Optical parameters of the Black Sea waters: long-term variability and present status

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ABSTRACT

Seasonal and long-term variability of the Black sea optical parameters are analyzed using valuable data set from the data bases of Marine Hydrophysical Institute and Institute of Marine Sciences. The drastic decrease of the water transparency was observed during 1986-1992. It coincided with the big changes of the spectral distribution of water optical parameters. The main causes of these changes are eutrophication, influence of biological invader *Mnemiopsis leidyi* on the sea ecosystem, and the natural 11-years cycle.

Keywords: marine optics, Black Sea, water transparency, Secchi disk, attenuation coefficient, climatic changes, spectra of optical properties, yellow substance

1. INTRODUCTION

In situ measurements of optical characteristics are conducted in the Black Sea since 1960s and Secchi disk measurements are conducted since 1920s. A valuable data set of the optical characteristics is available at present at Marine Hydrophysical Institute (MHI) and Institute of Marine Sciences (IMS). There are, in total, more than 13000 Secchi disk measurements, 2500 profiles of light attenuation coefficient, etc. These data permit to estimate vertical, spatial, seasonal and long-term variability of some optical characteristics of the Black Sea and to analyze their relations with biological variables and water dynamics.

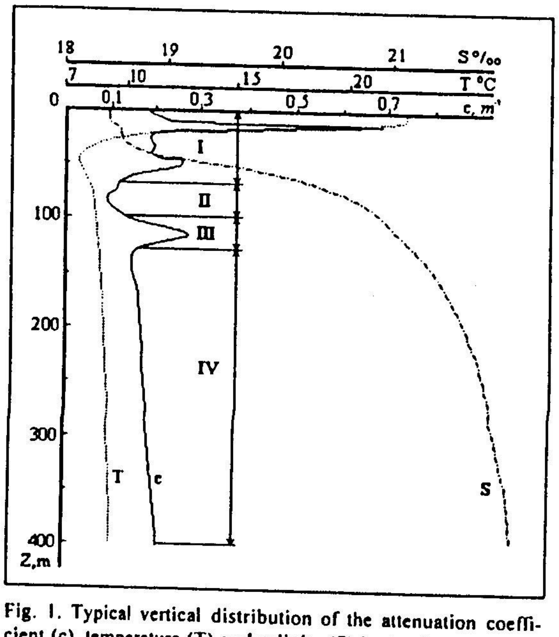

Fig. 1. Typical vertical distribution of the attenuation coefficient (c), temperature (T) and salinity (S) in the deep region of the Black Sea in summer.

2. VERTICAL OPTICAL WATER STRUCTURE AND ITS SEASONAL VARIABILITY

Vertical distribution on the optical water properties is determined by the peculiarities of the distribution of physical, chemical and biological properties and by the water dynamics. Main of those in the Black Sea are: existence of the anaerobic hydrogen sulfide zone deeper 120 --140 meters, cold intermediate layer at depths 40 --75 meters, cyclonic current system containing rim current along all the sea coast *and some eddies.*

There are four typical layers of the vertical profiles of the light attenuation coefficient (c(z)) in the deep area of the sea: upper, intermediate, boundary and deep (Fig. 1), which correspond to the layers with different hydrological, chemical and biological properties.[1] The upper layer locates in the euphotic zone. The intermediate layer housing the most transparent water, centered near the low boundary of the cold intermediate layer. The boundary turbid layer exists at the oxic/anoxic interface. The deep layer is spreading over the hydrogen sulfide zone. Seasonal variability of c(z) is best pronounced in the up-

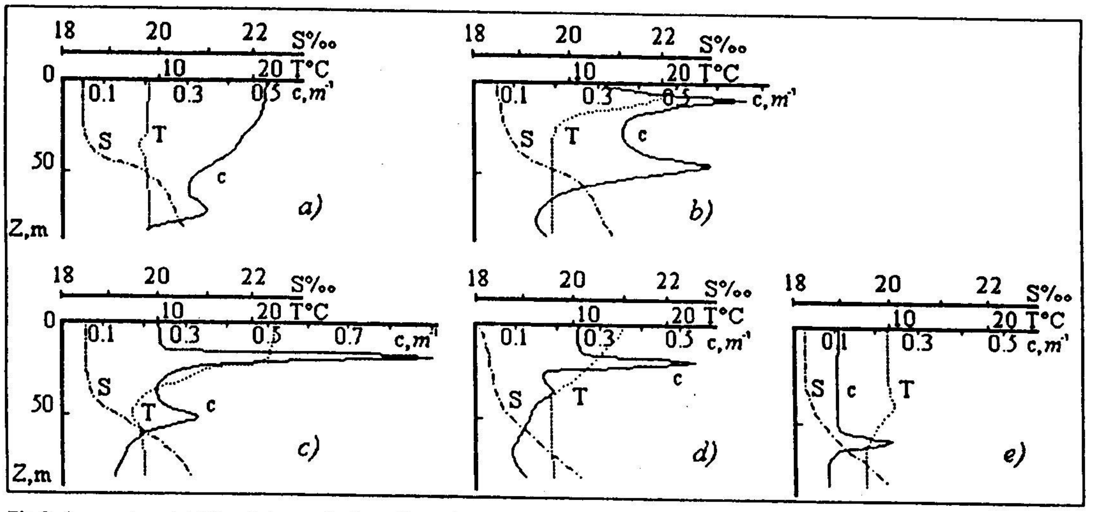

Fig.2. Seasonal variability of the vertical profiles of attenuation coefficient (c), temperature (T) and salinity (S) in the upper layer: *a*) - April, *b*) - June, *c*) - August, *d*) - October, *e*) - December.

per layer (Fig. 2). Two typical maximums of c(z) occur within this layer in summer, which are connected with the vertical distribution of the phytoplankton. One of those is connected with the upper part of the seasonal thermocline and the other - with upper part of the permanent halocline. Often, some maximums of the second order of magnitude occur in the thermocline in summer, which are connected with the fine structure of the seasonal thermocline. There is only one maximum of c(z) in winter (after the destruction of the seasonal thermocline), which connected with halocline and which is deeper then in summer. An intermediate layer with minimum values of c(z) exists throughout the year, its seasonal variability being low. The boundary turbid layer is more powerful on the periphery of the sea within the Black Sea Rim current area and it is absent at the centers of the main cyclonic circulation cells. This layer is more pronounced in winter, with its depth also being larger. Within the deep layer, a seasonal variability is very small. The attenuation coefficient is changing monotonous with depth in this layer depending on the wavelength. It is approximately constant at the long wavelength and it increases with depth at the short ultraviolet spectral band. This fact shows the growth of the "yellow substance" concentration with depth.

3. SEASONAL AND LONG-TERM VARIABILITY OF WATER TRANSPARENCY

Figure 3 shows the seasonal variability of the Secchi disk depth (Z_d) analyzed using monthly mean values, calculated for 1922-1985 for the central deep part of the Black Sea, limited by the latitudes 42°20' and 44°15'N and longitudes 31° and 38° E. There are two minimum in the interannual variability of Z_d namely in spring and at the end of autumn and two maximums, namely in summer and at the end of winter. The difference between maximum and minimum mean month values is about 6.2 meters or 37% of mean annual value (16.8 m).

Very interesting phenomenon is the strong changes occurred in the Black Sea recent years.[2] From the early 1920s to the mid-1980s, the weakly pronounced transparency decrease was observed. Over 60 years, Secchi disk visibility depth had decreased from 20-21 to 15-16 meters (mean values in the deep central part of the sea), however, single values up to 25 meters were occasionally observed. The Black Sea water transparency has decreased dramatically since 1985. In 1990-1993, the values in excess of 15 meters were no longer observed and mean values were only 6-10 meters (Table 1). It is worth to mention that the water transparency in the Black Sea started to increase since 1993.

Water transparency measurements using *in situ* sounding instruments, which were performed by MHI during Black Sea surveys, also indicate the same decrease of transparency. Mean, maximum, minimum values and standard deviation of the attenuation coefficients (wavelength 410-420 nm) in the surface layer of the central, deep part of the sea for summer are shown in Table 2. Values for 1977-85 which are considered as the "background" data show large changes compared to 1990, 1991, and 1992 data.

Spectral optical properties of the Black Sea water had also changed. In 1990s compared with 1984, not only the values of the light attenuation coefficient strongly increased, but as well, the shape of spectral curves changed, due to the initial enhanced increase in the short wavelength band. The minimum values, which were at 480 nm in 1984, shifted to the 550-570 nm in 1992. Spectra of the light attenuation coefficient c(λ) for 1984, 1991, 1992, 1995, and for the optical pure sea water

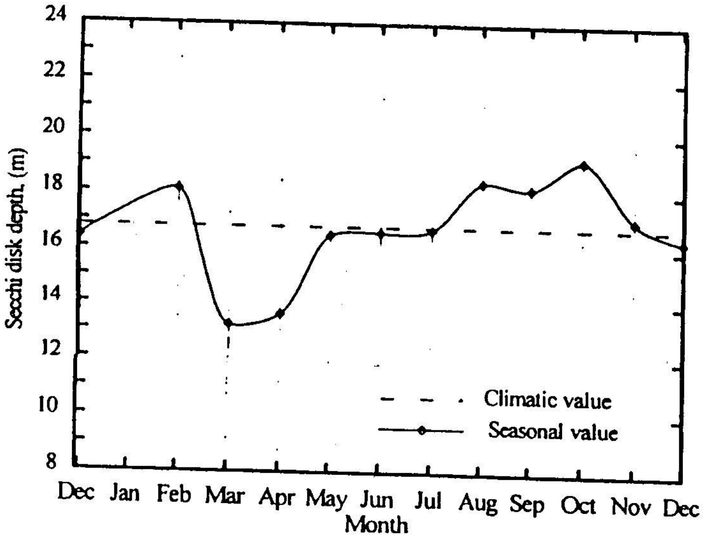

Fig. 3. Monthly variation of the mean Secchi disk depth in the central part of the Black Sea in 1922-1985. Vertical bars show the standard deviations.

are presented in the Figure 4 for the subsurface water of the deep central part of the sea. The Secchi disk depth values corresponding to the each spectrum are showed in a legend.

Similar shift in the spectral minimum was also observed recent years in the spectra of the vertical attenuation coefficients, K(λ), of the sunlight. Measurements of K(λ) were performed by the authors of [11] in the central part of the sea in February-March of 1991 at the Secchi disk depth of 5-6 meters. The spectral minimum of K(λ) at 520-560 nm calculated for these measurements was observed at 490-530 nm in the central part of the Black Sea before 1979 (Table 3).

Parallel changes have occurred in the radiance spectra of the sea. The radiance index increased four-five times in the band of spectral maximum, and the maximum proper displaced from 480 nm to 540-560 nm in 1992, as compared with 1984.

Such changes in the spectra of radiance index show that the concentration of particulate matter, which scatter the light, increased in the upper layer of the sea. This fact caused an increase in the radiance index values and a shift in the maximum of radiance index to the longer wavelengths due to the increase in the dissolved organic matter concentration, especially of yellow substance.

Table 1. The annual mean, maximum, minimum Secchi disk depth values and standard deviations for each year for the central part of the Black Sea

Year	Mean	Max	Min	STD	Number of data points
1923	20.2	23.0	19.0	1.44	5
1924	19.9	28.0	13.5	4.18	20
1925	19.8	30.5	11.0	4.32	24
1927	20.9	25.0	16.0	2.70	10
1953	18.0	20.0	17.0	1.22	4
1956	13.8	20.0	8.0	3.99	10
1957	19.5	25.5	13.0	3.53	22
1958	21.5	30.0	10.0	7.31	14
1960	19.9	22.0	19.0	0.99	9
1961	17.1	20.0	13.0	2.08	10
1962	21.1	27.0	16.6	2.92	11
1963	17.0	22.0	11.0	3.74	9
1964	17.4	24.0	3.5	4.21	29
1965	13.7	20.5	9.0	3.78	10
1966	15.4	22.0	9.0	4.58	10
1967	16.7	23.0	10.0	5.31	3
1968	17.4	26.0	9.0	5.69	5
1969	13.0	15.0	10.0	2.12	4
1970	20.0	22.0	18.0	2.00	2
1972	20.1	28.0	13.0	4.10	11
1973	14.1	20.0	6.0	4.22	7

Year	Mean	Max	Min	STD	Number of data points
1974	19.0	27.0	15.0	3.12	15
1975	18.8	24.0	9.0	2.86	58
1978	17.7	23.0	14.0	2.35	18
1979	19.3	20.0	18.0	0.94	3
1980	16.1	21.0	7.0	4.31	14
1981	16.9	29.0	12.0	4.33	12
1982	14.0	18.0	9.0	2.92	29
1983	13.9	20.0	10.0	2.82	15
1984	16.2	24.0	5.0	3.29	113
1985	15.1	27.0	6.0	4.87	38
1986	17.5	25.0	6.0	5.10	14
1987	12.5	19.0	7.0	3.11	65
1988	12.5	18.0	8.0	2.45	54
1989	12.0	25.0	2.0	4.73	179
1990	8.2	13.0	3.0	2.16	53
1991	8.7	14.0	5.5	1.92	90
1992	6.2	11.0	2.0	2.51	51
1993	10.0	16.0	7.0	1.76	94
1994	12.7	16.0	9.0	1.52	33
1995	13.9	21.0	6.7	3.89	13

Table 2. Attenuation coefficients (wavelength 410-420 nm) in the upper water layer in the central deep part of the Black Sea in summer, c(λ) [m^{-1}]

Year	Mean	Max	Min	STD.
1977-1985	0.55	1.38	0.23	0.32
1990	1.17	1.86	0.78	0.23
1991	1.03	2.16	0.69	0.21
1992	1.70	2.76	0.55	0.60

4. CLIMATIC DISTRIBUTION OF WATER TRANSPARENCY

The climatic characteristics of the Black Sea Secchi disk depth in the years preceding the large changes of water transparency were calculated and evaluated for summer and autumn seasons since the most part of the Secchi disk measurements were done during these seasons (Fig.5). The climatic transparency field has the following features. Water with Z_d <6m is found only in a narrow band in the regions of big river mouths: Danube and Dnieper on the northwest shelf, Inguri and Rioni near the Caucasus, and near the Kerch strait. Transparency in nearly 60% of the deep regions of the sea, is more than 16 m. The most transparent waters (Z_d > 22m) occur in the middle part of the sea where eastern and western cyclonic rings come into contacts with each other and where surface waters with low concentration of nutrients downwells. Relatively higher transparencies (up to 10-20 m) occurs in the shelf zone and often near the coast; for example, near the Bosphorus Z_d exceeds 18 m. There is a difference in the transparency of the eastern and western deep regions of the sea: the eastern part shows considerably lower Z_d values due to higher biological productivity.

Table 3. Minimum values of the vertical attenuation coefficients and corresponding wavelengths

Time of measurements	$\lambda(k_{min})$, nm	k_{min}, m^{-1}
1962-1963, March-August	490 - 530	0.069
1984, April-May	500 - 525	0.099
1989, July-August	525 - 554	0.104
1991, February-March	525 - 554	0.115

5. FACTORS INFLUENCED ON THE DRASTIC DECREASE OF WATER TRANSPARENCY

Analysis of the total collected information has enabled to understand the main causes of the drastic transparency decrease in the deep basin of the Black Sea from 1986 to 1992 and to reach the conclusions stated below.[5]

Significant eutrophication occurs both in the near-shore areas of the Black Sea and in the deep ones, being connected with the long-term increasing input of nutrients of anthropogenic origin. For example, an input of biogenic compounds of nitrogen and phosphorus by the Dnieper and Danube waters, which are responsible for 3/4 of the overall river input to the Black Sea, increased 5-7 times from the 1960s to the 1980s.[6] The mean chlorophyll concentration has become one and a half time larger in deep part of the sea throughout the same period (Fig. 6).[7]

Water transparency gradually declined due to the increase of the content of optically active matter in the sea. Over 20 years, from the mid-1960s to the mid-1980s, the mean annual decrease of the Secchi disk depth has attained about two meters.

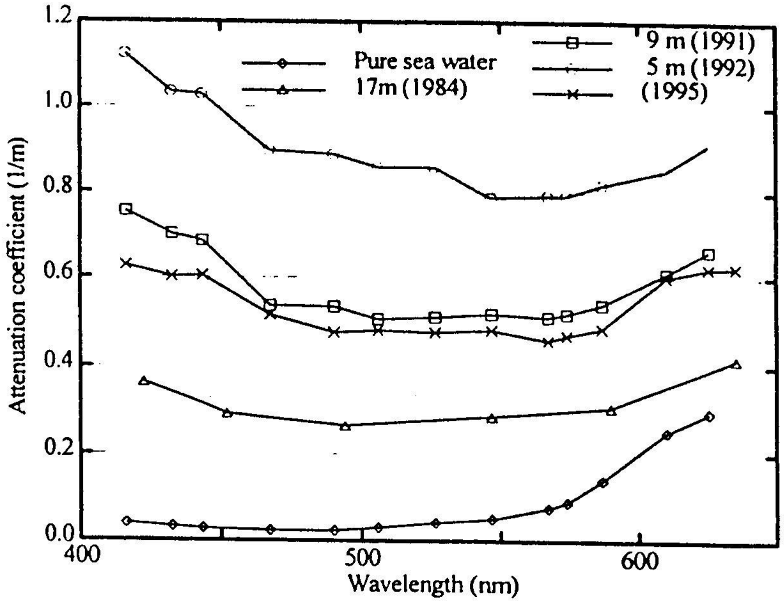

Fig. 4. Spectra of the light attenuation coefficient c(λ) for the subsurface water of the deep central part of the sea for the different years and for the pure sea water. The Secchi disk depth values measured at the same station are included in a legend.

However, the direct cause of the drastic transparency decrease from 1986 to 1992 was the enhanced bloom of *Peridinium* and *Coccolitophores*. Their number in the Black Sea was 1.5 - 2 orders of magnitude larger than in previous years and reached 2-3 billions per cubic meter. A significant increase in the biomass of these planktonic organisms has changed the structure of the plankton community. Now nanoplankton, which contributes immensely to the light scattering, accounts for 90% of the phytoplankton content.[5]

The intense blooms of *Peridinium* might have been also caused by the increased concentration of particulate organic matter, as *Peridinium* can switch to heterotrophic nutrition.

Coccolitophores also play a significant role in the changes of water transparency, due to their crustal structure containing a number of disks, namely, coccolits, which can be separated. These disks cause an intensive scattering of light. That is why, when the *Coccolitophores* concentration is high, sea water becomes whitish. This effect has been observed in the Black Sea over the last few years.[5]

Phytoplankton structure was also strongly impacted by the biological invaders, such as *Mnemiopsis Leidyi* which appeared in the Black Sea in the early 1980s and is biomass amounted to one billion tons in 1989.[8] As a result, the amount of

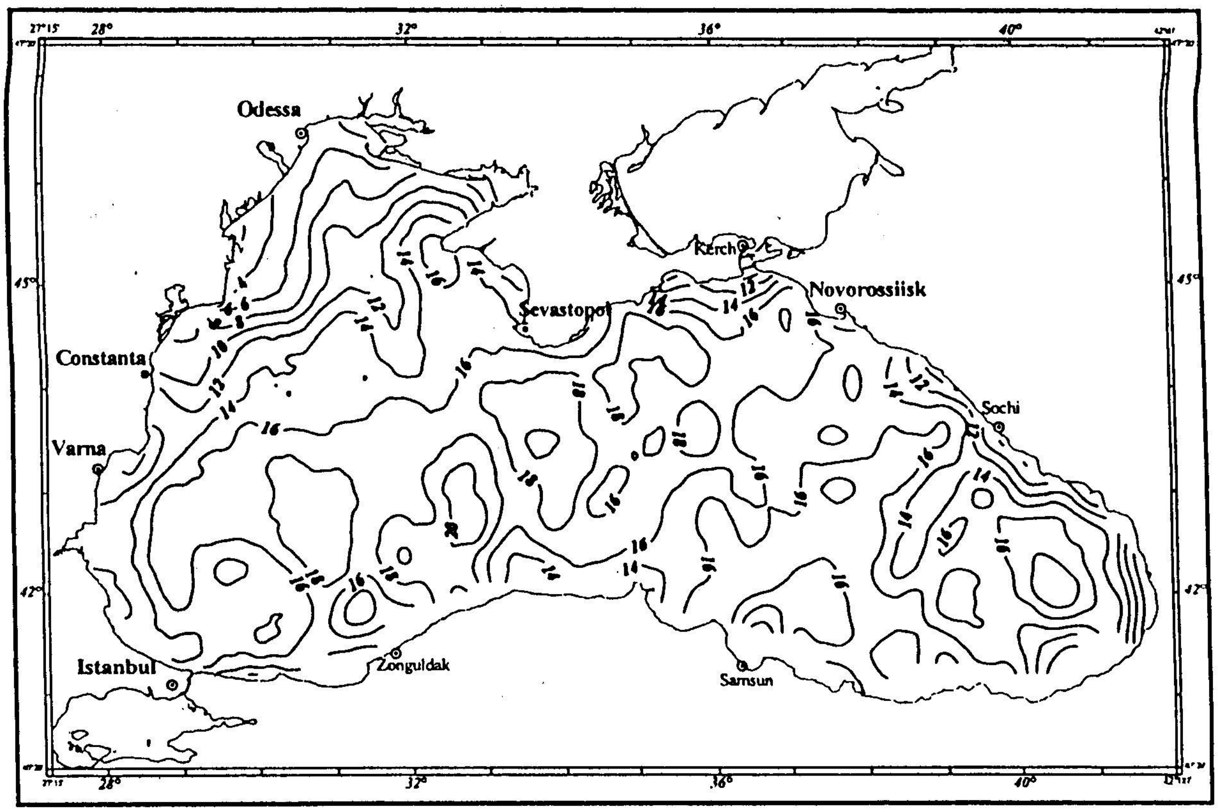

Fig. 5. The climatological field of mean Secchi disk depths in the Black Sea for June - October 1922-1985.

herbivorous microzooplankton, which is a part of the *Mnemiopsis* food, has decreased by several times, whereas the phytoplankton content conversely, increased. The great amount of dissolved organic matter released by *Mnemiopsis* also facilitated the increase of some types of phytoplankton and bacteria.

Long-term periodical oscillations in the Black Sea water transparency have been found to occur, which seems to be correlated with the 11-year cycle of solar activity. Water transparency increases during the second half of the cycle and decreases during the first one. This fact shows the same cyclicity is inherent to the planktonic community.

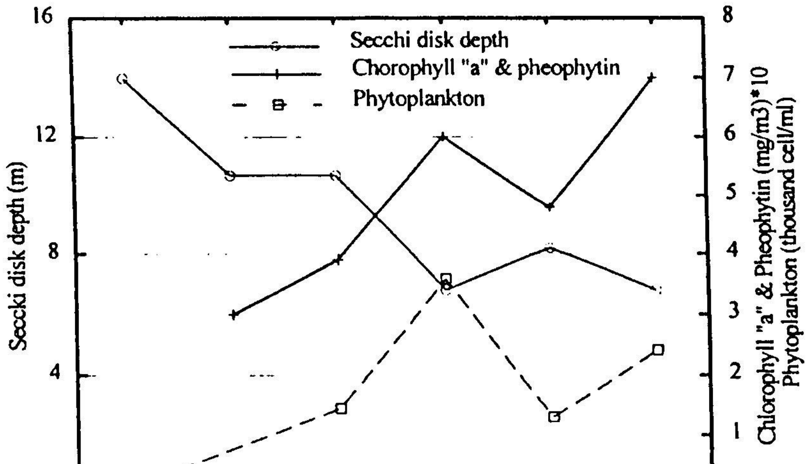

Fig. 6. Secchi disk depth, chlorophyll "a"+ pheophytin, and phytoplankton concentration in the western deep part of the sea for 1987-1992. Mean values for May-September.

Drastic decrease in the transparency in late 1980s coincided with the second half of the 1980-1991 solar activity cycle. However, the magnitude of the transparency decrease was more intense during this cycle than those during the previous cycles.

Analyses of the collected data, it may be concluded that the catastrophic transparency decrease in 1990-1992 took place due to the combined effect of three factors coinciding in time and sign: (1) the natural 11-year cycle, (2) increased eutrophication, and (3) the influence of the biological invader *Mnemiopsis Leidyi* on the ecosystem structure.

It is important to emphasize that the intense decrease in water transparency discontinued in the Black Sea in 1992, and in 1993 water transparency started slightly to improve. As a result, already by the end of 1995, the mean Secchi disk depth in the deep central part of the Black Sea had reached to the levels observed for the early 1980s, i.e. about 17 meters. Regretfully, we have no evidence on the changes that took place in the ecosystem of the sea during these years, which made this transparency to increase.

6. ACKNOWLEDGMENTS

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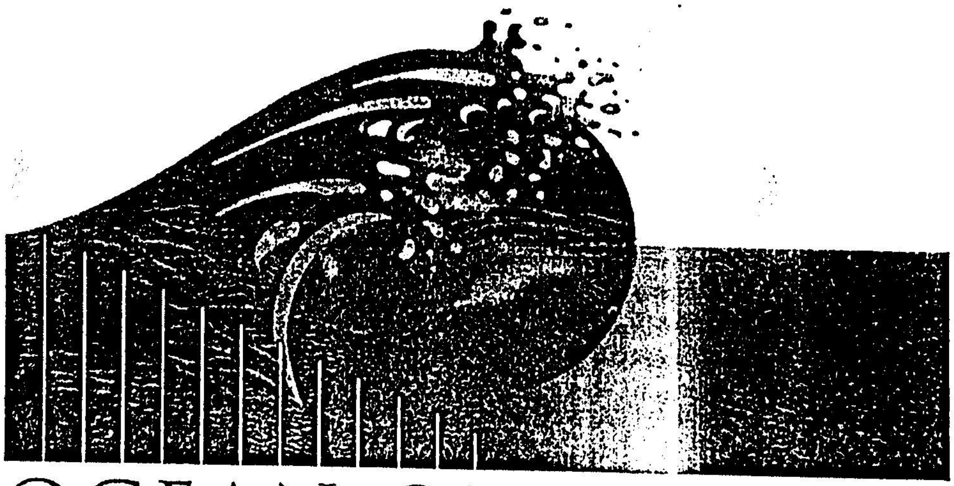

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