eld 1978. The
erstitial waters
p Sea Drilling
23–432.
Bowen 1968.
ide elements in
e Inorganics in
ashington DC,

Hudson 1983.
r hydrothermal

ariations in the
ra from Atlan-
Sci. Lett., 73:

r isotopic com-
5 million years.

. A. Tourtelot
m in sea water
chim. Cosmo-

980. Neodymi-
rth Planet. Sci.

ce of the Medi-
composition of
tlantic. J. Geo-

in the sedimen-
14: 285–304.
n isotopic com-
– oceanic crust
1: 167–174.
r/^{86}Sr composi-
zoic. Geochim.

On the use of optical tracers in the sea

Gunnar Kullenberg
Department of Oceanography
University of Copenhagen
Haraldsgade 6, 2200 Copenhagen N, Denmark

ABSTRACT

Optical tracers are interpreted as those tracers which can conveniently be traced in the ocean by means of optical methods: measurements of light scattering, transmission and fluorescence. The tracers can be naturally present in, and transferred to, or produced in the sea, such as suspended particulate matter including plankton, yellow substance, chlorophyll of various types, or they can be artificially introduced into the sea, such as from sewage disposal operations or through different types of fluorescent dye tracer injections.

The optical measuring techniques are usually adapted for *in situ* observations. In many cases different detecting methods can be used simultaneously for the same tracer. The relationship between signal and concentration of tracer is, however, often not unique. The particle scattering depends upon size, shape and composition of the particles apart from the amount present. The relative importance of these factors varies with the scattering angle. The light transmission of the water varies strongly with wavelength and depends on suspended and dissolved substances. The chlorophyll *a* fluorescence depends on the state and type of phytoplankton and also may vary with daylight. Thus there are serious problems of absolute calibration in all of these cases. Artificial dye tracers suffer from interference problems with particles in the sea and are also influenced by daylight and temperature.

Optical tracers can be used over a large range of scales and are also used to study basin-wide phenomena (e.g. satellite remote sensing; plankton recorder). Apart from use in many applications, such as in relation to sewage disposal problems, these tracers have been used for a number of basic investigations: small-to-medium scale mixing studies; circulation features in upwelling areas and frontal zones; water exchange in fjords, shelf seas and between basins; conditions at the air-sea interface.

INTRODUCTION

The aim of this note is to give a brief description of optical measuring techniques which can be used for tracing certain properties in the ocean, and to present examples of results. It is not intended to give a complete review of results from such optical measurements in different parts of the ocean, or to treat marine optics in general (see Jerlov 1976).

Optical tracers are ocean properties which can conveniently be measured by optical methods, and the distribution of which are such that information on oceanic motions or conditions can be obtained. The optical methods are measurements of light transmission, scattering and fluorescence. The tracers include: suspended matter, including plankton; humic substances; various types of chlorophyll; various types of fluorescent dyes injected into the sea for the purpose of tracing; and other injections of substances, e.g. associated with waste disposal operations. The optical measuring techniques are used to locate and identify the various tracers. The measurements can be performed *in situ*, in the laboratory, or by remote sensing from an aeroplane or a

TABLE 1

Examples of applications, optical parameters and instrumentation. The parameters a, b, c, $\beta(\theta)$ and a_y are explained in the text.

Application or type of study	*Optical*			*Instrumentation*
	Property	*Parameter*		
		Notation	*Unit*	
A. Basic Oceanography				
Water masses, fronts, upwelling	Beam transmittance	c	m^{-1}	Beam transmittance or transparency meter
Stratification, layering and interleaving, ergoclines	Scatterance (scattering)	b $\beta(\theta)$	m^{-1} m^{-1} str^{-1}	Nephelometer scattering meter ß-meter
Biological features	Absorptance	a	m^{-1}	Beam transmittance as function of wavelength
	Fluorescence	—	Relative	Fluorometer
Characteristics of suspended matter	Scatterance Scatterance	$\beta(\theta)$ $\beta(\theta_1)$ $\beta(\theta_2)$	$m^{-1}\ str^{-1}$ $m^{-1}\ str^{-1}$ $m^{-1}\ str^{-1}$	ß-meter ß-meter — wavelength dependancy
Surface patterns (fronts, eddies)	Colour	Colour index	Ratio dimensionless	Upwelling irradience, colour meter (ship; remote sensing)
Dispersion (dye)	Fluorescence	Concentration	Mass per volume	Fluorometer
(Suspended matter, dissolved substances)	Beam transmittance	c	m^{-1}	Transparency meter
B. Practical Applications				
River plumes, land runoff	Beam transmittance	c	m^{-1}	Transparency meter
Baltic type outflow	Fluorescence Absorptance	— a_y	— m^{-1}	Fluorometer Transparency as function of wavelength
Sewage dispersion	Beam transmittance	c Concentration	m^{-1} Mass per volume	Transparency meter
Dispersion of dumped sludge				
Sewage outfall	Fluorescence	—	—	Fluorometer
Oil spill dispersion	Fluroescence	Concentration	Mass per volume	Fluorometer (UV)

satellite. An attempt to summarize applications, optical parameters and instrumentation is given in Table 1.

OPTICAL PROPERTIES

Light attenuation by sea water occurs through absorption and scattering by dissolved substances and suspended matter. The total attenuation coefficient c is

$$c = a + b = c_w + b_p + a_p + a_d \qquad (1)$$

where a and b are the absorption and total scattering coefficients, respectively, a_p and b_p the same coefficients for particulate matter in the water, and a_d the absorption coefficient for dissolved substances, mainly organic, humic type substances.

The attenuation by water itself (c_w) is strongly wavelength-dependent both as regards absorption and scattering (Morel 1974a; Jerlov 1976). The absorption by dissolved substances shows a strong wavelength dependence, the absorption increasing by a factor of about 100 from the red to the UV part of the spectrum (Jerlov 1976, p. 56). Absorption by particles can also be selective, mainly depending upon the colour of the particles. The scattering by suspended particles shows a weak wavelength selectivity, usually related to the smallest particles, 0.4 μm to about 1 μm in diameter (Burt 1956; Morel 1973; Højerslev 1974; Kullenberg 1974a, 1984a; Aas 1984a).

The spatial variation of the optical properties is to a large extent determined by the variation in the content of dissolved organic matter and suspended particulate matter. This is so since both the scattering and absorption of pure sea water is almost constant over the normal oceanic salinity and temperature ranges. The pressure effect is also quite small (e.g. Morel 1974a; Kullenberg 1984a). Due to the different degree of wavelength selectivity of the attenuation, absorption and scattering by particles and dissolved substances, relationships can be established between attenuation at different wavelengths and absorption by dissolved substances. Jerlov (1955, 1976) found the relationship

$$(c - c_w)_{380\mathrm{nm}} - K(c - c_w)_{655\mathrm{nm}} = a_y \qquad (2)$$

where a_y is the absorption by dissolved humic substances. This has been used by Ivanoff et al. (1961) in waters around Bermuda and by Malmberg (1964) for studying water masses in the Skagerak. Various types of relationships can also be established between the absorption and scattering coefficients. These optical properties may then be used as one characteristic of a water mass (e.g. Jerlov 1974).

The scattering properties determine the shape of the volume scattering function $\beta(\theta)$, i.e. the angular distribution of the scattered light.

$$\beta\,(\theta) = \frac{dI(\theta)}{E\,dv} \qquad (3)$$

where $dI(\theta)$ is the intensity of the light scattered in the direction (θ) from the incoming beam by the volume element dv irradiated by the irradiance E. The total scattering coefficient b is found from

$$b = 2\pi \int_0^{\pi} \beta(\theta) \sin\theta \; d\theta \qquad (4)$$

The scattering by the suspended particulate matter depends upon the particle size, the size distribution, the shape, and composition of the particles. Assuming that the particles are spherical, the volume scattering function can be calculated by the Mie theory (Mie 1908; van de Hulst 1957) with a known particle size distribution and composition (e.g. Kullenberg 1974a). Aas (1984a) has presented new theoretical results for computing the scattering by differently shaped particles.

Natural fluorescence in sea water can be due to humic substances and chlorophyll pigments. The fluorescence usually shows a fairly strong wavelength dependence and therefore the sources of fluorescence can be separated by using the most appropriate excitation and emission (detection) spectral filter combinations (e.g. Brown 1974; Jerlov 1976). Absolute determination of the fluorescence, due to humic substances, requires an appropriate standardization. Morel (1973) and Brown (1974) have suggested the use of Raman scattering for measurements below 420 nm.

Chlorophyll pigments show a varying degree of fluorescence depending upon the excitation (production) state and the species. Chlorophyll *a* fluorescence can be determined directly by *in situ* measurements. Phinney and Yentsch (1984/85) have demonstrated a marked increase in sensitivity by using improved optical filters and detectors so that concentration levels below 0.1 μg/l of chlorophyll *a* can be detected. The *in situ* instrument developed by Hundahl and Holck (1980) has a similar sensitivity.

Hydrocarbons can also be measured through their fluorescence, but in natural conditions an extract concentrate is used (Grasshoff et al. 1983). A characterization of the hydrocarbons usually requires more elaborate measurements.

It would lead too far to discuss the optical properties of various substances which can be traced optically, like sewage, dyes, sludge, dredge spoils, injected in the sea. Reference is made to recent specialized series (e.g. Duedall et al. (eds.) 1983 and 1986, in press).

TECHNIQUES

The total attenuation is measured *in situ* by means of beam transmittance meters (Bartz et al. 1978; Gibbs 1974; Jerlov 1955, 1976; Joseph 1955), consisting of a light source and a detector measuring the total attenuation over a given path length. A basic design criterium is to exclude the scattered light as much as possible from reaching the detector since the combined effect of absorption and scattering should be determined. Usually, the instruments measure at a narrow, well-defined wavelength, with the possibility of changing filters mechanically although spectral transmissometers, measuring continuously over the spectrum, also exist (e.g. Lundgren 1975).

There are two kinds of *in situ* scattering meters: those which measure the scattering integrated over a range of scattering angles, integrating meters, and those which measure the volume scattering function or a part of this, i.e. the scattering at a series of discrete scattering angles (Gibbs 1974; Jerlov 1976; Kullenberg 1968; 1978). Relatively more information is obtained from the volume scattering function measurement, particularly if this is done at several wavelengths. However, it is very difficult to measure the forward scattering close to the light beam, which can be important since about 90% of the scattering is in the angular interval 0–20° (e.g. Kullenberg 1968, 1974a). Measurements at selected discrete angles are usually also quite informative, e.g. at 15–20°, 45°, 90°, 135°, and 165°. This will show basic features of the volume scattering function. Integrating scattering meters, giving an approximation of b, suffer from the problem of covering all angles in one practical device.

The scattering measurements should be made over a well-defined (narrow) spectral range. For studies of particles, it is advantageous to measure the scattering at several wavelengths, since this makes it possible to determine the refractive index of the particles and thus, indirectly, the composition (Zaneveld and Pak 1973; Zaneveld et al. 1974). Singular wavelength measurements should normally be made in the red part of the spectrum.

Fluorescence measurements are usually done at an angle of 90° between excitation and detecting directions, often using chopped light sources. *In situ* instruments for chlorophyll, dye, and oil-hydrocarbon tracing have been developed (Hundahl and Holck 1980; Kullenberg et al. 1986; Law 1984).

Remote sensing (satellites, aeroplanes) of the surface or near-surface properties in the visible part of the spectrum is based on measuring the upward irradiance at a series of different wavelengths, supplemented by sea truth data. The ratio of the signals gives a colour index which can be related to the properties influencing the signals, i.e. the content of chlorophyll *a,* suspended particulate matter, dissolved organics, film on the surface, and the relative importance of the water itself. The basis for these colour measurements has been presented by Jerlov (1974). The interpretation of the data can be rather intricate (e.g. Højerslev 1980; Gordon and Morel 1983).

There are, of course, several laboratory techniques which can be used to refine or supplement the *in situ* observations, e.g. the laboratory angular scattering meter (e.g. Reuter 1980), and the spectrophotometers and spectrofluorometers. These are normally used to study the optical properties and to help identify the substances localized by means of the *in situ* measurements. The laboratory studies are also used to calibrate *in situ* instruments, the absolute calibration of which is always a major problem (Gibbs 1974; Jerlov 1976; Kullenberg 1984a). The calibration requires great care and often the use of the appropriate standards (in relation to fluorescence, e.g. Brown 1974). Reference should be made to relevant original literature in individual cases.

Advanced packages of *in situ* instrumentation combining water bottles, CTD, transmissometer, and scattering meter (or nephelometer) have also been used in recent experiments (e.g. Kullenberg and Zaneveld 1983; Smith et al. 1984). An early version of this approach was the GEOSECS package with the Lamont nephelometer as the sensor, indicating the levels where water samples for suspended particulate matter should be taken (e.g. Ettreim and Ewing 1974). Several optical parameters can also be measured simultaneously, like fluorescence and scattering at 90°, as well as transmission and scattering at selected angles. This will yield additional information about the properties being traced. Finally, the problems of interference and interaction should be mentioned; they are related both to the material properties of the substance and to the measuring technique. Chlorophyll *a* and rhodamine dye fluorescence may interfere if sharply defined filters are not used. The chlorophyll *a* fluorescence varies according to species, time of the day, and the time of the production cycle, and great care is needed for the interpretation. The scattering of particles can change markedly from place to place and across fronts due to the change in particle properties, namely the shape, size, and composition. Artificial dyes get absorbed by particles and their fluorescence is usually temperature dependent and decays in sunlight, factors which will have to be taken into account when interpreting tracer studies. All of these problems are also discussed in the references given above.

RESULTS

Classical results using some of the optical methods of tracing described above have been presented by Jerlov (1953, 1955, 1959, 1976), Joseph (1955, 1961), Joseph and Sendner (1958), Kalle (1949), and several developments and relatively recent results were presented by Jerlov and Steemann Nielsen (1974). The Oregon School of Oceanography group has been very active in the field: Burt (1958), Beardsley et al. (1970), Pak et al. (1970), Pak (1974), Bartz et al. (1978). They have studied the optical properties of sea water experimentally and theoritically and have applied optical

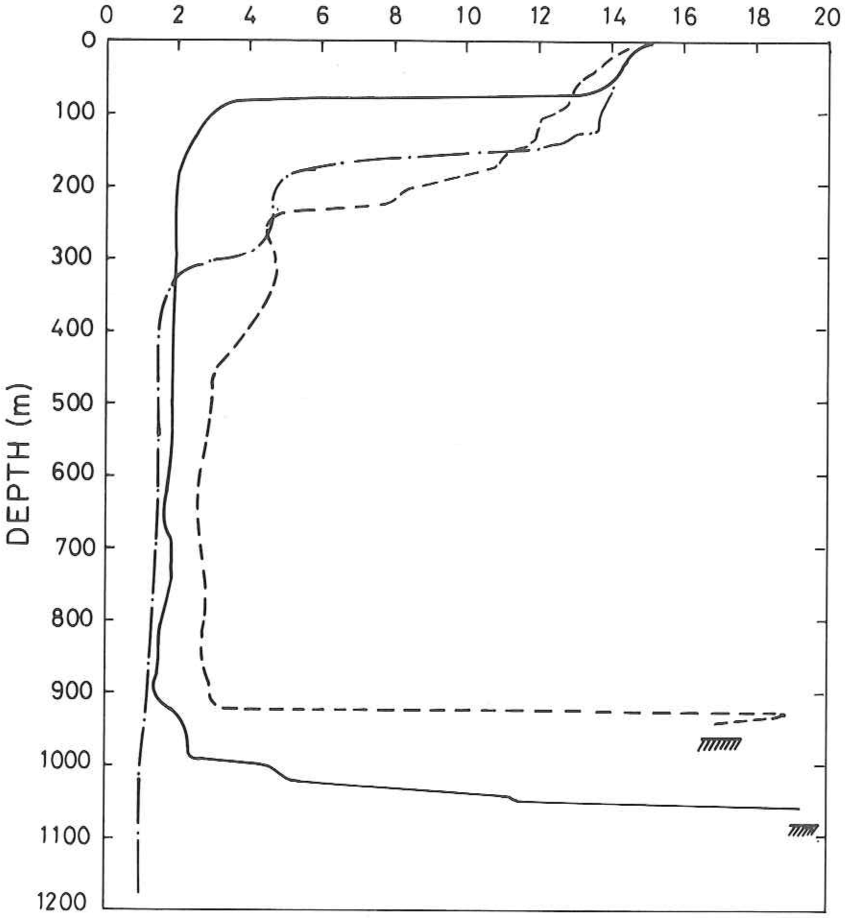

Fig. 1. Vertical profiles of light-scattering (in relative units) on and off the Campell Plateau (52°–55°S along 168°E) in the Southern Ocean. These show examples of near-bottom boundary layer of scattering material for the stations on the Plateau. The third profile, taken off the Plateau, did not reach down to the bottom. The observations were made in October 1978 using the ß(θ) meter.

studies to frontal and upwelling dynamics as well as to biological oceanography.

The Lamont group has in particular studied the deep sea light scattering layers (e.g. Ettreim and Ewing 1974). There are, of course, a large number of individual results in recent publications, and only a few of these will be reviewed here. Some specific results on the use of optical methods in waste disposal studies were presented by Kullenberg (1983). Here a few examples of results will be presented from the author's own studies of the distribution of suspended particulate matter in various areas by means of light scattering.

The tracing of an outflow of particle-rich water forming an internal layer at the shelf and slope in the Northwest African upwelling area was shown by means of an integrating type scattering meter (Kullenberg 1974c). Subsequently, a ß(θ) meter was developed. By means of measurements at a single scattering angle of 20°, it was demonstrated that internal layers, interleaving across the Antarctic Polar Frontal Zone in the Drake Passage area, could be clearly distinguished on the basis of their scattering properties (Kullenberg 1978). The low-temperature water coming from the south and sinking at the front showed a relatively large scattering, presumably related to a higher primary production south of the frontal zone than north of it.

An example of a well-mixed bottom

ertical profiles
attering (in
nits) on and
mpell Plateau
along 168°E) in
ern Ocean.
w examples of
om boundary
cattering
or the stations
ateau. The third
aken off the
did not
wn to the
The observations
de in October
g the ß(θ) meter.

frican upwell-
of an integrat-
(Kullenberg
meter was de-
urements at a
it was demon-
, interleaving
ontal Zone in
uld be clearly
heir scattering
The low-tem-
the south and
relatively large
ed to a higher
of the frontal

mixed bottom

---

boundary scattering layer observed by means of the ß(θ) meter is shown in Figure 1. This is due to the swift Antarctic Circumpolar Current. It is noted that no scattering effects were detected on the sides of the bank (Fig. 1). Unfortunately, no downstream observations could be made.

Upwelling influences the amount of particles in the water column through its influence on the biological production. Effects of the equatorial upwelling and circulation were elucidated by means of optical measurements by Pak and Plank (1974). In coastal upwelling systems and adjacent areas, large variations of the suspended matter content can be expected, as demonstrated by Kullenberg (1978, 1981) and Pak et al. (1980, Fig. 2a, b, c). The Peru upwelling, in particular, is of great interest in this connection due to the large secondary nitrite maximum there, centered at 200 m at 15°S, and with globally significant denitrification (Codispoti and Packard 1980). The nitrite maximum is very conspicuously connected with a suspended particle maximum (Fig. 2a), observed both by means of beam transmission and scattering measurements (Pak et al. 1980; Kullenberg 1981). The explanation for this situation is not clear. Ideas related to the role of the Ekman bottom boundary layer over the shelf break and slope, the circulation in the upwelling area and the adjacent ocean, the biology (e.g. grazing pressure by zooplankton) and biochemical processes have been identified (Pak et al. 1980; Kullenberg and Codispoti, submitted). An example of profiles in a section at 15°S is shown in Figure 2a. The layering and small-scale structure of the scattering profile should be noted, the other profiles having been obtained through water samples.

The Arctic areas and especially the transition zones between the Atlantic Ocean conditions south and north of the Scotland-Greenland ridge, as well as between the Norwegian-Greenland Seas and the Polar

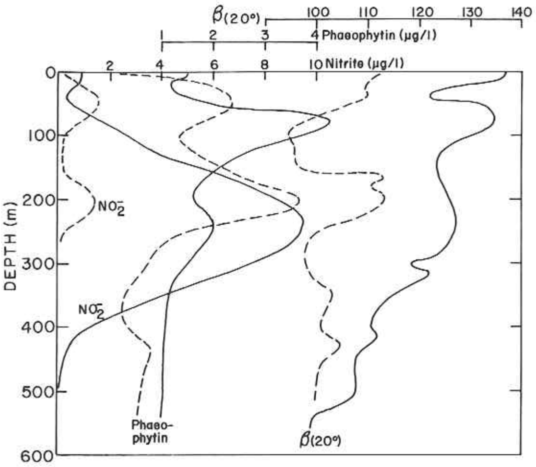

Fig. 2a. Vertical profiles along 15°S, off Peru, showing light scattering, (20°), in relative units (100–140), compared with phaeophytin and nitrite.

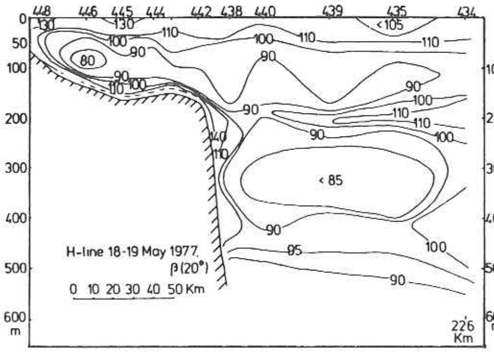

Fig. 2b. Section along 10°S off Peru, showing light scattering in relative units (from Kullenberg 1981).

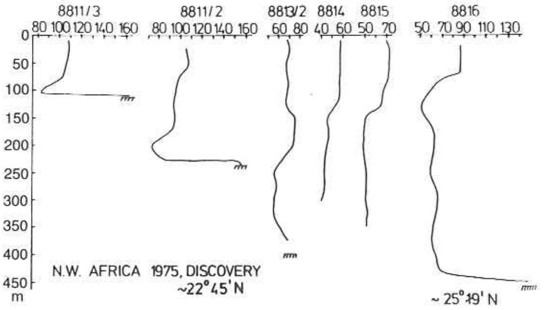

Fig. 2c. Vertical profiles of light scattering in an upwelling area off NW Africa (from Kullenberg 1981).

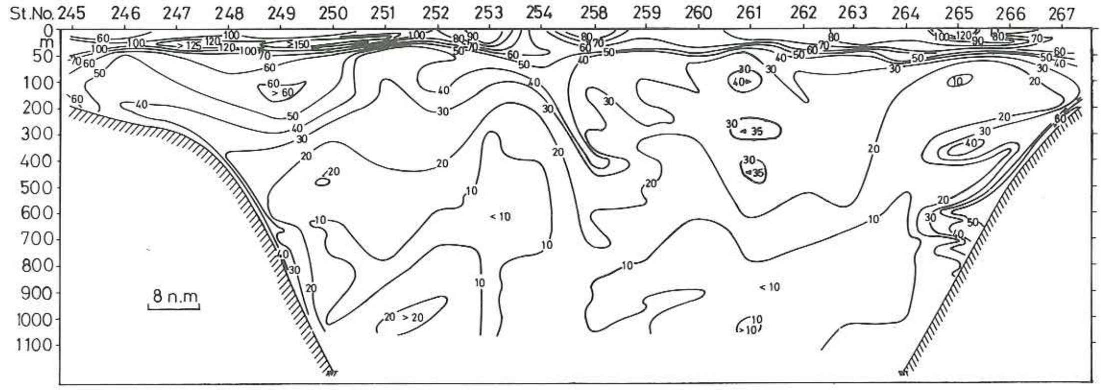

Fig. 3. Section showing light scattering across the Fram Strait from Greenland (St. 245) to Spitsbergen (St. 267), obtained in August 1984 at about 79°N.

Sea, are also regions where optical tracers may yield important information. Light-scattering observations east, west, and north of Spitsbergen made in 1980 and 1981 suggested that water masses could be characterized by their scattering properties, in addition to their T,S properties (Kullenberg 1984b). The highly saline and warm North Atlantic water flowing towards, and into, the Polar Sea was characterized by minimum scattering. Similar observations carried out in the same areas in 1984 tend to corroborate the findings. Figure 3 shows a section across the Fram Strait of light scattering at 15° scattering angle. The following observations may be made: The scattering in the surface layer was much larger on the western side associated with the East Greenland Current than on the eastern side. At the slope (300–800 m) several marked layers of high scattering extending out from the slope were present on the Spitsbergen side, but not on the Greenland side. This presumably indicates a difference in the strength of the near-bottom and intermediate level currents. In the centre of the section an eddy structure is indicated with a rather complicated pattern of interleaving layers. This may suggest active vertical motion (convection). These results are preliminary.

CONCLUDING REMARKS

In this brief review certain pertinent questions of the use of optical tracers have been discussed, but by no means exhaustively. It is hoped that the impression given is that optical tracers can often be used with great advantage in locating areas and features of interest, and that the optical methods are rapid and relatively easy to apply. The observations need to be supplemented with other data to facilitate interpretation.

REFERENCES

Aas, E. 1984a. The wavelength selectivity of light scattering in the Barents Sea. Institutt for Geofysik, Universitetet i Oslo, Institute Report Series No. 54, 20 pp.

—— 1984b. Influence of shape and structure on light scattering by marine particles. Institutt for Geofysik, Universitetet i Oslo, Institute Report Series No. 53, 112 pp.

Bartz, R., J. R. V. Zaneveld and H. Pak 1978. A transmissometer for profiling and moored observations in water. Society Photo-Optical Instrumentation Engineers 160, Ocean Optics V: 102–108.

Beardsley Jr., G. F., H. Pak, K. Carder and B. Lundgren 1970. Light scattering and suspended particles in the Eastern Equatorial Pacific Ocean. J. Geophys. Res. 75: 2837–2845.

Brown, M. 1974. Laboratory measurements of fluorescenc spectra of Baltic waters. Univeristy of

Copenhagen, Institute of Physical Oceanography Report No. 29, 31 pp.

Burt, W. V. 1956. A light-scattering diagram. J. Mar. Res. 15: 76–80.

—— 1958. Selective transmission of light in tropical Pacific waters. Deep-Sea Res. 5: 51–61.

Codispoti, L. A. and T. T. Packard 1980. Denitrification rates in the eastern tropical South Pacific. J. Mar. Res. 38: 453–477.

Duedall, I. W., B. H. Ketchum, P. K. Park and D. R. Kester (Eds.) 1983. Wastes in the Ocean, Vol. 1. Industrial and Sewage Wastes in the Ocean. John Wiley and Sons, New York, 431 pp.

——, P. K. Park and D. R. Kester (Eds.) 1986. Scientific Monitoring Strategies for Ocean Waste Disposal. John Wiley and Sons, New York. In press.

Eittreim, S. L. and M. Ewing 1974. Turbidity distribution in the deep waters of the Western Atlantic Trough. In R. J. Gibbs (Ed.) Suspended Solids in Water. Plenum Press, New York, pp. 213–226.

Gibbs, R. J. (Ed.) 1974. Suspended solids in water. Plenum Press, New York, 320 pp.

Gordon, H. R. and A. Y. Morel 1983. Remote Assessment of Ocean Color for Interpretation of Satellite Visible Imagery. Lecture Notes on Coastal and Estuarine Studies. Springer Verlag, Berlin, 130 pp.

Grasshoff, K., M. Ehrhardt and K. Kremling (Eds.) 1983. Methods of seawater analysis. Second, revised and extended edition. Verlag Chemie, Weinheim, 419 pp.

Hundahl, H. and J. Holck 1980. A new *in situ* fluorometer for detection of rhodamine B and chlorophyll. University of Copenhagen, Institute of Physical Oceanography Report No. 42, pp 145–154.

Höjerslev, N. K. 1971. Tyndall and fluorescence measurements in Danish and Norwegian waters related to dynamical factors. University of Copenhagen, Institute of Physical Oceanography Report No. 16, 46 pp.

—— 1974. Inherent and apparent optical properties of the Baltic. University of Copenhagen, Institute of Physical Oceanography Report No. 23, 70 pp.

—— 1980. Water Color and its Relation to Primary Production. Boundary-Layer Meteorology, 18, 2: 203–220.

Ivanoff, A., N. G. Jerlov and T. H. Watermann 1961. A comparative study of irradiance beam transmittance and scattering in the sea near Bermuda. Limnol. Oceanogr. 6: 129–148.

Jerlov, N. G. 1953. Particle distribution in the ocean. Report Swedish Deep-Sea Expedition 3: 73–97.

—— 1955. Factors influencing the transparency of the Baltic waters. Meddelanden Oceanografiska Institut Göteborg 25: 1–19.

—— 1959. Maxima in the vertical distribution of particles in the sea. Deep-Sea Res. 5: 178–184.

—— and E. Steemann Nielsen (Eds.) 1974. Optical aspects of oceanography. Academic Press, London, 494 pp.

Jerlov, N. G. 1974. Significant relationships between optical properties of the sea. In N. Jerlov and E. Steemann Nielsen (Eds.) Optical Aspects of Oceanography. Academic Press, London, pp. 74–94.

—— 1976. Marine Optics. Elsevier, Amsterdam, 231 pp.

Joseph, J. 1955. Extinction measurements to indicate distribution and transport of water masses. In Proceedings UNESCO Symposium on Physical Oceanography, Tokyo, pp. 59–75.

—— 1961. Trübungs- und Temperatur-Verteilung auf den Stationen und Schnitten von V. F. S. Gauss 1957–58. Deutsche Hydrographische Zeitschrift 5.

—— and H. Sendner 1958. Über die horizontale diffusion im Meere. Deutsche Hydrographische Zeitschrift 11: 47–77.

Kalle, K. 1949. Fluoreszenz und Gelbstoff im Bottnischen und Finnischen Meerbusen. Deutsche Hydrographische Zeitschrift 2: 117–124.

Kullenberg, G. 1968. Scattering of light by Sargasso Sea water. Deep-Sea Res. 15: 423–432.

—— 1974a. Observed and computed scattering functions. In N. Jerlov and E. Steemann Nielsen (Eds.) Optical Aspects of Oceanography. Academic Press, London, pp. 25–50.

—— 1974b. An experimental and theoretical investigation of the turbulent diffusion in the upper layer of the sea. University of Copenhagen, Institute of Physical Oceanography Report No. 25, 212 + 60 pp.

—— 1974c. The distribution of particulate matter in a Northwest African Upwelling Area. In R. J. Gibbs (Ed.) Suspended Solids in Water. Plenum Press, New York, pp. 195–202.

—— 1978. Light scattering observations in frontal zones. J. Geophys. Res. 83: 4683–4690.

—— 1981. A comparison of distributions of suspended matter in the Peru and northwest African upwelling areas. In F. A. Richards (Ed.) Coastal Upwelling. American Geophysical Union, Washington D. C., pp. 282–290.

—— 1982. Experimental techniques. In G. Kullenberg (Ed.) Pollutant transfer and transport in the sea, Vol. 1, CRC Press, Boca Raton, Fl., pp. 161–176.

—— 1983. Physical oceanography studies related to waste disposal in the sea. In I. W. Duedall, B. H. Ketchum, P. K. Park and D. R. Kester (Eds.), Industrial and sewage wastes in the ocean. Wiley and Sons, New York, pp. 87–102.

—— 1984a. Observations of light scattering functions in two oceanic areas. Deep-Sea Res. 31: 295–316.

—— 1984b. Observations of light scattering distributions in the transition zone to the Arctic Ocean. In J. Meincke, L. Otto, A. J. Lee and R. R. Dickson (Eds.), Hydrobiological variability in the North Atlantic and adjacent seas. Rapp. P.-v. Réun. Cons. int. Explor. Mer, 185: 102–110.

Kullenberg, G. and R. V. J. Zaneveld 1983. Aspects of bottom boundary layers in the ocean. In M. H. P. Bott, S. Saxov, M. Talevani and J. Thiede (Eds.), Structure and development of the Greenland-Scotland Ridge. Plenum Press, New York, pp. 287–310.

——, H. Hundahl and J. Holck 1986. Fluorescence techniques in waste disposal and oil spill studies. In the series Waste Disposal in the Oceans. In press.

—— and L. A. Codispoti. On the distribution of suspended matter in and off the Peru upwelling area. Submitted to Journal of Marine Research.

Law, R. J. 1984. The continuous measurement of low concentrations of hydrocarbons in water using a towed fluorometer. ICES C. M. /84/E:7, 10 pp. (mimeo).

Lundgren, B. 1975. Measurements in the Baltic with a spectral transmittance meter. University of Copenhagen, Institute of Physical Oceanography Report No. 30, 28 pp.

Malmberg, S. A. 1964. Transparency measurements in the Skagerak. Medd. Oceanogr. Inst. Göteborg, 31: 18 pp.

Mie, G. 1908. Beiträge zur Optik trüber Medien speziell kolloidalen Metall-lösungen. Annalen der Physik 25: 377 pp.

Morel, A. 1973. Diffusion de la lumière par les eaux de mer. Résultats expérimentaux et approche théorique. In Optics of the Sea. AGARD Lecture Series No. 61, 3.1-1-71.

—— 1974a. Optical properties of pure water and pure sea water. In N. Jerlov and E. Steemann Nielsen (Eds.). Optical Aspects of Oceanography. Academic Press, London, pp. 1–24.

—— 1974b. Figure 8 in Duursma, E. K. The fluorescence of dissolved organic matter in the sea. In N. Jerlov and E. Steemann Nielsen (Eds.), Optical Aspects of Oceanography. Academic Press, London, p. 247.

Pak, H. 1974. Distributions of suspended particles in the equatorial Pacific Ocean. In R. J. Gibbs (Ed.) Suspended Solids in Water. Plenum Press, New York, pp. 261–270.

——, G. F. Beardsley Jr. and P. K. Pak 1970. The Columbia River as a source of marine light scattering particles. J. Geophys. Res. 75: 4570–4578.

—— and W. S. Plank 1974. Some applications of the optical tracer method. In N. Jerlov and E. Steemann Nielsen (Eds.) Optical Aspects of Oceanography. Academic Press, London, pp. 221–236.

——, L. A. Codispoti and J. R. V. Zaneveld 1980. On the intermediate particle maxima associated with oxygen-poor water off western South America. Deep-Sea Res. 27: 783–797.

Phinney, D. A. and C. S. Yentsch 1984/85. A novel phytoplankton chlorophyll technique: Toward automated analysis. Submitted to J. Plankton Research.

Reuter, R. 1980. Characterization of marine particle suspensions by light scattering II. Experimental results. Oceanologica Acta 3: 325–332.

Smith, R. C., C. R. Booth and J. L. Star 1984. Oceanographic biophysical profiling system. Journal of Applied Optics, 23 (16): 2791–2797.

Van de Hulst, H. C. 1957. Light scattering by small particles. Wiley, New York, 470 pp.

Zaneveld, J. R. V. and H. Pak 1973. Method for the determination of the index of refraction of particles suspended in the ocean. Journal of the Optical Society of America 63: 321–324.

——, D. M. Roach and H. Pak 1974. The determination of the index of refraction distribution of oceanic particles. J. Geophys. Res. 79: 4091–4095.