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Particle-size distributions in the Baltic

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ABSTRACT

Over 160 particle-size distributions were measured with the use of a Coulter Counter in the particle diameter D range of 2 to 32 μm in the Baltic waters in different seasons during 1975–78. The particle-size distributions were found to be fairly well described by the following sum of Gaussian and hyperbolic functions:

$$\alpha \exp|-\gamma(D - D_0)^2| + \begin{cases} k_1 D^{-m_1} & 2\,\mu\text{m} \leqslant D \leqslant D_b \\ k_2 D^{-m_2} & D_b < D \leqslant 32\,\mu\text{m}, \end{cases}$$

where α, γ, D_0, k_1, m_1, m_2 and D_b are coefficients of fit and $K_2 = k_1 D_b^{m_1+m_2}$. The Gaussian term was found to be related to phytoplankton and present when phytoplankton was at sufficient concentration. The hyperbolic term, always present, appears to be related to particles formed by non-biological processes. The average values of the parameters were found to be: $\alpha = \sim 800$ cm^{-3} μm^{-1}, $\gamma = \sim 0.7$ μm^{-2}, $D_0 = \sim 6$ μm for June samples, while $k = 10^5$ (0.99×10^5) cm^{-3} μm^{-1}, $m_1 = 3.2$ (0.5), $m_2 = 5$ (0.6) and $D_b = 7.5$ (1.8) μm for the whole open Baltic data set, with one standard deviation in parentheses.

The particle-size distribution was found to vary greatly in the Baltic, depending on season, depth and location. The greatest variations were encountered in the layer extending from the surface to the seasonal thermocline located at about 20–30 m in summer. The concentrations of all particles counted (with diameters >2 μm) in this layer was found to vary between 2000 and 35,000 particles/cm^3, corresponding to late winter and late summer, respectively. The layer extending between the thermocline and permanent Baltic halocline (60–70 m) was found to be the clearest water mass in the Baltic throughout entire year, with minimum concentrations of all particles counted as low as 1000–1500 particles/cm^3. Below the halocline, the concentration of suspended particles was found to rise steeply with depth down to $\sim$10 m above bottom not exceeding, however, $\sim\frac{1}{4}$ of the maximum surface value.

The major part of the variability of the particle-size distribution was found to be related to variations in particle concentration. The shape of the non-biological particle-size distribution function was found to be fairly stable and similar to that of other seas and oceans.

1. Introduction

Particles suspended in sea water play an essential rôle in many natural processes that occur in the sea. Important examples are: the scattering and absorption of light by sea water, the exchange of substances between solid and liquid phases in sea water, the transport of substances in the sea and to the seabed and also a vast group of biological processes.

The extent to which suspended particles influence these processes depends strongly on their size distribution, i.e. a function that relates concentration of particles to their size. A few data on the size distribution of suspended marine particles were obtained with the use of laborious optical microscopic techniques (Jerlov, 1955; Ochakovsky, 1966; Gordon, 1970). Application of electronic particle counters of the Coulter type resulted in a broadened collection of data on the particle size distribution for oceanic waters (Carder et al., 1971; Sheldon et al., 1972; Brown and Gordon, 1974; Kitchen et al., 1975; Kitchen, 1977) and deep seas (Brun-Cottan, 1971). Only a few

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data, however, are available for the Baltic Sea (Jonasz and Zalewski, 1978; Reuter, 1980), which is an area of considerable seasonal and spatial variability of environmental factors.

The aim of this paper is to characterize the particle-size distributions in the Baltic and to outline their spatial and temporal variability. The data discussed here were collected by the author and Dr. M. S. Zalewski during the years 1975–78 during international oceanographic expeditions on board the research vessels: "Prof. A. Penck" of the Academy of Sciences of the GDR (Gohs et al., 1978) and "Ayu-Dag" of the Academy of Sciences of Estonian SSR. The measurements were made at locations shown in Fig. 1.

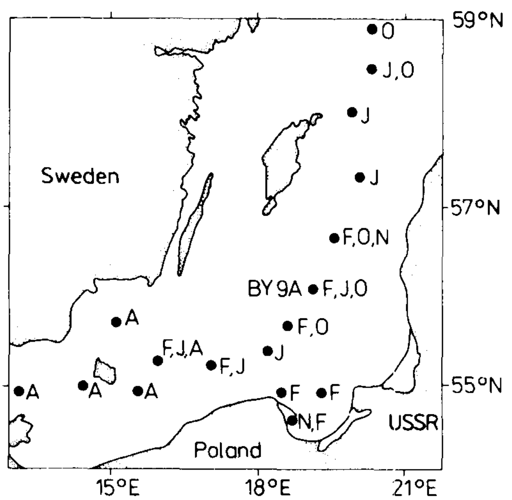

Fig. 1. The measuring sites of the particle-size distribution in the Baltic. Capital letters denote the period of sampling as follows: N—Nov./Dec. 1975, F—Feb./March 1976, J—June 1977, A—Aug. 1977, O—Oct. 1978.

2. The definition of particle size and the size distribution of suspended particles

Quantitative characterization of particles suspended in sea water requires the definition of the size of these irregularly shaped particles. The solution of this problem is most often forced by the measurement technique employed. This is also the case here, where the so-called spherical diameter of a particle, i.e. the diameter D of a sphere having a volume equal to that of the particle, is used to characterize the size of the particle. This definition is a consequence of the Coulter Counter's sensitivity to the volume of a particle (e.g., Sheldon and Parsons, 1967).

The particle size distribution FD(D) is defined by the following equation

$$dN = \mathrm{FD}(D)dD, \tag{1}$$

where dN is the number of particles per unit volume of sea water with diameters D in the range of $(D, D + dD)$. The particle-size distribution will be referred to as PSD for brevity in the following discussion.

Due to passage to the limit in the definition (1), one can determine FD(D) only by differentiation of the cumulative distribution, CD(D), of particle diameters defined by the equation

$$\mathrm{CD}(D) = \int_D^\infty \mathrm{F}D(D')\, dD'. \tag{2}$$

It follows from (2) that CD(D) is simply the number of particles per unit volume of sea water having diameter greater than D, and can thus be readily determined by counting such particles.

3. Method of measurement of particle-size distribution

Sea water was usually sampled using remotely controlled PTE samplers of the van Dorn type. Some samples were taken with a pump (Oceanic Inc.). No significant differences were found between samples taken with a pump and a regular sampler. The measurements were completed within at most 4 h after collection of the samples. They were gently and thoroughly mixed prior to measurement. In order to minimize changes taking place during storage, large quantities of sea water (~10 l) were sampled.

A Coulter Counter model ZBI with 100 μm orifice was used to measure CD(D) for about 20 values of D in the range of 2 to 32 μm. The upper limit of the range was sometimes lowered in order to keep counts at a level not smaller than ~1 particle/cm^3. Standard procedure was followed (Sheldon and Parsons, 1967; Jonasz, 1980).

Two main sources of error of measurement of CD(D) are: (1) spatial inhomogeneity of distribution of particles in a processed volume of sea water, and (2) calibration errors. Errors due to both sources are of the same order of magnitude ($\sim 1\%$) at the lower end of the diameter range, but at the upper end, the error due to (1) is about 2 orders of magnitude greater and reaches $\sim 300\%$ in a single count for a typical PSD in the Baltic (Jonasz, 1982). Consequently, only errors due to the source (1) were considered. They are determined from eq. (3):

$$\sigma[\mathrm{CD}(D)] = \left[\frac{\mathrm{CD}(D)}{n_c v_s}\right]^{1/2}, \tag{3}$$

where n_c is the number of countings and v_s is Coulter Counter sample volume. This relationship follows from the fact that a random spatial distribution of particles in the sample volume obeys Poisson's law. It agrees well with our experimental data.

For a given particle volume, the Coulter Counter response can vary up to $\sim 30\%$ due to the effect of particle shape (Golibersuch, 1973) and up to $\sim 80\%$ due to the effect of the way the particle crosses the orifice (Kachel et al., 1970). This introduces an additional random error but its actual effect on the PSDs measured is difficult to estimate for particles analysed.

The reduction of counts by the coincidence of particles within the sensing zone of Coulter Counter is not considered to be an error because its effect can successfully be removed using a suitable correction (e.g. Sheldon and Parsons, 1967).

The following procedure was used to convert CD(D_i) into FD(D_i), $i = 1 \ldots n$. For $i = 1$ to $n - 2$, three values of CD(D) at $D = D_i, D_{i+1}, D_{i+2}$ were used to compute FD(D) at $D = D_{i+1}$. If the relative error of CD(D) at D_{i+1} was smaller than 0.1, then the Lagrange interpolation polynomial (e.g. Ralston, 1965) for $\ln \mathrm{CD} = f(\ln D)$ was built at the three points D_i, D_{i+1}, D_{i+2}, the value of its derivative at $D = D_{i+1}$, multiplied by $-\mathrm{CD}(D_{i+1})/D_{i+1}$, was assigned to FD($D_{i+1}$), and its value at $D = D_1$, multiplied by $-\mathrm{CD}(D_1)/D_1$, to FD(D_1). Otherwise, the least squares approximation to CD(D) by the function kD^{-m} was constructed at the points D_i, D_{i+1}, D_{i+2}, the value of its derivative at $D = D_{i+1}$ was assigned to FD(D_{i+1}), and its value at $D = D_n$ to FD(D_n).

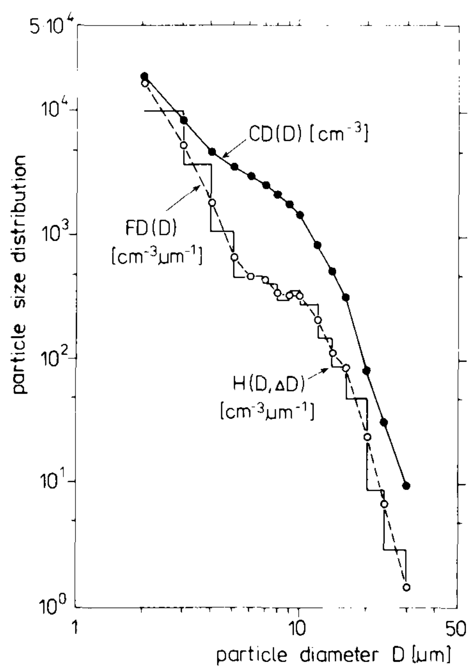

Fig. 2. Various manners of presentation of the particle-size distribution. The particle-size distribution typical for a spring phytoplankton bloom in the surface waters of the southern Baltic is used as an example. Experimental values are shown as full circles.

Comparison of FD(D) computed in this manner with the histogram $H(D, \Delta D)$ (Fig. 2) validates the use of this differentiation procedure. The histogram, defined as follows,

$$H(D, \Delta D) = \left|\frac{\mathrm{CD}(D + \Delta D) - \mathrm{CD}(D)}{\Delta D}\right|, \tag{4}$$

is simply a set of average values of FD(D) in each diameter increment ΔD. This makes obvious its use as a test of the quality of the CD(D) differentiation procedure.

4. Comparison of methods of parametrization of the particle-size distribution

Given a set of values of FD(D) measured at D_i, $i = 1 \ldots n$ with n large enough to describe FD(D) sufficiently accurately, it is hard to relate them to other properties of marine particles or sea water. It is therefore necessary to replace this set with a more compact set of parameters of an appropriate function that approximates the actual FD(D)

equally well. This replacement is called the parametrization.

4.1. *Parametrization by a sum of hyperbolic and Gaussian functions*

The best known method to parametrize the PSD of suspended marine particles is that using a hyperbolic function kD^{-m}, where k and m are parameters of the best fit (Bader, 1970). This law was also found valid for the majority of Baltic PSDs (Jonasz and Zalewski, 1976; Zalewski, 1977) but in a slightly more complicated form (Fig. 3a):

$$\mathrm{FD}(D) = \begin{cases} k_1 D^{-m_1} & 2\,\mu\mathrm{m} \leqslant D \leqslant D_b \\ k_2 D^{-m_2} & D_b < D \leqslant 32\,\mu\mathrm{m}, \end{cases} \quad (5)$$

where k_1, m_1, m_2, D_b are parameters of the best fit and

$$k_2 = k_1 D_b^{-m_1+m_2}. \quad (6)$$

Parameters m_1 and m_2 were found to satisfy the following relation

$m_1 < m_2$.

The average values of m_1, m_2 and k_1, D_b for the open Baltic are 3.2 (0.5), 5 (0.6) and 10^5 (0.99×10^5) $\mathrm{cm^{-3}\,\mu m^{-1}}$, 7.5 (1.8) μm respectively, with one standard deviation in parentheses.

Those PSDs which could not be approximated using the function (5) were found to be fairly well described by the following sum of that function and a Gaussian function (Jonasz, 1980) (Fig. 3b, Table 1):

$$\mathrm{FD}(D) = \alpha \exp\left[-\gamma(D - D_0)^2\right] + \begin{cases} k_1 D^{-m_1} & 2\,\mu\mathrm{m} \leqslant D \leqslant D_b \\ k_2 D^{-m_2} & D_b < D \leqslant 32\,\mu\mathrm{m}, \end{cases} \quad (7)$$

where α, γ, D_0 and k_1, m_1, m_2 and D_b are parameters of the best fit and k_2 is given by (6). The

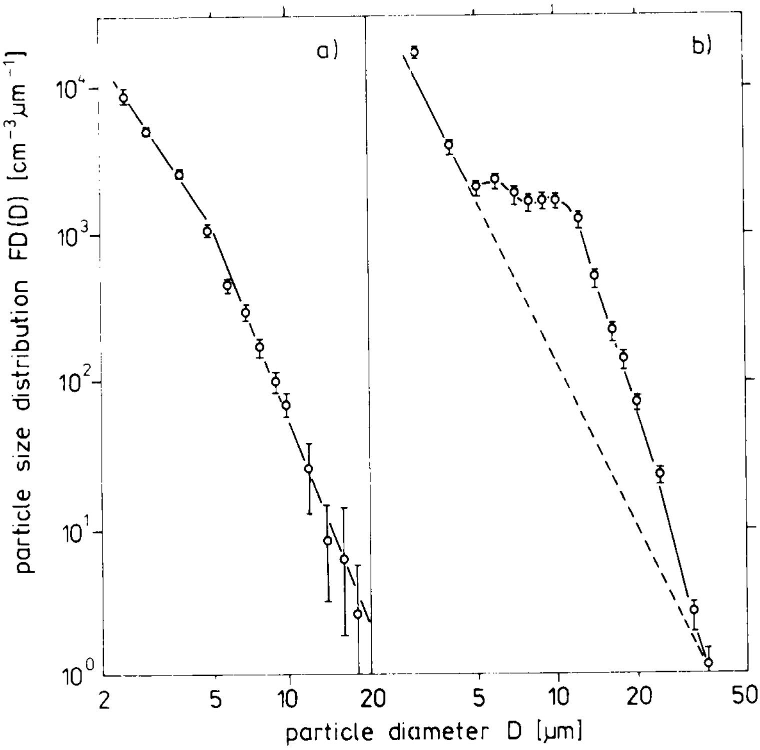

Fig. 3. Particle-size distributions in the open Baltic typical for a season of low (a) and high (b) biological activity as parametrized by the hyperbolic function ($k_1 = 1.2 \times 10^5\ \mathrm{cm^{-3}\,\mu m^{-1}}$, $m_1 = 2.9$, $m_2 = 4.7$ and $D_b = 5.4\ \mu$m) and a sum of Gaussian (Fig. 4) and hyperbolic ($k = 8.6 \times 10^5\ \mathrm{cm^{-3}\,\mu m^{-1}}$, $m = 3.8$) functions, respectively. Measurement errors are shown as vertical bars.

Table 1. *Accuracy of approximation of the particle-size distribution for parametrization methods employed, indicated by the relative square error, ε, of approximation (in %)*

$$\varepsilon = \frac{\sum_{i=1}^{n} [\mathrm{FD}(D_i) - \mathrm{FD}_a(D_i)]^2}{\sum_{i=1}^{n} [\mathrm{FD}(D_i)]^2},$$

where FD is the particle-size distribution measured at n points D_i, $i = 1 \ldots n$ and FD_a is its approximation calculated at the same points

		Relative error ε of approximation of FD(D) by				
			Characteristic vectors			
Area	Number of data	Gauss + kD^{-m}	ψ_1	ψ_1, ψ_2	ψ_1, ψ_2, ψ_3	Average PSD
Open Baltic	102	0.60	2.53	1.13	0.37	1.86
Coastal Baltic (Gdansk Bay)	67	0.27	0.72	0.08	0.01	0.72

Gaussian term in (7) can itself be a sum of 2–3 Gaussian functions (Fig. 4).

A smaller number of such data (~10 PSDs from June 1976) makes it only possible to give rough estimates of the parameters of the Gaussian term. These are ~800 $\mathrm{cm^{-3}\ \mu m^{-1}}$, ~0.7 $\mu\mathrm{m}^{-2}$ and ~6 μm for α, γ and D_0, respectively. When the Gaussian term was composed of a number of Gaussian functions, parameters of the major function only were included.

The method of parametrization of the PSD, applying function (7), has also been found useful for several PSDs measured by the author in the surface waters of the equatorial Atlantic, which showed a distinct peak at about $D = 16\ \mu$m. This suggests that the function (7) provides quite a general description of PSD in the ocean.

Simultaneous measurements of the PSD in samples originating in the spring and autumn phytoplankton bloom in the south Baltic made with the use of a Coulter Counter and an optical microscope have revealed that the Gaussian component of PSD can be related to phytoplankton populations (Fig. 4).

Deviations of the size distribution of particles suspended in sea water from that described by the hyperbolic function (5) were also reported and related to marine plankton by Parsons (1969) and Sheldon et al. (1972). It should, however, be stressed that the appearance of such peaks in a PSD is not a sufficient condition for a statement of the presence of phytoplankton in the sample, as other particles (e.g. pollen) have similarly peaked PSDs. An additional proof by microscopic analysis is therefore necessary.

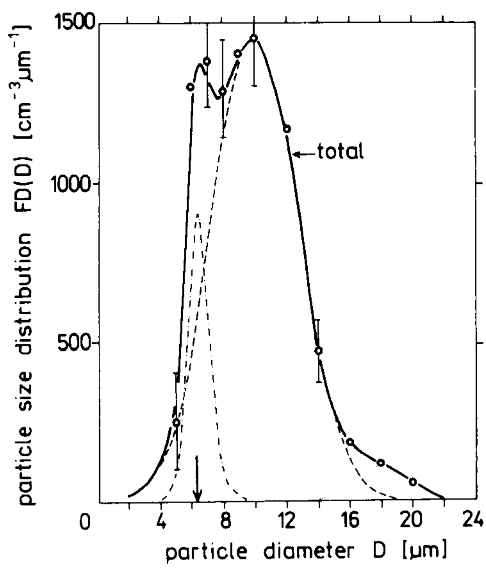

Fig. 4. The Gaussian part of the particle-size distribution shown in Fig. 3b ("total") and its three components (dotted lines). It is related to the chain-forming phytoplankton species Chaetoceros with 6.3 μm single-cell average spherical diameter (arrow) from optical microscope measurements. Parameters of the major component are: $\alpha = 1460\ \mathrm{cm^{-3}\ \mu m^{-1}}$, $\gamma = 0.07\ \mu\mathrm{m}^{-2}$ and $D_0 = 10\ \mu$m. The latter is the spherical diameter of a four-cell chain.

The PSD in the measured range of particle diameter assumes its most pure hyperbolic shape in waters where minerals and non-living organic particles are likely to dominate. Free-living marine bacteria, which apart from phytoplankton constitute another set of biological particles, have equivalent spherical diameters below 1 μm (Azam and Hodson, 1977; Larsson and Hagstrom, 1982). This makes their major influence on the PSD for diameters greater than 2 μm unlikely. A hyperbolic function would therefore appear to describe the PSD of non-biological particles.

4.2. *Parametrization by characteristic vectors*

The methods of parametrization of the PSD using eq. (5) or (7) are closely related to physical (Hunt, 1980) and biological processes underlying the formation of particles in sea water. The following method of characteristic vectors (Kitchen et al., 1975; Jonasz, 1975; Jonasz and Zalewski, 1976) presents a purely statistical approach to the problem. In contrast to the previous method, this requires that prior to any single PSD parametrization, a fairly large number of PSDs have to be measured.

Each PSD is then considered as an n-dimensional vector with components $\mathrm{FD}(D_i)$, $i = 1 \ldots n$. The covariance matrix $S_{n \times n}$ of the set of N measured PSDs is then evaluated with its characteristic vectors $\psi(D_i)$, $i = 1 \ldots n$, which are determined by eq. (8)

$$S\psi = \lambda\psi, \tag{8}$$

where λ is a root of the matrix S corresponding to a characteristic vector ψ (e.g. Anderson, 1958). It can be proved that each vector FD from the set can, on average, be most accurately approximated by the sum

$$\mathrm{FD}(D_i) = \mathrm{FD}(D_i)_{\mathrm{av}} + \sum_{l=1}^{r} c_l\, \psi_l(D_i), \quad i = 1 \ldots n, \tag{9}$$

where $\mathrm{FD}(D_i)_{\mathrm{av}}$, $i = 1 \ldots n$ is the average vector for the considered set, c_l, $l = 1 \ldots r$ are parameters of the best fit for $r < n$.

That part of the variability of FD(D) due to each parameter c_l is determined by the lth root of the matrix S. The analysis of a sequence of these roots for the open Baltic (Table 2) clearly shows that the first few characteristic vectors already account for almost all the variability of FD(D) represented by

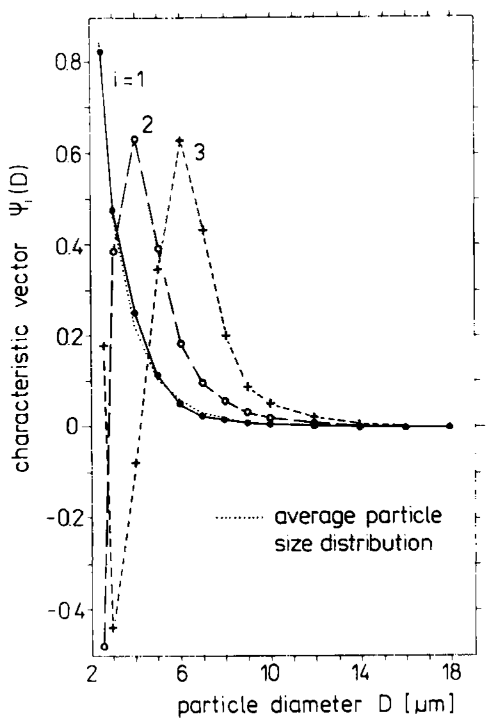

Fig. 5. The first three characteristic vectors ψ of the covariance matrix and the average particle-size distribution, all normalized to unit length, for 102 open Baltic particle-size distributions.

Table 2. *The sequence of several first roots λ of a covariance matrix of 102 particle-size distributions from the open Baltic; the sum of all roots is equal to 2.98×10^7*

i	1	2	3	4	5
λ_i	2.91×10^7	5.08×10^5	9.26×10^4	4.89×10^4	1.31×10^4

the total variance of FD(D) which is equal to the sum

$$\sum_{i=1}^{n} \lambda_i.$$

Therefore, only these ψs should be retained in the sum in (9), greatly reducing the number of parameters, with only a small loss of average reproducibility of actual PSDs. In fact, it is sufficient to take only the first three characteristic vectors (Fig. 5) to obtain an excellent approximation (Fig. 6a, Table 1), and in many cases, ψ_1 is quite enough. This, however, holds only in a statistical sense, which means that significant deviations of the approximated FD(D) from the actual one can be expected in individual cases (Fig. 6b).

As this method is purely statistical and applicable to any empirical set of vectors, it is hard to establish clear relationships between the parameters c_i and parameters of any deterministic physical model of particle formation or physical process involving suspended particles.

4.3. *Parametrization by the average PSD*

In the first approximation, the number of characteristic vectors necessary to describe a PSD using eq. (9) reduces to one, ψ_1. In fact, it accounts itself for ~97% of the total variance of the PSD in the open Baltic (Table 2). As it does not differ significantly from the average FD(D) for the area (Fig. 5), the following crude but simple and quite accurate (Table 1) parametrization is possible (Jonasz and Zalewski, 1978)

$$\mathrm{FD}(D) = a\,\mathrm{FD}(D)_{\mathrm{av}}, \tag{10}$$

where a is a parameter of the best fit and $\mathrm{FD}(D)_{\mathrm{av}}$ is the average PSD for the area of interest.

As the parameter a is approximately equal to 1 + $c_1 f$, where f is a constant adjusting ψ_1 to the FD scale, it is clear that c_1 controls the concentration of suspended particles primarily, while $c_2, c_3 \ldots$ control the shape of the PSD function. Thus the relation between the values of successive roots λ of the covariance matrix S clearly shows that in the first approximation, the variability of the PSD in the open Baltic is due to variations in the con-

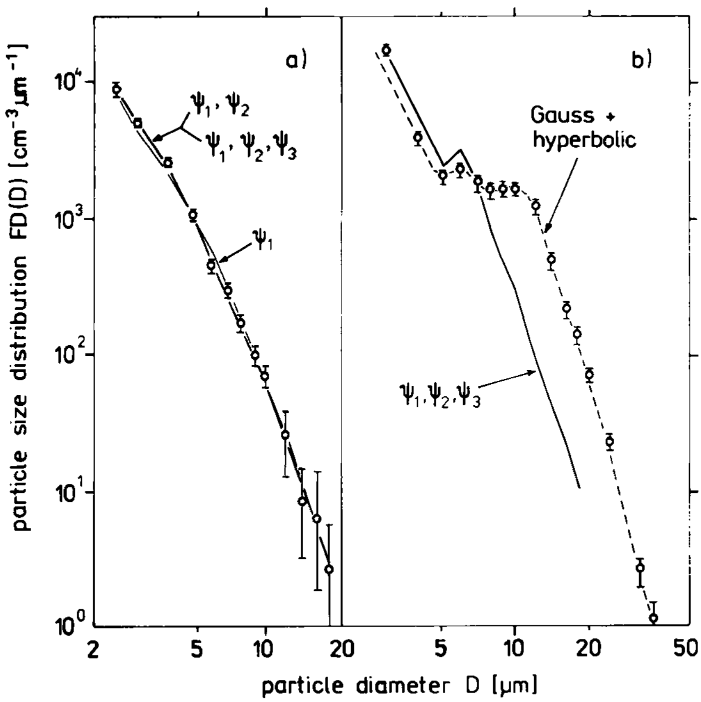

Fig. 6. The particle-size distributions (Fig. 3) parametrized by characteristic vectors ψ (Fig. 5). The ψs used are indicated by the curves.

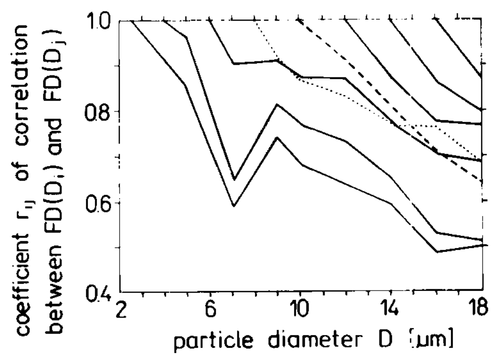

Fig. 7. Upper triangular part of the correlation matrix $|r_{ij}|$ of 102 particle-size distributions from the open Baltic (depth 0 to 200 m). Each curve shows the correlation between FD(D_i) and FD(D_j) for 2 μm $\leqslant D_i \leqslant D_j \leqslant$ 18 μm. Various line types are used to distinguish different curves.

centration of suspended particles. This is also supported by the form of the correlation matrix $|r_{ij}|$ of the PSD for the area (Fig. 7).

4.4. *Other methods of parametrization of the PSD in sea water*

The author has tested the gamma function

$$\mathrm{FD}(D) = a\, D^b \exp(-cD), \tag{11}$$

where *a*, *b* and *c* are parameters of the best fit, as an approximation of the PSD in the Baltic and other areas, but the average accuracy of approximation was lower than that of the other methods by about an order of magnitude, though in some cases, the function (11) has fitted the PSD excellently.

To complete this short presentation of the methods of parametrization of the PSD in the Baltic, those using the Weibull (Carder et al., 1971) and the exponential function (Zaneveld and Pak, 1973) should be noted. These methods, however, are not well suited to actually observed PSD in the Baltic as well as in other areas (Kitchen, 1977).

5. Seasonal and spatial variations of the PSD in the Baltic

The analysis of the PSD in the Baltic (Zalewski, 1977; Jonasz, 1980) has revealed its large cyclic variability in relation to annual changes in environmental factors: thermohaline stratification of water masses, primary production and runoff of particulate matter from the land.

In the open Baltic waters, horizontal variations of the PSD appear to be much weaker than vertical and seasonal variations. A number of water layers can therefore be distinguished in the area, which amounts to two in winter and three in the other seasons of the year. Winter and summer can be regarded as two turning points in the annual cycle of both PSD and its vertical profile in the open Baltic. Only these two seasons will thus be discussed here.

5.1. *Winter*

Results of measurements made during two consecutive winters (November/December 1975 and February/March 1976) suggest the division of the water column into two layers: a mixed layer extending from the surface to the permanent halocline (~60 m) and a deep layer from the halocline to the bottom (Fig. 8a).

The least variable PSD was observed in the mixed layer (Fig. 9a), characterized by uniform sea water density and particle concentration (Fig. 8a). Its standard deviation was then of the order of 0.1 of that computed for the entire open Baltic data set. Also very low particle concentrations (CD (2 μm) ~2000 cm^{-3}), especially at the end of winter, were encountered in the layer. Both these facts are thought to be a direct consequence of a winter minimum in biological activity and land runoff of particulates.

The concentration of suspended particles in the

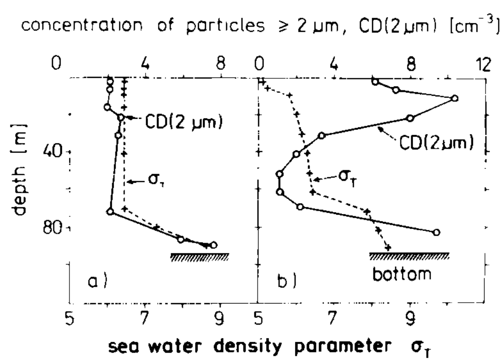

Fig. 8. Depth profiles of particle concentration and sea water density typical for winter (a—10 March 1976) and summer (b—19 June 1977) in the open Baltic (station BY 9A, Fig. 1).

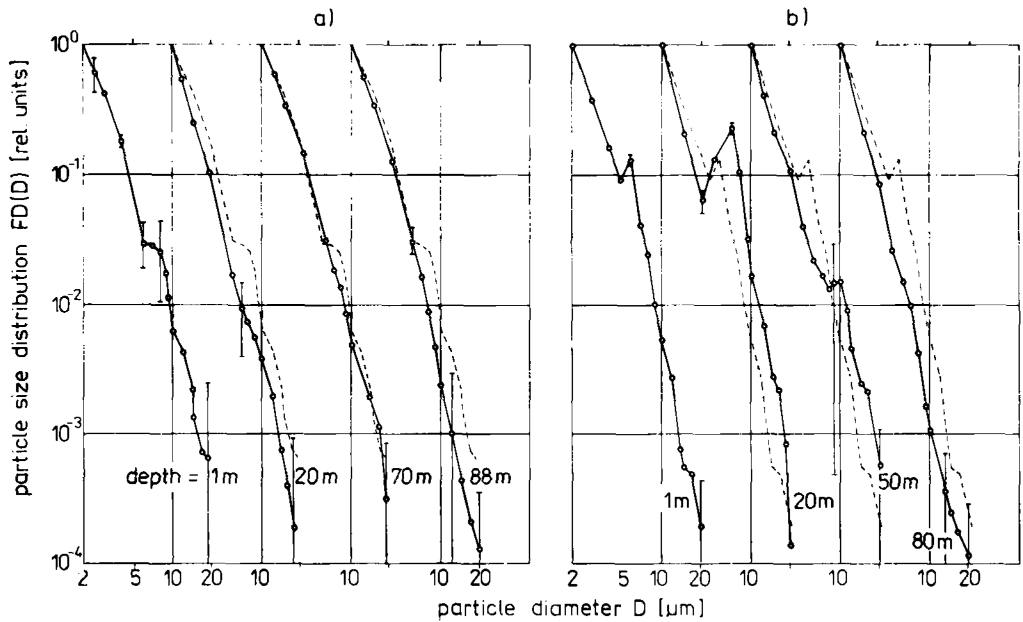

Fig. 9. The evolution of the particle-size distribution with depth in winter (a) and summer (b). The size distributions, normalized so that FD (2 μm) = 1 cm^{-3} μm^{-1}, correspond to the data presented in Fig. 8. The surface particle-size distributions are also shown with thin dotted lines at other depths for comparison.

deep layer was found to rise steeply with depth to values of CD (2 μm) of the order of 10^4 cm^{-3}, following sea water density (Fig. 8a). However, the relative concentration of larger particles ($D > 10$ μm) appears to decrease in the layer as compared to the mixed layer (Fig. 9a).

5.2. *Summer*

The situation becomes more complicated after increasing heating of the surface layer in spring results in the splitting of the winter mixed layer into two new layers: a surface layer extending from the surface to the thermocline (20–30 m in summer) and an intermediate layer, from the thermocline to the halocline. These layers are to a great extent separated by a strong density gradient at the thermocline (Fig. 8b).

Early summer measurements (June 1976) have revealed considerable stratification of the water column, also with respect to PSD (Fig. 9b), as suggested by light scattering measurements (Kullenberg, 1969; Prandke, 1978), with a strong maximum in the profile of particle concentration in the vicinity of the thermocline (Fig. 8b). The concentration of suspended particles moderately increased in early summer (CD (2 μm) $\sim 10^4$ cm^{-3}) but was as high as $\sim$15 times the winter value in late summer (August 1977, CD (2 μm) $\sim 3.5 \times 10^4$ cm^{-3}). The latter value was the upper limit of particle concentration measured by the author in the Baltic waters, except for a strictly coastal zone (Gdansk Bay) where CD (2 μm) about 1.6×10^5 cm^{-3} was recorded in the surface layer in summer. In late summer, the maximum in the vertical profile of particle concentration moved from the vicinity of the thermocline to just below the surface.

The PSD measured in June in the surface layer exhibited a considerable peak at about $D = 6$ μm (Fig. 9b). Its origin may be due to phytoplankton, although there is no direct evidence. This peak, which was not found in late summer, was responsible for a considerable decrease in correlation in the correlation matrix for PSD in the vicinity of that diameter (Fig. 7).

The intermediate layer, in contrast, became even cleaner during the periods that follow winter. This layer was found to be the most clear water mass in the Baltic with CD (2 μm) as low as 1000–1500 cm^{-3}. The PSDs measured in the layer in June were found to be quite irregular as compared to other layers, except for the summer surface layer. These irregularities were, however, substantially reduced after averaging the PSD, which suggests that they have a random nature, in contrast to the summer surface layer in June. The average slope, m, of PSD in the layer, which could be described with one hyperbolic segment in the 2 to 32 μm particle diameter range, was found to be smaller than that in other layers, amounting to 2.8 in comparison with the average slopes $m_1 = 3.2$ and $m_2 = 5$.

Neither the PSD nor its vertical profile in the deep layer in summer were found to be different from those in winter.

It is worthwhile to note that the concentration of larger particles counted ($D > 20$ μm) was found not to vary so strongly as that of all particles counted ($D > 2$ μm), appearing to stay at approximately the same level in the entire water column.

Autumn measurements (October 1978) added no new features to PSD measured in winter and summer. It should be noted that the autumn maximum in biological production in the Baltic is not reflected in the total concentration by number of particles CD (2 μm). This is because phytoplankton appearing there are much larger than the upper limit of the diameter range considered here and even during a phytoplankton bloom they are present in sea water at a concentration of the order of 1 particle/cm^3. Such a bloom may, however, be reflected in the PSD. A bloom of Coscinodiscus granii was detected that way in October 1978 in a few samples analysed with a Coulter Counter and an optical microscope.

Although the data are not complete with regard either to time or space, the image of an annual and spatial evolution of PSD in the Baltic presented here agrees with that for other particle properties: mass concentration (Gudelis and Emelianova, 1975) and light scattering (Prandke, 1978).

6. Comparison of PSD in the Baltic with other areas

The fairly stable shape of PSD in the Baltic waters invokes comparison with those reported for other areas. Pertinent data concerning the slope parameter, m, of the hyperbolic approximation (5) of PSD are shown in Fig. 10. Details concerning the data are shown in Table 3. The selection of the hyperbolic function is due both to its simplicity and its wide use throughout the literature. In the present data, where the Gaussian component of PSD was significant, only the hyperbolic component was considered. The data are therefore related to minerals and non-living organic matter, rather than to the whole population of particles.

It is clear from Fig. 10 that slopes of PSD in the Baltic waters are quite similar to those in other areas, the differences not being greater than $\frac{1}{3}$ of the values of the Baltic slopes.

The segmented nature of PSD in the diameter range 2 to 32 μm encountered in the Baltic is a common pattern. This appears to be directly related to the fact that the principal processes which take part in the formation of PSD in sea water (e.g. Brownian and shear coagulation and differential settling) exhibit their maximum effectiveness in different particle diameter ranges (Hunt, 1980).

With respect to the concentration of suspended particles, the surface Baltic waters are richer than open ocean waters in suspended particles rather than 2 μm in diameter by about one order of magnitude in warm seasons of the year. In winter, however, the concentration of particles in the mixed layer of the Baltic Sea decreases to the level characteristic for surface open ocean waters.

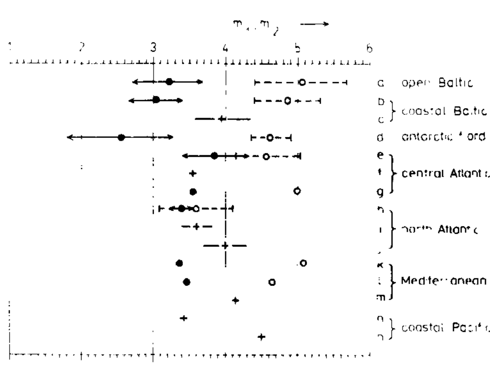

Fig. 10. Comparison of slopes, m, of the particle-size distribution in the Baltic and other areas as parametrized by the hyperbolic function kD^{-m}. Slopes m_1, m_2 are denoted by solid and open circles, respectively. A single slope of particle-size distribution approximated by one segment only is denoted by a cross. Bars denote standard deviations.

Table 3. *Details concerning the data on the slopes of particle-size distribution from Fig. 10*

Data identifier	Source	Number of data	Area	Depth [m]	Diameter range [μm] for m_1	m_2
a	Author	74	Open Baltic	0–400	2–7.5 (1.8)	7.5–32
b	as (a)	67	Coastal Baltic (Gdansk Bay)	0–50	2–7.0 (2.1)	7.0–32
c	Reuter (1980)	4	Coastal Baltic (Eckenforde)	2–25	2–10	
d	as (a)	83	Antarctic fjord (Ezcurra Inlet, King George I.)	8–80	2–3.7 (0.7)	3.7–32
e	as (a)	29	Central Atlantic	6	2–7.2 (3.0)	7.2–32
f	Brown and Gordon (1974)	average values	Bahama Islands: Tongue of the Ocean	0–>240	1.25–10	
g	Brown and Gordon (1974)	as (f)	High Cay	0–8	1.25–3.75	3.75–10
h	Sheldon's data reported by McCave (1975)	4	North Atlantic	0–200	1–4	4–20
i	as (h)	5	North Atlantic	>200	1–30	
j	Lerman et al. (1977)	53	North Atlantic	0–4000	2–12	
k	Brun-Cottan (1971)	1	Mediterranean	20	1–5	5–20
l	as (k)	1	Mediterranean	20	1–5	5–20
m	as (k)	1	Mediterranean	1600	1–20	
n	Kitchen (1977)	1	Pacific, off Oregon	no data	5–100	

7. Comparison of PSD measured with Coulter Counter with that measurd using optical methods

There is a favourable agreement between Coulter Counter and optical microscope particle sizing for spherical particles (Brun-Cottan, 1971, author's measurements of PSD of large calibration particles, $D \sim 39$ μm). Equivalent spherical diameters of cylindrical phytoplankton cells from optical microscope measurements also agree with Coulter Counter estimate (Fig. 4).

A few measurements of PSD of suspended marine particles made using an optical microscope (Jerlov, 1955; Ochakovsky, 1966; Gordon, 1970) appear, however, to give values of the slope, m, smaller than that from Coulter Counter measurements by about 1. Although the first two authors do not state the definition of the particle size employed, their results are similar to those of the third author, which suggests that the particle size was defined as the greatest dimension of a particle. In such PSDs, needle and plate-like particles having a large greatest dimension but small volume, and consequently small diameter D, will be counted in a larger size range than in a PSD obtained using a Coulter Counter. This should make the slope of such a PSD smaller in comparison with that obtained using a Coulter Counter.

Several reports on the use of light scattering to predict the PSD of suspended marine particles (e.g. Kullenberg and Olsen, 1972; Brown and Gordon, 1974; Reuter, 1980; Jonasz, 1980) give values of the slope, m, comparable to that obtained using a Coulter Counter. The latter device is in fact used to verify light scattering predictions.

8. Conclusions

The particle size distributions (PSD) measured in the Baltic waters, and also in the Atlantic can be described fairly well and easily interpreted in the particle diameter D range of 2 to 32 μm, using a sum of two terms: Gaussian and hyperbolic functions. The Gaussian term was found to be related to phytoplankton and can itself be a sum of a number of Gaussian functions. In periods and/or areas of weak biological activity, this term becomes negligible or disappears and only the second term is left. The latter can thus be related to non-living particles, i.e. those formed by physical and chemical processes.

The description of PSD by characteristic vectors was found to be even more accurate on average than the previous method. This method, however, requires accumulation of a number of PSDs prior to an analysis of an individual PSD. Also, the physical significance of the parameters involved is unclear.

The greatest variations of PSD in the diameter range 2 to 32 μm in open Baltic waters were encountered in the layer extending from the surface to the seasonal thermocline. The layer situated between the thermocline and the permanent Baltic halocline was found to be the clearest water mass in the Baltic. Below the halocline, a fast rise of particle concentration with depth was observed. However, the concentration of large particles ($D > 20$ μm) was found not to vary so strongly with depth as that of all particles counted.

The major part of the variability of the PSD in the Baltic can be attributed to variations in particle concentration. The shape of non-biological PSD remains fairly stable. It is also similar to that observed in other areas. The stability of the shape of PSD observed when non-living particles are likely to dominate, suggests that it is determined mainly by fundamental physical and chemical processes of production and removal of particles in the sea (e.g. coagulation and settling) common to all localities. Local conditions appear to affect the shape of the PSD to a lesser extent, determining rather the concentration of suspended particles.

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REFERENCES

Anderson, T. W. 1958. *An introduction to multivariate statistical analysis*, Wiley, New York.

Azam, F. and Hodson, R. E. 1977. Size distribution and activity of marine microheterotrophs. *Limnol. Oceanogr. 22*, 492–501.

Bader, H. 1970. The hyperbolic distribution of particle sizes. *J. Geophys. Res. 75*, 2822–2830.

Brown, O. B. and Gordon, H. R. 1974. Size-refractive index distribution of clear coastal water particulates from light scattering. *Appl. Opt. 13*, 2874–2882.

Brun-Cottan, J. C. 1971. Étude de la granulometrie des particules marines. Mesures effectues avec un Coulter Counter. *Cah. Oceanogr. 23*, 193–205.

Carder, K. L., Beardsley, G. F. Jr. and Pak, H. 1971. Particle size distribution in eastern equatorial Pacific. *J. Geophys. Res. 76*, 5070–5078.

Gohs, L., Dera, J., Gedziorowska D., Hapter, R., Jonasz, M., Prandke, H., Siegel, H., Schenkel, G., Olszewski, J., Wozniak, B. and Zalewski, M. S. 1978. Untersuchen zur Wechselvirkung zwischen den optischen, physikalischen, biologischen und chemischen Umweltfaktoren in der Ostsee aus den Jahren 1974, 1975 und 1976. *Geod. Geophys. Veroff. Serie 4*, no. 25.

Golibersuch, D. C. 1973. Observation of aspherical particle rotation in Poisseuille flow via the resistance pulse technique (I). Application to human erythrocytes. *Biophys. J. 13*, 265–280.

Gordon, D. C., Jr. 1970. A microscopic study of organic particles in the North Atlantic Ocean. *Deep-Sea Res. 17*, 175–185.

Gudelis, V. K. and Emelianova, E. M. (eds). 1975. *Geology of the Baltic Sea*. Acad. Sci. Latvian SSR, Riga (in Russian).

Hunt, J. 1980. Prediction of oceanic particle size distribution from coagulation and sedimentation mechanisms. In: *Advances in Chemistry Series*, no. 189.

Jerlov, N. G. 1955. The particulate matter in the sea as determined by means of the Tyndall meter. *Tellus 7*, 218–225.

Jonasz, M. 1975. A preliminary study on a method of examination of statistical relations between physical and optical properties of marine particles. Internal Report of the Institute of Oceanology, Polish Academy of Sciences, Sopot (in Polish).

Jonasz, M. and Zalewski, M. S. 1976. Studies of particle-size distribution in the Baltic waters. Proceedings of the 10th Conference of Baltic Oceanographers, Göteborg, Sweden, June 1976.

Jonasz, M. and Zalewski, M. S. 1978. Stability of the shape of particle-size distribution in the Baltic. *Tellus 30*, 569–572.

Jonasz, M. 1980. The use of light scattering for the determination of physical properties of marine particles. Ph.D. Thesis, Institute of Oceanology, Polish Academy of Sciences, Sopot (in Polish).

Jonasz, M. 1982. The conditions of correctness of the examination of particle size distribution with the use of Coulter Counter. Studia i Materialy Oceanologiczne, Committee of Sea Research, Polish Academy of Sciences (in print, in Polish).

Kachel, V., Metzger, H. and Ruhenstroth-Bauer, G. 1970. The influence of the particle way on the volume distribution according to the Coulter principle. *Z. Gesamte Exp. Med. Exp. Chir. 153*, 331–347 (in German).

Kitchen, J. C., Menzies, D., Pak, H. and Zaneveld, J. R. V. 1975. Particle-size distribution in a region of coastal upwelling analysed by characteristic vectors. *Limn. Oceanogr. 20*, 775–783.

Kitchen, J. C. 1977. Particle-size distribution and the vertical distribution of suspended matter in the upwelling region off Oregon. Oregon State Univ. Rept 77–10.

Kullenberg, G. 1969. Light scattering in the central Baltic. Københavns Univ. Inst. Phys. Oceanogr. Rept 5, Copenhagen.

Kullenberg, G. and Olsen, N. B. 1972. A comparison between observed and computed light scattering functions (II). Københavns Univ. Inst. Phys. Oceanogr. Rept 19, Copenhagen.

Larsson, U. and Hagstrom, A. 1982. Fractionated phytoplankton primary production, exudate release and bacterial production in a Baltic eutrophication gradient. *Mar. Biol 67*, 57–70.

Lerman, A., Carder, K. L. and Betzer, P. R. 1977. Elimination of fine suspensoids in the ocean water column. *Earth and Planetary Sci. Lett. 37*, 61–70.

McCave, I. N. 1975. Vertical flux of particles in the ocean. *Deep-Sea Res. 22*, 491–502.

Ochakovsky, Yu. E. 1966. On the dependence of the light attenuation coefficient on suspended marine particles in sea water. *Trudy Inst. Okeanologyi 77*, 35–40 (in Russian).

Parsons, T. R. 1969. The use of particle-size spectra in determining the structure of a plankton community. *J. Oceanogr. Soc. Japan 25*, 172–181.

Prandke, H. 1978. Seasonal variations in the vertical distribution of light-scattering properties in the central Baltic. Proceedings of the 11th Conference of Baltic Oceanographers, Rostock, 1978.

Ralston, A. 1965. *A first course in numerical analysis*. McGraw-Hill, New York.

Reuter, R. 1980. Characterization of marine particle suspensions by light scattering (II). Experimental results. *Oceanol. Acta 3*, 325–332.

Sheldon, R. W. and Parsons, T. R. 1967. *Practical manual on the use of the Coulter Counter in marine sciences*. Coulter Electronics, Toronto, 1967.

Sheldon, R. W., Prakash, A. and Sutcliffe, W. H. Jr. 1972. The size distribution of particles in the ocean. *Limnol. Oceanogr. 17*, 327–340.

Zalewski, M. S. 1977. The analysis of size distributions of particles suspended in sea water. Ph.D. thesis, Institute of Oceanology, Polish Academy of Sciences, Sopot (in Polish).

Zaneveld, J. R. V. and Pak, H. 1973. Method for determination of the index of refraction of particles suspended in the ocean. *J. Opt. Soc. Am. 63*, 321–324.