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Distribution of underwater irradiances and estimated light attenuation by oil slick in the ROPME Sea area

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Abstract : Classifying seawater in the ROPME Sea area by optical water type (JERLOV, 1964), the water masses of Oceanic Types II and III were distributed at its centre, and those of Coastal Types 1 and 3, in the coast of UAE and the Arabian side in the vicinity of lat. 27°30′ N, respectively. The depths of water at which PAR attenuated to 1% of its surface value were 26 m and 37 m in the former, and 18 m and more and approximately 18 m in the latter. At the centre of the sea area, the diffuse attenuation coefficients for ultraviolet light A and B were 0.26～0.33 m^{-1} and 0.39～0.53 m^{-1}, respectively. They are several times greater than those of PAR. Based on the experiment about an oil slick on sea surface, the ratio of penetrated light into water became to be smaller as the wavelength was shorter. When the thickness of an oil slick was 0.2 mm, the value of PAR just below that decreased to approximately 1% of the sea surface. The relationship between the thickness of an oil slick and the ratio of PAR attenuation can be expressed by a following formula : $E_{PAR}=100\exp(-23.3\ h)$ $r^2=0.989$, where E_{PAR}, h, and r are relative irradiance (%), thickness of oil slick (mm), and correlation coefficient, respectively. The slicks of crude oil spilled into this Sea area are considered to have an impact on the optical environment underwater.

Key words : *spectral irradiance, optical water type, oil slick, ROPME Sea area*

1. Inyroduction

The ROPME Sea area (hereinafter abbreviated as "RSA") is bounded by seven countries-United Arab Emirates, Qatar, Bahrain, Saudi Arabia, Kuwait, Iraq and Iran, and it has traditionally been called the Persian Gulf or the Arabian Gulf. This sea area is connected to the Arabian Sea through the Strait of Hormuz and the outer Gulf of Oman. The mean depth of water is approximately 35 m with the utter absence of water depths over 100 m. The shape of this sea area is rectangular with a length of approximately 960 km and a width of approximately 250 km, and the total area is 240,000 km^2 which is nearly equal to the area of Honshu Island, Japan.

During the Gulf War in 1990, 1.08×10^7 barrels of crude oil spilled into the RSA, and there were enormous impacts upon diverse marine animals and plants (FAYAD and OVERTON, 1995; READMAN *et al.*, 1996). Oils spilled into oceans are considered to have impacts on not only aquatic animals and plants but also their habitat conditions. Detailed studies are available on physiology and ecology of fish and algae ; e. g. HOLT *et al.*, 1978; PROFFITTE *et al.*, 1995 ; WATANABE *et al.*, 1998. Also, studies on water quality, sea bottom sediments and the effects upon sand shoals are conducted ; OTSUKI *et al.*, 1998 ; I. ALAM *et al.*, 1998. We anticipate that oil slicks hamper the penetration of sun light, with consequential degradation of the optical environment underwater.

Historical studies were more papers, e.g. SCOTT, 1908; SCHULY, 1914; BLEGVAD, 1944; EMERY, 1956. For example, EMERY (1956) provided the first detailed map of the surface salinity distribution, together with some vertical profiles, from data obtained on board the RV Meteor. After that, a joint research by Tokyo University of Fisheries and Kuwait Oceanographic Institute was conducted on board the RT/V Umitaka-Maru in 1968 (Tokyo Univ. of Fish., 1974). OSHITE (1974), one of investigators on board, reported that the values of

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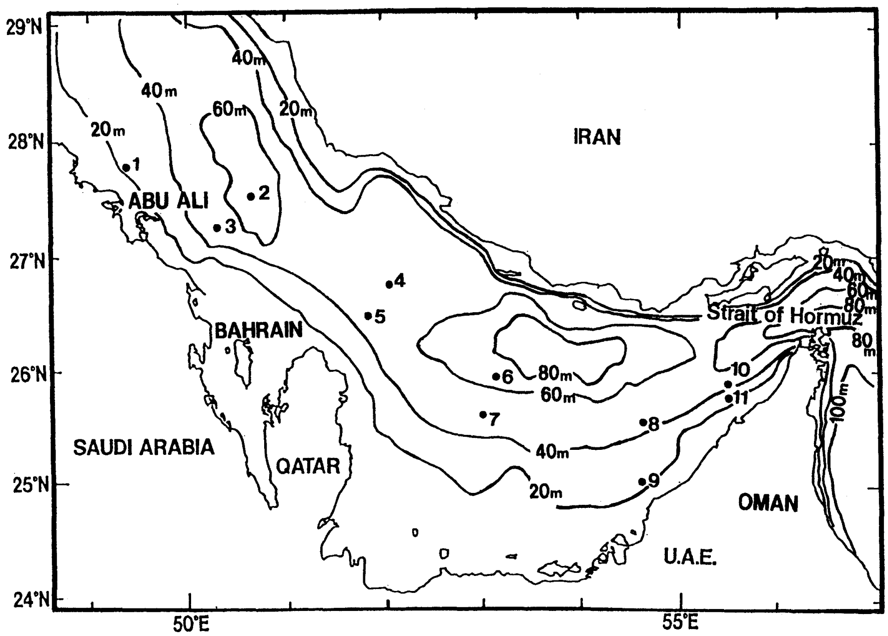


Fig. 1. Map showing the observation Stations in Dec. 1994. The numerals are Station numbers from 1 to 11.

transparency and SS in the Gulf ranged from 8 to 16 m and 0.2 to 1.8 mg/l, respectively. From a recent survey by the RV Mt. Mitchell of NOAA, USA, Reynolds (1993) found out that the low salinity water near the mouth of the Gulf might be associated with an inflow of water from the Gulf of Oman through the Strait of Hormuz. However, none made the optical oceanographic study.

This study was conducted as an integral part of the International Scientific Research Programme "An Integrated Study on the Effects of Crude Oil Spills in the ROPME Sea Area" In the study, relative irradiance of visible light by wavelength, photosynthetically available radiation (PAR) and ultraviolet light in lat. 28° N and further south of the RSA was observed concurrently, assessing how far light in what wavelength penetrates sea water, whereby the effects of slicks caused by crude oil spills in this sea area on light attenuation were investigated.

2. Observation Method

Oceanographic observations were carried out aboard the RT/V Umitaka-Maru (1,828 G/T) of Tokyo University of Fisheries from 15 to 17 December, 1994. A total of eleven observation stations were arranged in the RSA on lat. 28° N and further south (Fig. 1). Conventional oceanographic observation elements such as visible light, PAR, and ultraviolet light (A and B) were taken up in this study. Observations of visible light were made at all stations, PAR at Stations 1, 3, 5, 6, 7, 8, 9, 10 and 11, and ultraviolet (A and B) at Stations 5, 7, 8, and 10, respectively. An irradiance meter, PRR-600 (Biospherical Instruments Inc.) provided with a depth sensor was used to measure the relative irradiance of visible light by wavelength 412, 443, 490, 510, 555, 665 nm and PAR, 400–700 nm. An another meter, IL-1700 (International Light Inc.) was also used with the ultraviolet light A, 326–380 nm (the maximum transmittance: 355 nm, hereinafter called "UV-A"), and B, 270–306 nm (the maximum transmittance : 288 nm, hereinafter called "UV-B"). The observation method was such that the each instrument was lowered from the ship's sunny side, whereby observations were carried out on the sea surface and the bottom or continueously down to the limit of observations by pre-set water

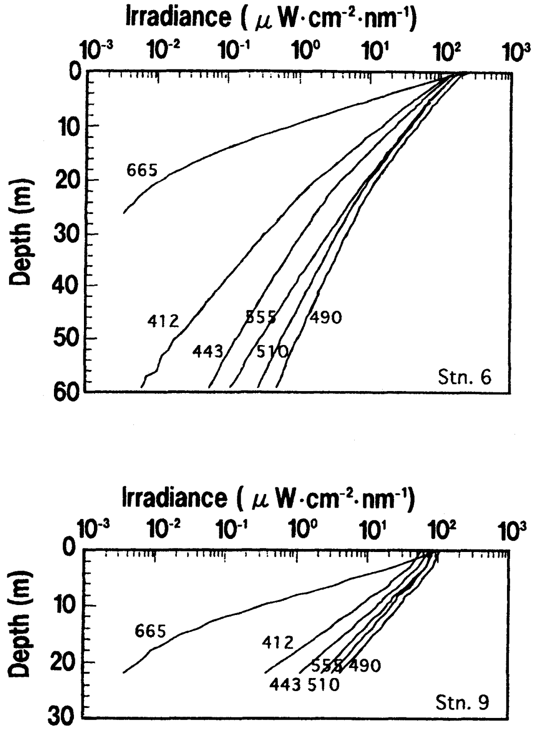


Fig. 2. Depth profiles of downward irradiance at Stn. 6 (upper) and at Stn. 9 (lower). The numerals in the figures indicate wavelength (nm) of visible light.

depth.

The effects of oil slicks on submarine irradiance distribution were experimentally investigated in the following method. At culmination on a fine day, measurements were taken with an instrument, PRR-600, which was used in field observations, soaked near the surface of distilled water contained in a cylindrical tank coated black inside (70cm both in dia. and depth) placed on the rooftop of our laboratory. The Iranian heavy crude oil was used with a specific gravity of 0.87 g/cm^3.

3. Results and Discussions

3-1 Irradiance distribution of visible light by wavelength

Figure 2 shows measurements of irradiance of visible light by wavelength taken at Station 6 in the central region of the Sea area and at Station 9 on the coast of UAE. At Station 6, the wavelengths in descending order of light penetration were 490, 510, 555, 443, and 412 nm, and the reading of 665 nm was assumed to be below the measuring limit at the depth of 25 m. On each the wavelengths given, the inclination of attenuation was approximately the same from the sea surface down to the vicinity of bottom. It follows that the water mass under investigation is optically uniform. At Station 9, it was observed that the irradiance decreased as a function of water depth tended to be steeper than that at Station 6. However, the sequential order of wavelengths with good light penetration was identical. Light attenuation of each wavelength is approximately linear, indicating that the water mass is optically homogeneous, even in the coastal waters, except at the bottom layer.

Figure 3 illustrates the relative irradiance distribution of visible light by wavelength at the depth of 10 m at all stations. It could be seen from the figure that the value of relative irradiance was lower on the shorter wavelength side, with peaks at 490 or 510 nm, and registered sharp falls on the longer wavelength side. This distribution pattern was commonly

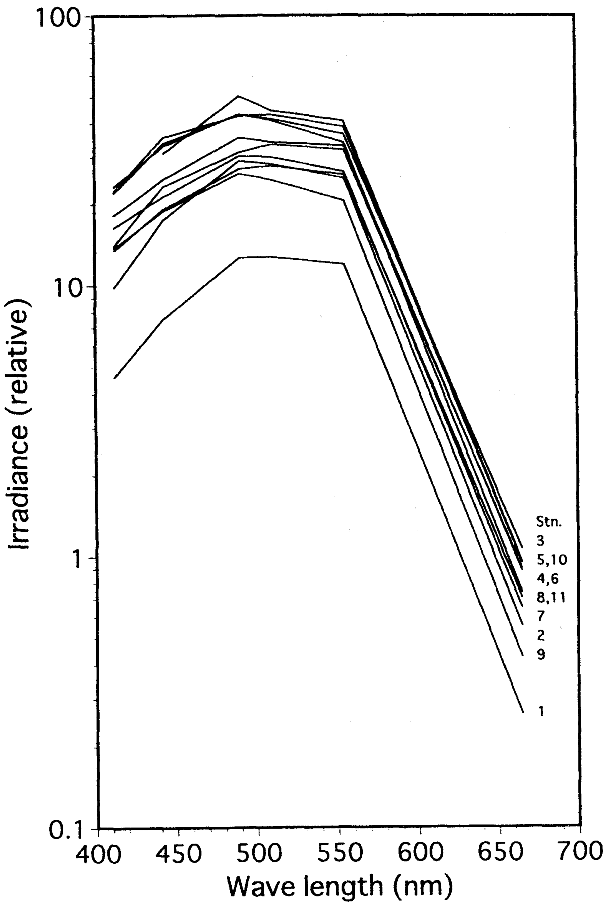


Fig. 3. Spectral distributions of downward irradiance at the depth of 10m.

seen at all stations within the Sea area. When arranged in descending order, the magnitude of light penetration took the following order: Stations 3, 5, 10, 4, 6, 8, 11, 7, 2, 9, and 1. The relative values of irradiance at Station 1 to that at Station 3 for the range of wavelength from 412 to 665 nm are within 10 to 40%. In other words, there are optically different water masses in this Sea area. According to JERLOV's optical water mass classification (1964), the Oceanic Types II and III are widely distributed in waters at the central part of the Sea area from the Strait of Hormuz to off Qatar Peninsula. The coast of UAE (Station 9) corresponds to Coastal Type 1, and water area in the vicinity of 27°30′ N correspond to the Coastal Types 1 to 3.

ARAKAWA *et al.* (1998) carried out the observations of irradiance and turbidity concurrently in this Sea area, and they clarified that there was a clean water mass at the central part of RSA with increasing turbidity in waters closer to the coasts ; and consistent turbidity from the surface to the bottom layer. There results are in good agreement with the results of the present study on relative irradiance distribution.

3-2 Distribution of PAR

Figure 4 shows the depth profile of relative irradiance of PAR at each station. PAR on the sea surface at Station 10 (17 December, 1994, noon, fine) was approximately $1.8 \times 10^3 \mu$ mol · m^{-2} · s^{-1}. The attenuation trends of PAR were

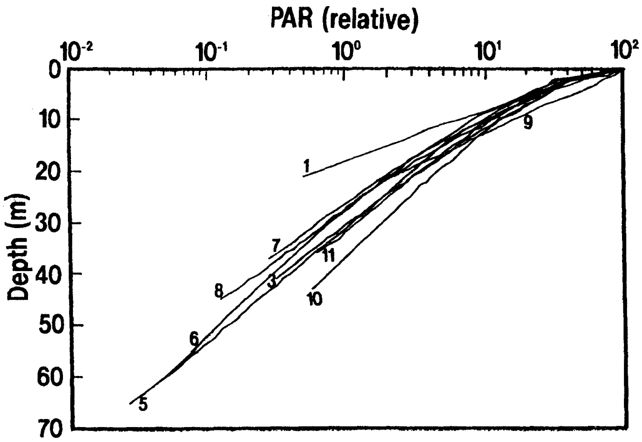


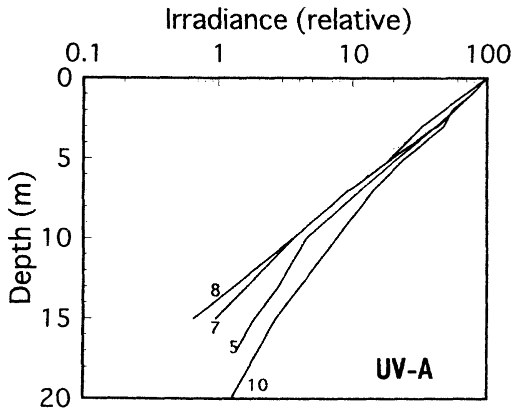
Fig. 4. Depth profiles of PAR at each station.

approximately linear at all stations from the sea surface to the vicinity of bottom. The stations in descending order of good irradiance of PAR were Stations 10, 11, 5, 3, 6, 8, 7, 9 and 1. The relative values at the depth of 10 m were 16% at Station 10, and 8% at Station 1, and the latter was approximately half of the former. The water depth at which PAR assumed 1% of the sea surface was in the range from 26 to 37 m for generous areas of waters, except for approximately 18 m in the Gulf water at Station 1, and greater in other areas of Gulf water. Furthermore, the diffuse attenuation coefficient for PAR was between 0.20 and 0.29 m^{-1}, which was smaller at the center of the Gulf water and greater in the coasts and peripheral waters. This is in close agreement with the results of the distribution of optical water mass types.

3-3 Distribution of Ultraviolet Light (A, B)

When PAR on the sea surface at Station 10 was approximately $1.8 \times 10^3\ \mu mol \cdot m^{-2} \cdot s^{-1}$, irradiance of UV-A and UV-B were about $1.4 \times 10^{-4} W \cdot m^{-2}$, and $1.3 \times 10^{-4} W \cdot m^{-2}$, respectively.

Figure 5 shows the relative irradiance of UV-A and UV-B. Supposing that UV-A just beneath the sea surface is 100%, UV-A at Station 10 assumed 24.3% at the depth of 5 m, 7.6% at 10 m, and it reached the limit of measurement at the depth of 20 m. The trend for the attenuation of UV-A at each station was linear. The diffuse attenuation coefficients for UV-A ranged from 0.26 to 0.33 m^{-1}, and there were slight dispersions.



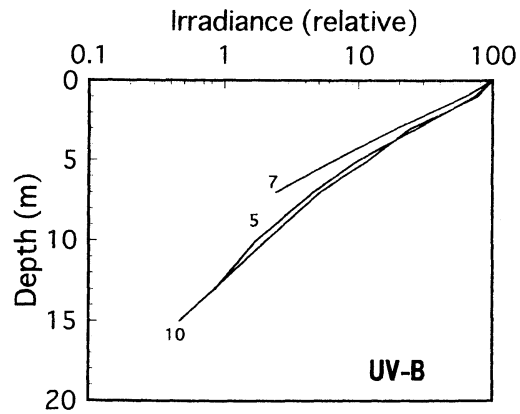


Fig. 5. Depth profiles of UV-A (upper) and UV-B (lower) at each station.

The attenuation trends of UV-B were also

Table 1. Each value of the diffuse attenuation coefficients for visible light, PAR and ultraviolet light under different optical water types. Unit is indicated as m^{-1}.

Stn.	1	2	3	4	5	6	7	8	9	10	11
Water Type	3	1	Ⅲ	Ⅲ	Ⅱ	Ⅲ	Ⅲ	Ⅲ	1	Ⅲ	Ⅲ
$K_{MAX.\ TRANS.}$	0.19	0.12	0.11	0.11	0.06	0.11	0.11	0.11	0.12	0.11	0.11
K_{PAR}	0.290	–	0.208	–	0.234	0.224	0.252	0.239	–	0.207	0.226
K_{UV-A}	–	–	–	–	0.310	–	0.332	0.333	–	0.258	–
K_{UV-B}	–	–	–	–	0.406	–	0.531	–	–	0.389	–

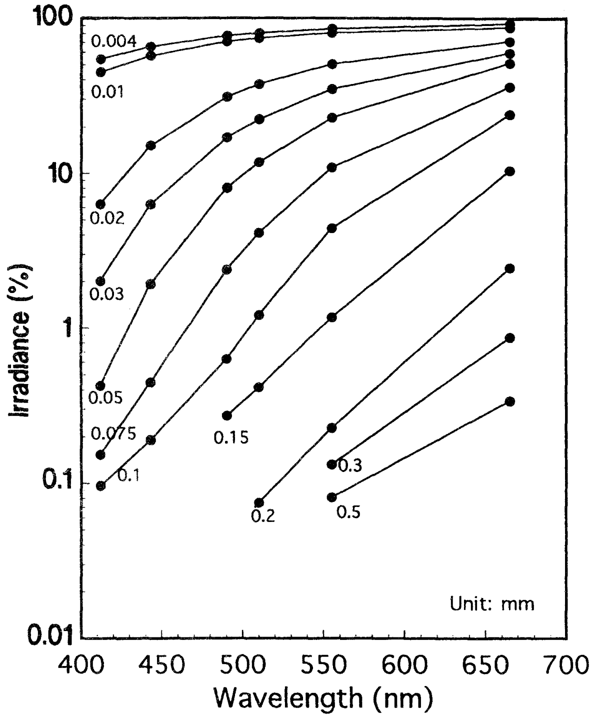


Fig. 6. Spectral distributions of relative downward irradiance just under oil slick. The numerals are thickness of oil slick on water surface.

linear. Due to significant attenuation, the limit of measurement was ranged from 7 to 15 m. The diffuse attenuation coefficients for UV-B were between 0.39 and 0.53 m^{-1}, which were greater than those for UV-A. It follows that UV-A at the central part of the Gulf featuring clear water is such that approximately 1% or more of the ultraviolet light on the sea surface penetrates 15 m or more.

3-4 Relationships between Optical Water Type, PAR and Ultraviolet Light (A, B)

Table 1 shows the relationships between the optical water mass type at each station and the diffuse attenuation coefficients for PAR and ultraviolet light (A, B). $K_{MAX.TRANS.}$ in the table indicates the diffuse attenuation coefficient for the wavelength at which light penetration is highest. Concerning the relationship between the optical water mass type and the diffuse attenuation coefficient for PAR (K_{PAR}), to begin with, K_{PAR} of 0.21–0.25 m^{-1} corresponds to the Oceanic Types Ⅱ and Ⅲ (K_{475}: 0.06 m^{-1}, K_{500}: 0.11 m^{-1}) and K_{PAR} of 0.29m^{-1} corresponds to the Coastal Type 3 (K_{550}: 0.19m^{-1}), respectively. Therefore, values of K_{PAR} correspond to

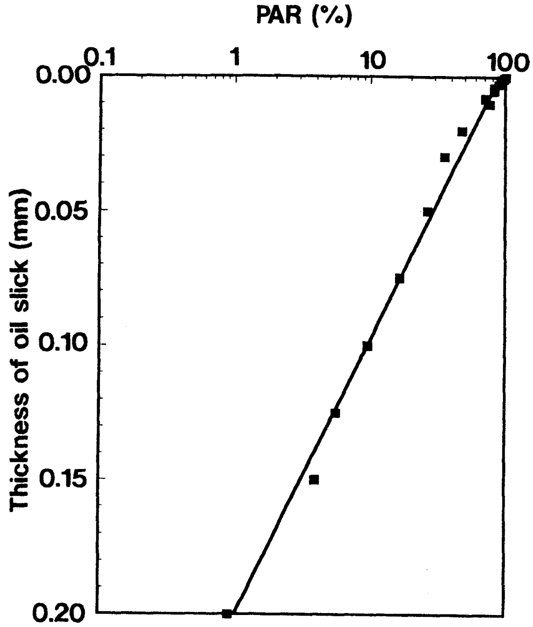


Fig. 7. Correlation between the thickness of oil slick and the ratio of PAR attenuation.

approximately 1.5 to 4.0 times the diffuse attenuation coefficients (K_{475}, K_{500}, K_{550}) of each water mass, which are slightly larger than the theoretical results of OKAMI (1978) ; i. e., 1.6 to 2.1. In the next attempt to obtain similar relationships as those above on the relation between the diffuse attenuation coefficients for UV (K_{UV-A} and K_{UV-B}) and K_{PAR}, we found that K_{UV-A} was approximately 2.5 to 5.0 times K_{PAR}, and K_{UV-B} was approximately 4.0 to 6.0 times K_{PAR}. From the discussion above, it can be found that the ultraviolet lights (A, B) attenuate most violently.

3-5 Effects of Oil Slicks on Underwater Irradiance Distribution

Crude oil spilled into the sea immediately propagetes over wide areas of water under the effects of wind and waves, and forms oil slicks. Fig.6 shows the relative irradiance distribution of visible light just below oil slicks by thickness. Relative irradiance is shown taking the value in the absence of oil slicks as 100. When the thickness of an oil slick is 0.02 mm, submarine irradiance just below that is 6.3, 37.5 and 71.1% at wavelengths of 412, 510 and 665 nm. When the thickness of an oil slick is 0.1 mm, 0.10% at 412 nm, 1.22 % at 510 nm and 24.1 % at 655 nm, respectively. Namely, greater attenuation of irradiance is caused by oil slicks on the sea surface at shorter wavelengths. Besides, the diffuse attenuation coefficients due to slicks were 6.9×10^{3} m^{-1} at a wavelength of 412 nm, and 1.4×10^{3} m^{-1} at a wavelength of 665 nm.

Figure 7 shows the relationship between PAR just below the sea surface and the thickness of an oil slick. If the irradiance in the absence of oil slicks is taken as 100, irradiance was 47.8% when the thickness of an oil slick is 0.02 mm, 9.62% to 0.1 mm, and 0.91% to 0.2 mm. The relationship between the thickness of an oil slick and the ratio of PAR attenuation is expressed by the formula below.

$$E_{par}=100\cdot\exp(-23.3\cdot h),\quad r^2=0.989$$

where,

E_{par} : relative value of PAR,
h : thickness of crude oil slick (mm)
r : correlation coefficient

From the above discussion, we can see that the value of PAR sharply drops as the thickness of an oil slick increases, and the irradiance just below that when the thickness of slick is even with only 0.2 mm assuming approximately 1% of the case without slick. At this time, the value of diffuse attenuation coefficient for PAR is $2.3 \times 10^3 m^{-1}$.

Concerning with UV, the attenuation of irradiance due to oil slick is quite violent at shorter wavelengths, thus penetration of UV into sea water is considered to become almost nil if there are oil slicks.

On the basis of the investigation stated above, the effects of crude oil spills in the RSA on submarine irradiance are examined. The quantities of crude oil spilled as a consequence of the Gulf War were reported to be 1.08×10^7 barrels (1.7×10^6 kl). The spilled crude oil ran along the coast of Saudi Arabia, reaching near the Abu Ali Peninsula, fouling 640 km of the coasts (HAYES *et al.*, 1993). The scope of crude oil propageted at this time was reportedly 35 linear miles (64.8 km), with a width of 10 miles (18.5km) (Peter, 1991), and the area was approximately 1,200km². Assuming that the crude oil propageted at an uniform thickness, the thickness of an oil slick is calculated to be 0.14 mm or more. This suggests that the submarine space at the time of the crude oil spills is a black world.

In this study, the effects of crude oil slicks on the submarine optical environment were investigated. Several tens percent of the spilled oil is said to solve into the sea. In future, it is therefore necessary to investigate the effects of emulsified oil in the sea for assessing precisely the influences of spilled oil on the changes of underwater irradiance.

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