UNIVERSITA' DEGLI STUDI DI TRIESTE
DIPARTIMENTO DI SCIENZE DELLA TERRA
OM OCEANOGRAFIA e METEOROLOGIA

Rapporto N. 68 OM 98/6

Franco Stravisi

Optical seawater properties in the Gulf of Trieste

International Workshop on the
"Oceanography of the Adriatic Sea"

ICTP, Trieste, 21-25 September 1998

Trieste, 1998

CONTENTS

Optical seawater properties in the Gulf of Trieste

Franco Stravisi
University of Trieste,
Department of Earth Sciences,
Oceanography and Meteorology

The irradiance measurements

An extended research was performed in the years 1979-1984 in the Gulf of Trieste, sponsored by the National Research Council, Experimental Thalassographic Institute of Trieste (IST) ; 147 stations were visited, measuring vertical profiles of seawater temperature, conductivity, velocity and irradiance, and Secchi disc depths. This project was named “Thalassia II” ; further details and the whole data set are reported by Stravisi (1990). A Kahlsico irradiameter mod. 268WA315 n. 8102 was used to measure the PAR irradiance over a horizontal surface just above the sea (on the boat deck) and underwater at the depth of 0.1, 0.5, 1 ,2 , 3 m ... to the bottom. This instrument has three selenium photocells. Each of them has a corrective filter transmitting the PAR band (a 425-665 nm “spectral measuring range” is certified, fig. 1), and a white plastic diffusor that assures the correct cosine response of the collecting surface and, reducing to about 10 % the light intensity on the photocell, makes it work almost linearly. The external (ambient) photocell, mounted on gimbals, measures the solar irradiance above the sea surface E_o; the underwater unit consists of two photocells, facing upwards and downwards, measuring the *downwelling* (or downward) irradiance E_d and the *upwelling* (or upward) irradiance E_u respectively. A reading unit ("deck control module") has two LCD displays: one gives E_o, the second E_d or E_u according to the position of a switch. Auto-zero and auto-ranging are assured by a microprocessor ; mean values are displayed every 5 s. The irradiameter was calibrated at the factory against a secondary standard, based on the 1973 National Bureau of Standards scale of spectral irradiance.

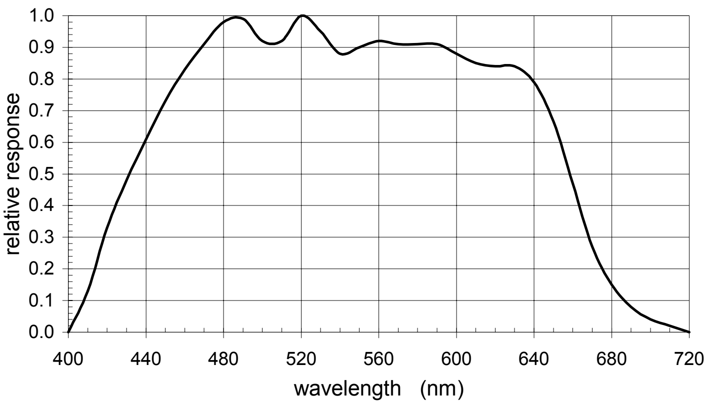


Fig. 1. *Spectral response of the Kahlsico mod. 268WA315 PAR irradiameter (according to the reference manual).*

Measures obtained by means of the ambient (E_o) and underwater (E_d, E_u) photocells have been compared between them and with a conventional Kipp & Zonen CM11 pyranometer (short wave band); the ratio between the global solar irradiance E_G and the corresponding PAR irradiance is $E_G/E_o = 2.94 \pm 0.03$.

The irradiance measurements exhibit a variability which is strongly related to the surface wave height (usually in the range 0-50 cm). Therefore, at each depth, about ten readings of simultaneous ambient/downwelling and ambient/upwelling irradiance, (with averages E_o, E_d and E_o, E_u) were taken in the surface layer and five readings below the depth of a wavelength ; homogeneous z profiles, reduced to the same average irradiance over the sea surface $<E_o>$, were computed as $E_d(z) = <E_o>E_d / E_o$, , $E_u(z) = <E_o>E_u/E_o$. The vertical axis z is taken positive downward. At each station seawater temperature/conductivity profiles were measured by means of a Martek Mark VII probe, calibrated at the IST laboratory, and the corresponding PSS-1978 practical salinity and IESS-1980 density data were computed. Conventional white and black Secchi disc (30 cm diameter) depths z_w, z_b were determined as well, looking from about 1.5 m above the sea surface.

The Thalassia II irradiance profiles considered in this paper, reported in tables 1, 2, are 23. The location of each station is represented in fig. 2 ; the "offshore" group (D) has an average depth h = 23 m, the "coastal" group (A, W, M, V) has an average depth h = 17 m.

Seawater optical properties

The measured quantities E_d, E_u (down and upwelling irradiance - *irradiance* is the radiant energy collected by a plane unit surface per unit time) have been already defined. The irradiance ratio or *reflectance* is $R = E_u/E_d$. The *scalar irradiance* E_s is defined as the light power collected by a spherical unit surface ; $\boldsymbol{E}$ is the *irradiance vector*, with a vertical component $E_z = E_d - E_u$ representing the *net* downward irradiance. The quantity $\mu = E_z/E_s$ is called the *average cosine*. These are known also as "apparent" optical properties, since depend on the external solar irradiance. The *vertical attenuation coefficient* for irradiance E_x is defined by

$$K_x(z) = -(\partial E_x / \partial z) / E_x = -\partial \ln E_x / \partial z \quad ;$$

"Inherent" optical properties, depending on seawater characteristics, are the *absorption* coefficient a, the *scattering* coefficient b and the *beam attenuation* coefficient $c = a + b$. Absorption and irradiance are related by the classical Gershun equation

$$a\, E_s = -\nabla \cdot \boldsymbol{E} \quad ;$$

if the irradiance vector is locally uniform on the horizontal plane, its horizontal divergence vanishes and absorption is proportional to the average cosine and to the attenuation coefficient of the net downward irradiance (Jerlov 1976) :

$$a = -(\partial E_z / \partial z)/E_s = K_E\, E_z/E_s = \mu\, K_E \qquad (1)$$

According to Kirk (1981b), the irradiance reflectance R and the average cosine μ are functions only of the ratio b/a of the scattering to the absorption coefficient ; given R and the sun zenith angle θ he finds, by means of Monte-Carlo simulations, the relationships $\mu(R, \theta)$ and $b/a(R, \theta)$ at the middle of the euphotic zone, and reports the corresponding plots. According to Kirk diagrams, we computed the relationships above in the following analytical form (errors are less than 1%) :

St.	D		D		D		D		D		D		D		D		D		D		D	
no.	101		102		111		113		114		115		116		117		128		129		130	
	10 Jul 81		7 Aug 81		19 Sep 81		26 Mar 82		24 Apr 82		27 May 82		29 Jun 82		6 Aug 82		16 Oct 82		20 Nov 82		11 Jan 83	
	10:41-11:00		12:25-12:40		10:15-10:26		13:45-14:15		11:30-12:00		11:05-11:42		12:10-12:57		12:25-13:05		11:21-12:03		11:53-12:29		11:55-12:35	
θ	29°		29°		50°		49°		33°		26°		23°		29°		54°		65°		68°	
$\langle E_o \rangle$	301 W/m²		304 W/m²		56 W/m²		202 W/m²		309 W/m²		321 W/m²		353 W/m²		311 W/m²		195 W/m²		145 W/m²		114 W/m²	
z_w	17.0 m		10.3 m		10.9 m		10.3 m		8.7 m		6.5 m		12.8 m		9.6 m		6.2 m		7.0 m		5.5 m	
z_b	4.5 m		5.7 m		4.0 m		5.9 m		4.9 m		2.7 m		5.2 m		4.3 m		3.8 m		3.7 m		3.2 m	
z	E_u	E_u	E_d	E_u	E_d	E_u	E_d	E_u	E_d	E_u	E_d	E_u	E_d	E_u	E_d	E_u	E_d	E_u	E_d	E_u	E_d	E_u
m	W/m²	W/m²	W/m²	W/m²	W/m²	W/m²	W/m²	W/m²	W/m²	W/m²	W/m²	W/m²	W/m²	W/m²	W/m²	W/m²	W/m²	W/m²	W/m²	W/m²	W/m²	W/m²
0.1			182.0	4.686	26.0	0.519	141.7	5.632			179.7	4.863	216.8	3.741	191.5	4.266	134.7	5.212	110.6	4.167	66.2	5.215
0.5	155.0	2.498	174.3	4.706	23.9	0.522	159.0	5.447	147.5	5.678	161.1	4.655	183.8	3.681	181.8	4.127	125.1	4.955	102.1	4.148	63.9	4.731
1	143.7	2.424	165.1	4.543	22.7	0.527	114.7	5.378	112.1	5.629	151.8	4.532	172.9	3.534	141.6	4.007	103.5	4.558	77.3	3.800	52.7	4.330
2	108.8	2.129	164.5	4.689	16.7	0.442	92.9	4.913	122.7	4.996	110.7	3.995	149.7	3.427	121.6	3.700	68.7	3.713	51.5	3.110	34.0	3.439
3	98.7	2.038	124.1	4.314	14.3	0.405	76.2	4.287	94.1	4.397	84.2	3.154	132.3	3.308	96.6	3.407	52.8	2.872	38.2	2.399	24.1	2.473
4	87.0	1.866	98.2	3.848	13.2	0.340	65.1	3.881	89.0	3.855	71.2	2.232	128.4	3.168	93.8	3.093	42.6	2.167	28.8	1.832	18.8	1.904
5	84.6	1.671	75.7	3.694	11.6	0.280	55.9	3.357	77.6	3.331	62.5	1.864	116.1	2.923	87.4	2.737	30.8	1.697	23.8	1.502	15.2	1.542
6	76.0	1.520	74.2	3.244	9.8	0.235	49.6	3.100	65.5	2.930	50.3	1.507	105.1	2.752	72.1	2.457	23.9	1.301	19.6	1.204	11.8	1.181
7	73.4	1.429	64.5	2.873	8.4	0.211	41.6	2.655	57.9	2.491	42.1	1.279	98.7	2.554	66.2	2.181	18.6	1.031	14.9	0.980	9.2	0.944
8	65.9	1.338	48.8	2.566	7.3	0.179	34.7	2.296	48.0	2.163	36.5	1.150	80.8	2.333	57.9	1.956	13.0	0.777	11.8	0.799	6.8	0.687
9	62.2	1.290	46.0	2.410	6.0	0.148	30.8	2.008	41.7	1.894	31.6	1.063	73.2	2.202	51.5	1.785	10.6	0.671	9.2	0.635	5.4	0.550
10	57.8	1.228	37.5	2.203	5.0	0.121	26.5	1.770	34.3	1.585	27.7	0.966	59.1	2.051	45.2	1.588	8.2	0.558	7.2	0.520	4.0	0.391
11	52.1	1.205	35.4	1.775	4.4	0.105	23.8	1.530	29.2	1.375	23.4	0.901	55.4	1.885	41.4	1.442	6.7	0.475	5.8	0.427	3.3	0.335
12	46.9	1.103	25.5	1.527	3.6	0.090	20.1	1.305	25.6	1.226	20.0	0.870	46.7	1.800	36.9	1.296	5.4	0.370	4.7	0.370	2.4	0.248
13	41.6	1.059	25.0	1.320	2.9	0.069	17.2	1.100	21.0	1.027	17.4	0.858	40.6	1.678	32.3	1.124	4.5	0.324	3.9	0.312	1.8	0.186
14	39.1	1.009	21.4	1.090	2.1	0.058	14.4	0.941	17.6	0.941	14.7	0.860	36.0	1.579	29.9	1.070	3.7	0.281	3.0	0.261	1.4	0.148
15	35.3	0.971	15.7	0.932	1.7	0.055	12.7	0.858	15.0	0.884	13.1	0.927	33.2	1.534	24.9	0.900	3.0	0.234	2.6	0.231	1.2	0.119
16	32.2	0.923	12.8	0.894	1.4	0.052	10.0	0.743	12.9	0.814	11.5	0.878	29.9	1.524	21.8	0.794	2.5	0.195	2.1	0.198	0.9	0.101
17	28.2	0.902	11.0	0.908	1.2	0.048	9.5	0.696	11.0	0.731	9.5	0.806	26.0	1.589	19.3	0.721	1.9	0.165	1.7	0.167	0.7	0.077
18	25.3	0.919	8.7	0.845	1.0	0.051	7.9	0.623	9.1	0.685	7.7	0.714	22.0	1.569	17.0	0.709	1.4	0.127	1.3	0.143	0.5	0.059
19	22.6	0.839	6.7	0.653	0.9	0.053	7.1	0.587	8.0	0.645	6.4	0.656	18.2	1.515	15.1	0.717	1.2	0.111	1.1	0.128	0.4	0.051
20	19.2	0.881	4.4	0.472	0.8	0.057	6.3	0.543	6.6	0.591	5.1	0.569	14.9	1.388	13.1	0.722	0.9	0.089	0.9	0.102	0.3	0.042
21	16.2	0.968	2.9	0.313	0.6	0.057	5.4	0.517	5.4	0.513	4.1	0.488	11.9	1.166	10.1	0.643	0.6	0.074	0.7	0.094	0.3	0.035
22	12.0	0.988	2.0	0.196			4.9	0.475	4.7	0.450			8.7	1.031	6.2	0.529	0.5	0.052	0.5	0.077	0.2	0.030
23															4.8	0.463						

Table 1.- Group (h=23 m) : station code/number, date and local time (GMT + 1h), sun zenith angle, mean surface irradiance E_o, white and black Secchi disc depths $z_{w,b}$, down/upwelling irradiance profiles E_d, E_u .

St.	A		A		A		A		A		A		A		A		V		M		M		W	
no.	**103**		**104**		**105**		**106**		**107**		**108**		**109**		**110**		**127**		**136**		**138**		**147**	
	7 Sep 81		7 Sep 81		8 Sep 81		8 Sep 81		9 Sep 81		9 Sep 81		10 Sep 81		10 Sep 81		14 Sep 82		1 Aug 84		4 Aug 84		30 Aug 84	
	12:35-12:45		15:50-16:05		10:40-10:55		15:55-16:07		11:50-12:05		16:16-16:25		11:25-11:45		16:00-16:22		12:20-12:55		11:15-11:45		11:17-11:52		15:04-15:27	
θ	40°		63°		43°		65°		40°		68°		41°		67°		43°		29°		29°		55°	
$\langle E_o \rangle$	273 W/m^2		154 W/m^2		268 W/m^2		134 W/m^2		232 W/m^2		77 W/m^2		67 W/m^2		107 W/m^2		238 W/m^2		219 W/m^2		301 W/m^2		165 W/m^2	
z_w	8.3 m		8.0 m		7.1 m		6.0 m		8.5 m		8.0 m		9.0 m		8.5 m		7.3 m		11.0 m		8.5 m		12.0 m	
z_b	5.0 m		4.3 m		4.5 m		3.3 m		4.0 m		3.9 m		4.3 m		4.0 m		4.9 m		4.5 m		3.9 m		6.3 m	
z	E_u	E_u	E_d	E_u	E_d	E_u	E_d	E_u	E_d	E_u	E_d	E_u	E_d	E_u	E_d	E_u	E_d	E_u	E_d	E_u	E_d	E_u	E_d	E_u
m	W/m^2	W/m^2	W/m^2	W/m^2	W/m^2	W/m^2	W/m^2	W/m^2	W/m^2	W/m^2	W/m^2	W/m^2	W/m^2	W/m^2	W/m^2	W/m^2	W/m^2	W/m^2	W/m^2	W/m^2	W/m^2	W/m^2	W/m^2	W/m^2
0.1	172.4	5.596	87.2	2.880	103.7	5.639	65.2	3.482	138.1	3.926	26.1	1.499	38.8	1.073	68.1	1.649	193.0	3.661	111.7	2.083	199.3	3.491	87.8	1.626
0.5	135.7	5.850	54.0	2.976	95.5	5.397	20.9	3.637	172.5	3.766	39.2	1.583	24.4	1.069	45.1	1.514	126.8	3.304	110.4	1.972	181.5	3.497	76.3	1.524
1	112.0	5.312	48.2	3.014	86.1	5.188	47.1	3.224	98.0	3.391	31.4	1.222	23.6	1.000	39.6	1.403	103.9	3.052	93.1	1.842	168.8	3.446	69.7	1.442
2	110.0	5.712	46.2	2.408	70.0	4.711	31.7	2.649	91.2	2.875	23.8	1.000	17.5	0.966	29.7	1.301	85.5	2.683	71.1	1.629	150.3	3.182	59.4	1.297
3	72.4	4.791	26.2	2.644	56.7	4.441	16.1	2.022	55.7	2.605	15.6	0.843	14.3	0.824	23.7	1.138	63.4	2.048	61.6	1.383	108.7	2.918	55.7	1.302
4	85.0	3.779	27.8	1.905	46.2	3.745	17.6	1.631	58.1	2.376	14.2	0.756	14.4	0.739	21.9	0.953	53.5	1.699	56.2	1.239	88.7	2.598	49.0	1.209
5	63.1	3.718	21.4	1.582	36.4	3.002	16.2	1.244	41.9	2.200	12.3	0.663	13.1	0.668	17.0	0.829	40.2	1.318	50.2	1.117	86.3	2.378	39.5	1.055
6	56.7	3.467	23.6	1.420	33.2	2.527	14.1	0.994	38.3	2.041	10.7	0.591	11.1	0.606	16.1	0.754	30.9	1.088	43.8	1.028	70.1	2.032	33.7	0.976
7	40.8	3.052	18.9	1.357	26.4	2.037	11.6	0.804	34.4	1.868	9.1	0.500	9.9	0.557	12.1	0.700	25.7	0.947	38.5	0.960	61.5	1.688	27.0	0.803
8	35.2	2.941	12.8	1.102	22.5	1.732	8.1	0.685	28.8	1.760	7.9	0.502	9.1	0.509	10.7	0.588	19.7	0.983	35.0	0.922	52.4	1.508	23.9	0.652
9	28.3	2.617	13.1	1.005	17.3	1.462	7.3	0.625	23.8	1.642	7.0	0.456	7.8	0.482	8.6	0.537	15.5	0.933	32.3	0.887	44.6	1.257	19.8	0.554
10	19.5	1.646	8.9	0.825	14.1	1.254	6.0	0.533	20.6	1.546	5.7	0.443	6.1	0.461	7.9	0.505	12.3	0.842	28.4	0.858	41.9	1.170	16.7	0.509
11	13.1	1.196	7.1	0.660	11.2	1.093	4.5	0.451	17.2	1.475	4.7	0.411	5.1	0.421	6.9	0.482	10.5	0.720	25.6	0.802	35.4	1.097	14.5	0.501
12	10.3	1.035	5.3	0.527	10.2	0.990	3.9	0.344	13.8	1.408	4.2	0.418	4.0	0.437	5.7	0.459	7.9	0.594	23.2	0.780	31.4	1.070	12.7	0.474
13	7.1	0.843	4.0	0.481	7.7	0.893	2.7	0.341	9.1	1.341	3.4	0.392	3.7	0.401	4.7	0.480	6.0	0.465	20.9	0.750	28.8	1.034	11.6	0.480
14	5.6	0.787	2.9	0.384	5.9	0.794	2.0	0.271	7.6	1.099	2.3	0.369	2.5	0.401	3.7	0.472	4.8	0.394	19.0	0.734	25.4	1.047	9.0	0.523
15	4.0	0.661	2.4	0.351	4.4	0.668	1.3	0.209	5.3	0.840	1.6	0.262	1.9	0.337	2.8	0.423	3.4	0.282	16.8	0.733	22.0	1.039	8.3	0.613
16	2.5	0.444	1.6	0.237	3.0	0.449	0.9	0.138	3.8	0.582	1.0	0.156	1.6	0.250	1.6	0.255	2.3	0.214	15.0	0.755	20.0	1.072	7.2	0.678
17																	1.4	0.121	13.3	0.788	17.3	1.121		
18																	0.9	0.082	12.1	0.834	15.3	1.201		
19																			10.5	0.920	12.7	1.342		

Tab. 2.- Group (h=17 m) : station code/number, date and local time (GMT + 1h), sun zenith angle, mean surface irradiance E_o, white and black Secchi disc depths $z_{w,b}$, down/upwelling irradiance profiles E_d, E_u .

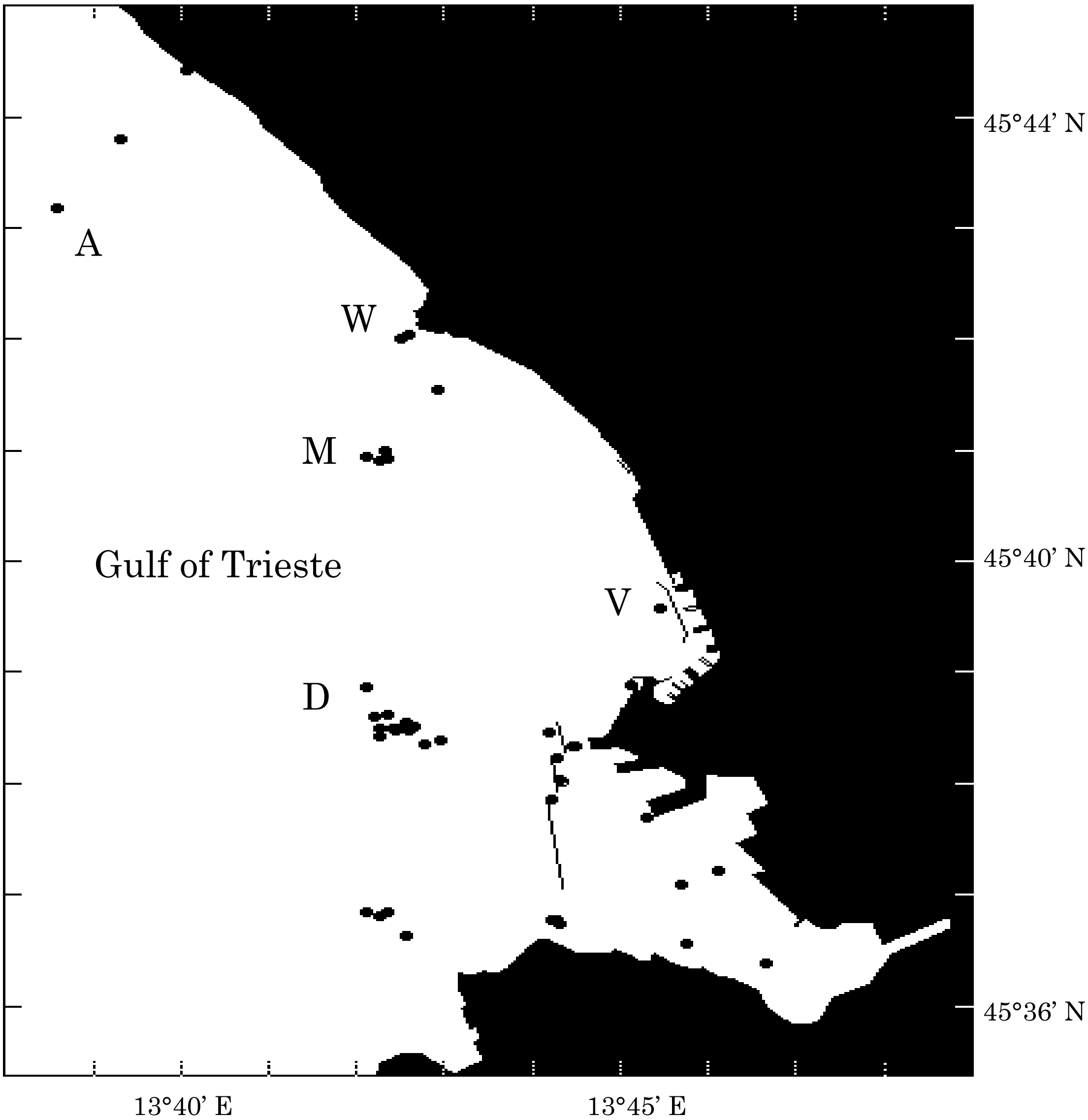


Fig. 2.- *Thalassia II irradiance stations in the Gulf of Trieste.*
Group (h = 23 m*) :* D *; group (h = 17* m*) :* A, W, M, V.

$$\mu \quad = \quad \mu_o + \exp(\mathrm{A}R + \mathrm{B}) \quad , \qquad (2)$$

$$\mu_o \quad = \quad 0.581 - (0.9993 + 0.0003\ \theta) \quad ,$$

$$\mathrm{A} \quad = -26.119 + 0.0537\ \theta - 0.000447\ \theta^2 \quad ,$$

$$\mathrm{B} \quad = \quad -0.918 + 0.0014\ \theta - 0.000258\ \theta^2 \quad ;$$

$$b/a \quad = \quad 0.4100 + 110.82\ R - 185.8\ R^2 + 1095\ R^3 + \mathrm{C} \quad , \qquad (3)$$

$$\mathrm{C} \quad = (-8.025 + 0.2775\ \theta)\,|\mathrm{R} - 0.09| + 0.725 - 0.0250\ \theta \quad ,$$

$$(\text{if } \mathrm{C} > 0 \text{ then } \mathrm{C} = 0, \quad \text{if } \mathrm{R} > 0.18 \text{ then } \mathrm{C} = 0) \quad .$$

In this way, starting from conventional down/upwelling irradiance measurements, we can compute the reflectance R , the net downward irradiance $E_z = E_d - E_u$ and the corresponding attenuation coefficient K_E, the average cosine (2) and the b/a ratio (3), and at last the coefficients a (1), b, c. Fig. 3 represents (2,3).

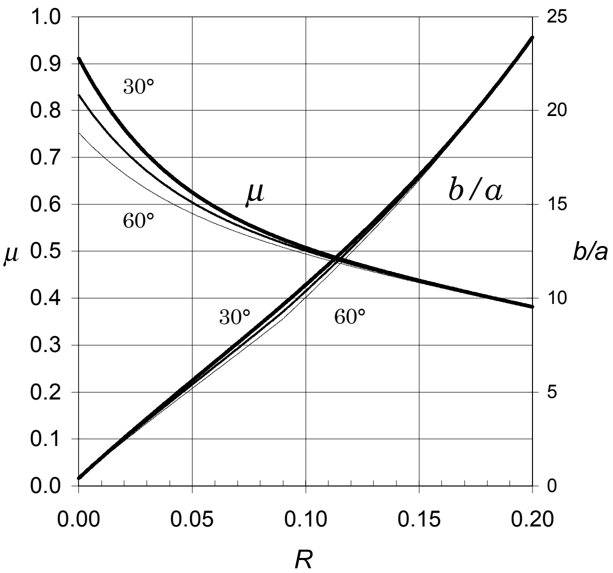


Fig. 3.- *Plots of μ(R) and b/a(R), sun zenith angle 30°, 45°, 60° ; computed after Kirk (1981b).*

Analysis of the irradiance data

The Thalassia II irradiance stations (table 1, 2) refer to years 1981-1984. The overall temperature/ salinity diagram is represented in fig. 4 : seawater temperature is between 8 and 26 °C, practical salinity between 30 and 39 psu ; typical values are 21 °C and 37.5 psu. The temperature and salinity annual cycles vs. depth and the circulation patterns in the Gulf of Trieste are described by Stravisi (1983a,b).

The 23 reflectance profiles *R(z)* are plotted in fig. 5 ; depth is between 16 and 23 m. Since *R* increases with *b/a* (fig. 3), the irradiance ratio generally increases approaching the bottom. This is usually due not to the bottom reflectance, which is very low, but to an often present bottom cloud of light scattering suspended sediments. Irradiance stations have been therefore divided into two groups, according to the mean depth, as already specified. The mean vertical *in situ* density excess profiles $\gamma(z) = \rho$€– 1000 kg/m^3 , and the mean vertical Brunt-Väisälä period $T_{BV}(z) = 2\pi/\nu$ under stability conditions, are represented in fig. 6, for both station groups. The Brunt-Väisälä frequency ν is defined by $\nu^2 = g(\partial\rho/\partial z)/\rho$; the vertical equilibrium is stable when $\nu^2 > 0$, unstable when $\nu^2 < 0$. Instability often occurs, in the Gulf of Trieste, during autumn and winter. The mean density excess increases almost linearly at the offshore station D from 26.5 to 28.5 kg/m^3 ; near the coast, freshwater often spreads at the surface. The probable internal wave period is between 2 and 6 min.

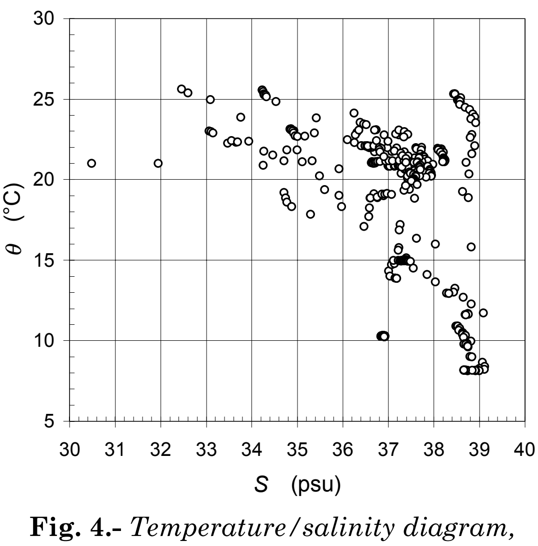


Fig. 4.- *Temperature/salinity diagram, Thalassia II irradiance stations.*

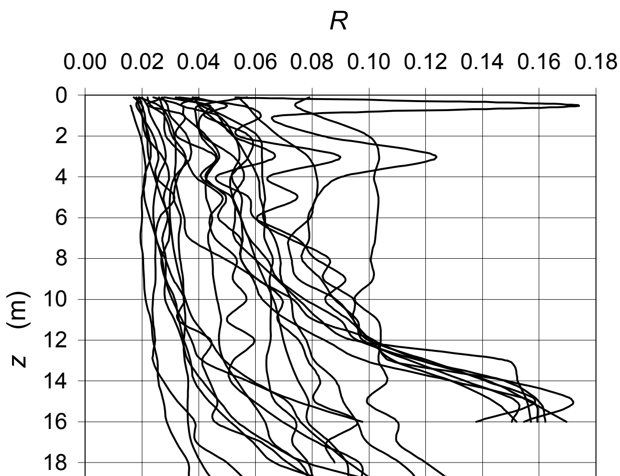


Fig. 5.- *Thalassia II stations : reflectance profiles.*

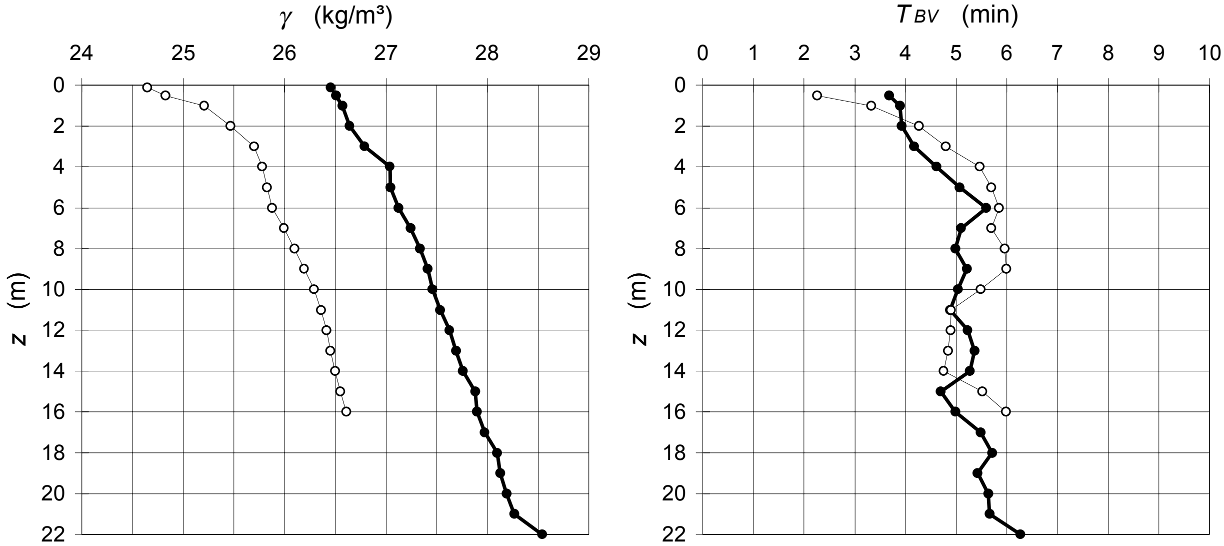


Fig. 6.- *In situ mean density excess γ and mean Brunt-Väisälä period* T_{BV} *: station groups h = 23* m *and h = 17* m.

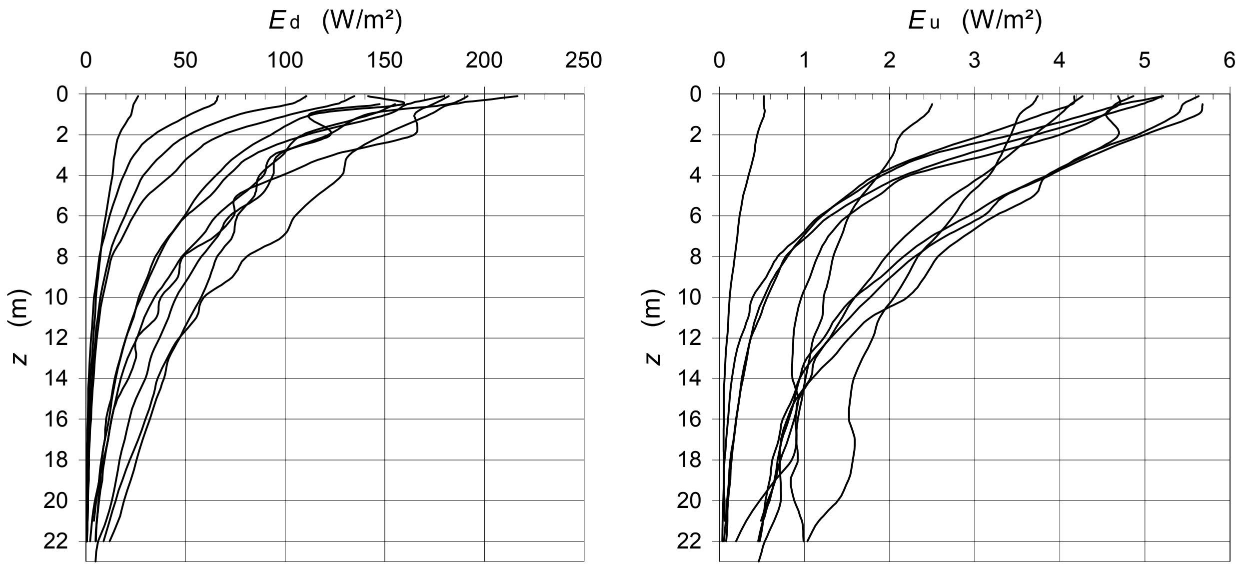


Fig. 7.- *Downwelling and upwelling irradiance, group (h = 23 m).*

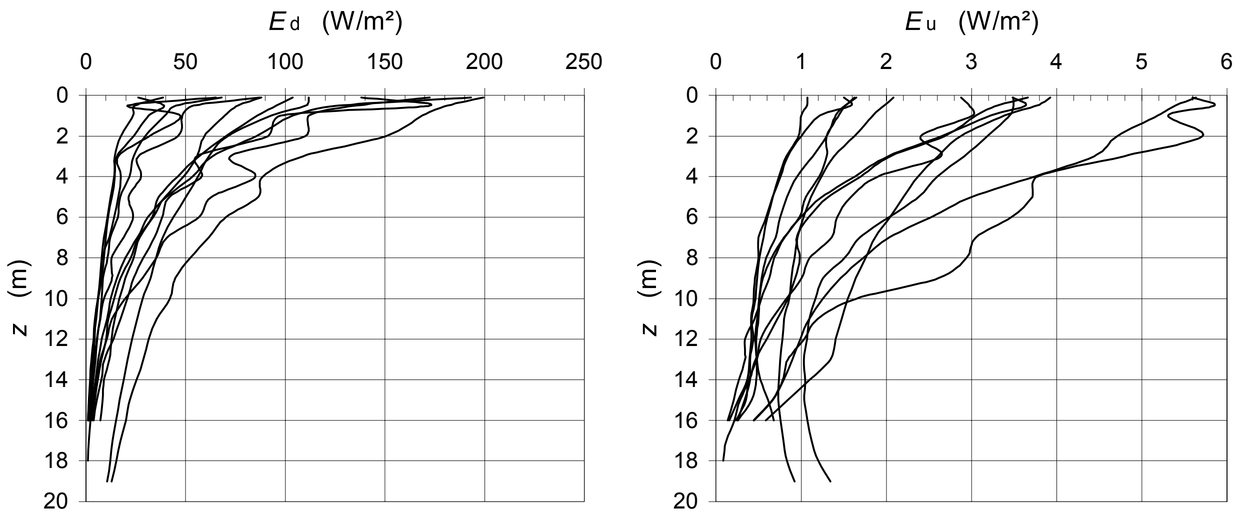


Fig. 8.- *Downwelling and upwelling irradiance, group (h = 17 m).*

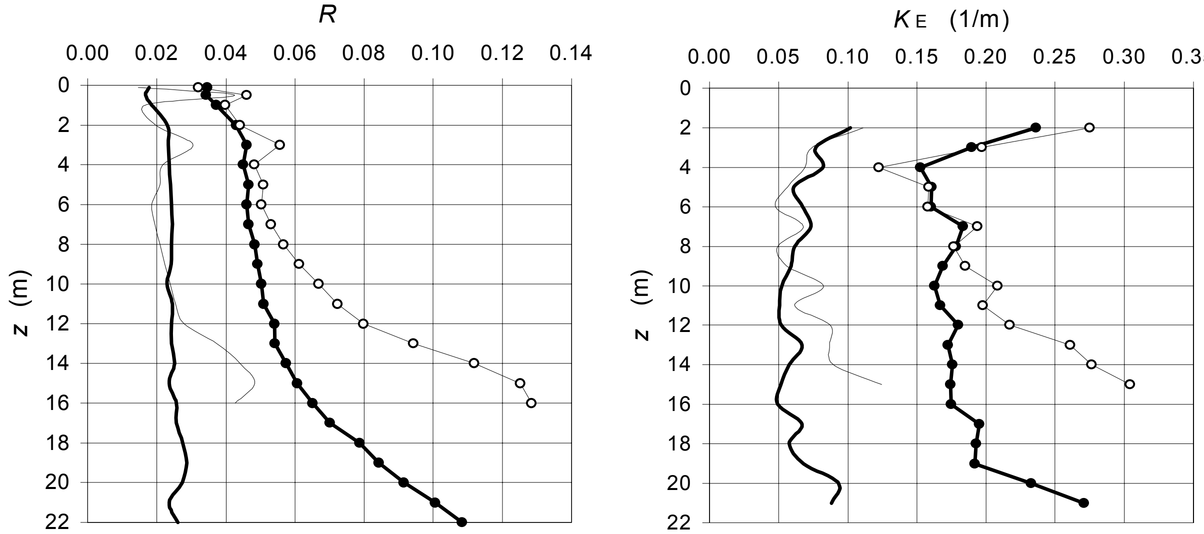


Fig. 9.- *Irradiance reflectance R and attenuation coefficient K_E for net downward irradiance ($E_z = E_d - E_u$) : mean and standard deviation, station groups h = 23* m *and h = 17* m.

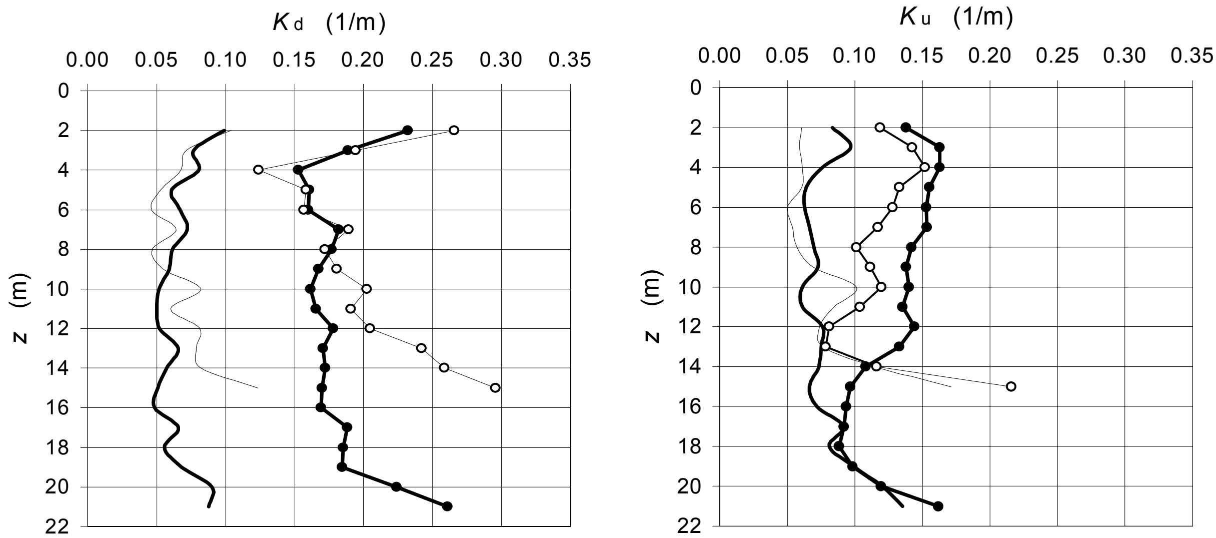


Fig. 10.- *Attenuation coefficients K_d , K_u for downwelling(E_d) , upwelling (E_u) irradiance : mean and standard deviation, station groups h = 23* m *and h = 17* m.

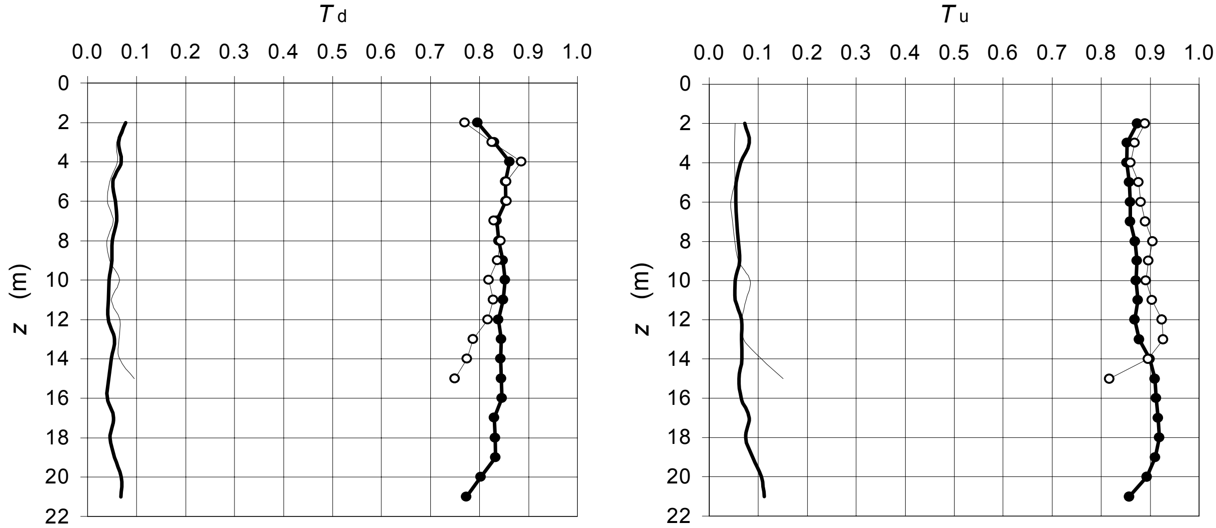
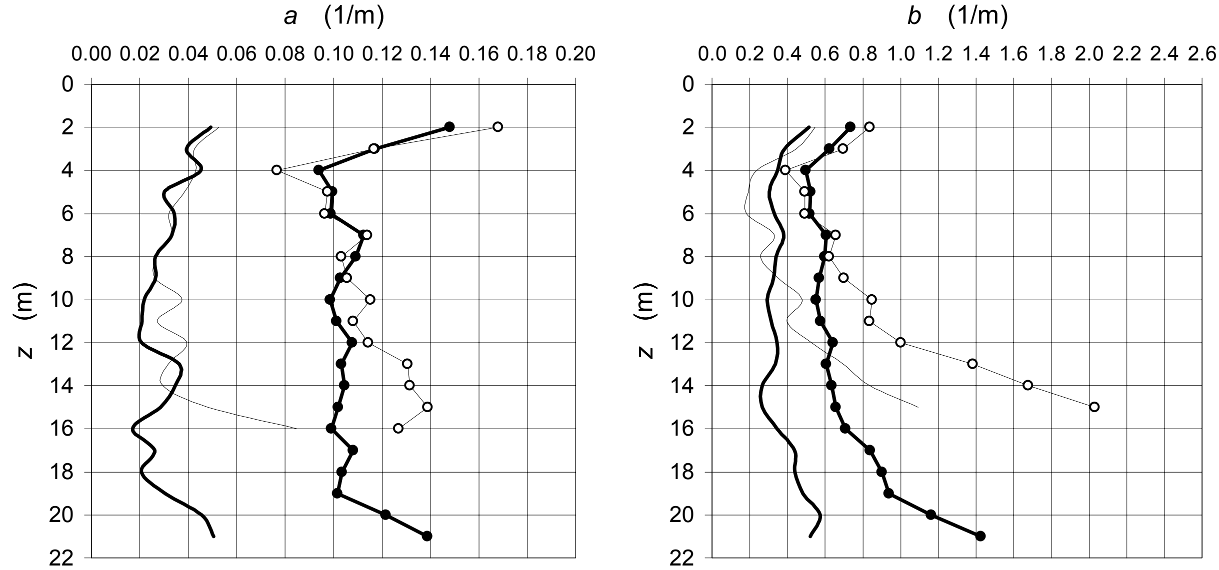


Fig. 11.- *Transmittance T_d , T_u of downwelling (E_d), upwelling (E_u) irradiance : mean and standard deviation, station groups h = 23* m *and h = 17* m.



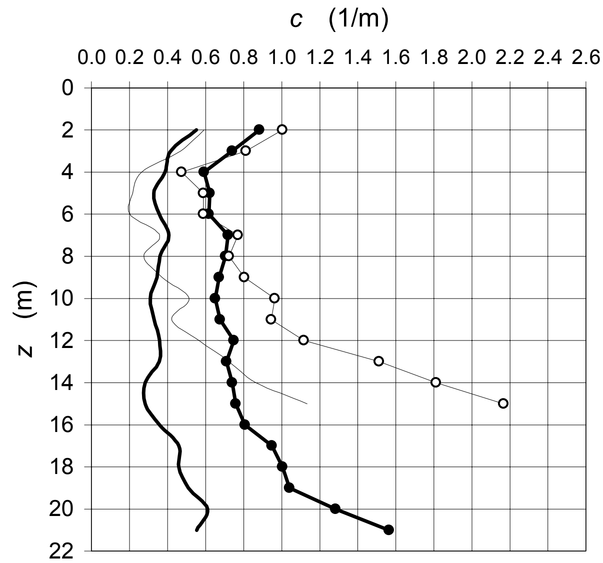


Fig. 12.- *Absorption coefficient a, scattering coefficient b, beam attenuation coefficient c : mean and standard deviation, station groups* $h = 23$ m *and* $h = 17$ m.

The down/upwelling irradiance data of the two station groups (tables 1, 2) are represented in figs. 7, 8 ; it can be observed that sometimes E_u increases close to the bottom, when suspended matter is present (see also fig. 5). This situation usually occurs after strong bora wind events : these speed up the water circulation in the Gulf of Trieste, rising and spreading sediments. The mean *R(z)* (and the standard deviation) of the vertical reflectance profiles and the mean $K_E(z)$ (and the standard deviation) of the attenuation coefficients for net downward irradiance are represented in fig. 9, for both groups. At each station, attenuation coefficients K at z_i have been computed by means of a linear regression between (z_{i-1}, z_i, z_{i+1}) and $(\ln(E(z_{i-1})), \ln(E(z_i)), \ln(E(z_{i+1})))$. The mean $K_d(z)$, $K_u(z)$ (and the corresponding standard deviations) of the attenuation coefficients for down/upwelling irradiance are represented in fig. 10. The irradiance transmittances (through $dz = 1$ m) $T_{d,u}(z) = \exp(-K_{d,u}(z)\ dz)$ are represented in fig. 11. The mean *a(z)*, *b(z)*, *c(z)* (and the corresponding standard deviations) of the absorption, scattering and beam attenuation coefficients, computed as functions of reflectance and sun zenith angle as above indicated, are represented in fig. 12. The mean and extreme values of the optical quantities above, computed for the whole set of stations and the whole water column, are reported in table 3.

The following relations are found, which can be conveniently used for a speed evaluation, at any depth and with a probable error of 10 %, of the absorption coefficient as a function of the measured downwelling irradiance:

	mean		s.d.	min	max	
a	= 0.11	±	0.04	0.03	0.29	m^{-1}
b	= 0.80	±	0.57	0.13	3.24	m^{-1}
c	= 0.91	±	0.60	0.16	3.43	m^{-1}
K_d	= 0.19	±	0.08	0.05	0.54	m^{-1}
K_u	= 0.13	±	0.09	–0.13	0.48	m^{-1}
K_E	= 0.20	±	0.08	0.04	0.57	m^{-1}
T_d	= 0.83	±	0.06	0.58	0.95	
T_u	= 0.89	±	0.08	0.62	1.14	
R	= 0.064	±	0.033	0.02	0.17	

Table 3.- *Mean, standard deviation and extreme values of optical quantities in the Gulf of Trieste (all stations and depths).*

$$a(z) = 0.57\, K_d(z) \quad ,$$
$$a(z) = 0.64\, (1 - T_d(z)) \quad .$$

Secchi disc depth and optical properties

Mean values of the Secchi disc depths, from tables 1,2, are :

$$z_w = 9.0 \pm 2.6 \text{ m} \quad ,$$
$$z_b = 4.4 \pm 0.9 \text{ m} \quad .$$

The mean black/white disc depth ratio is $z_b / z_w = 0.50$, close to the 0.53 value found by Stravisi (1983c) for a wider set of transparency measurements in the Gulf of Trieste. At each station, downwelling and scalar irradiance $E_{d,s}(z_{w,b})$ were computed at the disc depths by means of a linear interpolation of ln $(E_{d,s})$ at the top and at the bottom of the 1 m layer containing $z_{w,b}$; the vertical mean attenuation coefficient K_d was obtained by computing the slope of the downwelling irradiance logarithmic profile between 1 m and $z_{w,b}$, and the mean absorption, scattering and beam attenuation coefficients by averaging the corresponding values in the same layers. These data are reported in table 4 : irradiance values are expressed as percentage of the surface global PAR solar irradiance. The relation reported above, but computed for average values in the z_w layer, is $a = 0.65/K_d$.

	mean		s.d.			mean		s.d.	
$E_d(z_w)/E_o$	= 11	±	2	%	$E_d(z_b)/E_o$	= 23	±	5	%
$E_s(z_w)/E_o$	= 18	±	3	%	$E_s(z_b)/E_o$	= 35	±	6	%
$K_d(1,z_w)$	= 0.17	±	0.05	m^{-1}	$K_d(1,z_b)$	= 0.21	±	0.08	m^{-1}
$a(1,z_w)$	= 0.11	±	0.02	m^{-1}	$a(1,z_b)$	= 0.13	±	0.04	m^{-1}
$b(1,z_w)$	= 0.59	±	0.29	m^{-1}	$b(1,z_b)$	= 0.69	±	0.46	m^{-1}
$c(1,z_w)$	= 0.70	±	0.30	m^{-1}	$c(1,z_b)$	= 0.82	±	0.49	m^{-1}

Table 4.- *Mean ratio of downwelling to surface irradiance at the Secchi disc depth (white and black) ; average K_d, a, b, c in the layer (1 m, $z_{w,b}$).*

The classical Poole-Atkins relation $K_d = P / z_w$ between the vertical mean attenuation coefficient for downwelling irradiance and the Secchi disc depth, gives in our case the constant $P = 1.4 \pm 0.2$ ($P_b = 0.9 \pm 0.2$ for the black disc). Furthermore, we can compare our regression $K_d = 1.19/z_w + 0.03$ for the Gulf of Trieste with the corresponding $K_d = 1.13/z_w + 0.10$ found by Holmes (1970) in Goleta Bay, California. Holmes data refer to visible irradiance, our data to PAR irradiance : however colors outside the blue-green range almost disappear after 2 m depth. Tyler's relation (1968) $(K_d + c) = T / z_w$, with $T = 8.69$ in the case of rather clear water (z_w about 30 m), yields in our case $T = 7.2 \pm 1.3$.

The Kirk (1981a) relation, accounting for the dependence of the attenuation coefficient for downwelling irradiance on the inherent optical properties, for the Gulf of Trieste is

$$K_d/a = (1 + 0.257\, b/a)^{1/2} \quad ,$$

the coefficient being the same found by that author at the middle of the euphotic zone.

Conclusions

Starting from conventional down/upwelling irradiance vertical profiles, the inherent optical seawater properties (absorption, scattering and beam attenuation coefficients) can be conveniently computed in the Gulf of Trieste by using classical theory and equations according to Kirk's (1981b) model. The Secchi disc depth can be used to estimate the attenuation coefficient of downwelling irradiance and the absorption and scattering coefficients. At the Secchi disc depth the expected values of downwelling and scalar PAR irradiance are respectively 11 % and 18 % of the PAR irradiance above the sea surface.

REFERENCES

Holmes R.W. (1970) : *The Secchi disk in turbid coastal waters*, Limnol. & Oceanogr., XV, 688-694.

Jerlov N.G. (1976) : *Marine optics*, Elsevier, Amsterdam.

Kirk J.T.O (1981a) : *Monte Carlo study of the nature of underwater light field in, and the relationship between optical properties of, turbid yellow waters*, Aust. J. Mar. Freshwater Res., 32, 517-533.

Kirk J.T.O (1981b) : *Estimation of the scattering coefficient of natural waters using underwater irradiance measurements*, Aust. J. Mar. Freshwater Res., 32, 533-539

Stravisi F. (1983a) : *The vertical structure annual cycle of the mass field parameters in the Gulf of Trieste*, Boll. Oceanol. Teor. Appl., I, 3, 239-250.

Stravisi F. (1983b) : *Some characteristics of the circulation in the Gulf of Trieste*, Thalassia Jugos., 19, (1-4), 355-363.

Stravisi F. (1983c) : *Misure di trasparenza (disco Secchi) nel Golfo di Trieste*, IV Congresso AIOL, 1980, Atti Ass. It. Oceanol. Limnol., 42.1-42.13.

Stravisi F. (1990) : *Thalassia II : seawater temperature, salinity, current velocity, Secchi disc and underwater irradiance data in the Gulf of Trieste (1979-1984)*, University of Trieste, Dept. Earth Sciences, Rep. LC 90/2 (119 p.).

Tyler J.E. (1968) : *The Secchi disc*, Limnol. & Oceanogr., XIII, 1-6.