Modelling the light absorption properties of particulate matter forming organic particles suspended in sea water. Part 3. Practical applications*

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Abstract

This paper brings to a close our cycle of articles on modelling the light absorption properties of particulate organic matter (POM) in the sea. In the first two parts

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of this cycle (Woźniak et al. 2005a,b) we discussed these properties with reference to various model chemical classes and physical types of POM. We have put these results into practice in the present third part. As a result of the appropriate theoretical speculations, logically underpinned by empirical knowledge, we selected 25 morphological variants of marine organic detritus, to which we ascribed definite chemical compositions and physical types. On this basis and using known spectra of the mass-specific coefficients of light absorption by various naturally occurring organic substances (systematised in Parts 1 and 2), we determined the absorption properties of these 25 morphological groups of particles, that is, the spectra of the imaginary part of the refractive index $n'_p(\lambda)$ (in the 200–700 nm range) of the particulate matter. They can be applied, with the aid of Mie's or some other similar theory, to calculate the bulk optical properties (absorbing and scattering) of such sets of particles in the sea.

1. Introduction

In the marine environment one can expect the presence of many different types of suspended organic particles with a diversity of optical properties, including some with widely differing absorption properties. We provided ample demonstration of this in Parts 1 and 2 of this cycle of articles (Woźniak et al. 2005a,b). The different absorption properties of these particles are due to their different physical structures and chemical compositions. It turns out, however, that in spite of this huge diversity of particles suspended in the sea (suspended particulate matter – SPM), for practical purposes one can differentiate c. 5–15 groups of particles with similar properties. This applies not only to the morphological properties of these particles (external structure, size, shape and consistency), but also to their origin, chemical composition and physico-chemical state (i.e., density, relative hydration, relative content of organic matter and air or other inorganic matter). Such similarity among groups of suspended particles seems fairly obvious in regard to living particles (bacteria, phytoplankton, zooplankton), but it also applies to non-living suspended particles (organic detritus), as the results of the relevant geochemical research will testify (e.g., Riley et al. 1965, Bogdanov & Lisitsyn 1968, Gordon 1970, Riley 1970, Melnikov 1975a,b, and others). As far as we are aware, the first author to review the results of these investigations was Romankevich (1977), who produced a preliminary classification of the main morphological types of coarse- and fine-grained organic detritus found in sea and ocean waters. He also outlined some of the probable mechanisms of their formation and provided data on their internal structure, i.e., their chemical composition, physical features and typical natural concentrations.

Research on particulate organic matter (POM) has since intensified, particularly with respect to its sedimentation and in the palaeo-oceanographic context (e.g., Wassmann & Heiskanen 1988, Wassmann et al. 1991, Fischer & Wefer 1999). The following issues have been studied empirically and modelled theoretically: the provenance of different fractions of SPM (e.g., Lee & Wakeham 1991, Wakeham & Lee 1993), the occurrence and concentrations of different morphological types of particle in various basins (e.g., Heiskanen 1988, Peinert 1988, Kotwicki et al. 2005a,b), some aspects of the chemical composition of organic matter in particles (e.g., Sheridan et al. 2002, Burska et al. 2005), sedimentation fluxes and rates (e.g., Armstrong et al. 2002, Berelson 2002). Also, the optical properties of POM, including their absorption properties, have been investigated experimentally and modelled for a range of contexts. The bulk spectral coefficients of light absorption[1] by a single particle or a cluster of particles in the medium $a_p(\lambda)$ have been determined (see, e.g., Roesler et al. 1989, Iturriaga & Siegel 1989, Bricaud et al. 1998), as have the light absorption coefficients of particulate matter $a_{pm}(\lambda)$ or the associated imaginary complex refractive indices of detrital POM $n'_p(\lambda)$ (e.g., Stramski et al 2001, Stramski & Woźniak 2005).

Notwithstanding their meticulous analyses of the relevant issues, the above-mentioned studies examine various features of SPM in isolation. And although the results are extremely interesting, they refer only to separate, narrowly specific aspects of certain sets of organic particles, e.g., their morphology, their chemical composition, or their optical properties. At the present time, there is in the literature no general description of the different morphological types of detritus and their associations with the physical types and chemical classes of POM, one that would enable the absorption properties of the various groups of detritus actually occurring in sea waters to be defined unequivocally, even if only approximately. Neither has a uniform nomenclature been established for describing the many morphological types of SPM.

In view of the above arguments, our research objectives were the following:

1) to select major, morphologically coherent, groups of organic detritus occurring in the sea and to present a morphological classification of marine POM;

2) to ascribe to these morphological groups relevant subgroups of particles belonging to the different chemical classes (compositions of organic matter) and physical types that we wrote about earlier in Parts 1 and 2 (Woźniak et al. 2005a,b);

[1] i.e., determined from the packaging effect – see e.g., Morel & Bricaud 1981, Woźniak et al. 1999, 2003.

3) to define for these morphological groups and subgroups of particles typical absorption properties of the particulate matter they contain. These properties are represented by two spectral coefficients: (1) the mass-specific absorption coefficients of the unpackaged organic matter contained in the particles a^*_{OM}, and (2) one of a pair of coefficients describing the bulk absorption of light by the whole unpackaged (not just the organic) matter of the particle, i.e., the absorption coefficient of particulate matter – $a_{pm}(\lambda)$, or alternatively, the imaginary part of the absolute complex refractive index for particulate matter – $n'_p(\lambda)$. Since these two parameters ($a_{pm}(\lambda)$ and $n'_p(\lambda)$) are strictly related to each other[2] (see, e.g., Born & Wolf 1968), we present here the results of calculations of the latter coefficient, the refractive index $n'_p(\lambda)$.

These objectives were achieved in stages, the details of which we shall now proceed to describe in section 2 (objective 1), section 3 (objective 2) and section 4 (objective 3). Sections 5 and 6 respectively contain a discussion and summary of our results. An Appendix lists the most important abbreviations and symbols for the physical magnitudes used in this paper.

2. Selection of morphologically similar groups of marine particulate organic matter; morphological classification of POM

In the light of the above-mentioned lack of an unambiguous yet detailed morphological classification of POM in the most recent world literature, we decided on a simplified division of all organic detritus into two major morphological types and six morphological subtypes – see Fig. 1. We then further divided each subtype into a number of groups of particles (25 in all – see sections 3 and 4), which we named 'optico-morphological variants'. These are sets of particles with similar physical features and chemical compositions, and therefore with similar absorption properties. Each of these distinct systematic units of detritus is characterised by a similar external structure and physical features. In other words, the particles in a given optico-morphological group are roughly similar in size, shape and organic matter composition, and also in the inorganic content (water, air, etc.) which, besides the organic matter, makes up the volume of the particle. In making this classification, we availed ourselves of the terminology suggested by Romankevich (1977); we also took account of the new trends appearing in later papers (cited in section 1).

[2]We discussed the relationship between coefficients $a_{pm}(\lambda)$ and $n'_p(\lambda)$ in detail in Parts 1 and 2 (Woźniak et al 2005a,b). It takes the form $n'_p(\lambda) = a_{pm}(\lambda) \times (\lambda/4\pi)$.

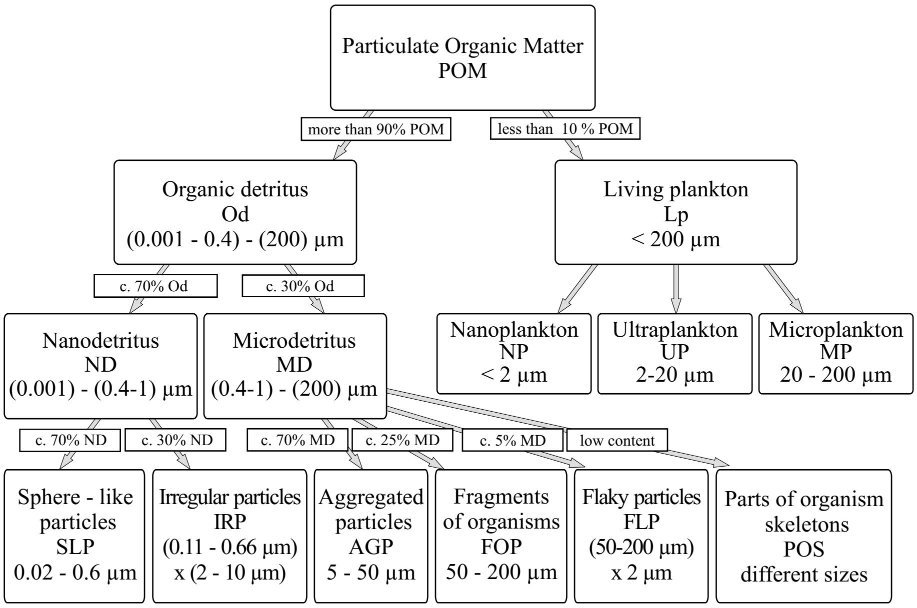

Fig. 1. Simplified division of particulate organic matter in the sea (POM) into morphological groups of particles. Each block gives the approximate range of particle sizes. The panels placed across the arrows give the percentage shares of particles, typical of oceans, from each morphological subgroup in the overall mass of particles in a group

2.1. Major morphological groups of POM

Particulate organic matter (POM) in the sea contains both living and non-living components – see Fig. 1. The living part of POM comprises mainly planktonic organisms – Lp (phyto- and zooplankton, and in smaller numbers also bacteria and fungi), which usually make up less than 10% of the total mass of POM in the sea. Ecologists have long divided these organisms into three principal morphological groups on the basis of equivalent diameters: nanoplankton (NP) – < 2 μm, ultraplankton (UP) – 2–20 μm, and microplankton (MP) – 20–200 μm and larger (see, e.g., Parsons et al. 1977).

But the absolutely predominant fraction of POM (usually 90% and more by mass), which we are analysing in this work, consists of organic detritus (Od). This component of POM is usually divided into two morphological size groups. One comprises the fine-grained fraction of organic detritus (including colloids) with particle sizes < 1 μm; by analogy to the nanoplankton, it is known as nanodetritus (ND). The other is made up of particles in the 1 to 200 μm (and larger) size range, and can be called microdetritus (MD). It is quite clear, however, that this division is purely a matter of convention, based more on tradition and the availability of apparatus than on the real nature of things. To illustrate the problem: particles < 1 μm in size come under the heading of 'nanodetritus' because in practice they can be examined and analysed only under an electron microscope.

2.2. Types of organic detritus

The two major morphological groups of organic detritus particles can be further divided into numerous subgroups of particles differing not only in their size ranges, but also in shape, and, as it turns out, in their chemical and physical properties, origin and numbers. In view of the complex nature of these particles and the currently rather poor understanding of them, we have distinguished, to a first approximation, six types of organic detritus particles: two types of fine-grained particles differing in shape – sphere-like particles (SLP) and irregular particles (IRP), and four types of coarse-grained particles – aggregated particles (AGP), particles composed of fragments of organisms (FOP), flaky particles (FLP), and parts of organism skeletons containing organic matter (POS) (see Fig. 1). Table 1 lists the probable, approximate sizes and shapes of these morphological types of Od. We now describe the most important features of these six types of organic detritus particle.

Table 1. Approximate geometrical characteristics of different morphological types of organic detritus (Od)

	Group and type of detritus	Shapes	Diameter [μm]	Length (and width) [μm]	Thickness [μm]
Nanodetritus	Sphere-like (SLP)	single spherical	0.02–0.6	-	-
		chains of spheres	0.01–0.016	4–10	-
		tangled fibres of spheres	~ 0.2	up to 10	-
	Irregular (IRP)	various, mainly membranous	-	0.11–0.66	2×10^{-4} -1×10^{-3}
Microdetritus	Aggregated (AGP)	spherical and various	5–25* 25–50**	- -	-
	Fragments (FOP)	spherical and various	50–200	-	-
	Flakes (FLP):	flaky			
	small		-	15–35	$\sim$2
	large		-	50–200	$\sim$2

* for the Pacific (according to Romankevich 1977);
** for the Atlantic (according to Romankevich 1977).

- *Sphere-like particles* (SLP). The basic structural units of the nanodetritus fraction (ND) with a molecular mass > 10 000 daltons are *sphere-like* forms with diameters from 0.02 to 0.06 μm. These particles occur in suspension both as discrete spheres, and as chains consisting of a few spheres, aggregates up to 1 μm in size made up of different spherical forms, and multifarious tangles of fibrous aggregates 4–10 μm in size, composed of spheres with diameters in the 0.01–0.16 μm range. It also happens that a few spheres surround a cloudlet of optically thinner substances; the suspended particles then take on bizarre 'artistic' forms. These spherical forms may consist of various organic compounds, but the separate spheres are usually homogeneous, i.e., they consist of one material. The SLP fraction is quantitatively dominant in ND, making up some 70% of its mass.
- *Irregular particles* (IRP). The remainder of the fine-grained organic detritus (c. 30% of the mass of ND), consists of irregularly shaped particles, very many of which are transparent and membranous forms 0.11–0.66 μm in diameter and 0.2–1 nm in thickness. Spherical structures are not observed among such particles. Like SLP, most IRP are chemically homogeneous; they can be constructed of the many and various organic compounds present in sea water.
- *Aggregated particles* (AGP). Heterogeneous forms with varied internal structures, AGP range widely in size from 1 μm or less to 200 μm and more, though usually from 5 to 50 μm. In some cases, however, AGP can also be numerously represented by forms smaller than 5 μm or larger than 50 μm. These particles are 'glued together' from various smaller fragments (wet and dry) of organic matter, derived directly and indirectly from plants[3] and animals; there will also be certain amounts of humus, and also empty spaces, which may be filled with bacteria and inorganic admixtures. The proportions between the components of AGP, i.e., the smaller substructures of these aggregates, vary in different basins and at different depths. Usually, though, the organic matter they contain is not identifiable with the immediate remains of organisms. Most of this organic matter probably consists of carbohydrates and their derivatives. Some authors (e.g., Bogdanov & Lisitsyn 1968, Silver et al. 1991, Lin et al. 1989) have divided this group of particles into many subgroups according to provenance, morphological features, size and composition. We may mention two such subgroups: larger, less rounded, yellow-grey particles with a fairly

[3]These may also be living cells, e.g., of diatoms; AGP fluoresce in the red range, which is evidence that they contain 'living' chlorophyll.

irregular structure, and quite well-rounded, yellow-brown, wax-like particles, usually smaller than 2.5 μm. In total AGP are the most abundant (c. 70%) morphological subtype among the coarse-grained organic detritus and are present at all depths in all seas.

- *Fragments of organisms* (FOP). These are wet particles of various shapes that are parts of phyto- and zooplanktonic organisms or the nekton, or their faeces. In size they usually range from 50 to 200 μm. FOP are the second most numerous subtype among the coarse-grained organic detritus in the sea and can make up c. 25% of its mass. They are found in all seas and oceans, usually in the 0–200 m layer.
- *Flaky particles* (FLP). Like the two previous subtypes of coarse-grained detritus, this one is also of biogenic origin. FLP are dry (anhydrous) fragments of animal or plant organisms, though besides organic matter, they may also contain some inorganic admixtures. Occurring in the form of flakes, they are usually homogeneous, with diameters of 50–200 μm and thickness c. 2 μm. FLP of smaller dimensions (15–35 μm) have sometimes been observed. FLP are present in much smaller amounts than AGP or FOP, and their percentage share does not normally exceed 5% of the mass of microdetritus MD.
- *Organic matter in skeletons* (POS). The last subtype of coarse-grained organic detritus consists of organic matter 'locked up' in the remains of skeletons of organisms or in all manner of cocoons and shells. It is present in very much smaller amounts (sporadically) than the other three subtypes and will not be analysed here.

3. Various forms of organic detritus (Od): formation, evolution and principal chemical and physical properties

The next step towards achieving our research objectives was to classify the chemical compositions of the organic matter in the particles belonging to the major types of organic detritus outlined in section 2, and to ascribe to each of them a particular physical type, i.e., to establish the intraparticular concentration of organic matter. Since no suitable empirical material applicable to these two features of particles was available, we made use of a range of empirical premises on the manner of formation of various morphological forms of POM and the possible transformations they could undergo.

The formation, transformation and disappearance of the several morphological forms of POM are controlled by an exceedingly complex set of mutually interacting chemical and biological phenomena which, in addition, variously affect the numbers of the different morphological forms of (see, e.g., Wassmann & Heiskanen 1988, Wassmann et al., 1991 and the papers cited therein). To begin with, the quantities of living POM fractions (the various groups of living plankton (Lp)) together with larger quantities of animals (nekton) – are governed by a set of processes that includes photosynthetic (and to a lesser extent chemosynthetic) primary production, grazing, respiration, excretion, dying and active vertical migration. On the one hand, these processes are the production and transformation of this POM, and on the other, its recycling and disappearance. At the same time, this recycling and disappearance of living forms is usually the source of the major part of the supplies of dead POM (organic detritus, Od). In other words, being derived directly from living organisms, much Od is of directly biological origin. The resources of this biological Od are additionally replenished from the similar decomposition of larger organisms not belonging to the POM – the nekton. But the combined resources of Od also depend on possible repacking processes (sorption, sedimentation, precipitation), which generate supplies of 'new' Od from the available dissolved organic matter. The origin of this new Od is thus only indirectly biological. Again, the morphological forms of Od from both these sources (directly and indirectly biological) depend on subsequent complex processes giving rise to changes in their amounts, transformation and recycling. These processes include aggregate formation, lateral advection, bacterial decomposition, consumption by zooplankton and other animals, and passive sinking.

To describe completely the mechanisms of the formation, evolution and disappearance of the various forms of POM taking into account all the above-mentioned governing processes and mutual connections is an exceedingly complicated but nonetheless feasible task. This is because these elements constitute one of the links in the so-called biogeochemical cycle of organic carbon, which has been a subject of study for many years now, and has been modelled quantitatively on various scales with greater or lesser success (see, e.g., Libes 1992). The schemes of this carbon cycle published in the available literature (see, e.g., Lancelot & Billen 1985, Leppanen 1988, Pempkowiak 1997, Lee 2005) do, however, tend to treat organic detritus as a single entity, making no distinction between the various morphological forms of Od and taking no account of the flow of organic matter between these forms. So for the purposes of this article, we have compiled a simplified scheme of the formation and transformation of the major morphological forms of POM, with particular emphasis on organic detritus (Od), on the basis of empirical knowledge drawn from the works cited in the introduction (Romankevich 1977, Wassmann & Heiskanen 1988, Wassmann et al. 1991) (see Fig. 2). The scheme applies to just one link in the multi-stage carbon cycle in the marine ecosystem, namely, the formation and flow of organic carbon through POM. Moreover, we have restricted it to just the main, most prolific, streams of carbon without attempting to maintain the zero balance of the matter flowing through the ecosystem. But it does contain premises, important for achieving the objectives of this work, enabling the approximate composition and intraparticular concentration of organic matter to be established for particles belonging to various morphological forms of Od (see section 4).

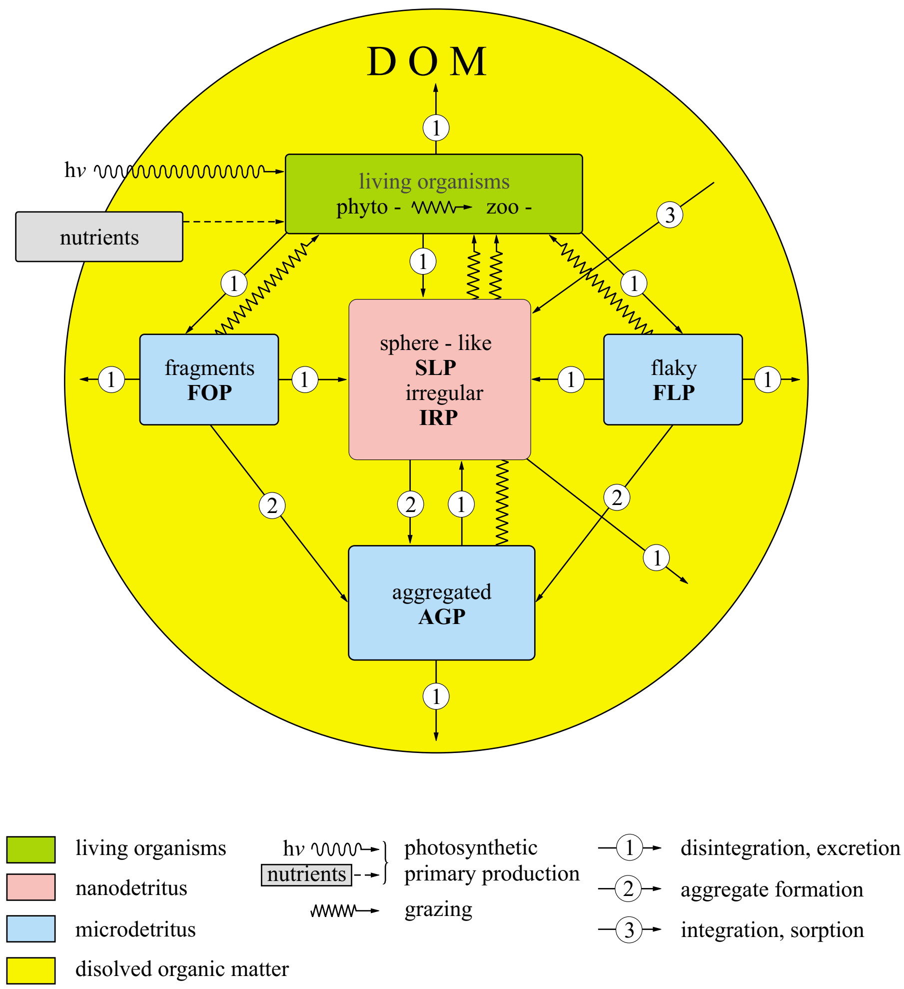

Fig. 2. Simplified scheme of the formation and evolution of the various morphological groups of POM

In order to establish the concentration and composition of organic matter of the various morphological forms of particles, we made the following simplifying assumptions:

- Discrete particles of the various morphological forms of organic detritus (Od) arise as a result of:
  - the decay and secretions of living forms of POM and nekton;
  - the decay or aggregation of other morphological forms of Od;
  - the sorption (sedimentation, precipitation) of dissolved organic matter (DOM).
- The formation and transformations of particles take place according to the scheme shown in Fig. 2 and in the order emerging from this scheme.
- In many cases, the organics composition and the concentration of given portions (not necessarily whole particles) of organic matter transferred during particle transformations from one morphological form to another either do not change at all or do so only to an insignificant extent.
- Nevertheless, the composition and intraparticular concentration of the organic matter in 'whole' particles belonging to two adjacent morphological forms in this chain of cause and effect can also be different. Such a situation may occur, e.g., when:
  - a new particle comes into being as a result of the selective break-up (or secretion) of a source particle into fragments with organics compositions or concentrations differing from these two properties averaged for the whole source particle;
  - new particles come into existence as a result of the aggregation of fragments with different physical and chemical features, and/or also by the sorption of DOM;
  - particles arising as a result of aggregation can enclose certain portions of water or gas, and also of other inorganic substances.
- We have not taken into consideration the possible changes a particle may undergo while remaining (existing) in a given morphological form, i.e., changes taking place as a result of a range of different chemical, biochemical and physico-chemical processes, such as chemical decomposition, bacterial degradation, humification, hydration and dehydration, aeration and de-aeration. It seems, however, that these 'internal' processes cause the chemical and physical features of SPM to differ to a far lesser extent than do the ways of their formation.

Table 2. Selected chemical and physical characteristics of model morphological groups of POM

a – nanodetritus, sphere-like particles (SLP) and irregular particles (IRP)

Symbol	Composition of organic matter	Physical type*	C_{OM}^{**} [kg m^{-3}]
1	2	3	4
SLP(A1), IRP(A1)	as chemical class A1	PH	1220
SLP(A2), IRP(A2)	as chemical class A2	PH	1220
SLP(A3), IRP(A3)	as chemical class A3	PH	1220
SLP(P1), IRP(P1)	as chemical class P1	PH	1120
SLP(P2), IRP(P2)	as chemical class P2	PH	1120
SLP(N), IRP(N)	as chemical class N	PH	1530
SLP(L), IRP(L)	as chemical class L	PH	1220
SLP(H1), IRP(H1)	as chemical class H1	PH	1530
SLP(H4), IRP(H4)	as chemical class H4	PH	1530
SLP(D1), IRP(D1)	as chemical class D1	PH	1400
SLP(D2), IRP(D2)	as chemical class D2	PH	1400

b – microdetritus, aggregated particles (AGP)

1	2	3	4
AGP(D1)	as chemical class D1	PH	1400
AGP(D2)	as chemical class D2	PH	1400
AGP(D1/Ph1/Z)	as a mixture of morphological groups IRP(D1)-FOP(Z)-FLP(Z)-FOP(Ph1)-FLP(Ph1) in the respective proportions: 0.8861; 0.0854; 0.0171; 0.0095; 0.0019	NW	862
AGP(D2/Ph2/Z)	as a mixture of morphological groups IRP(D2)-FOP(Z)-FLP(Z)-FOP(Ph2)-FLP(Ph2) in the respective proportions: 0.8861; 0.0475; 0.0095; 0.0475; 0.0095	NW	760
AGP(Ph1/Z)	as a mixture of morphological groups FOP(Z)-FLP(Z)-FOP(Ph1)-FLP(Ph1) in the respective proportions: 0.7498; 0.1501; 0.0834; 0.0167	NW	210
AGP(Ph2/Z)	as a mixture of morphological groups FOP(Z)-FLP(Z)-FOP(Ph2)-FLP(Ph2) in the respective proportions: 0.4167; 0.0833; 0.4167; 0.0833	NW	150

Table 2. (*continued*)
c – microdetritus, fragments of organisms (FOP)

1	2	3	4
FOP(Ph1)	as chemical class Ph1	NW	110
FOP(Ph2)	as chemical class Ph2	NW	110
FOP(PhM)	as chemical class PhM	NW	110
FOP(Z)	as chemical class Z	NW	200

d – microdetritus, flaky particles (FLP)

1	2	3	4
FLP(Ph1)	as chemical class Ph1	PH	1300
FLP(Ph2)	as chemical class Ph2	PH	1300
FLP(PhM)	as chemical class PhM	PH	1300
FLP(Z)	as chemical class Z	PH	1250

* physical types: PH – pure heavy particles, NW – neutral (free) wet particles or similar particles;
** C_{OM} – intraparticulate concentration of organic matter.

Setting out with these five main simplifying assumptions (along with a few others which we shall mention in due course), we were able to distinguish 25 optical variants of particles belonging to different morphological types of Od. Table 2 lists their strictly defined basic chemical and physical properties, and Table 3 sets out their organic matter compositions. Below we discuss these chemical and physical properties, retaining more or less the order of their formation according to the scheme in Fig. 2. (1) In the beginning, particles of microdetritus – fragments of organisms (FOP) and flaky particles (FLP) – come into being, mainly as a result only of the decay of living organisms. (2) This process also yields particles of nanodetritus – sphere-like particles (SLP) and irregular particles (IRP). But the generation of SLP and IRP is additionally reinforced by the break-up of other detritus particles and also by the sorption of DOM. (3) Finally, microdetritus of the AGP type is not directly biological in origin and comes into existence mainly through the aggregation of all other morphological types of detritus.

3.1. Microdetritus: fragments of organisms (FOP) and flaky particles (FLP)

As we have just said, most particles of these two types of microdetritus (FOP and FLP) are of directly biological origin, forming as a result of the decay of living organisms, that is, living plankton (Lp – living forms of

Table 3. Chemical composition of organic matter in model morphological groups of POM

Optico-morphological group	Organic substances content c_i (mass of substance [%] relative to the total mass of organic matter)									
	Natural proteins or aminoacids and their derivatives			*Purine and pyridine compounds*	*Humus (oceanic or Baltic)*		*Lignins*	*Plant pigments (oceanic or Baltic)*		*Other organic matter (not absorbing light)*
	A1	A2	A3	N	H4	H2	L	P1	P2	
SLP(A1), IRP(A1)	100									
SLP(A2), IRP(A2)		100								
SLP(A3), IRP(A3)			100							
SLP(P1), IRP(P1)								100		
SLP(P2), IRP(P2)									100	
SLP(N), IRP(N)				100						
SLP(L), IRP(L)							100			
SLP(H1), IRP(H1)						100				
SLP(H4), IRP(H4)					100					
SLP(D1), IRP(D1)			1.2	0.3	10					88.5
SLP(D2), IRP(D2)			8	2		55	18			17
AGP(D1)			1.2	0.3	10					88.5
AGP(D2)			8	2		55	18			17
AGP(D1/Ph1/Z)	7.7		1.1	0.3	8.9			< 0.5		82
AGP(D2/Ph2/Z)	7		7.1	1.8		49	16		< 0.5	18.6
AGP(Ph1/Z)	67.7							0.3		32
AGP(Ph2/Z)	57.3								2.7	40
FOP(Ph1)	46.9							3.1		50
FOP(Ph2)	44.7								5.3	50
FOP(PhM)	Composition typical of *Phaeocystis antarctica* (Moisan & Mitchell 2001)									
FOP(Z)	70									30
FLP(Ph1)	46.9							3.1		50
FLP(Ph2)	44.7								5.3	50
FLP(PhM)	Composition typical of *Phaeocystis antarctica* (Moisan & Mitchell 2001)									
FLP(Z)	70									30

POM) and of nekton (see transformation 1 in Fig. 2). In line with our assumptions, the composition of the organic matter scarcely changes at all during this decay, although its intraparticular concentration may do so.

We have therefore distinguished four major optical (or more precisely, optico-morphological) variants of particles belonging to each of these two types of detritus. They are (see Tables 2c and 2d):

- FOP(Ph1) and FLP(Ph1) – fragments and flakes consisting of the same organic matter as in the model chemical particles of class Ph1[4], that is, oceanic phytoplankton-like particles;
- FOP(Ph2) and FLP(Ph2) – similar fragments and flakes of Baltic phytoplankton (chemical class Ph2);
- FOP(PhM) and FLP(PhM) – fragments and flakes of polar phytoplankton (chemical class PhM);
- FOP(Z) and FLP(Z) – fragments and flakes consisting of the same organic matter as in particles of the chemical class Z, that is, zooplankton and zooplankton and/or nekton-like particles.

The organic matter compositions of these optico-morphological variants of particles are thus identical with those of particles in the corresponding model chemical classes. Their intraparticular concentrations of organic matter C_{OM} are, however, different (see column 4 in Table 2). So in the case of FOP we assumed that these concentrations are the same as the concentrations C_{OM} characteristic of living organisms. But the mean concentrations $(C_{OM})_{PH}$ for FLP we estimated on the assumption that they belong to the physical type of 'pure heavy particles' (PH), which contain only dry organic matter. We further assumed that these are mixtures of different organic substances of known densities ρ and in known relative concentrations c_i. We thus calculated these mean values of $(C_{OM})_{PH}$ from the relationship:

$$(C_{OM})_{PH} = \sum_i \rho_i c_i, \qquad (1)$$

where $\sum_i c_i = 1$.

We took the relative concentrations c_i appearing in eq. (1) from Table 3, but assumed the mean densities ρ_i of various pure organic substances on the basis of data, gleaned from various papers by Aas (1996).

[4]The model chemical class Ph1 of suspended organic particles and many other such model classes of particles were discussed in detail in the earlier papers in this cycle. For example, Table 1 in Part 1 (Woźniak et al. 2005a) gives the compositions and/or origin of organic substances, and Tables 1,2,4 in Part 2 (Woźniak et al. 2005b) list their absorption properties. The symbols pertaining to these classes are also explained in the Appendix at the end of the present article.

3.2. Nanodetritus: sphere-like particles (SLP) and irregular particles (IRP)

It is to be expected that SLP and IRP come into existence largely as a result of the selective (in the chemical sense) decomposition both of living organisms and of the various morphological forms of detritus (see Fig. 2), i.e., the earlier-mentioned FOP and FLP, and also aggregated particles AGP, which we discuss in section 3.3. So for the purposes of the next step in this analysis, we assumed the existence of, among other things, nine chemically homogeneous optico-morphological variants of particles (see Table 2a) consisting of organic matter typical of chemical classes A1, A2, A3, P1, P2, N, L, H1 and H4. They can occur as both SLP and IRP.

There is, however, another possible way in which nanodetritus can form – as a result of sorption (sedimentation, precipitation) of DOM (see transformation No. 3 in Fig. 2). This sorption can lead to the formation of chemically fairly homogeneous particles of nanodetritus (like the nine variants just mentioned), as well as more complex, heterogeneous particles made up from different organic constituents. Therefore, besides the homogeneous optico-morphological variants of ND, we also distinguished two further, complex variants, with chemical compositions typical of DOM compositions occurring in oceanic (model chemical class D1) and Baltic waters (model chemical class D2). Such particles are probably larger than the chemically homogeneous ones and occur in the form of IRP, although their presence in the form of SLP cannot be ruled out.

As in the case of FLP, all the SLP and IRP analysed here are classified among the pure heavy particles, that is, they consist of dry organic matter. We therefore took their typical intraparticulate concentrations C_{OM} to be equal to the densities of the organic compounds of which they are composed, or the corresponding mean values $(C_{OM})_{PH}$ for mixtures of these compounds, calculated according to eq. (1).

3.3. Microdetritus: aggregated particles (AGP)

As we suggest in Fig. 2, these particles come into being as a result of aggregation (they are 'glued together') of other particles of nano- and microdetritus (see transformation No. 2 in Fig. 2). Their chemical compositions may thus vary; they may even be of the greatest complexity, displaying a diversity of intraparticular concentrations of organic matter (see Table 2b). For the analysis of AGP, we assumed the existence of six major optico-morphological variants of such particles, characteristic of different sea waters – three each for oceanic and Baltic Sea waters:

- AGP(D1) and AGP(D2) – aggregated oceanic DOM-like particles and aggregated Baltic DOM-like particles, respectively. Like the DOM in a given basin, they are particles with a simple organic matter composition, forming as a result of the aggregation of nanodetritus particles. And like SLP and IRP, they are present as pure heavy particles, with concentrations C_{OM} similar to the densities of dry organic matter of classes D1 and D2 ($C_{OM} = 1400$ kg m^{-3}).
- AGP(Ph1/Z) and AGP(Ph2/Z) – aggregated oceanic fragments and flaky particles, and aggregated Baltic fragments and flaky particles, respectively. These particles are characterised by relatively low concentrations C_{OM} and form as a result of the aggregation in a given basin of the microdetritus particles from four groups: the fragments and flakes of phytoplankton and zooplankton. In establishing the bulk compositions and the bulk intraparticular concentrations of organic matter in these particles (see the data in columns 2 and 4 of Table 2b, and also the data in Table 3), we assumed that they contain matter from the following four substrates: FOP(Ph1), FOP(Z), FLP(Ph1), FLP(Z) – in the case of oceanic particles AGP(Ph1/Z), and FOP(Ph2), FOP(Z), FLP(Ph2), FLP(Z) – in the case of Baltic particles AGP(Ph2/Z), mixed in the proportions that are characteristic of the contents of these substrates (the several variants of FLP and FOP) in a given sea. In establishing these proportions, we assumed that the ratio of the total content in the sea of all FOP to all FLP is 25:5; this is the ratio that emerges from the percentage shares of the total contents of the various forms of detritus, typical of seas in general (see Fig. 1). We additionally assumed that the ratios of the contents of phytoplankton and animal organisms (and hence the ratios between the contents of FOP and FLP arising from these two kinds of organisms) are different for oceanic and Baltic waters. They are, approximately[5] Ph1:Z = 1:9 (for oceans) and Ph1:Z = 1:1 (for the Baltic).
- AGP(D1/Ph1/Z) and AGP(D2/Ph2/Z) – all aggregated oceanic particles and all aggregated Baltic particles. These particles are characterised by intermediate values of C_{OM} and have the most complex chemical compositions and morphological structures. This is because they form from the aggregation of all the types of nano- and microdetritus present in a given sea. We therefore assumed that

[5]The proportions of phyto- and zooplankton assumed here are roughly the same as those given in numerous monographs on marine biology (Bogorov 1974, Gershanovich & Muromtsev 1982, Vinogradov & Shuskina 1987).

they consist not only of the four substrates that are the building blocks of the particles AGP(Ph1/Z) and AGP(Ph2/Z) mentioned above, but additionally of particles IRP(D1) or IRP(D2), the organics composition of which is the same as that of the DOM in the relevant basin. In establishing the bulk composition and intraparticular concentration of the organic matter in these particles (Table 2b columns 2 and 4, and Table 3), we assumed that, as in the case of AGP(Ph1/Z) and AGP(Ph2/Z), the proportions between the various substrates are those emerging from their resources in a given sea. We also assumed, therefore, that the ratio of the content of nanodetritus in IRP to its microdetritus content is, according to the data given in Fig. 1, in both cases equal to IRP:(FOP+FLP) = 0.8861:0.1139. At this point, it is worth drawing attention to a certain fact. The data on the typical sizes of the various forms of detritus, given in Fig. 1, Table 1 and section 2.2, indicate that even though AGP are formed from the aggregation of quite large particles of the FOP and FLP type, they do not have to be larger than the latter. Indeed, in most cases, they are actually smaller. This is because in parallel to the aggregation of FOP and FLP to form AGP, the former particles are continually disintegrating into smaller ones, which then stick together all the more easily.

4. Determination of the light-absorption properties of the different optico-morphological variants of organic detritus (Od)

The final and most important stage of this research project was to define the light absorption properties characteristic of the particulate matter in all 25 optico-morphological variants of detrital particles. For each j-th optico-morphological variant these properties can be represented by either of two spectral coefficients: $a^*_{OM,j}(\lambda)$ – the mass-specific absorption coefficient of the unpackaged organic matter contained in these particles, or $n'_{p,j}(\lambda)$ – the imaginary part of the absolute refractive index of the particles. They were determined on the basis of (a) the chemical compositions of each of the 25 types of optico-morphological particle (data in Tables 2 and 3), and (b) the mass-specific light absorption coefficients of the individual constituents of a given particle, which we analysed in Part 2 (see Tables 1 and 2 in Woźniak et al. (2005b)).

The coefficients $a^*_{OM,j}(\lambda)$ were calculated from the obvious relationship:

$$a^*_{OM,j} = \sum_i c_i a^*_{OM,i}(\lambda), \tag{2}$$

where

c_i – the relative content of the i-th organic constituent in a given particle, i.e., the ratio of the concentration of that constituent in the particle to the overall intraparticular organic matter concentration;

$a^*_{OM,i}(\lambda)$ – the mass-specific absorption coefficient for this i-th organic constituent.

These i-th constituents can be taken to be either the individual organic constituents of the particle (values of relative concentrations c_i are given in Table 3), or the individual substrate constituents of a detritus particle in the process of becoming part of newly forming detritus (in this case, values of concentrations C_{OM} are given in column 4 of Table 2).

The imaginary refractive indices of these optico-morphological variants $n'_p(\lambda)$ were calculated on the basis of coefficients $a^*_{OM,j}(\lambda)$ in conjunction with the following relationships, discussed in detail in Part 2 (see section 3 in Woźniak et al. (2005b)):

- For particles here classified as pure heavy particles (with concentrations $(C_{OM})_{PH} > 1000$ kg m^{-3})

$$n'_{p,j}(\lambda) = \frac{\lambda}{4\pi} a^*_{OM,j}(\lambda)(C_{OM})_{PH}. \tag{3a}$$

- For particles here classified as neutral, or almost neutral (free) wet particles (with concentrations $C_{OM} < 1000$ kg m^{-3})

$$n'_{p,j}(\lambda) = \frac{\lambda}{4\pi} \left[\frac{a_w(\lambda)}{\rho_w} (\rho_w - C_{OM,j}) + a^*_{OM,j}(\lambda) C_{OM,j} \right], \tag{3b}$$

where

ρ_w – density of water under normal conditions (here assumed to be 1000 kg m^{-3});

$a_w(\lambda)$ – spectral coefficients of light absorption by pure water (data in Part 2 – see Table 3 in Woźniak et al. (2005b));

$C_{\mathrm{OM},j}$ – intraparticular concentration of organic matter in the particle (data in Table 2, column 4).

The spectra of the imaginary part of the absolute refractive index of light in the UV-VIS (200–700 nm) range, calculated using the above algorithm (see eqs. (2) and (3)), are given in Table 4 and illustrated graphically in Fig. 3. This figure also shows, for comparison, the empirical spectrum of the imaginary refractive index $n'_{p,SS}(\lambda)$ for organic detritus in the Sargasso Sea (after Stramski et al. 2001), and the corresponding spectrum of $n'_w(\lambda)$ for water[6] (mentioned in Parts 1 and 2).

[6]Quantitatively, the spectrum of $n'_{p,SS}(\lambda)$ is described by an analytical expression, given in Part 1 (eq. (1) in Woźniak et al. 2005a); the spectrum of $n'_w(\lambda)$ is given in tabular form in Part 2 (see Table 4 in Woźniak et al. 2005b).

Table 4. The imaginary part of the absolute refractive index at selected wavelengths of UV-VIS light for model morphological groups of POM, n'_p

Particle groups	Imaginary part of the refractive index n'_p for wavelength λ [nm]						
	200	230	280	300	340	400	420
SLP(A1), IRP(A1)	-	6.03×10^{-2}	6.53×10^{-2}	2.04×10^{-3}	(0)	(0)	(0)
SLP(A2), IRP(A2)	-	-	-	8.07	1.19×10	-	(0)
SLP(A3), IRP(A3)	-	2.38×10^{-2}	2.08×10^{-2}	1.48×10^{-2}	1.22×10^{-2}	9.06×10^{-3}	8.17×10^{-3}
SLP(P1), IRP(P1)	(0)	(0)	(0)	(0)	-	5.70×10^{-1}	9.44×10^{-1}
SLP(P2), IRP(P2)	(0)	(0)	(0)	(0)	-	2.53×10^{-1}	3.44×10^{-1}
SLP(N), IRP(N)	-	1.76×10^{-1}	4.67×10^{-1}	7.67×10^{-2}	(0)	(0)	(0)
SLP(L), IRP(L)	4.11×10^{-1}	1.76×10^{-1}	7.61×10^{-2}	4.37×10^{-2}	2.11×10^{-2}	2.14×10^{-3}	(0)
SLP(H1), IRP(H1)	-	1.43×10^{-1}	9.89×10^{-2}	8.03×10^{-2}	4.97×10^{-2}	2.24×10^{-2}	1.79×10^{-2}
SLP(H4), IRP(H4)	2.97×10^{-2}	2.43×10^{-2}	1.67×10^{-2}	1.43×10^{-2}	1.03×10^{-2}	6.09×10^{-3}	5.09×10^{-3}
IRP(D1)	-	3.04×10^{-3}	3.10×10^{-3}	1.72×10^{-3}	1.11×10^{-3}	6.82×10^{-4}	5.77×10^{-4}
IRP(D2)	-	1.14×10^{-1}	7.59×10^{-2}	5.22×10^{-2}	3.05×10^{-2}	1.25×10^{-2}	1.00×10^{-2}
AGP(D1)	-	3.04×10^{-3}	3.10×10^{-3}	1.72×10^{-3}	1.11×10^{-3}	6.82×10^{-4}	5.77×10^{-4}
AGP(D2)	-	1.14×10^{-1}	7.59×10^{-2}	5.22×10^{-2}	3.05×10^{-2}	1.25×10^{-2}	1.00×10^{-2}
AGP(D1/Ph1/Z)	-	-	-	-	-	1.02×10^{-3}	-
AGP(D2/Ph2/Z)	-	-	-	-	-	6.92×10^{-3}	-
AGP(Ph1/Z)	-	-	-	-	-	1.39×10^{-3}	1.50×10^{-3}
AGP(Ph2/Z)	-	-	-	-	-	1.54×10^{-3}	1.80×10^{-3}
FOP(Ph1)	-	*1.07×10^{-3}*	*9.40×10^{-4}*	*6.65×10^{-4}*	*5.50×10^{-4}*	2.12×10^{-3}	3.22×10^{-3}
FOP(Ph2)	-	*1.07×10^{-3}*	*9.40×10^{-4}*	*6.65×10^{-4}*	*5.50×10^{-4}*	1.68×10^{-3}	2.12×10^{-3}
FOP(PhM)	-	-	-	3.28×10^{-3}	5.12×10^{-3}	1.84×10^{-3}	2.14×10^{-3}
FOP(Z)	-	2.73×10^{-3}	2.39×10^{-3}	1.70×10^{-3}	1.40×10^{-3}	1.04×10^{-3}	9.37×10^{-4}
FLP(Ph1)	-	*1.27×10^{-2}*	*1.11×10^{-2}*	*5.29×10^{-3}*	*6.50×10^{-3}*	2.51×10^{-2}	3.81×10^{-2}
FLP(Ph2)	-	*1.27×10^{-2}*	*1.11×10^{-2}*	*5.29×10^{-3}*	*6.50×10^{-3}*	1.99×10^{-2}	2.51×10^{-2}
FLP(PhM)	-	-	-	3.87×10^{-2}	6.05×10^{-2}	2.18×10^{-2}	2.54×10^{-2}
FLP(Z)	-	1.71×10^{-2}	1.49×10^{-2}	1.06×10^{-2}	8.76×10^{-3}	6.50×10^{-3}	5.86×10^{-3}

Table 4. (*continued*)

Particle groups	Imaginary part of the refractive index n'_p for wavelength λ [nm]						
	440	500	550	600	650	675	700
SLP(A1), IRP(A1)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
SLP(A2), IRP(A2)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
SLP(A3), IRP(A3)	7.34×10^{-3}	5.25×10^{-3}	3.94×10^{-3}	2.93×10^{-3}	2.16×10^{-3}	1.85×10^{-3}	1.59×10^{-3}
SLP(P1), IRP(P1)	1.42	8.24×10^{-1}	1.96×10^{-1}	1.46×10^{-1}	2.52×10^{-1}	5.61×10^{-1}	1.33×10^{-1}
SLP(P2), IRP(P2)	3.90×10^{-1}	2.19×10^{-1}	1.05×10^{-1}	6.40×10^{-2}	9.84×10^{-2}	2.76×10^{-1}	3.73×10^{-2}
SLP(N), IRP(N)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
SLP(L), IRP(L)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
SLP(H1), IRP(H1)	1.43×10^{-2}	7.30×10^{-3}	4.42×10^{-3}	2.56×10^{-3}	-	-	-
SLP(H4), IRP(H4)	4.24×10^{-3}	2.44×10^{-3}	1.52×10^{-3}	9.34×10^{-4}	5.73×10^{-4}	4.47×10^{-4}	3.49×10^{-4}
IRP(D1)	4.88×10^{-4}	2.95×10^{-4}	1.93×10^{-4}	1.26×10^{-4}	-	-	-
IRP(D2)	8.05×10^{-3}	4.16×10^{-3}	2.59×10^{-3}	1.56×10^{-3}	9.37×10^{-4}	7.29×10^{-4}	5.68×10^{-4}
AGP(D1)	4.88×10^{-4}	2.95×10^{-4}	1.93×10^{-4}	1.26×10^{-4}	-	-	-
AGP(D2)	8.05×10^{-3}	4.16×10^{-3}	2.59×10^{-3}	1.56×10^{-3}	9.37×10^{-4}	7.29×10^{-4}	5.68×10^{-4}
AGP(D1/Ph1/Z)	-	6.71×10^{-4}	3.73×10^{-4}	2.68×10^{-4}	-	-	-
AGP(D2/Ph2/Z)	-	2.66×10^{-3}	1.62×10^{-3}	9.99×10^{-4}	7.41×10^{-4}	-	4.14×10^{-4}
AGP(Ph1/Z)	1.68×10^{-3}	1.09×10^{-3}	5.73×10^{-4}	4.26×10^{-4}	3.98×10^{-4}	-	2.62×10^{-4}
AGP(Ph2/Z)	1.90×10^{-3}	1.15×10^{-3}	6.51×10^{-3}	4.33×10^{-3}	5.02×10^{-3}	1.11×10^{-3}	2.44×10^{-3}
FOP(Ph1)	4.62×10^{-3}	2.73×10^{-3}	7.64×10^{-4}	5.70×10^{-4}	8.59×10^{-4}	1.91×10^{-3}	4.71×10^{-4}
FOP(Ph2)	2.33×10^{-3}	1.35×10^{-3}	7.06×10^{-4}	4.51×10^{-4}	5.99×10^{-4}	1.51×10^{-3}	2.58×10^{-4}
FOP(PhM)	2.42×10^{-3}	1.34×10^{-3}	2.93×10^{-4}	3.11×10^{-4}	4.34×10^{-4}	1.29×10^{-3}	6.65×10^{-5}
FOP(Z)	8.42×10^{-4}	6.03×10^{-4}	4.52×10^{-4}	3.36×10^{-4}	2.48×10^{-4}	2.12×10^{-4}	1.82×10^{-4}
FLP(Ph1)	5.46×10^{-2}	3.22×10^{-2}	9.03×10^{-3}	6.74×10^{-3}	1.01×10^{-2}	2.24×10^{-2}	5.57×10^{-3}
FLP(Ph2)	2.75×10^{-2}	1.60×10^{-2}	8.35×10^{-3}	5.33×10^{-3}	7.09×10^{-3}	1.79×10^{-2}	3.05×10^{-3}
FLP(PhM)	2.86×10^{-2}	1.58×10^{-2}	3.46×10^{-3}	3.68×10^{-3}	5.14×10^{-3}	1.53×10^{-2}	7.86×10^{-4}
FLP(Z)	5.26×10^{-3}	3.77×10^{-3}	2.82×10^{-3}	2.10×10^{-3}	1.54×10^{-3}	1.33×10^{-3}	1.13×10^{-3}

(-) – the values of the index n'_p were not defined; (0) – the values of the index n'_p are much smaller than in other spectral intervals; extrapolated values are given in italics.

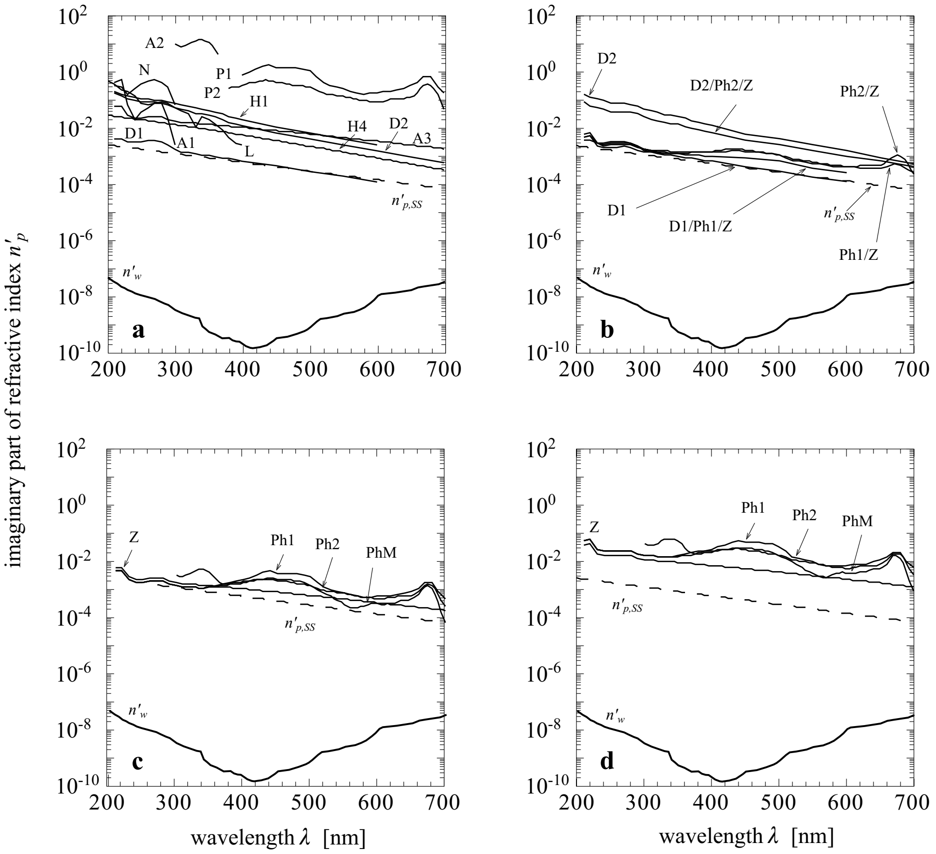

Fig. 3. Possible spectra of the imaginary part of the absolute refractive index for selected morphological groups of POM: sphere-like particles (SLP) and irregular particles (IRP) (a); aggregated particles (AGP) (b); fragments of organisms (FOP) (c); flaky particles (FLP) (d). The symbols on the plots stand for the model chemical classes of POM contained in the morphological forms of particles in the proportions given in Table 3. Solid line – the spectrum of the absolute imaginary refractive index of water $n'_w(\lambda)$ (or of a particle composed exclusively of water); dashed line – the empirical spectrum $n'_{p,SS}(\lambda)$ for Sargasso Sea detritus

5. Results and conclusions

As a result of these theoretical speculations, which we consider to be founded logically on empirical knowledge, we have selected major, morphologically coherent groups of organic detritus occurring in sea waters and have attributed to them certain chemical compositions and physical types. On this basis, and applying known spectra of the mass-specific light absorption coefficients for various organic substances occurring naturally in the sea, we have determined the absorption properties of these morphological groups of particles, in particular, spectra of the imaginary refractive index of particulate matter, $n'_p(\lambda)$, which are given in Table 4 and illustrated graphically in Fig. 3.

As the data in Table 4 and Fig. 3 show, the theoretically estimated values of the spectral coefficients of n'_p for our 25 morphological variants of organic detritus exhibit quite a considerable differentiation, especially in the case of SLP and IRP from the nanodetritus group (ND). The highest values, of the order of $n'_p \approx 10$ and more in the UV range, and of the order of $n'_p \approx 1$ and more in the VIS range are respectively characteristic of particles consisting of pure MAA's (see A2 in Fig. 3a) and of pure phytoplankton pigments (P1 in Fig. 3a). In contrast, the lowest values of n'_p, smaller by some 3–4 orders of magnitude than the ones given above, are typical of particles made up of DOM that has solidified as a result of sorption processes such as sedimentation and precipitation (see D1 in Fig. 3a). Such low values of n'_p are also displayed by AGP and FOP (Figs 3b and c), especially those particles that came into being as a result of the non-selective break-up followed by the direct aggregation of the matter of which organisms consist (see, e.g., particles AGP(D1), AGP(D1/Ph1/Z), FOP(Z) and FOP(Ph1)). Their coefficients $n'_p(\lambda)$ take values approaching those of the coefficients $n'_{p,SS}(\lambda)$ determined for detritus on the basis of empirical data from the Sargasso Sea.

Noteworthy is the almost perfect convergence of the values of $n'_p(\lambda)$ determined theoretically for nanodetritus containing solidified DOM (see, e.g., D1 in Fig. 3a) with the empirical values of $n'_{p,SS}(\lambda)$. One can therefore risk the judgement that there are more particles of this type than of all the other morphological variants of organic detritus taken together. Such a conclusion is corroborated by the fact that DOM is the most abundantly occurring substrate from which SPM can be formed.

Notice, too, that the values of $n'_p(\lambda)$ estimated here for all the 25 distinct variants of POM are higher than or at least close to the empirical values of this coefficient for the Sargasso Sea, $n'_{p,SS}(\lambda)$. This is because in the calculations presented here we took into consideration only those groups of POM containing at least one of the substances that we classified as strong UV or VIS absorbers. Therefore, the values of $n'_p(\lambda)$ listed in Table 4 and shown in Fig. 3 can be used directly to determine, with the aid of Mie's theory, the optical properties of only the strongest absorbing fractions of POM. In actual fact there are in the sea many more variants of organic particles with n'_p values lower than those given here; they consist solely of weakly absorbing organic substances. This group of particles can also contain strongly absorbing substances, but which are present in minute quantities. They could be AGP that have become diluted. In line with our assumptions about AGP formation, we have not taken the processes involved in the dilution of particle-forming material into consideration here, although they are likely. It seems, however, that their influence on the bulk absorption capacity of all POM is small, and so to a first approximation can be neglected.

6. Final remarks

In conclusion, we would like to emphasise that this analysis and the calculated absorption properties of the various organic substances of which the diverse morphological groups of detritus can consist are of a preliminary, hypothetical nature. They have not yet been subjected to rigorous empirical verification. This problem requires further study, both in respect of the structural features (morphology) of real particles of organic matter suspended in the sea, and in the context of their chemical compositions and physical properties. It would be important to expand our sets of model chemical classes, physical types and morphological groups of organic particles (containing only possible admixtures of water and/or gas) to include 'mixed' particles, i.e., those containing also inorganic matter, like minerals. Finding a solution to these problems is thus a matter for the future.

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Appendix

List of symbols and abbreviations

Symbol	Denotes	Unit
A1	aromatic amino acids (a chemical class of SPM)	
A2	mycosporine-like amino acids (a chemical class of SPM)	
A3	natural proteins (a chemical class of SPM)	
AGP	aggregated particles	
C_{OM}	intraparticulate concentrations of organic matter	kg m^{-3}
DOM	dissolved organic matter	
D1	oceanic DOM-like particles (a chemical class of SPM)	
D2	Baltic DOM-like particles (a chemical class of SPM)	
FLP	flaky particles	
FOP	fragments of organisms	
H1	Baltic humus (a chemical class of SPM)	
H4	marine humus (a chemical class of SPM)	
IRP	irregular particles	
L	lignins (a chemical class of SPM)	
Lp	living plankton	
MAAs	mycosporine-like amino acids	
MD	microdetritus	
MP	microplankton	
N	purine and pyridine compounds (a chemical class of SPM)	
ND	nanodetritus	
NP	nanoplankton	
NW	neutral (free) wet particles or similar particles	
Od	organic detritus	
OM	organic matter	
P1	oceanic phytoplankton pigments (a chemical class of SPM)	
P2	Baltic phytoplankton pigments (a chemical class of SPM)	
Ph1	oceanic phytoplankton and phytoplankton-like particles (a chemical class of SPM)	
Ph2	Baltic phytoplankton and phytoplankton-like particles (a chemical class of SPM)	
PhM	polar phytoplankton and phytoplankton-like particles (a chemical class of SPM)	
POM	particulate organic matter	
PH	pure heavy particles	
POS	particulate organic matter in skeletons	

List of symbols and abbreviations (*continued*)

Symbol	Denotes	Unit
SLP	sphere-like particles	
SPM	suspended particulate matter	
UP	ultraplankton	
UV	ultraviolet light	
VIS	visible light	
Z	zooplankton and zooplankton and/or nekton-like particles (a chemical class of SPM)	
a	coefficient of light absorption	m^{-1}
a_p	bulk spectral coefficients of light absorption by a whole particle or by a set of particles in the medium	m^{-1}
a_{pm}	coefficient of light absorption by particulate matter	m^{-1}
a_w	coefficient of light absorption by pure liquid water	m^{-1}
a^*	mass-specific absorption	$m^2\ g^{-1}$
a^*_{OM}	mass-specific absorption coefficient of light by organic matter	$m^2\ g^{-1}$
c_i	relative content of the i-th organic constituent in a given particle (i.e., the ratio of the concentration of this constituent in the particle to the total concentration of intraparticular organic matter)	
n'	imaginary part of the absolute complex refractive index	dimensionless
n'_p	imaginary part of the absolute refractive index of particulate material	dimensionless
$n'_{p,SS}(\lambda)$	spectrum of the imaginary refractive index of organic detritus in the Sargasso Sea	dimensionless
$n'_w(\lambda)$	spectrum of the imaginary refractive index of water	dimensionless
λ	wavelength	nm
ρ	density	$kg\ m^{-3}$
ρ_w	density of water under normal conditions	$kg\ m^{-3}$