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The Potential Role of Large, Fast-Sinking Particles in Clearing Nepheloid Layers [and Discussion]

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The potential role of large, fast-sinking particles in clearing nepheloid layers

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The concentration of fine $O(1\ \mu m)$ suspended sediment in deep-sea nepheloid layers is roughly 10^5 particles cm^{-3}. Given this concentration, aggregation theory dictates that marine snow particles must remove fine particles at a rate of 3.5×10^{-4} particles $cm^{-3}\ s^{-1}$ for scavenging of small particles by large, fast-sinking ones to play a significant role in deposition from nepheloid layers. Assuming that one in every 10 fine particles that collide with a marine snow particle sticks to it, to achieve the above removal rate given a marine snow concentration of 10^{-4} particles cm^{-3} requires contact efficiencies of 10^{-1} to 10^{-2}. Such values of contact efficiency are significantly larger than theoretical predictions of contact efficiency, but are supported by evidence from studies of radionuclide fluxes and particle size distributions. Discrepancies between inferred and predicted values of contact efficiency arise from differences in actual and model particle properties. Contact by direct interception potentially is enhanced by roughened particle surfaces and by wake capture. Wake capture is the process whereby fine particles are entrained in the recirculating eddies present behind settling particles with Reynolds numbers greater than one.

Introduction

The lowest 1000 m of the world's oceans is a region marked by suspended sediment concentrations significantly greater than those observed in oceanic mid-waters. Nearly ubiquitous features of ocean basins, these nepheloid layers possess mass concentrations of 10–$10^2\ \mu g\ dm^{-3}$ and particle sizes in the range of 1–30 μm (see, for review, McCave 1986). Deep-sea nepheloid layers are primary agents of sediment transport in the abyss (see, for review, Stow & Holbrook 1984). As such, predicting dispersal of suspended sediment and particle-associated species demands knowledge of the dynamics of nepheloid layers. Interpreting deep-sea facies likewise hinges on an understanding of nepheloid layer dynamics (see, for review, Stow & Piper 1984).

A qualitative view of nepheloid layers has emerged in which sediment is supplied primarily by resuspension from the bed (Eittreim *et al.* 1969; Betzer & Pilson 1971; Eittreim & Ewing 1972; Biscaye & Eittreim 1977; McCave *et al.* 1980; Spinrad & Zaneveld 1982; McCave 1983), likely during episodic high energy events (Spinrad & Zaneveld 1982; Pak 1983; Pak & Zaneveld 1983; Hollister & McCave 1984). While in suspension, particles interact to form particle aggregates (McCave 1983, 1985) on timescales shorter than that required for grain-by-grain deposition. Sediment returns to the bed primarily in aggregate form.

The picture painted above is one in which ageing of the suspension within (*sensu* McCave 1983) and clearance of material from nepheloid layers involves local parameters exclusively. Aggregation and deposition rates are governed by turbulent dissipation rate, mean flow speed, sediment concentration and size distribution, and bed geometry (McCave 1985; Gross &

Nowell, this Symposium). Omitted is the role of the incessant rain of particles from above in clearing suspended sediment from nepheloid layers.

Large particles with diameters of hundreds to thousands of micrometres and settling velocities in the range of 0.1 cm s^{-1} dominate the vertical flux of material in the ocean. These large particles are fecal pellets and large, amorphous aggregates of smaller particles of diverse origin. To the latter particle type has been attached the name 'marine snow' (see, for review, Fowler & Knauer 1986). Crude scaling arguments are ambiguous about the significance of large, fast-settling particles to the dynamics of deep-sea sediment clouds.

The potential role played by particulate rain in clearing nepheloid layers bears close analogy to the wet deposition process in the atmosphere. Wet deposition is the process whereby aerosol particles are scavenged by raindrops, which carry them quickly to the Earth's surface. The rate at which aerosols reach the surface depends upon the intensity and frequency of precipitation. By contrast, in dry deposition, aerosol particles gain the surface without interacting with scavenging raindrops, and flux to the surface varies with aerosol concentration. External parameters do not assume as large a role as in wet deposition models (see, for example, Slinn 1984). The foci of wet and dry deposition models in the aerosol literature are naturally very different. The thrust of wet deposition models aims at estimating the frequency with which an air mass experiences precipitation events. Dry deposition models are necessarily linked more closely to spatial and temporal distribution of aerosol sources and to horizontal and vertical gradients of aerosol concentration. Wet deposition models predict episodic deposition, whereas dry deposition models produce more constant deposition rates for aerosol particles.

The qualitative traits that distinguish predictions of wet and dry deposition models provide insight into the importance of establishing the magnitude of the role of the particulate rain in clearing nepheloid layers. If particulate rain proves important, deposition from nepheloid layers responds to the temporally and spatially variable flux of material from the surface ocean. The clearance of material from a water mass is tied to the frequency with which that water mass passes under regions of high export production. If particulate rain proves unimportant in clearing nepheloid layers, the dynamics of suspended sediment transport in the deep sea are effectively isolated from particle production at the sea surface.

To formulate accurate models of sediment dispersal in the abyss demands a thorough assessment of the magnitude of the effect that the particulate rain has on deep-sea nepheloid layers. A body of evidence exists from studies of marine particle properties and chemical and material fluxes in the sea that places constraints on the scavenging rate of fine suspended matter by large, fast-sinking particles. Estimates garnered from this evidence may be compared with order-of-magnitude estimates for scavenging rate required to endow fast-sinking particles with a role in clearing nepheloid layers (McCave 1985). Such scaling arguments are useful for assessing whether the inclusion of particulate rain terms in models of deep-sea sediment dynamics is warranted.

Partitioning of mass among size classes in the deep-sea

Deposition rate of fine sediment in the sea is a strong function of particle diameter (McCave & Swift 1976; Dade *et al.* 1989). The deposition rate of individual $O(1\ \mu m)$ (where the $O(\ )$ indicates 'of order') particles characteristic of deep-sea sediment is vanishingly small. Particles in the $O(1\ \mu m)$ size range are too massive to undergo significant brownian diffusion, and yet too small to reach the sea floor by settling (Dade *et al.* 1989). The average residence time, calculated as nepheloid layer thickness divided by settling velocity, of a 1 μm particle with a settling velocity of 4×10^{-5} cm s^{-1} in a 10^5 cm thick nepheloid layer is roughly 80 years, if it is not allowed to interact with any other particles. If fine particles encounter other particles at a sufficient rate, however, the time required for a 1 μm particle to migrate into larger size classes and then deposit can be significantly shorter than the 80 years needed to gain the bed independently.

Measurements of particulate size spectra made over the Nova Scotian continental rise by McCave (1983) provide indirect evidence that aggregation is active in the deep sea. McCave found two types of size distribution. One possessed distinct modality in the fine size classes, which McCave inferred to reflect the size spectra of the source sediment. The other displayed less distinct modality which led McCave to hypothesize greater age for sediment clouds characterized by 'flat' size distributions. He envisioned a transfer of sediment into larger size classes by aggregation, widening and flattening the modal peak. Motivated by these observations, McCave (1983, 1984) undertook an analysis of aggregation rates in the deep sea, drawing on previous work conducted in the fields of aerosol science and wastewater treatment. Aggregation rate defines particle residence time in the water column and the average size of the aggregate in which a particle is eventually deposited. Residence time and size of depositing aggregates must be known to predict sediment dispersal pathways and to provide insight into deep-sea sediment microfabric.

Conceptually, aggregation may be decomposed into three processes, which together define the rate at which particles coalesce to form larger particles. First, particles must be brought into close proximity. For clarity, this process is termed 'encounter' throughout. Second, given that two particles are in close proximity, the two must be brought into direct contact. This step is distinct from the first in that as two particles approach one another, the flow fields around them interact. This situation poses a hydrodynamic problem quite different from the task of calculating the probability of one particle being in close proximity to another. The second process is referred to as 'contact'. This terminology departs from convention established in aerosol science where the process is called 'capture'. This departure is deemed necessary in order to avoid ambiguity associated with the term 'capture'. Capture implies contact and retention. In the atmosphere where it is often assumed that collision results in retention (Pruppacher & Klett 1978), the ambiguity vanishes. In natural waters where particles are immersed in electrolyte of varying ionic strength, however, retention does not always occur given contact (see, for example, Hahn & Stumm 1970) and the word 'capture' does not accurately describe the process. The probability of retention is better treated as an independent process that depends primarily upon surface chemical properties. This third process is called 'sticking'.

Aggregation is a binary process and, as such, has been modelled as a second-order rate process (Smoluchowski 1916, 1917). The aggregation rate of particles of size i and j may be expressed as:

$$dn_{ij}/dt = \tfrac{1}{2}\alpha_{ij} E_{ij} K_{ij} n_i n_j, \qquad (1)$$

where α_{ij} is a non-dimensional coefficient describing sticking efficiency (Hahn & Stumm 1970), E_{ij} is mechanism dependent, non-dimensional contact coefficient for i and j particles (Fuchs 1951; Friedlander 1957), K_{ij} is a second-order rate constant with units of cubic centimetre per second, which describes mechanism dependent encounter rate, and n_i and n_j are the number concentrations of i and j particles. The factor $\frac{1}{2}$ ensures that each collision is counted only once.

Particle encounter is encouraged by any process which produces relative motion between particles. At the molecular level the random motion of molecules can jostle particles and generate relative motion between them. This process is brownian motion. The random fluid motion associated with turbulence may cause relative motion between particles in two ways. At small (less than $O(1\text{ cm})$) scales in the ocean, the dissipation of turbulence by viscous forces within the fluid produces linear velocity gradients within the fluid. By implication neighbouring particles possess different velocities. The fluctuating nature of fluid forcings on particles in turbulent flows also may generate relative motion between particles of different size due to the differing inertial response of the dissimilar particles. Lastly, relative motion exists between particles of different settling velocity. A faster settling particle may encounter slower settling ones. Associated with each of these mechanisms is a second-order rate constant, K_{ij}. Friedlander (1977) and Pruppacher & Klett (1978) provide lucid summaries of the mechanisms and expressions for the rate contants.

The rate constant for encounter due to brownian motion is (Smoluchowski 1916, 1917):

$$(K_\text{B})_{ij} = 2kT(d_i+d_j)^2/3\mu\, d_i\, d_j, \tag{2}$$

where k is Boltzmann's constant, T is temperature, μ is dynamic viscosity, and d_i and d_j are the diameters of i and j particles respectively. The rate constant for encounter due to turbulent shear is (Saffman & Turner 1956):

$$(K_\text{TS})_{ij} = 0.16(d_i+d_j)^3\,(\epsilon/\nu)^{\frac{1}{2}}, \tag{3}$$

where ϵ is turbulent dissipation rate (square centimetres per second cubed) and ν is kinematic viscosity. The rate constant for encounter of i and j particles by turbulent inertial encounter is (Levich 1954):

$$(K_\text{TI})_{ij} = \tfrac{1}{4}\pi(d_i+d_j)^2\,(t_j-t_i)\,\epsilon^{\frac{3}{4}}\nu^{-\frac{1}{4}}, \tag{4}$$

where t_j and t_i denote the relaxation times of j and i particles respectively. Relaxation time for a stokesian particle is equal to (w_s/g) where w_s is the stokesian settling velocity and g is gravitational acceleration. Finally, the rate constant for encounter by gravitational settling is (Fuchs 1951; Friedlander 1957):

$$(K_\text{GS})_{ij} = \tfrac{1}{4}\pi(d_i+d_j)^2\,(w_{\text{s}j}-w_{\text{s}i}), \tag{5}$$

where $w_{\text{s}j}$ and $w_{\text{s}i}$ are the settling velocities of j and i particles respectively.

Following the lead of McCave (1984, 1985), the magnitude of the various encounter rate constants may be ascertained by choosing particle and fluid parameters appropriate to nepheloid layers. Attention is focused on encounter between 1 μm and 2 μm particles. Number concentration is 10^5 cm^{-3} and settling velocity is $4\times10^{-5}\text{ cm s}^{-1}$ for 1 μm particles and $1.25\times10^4\text{ cm}^{-3}$ and 1.2×10^{-4} for 2 μm particles. Turbulent dissipation rate is $10^{-4}\text{ cm}^2\text{ s}^{-3}$, temperature is 2 °C, dynamic viscosity is $0.015\text{ g cm}^{-1}\text{ s}^{-1}$ and fluid density is 1.05 g cm^{-3}. The weak turbulence characteristic of the deep ocean and the small diffusion coefficients for $O(1\text{ μm})$ particles make the encounter rate constant for differential settling greatest (table 1). Note that large particles have been omitted from the preceding calculations.

By making assumptions regarding sticking efficiency, α_{ij}, and contact efficiency, E_{ij}, for

TABLE 1. ENCOUNTER RATE CONSTANTS CALCULATED FOR TWO CASES

(Case 1 is for encounter between 1 μm and 2 μm particles. Case 2 is for 1 μm and 0.3 cm particles.)

encounter mechanism		case 1 ($cm^3\ s^{-1}$)	case 2 ($cm^3\ s^{-1}$)
brownian motion	$(K_B)_{ij} = 2kT(d_i+d_j)^2/3\mu\, d_i\, d_j$	9.6×10^{-13}	6.4×10^{-10}
turbulent shear	$(K_{TS})_{ij} = 0.16(d_i+d_j)^3\,(\epsilon/\nu)^{\frac{1}{2}}$	3.6×10^{-13}	3.6×10^{-4}
turbulent inertia	$(K_{TI})_{ij} = \frac{1}{4}\pi(d_i+d_j)^2\,(t_j-t_i)\,\epsilon^{\frac{3}{4}}\nu^{-\frac{1}{4}}$	1.7×10^{-17}	3.1×10^{-8}
differential settling	$(K_{DS})_{ij} = \frac{1}{4}\pi(d_i+d_j)^2\,(w_{sj}-w_{si})$	5.6×10^{-12}	1.1×10^{-2}

interaction of 1 μm and 2 μm particles, equation (1) may be solved for aggregation rate by various mechanisms. Very little is known about sticking efficiency for marine particles. McCave's (1984, 1985) conservative assumption that $\alpha = 0.1$ is maintained. Contact efficiency for like-sized particles is generally assumed to be $O(1)$ (Pruppacher & Klett 1978). Applying the above assumptions to equation (1) and using $n_i = 10^5\ cm^{-3}$ and $n_j = 1.25\times10^4\ cm^{-3}$, maximum aggregation rates fall in the range of 10^{-3}–$10^{-4}\ cm^{-3}\ s^{-1}$ (table 2).

TABLE 2. AGGREGATION RATES IN NEPHELOID LAYERS CALCULATED FOR TWO CASES (SEE TABLE 1)

encounter mechanism	case 1 ($cm^{-3}\ s^{-1}$)	case 2 ($cm^{-3}\ s^{-1}$)
brownian motion	6.0×10^{-5}	$E_{ij}\,6.4\times10^{-10}$
turbulent shear	2.2×10^{-5}	$E_{ij}\,3.6\times10^{-4}$
turbulent inertia	1.1×10^{-9}	$E_{ij}\,3.1\times10^{-8}$
differential settling	3.5×10^{-4}	$E_{ij}\,1.1\times10^{-2}$

To gauge the role of large, fast-sinking 'marine snow' particles in removing fine material, encounter rate constants for encounter between 0.3 cm and 1 μm particles are calculated as representative. Average concentrations of marine snow particles in the deep sea are of the order $10^{-4}\ cm^{-3}$, and settling velocities equal $0.15\ cm\ s^{-1}$ (Honjo *et al.* 1984; McCave 1984; Asper 1985; Alldredge & Gotschalk 1988). The encounter rate constant is greatest for differential settling (table 1). To estimate aggregation rate $\alpha = 0.1$ is assumed. The assumption that contact efficiency equals one between unlike-sized spheres is generally not considered valid in the case of a large-sphere settling through a field of fine, suspended particles (Fuchs 1951; Friedlander 1957; Beard 1974; Grover 1978). Models suggest that E_{ij} is several orders of magnitude less than one. The efficiency of contact of a large particle suspended in a shear field has not been treated rigorously, and has been assumed equal to unity by some (McCave 1984, 1985). By setting E_{ij} as order unity for a large collector in a shear flow populated with fine, suspended particles, McCave (1984, 1985) made the implicit assumption that hydrodynamic interaction between unlike-sized particles is negligible in shear flows. Such an assumption implies that hydrodynamic retardation of contact is drastically different for a settling collector from what it is for a collector in a shear flow. Given the lack of theory or experiment to warrant such an assumption, the most prudent course is to assume that E_{ij} is the same order of magnitude for all mechanisms describing the aggregation of large and small particles. Thus in table 2 E_{ij} is left undefined in expressions for aggregation rate, and assuming it constant for each mechanism, gravitational settling emerges as the dominant aggregation mechanism between marine snow and 1 μm particles suspended in nepheloid layers.

From table 2 it is apparent that for marine snow to remove 1 μm particles from suspension as quickly as these particles are picked up by near neighbours, E_{ij} must assume values of $O(10^{-2}–10^{-1})$. Such values are significantly greater than those yielded by models of raindrop scavenging of aerosol particles (Fuchs 1951; Friedlander 1957; Beard 1974; Grover 1978). The disparity between model values of E_{ij} and those values required to endow marine snow with a role in clearing nepheloid layers would elicit a conclusion that large particles play no role in nepheloid layers were it not for independent lines of evidence that suggest that values for E_{ij} in the range of 0.01–0.1 are not unrealistic. The evidence comes from particle size spectra and from radionuclide fluxes in the ocean.

Contact efficiency of large particles

The size spectra of source distal particle populations and the residence time of fine ($O(1\ \mu m)$) particles in the world's oceans may be used to constrain contact efficiency of large, fast-sinking particles. In a variety of environments, the size spectrum of fine, suspended particles has been found to be described by a power law relation of the form

$$N = ad^{-b}, \tag{6}$$

where N is the number of particles greater than diameter d, and a and b are constants. The value of b is around three (Bader 1970; Brun-Cottan 1971; Carder *et al.* 1971; Sheldon *et al.* 1972; McCave 1975; Lerman *et al.* 1977; Pak *et al.* 1980; Richardson 1980; McCave 1983; Spinrad *et al.* 1983). The residence time of $O(1\ \mu m)$ particles in the water column as inferred from radionuclide and particulate aluminium fluxes is of order 10–100 years (see, for example, Baht *et al.* 1969; Krishnaswami & Sarin 1976; Krishnaswami *et al.* 1976; Somayajulu & Craig 1976; Lal & Somayajulu 1977; Bacon & Anderson 1982; Bacon *et al.* 1985). Simpson (1982) provides a review of the extensive radionuclide literature. Models of particle dynamics in the sea must accommodate these observed properties of marine fine-particle populations.

The simplest model for maintaining the particle size spectrum assumes no particle–particle interactions. Size specific loss due to sedimentation and dissolution is balanced by size specific production terms. Neglecting the role played by eddy diffusion in the vertical transit of fine particles through the water column (Lerman *et al.* 1977), residence time for a 1 μm particle with a settling velocity of 4×10^{-5} cm s^{-1} in a 5000 m deep ocean is 400 years. This value exceeds residence time estimates yielded by radionuclide fluxes by one to two orders of magnitude and it compromises the applicability of any model that ignores particle interactions.

An alternative model of particle size distribution provides the observed size spectrum by invoking a quasi-stationary distribution (Friedlander 1960*a*, *b*; Hunt 1980, 1982). This steady-state model assumes that there is a constant flux of mass through the size spectrum, that particles are supplied at the fine (1 μm) end of the spectrum, and that mass is lost from the system by sedimentation. Transit of particles up the size spectrum is by aggregation with particles of like size. Thus in this model the egress of particle mass from the 1 μm size class via aggregation must balance the sedimentation of mass out of the water column. Large, fast-sinking particles do not play a role.

Focusing on oceanic mid-waters, where the assumption of steady state is least likely to be violated, the sedimentation flux may be calculated by dividing mass concentration by particle residence time in the mid-water. Mass concentration is the product of particle number concentration, particle bulk density, and volume per particle. Observations suggest that aggregates reach a size of 20 μm in the mid-water (McCave 1975; Lal 1980; Hunt 1982). The concentration of 20 μm particles in the mid-water is taken as 0.06 cm^{-3}. Bulk density of 20 μm aggregates is taken as 1.3 g cm^{-3} (McCave 1984) and the volume of a 20 μm particle is 5.4×10^{-9} cm^{-3}. Mass concentration is thus 3.3×10^{-10} g cm^{-3}. Residence time for 20 μm aggregates in the mid-water is defined as (h/w_s) where w_s is settling velocity (4×10^{-3} cm s^{-1}) and h is mid-water thickness (10^5 cm). Residence time is thus 2.5×10^7 s, and mass flux per unit of volume is 1.3×10^{-17} g cm^{-3} s^{-1}. This figure represents the rate at which mass must leave the 1 μm size class via aggregation for the type of quasi-stationary model developed by Friedlander (1960*a*, *b*) and Hunt (1980, 1982) to explain the observed size distribution.

The mass flux calculated above may be related to aggregation rate by noting that each collision removes 10^{-12} g of sediment from the 1 μm size class, assuming the density of a 1 μm particle is 2.0 g cm^{-3}. Thus particles must aggregate at a rate of 10^{-5} cm^{-3} s^{-1}. Using mid-water concentrations of $n_i = 10^4$ cm^{-3} and $n_j = 625$ cm^{-3} (Brewer *et al.* 1976), equation (1) is solved for a second-order rate constant, K. This exercise yields a value for K of 2×10^{-11}, which is significantly larger than any of the rate constants in table 1. The sedimentation flux of 20 μm aggregates cannot be supported by the slow transit of particles up the size spectrum, given the assumptions herein. McCave (1984) reached similar conclusions.

Continuing under the premise that the aggregation with particles of like size cannot support the settling flux of 20 μm aggregates, other ways must be sought for maintaining the size spectrum. The radionuclide and size spectra data may be reconciled by invoking a model in which material is delivered to mid-water depths with a size distribution described by equation (6). The size spectrum is defined not by aggregation but by disaggregation, degradation and dissolution of particles delivered from the surface. In this model removal of $O(10$ μm$)$ material occurs by settling and $O(1$ μm$)$ material is maintained in proper relative proportion to the $O(10$ μm$)$ particles by removal by large, fast-sinking marine snow. This model bears some similarity to a model proposed by Lerman *et al.* (1977). From equation (6), for each 20 μm aggregate supplied to the mid-water, 1.6×10^5 1 μm particles must be delivered. The supply rate of 20 μm particles must balance settling flux at steady state. Settling flux of 20 μm particles based on previously quoted values for number concentration, settling velocity and mid-water thickness is 2.4×10^{-9} particles cm^{-3} s^{-1}. Therefore the rate at which large, fast-sinking particles must remove 1 μm particles from a unit volume must be 3.8×10^{-4} particles cm^{-3} s^{-1}. This value represents the aggregation rate between marine snow and 1 μm particles needed to maintain the observed mid-water size distribution.

Equations (1) and (5) may be combined and solved for contact efficiency of a large particle sinking through a field of suspended fine particles. The resulting value for E_{ij} is in the range 0.1–1. A contact efficiency in this range is similar to the value needed to give marine snow a role in clearing nepheloid layers. This evidence for contact efficiencies significantly larger than one would predict using available aerosol models suggests that the theories should be examined in a marine context, specifically addressing deviation of the marine particulate system from the assumptions underlying the aerosol models of contact.

Contact mechanisms and efficiencies

To this point the mechanisms that control contact efficiency have been left unaddressed. To derive theoretical estimates of contact efficiency demands treatment of the dynamics of contact by various mechanisms.

In the ocean, deposition to a collector surface may occur by four primary mechanisms (see, for review, Spielman 1977; Rubenstein & Kohl 1977). Attention here is is focused on contact efficiencies of large particles settling rapidly through a field of fine suspended particles. First, the random motion of particles induced by molecular jostling (brownian motion) can bring small particles to the surface of large ones. Secondly, owing to the finite size of the particles, those which follow streamlines that come within one particle radius of the collector surface contact it. Thirdly, if particles carry sufficient inertia, they may fail to follow streamlines as streamlines diverge around collectors. Failure to follow streamlines results in an inertial 'flight' toward the collector, which can result in contact if flight distance is larger than separation distance at the beginning of the flight. Lastly, contact with fixed collectors may occur by gravitational settling. Because the collectors of interest herein settle rapidly through a population of essentially non-sinking particles, this contact mechanism is ignored (figure 1).

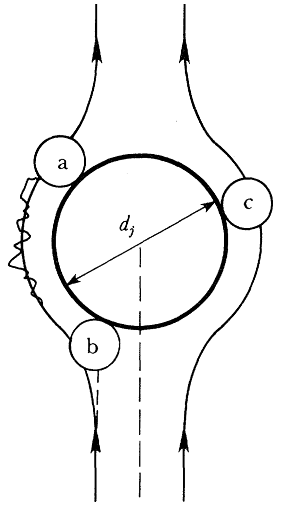

Figure 1. Large, fast-sinking particles may contact fine, suspended material by several mechanisms. Illustrated here are contact by brownian diffusion (particle a), contact by inertial impaction (particle b), and contact by direct interception (particle c).

Models of particle contact are generally formulated in context of contact efficiency, a legacy from the fields of filter technology and precipitation scavenging from whence most theory on contact comes. The motivation of contact models lies in gaining an estimate of the fraction of the total number of particles incident on a collector which actually contact that collector. The number of particles per unit time in the path of a particle is set as the product of the cross-sectional area of the collector, number concentration of particles in the bulk of the fluid, and an appropriate velocity scale. For a collector settling through a suspension of non-sinking particles

$$F = nAw_s, \tag{7}$$

where F is number of particles per unit time moving past the collector ($\mathrm{N\,T^{-1}}$), n is number concentration of incident particles ($\mathrm{N\,L^{-3}}$), A is projected area of the collector ($\mathrm{L^2}$), and w_s is settling velocity of the collector ($\mathrm{L\,T^{-1}}$). The number contacted per unit of time similarly must assume dimensions of $\mathrm{N\,T^{-1}}$, so

$$F_c = nA_c w_s, \tag{8}$$

where F_c is the number contacted per time, n and w_s are as defined previously, and A_c is the effective area of contact. In other words A_c is the cross-sectional area a collector with settling velocity w_s would require to pick up particles at a rate F_c, were the collector perfectly efficient. Contact efficiency then is the ratio of F_c (equation (8)) to F (equation (7)), which reduces to

$$E = d_c^2/d^2, \tag{9}$$

where d_c is a contact diameter and d is collector diameter (Pruppacher & Klett 1978). Calculating efficiency reduces to the task of defining a contact length scale, d_c, appropriate to the mechanism of interest (figure 2).

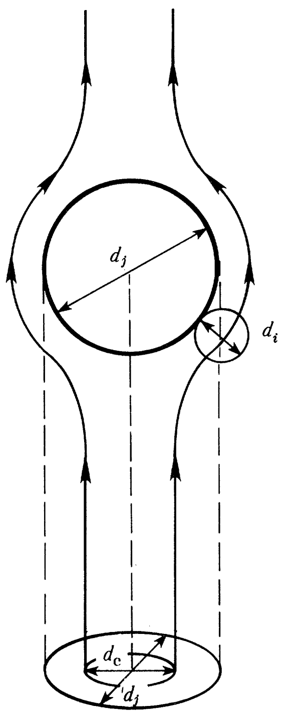

FIGURE 2. Diagram of contact efficiency and the relationship between contact length scale, d_c, and collector length scale, d_j. Contact efficiency is the ratio of effective contact cross section to collector cross section. Calculating efficiency reduces to estimating an appropriate, mechanism-dependent contact length scale.

An extensive body of literature devotes itself to the task of defining contact length scale for various mechanisms (Spielman 1977). A thorough review of this work is beyond the scope of this paper. Expressions for contact efficiency at low Reynolds number are simply summarized. The contact efficiency of a sinking particle when contact is by brownian diffusion is discussed in detail by Levich (1962) and by Csanady (1986) in a marine context. Efficiency is

$$(E_B)_{ij} = 4.04(D_i/w_s d_j)^{\frac{2}{3}}, \tag{10}$$

where D_i is the diffusion coefficient of the collected particles, w_s is the settling velocity of the collector and d_j is the diameter of the collector. Contact efficiency by direct interception is (see Pich 1966):

$$(E_{DI})_{ij} = (d_i/d_j)^2. \quad (11)$$

Contact by inertial impaction (see Fuchs 1964) is:

$$(E_I)_{ij} = (w_{si}\, w_{sj}/gd_j)^2, \quad (12)$$

where w_{si} is settling velocity of contacted particles, w_{sj} is the settling velocity of the collector, g is gravitational acceleration and d_j is collector diameter.

Addressing the case of a 0.3 cm sphere with settling velocity of 0.15 cm s^{-1} sinking through a population of 1 μm particles with settling velocity of 4×10^{-5} cm s^{-1} demonstrates that classical models of contact predict very small contact efficiencies (table 3). Contact by diffusion is most effective with a calculated efficiency of $O(10^{-5})$. This value is well below that required to bestow on marine snow a role in clearing nepheloid layers. Likewise, efficiencies this low severely limit the role of large particles in regulating mid-water size spectra and radionuclide fluxes. For example, using an efficiency of 10^{-5} in equation (1) and other values as given previously for mid-waters, the aggregation rate between marine snow particles and fine material is 10^{-8} cm^{-3} s^{-1}. Under the assumption that scavenging by marine snow is the only removal mechanism for fine material in the mid-ocean, the above aggregation rate yields a residence time of fine particles of order 10^4 years!

TABLE 3. CONTACT MECHANISMS AND EFFICIENCIES BETWEEN 1 μm AND 0.3 cm PARTICLES

contact mechanism		contact efficiency
brownian motion	$(E_B)_{ij} = 4.04(D_i/w_{sj}\,d_j)^{\frac{2}{3}}$	1.6×10^{-5}
direction interception	$(E_{DI})_{ij} = (d_i/d_j)^2$	1.0×10^{-7}
inertial impaction	$(E_I)_{ij} = (w_{si}\,w_{sj}/gd_j)^2$	4.2×10^{-6}

The low values for E_{ij} are puzzling, and suggest either that models of contact are unsound for marine particles or that the size spectrum can indeed be maintained by aggregation with near neighbours. Work by Lal (1980) supports the latter solution to this dilemma, yet the prevailing view in oceanography favours a rapid and reversible exchange between fine suspended matter and fast-sinking particles (Bacon *et al.* 1985; Cho & Azam 1988; Wakeham & Canuel 1988). To pursue a resolution to this important problem, the key assumptions underlying the contact models need to be assessed in a marine context and the possible effects of violation of assumptions on contact efficiency gauged.

ENHANCED CONTACT EFFICIENCIES OF NATURAL PARTICLES

Expressions for contact efficiency (equations (10)–(12)) are derived for solid, smooth, spherical collectors and low particle Reynolds numbers. Particle Reynolds number, *Re*, is defined as $Re = (dw_s/\nu)$, where d is collector diameter, w_s is collector settling velocity, and ν is kinematic viscosity. Marine snow particles are porous and amorphous. In addition, the Reynolds number can exceed unity (Alldredge & Gotschalk 1988). Violation of these assumptions may make this class of particles more efficient collectors than classical theory would predict.

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Direct interception efficiency is the most likely mechanism to be affected by the permeable, irregular nature and high particle Reynolds numbers of marine snow. Brownian contact is controlled by parameters intrinsic to the fluid and to collected particles. Assumptions concerning the collector thus do not affect contact efficiency to a great extent. Inertial contact is quite inefficient because of the vanishingly small inertia of fine marine particles. Inertia is defined by fine-particle parameters and remains relatively unaffected by assumptions regarding the collector. Direct interception is a function of relevant collector diameter and of the likelihood of a particle being located on a streamline which passes within a particle radius of the collector. The choice of a proper collector diameter and definition of streamlines can be affected dramatically by smoothness, sphericity, permeability and Reynolds number of the collector.

Overestimation of collector diameter can occur by using a smooth, impermeable sphere as a model collector. Irregular particles have projections from their surfaces which may act as collectors. The diameter of projections can be much less than overall particle diameter, resulting in enhanced contact efficiency (figure 3). Permeable particles may act as 'roving filters' for which the relevant collector diameter is some function of pore size within the aggregate. This collector diameter is clearly smaller than particle diameter.

The probability of a particle occupying a streamline that takes it within one particle radius of the collector may be underestimated by imposing a smooth, impermeable, spherical, low Reynolds number morphology on marine particles. The penetration of a permeable collector by some streamlines increases contact cross section, thus enhancing efficiency. A roughened surface likewise improves the chances that a particle will occupy an appropriate streamline (figure 3). Finally, for spheres with $Re > 20$ a recirculating eddy forms in the lee of a settling particle (see van Dyke 1982). A fine particle entrained in a wake may approach a collector several times, and gravity favours contact in the lee of a collector whereas it opposes contact on the leading edge of a collector (figure 3). Because fine particles are caught and retained by a wake for a finite amount of time, we propose adoption of the generic term 'wake capture' from the field of cloud microphysics. The term 'wake capture' encompasses two distinct processes in cloud microphysics, the mechanism discussed here which involves particles of disparate sizes and another mechanism by which contact is achieved when a particle is drawn into the wake of a leading particle of like size (see, for review, Pruppacher & Klett 1978). The low number concentration of large particles with trailing wakes in the ocean suggests that encounters between two such particles are rare, thereby limiting the significance of the second mechanism. Thus we opt for the more graphic, less specific term 'wake capture' over the more specific, less descriptive term 'rear capture' proposed by Beard (1974) and Grover (1978).

Of the above mechanisms for enhancing contact efficiency by direct interception, surface roughening may be significant. Because of the difficulties attendant upon modelling flow around all but the simplest geometries (Happel & Brenner 1965), this effect must be explored empirically. By contrast, the very low intra-aggregate flow velocities hypothesized by Logan & Hunt (1987) suggest that penetration rate of particles into an aggregate is quite small. Interception efficiency is not likely to be enhanced dramatically by this mechanism.

Several intriguing lines of evidence argue for a significant role for wake capture in enhancing contact efficiency of marine snow. Wake capture is most effective when the wake is large and when the inertia of collected particles is small. The inertia of fine marine particles is negligible. Large, well-developed, non-shedding wakes develop behind spheres with particle Reynolds numbers of 20–130 (Pruppacher & Klett 1978). Although these Reynolds numbers range

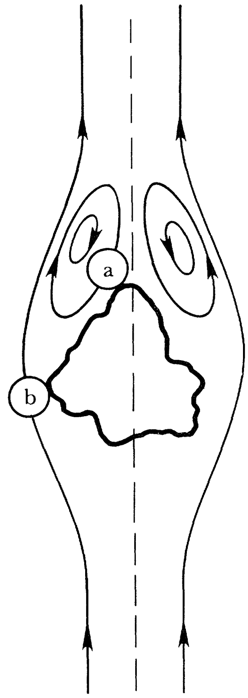

FIGURE 3. Amorphous marine snow particles with Reynolds numbers greater than unity may contact fine material by direct interception more efficiently than low Reynolds number spheres. Two mechanisms are proposed for enhancing the contact efficiency of marine snow. Facilitation of contact of particle a occurs because it is entrained in the wake of the marine snow particle where it may make several passes at the collector and where gravity favours rather than opposes contact. Particle b contacts a projection of the particle with a smaller collector length scale than the entire particle.

somewhat higher than the Reynolds numbers of marine snow particles (Alldredge & Gotschalk 1988), the onset of flow asymmetry and wake formation is likely to occur at lower Reynolds numbers for flow around irregularly shaped marine snow particles. Limited theoretical (Beard 1974; Grover 1978) and experimental studies (Rajagopalan & Tien 1977) suggest that contact efficiencies, when wake capture is considered, may be orders of magnitude greater than contact efficiencies yielded by classical models. Finally, many marine snow particles are comet-shaped. Collection on the trailing side of an initially more spherical particle provides an intuitively simple and physically appealing means for explaining a comet-like morphology.

Wake capture has received little attention in studies of precipitation scavenging because of the larger inertia of collected particles and high Reynolds number of collector drops. Reynolds numbers are kept low in filtration processes, limiting interest in wake capture in this field. Reynolds numbers and particle inertia are in the proper range in the ocean and strongly suggest further study of the mechanism. Such studies are underway at the University of Washington.

CONCLUSION

Predicting suspended sediment dispersal pathways and analysing deep-sea facies both demand knowledge of the mechanisms by which particles reach the bed. Deposition may be controlled entirely by local processes, with particles making a gradual transit into larger size classes by interacting with particles of similar size and depositing in aggregates. Alternatively, nepheloid layers may be swept clean by the rain of particulates from the surface ocean, a process external to the formation of nepheloid layers.

Evidence gleaned from particulate size spectra in the oceans' interiors and from the vertical flux of radionuclides argues in favour of inclusion of a particulate rain term in the modelling of deep-sea sediment dynamics. Paradoxically, however, the values for contact efficiency yielded by particle and radionuclide studies exceed those values predicted by theory by several orders of magnitude.

A review of models of particle contact suggests that the discrepancies between inferred and predicted values of efficiencies arise from differences in actual and assumed particle morphologies. Marine snow particles are permeable and amorphous, they have irregular surfaces, and particle Reynolds numbers are not uniformly less than one. These properties of marine particles open the possibility of significant deviation of actual contact efficiencies from predicted ones. Contact due to direct interception is postulated to be more efficient than predicted because of surface irregularities and because of entrainment of fine particles in the wakes of large snow particles. Good evidence exists for the latter mechanism which is termed 'wake capture'. Little attention has been focused on wake capture, because of its relative lack of importance in the fields that have spawned much of the theory used in studies of aggregate dynamics in the sea.

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Discussion

I. N. McCave (*Department of Earth Sciences, University of Cambridge, U.K.*). It is suggested from time to time in biological circles that organisms can in some way circumvent the physical problems inherent in bringing particles together to form aggregates. Does Professor Nowell think that organisms provide new and different methods of particle aggregation?

A. R. M. Nowell. Organisms are bound by the same physics that govern particle aggregation. Encounter and contact mechanisms are identical. Organisms cannot circumvent physics; however, selective pressure over evolutionary timescales favours optimizing encounter rate and contact efficiency. Such selective pressure manifests itself, for example, in foraging strategy or in the architecture of feeding appendages. Thus organisms do not provide new and different methods of particle aggregation, but they do provide *rates* of particle aggregation that potentially exceed rates in abiotic systems with similar controlling parameters. Defining these biotic aggregation rates must necessarily involve physical as well as biological considerations.

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