Journal du Conseil 24:215-220 (1959)

The Seasonal Incoming Radiation in Norwegian and Arctic Waters, and Indirect Methods of Measurement[1])

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THE importance of light in governing primary production in the sea has been well documented. Furthermore, it is common knowledge that the amount and quality of light reaching a cell surface is a function of many physical determinants which reflect, scatter, or absorb radiation causing an attenuation with depth. Measurements of this energy are easily made by any of a variety of instruments now available (LUND and TALLING, 1957), or indirectly by employing a formula.

KIMBALL (1928) calculated the average daily totals of solar radiation (Q) reaching the sea surface at different latitudes by the formula:

$$Q = Q_0\,(0{\cdot}29 + 0{\cdot}71\,[1{\cdot}0 - C])\ \text{g cal. per cm}^2\text{ per day} \qquad (1)$$

where Q_0 represents total radiation assuming a clear sky and C is the proportion of the sky covered by clouds.

MOSBY (SVERDRUP, 1953) also derived a formula to estimate incoming radiation ($\bar{I}_0$):

$$\bar{I}_0 = 0{\cdot}026\,(1 - 0{\cdot}075\,\bar{C})\,\bar{h}\ \text{g cal. per cm}^2\text{ per min.} \qquad (2)$$

where $\bar{C}$ is the average cloud cover on the scale 0–10 and $\bar{h}$ is the average altitude of the sun. The constant (0·026) expresses the atmospheric turbidity at 60°N; at 70°N it becomes 0·027 (SVERDRUP, JOHNSON, and FLEMING, 1942).

Incoming total (global) radiation (G_H^N) can also be calculated by WERNER JOHANNESSEN's (1956) formula:

$$G_H^N = \bar{C}_H \cdot \bar{G}_H\ \text{k cal. per m}^2\text{ per day} \qquad (3)$$

where $\bar{C}_H$ is a cloud factor expressing the relationship between cloud cover and radiation as found at Bergen, Norway and is defined as:

$$\bar{C}_H = 1{\cdot}339 - 0{\cdot}1073 \cdot \bar{N} \qquad (4)$$

[1]) Contribution No. 964 from the Woods Hole Oceanographic Institution.

Journal du Conseil 24:215-220 (1959)

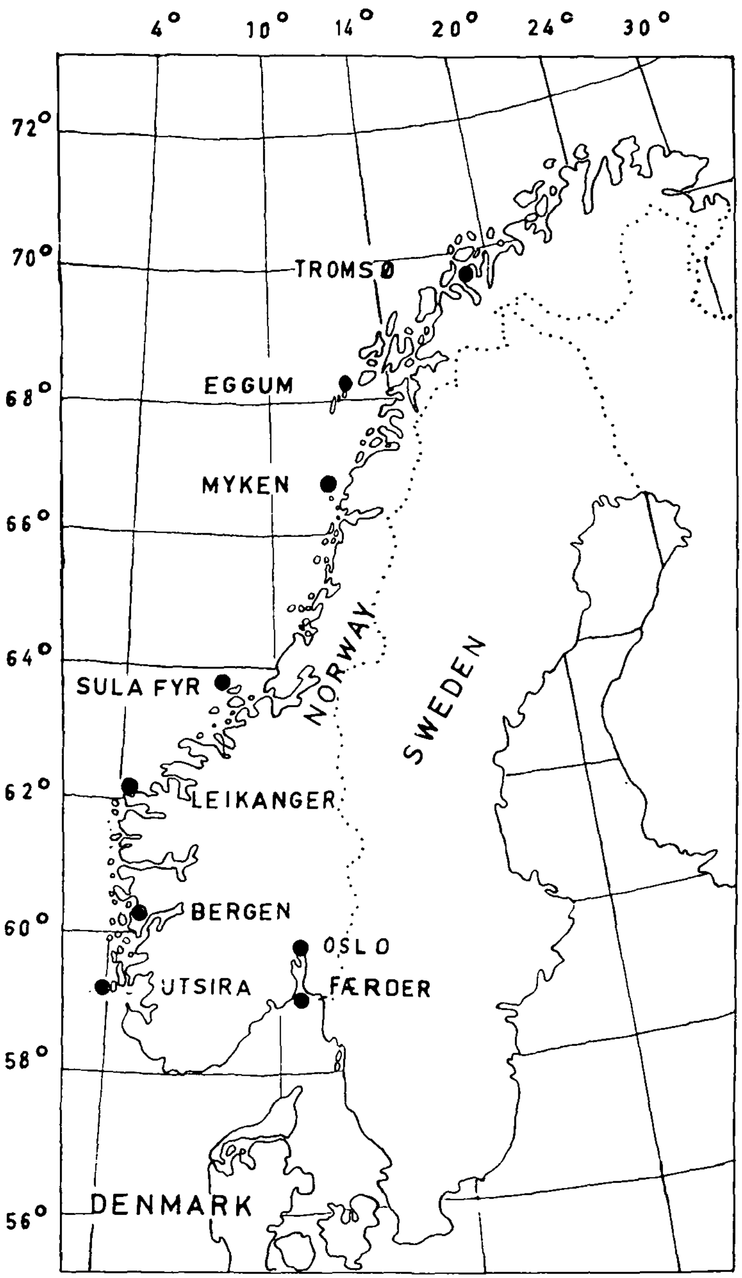

Figure 1. Sites along the Norwegian coast where the seasonal radiation cycle has been calculated.

Journal du Conseil 24:215-220 (1959)

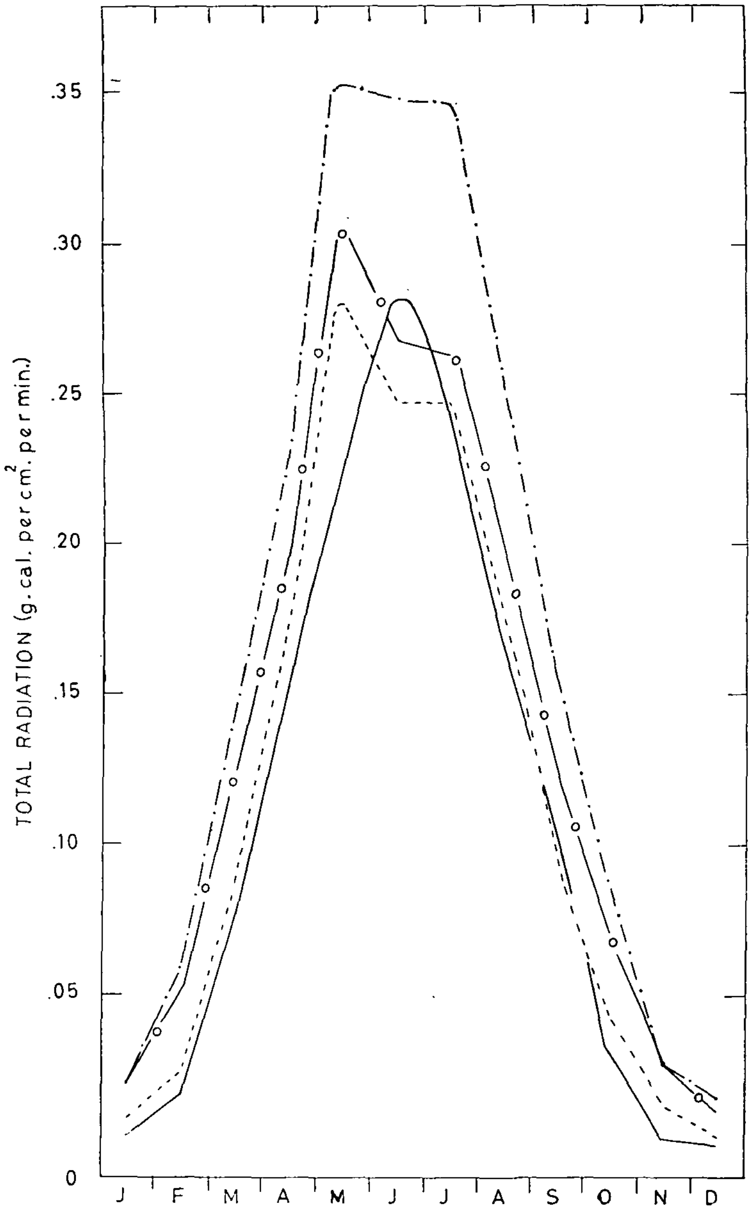

Figure 2. Seasonal radiation cycle at selected points along the Norwegian coast.

——— · ——— Færder 59°N
——— o ——— Utsira 59°N
· · · · · · · · · · Sula Fyr 64°N
————————— Eggum 68°N

Journal du Conseil 24:215-220 (1959)

Table 1

Average daily total radiation (G_H^N) reaching the sea surface at selected points along the Norwegian coast

(g cal. per cm² per min.)

Date	Færder 59°N	Utsira 59°N	Oslo 60°N	Bergen 60°N	Leikanger 62°N	Sula Fyr 64°N	Myken 66°45'N	Eggum 68°N	Tromsø 70°N
19. January	·021	·022	·019	·021	·014	·009	·004	·002	–
13. February	·057	·052	·051	·049	·041	·025	·019	·016	·013
17. March	·144	·119	·132	·119	·121	·083	·078	·076	·069
16. April	·233	·196	·202	·174	·185	·170	·164	·152	·147
15. May	·352	·304	·297	·290	·316	·280	·257	·225	·199
10. June	·347	·268	·293	·277	·305	·248	·279	·281	·278
19. July	·346	·262	·275	·256	·300	·248	·262	·244	·271
17. August	·252	·198	·208	·204	·224	·180	·181	·165	·161
17. September	·157	·126	·128	·118	·121	·098	·095	·107	·095
14. October	·088	·070	·079	·069	·066	·044	·037	·033	·027
15. November	·028	·028	·023	·026	·019	·014	·007	·005	·003
11. December	·016	·013	·011	·012	·008	·004	–	–	–

where $\overline{N}$ is the average monthly cloud cover on the scale 0–10. For any given day the relationship becomes:

$$\overline{C}_H = 0{\cdot}950 - 0{\cdot}0237 \cdot N_d - 0{\cdot}00907 \cdot N_d^2 \quad (5)$$

where N_d represents the mean cloud cover.

The expression $\overline{G}_H$, in equation (3), represents the mean total daily radiation (direct + diffuse) on a horizontal surface assuming a cloudless sky.

Inserting the mean monthly cloud covers for the period 1941–1950 in WERNER JOHANNESSEN's formula, the seasonal radiation cycle has been calculated for selected points along the Norwegian coast from 59° to 70°N (Figs. 1, 2; Table 1). The values for $\overline{G}_H$, representing those days when the solar declination corresponded to the monthly mean, were abstracted from WERNER JOHANNESSEN's report and are presented here in tabular form (Table 2).

The decrease in radiation with increasing latitude is well defined (Table 1). Comparison of the seasonal cycles at Færder located at the entrance to Oslo-, fjord, and Utsira, on the western coast, both at approximately 59°N (Fig. 1),

Table 2

Daily total radiation (direct + diffuse) ($\overline{G}_H$) received on a horizontal surface in the absence of clouds

(k cal. per m² per day)

Date	59°N	60°N	62°N	64°N	66°N	68°N	70°N
19. January	565	480	325	185	115	40	–
13. February	1305	1210	960	785	575	430	305
17. March	3030	2910	2665	2430	2160	1975	1720
16. April	4895	4785	4610	4400	4210	4100	3885
15. May	6320	6195	6160	6080	5875	5835	5750
10. June	7075	7035	6960	6975	7015	6875	6945
19. July	6550	6390	6310	6320	6180	6205	6195
17. August	5140	5000	4950	4765	4550	4455	4265
17. September	3460	3310	3195	2940	2635	2450	2165
14. October	1970	1890	1650	1405	1175	950	790
15. November	775	660	510	360	205	130	65
11. December	370	320	200	100	25	–	–

Journal du Conseil 24:215-220 (1959)

reveals the importance of cloud cover in determining the amount of incoming radiation. The occurrence of a maximum energy flux during May between 59° and 64°N (Table 1) results from reduced cloud cover. Although the daily total radiation under cloudless conditions is at a maximum during June (Table 2), the observed cloud cover is from 1·0 to 1·5 units greater than that prevailing during May.

The development of the spring phytoplankton along the Norwegian coast is coincident with the marked increase in radiation occurring during March (BRAARUD and BURSA, 1939; BRAARUD, GAARDER, and NORDLI, 1959; FØYN, 1929; GAARDER, 1938; GRAN, 1927, 1929). This flowering begins approximately a month earlier at 59°–60°N than at 68°–70°N. In general, the radiation is between 0·090–0·100 g cal. per cm^2 per min. at this growth phase, and maximum abundance is not attained until the intensity is approximately 0·150 g cal. per cm^2 per min. As the conditions of turbidity and stability influence the light-phytoplankton relationship, deviations from the above correspondence can be expected.

Using MOSBY's formula, results in close agreement with those obtained with WERNER JOHANNESSEN's formula are found for cloud covers greater than 6·5 on the scale 0–10, the average difference being only 0·005 g cal. per cm^2 per min. At cloud covers less than 6·5, MOSBY's formula gives significantly lower results, the divergence being inversely related to the degree of cloud cover. At a cloud cover of 5·0 the difference was 0·030 g cal. per cm^2 per min., and the mean difference between 5·0 and 6·5 was 0·016 g cal. per cm^2 per min. KIMBALL's formula consistently gave lower results than the other two, especially during the period April–August when differences greater than 0·050 g cal. per cm^2 per min. were common; the mean difference for the other months was only 0·009 g cal. per cm^2 per min.

The purpose of this note is to depict the seasonal radiation cycle along the Norwegian coast, and to present data enabling the calculation of incoming radiation on the sea surface between latitudes 59° and 70°N. Should MOSBY's formula be used, the appropriate solar altitude can be obtained from a nautical almanac or through interpolation of the rather incomplete data presented here (Table 3), condensed from WERNER JOHANNESSEN's tables. Should WERNER JOHANNESSEN's or KIMBALL's formula be employed, Table 2 can be consulted

Table 3

Mean solar altitude ($\bar{h}$) on days when solar declination corresponds to monthly means

Date	59°N	60°N	62°N	64°N	66°N	68°N	70°N
19. January	2·0	1·8	1·2	0·9	0·5	0·2	–
13. February	4·2	3·9	3·3	2·8	2·2	1·7	1·2
17. March	9·0	8·7	8·1	7·5	6·9	6·3	5·6
16. April	14·7	14·5	14·3	13·5	13·0	12·4	11·9
15. May	19·8	19·6	19·3	19·0	18·7	18·5	18·4
10. June	22·1	22·4	22·2	22·0	22·0	22·1	22·3
19. July	21·1	21·0	20·7	20·5	20·3	20·3	20·4
17. August	16·7	16·4	16·0	15·5	15·1	14·7	14·2
17. September	10·9	10·7	10·1	9·4	8·9	8·2	7·7
14. October	6·3	6·0	5·3	4·7	4·2	3·5	3·0
15. November	2·6	2·3	1·8	1·4	0·9	0·5	0·2
11. December	1·4	1·1	0·8	0·4	0·06	–	–

Journal du Conseil 24:215-220 (1959)

to obtain incoming radiation for a *cloudless sky* anywhere between 59°–70°N. These data, then, make it necessary to know only the degree of cloudiness for the area in question.

Although here the data are applied to Norwegian coastal waters, they have also been used to estimate incoming radiation within the Norwegian Sea around Jan Mayen Island (SMAYDA, 1958). SVERDRUP (1953) outlines a procedure to calculate the amount of light reaching any depth after knowing the incoming radiation and extinction coefficient of the water mass. The values obtained by indirect measurements represent total radiation, whereas the radiation active in photosynthesis, that in the spectral region 400–700 mμ, represents an average fraction of 0·46 of the total energy (TALLING, 1957).

While direct measurements of radiation should be made when possible, indirect measurements yield results of considerable accuracy (KIMBALL, 1928) that can be used with profit.

Summary

1. The seasonal radiation cycle along the Norwegian coast has been calculated for nine localities between latitudes 59°–70°N by means of WERNER JOHANNESSEN's formula. It has been found that the incoming radiation amounts to 0·090–0·100 g cal. per cm^2 per min. when the phytoplankton initiate their spring development; maximum abundance is obtained when incident radiation is approximately 0·150 g cal. per cm^2 per min.

2. A comparison has been made of radiation estimates by three different formulae, and data have been presented enabling the calculation of incoming radiation between latitudes 59°–70°N.

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