bias.

TABLE 3. Determination of Atmospheric Radiation for Lake Erie During 1952–1968

Period	$Q_{act} = \sigma T_a^4 - 288.0 - 11.16 \cdot [(e_{sa})^{1/2} - (e_a)^{1/2}]$ e_{sa}, mbar	 $[(e_{sa})^{1/2} - (e_a)^{1/2}]$, mbar$^{1/2}$	 Q_{act}, Ly/d	$A = 5.0(T_{ua} - T_{ut})$ T_u, °C	 $(T_{ua} - T_{ut})$, °C	 A, Ly/d	$Q_{sc} = Q_{se}(a + 0.5s)$ a	 s	 Q_{sc}, Ly/d	Q_a, Ly/d
January	4.41	0.270	378	−8.3	5.4	27	0.38	0.51	293	570
February	4.75	0.284	387	−8.5	4.2	21	0.45	0.45	399	571
March	6.52	0.330	427	−5.2	3.2	16	0.46	0.43	490	584
April	10.94	0.542	499	1.2	2.2	11	0.49	0.41	629	652
May	15.67	0.693	525	6.0	1.6	8	0.46	0.42	649	622
June	22.80	0.828	621	11.5	1.2	6	0.46	0.40	725	721
July	25.95	0.845	646	12.9	0.5	2	0.45	0.41	672	733
August	24.56	0.704	637	12.3	0.8	4	0.44	0.42	609	737
September	19.49	0.626	594	9.7	1.9	10	0.41	0.45	516	714
October	13.21	0.517	529	4.8	3.0	15	0.39	0.48	384	665
November	8.54	0.372	464	−1.2	3.4	17	0.39	0.48	295	649
December	5.35	0.264	402	−6.6	4.5	22	0.36	0.53	229	586
Annual	13.52	0.523	509	2.4	2.7	13	0.43	0.45	491	650

$Q_a = \sigma T_a^4 + \{288.0 - 11.16[(e_{sa})^{1/2} - (e_a)^{1/2}] - A\} \times (Q_s/Q_{sc})^n$

Upper air temperatures T_u were obtained from Buffalo radiosonde data at 850 mbar or approximately 150 mbar above the surface. Transmission coefficient a and solar attenuation s were obtained according to the method presented by *Bolsenga* [1964].

BACK RADIATION

Emitted radiation. Long-wave radiation emitted from the lake is a function of the Stefan-Boltzmann law for black body radiation and the emissivity of the surface water. Emissivity indicates the relative power of a surface to emit heat by radiation in comparison with the maximum possible intensity of a black body. Emissivity of the water surface was determined to be 0.97 [*Anderson,* 1954]. The relationship for the emitted radiation is expressed by the equation

$$Q_b = \epsilon \sigma T_w^4 \qquad (4)$$

where

Q_b radiation emitted from the lake, langleys per day;
ϵ emissivity of the water surface (0.97);
σ Stefan-Boltzmann constant (11.71×10^{-8} Ly/d/°K^4);
T_w water surface temperature, degrees Kelvin.

The average monthly emitted radiation from Lake Erie for the 1952–1968 period varied from 631 Ly/d in February to 859 Ly/d in August; the average annual value was 731 Ly/d (Table 4). These values are based on shoreline temperatures adjusted to open-lake conditions. The water temperatures contain some estimates but should reflect lake surface temperatures within 1°C. A change of 1°C in the water surface temperature produces a corresponding change of 10 Ly/d in the emitted radiation.

Net back radiation. On the basis of the average 1952–1968 lake perimeter data, emitted radiation exceeded incident atmospheric radiation by 80 Ly/d. This long-wave radiation loss combined with the 20 Ly/d from reflected atmospheric radiation produced a net back radiation to the atmosphere of 100 Ly/d (Table 4).

The net back radiation obtained as a residual of terrestrial radiation components is affected by the accuracy of these components. Limited sensitivity analysis conducted for the atmospheric and emitted radiation indicates that solar radiation is the most sensitive parameter for computing terrestrial radiation and, consequently, the net back results. Since solar radiation was used to indicate cloud cover, it appears that cloud cover variation over land and lake areas is the main data problem when the perimeter data are employed to compute over-water radiation. *Atwater* [1974] identifies the lack of proper cloud observations as one of the major difficulties in computing net radiation (solar and terrestrial) for Lake Ontario from land station data during the International Field Year for the Great Lakes. Atwater also found that seasonal fog increase over the lake, which is not indicated by land stations, causes systematic overcomputation of net radiation. This particular aspect of the over-water radiation computations has been generally disregarded and was not considered in this study.

SUMMARY AND CONCLUSIONS

Lake Erie terrestrial radiation components were determined for monthly periods from long-term data and indicate normal monthly values. These long-wave radiation components consist of the incident and reflected atmospheric radiation over the lake and the radiation emitted by the lake. The net result is the net back radiation, an energy loss from the lake to the atmosphere. Values presented are based on 17 years of lake perimeter data (1952–1968). Records from the perimeter stations contain inherent land bias but represent the only source of required long-term data. Derived terrestrial radiation values are listed in Table 4. They indicate a total energy loss from the lake through long-wave radiation of 100 Ly/d, which consists of 650 Ly/d for incident atmospheric radiation, 20 Ly/d for reflected atmospheric radiation, and 730 Ly/d for emitted radiation.

Because of data limitations, values determined for the terrestrial radiation components contain some errors. Because of their large magnitudes the incoming atmospheric and emitted radiation are of primary interest. The emitted radiation is a function of the water surface temperature, and incident atmospheric radiation was determined primarily from the air temperature and solar radiation (humidity was relatively unimportant). Estimated extreme monthly errors for these parameters were 1°C for the temperatures and 50 Ly/d for solar radiation. The effect of these errors on computed terrestrial radiation is about 10 Ly/d for the temperatures and 30 Ly/d for solar radiation. For most months, expected accuracy should be much better than that indicated above for the extreme errors.

NOTATION

A	station adjustment term, langleys per day.
a	total transmission coefficient.
e_a	vapor pressure of the air at T_a, millibars.
e_{sa}	saturation vapor pressure at T_a, millibars.
H	relative humidity, percent.
n	exponent of ratio for degree of cloudiness (~2.0).
Q_a	incident atmospheric radiation, langleys per day.

TABLE 4. Terrestrial Radiation for Lake Erie During 1952–1968

Period	Incident Q_a	Reflected Q_{ar}	Emitted Q_b	Net Back Q_{nb}
January	570	17	632	79
February	571	17	631	77
March	584	18	635	69
April	652	20	662	30
May	622	19	720	117
June	721	22	792	93
July	733	22	841	130
August	737	22	859	144
September	714	21	830	137
October	665	20	783	138
November	649	19	729	99
December	586	18	660	92
Annual	650	20	731	100

$Q_{nb} = Q_a - Q_{ar} - Q_b$
Units are langleys per day.

Q_{act}	typical clear sky atmospheric radiation, langleys per day.
Q_{ar}	reflected atmospheric radiation, langleys per day.
Q_b	radiation emitted by the water body, langleys per day.
Q_{nb}	long-wave net back radiation, langleys per day.
Q_s	incident solar radiation, langleys per day.
Q_{sc}	clear sky solar radiation, langleys per day.
Q_{se}	extraterrestrial solar radiation, langleys per day.
s	total depletion by atmospheric scattering and diffuse reflection.
T_a	surface air temperature, degrees Kelvin or degrees Celsius.
T_u	upper air temperature, degrees Celsius.
T_{ua}	difference between actual upper air and surface temperature from a long-term relationship, degrees Celsius.
T_{ut}	same difference for typical temperature profile, degrees Celsius ($-9.3°$C for 150 mbar).
T_w	water surface temperature, degrees Kelvin or degrees Celsius.
ϵ	emissivity of the water surface (0.97).
σ	Stefan-Boltzmann constant (11.71×10^{-8} Ly/d/°K^4).

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