THE ESTIMATION OF THE YEARLY CYCLE OF SUBMARINE IRRADIANCE FOR ECOLOGICAL PURPOSES

A METHODOLOGICAL EXAMPLE BASED ON DATA FROM BANYULS-SUR-MER (FRANCE)

by

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ABSTRACT

The yearly cycle of surface solar irradiance at Banyuls-sur-Mer is derived from meteorological data. Monthly irradiance attenuation coefficients of the seawater were obtained from Secchi disc readings, which enabled the authors to classify the monthly optical water types according to Jerlov's classification. The average daily values of submarine irradiance are calculated for each month, and for different depths. Calculations have been carried out for the visible spectrum (350-710 nm) subdivided into 20 nm bands. Submarine irradiance is given in energetic (cal cm^{-2} day^{-1}) as well as quantum (μE m^{-2} s^{-1}) units. Some considerations are given for underwater stations with different degrees of exposition to available light.

RÉSUMÉ

Le cycle annuel de l'insolation à Banyuls-sur-Mer est établi à partir de données météorologiques. Les coefficients mensuels d'atténuation de l'eau de mer sont obtenus à partir des profondeurs de disparition du disque de Secchi. Se basant sur ces données, les auteurs ont établi le type optique d'eau pour chaque mois selon la classification de Jerlov. Les valeurs moyennes de l'irradiance sous-marine sont calculées pour chaque mois et pour plusieurs profondeurs. Les calculations sont effectuées pour le spectre visible (350-710 nm) subdivisé en bandes spectrales de 20 nm. L'irradiance sous-marine est donnée en unités énergétiques (cal cm^{-2} jour^{-1}) et en quanta (μE m^{-2} s^{-1}). Le problème des surfaces élémentaires avec des degrés d'exposition différents est abordé sommairement.

I. INTRODUCTION

The ecologist, whether working on land or in the sea, often needs to know the amount of light reaching the organisms he studies. Measurements of submarine daylight are difficult to carry out (Weinberg, 1976). Consequently they are for most regions either totally lacking, or performed with insufficient frequency to allow for an estimation of the seasonal variations in submarine irradiance.

An alternative to permanent underwater irradiance measurements is the calculation of submarine daylight from easily obtained data. In the aforementioned paper (Weinberg, 1976) such a method was developed which had the disadvantage of taking into consideration only one spectral band (maximum at 480 nm, band-width 60 nm). In the present paper the method will be further refined, by which it becomes possible to obtain a good estimation of submarine spectral irradiance distribution based on optical water types and from which it is easy to derive total numbers of quanta, or energy values, for whatever spectral region desired.

In order to employ this method, only the following parameters need to be known: (1) total solar irradiance (sun + sky) reaching the sea surface, (2) percentage of sunny and of overcast hours and (3) depth of disappearance of the Secchi disc. In order to illustrate the method clearly, a concrete example has been chosen: the calculation of the yearly cycle of submarine irradiance between 0 and 40 m in the coastal waters off Banyuls-sur-Mer (France) in the Mediterranean. The results are only approximate, since the input data are average values. Even so, we believe this attempt to estimate the seasonal variations of submarine daylight to be far more accurate than estimations from some random accurate measurements throughout the year.

II. COMPUTATION METHOD

The sequence of the calculation is given by fig. 1. Starting point of the computations is I_{tot} = total surface irradiance (300-3000 nm). If this value is not measured at the locality considered, there are other means to obtain reliable data, as will be shown in the next paragraph.

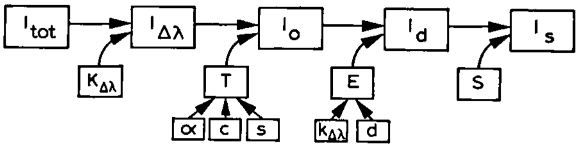

Fig. 1. Schematic representation of the different steps involved in computation of submarine irradiance at a given station. For explanation, see text.

Because we want to deal with visible light only (350-710 nm) and because calculations are to be carried out for narrow spectral bands separately, the next step calculates the amount of irradiance represented by each spectral band $\Delta\lambda$. As will be seen, this is a simple multiplication of I_{tot} with a different constant $K_{\Delta\lambda}$ for each spectral band.

Now that we know $I_{\Delta\lambda}$ = surface irradiance in the spectral band $\Delta\lambda$ considered, we want to calculate subsurface irradiance I_0 (also for the spectral range $\Delta\lambda$). This is obtained by multiplication of $I_{\Delta\lambda}$ with the transmission coefficient T. $T = 1 - A$, A being the apparent albedo, a quantity analogous with reflection, and depending on solar altitude α (hence on the date and the hour of the day), on the degree of cloudiness of the sky c and surface condition of the sea s (Weinberg, 1976).

The next step is the computation of irradiance at depth d, following the attenuation law $E = e^{-kd}$. This is where the method developed in an earlier paper (Weinberg, 1976) is going to be further refined. Because the attenuation coefficient k is different for each spectral band, and will also depend on water transparency, we developed a method allowing the determination of the different $k_{\Delta\lambda}$ values from Secchi disc readings. As will be shown in section IV, if one knows the (average) depth of disappearance of the Secchi disc, it is possible to decide what the optical water type (classification of Jerlov, 1976) is, from which the different $k_{\Delta\lambda}$ values can be derived.

In a final step, multiplication with the station coefficient S (a constant for each station) yields the irradiance received by a given station at depth d, S being 1 for horizontal surfaces, but assuming values smaller than 1 for other slope types.

In the next two sections we will go through such a calculation in detail, the example chosen being the coastal water off Banyuls-sur-Mer (Mediterranean Sea).

III. TOTAL SOLAR IRRADIANCE REACHING THE SEA SURFACE

In order to know exactly the yearly cycle of solar irradiance at a certain place, pyranometer measurements over several years are needed. Reliable data

TABLE I

Average monthly total solar irradiance (sun + sky, 300-3000 nm) at Banyuls-sur-Mer in cal cm^{-2} day^{-1}. Data are derived from Jacques et al. (1968) and Ashbel (1970).

Month	Jacques et al. '65-'66	Jacques et al. '66-'67	Jacques et al. '67-'68	Jacques et al. '68-'69	Ashbel '57-'58	Ashbel '64-'66	Mean Jacques + Ashbel
01	149.10	156.03	188.29	167.74	170	150	163.52
02	188.77	228.91	194.27	247.07	230	250	223.17
03	398.81	353.40	348.86	303.23	300	320	337.38
04	442.53	451.61	382.08	367.26	400	450	415.58
05	545.52	512.54	523.06	466.43	530	550	521.26
06	533.33	575.39	591.88	559.14	550	580	564.96
07	508.96	559.62	587.34	534.77	570	600	560.11
08	500.12	437.75	481.00	474.31	540	500	488.86
09	335.48	409.32	349.82	358.18	360	390	367.13
10	194.50	241.58	266.91	270.97	300	250	254.00
11	164.16	173.00	144.80	144.80	200	190	169.46
12	125.21	145.28	153.17	140.26	130	110	133.99

of this type are difficult to obtain [1]), since most meteorological stations do not carry them out as a routine measurement.

For this reason it is necessary to consider two other methods, which will yield fairly good approximations. The first one is the calculation of monthly irradiance from monthly number of sunshine hours as employed by Jacques et al. (1968). The other method consists in the examination of available meteorological data of nearby places. We have used the world solar radiation maps (Ashbel, 1970), by interpolating between existing monthly iso-energy lines. Mean monthly values were computed using all data available. They appear in the last column of table I.

In some cases, as for the calculation that will be presented in the next paragraph, we need to know the average irradiance for each hour of the typical monthly day. As we do not possess continuous recordings of solar irradiance at Banyuls-sur-Mer, we have to reconstruct the daily cycles. Liu & Jordan (1960) developed a method to calculate irradiance values at any time of the day, provided the following parameters are known: (1) total daily irradiance, and (2) astronomical daylength. For (1) we take the values of the last column of table I, while (2) is easily calculated for any given location. We have taken the daylength for the 15th of each month (table II).

TABLE II

Astronomical daylength at the 15th of each month at Banyuls-sur-Mer.

Month	Minutes	Month	Minutes
01	568	07	897
02	637	08	834
03	714	09	750
04	801	10	667
05	873	11	589
06	913	12	548

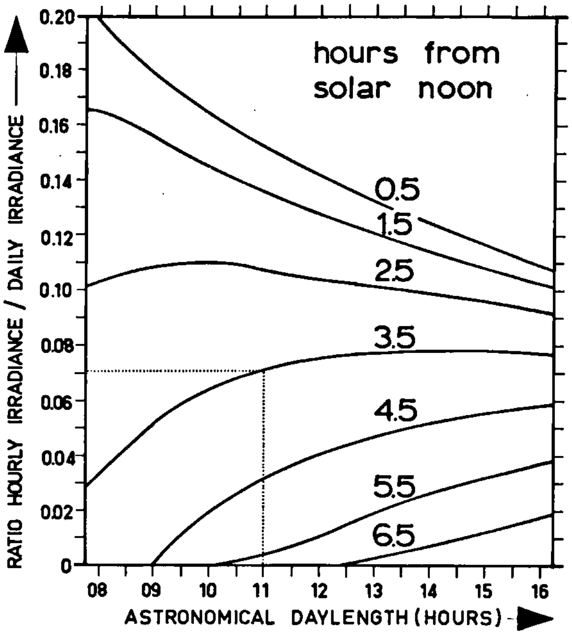

Fig. 2. Relationships between total hourly irradiance and total daily irradiance as a function of astronomical daylength and deviation before or after solar noon in hours (after Liu & Jordan, 1960). Example (dotted line): for a day with astronomical daylength of 11 hours, the ratio between hourly irradiance (which we wish to know) and total daily irradiance (which is known) is 0.071 for the fourth hour (curve 3.5) before or after solar noon.

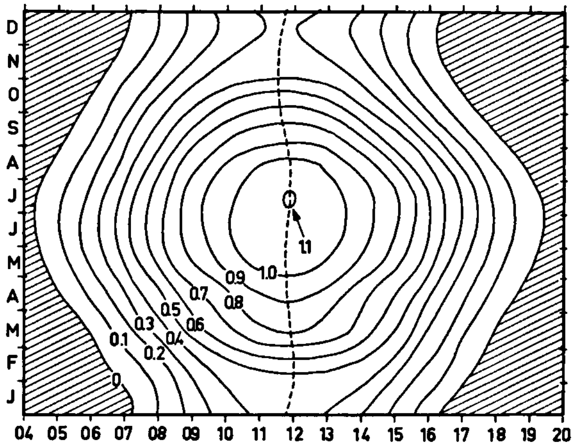

Fig. 3. Iso-energy lines (in cal cm^{-2} min^{-1}) for total solar irradiance at Banyuls-sur-Mer. The dotted line corresponds to G. M. T. of solar noon, hatched areas represent astronomical night.

The existing relationships between daily irradiance, hourly irradiance and astronomical daylength are given in fig. 2 (after Liu & Jordan, 1960). We have thus been able to reconstruct the average daily irradiance cycle for each month (table III). A graphical representation of the iso-energy lines of a yearly cycle (fig. 3) shows clearly the seasonal changes that occur throughout the year.

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[1]) The measurements used by one of the authors (Weinberg, 1975) in an earlier attempt to calculate submarine irradiance at Banyuls-sur-Mer, were unreliable because they had been carried out under glass.

IV. CALCULATION OF SUBMARINE DAYLIGHT

For the calculation of the amount of light reaching an underwater station, several parameters must be known (fig. 1). The first is total solar irradiance reaching the surface, which has been calculated for Banyuls-sur-Mer in the preceding paragraph. These data are defined for the total solar spectrum (300-3000 nm).

For our calculations we consider the visible spectrum (350-710 nm) only, which roughly represents 50% of the total solar energy reaching the sea surface. This spectrum itself has been subdivided into portions of 20 nm band-width, each representing a certain amount of the total solar energy reaching the sea surface (fig. 4). The spectral distribution of daylight is not constant, but shows minor fluctuations (Jerlov, 1976: fig. 30 B & C). As a result, the percentages for each spectral band will also fluctuate slightly, but they will be assumed constant here. Our calculations have been carried out separately for each spectral band, whereas Weinberg (1976) considered blue-green light only.

Part of the daylight is reflected at the sea surface. For our calculations we did not use true reflection, but apparent albedo values (table 3, j in Weinberg, 1976) which vary for cloudy and sunny conditions and with solar altitude. Knowing the (apparent) amount of light subsisting just below the surface, we can calculate the attenuation it will undergo following the Lambert-Beer law:

$$I_d = I_0 \cdot e^{-kd}$$

with

I_d = irradiance at depth d;
I_0 = irradiance just below the surface;
k = irradiance attenuation coefficient of seawater.

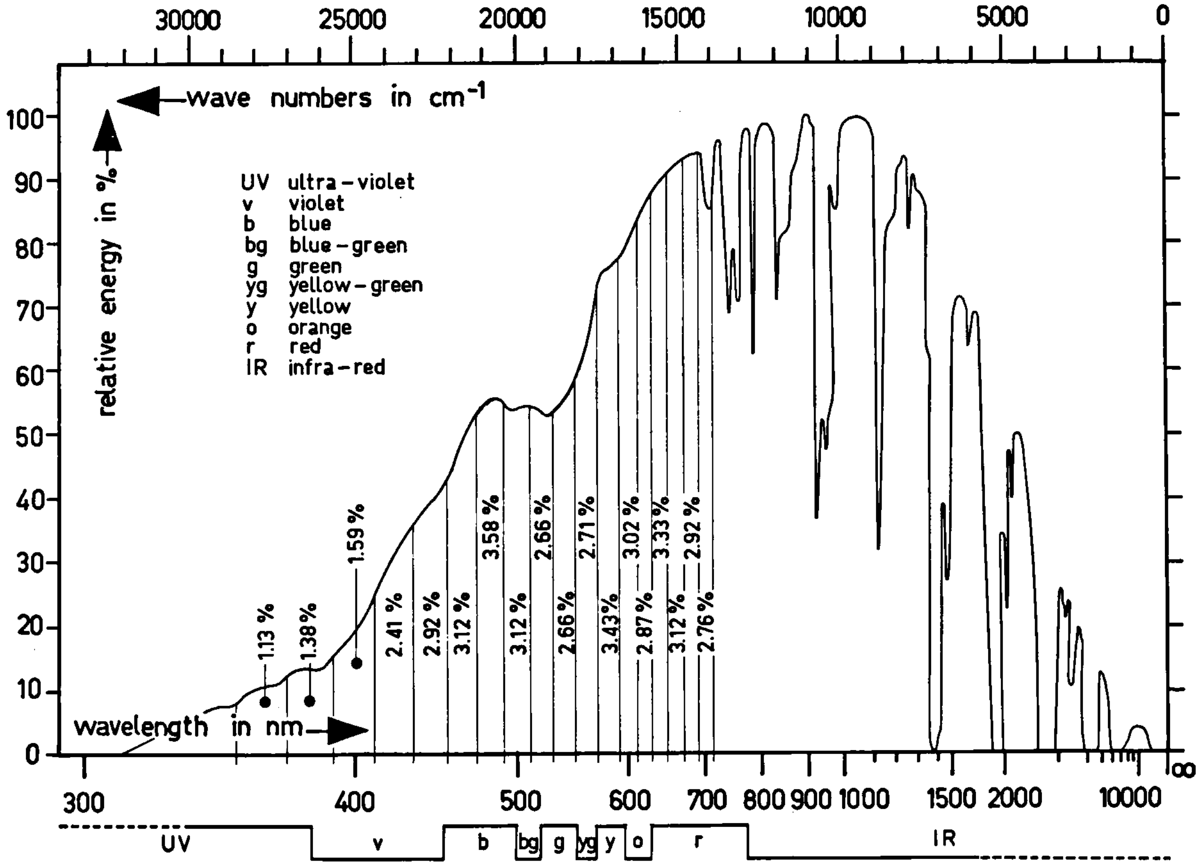

Fig. 4. Average spectral distribution of daylight (after Gates, 1965), with visible spectrum (350-710 nm) subdivided into 20 nm bands, each representing a certain amount of total daylight energy. Relative spectral energy is given as a linear function of wave number (frequency) rather than wavelength, since energy is linearly proportional to frequency (= inverse of wavelength).

The value of the irradiance attenuation coefficient k_{480} (for light with a wavelength of 480 nm, i.e. blue-green light) can be calculated from the depth of disappearance of the Secchi disc D_{sd} using the following empirical formula (Weinberg, 1976):

$$k_{480} = 2.6 / (D_{sd} + 2.5) - 0.048$$

The Secchi disc readings that have been carried out at Banyuls-sur-Mer during the years 1971-1977 (Panouse, unpublished results) have been plotted in a graph (fig. 5). The average monthly values for k_{480} have been calculated from the smooth curve representing the average yearly variation of D_{sd} at Banyuls-sur-Mer. These values appear in table IV.

For calculations taking into account the entire visible spectrum (350-710 nm), however, we need to know the irradiance attenuation coefficients for each spectral band (k_{360}, k_{380}, k_{400}, ..., k_{700}). These can be obtained by plotting the T_{480} (transmittance in % m^{-1} for 480 nm) values on a graph representing the optical water types defined by Jerlov (1976: 134, table 26). Conversion of k_{480} values into T_{480} values takes place according to: $T = 100 \cdot e^{-k}$. Interpolation of curves comprising our T_{480} values between the curves for existing water types (fig. 6) yields the intermediate water types describing the situation at Banyuls-sur-Mer for every month of the year. The water types occurring at Banyuls-sur-Mer vary greatly for different seasons. They range between oceanic type II and coastal type 1.

It is now possible to calculate the average daily amount of irradiance per month for each spectral band and each depth.

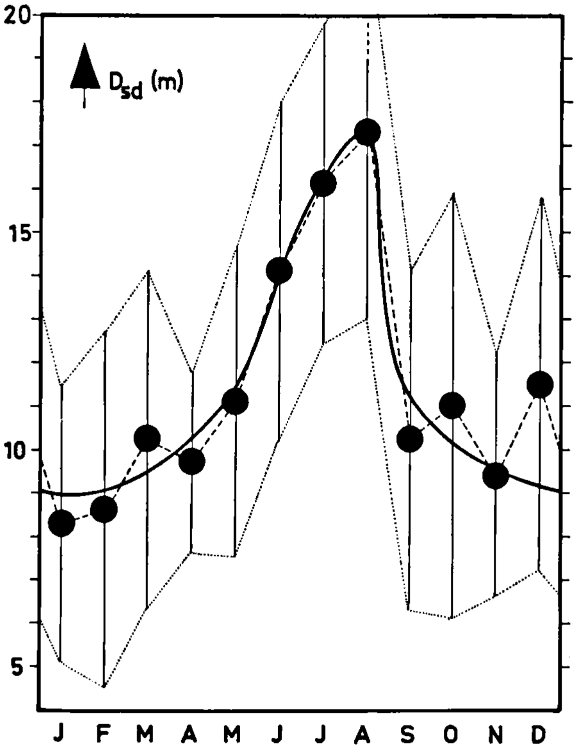

Fig. 5. Average values of depth of disappearance of Secchi disc (D_{sd}) at Banyuls-sur-Mer from October 1971 to May 1977 (unpublished data from Panouse). Vertical bars represent standard deviation for each month. The smooth curve was used in our calculations.

TABLE III

Total solar irradiance reaching the sea surface at Banyuls-sur-Mer, in periods of one hour from solar noon, in cal cm^{-2} $hour^{-1}$.

Period	1	2	3	4	5	6	7
Month							
01	27.80	24.53	17.99	9.81	1.64	0.00	0.00
02	33.70	30.13	24.55	15.62	6.70	0.89	0.00
03	47.91	43.18	35.42	25.30	13.50	3.37	0.00
04	54.03	48.21	41.56	32.00	20.78	9.14	2.08
05	62.55	57.86	50.56	40.66	28.15	15.64	5.21
06	64.97	61.02	53.67	44.07	31.64	19.21	7.91
07	65.53	60.49	54.33	43.69	30.81	17.92	7.29
08	61.11	56.22	47.31	37.64	25.42	12.71	3.42
09	49.93	45.16	37.81	28.72	16.52	5.51	0.37
10	38.10	34.29	26.96	18.29	8.13	1.27	0.00
11	27.96	24.57	18.64	10.68	2.88	0.00	0.00
12	23.85	20.63	14.47	7.64	0.40	0.00	0.00

TABLE IV

Average monthly values for depth of disappearance of Secchi disc (D_{sd}) at Banyuls-sur-Mer from October 1971 to May 1977, number of observations (N) for each month, and average attenuation coefficients (k_{480}) derived from these data. Secchi disc values (D'_{sd}) represent the smooth curve of fig. 4, with k'_{480} values corresponding to them.

Month	N	D_{sd} (m)	k_{480}	D'_{sd} (m)	k'_{480}
01	54	8.3	0.193	9.0	0.170
02	57	8.6	0.186	9.1	0.169
03	69	10.2	0.157	9.5	0.166
04	56	9.7	0.165	10.2	0.158
05	85	11.1	0.143	11.4	0.138
06	58	14.1	0.109	14.0	0.109
07	55	16.1	0.092	16.2	0.092
08	73	17.3	0.083	17.3	0.083
09	45	10.2	0.157	11.2	0.140
10	43	11.0	0.145	10.2	0.155
11	64	9.4	0.170	9.6	0.164
12	53	11.5	0.138	9.2	0.168

We have:

$$I_{\Delta\lambda,d,m} = K_{\Delta\lambda}\, e^{-k_{\Delta\lambda,m}d} \left[P_m \sum_{h=1}^{24} I_{mh}\, T_{mh} + (1 - P_m)\, T' \sum_{h=1}^{24} I_{mh}\right]$$

where:

$I_{\Delta\lambda,d,m}$ = total average daily irradiance at depth d, month m, for spectral band $\Delta\lambda$ considered;

$K_{\Delta\lambda}$ = conversion constant (energy percentage of spectral band $\Delta\lambda$ considered);

$k_{\Delta\lambda,m}$ = mean value of irradiance attenuation coefficient for spectral band $\Delta\lambda$ and month m;

P_m = percentage of sunny hours in month m;

I_{mh} = total irradiance reaching the water surface, month m, hour h;

T_{mh} = transmission (= 1 – apparent albedo) sunny weather, month m, hour h;

T' = transmission cloudy weather (T' = 0.55).

Conversion from energy (cal cm^{-2} day^{-1}) into number of quanta (μE m^{-2} s^{-1}) is carried out according to:

$$X = (5.83 \cdot Y \cdot \lambda)\,/\,D$$

where X = number of quanta (μE m^{-2} s^{-1});
Y = energy (cal cm^{-2} day^{-1});
λ = wavelength considered (nm);
D = daylength (min).

In this way the monthly spectral distribution of energy and quanta can be plotted as a function of depth. An example of spectral energy distribution is given for January and July for some chosen depths (fig. 7). By summation of the values found for the different spectral bands, we obtain (table V) the values for the entire visible spectrum (350-710 nm). One of the features appearing from this table is the increase in seasonal fluctuations with increasing depth. While, at Banyuls-

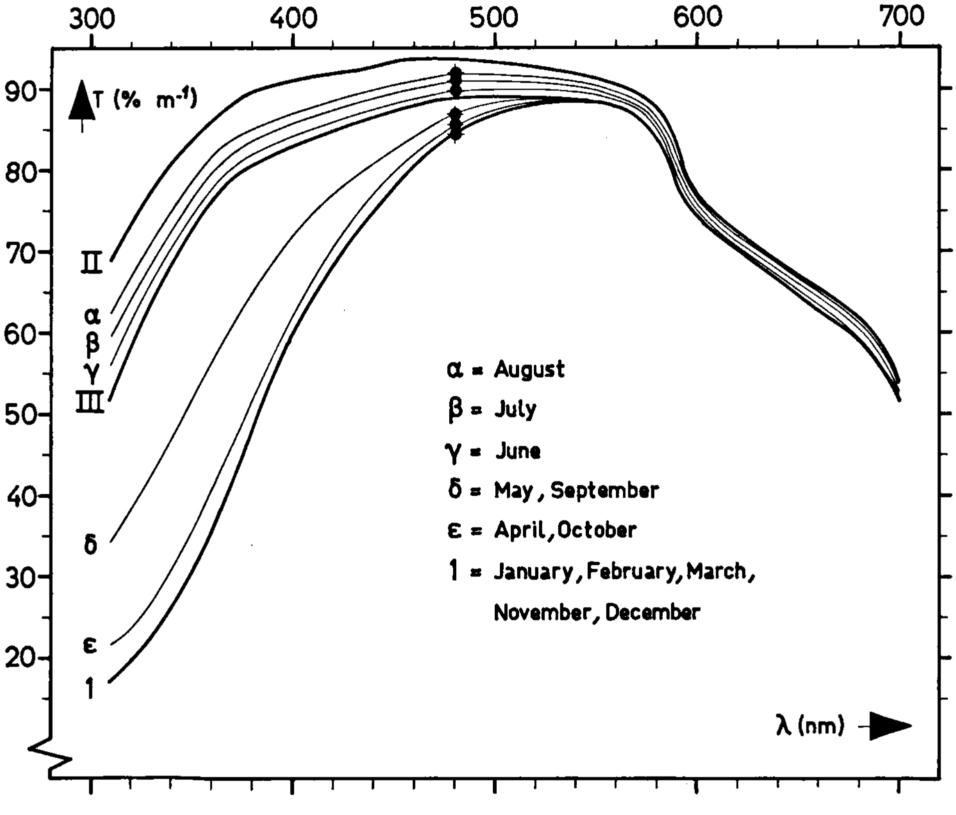

Fig. 6. Transmittance T in % m^{-1} as a function of optical water type. Types II and III are oceanic waters, type 1 coastal water according to Jerlov (1976); α, β, γ, δ and ε are interpolated water types corresponding to the monthly k_{480} values found at Banyuls-sur-Mer (black dots).

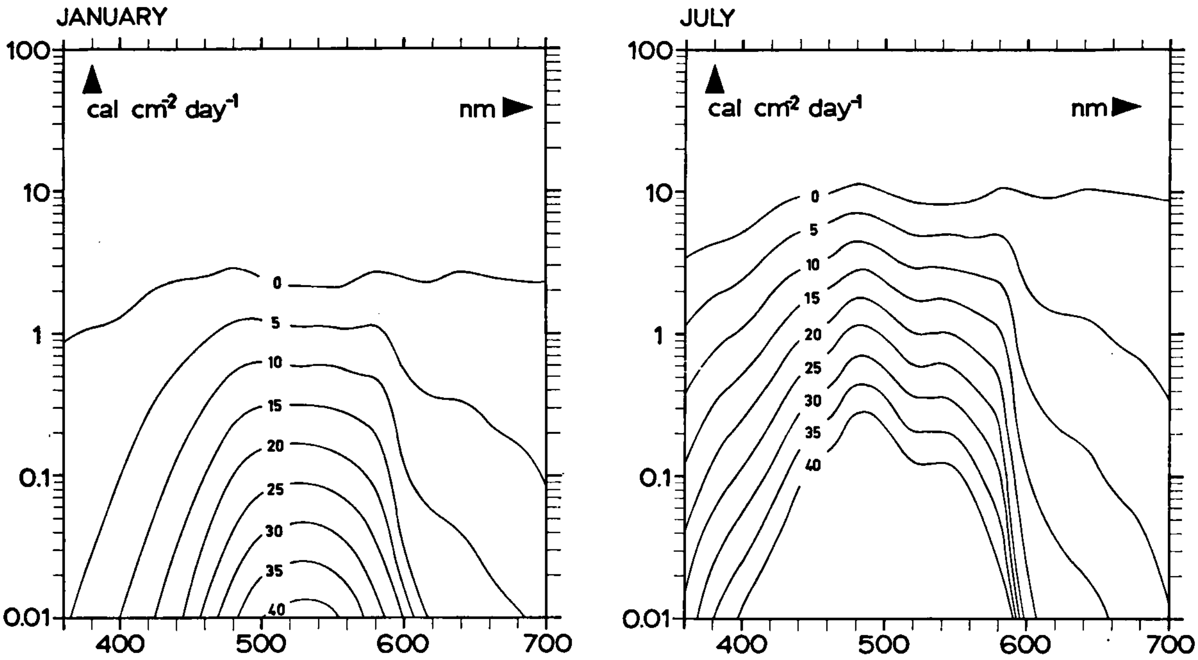

Fig. 7. Submarine irradiance as a function of wavelength for several depths at Banyuls-sur-Mer.

sur-Mer, at zero meters depth, the surface irradiance during the maximal month (June) is only 4.9 times that received during the minimal month (December), at 40 m, the irradiance in August is 33.4 times that in December. This phenomenon may have important ecological implications.

Thus far, the calculated values represent open water situations. For benthic organisms the degree of exposure of the stations where they live is very important: at the same depth a horizontal surface, a vertical wall or the interior of a cave will not receive the same amount of light. In order to estimate the amount of light received by a given station, it is necessary to determine experimentally its exposition coefficient *S*. This coefficient will have a value between 0 and 1. To give an idea of

TABLE V

Submarine irradiance in cal cm^{-2} day^{-1} (roman type) and number of quanta in μE^{-2} s^{-1} (italics) in the coastal water off Banyuls-sur-Mer, as a function of depth and month, for the visible spectrum ranging from 350 to 710 nm (listings with values per meter depth are available from the authors upon request).

Month	01	02	03	04	05	06	07	08	09	10	11	12
Depth (m)												
0	39.42	57.59	90.64	113.38	143.71	155.79	154.59	134.93	99.70	66.96	42.26	31.79
	220.95	*287.81*	*404.11*	*450.60*	*524.05*	*543.22*	*548.65*	*515.04*	*423.18*	*319.58*	*228.39*	*184.67*
5	10.62	15.52	24.43	31.72	43.74	57.28	60.23	55.22	30.34	18.73	11.46	8.62
	57.88	*75.39*	*105.85*	*121.97*	*152.26*	*185.35*	*197.59*	*194.66*	*122.95*	*86.50*	*60.19*	*48.67*
10	4.15	6.06	9.54	12.69	18.11	27.51	30.89	29.62	12.56	7.49	4.51	3.40
	22.35	*29.11*	*40.88*	*48.26*	*62.41*	*87.41*	*99.34*	*102.16*	*50.39*	*34.23*	*23.48*	*18.99*
15	1.85	2.70	4.24	5.76	8.39	14.33	17.13	17.21	5.82	3.40	2.03	1.53
	9.94	*12.95*	*18.18*	*21.90*	*28.94*	*45.44*	*54.92*	*59.09*	*23.37*	*15.53*	*10.57*	*8.54*
20	0.87	1.27	1.99	2.75	4.07	7.70	9.77	10.30	2.82	1.63	0.97	0.73
	4.67	*6.09*	*8.55*	*10.49*	*14.08*	*24.45*	*31.34*	*35.37*	*11.37*	*7.44*	*5.03*	*4.07*
25	0.42	0.61	0.96	1.35	2.02	4.21	5.66	6.27	1.40	0.80	0.47	0.35
	2.26	*2.94*	*4.13*	*5.16*	*7.00*	*13.37*	*18.16*	*21.53*	*5.65*	*3.66*	*2.46*	*1.99*
30	0.20	0.30	0.47	0.67	1.02	2.32	3.31	3.85	0.70	0.40	0.23	0.18
	1.11	*1.44*	*2.03*	*2.58*	*3.53*	*7.39*	*10.63*	*13.25*	*2.85*	*1.83*	*1.22*	*0.99*
35	0.10	0.15	0.23	0.34	0.51	1.29	1.95	2.39	0.36	0.20	0.12	0.09
	0.55	*0.72*	*1.01*	*1.30*	*1.79*	*4.11*	*6.27*	*8.22*	*1.45*	*0.92*	*0.62*	*0.50*
40	0.05	0.07	0.12	0.17	0.26	0.72	1.16	1.49	0.18	0.10	0.06	0.04
	0.27	*0.36*	*0.50*	*0.66*	*0.92*	*2.30*	*3.72*	*5.13*	*0.74*	*0.47*	*0.31*	*0.25*

the values this coefficient may assume we give (table VI) some values which we found for several slope types. The exposition coefficient will be fairly near our average values at depths where light distribution remains rather constant throughout the day, but will depend on the azimuth in shallow water.

TABLE VI

Exposition coefficients for some slope types.

Slope	Mean value for S	Range of S values observed
(sub)horizontal	0.997	0.96-1.00
sloping	0.859	0.59-1.00
(sub)vertical	0.294	0.046-0.760
overhanging	0.129	0.050-0.303
cracks & holes	0.044	0.0006-0.089

In order to check the method, we carried out the following experiment. On 3 August 1977 at about 11 a.m. Secchi disc readings and submarine irradiance measurements were carried out near Cap l'Abeille, Banyuls-sur-Mer. The weather was fair, the sky slightly hazy, the sea was calm and solar elevation approximately 60°. The depth of disappearance of the Secchi disc was found to be D_{sd} = 16.5 m. The theoretical (calculated) corresponding attenuation coefficient thus became k_{480} = 0.089.

Measurements were simultaneously carried out with Weinberg's (1974) Relative Hemispherical Irradiance Meter (RHIM), having a peak sensitivity at 480 nm and a band-width of 60 nm, and a Li-Cor underwater quantum sensor (Lambda Instruments Corp.), having approximately a uniform quantum response between 400 and 700 nm.

The resulting curves are plotted in fig. 8, where subsurface values are taken 100%. The decrease in irradiance becomes logarithmic from 5 m downwards for the RHIM, and from 10 m downwards for the Li-Cor, with its broader spectral sensitivity. From the logarithmic curves, the height of the water column in which irradiance diminishes to 10% (D_{10}) can be taken immediately. D_{10} = 27.6 m for the narrow-band 480 nm sensor, and D_{10} = 22.4 m for the quantum sensor. The corresponding attenuation coefficients are k_{480} = 0.083 and k_{quanta} = 0.103. Comparison with the k_{480} value found from the Secchi disc reading shows an overestimation by the latter of 7.2%.

Taking from table III the average value of surface irradiance for the July and August month on the first hour before or after solar noon, we find 62.32 cal cm^{-2} hour^{-1}. Assuming a water type which is intermediate between α and β (this assumption being based on the k_{480} value found) we calculated the values for submarine quantum irradiance at several depths according to the method exposed in this paper. In table VII these values are compared with the values actually measured by means of the Li-Cor quantum sensor. At depths below 25 m there is an important overestimation as a result of a very turbid layer below the thermocline, the presence of which was not assumed during the calculations. The subsurface value is also lower than the one found by calculation, possibly due to the hazy sky. As a whole, however, because we deal here with a single check only (viz., on 3 August 1977), the values found seem

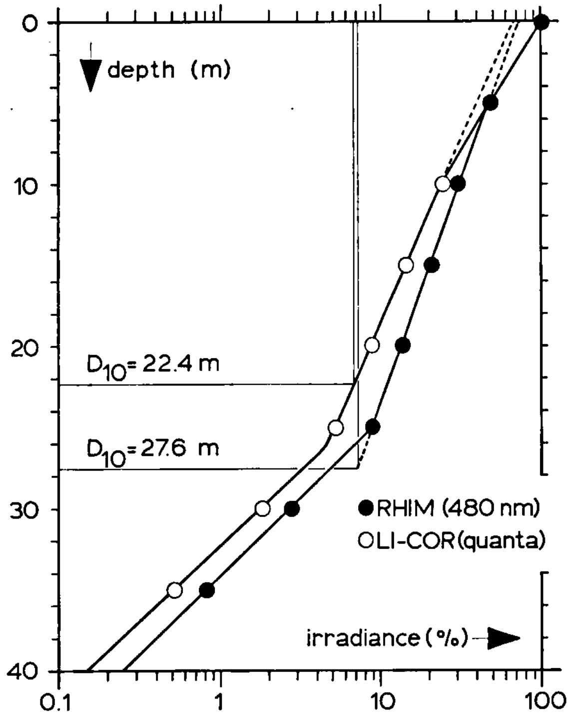

Fig. 8. Measurements of submarine irradiance at Banyuls-sur-Mer (August 1977). The Relative Hemispherical Irradiance Meter (RHIM) has a narrow-band sensor measuring in the blue-green part of the spectrum. The Li-Cor quantum sensor (Lambda Instruments) measures total quanta between 400 and 700 nm.

quite satisfying, and confirm the assumption that the method is reliable if only approximate values are needed, which for monthly and yearly averages is necessarily the case.

TABLE VII

Comparison of measured and calculated number of quanta at different depths in the coastal water off Banyuls-sur-Mer (August 1977). Thermocline and turbid layer below 25 m.

Depth	$\mu E\ m^{-2}\ s^{-1}$ calculated	$\mu E\ m^{-2}\ s^{-1}$ measured	Error in %
0	983	670	47
5	360	330	9
10	184	165	12
15	103	95	8
20	60	58	3
25	35	35	<1
30	21	12	75
35	13	3.4	282

V. DISCUSSION

Because of the fine agreement between the values for incident irradiance found by both Jacques et al. (1969, 1971) and Ashbel (1970), we are confident that the surface irradiance values we take as the starting point of our calculation are reliable, as are the conversion constants $K_{\Delta\lambda}$ which were derived from fig. 4. The calculation of k_{480} values from Secchi disc readings is subject to some uncertainty (see Weinberg, 1976: fig. 4). However, the use of average monthly Secchi disc values obtained from a great number of readings tends to give a far better estimation of the corresponding k_{480} values than would be the case for a single Secchi disc reading.

Interpolation of intermediate water-type curves between those determined by Jerlov (1976) yields $k_{\Delta\lambda}$ values. As Jerlov's curves are the result of many observations, we are confident that they reflect situations between which any intermediate water type is likely to occur. Our method of interpolating from k_{480} values could be improved by finding a formula enabling to calculate k values for shorter wavelengths from Secchi disc data, because at shorter wavelengths the water-type curves tend to diverge more from each other, thus making more precise interpolations possible.

No correction has been made for the "surface effect" mentioned by Weinberg (1976), as the values he gives are valid for one special water type and one spectral band only. More data are needed before this effect can be taken into consideration.

For the calculation, the water was assumed to be homogeneous at all depths (same k values). This is not always the case. In a calm sea like the Mediterranean (no tides), especially during the summer months, the water below the thermocline may at times be more turbid than the layer above (cf. table VII). For this reason, values beneath approximately 20 m depth may be overestimated.

It is necessary to point out once more that our calculation is based on *average* values of the yearly cycle of most parameters. The result can thus be an approximation only; important fluctuations may, of course, occur from day to day, and even from year to year as a result of particular meteorological or hydrological conditions. For the description of the underwater microclimate in benthic stations this is quite satisfying, since the composition of benthic associations remains rather stable over long periods of time, depending on average conditions. On account of the error sources mentioned above, true values of average monthly submarine irradiance will lie between limits that are twice as large and half as small as our estimates, but probably well within. Although this error may seem quite large, for submarine irradiance this is an acceptable approximation, since it corresponds to an error of about 5 m depth only, in the water types considered in this paper.

One final remark. The units used throughout this paper are not the legal metric (SI) units. We have used the calorie common in meteorology and the micro-einstein plant physiologists are familiar with. However, if one wishes to convert into SI units, the following constants should be used:

1 cal = 4.185 J (joule)
$1\ \mu E = 6.023 \cdot 10^{17}$ quanta.

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