Optical Measurement of Particle Distribution in the Sea

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Abstract

A method has been developed for studying the distribution of suspended particles in the sea. The intensity of the light from a Tyndall beam scattered in the water samples is measured. Essential precautions in the study of clear ocean water are given. The method is illustrated by the particle distribution found off the Nile estuary and in the Strait of Gibraltar. The possibilities offered by the method suggest that it should be more widely employed for characterizing water masses and for studying horizontal and vertical movements in the sea. Other pertinent problems, *re* the settling of suspensoids near land and the flushing of harbours, may also be investigated in this way.

Introduction

During recent years the study of particle distribution in the sea has gained new interest. In particular, attention has been paid to the production of living matter in the sea. The production problem has been closely investigated *i.a.* by RILEY, STOMMEL, and BUMPUS (1949) for the Western North Atlantic and by HARVEY (1950) for the sea off Plymouth.

By filtration of the water samples and determination of dry weight it is possible to obtain a measure of the total amount of suspended particles. ARMSTRONG and ATKINS (1950) have used this procedure, combined with an inorganic analysis of the ignited dry matter. KREY (1949) has developed a simple method of filtering particles according to size, followed by a microscopic analysis. In addition, he measured the content of chlorophyll and albumen in the suspended matter in order to arrive at a qualitative and quantitative control of the decrease or increase of its organic content.

In the upper strata, suspensoids are to a large extent living organisms but organic *detritus* also plays an important rôle. Besides, inorganic matter is present, derived from land or, in shallow water, from the bottom. By currents and horizontal eddies fine material can be transported far away from shore. Air-borne terrigenous dust is also an important contributor to marine suspensoids. While sinking, the dead planton or the *detritus* is gradually decomposed. From the upwelling water west of Africa WATTENBERG (1937) has followed the different stages of this disintegration process.

The biological interest in particle distribution is chiefly directed to the upper, illuminated water strata. From a hydrographical point of view the question has a somewhat different aspect, since the distribution of suspended matter in the whole water column is significant. Particles affect both physical and chemical conditions in the water, in the first place the optical conditions. These effects have been discussed by KALLE (1947).

The marked influence of suspended matter on light suggests the use of optical methods for studying the content of particles. In 1937, KALLE (1939) introduced a method in which the intensity of a Tyndall beam projected into the water sample is determined.

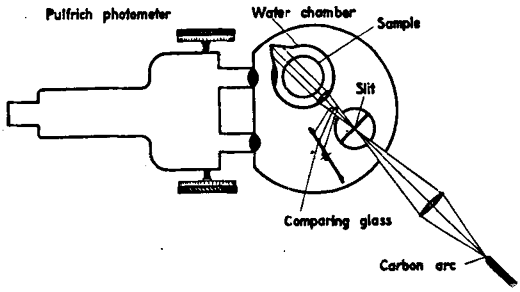

Fig. 1. Tyndall meter.

A similar method was developed and employed during the Swedish Deep Sea Expedition. Measurements of the particle content in the water samples were accordingly included in the routine hydrographical work on board.

Tyndall meter

The device used for measuring the intensity to the Tyndall beam is a Zeiss turbidity meter with some technical modifications. Since the high transparency of the samples requires an intense light source the electrical lamp in the original apparatus is replaced with a slit (width 1 mm) illuminated by a carbon arc (fig. 1). A parallel Tyndall beam is obtained in the sample, which is contained in a small glass flask (60 ml) and submerged in a chamber filled with water. The intensity of the light scattered from the Tyndall beam at an angle of 45° is measured by means of a Pulfrich photometer. A scattering glass, against which some initial light is reflected, serves as a comparison. Low-scattering samples are compared with a slightly etched glass, those of a medium scattering power with a more strongly etched glass, and high-scattering samples with a milkglass. The photometer is provided with a red filter (centre of gravity 615 mμ), a green filter (535 mμ), and a blue filter (470 mμ).

During the expedition the Tyndall meter was placed in the optical darkroom. An asbestos wall shielded the observer from light from the carbon arc. For the clearest samples it was necessary to work with completely adapted eyes. Then, the accuracy realized by the Tyndall reading is the same as that normally obtainable with the Pulfrich photometer (see URBACH, 1937).

Procedure

The method, if it is also to be employed for clear ocean water, demands that great care be taken to avoid contamination during the collection of samples, and that the samples are studied before any change of the particle content occurs.

For collecting samples at subsurface levels Knudsen water-bottles were used. As the nickel-plated interior of the bottle is likely to contaminate the enclosed water it is advisable to coat the inside of the bottles with ceresin which CLARKE and JAMES (1938) used when measuring the absorption of light by sea water. The covering power of ceresin was checked by us in the following way. An iron vessel with fresh rust was lined with ceresin. The transmission of double-distilled water to blue light did not show any measurable change after the water had been shaken in the vessel. Not only the metal parts, including the central spring, but also the rubber packings were lined but without preventing the lids to close properly. Although the central spring is stretched and slackened when the bottle is used its ceresin coating did not show any flaws.

When the water bottle was brought on board a sample was drawn off into a small glass flask with a ground stopper. The flasks were externally cleaned with 50% alcohol and placed in the Tyndall meter where tests were run. During the measurement the flask was kept rotating round its vertical axis, in order to eliminate the influence of small optical irregularities in the glass. The rotation also served to stir up big particles from the bottom. The water chamber was frequently refilled with clear deep-sea water.

The intensity of the Tyndall beam was determined in the blue and in the red, sometimes also in the green, three times for each colour.

Tyndall unit

It is worth while to ascertain whether the intensity of the Tyndall beam in an 45° direction, represented by the Tyndall reading, could be expressed in a known unit such as a scattering coefficient. The extinction of a beam of light by sea water is the sum of absorption and scattering. For the ocean the scattering coefficient attains only low values, and so, it is proportional to the amount of light lost by scattering. The problem of scattering by particles suspended in water has been treated for instance by BLUMER (1926) and by LE GRAND (1939) under the assumption that the particles are spherical and transparent. However, the ocean contains particles of different kinds, and it is therefore necessary to determine by experiment the ratio of the total scattering coefficient S and the Tyndall reading A.

Table 1. Ratio of total scattering coefficient S to Tyndall reading A for blue light (470 mμ)

Station	S/A
29	0.00046
46	54
108	62
111	51
123	50
338	50
371	53
Mean value	0.00052

Table 1 is prepared to show this ratio S/A for blue light and for different stations. The readings A are as determined with the low-scattering comparison glass. The values of S were derived through comparison between daylight measurements and transparency measurements (JERLOV, 1951).

In view of the accuracy attainable in determinations of S the variations found in S/A are unimportant and may be disregarded; the ratio may be considered as a constant = 0.00052. In the total scattering S, the scattering produced by the water itself (0.003 m^{-1} at 470 mμ) is also included. Hence the scattering caused by particles only, s, conveniently expressed in km^{-1}, is found by the formula:

$$s = 0.52\ A - 3$$

In the ocean the scattering by particles predominates over the absorption by particles and dissolved substance. Thus the Tyndall effect could be given almost as well as an extinction coefficient as KALLE (1939) has done.

The Tyndall effect produced by ocean particles was found to be only slightly dependent on the wave-length of the light. This indicates that the size of the suspended particles in general exceeds 3 μ. Thus, the derived scattering values give an approximate measure of the total particle surface (DALLA VALLE, 1948). The relation between scattering and mass per unit-volume is dependent on particle size. In nutrient-rich water the plankton is on an average of larger size than in less fertile areas. Therefore, for a given scattering the mass is higher in the former than in the latter case.

Table 2. Scattering values s for two samples taken in different flasks from the same water bottle

Depth m	s
145	68 60
185	55 57
344	56 56
440	55 55
538	50 54
728	50 53

Discussion of the method

Some experiments were devised to check the accuracy of the method and to delineate the necessary precautions.

From the same water bottle two samples were taken in different flasks. A comparison between the two s-values for various levels in Table 2 shows the normal uncertainty in the determination of s. Table 3 gives the results obtained from different ways of filling

Table 3. Different ways of filling the flask from the water bottle

Technique used	s
Rubber tube at the tap, the first water of the bottle	33
Rubber tube at the tap, the last water of the bottle	35
Flask close to the tap	31
Some distance between flask and tap....	30

Table 4. Influence of air dust on the samples

Treatment	s	
	before	after
Sample shaken with an air bubble from the laboratory	41	54
Sample shaken with an air bubble from the deck.....	41	44
Sample left open for three minuter in the laboratory...	27	42
Sample left open for three minutes on the deck.......	24	31

Table 5. Average decrease with the time of scattering s in a sample

Hours	*s*				
0	25	50	75	100	125
2	25	49	73	96	116
4	24	48	69	89	106
6	23	44	63	80	94
8	21	40	56	70	78
10	21	39	52	63	67
12	21	39	51	59	61

the flasks from the water bottle. In this case the bottle contained water from 2 500 m. In routine work the filling was made with the flask near the tap.

To demonstrate how easily the samples may be contaminated (Table 4), an air bubble was put into the flask which was shaken afterwards. The pure air taken from the deck did not affect the sample in a measurable degree, but the laboratory air, being full of dust, spoiled the sample. Likewise if the flask was left open for three minutes the sample receives enough dust to raise the *s*-value appreciably. The clarity of deep-sea samples is illustrated by the low *s*-value of 20 frequently found, whereas distilled water in the laboratory gave $s = 60$.

The change with time of the particle content in the sample remains to be considered. In some cases a sample was studied immediately and a control sample of the same water was left standing during 12 hours without exposure to light before the measurement. The change in *s* was from 39 to 41 (mean of three samples), *i.e.* negligible. But, if water is left in the water bottle for a day the particle content will decrease considerably because particles settle. A similar decrease occurs in a sample for which tests are run repeatedly. Table 5 based on observations made in the Indonesia seas contains the average decrease with time of different *s*-values. The reduction is only slight for clear water but grows to as much as 50 % for turbid samples. This decrease is caused by particles becoming disintegrated, associating with each other, or adhering to the walls and to the bottom of the flask, so that even a rapid rotation does not bring them into suspension. Apparently the effect in question is accelerated by irradiation.

As a precaution it is advisable to make measurements as soon as possible after the sample is taken.

A possible objection to the method concerns contaminations from the wire which is in close proximity to the water bottle. There is no reason to believe that the wire could supply the water sampled with an additional amount of particles. Loose particles at the wire, not being washed away when the wire runs through the water with a speed of three meters per second, are not likely to become detached at rest. During the hydrographical work the wire was rusty during long periods but among the numerous samples taken only a few were found to contain red or brown particles indicated by a higher scattering of red than of blue light. However, in these cases it is much more probable that the coloured particles are inherent in the water, *i.e* are plankton or *detritus*.

When the wire had been oiled, scattering values found before and afterwards did not differ appreciably.

Results

As has already been stated the Tyndall measurements reveal a fine-stratification in particle distribution in the interesting layers quite close to the ocean floor (JERLOV, 1950). A cloud of particles was repeatedly observed some tens of meters above the bottom, whereas the water below that level was very transparent. An explanation would be that currents are carrying sediment particles from ridges on adjacent parts of the ocean floor, which implies an influence on sedimentation from local topography.

Also in higher levels, layers rich in suspended matter were frequently encountered

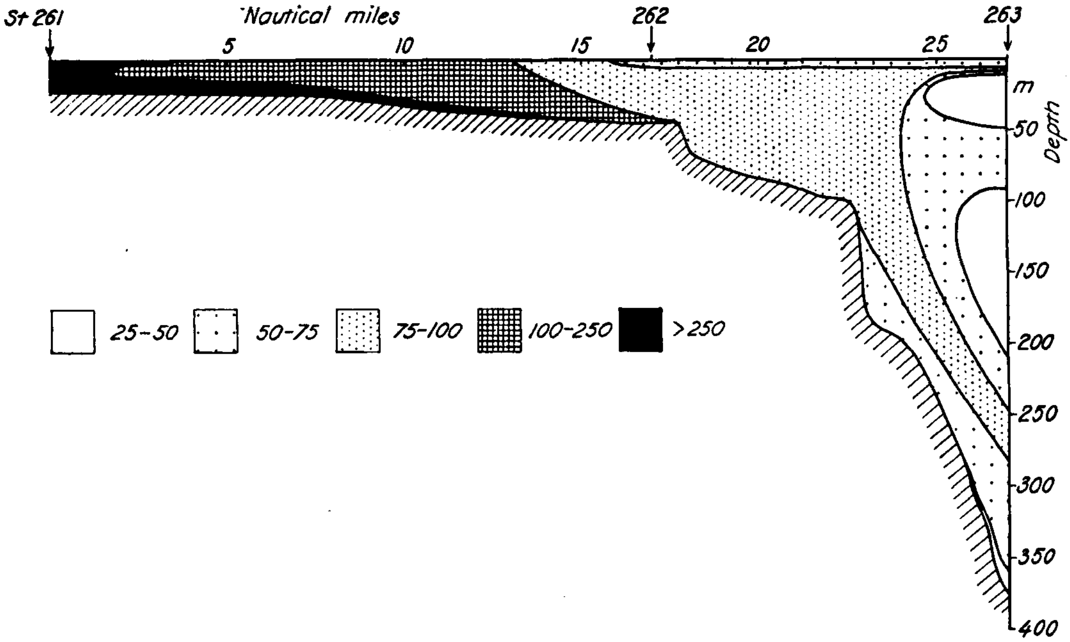

Fig. 2. Particle distribution in a vertical section off the Nile estuary.

(compare KALLE, 1939) for which a similar explanation may be valid. A typical illustration of particles characterizing the water is given for the Romanche Deep in the Atlantic (JERLOV, 1950). Here the inflow of the Antarctic Bottom Water at 4,000 m could be detected by a strong decrease in the content of particles.

It is not the aim of this paper to give a full report of the results from the expedition but only to demonstrate in some cases how the method is employed. The complete paper will appear in Reports of the Swedish Deep Sea Expedition, III.

As an illustration a vertical section of particle distribution off the Nile estuary near Port Said is shown in fig. 2. The positions of the stations are given in Table VI. Only three stations, 261—263, fall within this section but another, more easterly, section (not shown here) supports the main features of distribution in the shallow water.

Judging from observations of temperature and salinity the salt Mediterranean water is mixed with the Nile water, and no stratification is found. The temperature shows a slight decrease with increase of depth. The salinity ($\sim$ 38,9 ‰) also seems to be a little higher at the surface but the deviation is nearly within the limits of accuracy of the observations. On the other hand, conditions at Station 263 are typical for the eastern Meditarranean, the intermediate water exhibiting at 150 m a salinity maximum of 39,13 ‰ (SVERDRUP, JOHNSON and FLEMING, 1946).

From fig. 2 it is seen that the large amount of sediment carried by the Nile flocculates and settles rapidly. Thus, already some tens of miles from the coast the water is practically free from particles from the river. It must, however, be born in mind that sediment is also transported away by the prevailing current which is directed to the east.

Table 6. Stations

Area	Station number	Latitude	Longitude
Nile estuary	261	N 31° 25′	E 32° 25′
	262	31° 41′	32° 30′
	263	31° 51′	32° 34′
Strait of Gibraltar	306	N 36° 02′	W 02° 59′
	307	35° 52′	05° 54′
	308	35° 45′	06° 50′
	309	34° 56′	07° 44′

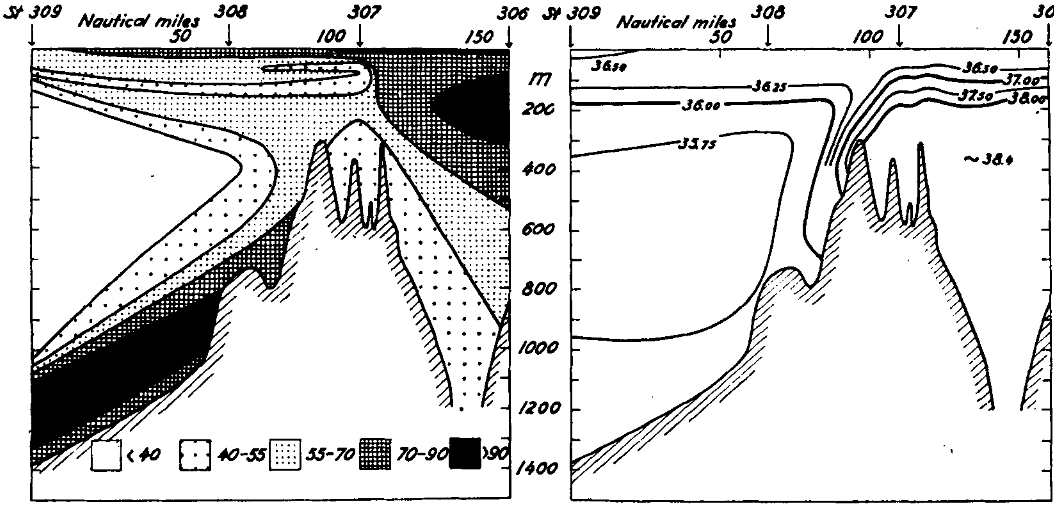

Fig. 3. Distribution of particles and salinity in a vertical section through the Strait of Gibraltar.

The slope of the bottom characterized by ledges becomes very steep towards Station 263. Here the turbid water is free from the bottom and is present as a tongue at 250 m, whereas the water close to the bottom is clear. The content of particles in the surface water is already normal, and the very clear Mediterranean water is found at 25 m and at 100—200 m.

Another section shows the particle distribution in the Strait of Gibraltar (fig. 3). It is based on observations made on 12 June 1948 (Stations 306,307, and 308) and during the morning of the 13th (Station 309). Positions of the stations are given in Table 6.

Isohalines derived for the momentary hydrographical situation are presented in fig. 3. The well-known, main feature in the exchange of water through the Strait is the sinking of the salt Mediterranean water across the ridges and down the shelf and its replacement through inflow of Atlantic water in the upper layers. According to RAMALHO and DENTINHO (1931), the salt water does not, however, spread so far to the south as Station 309. Further details about the water exchange through the Strait have been given by SCHOTT (1928) who states that the average rate of inflow is of medium strength in spring.

The superimposed tidal currents do not play any important rôle at Stations 306 and 308; it may be mentioned that these observations were carried out at low tide. But Station 307 was occupied three hours after low tide and there was in the whole water column a west-moving current which was weak in the upper layers but grew in strength below 200 m. This is consistent with the salinity distribution as isohalines for Station 307 are at higher levels than in the normal situation.

As regards the particle distribution in the Strait, the following features are noticed. The Mediterranean water at Station 306 is characterized by an abundance of particles not only at the surface but also round 200 m. On the Atlantic side the water is fairly poor in particles except the layers near the bottom which contain large amounts. There is no obvious connection of very turbid water between these two large concentrations of particles on each side of the sill; no level at Station 307 attains an *s*-value of 70. Possibly the observations may have missed a cloud of particles at some intermediate depth but the intensive mixing in the Strait evidently favours a more homogenous distribution.

Summing up, it may be said that the exchange mechanism in the Strait of Gibraltar carries particles with the Mediterranean water across the sill to the bottom layers at the Atlantic shelf, in particular when the tidal currents are favourable for a strong depth current being developed. But the trend of the 36 ‰ isohaline indicates that to some degree a downward transport of Atlantic particles also takes place.

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