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EXPERIMENTAL STUDIES ON THE ATTENUATION OF UNDERWATER SOLAR IRRADIANCE IN SOME REGIONS OF THE BALTIC SEA AND SKAGERRAK

Abstract. The vertical profiles of the downwelling integral solar irradiance were measured in open Baltic Sea waters (Gotland Deep), coastal waters of the Gulf of Finland (mainly in Kunda Bay and the neighbouring regions), and Skagerrak waters in summer 1989 and 1990. Using these data the values of the integral transmittance function of solar irradiance, the depth of the euphotic zone, and the radiative heating of the water were computed. The results show that different regions can be distinguished in the Baltic on the basis of radiative characteristics. In these regions different conditions for the development of the underwater organisms may be expected.

Key words: underwater optical measurements, downwelling irradiance, radiative heating.

Introduction

Problems connected with the estimation of the ecological state of seas and inland waters have become especially topical today due to the increasing industrial and human impact on the natural environment. For a comprehensive survey of the ecological state of some waterbody complex investigations consisting of chemical, physical, optical, and biological measurements are necessary. However, quite essential conclusions may be drawn on the basis of one group of measurements. For instance, the data on the optical characteristics of the water mass enable to determine the transparency of this water and (together with the actinometric data) also the underwater radiation field; the latter is one of the main factors influencing underwater photosynthesis. The process of photosynthesis determines the growth of phytoplankton and the amount of primary production in the water mass. The growth of phytoplankton depends also on water temperature, which in its turn is influenced by solar radiative heating. So, the variability of the underwater radiation field is connected with the development and migration processes of the underwater organisms. The optical characteristics of the water mass are also indicators of certain kinds of water pollution. For instance, the presence of oil, cement, and organic substances (including some pollutants) in water mass reduces the transparency of the water and changes the spectral composition of the backscattered solar radiation. Hence, on the basis of optical measurements in and above the water mass some estimations on the ecological state of the waterbody under consideration can be made.

Several authors have proposed to classify the waters of oceans and marginal seas on the basis of their optical properties (Jerlov, 1976; Morel and Prieur, 1977; Маньковский, 1980; Афонин and Корчагина,

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1986). Such classifications are more or less detailed. Morel (Morel and Prieur, 1977) distinguishes only two types of waters: case I (open ocean clear water) and case II (coastal waters). Jerlov's classification (1976) includes ten types: five oceanic (I, IA, IB, II, III) and five coastal (1, 3, 5, 7, 9), the turbidity of water increasing with the type number. The Baltic waters belong indubitably to Morel II case waters. However, as natural environmental conditions and human impact vary in the Baltic, regional differences in optical and radiative characteristics (and several Jerlov's water types) can be expected to exist there. Also, certain differences should occur as compared with the neighbouring Kattegat and Skagerrak. This has been confirmed by Secchi disc depth values obtained during several of our marine expeditions as well as by measurements of the spectral attenuation coefficients of light in the Baltic Sea (Arst et al., 1989). Some data on the optical characteristics for the Baltic are presented also in (Højereslev, 1974; Lundgren, 1976; Czyszek, 1988; Копелевич et al., 1974; Иванов, 1975). It has been found (see the conclusions by Wozniak, Dera, and Gohs cited in Czyszek, 1988) that the open Baltic waters can be optically classified as belonging to Jerlov's water type III to 5 and more turbid near the shores. The measurements of the spectral values of the beam attenuation coefficient of light at some stations in the Baltic (near Bornholm, between Oland and Gotland, at the Landsort Deep) show that 1.5—3-fold differences may appear between the results for the regions under consideration. However, the amount of data for the Baltic is by no means sufficient. For determining the vertical profiles of the downward photon flux, the euphotic depth, and radiative solar heating of the water the full complex of spectral irradiance data in the photosynthetically active region of the spectrum and also the integral values of the downward irradiance in various depths are needed.

Measurements and Methods

The marine investigation programme carried out during research cruises of the RV *Arnold Veimer* (Estonian Academy of Sciences) included also telespectrometric and underwater optical measurements. In the summer of 1989 this programme contained for the first time measurements of the integral solar radiation in the sea by means of an underwater pyranometer. The present paper comprises mainly the description and analysis of the results obtained by means of this pyranometer during the 29th and 36th cruises of the *Arnold Veimer* in the Baltic Sea (respectively in summer 1989 and 1990). On the basis of these data the values of the integral transmittance function of the solar irradiance in the sea and the radiative heating of water were computed for the stations of radiation measurements during the cruises. Note also that one of our tasks was to estimate to what extent the underwater pyranometers designed by Gulkov et al. (Гульков et al., 1984) suit for measurements in turbid waters.

The downwelling irradiance ($E_d(z)$) in the sea was measured at several depths z by means of the pyranometer, which enables to determine the hemispherical radiation flux in the water within the spectral range 300—2800 nm, the precision of measurements in laboratory conditions is about 0.2 $W \cdot m^{-2}$ (Гульков et al., 1984). In our measurements from sea surface to 3 m the depth interval was 0.5 m and for depths more than 3 m it was 1 m. In the case of disturbing roughness of the sea 1-m depth interval was used in the whole layer investigated.

Simultaneously with underwater optical measurements actinometric measurements (incident total and direct solar radiation, reflected from the sea surface radiation, albedo of the sea surface, and the radiation balance) were carried out.

The first tests of the underwater pyranometer showed that there were difficulties in the fixing of the exact measurement depth even in the conditions of a moderately rough sea (wave heights exceeding 1 m). But it must be noted that the uncertainty in the determination of the measurement depth, caused by undulation, is not the only reason for the instability of the radiation readings in the surface layer of the sea. As known, in sunny weather there occur underwater irradiance fluctuations (light flashes) caused by the refraction of sun rays on the undulated sea surface (Stramski and Dera, 1982). Consequently, the values of the solar irradiance in the layer of flashes must be determined by averaging a sufficient amount of its individual values. However, usually one does not succeed in completely avoiding instability in the results of the underwater irradiance measurements.

In case of both these disturbing factors the best region for the radiation investigations is deeper than 3 m. However, in the midsummer of 1989 and 1990, when the expeditions were carried out, the Baltic waters contained a great amount of aggregations of blue-green algae in various stages in development. This and the high concentration of yellow substance in the Baltic Sea resulted in low transparency of water. In such conditions the relative error of the radiation measurements at greater depths becomes remarkable and increases rapidly with depth. Analysis of the whole set of results obtained shows that the accuracy of this underwater pyranometer in natural conditions is noticeably lower than given in its technical card. By rough estimations it is about 0.5—1.0 $W \cdot m^{-2}$, depending on the conditions in the region under consideration. The corresponding relative error for downward radiation flux measurements is about 5—10% in the surface layer and may be 100% or more for layers deeper than the 1%-zone (the depth where E_d is equal to 1% of its value at the surface).

In fact, we had also another underwater pyranometer, adjusted for the measurements of the upwelling radiation flux ($E_u(z)$) in the sea (Гульков et al., 1984). However, in the conditions of the Baltic turbid waters the upwelling radiation flux was found to fluctuate around 1—2 $W \cdot m^{-2}$ with the amplitude of 0.5—1 $W \cdot m^{-2}$, the last being just equal to the error in most of the measurements. In view of this we excluded the data of the upwelling radiation from the present paper.

For the reasons described above the determination of the vertical profiles of irradiance was not possible for all sampling stations located on the route of the cruises; measurements were made only under suitable weather conditions. All together 72 irradiance profiles were obtained (mainly in the southern part of the Gulf of Finland and the region of the Gotland Deep, in 1990 also in the Skagerrak).

Results

Some results obtained and also some other radiative characteristics, computed on the basis of these data, are presented below. Fig. 1 shows some vertical profiles of the downward irradiance measured in the polygons of Kunda Bay (in the southern part of the Gulf of Finland), the Gotland Deep, and the Skagerrak. As the corresponding values of incident irradiance are not far from each other (within the range

0.62—0.712 kW · m^{-2}), the values of $E_d(z)$ show expressively also the clarity of the water. The decrease of $E_d(z)$ with the increasing of depth is most remarkable in the Kunda Bay waters, suffering from strong human impact (the cement factory in the town of Kunda being the major polluter). The values of $E_d(z)$ in the waters of the Skagerrak at the depth 15 m are nearly the same as in Kunda Bay at the depth 4 m.

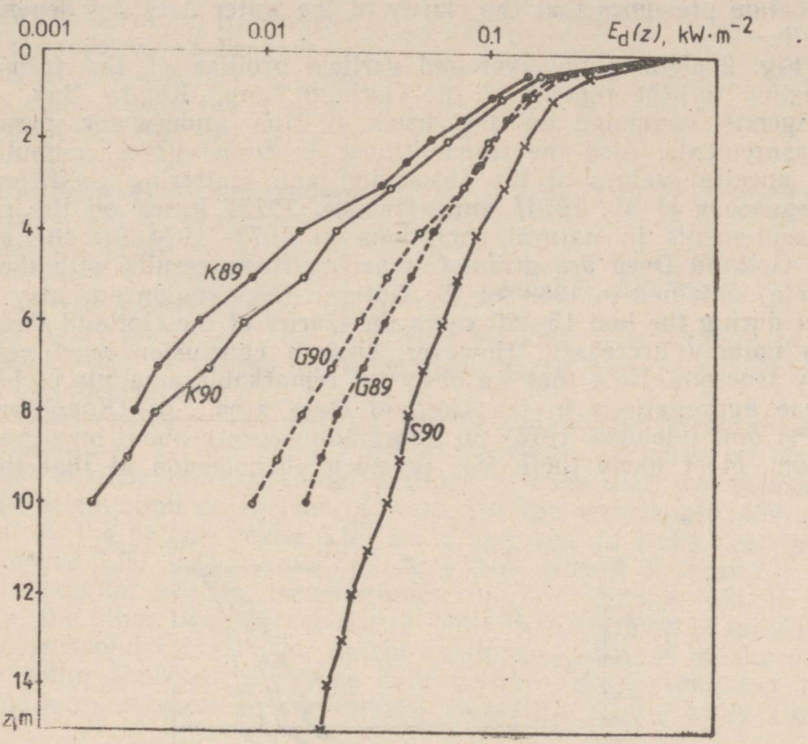

Fig. 1. Some examples of the vertical profiles of the downward irradiance in the sea (clear sky conditions): *K*89 and *K*90 — Kunda Bay, respectively June 23, 1989, 8.15 GMT and June 27, 1990, 12.50 GMT; *G*89 and *G*90 — Gotland Deep, July 21, 1989, 12.45 GMT and June 6, 1990, 14.30 GMT; *S*90 — Skagerrak July 7, 1990, 14.25 GMT.

The values of the integral transmittance function of the solar irradiance in the sea, $\tau(z)$, were computed on the basis of the actinometric and underwater radiation measurements as a function of the depth z:

$$\tau(z) = \frac{E_d(z)}{(1-A)E_{d,+0}} = \frac{E_d(z)}{E_{d,-0}}. \tag{1}$$

Here A is the albedo of the sea surface and $E_{d,+0}$ is integral solar irradiance just above the sea surface, $E_{d,-0}$ is the same just below the sea surface. The function $\tau(z)$ shows which portion of the solar irradiance just below the water surface penetrates to the depth z.

The computation results show that the vertical profiles of the transmittance function obtained for the region of Kunda Bay, the Gotland Deep, and the Skagerrak make up three groups, clearly different from one another. The averaged, typical values of $\tau(z)$ for the Gotland Deep exceed the corresponding values for Kunda Bay by 0.02—0.10, whereas these absolute differences are maximum in the layer 0.5—2 m and then start decreasing with depth. The variability of $\tau(z)$ inside both regions studied is considerably smaller. The values of $\tau(z)$ for the Skagerrak exceed those for the Gotland Deep by 0.03—0.08 and the maximum absolute differences occur in the layer 1—5 m. The comparison of the results obtained with the corresponding data for Jerlov's water types shows that the waters of Kunda Bay belong approximately to the 9th type, the Gotland Deep to the 5th and 7th type, and the Skagerrak to the 3rd type. Of course, such a comparison is quite rough, as Jerlov's classification presumes that the clarity of the water does not depend on the depth.

Fig. 2 pictures the averaged vertical profiles of the transmittance function for the regions of the Gotland Deep, Kunda Bay, and the Skagerrak computed on the basis of the underwater pyranometric measurements. Also the transmittance function curves computed using the spectral values of the absorption and scattering coefficients from (Копелевич et al., 1974) and (Иванов, 1975) based on the results of measurements in natural conditions in 1972—1974 for the region of the Gotland Deep are given. Comparing these results with the profiles of $\tau(z)$ obtained in 1989 for the Gotland Deep region one may conclude that during the last 15—20 years the clarity of the Gotland Deep waters has notably decreased. However, such a conclusion need not be the only true one. Note that we observed remarkable amounts of blue-green algae aggregations in the Gotland Deep area. In (Копелевич et al., 1974) and (Иванов, 1975) no information occurs about blue-green algae bloom. Most likely there was no such phenomenon at that time.

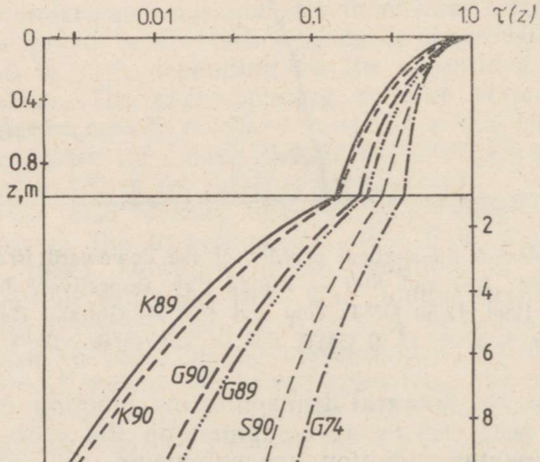

Fig. 2. Averaged vertical profiles of the integral transmittance function of downward solar irradiance in the sea $\tau(z)$: *K89* and *K90* — Kunda Bay, midsummer 1989 and 1990; *G*89 and *G*90 — Gotland Deep, midsummer 1989 and 1990; *S*90 — Skagerrak, midsummer 1990; *G*74 — Gotland Deep, computed on the basis of optical characteristics data presented in (Копелевич et al., 1974; and Иванов, 1975).

To determine the dependence of the differences in the water clarity on the depth we calculated the values of the transmittance function by layers, namely:

$$\tau(z_2 - z_1) = E_d(z_2)/E_d(z_1). \tag{2}$$

The results of these calculations are presented in Table 1.

It should be noted that $\tau(z_2—z_1)$ does not give entirely authentic data about the differences of the water clarity for the layers $z_2—z_1$; in fact, the value of the quotient $E_d(z_2)/E_d(z_1)$ is influenced by all the layers above the depth z_1. The amount of the radiation transmitted through the layer $z_2—z_1$ depends on the spectral composition of the radiation falling onto the level z_1; on the other hand, this spectral composition depends on the optical qualities of the whole water column lying above z_1. Nevertheless, it seems that the values of $\tau(z_2—z_1)$, shown in Table 1, reveal to some extent the real differences of the water clarity at the time of the two investigations. It is difficult to say which part of this is caused by blue-green algae bloom and which is induced by other factors.

Table 1

The values of $\tau(z_2—z_1)$ in % for the Gotland Deep polygon

z_1, m	z_2, m	Data from literature*	Present data
0.2	0.5	81	73
0.5	1	80	72
1	2	74	61
2	4	65	45
4	6	72	52
6	8	75	61

* Копелевич et al., 1974; Иванов, 1975.

Fig. 3 demonstrates the diurnal run of the integral transmittance function computed by formula (1) using the measured values of $E_d(z)$, $E_{d,+0}$, and A. The corresponding chlorophyll data and the values of the beam attenuation coefficient of light (at the wavelength 439 nm) measured by the optical device Liki are also given (a short description of the device Liki is presented in Arst et al., 1989). As expected, the diurnal maximum of the transmittance function corresponds to the minima of the other two characteristics. Note that the diurnal maximum of $\tau(z)$ corresponds also to the Secchi depth maximum (4 m, the other readings being about 3 m). These data confirm the assumption that one of the main reasons for the diurnal variability of the water clarity

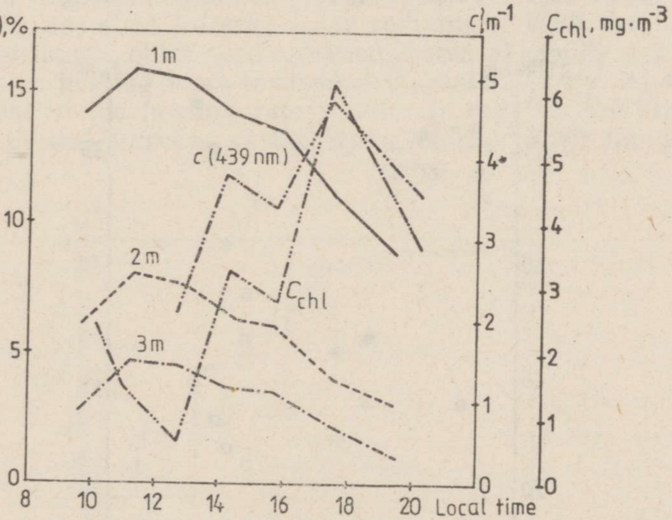

Fig. 3. Diurnal run of the integral transmittance function $\tau(z)$ on June 23, 1989 in the western part of Kunda Bay (Toolse Beach) at the depths 1, 2, and 3 m. C_{chl} and $c(439\text{ nm})$ are respectively chlorophyll *a* concentration and the spectral beam attenuation coefficient of light in water, measured by the optical device Liki at 439 nm (both at 3 m depth).

(as well as of the radiance factor of the sea) is the dial-vertical migration of the optically active substances in the sea (see also Postma and Spitzer, 1982; Васильков, 1982; and Васильков et al., 1985).

Note that for different reasons the quantity of the data on chlorophyll concentration and downward irradiance is not equal and their measurements were not always simultaneous. Therefore we could not apply traditional methods to investigate the correlative relationships between the values of C_{chl} and $\tau(z)$. However, there obviously exists some accordance between the values of these characteristics in different regions of the Baltic. Table 2 demonstrates that an increase in the irradiance transmission function corresponds to the decrease of chlorophyll concentration on the track from the Gulf of Finland through the Gotland Deep to the Skagerrak. The values of $\tau(z)$ presented in Table 2 were computed for the depth of 3 m, the values of C_{chl} were measured in the depth range 2—5 m.

Table 2

Average, maximum, and minimum values of chlorophyll *a* concentration (C_{chl}) in the water and the downward irradiance transmittance function (τ) obtained by measurements during two cruises of the RV *Arnold Veimer* (summer 1989 and 1990)

Region	Year	$\bar{C}_{chl}$	C_{chl} (max)	C_{chl} (min)	$\bar{\tau}$	τ (max)	τ (min)
		z=2—5 m			z=3 m		
Gulf of Finland	1989	2.80	6.50	0.74	0.049	0.071	0.027
	1990	3.61	5.22	2.06	0.057	0.063	0.042
Gotland Deep	1989	1.40	1.80	1.30	0.102	0.144	0.077
	1990	1.55	2.94	0.96	0.091	0.122	0.068
Skagerrak	1989	—	—	—	—	—	—
	1990	0.97	1.82	0.44	0.157	0.190	0.127

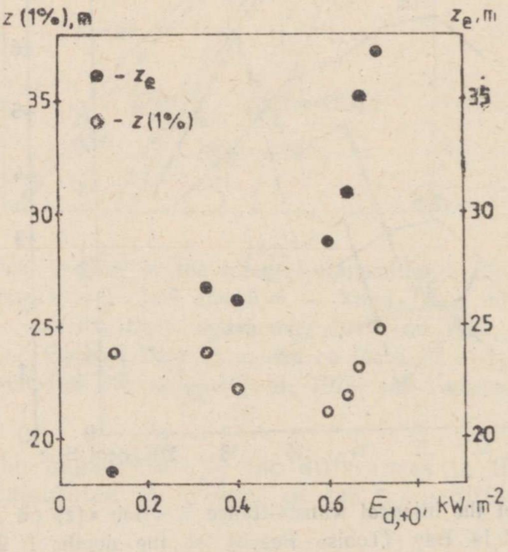

Fig. 4. The euphotic depth, z_e, and z (1%) in the Skagerrak waters for several values of incident irradiance, $E_{d,+0}$ (data obtained during the 36th cruise of the RV *Arnold Veimer*, July 1990).

Problems faced in investigating the process of photosynthesis and estimating primary production in the sea are obviously connected with the determination of the euphotic depth values. We accepted the definition of the euphotic depth (z_e) proposed by Chekhin (Чехин, 1987) saying that z_e is the depth where the downwelling irradiance is 0.75 $J \cdot cm^{-2} \cdot h^{-1}$ and below this depth the amount of solar light is insufficient to trigger the process of photosynthesis. The value 0.75 $J \cdot cm^{-2} \cdot h^{-1}$ usually lies within the range 0.03—10% of the irradiance value on the water surface. The latter, in its turn, depends on the solar zenith angle, atmospheric transparency, cloudiness, etc. So, the absolute value of the 1% from the irradiance just beneath the water surface (sometimes used as the basic value for estimating the euphotic depth) could be quite different.

It is clear that $z(1\%)$ strongly depends on the transparency of water: for instance, its mean value in Kunda Bay is about 5.5 m, in the Gotland Deep 11 m, and in the Skagerrak waters 23 m. The euphotic depth value depends on the water clarity as well as on the amount of incident irradiance. An example of the euphotic depth and $z(1\%)$ values in the Skagerrak waters is given in Fig. 4.

On the basis of the results of underwater radiation measurements it is possible to compute the radiative heating of seawater $(\partial T/\partial t)_r$:

$$(\partial T/\partial t)_r = -\frac{1}{\varrho c_P}\left[\frac{E_d(z_1)-E_d(z_2)}{z_1-z_2}-\frac{E_u(z_1)-E_u(z_2)}{z_1-z_2}\right], \qquad (3)$$

where ϱ is the thickness of the water and c_P is the specific heat capacity of the water. In the present investigation the values of the radiative heating were found using only the downwelling irradiance data. The last term of formula (3) is very small in comparison with the first term; besides, as was mentioned above, the values of the upwelling radiation flux were highly uncertain. Note that the radiative heating can also be computed from the data on $E_{d,-0}$ and $\tau(z)$, because $E_d(z) = E_{d,-0} \cdot \tau(z)$.

It should be noted that at the sea surface and up to the depth of about 1—2 cm the values of the radiative heating do not depend on water clarity (the radiative heating of this layer is formed on the account of the absorbed infrared solar radiation). With the increase of depth the contribution of infrared radiation decreases rapidly and the values of the radiative heating start to depend on water clarity. At the beginning the order of the heating rate profiles is regular: the heating rate increases with the decrease of the water clarity. Then the profiles of

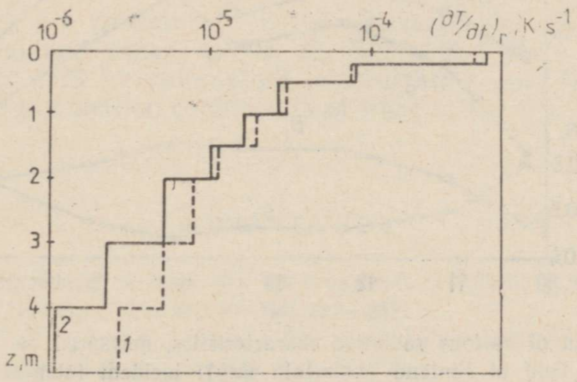

Fig. 5. Vertical profiles of the radiative heating of water for the regions of the Gotland Deep (*1*) and Kunda Bay (*2*), computed assuming that in both cases $E_{d,-0} = 0.7$ $kW \cdot m^{-2}$. The values of $\tau(z)$ needed for the computations are the same as in Fig. 2 for 1989.

the radiative heating run into another crossing at different depths and finally, at greater depths, the regular disposition of the curves is regained but in the reversed order (Arst and Soomer, 1987). Fig. 5 demonstrates the profiles of the radiative heating of the seawater for the regions of the Gotland Deep and Kunda Bay, computed on the basis of the $\tau(z)$ values of Fig. 2 (data of 1989) presuming that $E_{d,-0}=0.7$ $kW \cdot m^{-2}$ in both cases. One can see that in turbid waters of Kunda Bay

Table 3

Values of $(\partial T/\partial t)_r/E_{d,-0}$ for water layers of 1-m thickness at three sampling stations of the 36th cruise of the RV *Arnold Veimer*, 1990 (in relative units)

z, m	Station 13 Kunda Bay 27. 06. 90 14.50 GMT	Station 22 Gotland Deep 30. 06. 90 16.20 GMT	Station 48 Skagerrak 07. 07. 90 15.20 GMT
0—1	124	115	107
1—2	8.3	11.6	8.8
2—3	3.7	5.2	6.5
3—4	2.6	3.2	4.3
4—5	1.2	2.2	3.1
5—6	0.72	1.4	1.9
6—7	0.46	1.0	1.6
7—8	0.31	0.68	1.3

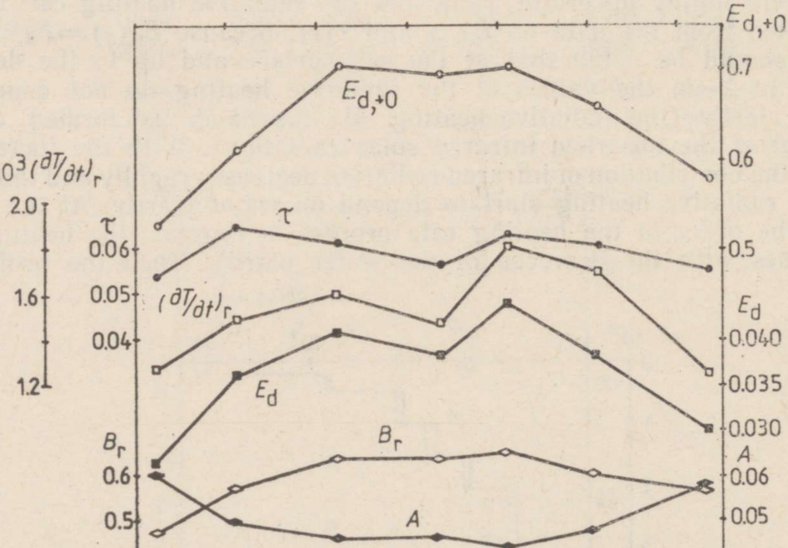

Fig. 6. Diurnal run of various radiative characteristics, measured on July 21, 1990 at a polygon in the Gulf of Finland (Lohusalu Bay): incident integral solar irradiance ($E_{d,+0}$) and downwelling irradiance (E_d) at the depth 3 m (both in $kW \cdot m^{-2}$); the integral transmittance function (τ) at the depth 3 m; radiative heating of the layer 0.50—0.75 m ($(\partial T/\partial t)_r$, in $K \cdot min^{-1}$); radiation balance (B_r, in $kW \cdot m^{-2}$), and albedo (A) of the sea surface.

we have got a warmer surface layer and less warm water in deeper layers than in the Gotland Deep. However, the crossing of two curves of radiative heating takes place quite near the surface, at about 0.5 m depth.

Table 3 presents the solar heating data for different groups of water turbidity. To demonstrate the influence of water turbidity on the character of the radiative heating profile, $(\partial T/\partial t)_r$ values were normalized to $E_{d,-0}$.

An example of the diurnal run of some radiative characteristics measured in Lohusalu Bay (Gulf of Finland) on July 21, 1990 are shown in Fig. 6. Note that the minimum of the curves $E_{d,+0}$, E_d, and $(\partial T/\partial t)_r$, taking place at 13.00—13.30, is caused mainly by Sc clouds covering practically the whole sky.

Conclusions

The above-described results of underwater optical measurements and some earlier findings (Arst et al., 1984) as well as the data on Pärnu Bay presented in (Arst et al., 1992) show that the Baltic Sea may be optically classified into several regions. This means that in these regions different conditions for the development of underwater life may also be expected. Our data set is insufficient for the estimation of the long-term trends of water turbidity in the Baltic. For this continuous prolonged measurements embracing all seasons of the year on various polygons in the Baltic area are needed. It seems reasonable to continue and extend the collecting of data for turbid waters to find out the seas, lakes, and coastal zones where the optical characteristics have extreme values.

In turbid waters the underwater pyranometer designed by Gulkov et al. (Гульков et al., 1984) is suitable only for measuring the downwelling irradiance in the surface layer of the sea. The precision of this instrument is insufficient for measurements at the depths where $E_d \leqslant 5\ \mathrm{W \cdot m^{-2}}$ and for measuring the upwelling radiation at all depths.

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