Particle Aggregation & Disaggregation

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A Tale of Two Bacons
A Tale of Two Bacons
A Tale of Two Bacons
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Aggregates

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Processes affecting particles

Figure 1: Particle aggregation processes and how they affect particles in the marine environment. Biological aggregation (e.g., fecal pellet production) and physical aggregation by (a) shear and (b) differential sedimentation form large, heterogeneous, rapidly settling particles in the surface waters. In deeper waters, fragmentation and repackaging of this material by zooplankton are the dominant processes that affect aggregate sizes and properties. Microbes decompose material throughout the water column.

Coagulation: the physical processes that bring particles together

TEP: transparent exopolymer particles

Physical processes that bring particles into contact with each other are studied under the label of coagulation. Biological processes are also important in the formation and decomposition of particulate material, but are more complex and involve the formation of constituent particles and colonization (Simon et al. 2002, Kiørboe et al. 2003, Grossart et al. 2006). We refer the reader to recent excellent reviews for more information on related topics such as diatom aggregation (Thornton 2002), transparent exopolymer particles (TEP) (Passow 2002), and the ecology of microbial communities on marine aggregates (Simon et al. 2002).

OBSERVATIONS OF AGGREGATION

Aggregates of detrital organic material have been observed in marine systems for many years (Riley 1963). This material was originally thought to consist of fecal matter and the remains of plankton (Burd & Jackson, Ann. Rev. Mar. Sci., 1, 65–90 (2009)).

Microbes

Zooplankton grazing

Zooplankton interactions

Fragmentation

Coagulation
\[
\frac{dn(m, t)}{dt} = \frac{\alpha}{2} \int_{0}^{m} \beta(m_j, m - m_j)n(m - m_j, t)n(m_j, t) \, dm_j \\
- \alpha n(m, t) \int_{0}^{\infty} \beta(m, m_j)n(m_j, t) \, dm_j \\
- n(m, t) \frac{\nu_s(m)}{z} + I(m, t)
\]
Particle Size Spectra

Variations in spectral slope


\[ n(r) = ar^{-b} \]
Modeled Size Spectra

The mean depth of the euphotic zone in this region was 160 m (DCM), indicating the photic layer where photosynthesis occurs. The GYR stations had extremely low levels of Chl-a, with values significantly lower than those at MAR. The mixed layer depth at GYR was around 170 m depth. The number of spectra from both instruments at both sites followed a nearly straight line at GYR but not at MAR. The slope is not as steep in the size ranges covered by the UVP.

The number of spectra from both instruments at both sites follows a nearly straight line at GYR but not at MAR. The slope is not as steep in the size ranges covered by the UVP. The data show differences in the vertical patterns for the two instruments. The small particle biomass assessment to the hypothesis made on the value increasing reported diameter (Fig. 3). Raw spectra from both instruments show the typical biases at either end of their size ranges.

The aims of the present study are to assess the vertical and temporal variability of the number and mass distributions of marine particles. Samples were collected from 12 L CTD ports the size as Equivalent Spherical Diameter (ESD). Size is a measure of the particle size. The instrument reports the ESD, which is a measure of the particle size. The instrument reports the size as Equivalent Spherical Diameter (ESD).

The two instruments showed different vertical patterns for the two populations of particles (Fig. 4). The small particle spectra detected by the HIAC showed higher concentrations in the lower and larger end truncated spectra to account for methodological biases. The different instruments have different size ranges covered by the UVP. The data follow a nearly straight line at GYR but not at MAR. In this latter site, the slope is not as steep in the size ranges. The data follow a nearly straight line at GYR but not at MAR. The slope is not as steep in the size ranges.
Export relative to single cells. Despite this, the model predicts both the existence of the contribution to export is only measurable using size-specific field data. The largest particles are still a small fraction of the total flux, and the formation of these particles and their decrease of sinking rate was confined to a small, feature driving export flux over the first 10 d. For the largest particles, however, the model indicates a clear increase in the dominance of the biomass by unaggregated particles. The flux of solitary cells would have been the dominant expected at 110 m if the flux from at 65 m is corrected for the travel times of the different size fractions to reach 110 m; the dashed blue line represents the flux predicted from the model using standard parameters, INside the fertilized patch (L); OUTside the control region after 11 d is consistent with the relatively small increase in biomass (3X increase in POC) and the bacterial solubilization of particles should have been slow because of the low water temperatures (2 ℃); lower shear = 1 s⁻¹; higher shear = 10 s⁻¹; N [C0/C24]/C24 = 7.75). See color version of this figure in the HTML.

The lack of a substantial (3X) observed in SOIREE, and a factor of 3 of the data; see Figure 2). The l a r g e s t d i f f e r e n c e s b e t w e e n o b s e r v e d a n d p r e d i c t e d size spectra are for the smallest particles, where the concentrations, as observed in the field data, were low near the surface and should have been lower than expected at 110 m. The accelerated flux in the large size fraction associated with the planktonic coagulation model in replicating the relatively fine fractal index Df = 2 (0.73). See color version of this figure in the HTML.

The model indicates it would take diatoms in the F. k e r g u e l e s i s layer and the sediment traps, we believe that these were the possible importance of the nanoplankton (see text). Solid black line denotes the amalgamated particle data points are shown, but lines connect acceptable points on the 11th day (lagged model). RMS difference between the flux spectra from the SOIREE and model at 65 m; the dashed blue line represents the flux with time, suggesting that it is possible to resolve the accelerated flux in the large size fraction associated with the planktonic coagulation model in replicating the relatively fine fractal index Df = 2 (0.73). See color version of this figure in the HTML.

4. Discussion

The measured particle flux spectra at day 11 of the fertilized patch (R). S2, S3 (4x S2), and S4 (24x S2) are (STD) parameters, INside the fertilized patch (L); OUTside the patch, with no curve fitting, was 0.89 (10⁻⁷). Validation yielded values from 0.44 to 2.3. Of all the extra parameters tested, only increasing the initial particle concentration improved the fit (to RMS = 0.44, or within 10 of the observations, with flux ranging over 6 orders of magnitude (Figure 2). Other parameter choices in the model at 65 m; the dashed blue line represents the flux predicted from the model using standard parameters, INside the fertilized patch (L); OUTside the control region after 11 d is consistent with the relatively small increase in biomass (3X increase in POC) and the bacterial solubilization of particles should have been slow because of the low water temperatures (2 ℃); lower shear = 1 s⁻¹; higher shear = 10 s⁻¹; N [C0/C24]/C24 = 7.75). See color version of this figure in the HTML.

Maximum Cell Concentrations

Coagulation kernels

\[
\frac{dn(m, t)}{dt} = \frac{\alpha}{2} \int_0^m \beta(m_j, m - m_j) n(m - m_j, t) n(m_j, t) \, dm_j \\
- \alpha n(m, t) \int_0^\infty \beta(m, m_j) n(m_j, t) \, dm_j \\
- n(m, t) \frac{\nu_s(m)}{z} + I(m, t)
\]

Determines the rate of collisions between particles — we have good theories for these
Physical Coagulation

**Brownian Motion**

\[ \beta(r_i, r_j) = \frac{2}{3} \frac{kT}{\mu} \frac{(r_i + r_j)^2}{r_i r_j} \]

**Fluid Shear**

\[ \beta(r_i, r_j) = 1.3 \left( \frac{\varepsilon}{\nu} \right)^{1/2} (r_i + r_j)^3 \]
\[ \beta(r_i, r_j) = \frac{p^2}{1 + 2p^2} \left( \frac{\varepsilon}{\nu} \right)^{1/2} (r_i + r_j)^3 \]

**Differential Sedimentation**

\[ \beta(r_i, r_j) = \pi (r_i + r_j)^2 |w_j - w_i| \]
\[ \beta(r_i, r_j) = 0.5\pi r_j^2 |w_j - w_i| \]
\[
\frac{dn(m, t)}{dt} = \frac{\alpha}{2} \int_0^m \beta(m_j, m - m_j)n(m - m_j, t)n(m_j, t) \, dm_j \\
- \alpha n(m, t) \int_0^\infty \beta(m, m_j)n(m_j, t) \, dm_j \\
- n(m, t) \frac{\nu_s(m)}{Z} + I(m, t)
\]

Determines the probability that particles will adhere once they have collided.
Nanoparticles

MA04CH09-Verdugo ARI 22 August 2011 9:32

of both tangles and weak, low-energy bonds (Verdugo 1990). These features make the assembly/dispersion dynamics of tangled networks depend primarily on polymer length—in fact, on the second power of the contour length of the assembled polymers (Edwards & Grant 1973). Assembly and dispersion are diffusion-limited processes. Longer flexible polymers have a higher probability of becoming entangled and forming networks. Conversely, dispersion of assembled networks requires that polymers randomly reptate (axially diffuse) their way out of the network. Diffusion times depend on the second power of the length of the random walk, which in this case is the length of the polymers. Thus, the stability of tangled networks and thereby the equilibrium size of tangle gels is critically limited by chain length (de Gennes & Léger 1982, Doi & Edwards 1998). Shorter polymers not only can walk out of tangles faster, but are likely to have a much lower number of low-energy cross-links. The resulting gels are smaller and short-lived. Axial reptational diffusion is also at the center of a critical feature of tangled networks—namely, it makes annealing between tangled gels possible. This is a paramount feature because it allows polymers from neighboring gels to interpenetrate their respective networks to form larger gels (Figure 1).

In short, low-energy interactions are an important additional factor that contributes to the stability of tangled gels. Physical gels reach an assembly/dispersion equilibrium that is reversible and depends not on specific chemical composition or complementary reactive residues but primarily on their concentration, and on physical features including charge density (ζ-potential), hydrophobic/hydrophilic domain ratios, flexibility, topology (linear, branched, star, etc.), quaternary conformation (globular, beta sheet, random coil, etc.), and particularly the size (contour length) of the polymer chains. Assembly also depends on the characteristics of the solvent—including dielectric...
\[
\frac{dn(m, t)}{dt} = \frac{\alpha}{2} \int_0^m \beta(m_j, m - m_j) n(m - m_j, t)n(m_j, t) \, dm_j \\
- \alpha n(m, t) \int_0^\infty \beta(m, m_j) n(m_j, t) \, dm_j \\
- n(m, t) \frac{w_s(m)}{z} + I(m, t)
\]
Settling Velocity


![Graph showing the relationship between settling speed (m d⁻¹) and apparent diameter (cm)].

- Carder et al., 1982
- Azetsu Scott & Johnson, 1992
- Smayda, 1970
- Shanks & Trent, 1980

Other lines and markers represent:
- Alldredge & Gotschalk, 1988
- Alldredge & Gotschalk, 1989
- Syvitski et al., 1995
- Stokes' Law
- Δ=0.01, D=1.79
- Δ=0.05, D=2.33
that much of the mass not represented by organic matter is composed of mineral ballast, the %OC results suggest that the OC:ballast ratio is slightly higher for more slowly settling material. During the second deployment, the %OC and %TN data displayed a fair amount of scatter (see analysis above), but the OC:TN ratios had a distinct step toward lower OC:TN values at SVs less than ~10 m d\(^{-1}\), again suggesting enrichment in carbohydrate-like material at slow settling velocities.

NetTrap and elutriator—The free-drifting NetTrap was deployed several times at the DYFAMED site in May 2003 for time periods ranging between 19 and 72 h and, because of the short deployment durations, with no poisons or preservatives in the cod end. Although the NetTrap was designed to collect large amounts of material rather than to quantitatively measure flux, the particle "flux" collected by this trap at 200 m (170 mg m\(^{-2}\) d\(^{-1}\)) was similar to fluxes measured by the moored 200-m arrays just before (153 mg m\(^{-2}\) d\(^{-1}\)) and after (165 mg m\(^{-2}\) d\(^{-1}\)) the NetTrap deployment. The NetTrap does not appear to collect suspended particles other than those in the trap at the time that it is closed. No particles were visible on the net walls after recovery, and the net was recovered in the closed position, so no particles would have been collected during ascent.

The large amount of material collected by the NetTrap allowed elutriation of the particles by SV into discrete classes. In these initial trials, the elutriator was operated with a water flow that separated particles into five fractions of >230, 230-115, 115-58, 58-29, and <29 m d\(^{-1}\). Particles with settling rates of <29 m d\(^{-1}\) were removed from the flow stream using a flow-through centrifuge. The elutriated mass was distributed into the 5 fractions as 57.2%, 13.4%, 1.54%, 4.74%, and 23.1% of the total (Fig. 7). Hence, 80% of the elutriated mass had SV >115 m d\(^{-1}\), consistent with the sinking velocity/mass flux profiles of the SV traps (62% of total mass flux sank at >98 m d\(^{-1}\); Figs. 2 and 6A, tubes 2-5).

The %OC in the elutriated fractions followed the inverse pattern as mass (Table 2; Fig. 7). The OC composition (20%) in the NetTrap samples was more similar to the higher values found in the later trap period between mid-May and July. Results showing differences in radionuclide and lipid composition and lability with respect to decomposition between elutriator stages are available on the MedFlux web site (see above) and will be published elsewhere.

We compared mass flux densities of elutriated particles with those separated by SV-IRS traps. Because the settling-velocity intervals of the elutriator and SV-IRS were not the same, a comparison requires that mass fluxes be normalized for the different settling velocities. We accomplished this by dividing mass fluxes in each settling-velocity interval by \(\log_{10}(SV_{max}) - \log_{10}(SV_{min})\) for that interval (Fig. 8). In this way, the area of each column represents mass flux, and the height of the column is the flux density, \(d\text{flux}/d\log_{10}(SV)\). As shown in Fig. 8, the May elutriator results fell between the March-May and May-June SV-IRS results.

Fig. 9. Effect of combining the higher subsurface nutrient concentration \( N_{/p15}/afii9839M \) with TEP (colloid) release as \( r_{/p2}/afii9839 \) m particle \( /p59; bT3xxx \) compared to the base case \( /p42; base \).

Fig. 10. Two-dimensional particle distribution at \( t_{/p30}50 \) d for base. The results are shown as the total mass per section (A) and flux per section (B) rather than as the more mathematical two-dimensional particle size spectra. The upper bounds of sections in the \( /afii9838 \) (length) direction are \( 2^{/p59}(2^{/p16/p30}/p66/p5/p18)^{/p59} \) those of the lower bounds; excess mass of the upper bounds in the mass direction are also \( 2^{/p59} \) those of the lower bounds.

Disaggregation

\[
\frac{dQ_i(t)}{dt} = - Q_i(t) \sum_{j=1}^{i-1} \int_{v_{j-1}}^{v_j} \int_{v_{j-1}}^{v_{j-1}+w} \frac{(v - w)p_e(w)g_e(v)}{v(v_i - v_{i-1})P_e(v_{i-1})} dv dw
\]

\[
- Q_i(t) \sum_{j=1}^{i-1} \int_{v_{j-1}}^{v_j} \int_{v_{j-1}}^{v_j} \frac{wp_e(w)g_e(v)}{v(v_i - v_{i-1})P_e(v_{i-1})} dv dw
\]

\[
+ \sum_{l=i+1}^{m} Q_l(t) \sum_{j=1}^{l-1} \int_{v_{j-1}}^{v_j} \int_{v_{j-1}+w}^{v_{j-1}+w} \frac{(u - w)p_e(w)g_e(u)}{u(u_l - u_{l-1})P_e(u_{l-1})} du dw
\]

\[
+ \sum_{l=i+1}^{m} Q_l(t) \int_{v_{l-1}}^{v_l} \int_{v_{l-1}}^{v_l} \frac{vp_e(v)g_e(u)}{u(u_l - u_{l-1})P_e(u_{l-1})} du dv
\]

\[
- Q_i(t) \int_{v_{l-1}}^{v_l} \frac{g_s(v)}{(v_i - v_{i-1})} dv
\]

\[
+ \sum_{l=i+1}^{m} Q_l(t) \int_{v_{l-1}}^{v_l} \int_{u_{l-1}}^{u_l} \frac{vp_s(v, u)\nu(u)g_s(u)}{u(u_l - u_{l-1})} du dv
\]

\[
+ Q_i(t) \int_{v_{l-1}}^{v_l} \int_{u_{l-1}}^{v} \frac{vp_s(v, u)\nu(u)g_s(u)}{u(u_l - u_{l-1})} du dv.
\]
Disaggregation

Erosion of Fines

Splitting into approximately equal particles
Bio-disaggregation

Fig. 4. Disruption of a fragile diatom aggregate by a tethered Euphausia pacifica adult (16 mm in length).

(A) A 4-mm aggregate sinking past the side of the animal’s head. (B) The aggregate has been entrained, struck by the beating pleopods, and ejected as a stream of fragments. Most marine snow is stronger than diatom snow and would break into a few, larger pieces. Aggregate strength is a function of aggregate size (Alldredge et al., 1990; Hill, 1998), and very small aggregates (1-2 mm diameter) required direct contact with a pleopod to fragment while larger aggregates were also fragmented by fluid shear in eddies generated by swimming.

Physical Disaggregation

Disaggregation: Theory

In general, the coagulation equation admits no analytical solution. In the absence of disaggregation, there are two mechanisms by which particles can leave the size domain of the concentration of colloids. Some of these particles will interact with larger particles via shear and other forces. The result is either an accumulation or relative deficit in the concentration of colloids. These interactions can be incorporated via different sedimentation. In order for steady-state assumptions made in the dimensional analysis to hold, the rates at which particles of a given size number concentration of particles in a particular size range increases the rate of aggregation and disaggregation. In this simulation, the accumulation of material between widely separated size classes without disaggregation im pedes the continual formation of particles at the transition size.

Disaggregation is an additional mechanism that can affect the shape of the particle size spectrum now arises from the rates of aggregation either side of the division are not equal. The result is either an accumulation or relative deficit in the size spectrum or inferring properties of the particles from material between widely separated size classes with and without disaggregation. In natural systems, these mechanisms operate over a range of particle creation, coagulation, sinking, and disaggregation. In natural systems, these mechanisms operate over a range of particle creation, coagulation, sinking, and disaggregation. In this simulation, the assumption of steady state but rather from the ancilliary assumptions listed in the Introduction do not hold. Consider, for example, by assuming that only particles larger than those being considered can aggregate forming particles larger than the size range. If one stops one of these mechanisms, for instance, by assuming that only particles larger than a particular size, either through forming larger particles or by removing particles from the system altogether, this may not be the case.

Incorporating the assumption that only one aggregation mechanism operates in each size range introduces sharp transitions in the particle size spectrum (Figure 1c) because the rates of aggregation either side of the division are not equal. The result is either an accumulation or relative deficit in the particle size spectrum now arises from the rates of aggregation either side of the division are not equal. The result is either an accumulation or relative deficit in the particle size spectrum now arises from the rates of aggregation either side of the division are not equal. The result is either an accumulation or relative deficit in the size spectrum or inferring properties of the particles from material between widely separated size classes with and without disaggregation. In natural systems, these mechanisms operate over a range of particle creation, coagulation, sinking, and disaggregation. In this simulation, the assumption of steady state but rather from the ancilliary assumptions made in the dimensionalanalysis. This indicates differences between the two methods arise not from the creation of fecal pellets, this may not be the case.
Disaggregation?

Jouandet et al. (2014, accepted)
Flux of Small Cells


Thorium Activity [dmp cm$^{-3}$]

Jackson & Burd, 2014
Integrated Approaches


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**Integrated Approaches**

**Figure 8.** Phytoplankton (broken line) and total (straight line) sedimentation at 800 m for different model scenarios, together with local measurements of sedimentation on station S04 (circles; data courtesy of S Honjo).

Upper panel: low (0.1) stickiness.

Mid panel: “Sticky” scenario.

Lower panel: “Detritus” scenario (no aggregation). Model results have been averaged over trap sampling intervals. Units are mmol N m$^2$/d.

**Table 3.** Maximum phytoplankton (max. PHY), Annual primary production (PP) (integrated over depth), grazing (integrated over depth, given as percent of primary production) and sedimentation 800 m for different simulations in the western and central Arabian Sea.

<table>
<thead>
<tr>
<th>Location</th>
<th>max. PHY</th>
<th>PP</th>
<th>Grazing</th>
<th>Flux (800 m)</th>
<th>% PHY</th>
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<td>Central Arabian Sea</td>
<td>0.6</td>
<td>210</td>
<td>73</td>
<td>2.6</td>
<td>18</td>
</tr>
<tr>
<td>Western Arabian Sea</td>
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<td>252</td>
<td>78</td>
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<tr>
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<td>76</td>
<td>4.1</td>
<td>-</td>
</tr>
</tbody>
</table>

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What do we still need to know?

- A lot more about disaggregation
  - Rates, daughter particle size distributions, particle strengths, preferred modes of breakup...

- The relative contributions to physical and biological aggregation.
  - Particle type & properties, concentration, settling speed, biology

- Representing remineralization in models
  - How do particles degrade? How does particle structure affect degradation rates?
What do we still need to know?

- Representing remineralization in models

  - How do particles degrade? How does particle structure affect degradation rates?
2 size classes, prescribed settling.

2 size classes, prescribed settling, high grazing.

Ballast Model

Simple Spectral Model