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Light conditions in the Antarctic waters of the Drake Passage and the South Shetland Islands region during summer 1981*)

ABSTRACT: Optical studies were carried out in waters of the Drake Passage and the South Shetland Islands region from February 14 to March 12, 1981. The total energy of solar radiation reaching the sea surface was continuously recorded over daytime hours. Spectral and energetic characteristics of natural light field in the sea were determined basing on underwater measurements of downwelling irradiance attenuation. The thickness of the euphotic zone and other characteristic optical depths were also evaluated. The investigated waters were conventionally classified into three groups of different optical water types as follows: a) Clear oceanic water, b) Oceanic water of intermediate type and water affected by coastal water, c) Coastal water and water with high biological productivity. The clearest waters were found in the Drake Passage where the average thickness of the euphotic zone was about 100 m. The turbid waters of coastal types were encountered in some areas around the South Shetland Islands. The relatively thin euphotic zone of about 30 m was observed in waters with high biological productivity west of Elephant Island and southwest of Anvers Island.

Key words: Antarctic, optical oceanography

1. Introduction

The paper presents the results of hydrooptical investigations carried out on board of the r/v "Profesor Siedlecki" during the "FIBEX" between February 14th and March 12th, 1981. The optical measurements were made simultaneously

*) FIBEX-1981 (First International Biological Experiment) — the first stage of an international programme "BIOMASS' the aim of which is the estimation of krill biomass in waters around the Antarctic continent.

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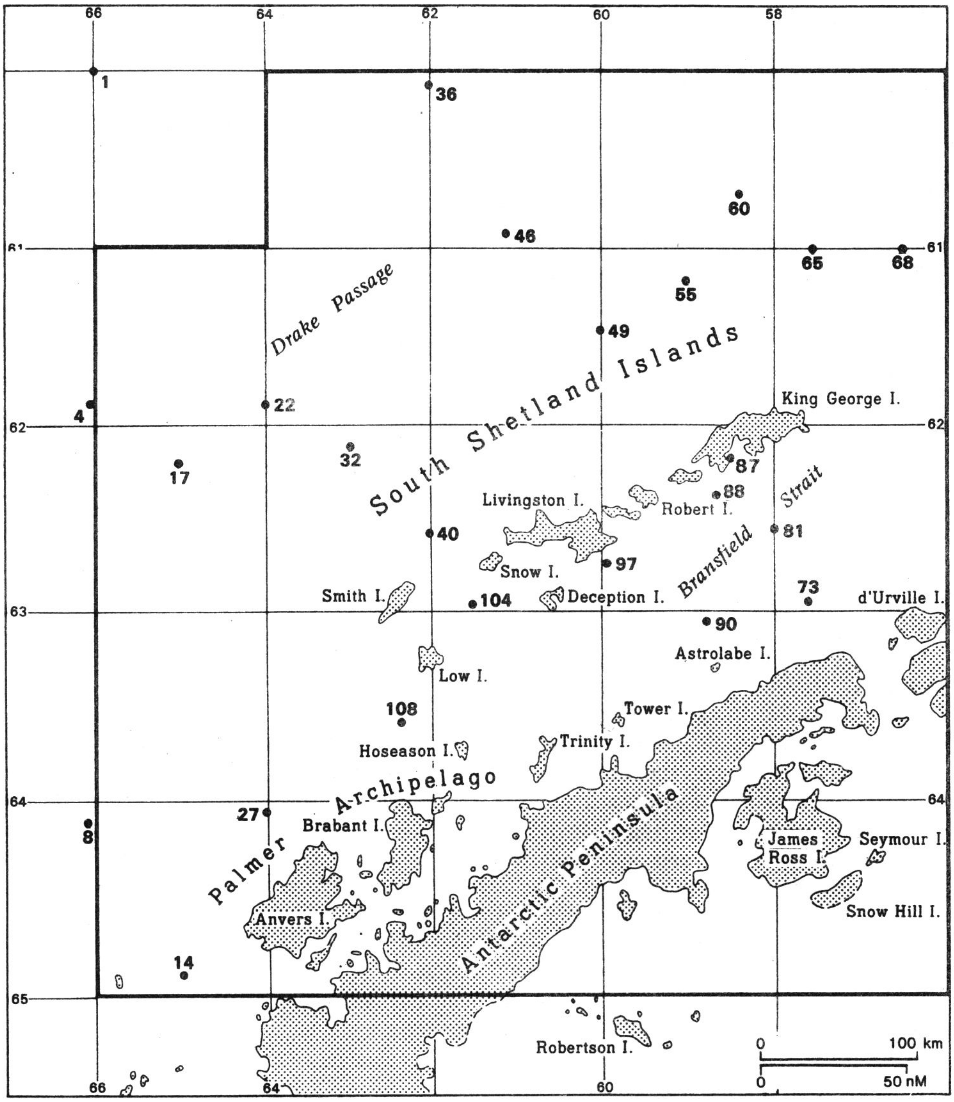

Fig. 1. The locations of oceanographic stations where underwater optical measurements were made

with other biological and oceanographic studies in waters of the investigated Antarctic region (Rakusa-Suszczewski 1982). The locations of the stations where the underwater optical measurements were made are shown in Fig. 1.

The paper contains also description of the research methods and analysis of basic optical quantities characterizing the natural light field in the sea.

The main aim of optical investigations was a determination of light conditions in the sea during hydroacoustic observations of krill occurrence and other biological studies. For this purpose, continuous actinometric measurements of the total energy of solar radiation reaching the sea surface over the whole period of the experiment were made. Underwater spectral measurements of attenuation of downwelling irradiance with the increasing depth were made once a day at noon. The light conditions in the sea were determined basing on experimental data and numerical calculations according to specially prepared programmes.[1])

2. Material and methods

2.1. Measurements

The following optical quantities were measured directly:

— Total energy of solar radiation reaching the sea surface (downwelling irradiance E_s).[2]) This was practically achieved by a pyranometer of uniform spectral sensitivity from 300 nm to 2800 nm calibrated in absolute units. The energy E_s was recorded continuously over all daytime hours from sunrise to sunset. The signal from the pyranometer was integrated over each 10-minute period and these totals were recorded on a digital counter. This time — integrating technique of radiation measurements was described by Dera et al. (1972).

— Underwater downwelling irradiance $E_{\downarrow}(\lambda, z)$ in relative units at various depths (z) in the sea, namely 0, 10, 20, 30, 50, 75, 100 meters (sometimes additionally 125 m). The $E_{\downarrow}(\lambda, z)$ values were measured at the following eight light wavelengths (λ) of the visible spectral range between 400 nm and 700 nm: 400 nm, 425 nm, 465 nm, 525 nm, 535 nm, 580 nm, 620 nm and 680 nm. This range practically covers the whole radiant energy spectrum which is active in photosynthesis of organic matter in the sea.

The measurements of irradiance $E_{\downarrow}(\lambda, z)$ were made using an irradiance meter constructed in the Institute of Oceanology, Polish Academy of Sciencies in Sopot. The irradiance meter is fitted with a flat Lambert collector, a photomultiplier and a spectral attachment with eight interference filters changed automatically. The signal from each channel of the spectrophotometer was integrated over 10 or 50 seconds and recorded on a digital counter.

During the underwater measurements the time variations of external irradiance at the sea surface were controlled at two light wavelengths, viz. 425 nm and 525 nm. For this purpose two irradiance meters appropriately installed on board the vessell were used.

2.2. Analysis and calculations

Basing on experimental data, the optical values were determined using the following procedures.

[1]) All the numerical calculations were made on board of the r/v "Profesor Siedlecki" using an ELLIOT-905 computer.

[2]) Definitions of all optical quantities mentioned in this paper are given in the monographs by Dera (1971) and Jerlov (1968)

The values of total irradiance at the sea surface E_s (see Table I, Chapter 3) were averaged over each 30-minute period during daytime. For instance, the E_s value at 1200 ZT denotes the average one between 1145 ZT and 1215 ZT.

The daily dose of the total energy reaching the sea surface η_s (see Table I, Chapter 3) is defined by:

$$\eta_s = \int_{t_1}^{t_2} E_s \, dt \tag{1}$$

where t_1 is approximately the time of sunrise and t_2 is that of sunset. The integration was realized automatically by measuring system of irradiance E_s.

The attenuation coefficients of downwelling irradiance $K_\downarrow (\lambda, z)$ were determined basing on the underwater measurements of relative irradiance. The values of underwater irradiance were at first related to the variable incident irradiance measured above the sea surface and appropriately corrected. The

Table II.

Spectral distributions of the attenuation coefficient of downwelling irradiance $K_\downarrow (\lambda)$ [m^{-1}] in the euphotic zone in the sea.*)

Station No	Date	Wavelength of light [nm]							
		400	425	465	525	535	580	620	680
1	14 Feb. 81	0.064	0.056	0.047	0.075	0.083	0.162	0.481	0.652
4	15 Feb. 81	0.076	0.067	0.054	0.082	0.095	0.176	0.310	0.611
8	16 Feb. 81	0.166	0.145	0.115	0.105	0.105	0.162	0.270	0.605
14	17 Feb. 81	0.298	0.243	0.230	0.158	0.172	0.215	0.328	0.689
17	18 Feb. 81	0.122	0.111	0.098	0.100	0.103	0.172	0.268	0.599
22	19 Feb. 81	0.073	0.065	0.050	0.074	0.078	0.149	0.336	0.595
27	20 Feb. 81	0.116	0.105	0.077	0.079	0.080	0.141	0.308	0.608
32	21 Feb. 81	0.168	0.167	0.156	0.130	0.128	0.179	0.356	0.616
36	22 Feb. 81	0.056	0.049	0.040	0.059	0.069	0.139	0.250	0.568
40	23 Feb. 81	0.175	0.160	0.126	0.121	0.123	0.177	0.330	0.602
46	24 Feb. 81	0.240	0.227	0.199	0.153	0.153	0.201	0.334	0.745
49	25 Feb. 81	0.102	0.092	0.072	0.078	0.084	0.168	0.329	0.623
55	26 Feb. 81	0.100	0.093	0.063	0.078	0.082	0.138	0.304	0.661
60	27 Feb. 81	0.062	0.055	0.044	0.065	0.072	0.131	0.287	0.594
65	28 Feb. 81	0.231	0.220	0.190	0.152	0.148	0.195	0.338	0.608
68	4 Mar. 81	0.310	0.300	0.248	0.175	0.171	0.202	0.347	0.673
73	5 Mar. 81	0.091	0.076	0.051	0.070	0.075	0.135	0.290	0.577
81	6 Mar. 81	0.139	0.121	0.094	0.072	0.084	0.134	0.286	0.707
87	7 Mar. 81	0.184	0.168	0.118	0.127	0.130	0.211	0.389	0.653
88	8 Mar. 81	0.153	0.139	0.106	0.109	0.113	0.142	0.316	0.716
90	9 Mar. 81	0.088	0.079	0.057	0.079	0.086	0.153	0.311	0.577
97	10 Mar. 81	0.174	0.165	0.141	0.124	0.130	0.184	0.318	0.757
104	11 Mar. 81	0.183	0.179	0.151	0.134	0.145	0.202	0.350	0.684
108	12 Mar. 81	0.142	0.122	0.094	0.098	0.101	0.164	0.292	0.583

*) The $K(\lambda)$ coefficients are given as mean values in the oceanic upper layer which is approximately equal to the euphotic zone.

Total energy of solar radiation at the sea surface

	Downwelling irradiance at the sea surface E_s [$mW \cdot cm^{-2}$]																							
Date Zone Time	14 Feb. 1981	15 Feb. 1981	16 Feb. 1981	17 Feb. 1981	18 Feb. 1981	19 Feb. 1981	20 Feb. 1981	21 Feb. 1981	22 Feb. 1981	23 Feb. 1981	24 Feb. 1981	25 Feb. 1981	26 Feb. 1981	27 Feb. 1981	28 Feb. 1981	4 Mar. 1981	5.Mar. 1981	6 Mar. 1981	7 Mar. 1981	8 Mar. 1981	9 Mar. 1981	10 Mar. 1981	11 Mar. 1981	12 Mar. 1981
0430	—	—	0.1541	0.2891	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
0500	0.4695	0.1771	0.8316	0.6075	0.0563	0.5789	0.0579	—	0.1663	0.8984	0.4066	—	11.2983	0.5816	1.0119	0.5766	—	—	—	—	—	—	—	—
0530	2.0280	0.5363	2.2631	1.7097	0.5929	1.0045	1.0045	0.2933	0.7711	3.0459	3.5114	0.7669	3.9475	2.4421	2.0400	3.4173	—	0.2467	0.2337	—	0.3922	0.2620	0.0473	0.0407
0600	3.1964	0.8806	4.5255	2.8476	1.0880	3.0684	2.9123	0.8240	3.6611	4.6942	6.1569	6.2068	5.3321	4.1656	1.9613	9.7146	0.5088	1.1022	1.1014	0.1375	1.8362	2.2738	1.2478	0.5606
0630	5.4507	1.5751	8.0589	4.7039	1.9958	8.2009	3.1113	1.5674	2.8218	6.5191	5.7177	8.0074	6.5635	9.3792	2.9050	15.8825	1.4009	3.2042	3.1939	0.4366	3.9959	6.9371	3.2913	3.4262
0700	6.3704	5.3790	27.4839	6.0607	2.5736	13.9890	5.7071	2.8161	7.0617	11.6949	9.1899	10.8712	7.9980	24.2738	7.8700	23.7451	2.3383	6.2615	6.8945	1.4458	11.8914	6.4126	6.5959	7.0054
0730	7.7435	4.9317	11.6838	6.9848	3.8459	22.6210	8.2405	3.9045	10.4001	25.2521	14.8855	23.0415	13.1845	26.6093	12.5989	33.8018	4.2698	8.3379	9.3559	4.5597	20.1714	8.1237	8.8972	12.1220
0800	10.9282	3.6993	31.8578	7.2811	5.0226	30.3151	51.5768	6.0989	13.4910	34.7028	16.5494	26.7382	17.8859	29.4967	11.9686	17.0468	5.0040	6.5019	22.2929	6.6385	15.3607	5.3515	12.4140	14.0849
0830	18.1895	3.4573	31.5766	8.6961	5.0354	52.1480	27.9416	10.7783	18.5991	40.9117	17.1951	46.5248	25.9473	42.4972	22.0266	15.8958	6.3612	14.8083	38.6038	6.2022	18.6101	10.2123	16.1744	21.8270
0900	20.7331	5.8817	77.7108	10.7652	7.2672	71.3161	65.6777	12.0876	16.4493	37.2320	12.3215	51.7385	43.6128	51.9025	29.2303	27.2060	18.2428	14.2358	31.3356	7.3868	13.6274	21.9038	16.2990	36.7406
0930	32.2823	7.0475	35.0754	11.5829	6.1331	76.3697	30.2063	17.5638	19.0179	50.4878	12.9584	44.4632	46.1030	54.9698	28.7564	23.0139	19.3647	11.9318	38.6081	6.5204	18.6402	38.4959	15.9008	45.1553
1000	37.7241	6.5019	59.8769	24.6017	9.7607	75.9635	25.9953	25.7088	25.3517	59.3394	20.0268	59.4852	56.1077	56.6429	39.9909	24.4059	25.8231	11.5768	45.1555	7.3758	20.4760	37.5670	28.6699	50.2158
1030	34.4910	9.9175	28.7300	20.3265	15.7442	52.7774	11.7859	47.2768	26.1579	59.0652	23.9713	51.8748	38.3171	65.4563	45.6789	24.2955	25.3172	19.1295	49.4851	7.9323	33.6591	39.8298	26.3324	55.8196
1100	44.5170	6.7114	42.3318	17.3667	22.7120	24.3623	10.4834	28.8372	46.5158	68.4033	17.6032	57.9426	33.8774	64.2921	53.5839	33.1711	12.6464	31.5419	67.5002	7.1996	29.0553	35.3413	28.8944	56.2209
1130	44.3087	7.5455	45.6339	14.5955	24.7770	21.9422	9.8607	26.6299	38.8271	66.8553	18.4974	57.1609	29.2831	53.9464	57.9244	31.9348	17.4222	25.6999	61.2402	7.6931	48.2128	43.5898	32.5430	42.4309
1200	49.9958	8.1594	6.4257	11.3481	23.1303	15.8558	12.4486	30.9448	37.8724	60.5209	20.7155	55.9031	24.9617	65.7336	57.4018	24.7972	20.3603	18.0331	27.5299	9.4184	43.8371	33.8560	27.7365	56.5191
1230	51.1786	10.8923	26.5503	12.9986	19.5852	16.5467	8.8308	21.0232	46.2925	22.4147	24.1608	62.0897	20.8110	65.3166	52.1854	21.8626	20.7810	17.6028	31.9703	9.1176	46.4960	13.2441	41.4216	59.3358
1300	38.2754	13.4852	27.2864	13.0879	20.4887	22.8231	7.1722	23.0861	36.5182	38.1682	27.8650	60.4566	22.5357	65.1233	49.7601	28.4182	19.6994	19.4603	41.1386	6.8144	49.7376	18.0676	22.3198	57.4353
1330	45.4952	8.9925	30.6682	12.8784	23.7868	26.0993	4.5650	21.3518	37.7607	34.1516	27.5938	52.4060	24.5101	60.1889	48.9872	25.6029	10.1131	21.1207	47.9312	4.8152	21.3051	43.1356	15.7927	46.6230
1400	50.6896	12.2314	39.5304	10.8307	22.1432	18.4348	4.6251	24.2162	39.1619	28.6617	26.7187	33.7235	20.7301	60.6288	46.4296	24.1039	11.8268	16.9586	41.8272	7.5360	22.7945	46.3554	14.4297	52.5630
1430	35.8217	17.6470	37.1214	10.9694	26.7322	18.1532	3.4602	14.0869	27.5755	32.9501	22.8104	31.3293	12.8750	58.7949	38.1375	24.3785	12.0869	12.0644	8.9617	9.6352	34.7079	39.0117	13.2604	46.4709
1500	41.4981	12.7519	45.2119	10.6607	31.1332	18.0027	2.1168	16.8353	17.5170	24.1110	13.8477	32.6225	6.4120	48.0924	33.8909	19.8364	9.4438	8.9595	9.1062	14.2709	21.1081	39.4647	8.5449	42.6777
1530	30.2487	16.9056	23.6848	12.0249	35.0105	15.1267	1.5361	9.6727	12.8073	18.6204	16.1489	44.2133	7.4206	34.6759	27.9998	14.4860	7.9000	9.8128	9.7824	11.2482	15.1204	37.0028	8.0556	37.7461
1600	28.6789	12.9254	11.4307	9.9141	48.7109	9.8006	3.3300	6.6982	23.8499	23.2537	13.6024	30.3911	8.8814	29.3576	23.5144	12.5202	8.9707	8.6940	12.8216	8.1748	6.2553	31.7585	8.0726	30.5352
1630	21.3733	9.7008	13.0661	8.3681	23.4418	9.5509	3.1334	4.5073	8.0684	29.6449	13.5997	27.9865	6.1264	28.3392	12.8456	10.2314	9.1156	6.0491	13.6722	7.3565	6.3004	25.7194	5.2590	23.1319
1700	15.3477	6.0710	10.6100	7.4140	18.1626	5.2693	3.5313	3.5111	8.0313	30.4297	11.4392	22.7365	11.1476	15.5718	10.8295	11.9196	6.7281	2.6078	4.5625	8.3138	8.7476	16.4063	2.4342	15.7003
1730	10.8064	6.3783	8.8389	5.7448	24.0526	4.9739	2.2771	2.3717	8.1522	21.5567	11.4039	14.9164	9.1228	8.4636	11.4602	8.6607	3.6961	1.5129	4.4608	5.4903	6.5419	6.4050	1.2844	10.1070
1800	11.7880	5.3575	7.2012	4.0845	27.8890	5.0998	1.3906	2.3470	4.9302	14.5551	8.6766	6.8410	7.0256	7.1898	3.5885	3.7303	0.9262	3.2582	1.5568	1.7989	1.5483	3.0144	0.4502	5.2942
1830	12.0636	4.0823	3.9776	3.0367	4.5261	3.2877	0.9387	1.5301	3.9410	11.2784	4.3422	2.5301	4.0453	4.5955	1.5355	1.7365	0.3165	0.6887	0.4923	0.8591	0.8552	0.8269	—	1.0125
1900	3.2302	3.1750	3.9494	1.8696	20.1778	0.7873	0.6346	0.5694	3.4434	4.9108	1.2929	0.9696	2.4843	1.1886	0.5627	0.0273	—	—	0.1393	0.0062	0.0680	0.0157	—	—
1930	4.2224	1.5778	1.9320	0.8544	13.0693	0.4540	0.4117	—	0.3271	1.1403	—	0.1274	0.3751	0.0818	0.0041	—	—	—	—	—	—	—	—	—
2000	0.5594	0.5549	1.2644	0.3260	1.0618	0.0139	0.0226	—	—	0.0123	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2030	0.1028	0.1160	0.2080	0.0252	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Daily dose η_s [$J \cdot cm^{-2}$]	1295.10	467.89	1272.15	494.79	874.22	1159.95	611.41	660.85	981.97	1557.87	761.78	1663.34	934.06	1872.00	1326.03	929.55	505.19	542.52	1135.72	303.09	938.43	1099.05	659.46	1491.69

attenuation coefficients $K_{\downarrow}(\lambda, z_1 \div z_2)$ in a water layer between z_1 and z_2 were obtained using the operational definition:

$$K_{\downarrow}(\lambda, z_1 \div z_2) = \frac{1}{z_2 - z_1} \ln \frac{E_{\downarrow}(\lambda, z_1)}{E_{\downarrow}(\lambda, z_2)} \tag{2}$$

where $E_{\downarrow}(\lambda, z_1)$ and $E_{\downarrow}(\lambda, z_2)$ denote the downwelling irradiance at the wavelength λ at the depths z_1 and z_2, respectively. Thus, the $K_{\downarrow}(\lambda, z_1 \div z_2)$ coefficient is the adequate value for describing the light transmittance in the arbitrary water layer between the depth z_1 and z_2. To represent the whole euphotic zone, the $K_{\downarrow}(\lambda)$ coefficients as mean values in appropriate thick upper layer of the oean were determined (see Table II, Chapter 3).

The spectral downwelling irradiance $E_{\downarrow}(\lambda, z)$ (see Table III, Chapter 3) at seven different wavelengths in the visible spectral range at various depths was calculated using the formula:

$$E_{\downarrow}(\lambda, z) = E_{\downarrow}(\lambda, z = 0) \exp\left[-K_{\downarrow}(\lambda, 0 \div z) \cdot z\right] \tag{3}$$

where $E_{\downarrow}(\lambda, z = 0)$ is the downwelling irradiance at the wavelength λ just under sea surface. The $K_{\downarrow}(\lambda, 0 \div z)$ values for the appropriate light wavelength λ were interpolated from discrete spectral measurements.

The spectral distribution of irradiance $E_{\downarrow}(\lambda, z = 0)$ was derived by the following way. At first, the total energy just under the sea surface was determined by substracting the reflected and emergent radiation from the incident radiation E_s. The albedo of the sea surface for the total range of solar spectrum at the sea surface was taken after Payne (1972). The sun altitude and the atmospheric transmittance were used as parameters versus which the albedo was expressed.

Just below the sea surface the energy of visible light $E_{\downarrow}^{vis}(z = 0)$ was assumed as equal to 50% of the total energy (Czyszek, Wensierski and Dera 1979, Rusin 1979). Such coefficient of transition from total radiation to photosynthetically active radiation is often used in biological studies. Basing on the experimental data obtained under marine conditions the 50% value is very close to average one though it may change from bout 30% to over 60% in extreme cases (Rutkovskaja 1972). Moreover, since the cloud coverage is usually considerable in investigated Antarctic region such assumption is the more motivated. It results from the fact that under cloudy weather the mentioned value is slightly variable in the vicinity of 50% (Rutkovskaja and Pelevin 1975).

Using the $E_{\downarrow}^{vis}(z = 0)$ values the spectral distribution $E_{\downarrow}(\lambda, z = 0)$ was estimated according to theoretical model elaborated by Wensierski (private communication). Here, the sun altitude was used as the parameter by which the spectral distribution $E_{\downarrow}(\lambda, z = 0)$ was expressed. The $E_{\downarrow}(\lambda, z = 0)$ values were assumed for the moderate wind velocities and were averaged over atmosphere turbidities represented by the horizontal visibility. Such assumptions do not introduce significant errors.

Table III.

Chosen optical values of undewater lightfield in the sea

Part. I.

Depth z [m]	Downwelling irradiance $E_{\downarrow}(\lambda, z)$ *) [$\mu W \cdot cm^{-2} \cdot nm^{-1}$]							$E_{\downarrow}^{vis}(z)$*) [$\mu W \cdot cm^{-2}$]	$P^{vis}(z)$*) [%]	$E_{abs}^{vis}(z)$*) [$\mu W \cdot cm^{-3}$]	$\eta^{vis}(z)$ [$J \cdot cm^{-2}$]
	Wavelength of light λ [nm]										
	412.5	450	500	550	600	650	687.5				
Station number: 1						Date: 14 Feb. 81					Zone time: 12^{54}
0	561497	70.0210	74.1568	75.1782	72.9553	66.9974	62.6736	20936.0310	100.00	—	601.52
10	25.0848	31.5833	28.8491	14.1419	2.0187	0.2315	0.0922	4470.6529	21.33	4.7485	126.67
20	14.7026	20.7634	15.8522	4.8624	0.0559	0.0008	0.0001	2444.3046	11.68	1.8221	69.94
30	9.0072	15.1620	11.0362	2.4095	0.0015	0.0001	<0.0001	1655.6396	7.91	0.9811	51.69
50	2.7955	5.7477	3.5120	0.2431	<0.0001	<0.0001	,,	545.0285	2.60	0.3065	17.09
75	0.6238	1.6467	0.7643	0.0138	,,	,,	,,	136.8357	0.65	0.0768	4.51
100	0.1392	0.4718	0.1663	0.0008	,,	,,	,,	35.4275	0.17	0.0201	1.22
150	0.0069	0.0387	0.0079	<0.0001	,,	,,	,,	2.5013	0.01	0.0015	0.09
Station number: 4						Date: 15 Feb. 81					Zone time: 12^{38}
0	11.9033	14.7690	15.5874	15.7785	15.2936	14.0318	13.1207	4398.6130	100.00	—	181.76
10	5.9677	7.5726	6.7311	4.3793	1.1898	0.1243	0.0291	1149.7803	26.11	1.1049	46.35
20	3.0138	4.1875	3.6699	1.4461	0.1197	0.0011	0.0001	546.5596	12.41	0.4176	21.91
30	1.5230	2.5072	2.0440	0.4378	0.0106	<0.0001	<0.0001	288.0520	6.54	0.1968	11.52
50	0.2839	0.6135	0.3564	0.0401	0.0001	,,	,,	57.6029	1.31	0.0407	2.30
75	0.0567	0.1811	0.1045	0.0020	<0.0001	,,	,,	15.7974	0.36	0.0099	0.63
100	0.0095	0.0418	0.0197	0.0001	,,	,,	,,	3.3165	0.08	0.0020	0.13
150	0.0003	0.0022	0.0007	<0.0001	,,	,,	,,	0.1528	<0.01	0.00009	0.01
Station number: 8						Date: 16 Feb. 81					Zone time: 11^{10}
0	34.1254	45.0432	48.9539	50.1743	49.1203	45.4037	42.6024	13867.9710	100.00	—	586.84
10	6.9945	11.0174	13.7423	12.2606	5.1773	0.5427	0.1001	2314.3767	16.69	3.5103	97.50
20	1.1521	2.6438	4.2929	3.5582	0.5961	0.0065	0.0002	583.6825	4.21	0.8003	24.59
30	0.3271	0.9142	1.7423	1.2224	0.0768	0.0001	<0.0001	205.9667	1.49	0.2529	8.68
50	0.0146	0.0680	0.2467	0.1027	0.0010	<0.0001	,,	21.2875	0.15	0.0245	0.90
75	0.0003	0.0027	0.0175	0.0046	<0.0001	,,	,,	1.2478	<0.01	0.0014	0.05
100	<0.0001	0.0001	0.0008	0.0002	,,	,,	,,	0.0780	,,	0.0001	<0.01
150	,,	<0.0001	<0.0001	<0.0001	,,	,,	,,	<0.0001	,,	<0.0001	,,
Station number: 14						Date: 17 Feb. 81					Zone time: 13^{38}
0	13.9164	18.0513	19.6186	20.1077	19.6853	18.1958	17.0732	5557.6742	100.00	—	232.22
10	0.7017	1.1824	2.2261	2.8786	1.3296	0.1520	0.0316	406.7659	7.32	0.9560	16.96
20	0.0627	0.1780	0.3954	0.4481	0.0898	0.0013	0.0001	57.1912	1.03	0.1184	2.38
30	0.0042	0.0177	0.0698	0.0759	0.0061	<0.0001	<0.0001	8.5732	0.15	0.0168	0.36
50	<0.0001	0.0002	0.0016	0.0018	<0.0001	,,	,,	0.1837	<0.01	0.0003	0.01
75	,,	<0.0001	<0.0001	<0.0001	,,	,,	,,	0.0016	,,	<0.0001	<0.01
100	,,	,,	,,	,,	,,	,,	,,	<0.0001	,,	,,	,,
150	,,	,,	,,	,,	,,	,,	,,	<0.0001	,,	,,	,,
Station number: 17						Date: 18 Feb. 81					Zone time: 11^{40}
0	26.0545	33.7959	36.7302	37.6458	36.8550	34.0665	31.9646	10405.1480	100.00	—	391.14
10	5.7162	9.4510	10.3818	8.6637	3.5194	0.4054	0.0801	1765.9749	16.97	2.6263	65.86
20	1.9448	3.6120	4.4287	2.8200	0.4486	0.0048	0.0002	614.3317	5.90	0.7325	22.87
30	0.6570	1.2942	1.5277	0.7718	0.0495	0.0001	<0.0001	198.5892	1.91	0.2270	7.38
50	0.0767	0.1939	0.2756	0.0578	0.0006	<0.0001	,,	28.3156	0.27	0.0295	1.05
75	0.0042	0.0147	0.0239	0.0023	<0.0001	,,	,,	2.1457	0.02	0.0022	0.08
100	0.0002	0.0011	0.0021	0.0001	,,	,,	,,	0.1691	<0.01	0.0002	0.01
150	<0.0001	<0.0001	<0.0001	<0.0001	,,	,,	,,	0.0011	,,	<0.0001	<0.01
Station number: 22						Date: 19 Feb. 81					Zone time: 11^{14}
0	23.8977	30.9983	33.6897	34.5295	33.8043	31.2465	29.3186	9543.8242	100.00	—	538.85
10	12.1605	17.5323	15.6068	9.8026	2.3956	0.2627	0.0764	2585.6214	27.09	2.3138	145.16
20	6.2610	10.1676	8.5760	3.6184	0.2490	0.0022	0.0002	1287.1914	13.49	0.9167	72.19
30	3.3198	6.1269	4.7402	1.2431	0.0214	<0.0001	<0.0001	689.5725	7.23	0.4466	38.65
50	0.7659	1.8197	1.4278	0.1985	0.0002	,,	,,	191.4601	2.01	0.1202	10.73
75	0.1503	0.4553	0.3338	0.0151	<0.0001	,,	,,	43.9664	0.46	0.0264	2.46
100	0.0246	0.1217	0.0828	0.0011	,,	,,	,,	10.8985	0.11	0.0063	0.61
150	0.0008	0.0086	0.0041	<0.0001	,,	,,	,,	0.6067	<0.01	0.0003	0.03
Station number: 27						Date: 20 Feb. 81					Zone time: 11^{02}
0	11.4852	14.8978	16.1912	16.5949	16.2463	15.0170	14.0905	4586.7562	100.00	—	260.43
10	2.6443	4.2482	5.4842	4.7849	1.6523	0.1539	0.0321	883.1158	19.25	1.1870	49.81
20	0.8361	1.5329	2.2090	1.7841	0.1682	0.0016	0.0001	305.6934	6.66	0.3436	17.23
30	0.3080	0.7383	1.2264	0.6893	0.0171	<0.0001	<0.0001	141.2507	3.08	0.1375	7.96
50	0.0459	0.1840	0.3833	0.0827	0.0002	,,	,,	33.6583	0.73	0.0281	1.89
75	0.0029	0.0205	0.0590	0.0058	<0.0001	,,	,,	4.3361	0.09	0.0035	0.24
100	0.0002	0.0023	0.0091	0.0004	,,	,,	,,	0.5926	0.01	0.0005	0.03
150	<0.0001	<0.0001	0.0002	<0.0001	,,	,,	,,	0.0123	<0.01	<0.0001	<0.01
Station number: 32						Date: 21 Feb. 81					Zone time: 12^{00}
0	32.0722	41.6017	45.2137	46.3408	45.3674	41.9347	39.3474	12808.4010	100.00	—	311.38
10	5.9645	7.9099	9.6655	10.3348	3.3883	0.3559	0.0828	1733.8982	13.54	2.9655	42.06
20	1.1074	1.6650	2.4634	2.2328	0.2122	0.0030	0.0002	356.5089	2.78	0.5583	8.65
30	0.2090	0.3626	0.6548	0.5873	0.0145	<0.0001	<0.0001	86.1848	0.67	0.1284	2.09
50	0.0073	0.0154	0.0400	0.0319	0.0001	,,	,,	4.5480	0.04	0.0067	0.11
75	0.0001	0.0003	0.0012	0.0008	<0.0001	,,	,,	0.1188	<0.01	0.0002	<0.01
100	<0.0001	<0.0001	<0.0001	<0.0001	,,	,,	,,	0.0032	,,	<0.0001	,,
150	,,	,,	,,	,,	,,	,,	,,	0.0001	,,	<0.0001	,,

Table III

Chosen optical values of underwater lightfield in the sea

Part II.

Depth z [m]	Downwelling irradiance $E_{\downarrow}(\lambda, z)$*) [$\mu$W·cm^{-2}·nm^{-1}] Wavelength of light λ [nm] 412.5	450	500	550	600	650	687.5	$E_{\downarrow}^{vis}(z)$*) [μW·cm^{-2}]	$P^{vis}(z)$*) [%]	$E_{abs}^{vis}(z)$*) [μW·cm^{-3}]	$\eta^{vis}(z)$ [J·cm^{-2}]
Station number: 36						Date: 22 Feb. 81					Zone time: 10^{52}
0	50.1306	63.6232	68.1779	69.4650	67.6849	62.3452	58.4037	19278.1670	100.00	—	457.29
10	24.5469	31.3823	29.7664	19.0148	7.2624	0.9378	0.1995	5036.8512	26.12	5.0480	118.12
20	15.8700	22.1905	20.4478	8.9542	1.3392	0.0141	0.0007	3044.0559	15.79	2.0211	71.19
30	9.8381	14.5258	11.9948	3.2554	0.1884	0.0002	<0.0001	1744.1827	9.05	1.0230	40.71
50	3.9146	6.4526	4.5707	0.6670	0.0037	<0.0001	„	682.5647	3.54	0.3525	15.90
75	1.2674	2.5720	1.6311	0.0653	<0.0001	„	„	245.1035	1.27	0.1142	5.71
100	0.2654	0.8520	0.5387	0.0064	„	„	„	76.4882	0.40	0.0352	1.78
150	0.0193	0.0986	0.0479	<0.0001	„	„	„	7.8096	0.04	0.0035	0.18
Station number: 40						Date: 23 Feb. 81					Zone time: 12^{00}
0	64.5288	83.7020	90.9692	93.2370	91.2784	84.3720	79.1664	25770.3080	100.00	—	706.51
10	10.7268	16.6664	19.4280	16.6943	5.4458	0.6630	0.1916	3217.8306	12.49	5.7186	87.59
20	1.9883	4.1041	5.9006	4.2898	0.4992	0.0052	0.0005	789.6586	3.06	1.1959	21.49
30	0.4208	0.9882	1.6410	1.3175	0.0369	0.0001	<0.0001	200.2991	0.78	0.2885	5.45
50	0.0147	0.0512	0.1911	0.0596	0.0002	<0.0001	„	15.4704	0.06	0.0206	0.42
75	0.0002	0.0013	0.0088	0.0025	<0.0001	„	„	0.5820	<0.01	0.0008	0.02
100	<0.0001	<0.0001	0.0004	<0.0001	„	„	„	0.0237	„	<0.0001	<0.01
150	„	„	<0.0001	„	„	„	„	0.0001	„	„	„
Station number: 46						Date: 24 Feb. 81					Zone time: 11^{01}
0	23.8250	30.9040	33.5872	34.4245	33.7014	31.1514	27.3445	9514.7907	100.00	—	352.93
10	1.9626	3.0994	4.5001	4.3393	1.9026	0.1414	0.0171	748.6289	7.87	1.6952	27.62
20	0.2200	0.4146	0.8073	1.0050	0.1074	0.0007	<0.0001	122.2506	1.28	0.2372	4.51
30	0.0218	0.0578	0.1910	0.2147	0.0060	<0.0001	„	24.0190	0.25	0.0428	0.89
50	0.0002	0.0009	0.0061	0.0072	<0.0001	„	„	0.7178	<0.01	0.0012	0.03
75	<0.0001	<0.0001	<0.0001	0.0001	„	„	„	0.0096	„	<0.0001	<0.01
100	„	„	<0.0001	<0.0001	„	„	„	0.0001	„	„	„
150	„	„	„	„	„	„	„	<0.0001	„	„	„
Station number: 49						Date: 25 Feb. 81					Zone time: 11^{36}
0	69.2333	89.8042	97.6013	100.0344	97.9331	90.5231	84.9380	27649.0890	100.00	—	764.47
10	21.4608	31.1201	36.4713	28.7918	6.5706	0.6237	0.1667	5719.5612	20.69	6.9342	157.35
20	9.5772	15.7021	17.8552	10.1195	0.7899	0.0043	0.0003	2462.9878	8.91	2.3555	67.68
30	3.6868	6.7820	7.9375	2.6859	0.0709	<0.0001	<0.0001	965.9904	3.49	0.8846	26.53
50	0.5356	1.3872	1.5629	0.2372	0.0006	„	„	173.0154	0.63	0.1501	4.75
75	0.0490	0.2362	0.4349	0.0119	<0.0001	„	„	35.3702	0.13	0.0169	0.97
100	0.0044	0.0326	0.0716	0.0006	„	„	„	5.3460	0.02	0.0040	0.15
150	<0.0001	0.0006	0.0019	<0.0001	„	„	„	0.1289	<0.01	0.0001	<0.02
Station number: 55						Date: 26 Feb. 81					Zone time: 10^{46}
0	30.8819	40.0577	43.5356	44.6209	43.6836	40.3783	37.8871	12333.0240	100.00	—	429.72
10	9.6960	14.8728	16.8796	10.8544	3.8698	0.3307	0.0511	2583.6131	20.95	3.1343	89.34
20	3.4237	6.6131	8.3988	3.9713	0.3821	0.0027	0.0001	1053.9990	8.55	1.0235	36.41
30	1.4023	3.1060	4.0585	1.5856	0.0357	<0.0001	<0.0001	474.3529	3.85	0.4214	16.38
50	0.2959	0.7758	1.1377	0.1714	0.0003	„	„	111.6590	0.91	0.0885	3.85
75	0.0290	0.1080	0.2035	0.0106	<0.0001	„	„	16.8274	0.14	0.0128	0.58
100	0.0028	0.0150	0.0340	0.0006	„	„	„	2.5561	0.02	0.0019	0.09
150	<0.0001	0.0003	0.0010	<0.0001	„	„	„	0.0629	<0.01	<0.0001	<0.01
Station number: 60						Date: 27 Feb. 81					Zone time: 11^{24}
0	74.4155	96.5261	104.9068	107.5220	105.2634	97.2957	91.2957	29718.0390	100.00	—	860.87
10	38.2325	52.9726	50.4158	45.1546	9.1530	0.9543	0.2407	8894.3438	29.93	7.4059	256.06
20	22.2130	33.4680	29.0271	12.8367	1.3842	0.0094	0.0006	4391.6114	14.78	2.9885	126.14
30	12.5303	20.2582	16.7256	5.2415	0.1587	0.0001	<0.0001	2432.4635	8.18	1.5061	69.82
50	3.8183	7.6577	5.4760	0.8594	0.0021	<0.0001	„	795.2160	2.68	0.4542	22.81
75	0.8416	2.1375	1.5002	0.0769	<0.0001	„	„	206.7645	0.70	0.1131	5.93
100	0.2172	0.7856	0.5159	0.0069	„	„	„	70.8486	0.24	0.0361	2.03
150	0.0117	0.0709	0.0362	<0.0001	„	„	„	5.6486	0.02	0.0028	0.16
Station number: 65						Date: 28 Feb. 81					Zone time: 11^{14}
0	63.5496	82.4318	89.5888	91.8221	89.8933	83.0916	77.9651	25379.254	100.00	—	611.85
10	7.8426	13.6645	18.7793	17.5779	6.3396	0.7335	0.1780	3055.2531	12.04	5.5993	73.42
20	0.7200	1.5154	2.9595	2.6853	0.4471	0.0065	0.0004	399.1084	1.57	0.7425	9.59
30	0.8000	0.2026	0.5943	0.6709	0.0309	0.0001	<0.0001	76.9324	0.30	0.1336	1.85
50	0.0008	0.0034	0.0208	0.0257	0.0002	<0.0001	„	2.5226	0.01	0.0426	0.06
75	<0.0001	<0.0001	0.0003	0.0004	<0.0001	„	„	0.0385	<0.01	0.0006	<0.01
100	„	„	<0.0001	<0.0001	„	„	„	0.0006	„	<0.0001	„
150	„	„	„	„	„	„	„	„	„	„	„
Station number: 68						Date: 4 Mar. 81					Zone time: 11^{14}
0	32.8658	42.6310	46.3324	47.4874	46.4899	42.9723	40.3210	13125.3240	100.00	—	418.45
10	1.9020	3.4627	6.0341	6.7996	2.7149	0.2624	0.0482	1012.4445	7.71	2.3065	32.12
20	0.0738	0.2039	0.7418	1.2252	0.1585	0.0016	0.0001	118.3944	0.90	0.2445	3.77
30	0.0035	0.0141	0.0939	0.1968	0.0092	<0.0001	<0.0001	15.7883	0.12	0.0312	0.50
50	<0.0001	0.0001	0.0015	0.0051	<0.0001	„	„	0.3342	<0.01	0.0006	0.01
75	„	<0.0001	<0.0001	0.0001	„	„	„	0.0031	„	<0.0001	<0.01
100	„	„	„	<0.0001	„	„	„	<0.0001	„	„	„
150	„	„	„	„	„	„	„	„	„	„	„

Chosen optical values of underwater lightfield in the sea

Part III.

Depth z [m]	Downwelling irradiance $E_{\downarrow}(\lambda, z)$ [$\mu W \cdot cm^{-2} \cdot nm^{-1}$] Wavelength of light λ [nm] 412.5	450	500	550	600	650	687.5	$E_{\downarrow}^{vis}(z)$*) [$\mu W \cdot cm^{-2}$]	$P^{vis}(z)$*) [%]	$E_{abs}^{vis}(z)$*) [$\mu W \cdot cm^{-2}$]	$\eta^{vis}(z)$ [$J \cdot cm^{-2}$]
Station number: 73						Date: 5 Mar. 81					Zone time: 12^{06}
0	20.9330	26.9903	29.5102	30.2865	29.6105	27.3701	25.6814	8359.8297	100.00	—	235.92
10	7.4490	11.0907	11.8354	8.2590	3.0726	0.3455	0.0803	1918.4045	22.95	2.2008	53.71
20	3.2214	6.7298	7.2920	3.3454	0.3938	0.0043	0.0002	936.0632	11.52	0.8027	27.18
30	1.3253	3.4989	3.9806	1.3742	0.0512	0.0001	<0.0001	478.3885	5.72	0.3599	13.38
50	0.3119	1.2145	1.4953	0.1749	0.0007	<0.0001	„	152.0743	1.82	0.0980	4.25
75	0.0381	0.2853	0.4025	0.0133	<0.0001	„	„	36.0108	0.43	0.0217	1.01
100	0.0046	0.0625	0.0961	0.0010	„	„	„	8.1006	0.09	0.0048	0.23
150	0.0001	0.0030	0.0055	<0.0001	„	„	„	0.4240	<0.01	0.0002	0.01
Station number: 81						Date: 6 Mar. 81					Zone time: 10^{58}
0	26.3071	34.1236	37.0863	38.0108	37.2124	34.3967	32.2745	10506.0420	100.00	—	253.38
10	7.4707	11.6890	16.1087	14.5143	4.6490	0.2412	0.0274	2547.5323	24.25	2.8175	62.23
20	2.0251	4.1935	9.3006	5.3420	0.5151	0.0017	<0.0001	925.2651	8.81	0.9229	22.55
30	0.5263	1.4422	3.4755	2.3321	0.0683	<0.0001	„	379.0627	3.61	0.3509	9.17
50	0.0388	0.1750	0.6386	0.3628	0.0010	„	„	59.8399	0.57	0.0536	1.44
75	0.0015	0.0125	0.0838	0.0355	<0.0001	„	„	6.6276	0.06	0.0058	0.16
100	<0.0001	0.0009	0.0110	0.0034	„	„	„	0.7692	0.01	0.0007	0.02
150	„	<0.0001	0.0002	<0.0001	„	„	„	0.0113	<0.01	<0.0001	<0.01
Station number: 87						Date: 7 Mar. 81					Zone time: 10^{55}
0	55.2585	71.6772	77.9004	79.8424	78.1652	72.2509	67.7932	22068.1030	100.00	—	522.71
10	7.6906	13.5569	15.9021	11.9586	3.6728	0.3951	0.0990	2469.0256	11.19	4.7988	58.15
20	0.9819	2.6589	4.1749	2.0137	0.1725	0.0021	0.0002	475.6655	2.16	0.7861	11.20
30	0.2799	0.9209	1.4158	0.4912	0.0081	<0.0001	<0.0001	148.8060	0.67	0.2167	3.50
50	0.0083	0.0498	0.1136	0.0165	<0.0001	„	„	9.2411	0.04	0.0129	0.22
75	0.0001	0.0013	0.0043	0.0002	„	„	„	0.2985	<0.01	0.0004	0.01
100	<0.0001	<0.0001	0.0001	<0.0001	„	„	„	0.0102	„	<0.0001	<0.01
150	„	„	<0.0001	„	„	„	„	<0.0001	„	„	„
Station number: 88						Date: 8 Mar. 81					Zone time: 10^{50}
0	9.8354	12.7577	13.8654	14.2110	13.9125	12.8598	12.0664	3927.8666	100.00	—	140.87
10	1.9214	3.0566	4.4788	3.9643	1.3445	0.0727	0.0090	704.4299	17.93	0.9848	24.98
20	0.5822	1.1665	1.7155	1.2149	0.1299	0.0004	<0.0001	164.3042	5.75	0.2699	7.99
30	0.1235	0.3842	0.7210	0.3982	0.0125	<0.0001	„	78.8886	2.01	0.0877	2.79
50	0.0066	0.0371	0.0635	0.0367	0.0001	„	„	7.0446	0.18	0.0080	0.25
75	0.0002	0.0020	0.0043	0.0018	<0.0001	„	„	0.4131	0.01	0.0005	0.01
100	<0.0001	0.0001	0.0003	0.0001	„	„	„	0.0248	<0.01	<0.0001	<0.01
150	„	<0.0001	<0.0001	<0.0001	„	„	„	0.0001	„	„	„
Station number: 90						Date: 9 Mar. 81					Zone time: 11^{28}
0	48.6043	63.0458	68.5196	70.2278	68.7526	63.5505	59.6296	19410.6680	100.00	—	430.23
10	17.6895	27.0679	27.8062	18.7778	4.7642	0.5883	0.1877	4397.1598	22.65	4.8843	96.55
20	7.6942	14.3555	15.4657	7.0811	0.6223	0.0054	0.0006	2068.8819	10.66	1.7646	45.36
30	3.6102	7.7474	8.2198	2.6643	0.0592	0.0001	<0.0001	1024.7994	5.28	0.7917	22.45
50	0.6776	2.2013	2.4700	0.2341	0.0006	<0.0001	„	262.3679	1.35	0.1839	5.75
75	0.0950	0.5154	0.6364	0.0135	<0.0001	„	„	60.6415	0.31	0.0391	1.33
100	0.0119	0.1038	0.0610	0.0008	„	„	„	8.5837	0.04	0.0058	0.19
150	0.0002	0.0042	0.0018	<0.0001	„	„	„	0.3066	<0.01	0.0002	0.01
Station number: 97						Date: 10 Mar. 81					Zone time: 11^{42}
0	36.5031	47.3491	51.4601	52.7430	51.6350	47.7281	44.7834	14577.9340	100.00	—	492.89
10	5.5469	8.7952	11.3318	8.6056	3.3523	0.2211	0.0231	1754.5593	12.04	3.1612	58.78
20	1.2100	2.2527	4.1401	2.7320	0.2176	0.0010	<0.0001	510.0620	3.50	0.7287	17.08
30	0.2257	0.6369	1.2771	0.6863	0.0141	<0.0001	„	136.370	0.94	0.1856	4.57
50	0.0076	0.0360	0.0747	0.0379	0.0001	„	„	7.6334	0.05	0.0105	0.26
75	0.0001	0.0010	0.0038	0.0010	<0.0001	„	„	0.2470	<0.01	0.0003	0.01
100	<0.0001	<0.0001	0.0001	<0.0001	„	„	„	0.0082	„	<0.0001	<0.01
150	„	„	<0.0001	„	„	„	„	<0.0001	„	„	„
Station number: 104						Date: 11 Mar. 81					Zone time: 10^{58}
0	37.7634	48.9838	53.2367	54.5639	53.4177	49.3759	46.3295	15081.2340	100.00	—	305.02
10	5.8447	9.0015	12.6148	9.2061	3.1649	0.2813	0.0496	1860.7934	12.34	3.2908	37.35
20	1.1562	2.1625	3.3791	1.6857	0.1875	0.0016	0.0002	399.7343	2.65	0.6255	8.01
30	0.2023	0.3858	0.8211	0.3949	0.0111	<0.0001	<0.0001	85.7070	0.57	0.1311	1.72
50	0.0062	0.0152	0.0508	0.0147	<0.0001	„	„	4.2032	0.01	0.0063	0.08
75	0.0001	0.0002	0.0016	0.0002	„	„	„	0.1063	<0.01	0.0002	<0.01
100	<0.0001	<0.0001	<0.0001	<0.0001	„	„	„	0.0029	„	<0.001	„
150	„	„	„	„	„	„	„	<0.0001	„	„	„
Station number: 108						Date: 12 Mar. 81					Zone time: 12^{00}
0	60.5711	79.2979	86.5956	88.9747	87.2705	80.7530	75.8562	24555.2670	100.00	—	670.20
10	13.6967	20.5325	23.2218	16.3200	6.6793	0.9526	0.2218	3728.8963	15.19	5.7381	98.27
20	5.2216	10.0808	12.9109	7.2738	0.9109	0.0046	0.0006	1689.6049	6.88	1.8545	45.71
30	1.1067	3.4325	5.3521	2.1901	0.0931	<0.0001	<0.0001	581.0588	2.37	0.6107	15.73
50	0.0942	0.5541	1.4329	0.2300	0.0010	„	„	113.2555	0.46	0.1031	3.07
75	0.0037	0.0463	0.0639	0.0117	„	„	„	6.1901	0.03	0.0062	0.17
100	0.0002	0.0038	0.0058	<0.0001	„	„	„	0.5158	<0.01	0.0005	0.01
150	<0.0001	<0.0001	<0.0001	<0.0001	„	„	„	0.0038	<0.01	<0.0001	<0.01

*) The listed $E_{\downarrow}(\lambda, z)$, $E_{\downarrow}^{vis}(z)$, $P^{vis}(z)$ and $E_{abs}^{vis}(z)$ values are averaged in time equal to that of oceanographic station activity, mostly from about 10^{45} ZT to about 13^{00} ZT.

The downwelling irradiance $E_{\downarrow}^{vis}(z)$ within the visible spectral range (between 400 nm and 700 nm) is expressed by the formula:

$$E_{\downarrow}^{vis}(z) = \int_{\lambda_1=400\text{nm}}^{\lambda_2=700\text{nm}} E_{\downarrow}(\lambda, z)\, d\lambda \tag{4}$$

The $E_{\downarrow}^{vis}(z)$ values at various depths were calculated numerically by summing the light energy over seven distinguished spectral bands (see Table III, Chapter 3). It should be stressed that $E_{\downarrow}^{vis}(z)$ value is very close to the daylight available for photosynthesis in the sea (Højerslev 1978).

The function of visible light transmission $p^{vis}(z)$ into various depths (see Table III, Chapter 3) were calculated according to the formula:

$$p^{vis}(z) = \frac{E_{\downarrow}^{vis}(z)}{E_{\downarrow}^{vis}(z=0)} \cdot 100\% \tag{5}$$

To obtain the power of visible light energy $E_{abs}^{vis}(z)$ absorded in unit water volume at various depths (see Table III, Chapter 3) the following expression was used:

$$E_{abs}^{vis}(z) = K_{\downarrow}^{vis}(0 \div z) \cdot E_{\downarrow}^{vis}(z) \tag{6}$$

where $K_{\downarrow}^{vis}(0 \div z)$ is the average attenuation coefficient of downwelling irradiance in the visible spectral range in a water layer between the sea surface and the depth z.
It may be expressed as:

$$K_{\downarrow}^{vis}(0 \div z) = \frac{\int_{\lambda_1=400\text{nm}}^{\lambda_2=700\text{nm}} E_{\downarrow}(\lambda, z) \cdot K_{\downarrow}(\lambda, 0 \div z)\, d\lambda}{\int_{\lambda_1=400\text{nm}}^{\lambda_2=700\text{nm}} E_{\downarrow}(\lambda, z)\, d\lambda} \tag{7}$$

Assuming the spectral distribution of the $K_{\downarrow}(\lambda, 0 \div z)$ coefficient to be constant over all daytime hours, the daily irradiance dose in the visible spectral range $\eta^{vis}(z)$ (see Table III, Chapter 3) at various depths was estimated as:

$$\eta^{vis}(z) = \int_{t_1}^{t_2} E_{\downarrow}^{vis}(z)\, dt \tag{8}$$

With a view to the biological interest the depth levels given in terms of percentage of surface irradiance were determined.

The lower limit of the euphotic zone z_e was presumed in this paper as a depth at which downwelling irradiance is equal to 1% of the surface irradiance (just below the sea surface) in the spectral band corresponding to maximum light transmission. The depth z_e (see Table IV, Chapter 3) was calculated according to the following formula:

$$z_e = \frac{\ln 100}{K_{\downarrow}(\lambda_{max}, 0 \div z)} \tag{9}$$

Table IV.

Characteristic optical depths in the sea

Station No.	Date	Depth (m)					
		z_{30}	z_{10}	z_3	z_1	z_e	
1	14 Feb.81	8	24	47	67	100	(457)*)
4	15 Feb. 81	9	23	40	55	90	(475)
8	16 Feb. 81	7	14	23	34	47	(530)
14	17 Feb. 81	5	9	15	20	29	(525)
17	18 Feb. 81	7	15	26	37	49	(490)
22	19 Feb. 81	9	25	44	62	98	(475)
27	20 Feb. 81	7	16	30	46	65	(485)
32	21 Feb. 81	6	12	20	27	36	(535)
36	22 Feb. 81	9	28	54	80	121	(475)
40	23 Feb. 81	6	12	20	28	38	(525)
46	24 Feb. 81	5	9	15	22	39	(530)
49	25 Feb. 81	8	18	32	45	69	(485)
55	26 Feb. 81	8	18	33	49	74	(475)
60	27 Feb. 81	10	27	48	68	107	(475)
65	28 Feb. 81	6	11	17	23	31	(535)
68	4 Mar. 81	5	9	14	20	27	(535)
73	5 Mar. 81	8	22	41	60	95	(475)
81	6 Mar. 81	8	19	32	44	64	(525)
87	7 Mar. 81	6	11	18	27	40	(485)
88	8 Mar. 81	7	15	25	36	48	(485)
90	9 Mar. 81	8	20	38	55	87	(475)
97	10 Mar. 81	6	12	21	30	37	(525)
104	11 Mar. 81	6	11	19	26	34	(525)
108	12 Mar. 81	6	15	28	41	55	(485)

*) The values in brackets denote the wavelength λ_{max} [nm] corresponding to maximum light transmission.

where $z \simeq z_e$ and λ_{max} is the most penetrating light wavelength obtained from spectral measurements of the $K_{\downarrow}(\lambda)$ coefficient.

It should be emphasized that the actual location of the compensation depth can be determined only approximately. The different optical criteria of the compensation depth are considered by marine investigators (Steeman-Nielsen 1974). One of the often assumed is the depth level z_1 where the 1% of photosynthetically active radiation occurs (Pelevin and Rutkovskaja 1978).

The optical depths as z_{30}, z_{10}, z_3 and z_1, at which the surface irradiance $E_{\downarrow}^{vis}(z=0)$, i.e. the light energy active in photosynthesis, is reduced to 30%, 10%, 3%, and 1%, respectively, were also evaluated (see Table IV, Chapter 3).

3. Results

All results are listed in Tables I÷IV. Explanatory information on the tables are contained in Chapter 2.2.

4. Discussion and conclusions

The intensity and quality of light energy avilable for marine organisms depend on the optical properties of water and on the incident light reaching the sea surface. Both the external light conditions and the optics of the water must be considered in optical studies for biological purposes.

In the investigated Antarctic region great variations in the radiant energy reaching the sea surface were observed from day to day and during the daytime due to varying weather conditions (sunny, foggy or completely overcast weather, intermittent clouds) (Table I).

The differing daily courses of the total irradiance E_s at the sea surface are illustrated in Fig. 2. One may expect that the maximum day — to —

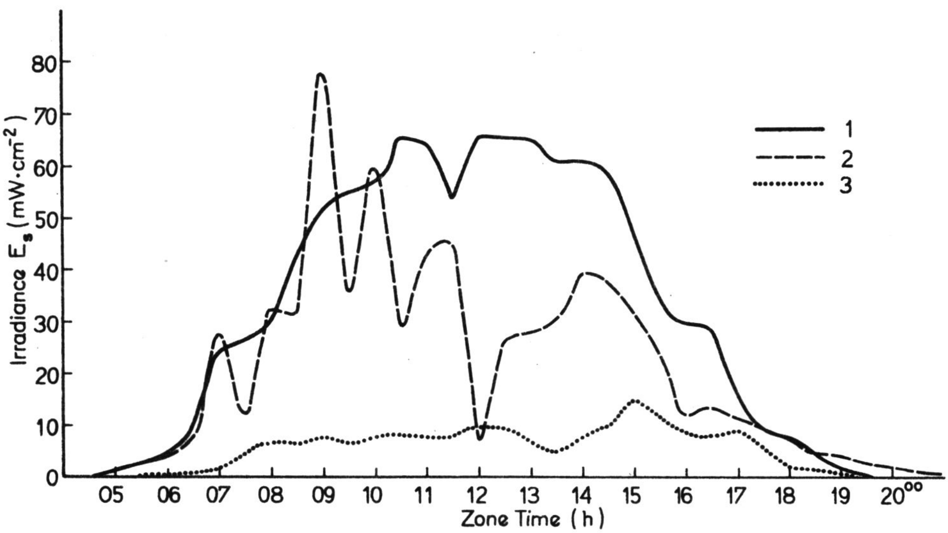

Fig. 2. Diurnal courses of the total downwelling irradiance above the sea surface under different meteorological conditions

1—28 Feb. 1981, 2—16 Feb. 1981, 3—8 Mar. 1981.

day differences in the E_s values are of the one order of magnitude at the same midday hours. The areas under the presented curves correspond to daily doses η_s of the incident solar energy. As can be easily noticed, the η_s values for bright days are several times higher than those for dark days. Such variations of external irradiation must in turn influence the natural light field in the sea and, consequently, the conditions of photosynthesis occuring there. It should be emphasized that from a biological point of view the day — to — day variations of the light penetrating the sea surface are especially important at higher latitudes. This relates mainly to winter season when the maximum energy values are low.

However these variations may also play a significant role during summer on dark days because the light saturation of photosynthesis in the euphotic zone is not reached or occurs only during a short period of these days. In addition, the irradiance fluctuations during the day, caused by changing atmospheric conditions, can affect marine organisms, especially primary production in connection with the photoadaptation ability of phytoplankton cells (Dera, Hapter and Malewicz 1975).

In spite of this, optical properties of water have a dominating influence on light conditions in the sea, i.e. on the amount and spectral distribution of light energy. It is discussed below.

The attenuation coefficient of downwelling irradiance $K_{\downarrow}(\lambda, z)$ is the basic function determining the transmission of radiant energy into the water. The $K_{\downarrow}(\lambda, z)$ values depend on inherent scattering — absorbing properties of the medium and also to the lower degree on the conditions of external irradiation, i.e. sun altitude, atmospheric state, dynamic state of the sea surface. Thus, the $K_{\downarrow}(\lambda, z)$ coefficient can be included among the apparent optical properties of the sea (Preisendorfer 1961).

Results obtained from the underwater measurements indicate the distinct spatial differentiation of the attenuation coefficient $K_{\downarrow}(\lambda)$ in waters of the investigated region (Table II). The spectral distributions of the $K_{\downarrow}(\lambda)$ values averaged in the relatively thick upper layer of he ocean (approximately equal to the euphotic zone) for different water masses are graphically shown in Fig. 3.

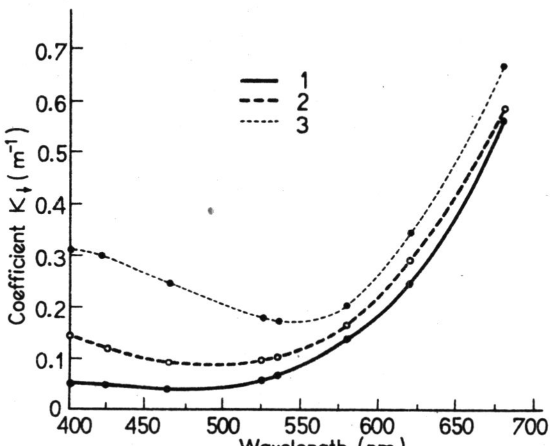

Fig. 3. Spectral distributions of the downwelling irradiance attenuation coefficient $K_{\downarrow}(\lambda)$ for different water masses in the investigated region

1—22 Feb. 1981 station No. 36, $K_{\downarrow}(\lambda)$ coefficient averaged in the water layer $0 \div 100$ m, 2—12 Mar. 1981 station No. 108, the water layer $0 \div 75$ m, 3—4 Mar. 1981 station No. 68, the water layer $0 \div 30$ m.

The spectra for the other measurements lie between the extreme presented curves. If water becomes more turbid, the shift of the minimum of the $K_{\downarrow}(\lambda)$ spectrum towards longer light waves, with a simultaneous increase in the absolute $K_{\downarrow}(\lambda)$ values, is observed. The discussed differentiation of this optical parameter is caused by considerable qualitative and quantitative changes in the concentration of dissolved organic substances as well as suspended organic and inorganic particles in the water.

Inferring from the results of both the irradiance attenuation spectra and the transmittance of visible light energy the following three main groups of optical water types can be distinguished in the investigated Antarctic region:

a. clear oceanic water,

b. oceanic water of intermediate type and oceanic water affected by coastal water,

c. coastal water and water with high biological productivity.

These water types correspond approximately to IA÷II, II÷1, 1÷3, respectively according to the Jerlov's optical classification of sea waters (Jerlov 1976, 1977).

Characteristic optical features for the distinguished water types are separately described below.

a. Clear oceanic water. This type of water was found in the northern part of the investigated region mainly along 60°S latitude, i.e. in the areas not influenced by land. These are open — ocean waters of the Drake Passage where the West Winds Drift (Antarctic Circum — Polar Current) has a predominant effect upon hydrological conditions prevailing in the Antarctic surface water (Deacon 1963).

The lowest $K_{\downarrow}(\lambda)$ values (Fig. 3 solid line) and the peak of the energy spectral distribution (Fig. 4a) indicate that the maximum of light transmission falls in the blue region in the vicinity of 475 nm. The somewhat more turbid layer is situated between the sea surface and the 10 m depth. The depth where the visible light energy is reduced to 1% of surface value is

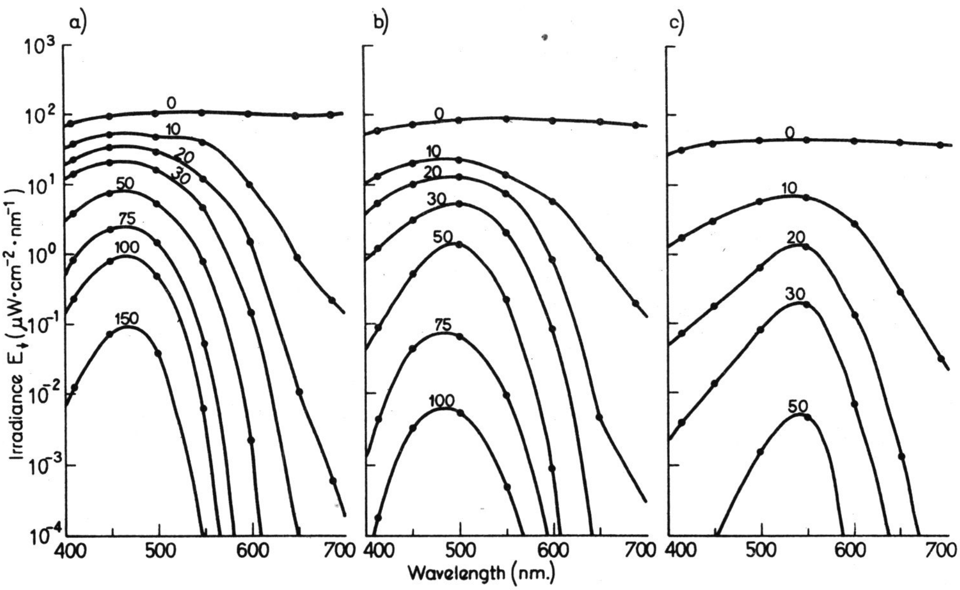

Fig. 4. Spectral distributions of downwelling irradiance $E_{\downarrow}(\lambda, z)$ at various depths in optically differentiated water masses of the investigated region

a — 27 Feb. 1981, station No. 60, b — 12 Mar. 1981, station No. 108, c — 4 Mar. 1981, station No. 68.

in the range between 55 m and 80 m (Table IV). It is in agreement with results of other optical measurements made in this area. According to Kullenberg (1980) the average 1% quanta (350 nm ÷ 700 nm) depth in the Drake Passage is equal to 75 meters. After Jerlov (1977) these waters are of I B type.

The 1% level of surface irradiance in spectral band of maximum light transmission (475 nm) was observed between 90 m and 121 m (Table IV). Relatively low biological productivity can be expected in this area.

b. Oceanic water of intermediate type and oceanic water affected by coastal water. These water types were most frequently observed in the investigated region. They were encountered south of the above mentioned parallel belt of clear oceanic water, i.e. northwest and west of South Shetland Islands and in Bransfield Strait. In other words, from the optical point of view, the area is located in the transitional zone from coastal water to oceanic one. The South Shetland Islands area is situated in the contact zone of the West Winds Drift waters and those flowing out from the Weddell Sea and as a result the hydrological conditions are affected (Chłapowski and Grelowski 1978). The optical parameters here are more changeable as compared with those of the typical open — ocean waters. It is due to the action of a complex group of environmental factors in this zone, i.e. dynamic processes, land effect, biological productivity. Thus, depending on the predominating factors, waters closer to clear oceanic water types or coastal types were there observed.

The typical example of spectral distributions of the $K_{\downarrow}(\lambda)$ coefficient and $E_{\downarrow}(\lambda)$ irradiance for the discussed waters are presented in Figs. 3 (dashed line) and 4b, respectively. As one can see the $K_{\downarrow}(\lambda)$ spectrum shows the relatively strong attenuation of violet light (as compared with clear oceanic water) which should be ascribed to organic matter dissolved in the water. The maximum of the energy spectral distribution lies in the transitional blue — green region in the vicinity of 500 nm, and shifts slightly towards the blue region with the increasing depth.

The characteristic spatial differentiation of optical parameters was observed in Bransfield Strait. The water showing a typical feature of the clear oceanic one: the spectral energy peak occurrence at 475 nm, was found in the middle part of the strait (Table II, stations Nos. 73, 90). A noticeable difference between these waters and clear oceanic ones consists in somewhat stronger attenuation of light in waters of the strait. It is particularly seen in the violet — blue region of the spectrum. Going farther towards to South Shetland Islands, a general tendency to increase turbidity of waters in the strait is observed. In the areas close to the islands the optical parameters are distinctly influenced by land material. The maximum of light transmission shifts towards longer lightwaves and the increase in the $K_{\downarrow}(\lambda)$ values over the whole visible spectrum can be found (Table II station No. 88). It results mainly from the non — selective scattering of light due to increasing concentration of large suspended particles of mineral origin. With coming nearer the coasts the mineral particles play larger and larger role as compared with organic matter in modifying underwater lightfield. In the extreme cases, the waters near the coasts reveal typical features of the optical coastal types which will be discussed later.

One may suggest that such distribution of optical values in Bransfield Strait during the summer season is mainly related to the circulation of water masses. Moreover it seems to be obvious that other enviromental factors and phenomena such as hydrometeorogical conditions, land effect and biological productivity play also an important role in modification of underwater lightfield in this area.

The 1% depth of surface irradiance (400 nm÷700 nm) was observed between about 30 m in waters approximating coastal types and 60 m in oceanic waters of intermediate type (Table IV). The 1% depth level for the most penetrating light wavelength was in a wide range from 40 m to 96 m, respectively (Table IV).

These optical data allow to suppose that medium values of the oceanic biological productivity are, with some deviations, typical for the mentioned areas.

c. Coastal water and water with high biological productivity. The considerably turbid water was found in some coastal areas around the South Shetland Islands (stations Nos. 40, 97, 104) and occasionally at greater distances from the coasts (stations Nos. 32, 46).

The turbid water with large amounts of suspended particles originating from processes of glacier ablation and rock material erosion spreads over the coastal areas. Due to relatively high concentration of inorganic suspensions in these waters the light scattering is a main phenomenon determining water transparency for visible radiation as was earlier found in Ezcurra Inlet (Dera 1980). The absorption of light due to organic components seems to be of secondary importance in the resultant effect of light attenuation (Table II stations Nos. 97, 104).

These features were not found in waters with high biological productivity where the strong light absorption in the violet — blue region reflects the great importance of organic matter. These waters were encountered in areas west of Elephant Island (Table II stations Nos. 65, 68) and southwest of Anvers Island (Table II station No. 14). Typical spectral distributions of the attenuation coefficient $K_{\downarrow}(\lambda)$ and irradiance $E_{\downarrow}(\lambda, z)$ for these waters are presented in Fig. 3 (dotted line) and 4c, respectively. The $K_{\downarrow}(\lambda)$ values are almost comparable with those for the Baltic Sea, although the attenuation in the blue region in Baltic waters is still greater.

As can be seen from the $K_{\downarrow}(\lambda)$ plots, the values of the coefficients in the violet region of the spectrum are of one order of magnitude higher than those observed in clear oceanic waters. As a consequence, the average (in euphotic zone) downwelling irradiance transmission in violet band (425 nm) does not exceed 80%/m in these productive waters when it reaches the 95%/m in clear waters of the Drake Passage.

The maximum of the spectral irradiance distribution occurs at the wavelength of about 540 nm, as a result of strong absorption in the shortwave region of the spectrum due to both dissolved and particulate organic matter. With the increasing depth, the availabe energy becomes concentrated in the green spectral band in the vicinity of 540 nm.

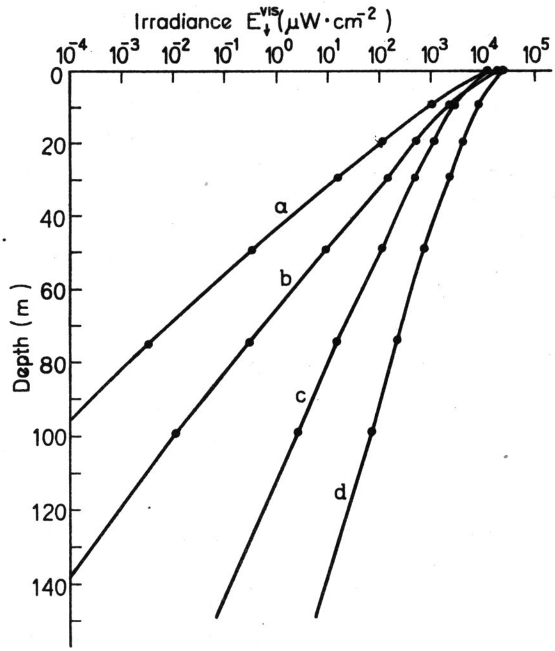

Fig. 5. Vertical distributions of the photosynthetically active radiation in the waters of the investigated region

a — 4 Mar. 1981, station No. 68, b — 7 Mar. 1981, station No. 87, c — 26 Feb. 1981, station No. 55, d — 27 Feb. 1981, station No. 60.

The euphotic zone according to the assumed optical criterion was limited to the relatively thin upper layer of about 30 m (Table IV). The 1% depth level of the photosynthetically active radiation between 20 m and 30 m was observed there (Table IV).

All the above discussed results are summarized in Figs. 5, 6 and 7. Fig. 5 shows typical vertical distributions of photosynthetically active solar energy in absolute values which were observed in optically differentiated water masses during the experiment. All other unshown cases assume the values between the extreme curves a and b.

Depth profiles of this energy in percent of surface value are illustrated in Fig. 6. For comparison the plots which represent some optical water types according to he Jerlov's classification of sea waters are also shown (Jerlov 1976). According to his classification five types of oceanic waters can be distinguished: I (optically purest water), IA, IB, II, and III (least transparent oceanic water). The classification comprises also coastal waters which are divided into nine types from the clearest water of the type 1 to the highly turbid one of the type 9.

The dashed curves in Fig. 6 denote the extreme cases found during the experiment. Thus, the dark area in the picture corresponds to the range of he observed optical water types.

The similar function but for the wavelength of maximum light transmission is presented in Fig. 7. The extreme cases noticed during the investigations

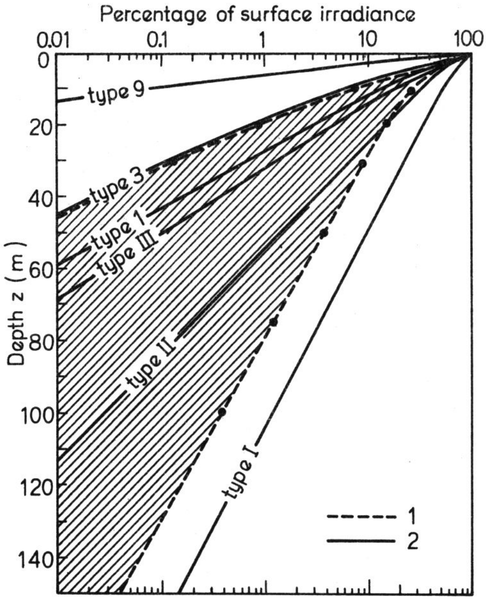

Fig. 6. Extreme depth profiles of percentage of surface downwelling irradiance (400 nm ÷ 700 nm) found in the investigated waters (dashed lines). For comparison the profiles corresponding to some optical water types after Jerlov (1976) are shown (solid lines)

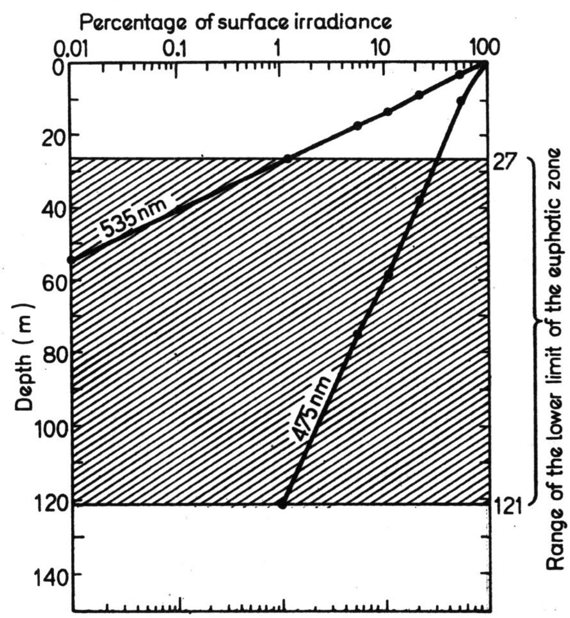

Fig. 7. Extreme depth profiles of percentage of surface irradiance for the most penetrating light wavelength found in the investigated waters
535 nm — 4 Mar. 1981, station No. 68, 475 nm — 22 Feb. 1981, station No. 36.

are shown. In connection with the optical criterion of determination of the euphotic zone the range of the lower limit of this zone is also shown. As seen, the euphotic zone thickness varies from 27 m in waters with high biological productivity (west of Elephant Island) to 121 m in optically clear waters in the Drake Passage.

Concluding, the discussed results reveal the general optical features of waters in the investigated Antarctic region during the summer season. They complete not numerous existing optical data from this region including those found by Polish Antarctic Expeditions in 1975—1979 (Wensierski and Woźniak 1978, Dera 1980).

It should be stressed that the data presented here are burdened with measurement errors and errors connected with computational procedures assumed.

The uncertainty in the values of solar radiation reaching the sea surface (Table I) amounts a few percent and is in the first place a consequence of instrumental errors.

The relatively high accuracy (the error from about one to a few percent) can be expected in values of the irradiance attenuation coefficient $K_{\downarrow}(\lambda)$ (Table II). These values were obtained basing on relative underwater irradiance measurements which are more accurate than absolute ones. The slight nonlinearity of the measuring integrating system was taken into account. The underwater observations were corrected with regard to changing light conditions above the sea surface. The fluctuations of underwater lightfield due to surface waves were eliminated by time — averaging of signals measured. Owing to time — integrating technique of measurements the random errors were reduced to negligible level. Thus, the main sources of experimental errors are the imperfect instruments, the determination of measuring depth, and disturbances from the ship either by shadowing or light reflection effect.

Considering the exponential decay with depth of downwelling irradiance (Eq. 3) an accuracy of computed energetic values (Table III) is mainly conditioned by the measurement errors of attenuation coefficient $K_{\downarrow}$. The errors connected with the assumptions of computational procedures seem to be less significant as compared with mentioned above.

Taking into account the investigating conditions of a complex experiment, the optical measurements and computations were devised in order to obtain a satisfactory approximation for many applications. Thus, the significant aspect is that the optical data allow to describe the underwater lightfield with an accuracy sufficient for many practical purposes. The presented data can be applied to such practical problems as studies of primary production and migration of krill swarms.

Due to a complex mechanism of formation of underwater lightfield, the more detailed interpretation of optical results would be possible with taking into account such phenomena as a system of water currents, inflow of biogenic substances into the surface water, land effect, biological productivity and others. In order to correlate the optical data with other processes occurring in environment, the comprehensive oceanographic and hydrobiological data obtained during the experiment are necessary.

The authors would like to acknowledge the support from institutes and colleagues who have made it possible for us to gather the data.

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5. Резюме

Проведены исследования световых условий в антарктических водах пролива Дрейка и в районе Южно-Шетландских островов во время летнего сезона февраль—март 1981 года. Для спектральных измерений показателя вертикального ослабления облученности в море в видимом диапазоне спектра от 400 нм до 700 нм использовался измеритель облученности сверху производства Института Океанологии ПАН в Сопоте. Для непрерывной регистрации суммарной солнечной радиации, приходящей к поверхности моря, использовался пиранометр (таблица I).

В таблицах II и III помещены спектральные и энергетические характеристики натурального поля света в море, а в таблице IV характерные оптические глубины.

Обнаружено значительную пространственную изменчивость оптических свойств исследуемых вод. На основе данных о вертикальном ослаблении облучённости воды эти были условно подразделены на три следующие группы различных оптических типов:

а. чистые океанические воды,

б. посредние океанические воды под влиянием прибрежных вод,

в. прибрежные воды и воды с высокой биологической продуктивностью.

Эти типы вод соответствуют типом: IA÷II, II÷1, 1÷3, по оптической классификации вод Ерлова (Jerlov 1976, 1977). Для каждой из выделенных групп отдельно рассмотрены характерные оптические свойства.

Оптически наиболее чистые воды со средней толщиной эуфотической зоны около 100 м были обнаружены в северной части исследуемого района то есть в проливе Дрейка. Остальные водные акватории вокруг Южно-Шетландских островов оптически более разнородны. В зависимости от доминирующих факторов среды наблюдались здесь или мутные воды прибрежных типов или относительно чистые воды посредних океанических типов. В некоторых районах (к западу от острова Элефант, к юго-западу от острова Анверс) регистрировались оптические свойства вод, в особенности сильное поглощение фиолетового и голубого света, свидетельствующие о высокой биологической продуктивности. Нижняя граница эуфотической зоны достигала в этих водах около 30 м.

6. Streszczenie

Zbadano warunki świetlne panujące w antarktycznych wodach Cieśniny Drake'a i w rejonie Wysp Południowych Szetlandów podczas sezonu letniego, w okresie luty — marzec 1981 r. Za pomocą miernika oświetlenia skonstruowanego w Zakładzie Oceanologii PAN w Sopocie wykonywano spektralne pomiary osłabiania oświetlenia odgórnego w morzu, w widzialnym zakresie widma od 400 nm do 700 nm. W sposób ciągły rejestrowano całkowitą energię promieniowania słonecznego docierającą do powierzchni morza wykorzystując piranometr (tabela I).

W tabelach II i III zamieszczono spektralne i energetyczne charakterystyki naturalnego pola światła w morzu, a w tabeli IV — charakterystyczne głębokości optyczne.

Stwierdzono znaczne przestrzenne zróżnicowanie właściwości optycznych badanych wód.

Na podstawie danych o osłabianiu oświetlenia odgórnego, wody te zostały umownie podzielone na trzy następujące grupy różnych typów optycznych:
a. czyste wody oceaniczne,
b. oceaniczne wody typu pośredniego i wody pod wpływem wód przybrzeżnych,
c. wody przybrzeżne i wody z wysoką produktywnością biologiczną.
Te typy wód odpowiadają odpowiednio typom: IA÷II, II÷1, 1÷3, według optycznej klasyfikacji wód (Jerlov 1976, 1977). Omówiono oddzielnie charakterystyczne cechy optyczne dla każdej wyróżnionej grupy wód.

Optycznie najczystsze wody, ze średnią grubością strefy eufotycznej około 100 m, stwierdzono w północnej części badanego rejonu, tj. w Cieśninie Drake'a. Pozostałe obszary wód wokół Wysp Południowych Szetlandów są pod względem optycznym bardziej zróżnicowane. W zależności od dominujących czynników środowiskowych obserwowano tu zmętnione wody typów przybrzeżnych bądź stosunkowo czyste wody pośrednich typów oceanicznych. W niektórych obszarach (na zachód od Wyspy Elephant, na południowy zachód od Wyspy Anvers) notowane własności optyczne wody, a w szczególności stosunkowo silne osłabianie światła fioletowoniebieskiego, świadczą o wysokiej produktywności biologicznej. Dolna granica strefy eufotycznej sięgała w tych wodach około 30 m.

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