The Fate of Particulate Organic Material in the Oceans

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Outline

- Why is remineralization in the oceans important?
- Processes affecting remineralization
 - Particle type & properties, concentration, settling speed,
 biology
- Representing remineralization in models

Why?

- Flux
 - Crucial role in biogeochemical cycles in the ocean.

Olimate

• Sinking particles can sequester carbon in the deep

Trace Metals

• Particles provide surfaces for trace-metal sorption

Deep Water Ecology

• Sinking particles provide food for deep water organisms

Processes affecting particles



Burd & Jackson, Ann. Rev. Mar. Sci., 1:65–90, 2009

eWOCE

Nitrate [µmol/kg]







Feeding the Deep Ocean?



Carbon sequestration



Kwon et al., *Nature Geosci.*, 2:630–635, 2009

What are marine particles?



Alice Alldredge



Debbie Steinberg



Richard Lampitt



Alice Alldredge

Nanoparticles



Verdugo, Ann. Rev. Mar. Sci., 4:375–400,2012

Capturing Particles

Stemmann et al., ICES J. Mar. Sci., 65:433-442, 2008

Particulate Flux

Particulate flux = Concentration × Settling Velocity

54:639–658, 2007

Particle type: fluffy aggregates

Ebersbach et al., Deep-Sea Res. II, 58:2260-2276, 2011

Fig. 2. Size characteristics of marine snow. A. Aggregate volume as a function of diameter (regression coefficient, rc, = 0.97; P < 0.001). B. Aggregate dry weight as a function of diameter (rc = 0.71; P < 0.001). C. Aggregate porosity as a function of diameter: O-diatom floos: -all other marine snow regardless of origin (rc = 0.79; P < 0.001). D. Aggregate excess density as a function of diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.79; P < 0.001). D. Aggregate excess density as a function of diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.71; P < 0.001). D. Aggregate excess density as a function of diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.71; P < 0.001). D. Aggregate excess density as a function of diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.71; P < 0.001). D. Aggregate excess density as a function of diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.71; P < 0.001). D. Aggregate excess density as a function of diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.71; P < 0.001). D. Aggregate excess density as a function of diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.19, P < 0.001) is the second diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.19, P < 0.001 is the second diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.19, P < 0.001) is the second diameter (rc = 0.19, P < 0.001 is the second diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.19, P < 0.001) is the second diameter (rc = 0.19, P < 0.001 is the second diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.19, P < 0.001 is the second diameter (rc = 0.19, P < 0.001 is the second diameter (rc = 0.19, P < 0.00

snow in situ as a function of various particle characteristics. Mean settling rate was 74 ± 39 m d⁻¹. Sinking speed increased exponentially with particle diameter (Fig. 3A). Settling velocities increased with the increasing ratio of volume to projected area, as predicted by settling theory (Fig. 3B).

Settling rate in situ increased exponentially with aggregate dry weight (Fig. 3C). We compared the size-specific settling rates of marine snow determined in the laboratory with rates for similarly sized and shaped aggregates determined in situ with dry weight as an accurate measure of aggregate size. Despite minimal handling of particles, settling velocities measured in the laboratory were consistently higher, by up to four times, than those of similarly sized aggregates measured in situ (Fig. 3C). No significant statistical correlation could be found between sinking rate and dry weight of aggregates studied in the laboratory.

Although settling theory predicts that the sinking rate of an object settling in a fluid is a function of the excess density of the object, our data did not yield a significant relationship between excess aggregate density, as calculated by our methods, and sinking rate (Fig. 3D).

We measured or derived all of the dimensional terms in the force balance Eq. 1 for a settling object. Thus, we can directly calculate the drag coefficient, C_D , for each sinking aggregate. Calculations of C_D for our nonspherical aggregates can provide insight into the effects of shape and other variables that potentially alter the settling behavior of marine snow relative to sinking spheres.

Particle type: fecal aggregates

Ebersbach et al., Deep-Sea Res. II, 58:2260-2276, 2011

Particle type: cylindrical pellet

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Particle type: ovoid pellet

Ebersbach et al., Deep-Sea Res. II, 58:2260-2276, 2011

Alldredge, Deep-Sea Res. 1, 45:529–541, 1998

Particle type: phyto cells

Ebersbach et al., Deep-Sea Res. II, 58:2260-2276, 2011

140 m 290 m

Ebersbach et al., *Deep-Sea Res. II*, 58:2260–2276, 2011

Smayda, Limnol. Oceanogr. 14:621–625, 1969

Fowler & Small, *Limnol. Oceanogr.*, 17:293– 296, 1972

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Picheral et al., *Limnol. Oceanogr. Methods*, 8:462–473, 2010

Particle Size Spectra

Jackson et al., Deep-Sea Res. 1997

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Particle Size Spectra

Jackson et al., Deep-Sea Res. 1997

Variations in spectral slope

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Settling Velocity

Stemmann et al., 2004

Peterson et al., Limnol. Oceanogr. Methods, 3:520–532, 2005

Non-calcifying

Calcifying

(A)

2.5

Engel et al., *Deep-Sea Res. II*, 56:1396–1407, 2009

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Engel et al., *Deep-Sea Res. II*, 56:1396–1407, 2009

Zooplankton

Vertical Migration

Steinberg et al., *Deep-Sea Res. II*, 55:1615–1635, 2008

Microbial Processes

COG FUNCTIONAL CATEGORIES

- C: Energy production and conversion
- **D:** Cell cycle control, cell division, chromosome partitioning
- E: Amino acid transport and metabolism
- F: Nucleotide transport and metabolism
- G: Carbohydrate transport and metabolism
- H: Coenzyme transport and metabolism
- I: Lipid transport and metabolism
- J: Translation, ribosomal structure and biogenesis
- K: Transcription
- L: Replication, recombination and repair
- M: Cell wall/membrane/envelope biogenesis
- N: Cell motility
- **O:** Posttranslational modification, protein turnover, chaperones
- P: Inorganic ion transport and metabolism
- **Q:** Secondary metabolites biosynthesis, transport and catabolism
- R: General function prediction only
- S: Function unknown
- T: Signal transduction mechanisms
- U: Intracellular trafficking, secretion, and vesicular transport
- V: Defense mechanisms

Ivars-Martinez et al., ISME Journal, 2:1194-1212, 2008

Degradation Rates

Iversen & Ploug, Biogeosciences, 10:4073–4085,2013

> C specific degradation rate = 0.03 ± 0.01

C specific degradation rate = 0.12 ± 0.03

Empirical Models

 $F(z) = F_{100} \left(\frac{z}{100}\right)^{t}$

$b = -0.973 \rightarrow -0.319$

b = -0.858

Burd and Passow (unpubublished)

2 size classes, prescribed settling, high grazing

Ballast Model

Gehlen et al., Biogeosciences, 2006

2 size classes, no aggregation, prescribed settling

Simple Spectral Model

Primeau, Deep-Sea Res. 1, 53:1335-1343, 2006

Filter feeder scaling factor = 0.307 m⁻³ Particle breaker scaling factor = 0.14 m⁻³ Passive flux feeder scaling factor = 0.063 m⁻³ Mesozooplankton scaling factor = 250 m⁻³

Stemmann et al., Deep-Sea Res. I, 51:885–908

Clegg & Whitfield, Deep-Sea Res. I, 37:91–120, 1991

Marchal & Lam, Geochim. Cosmochim. Acta, 90:126–148, 2012

Two Size-Classes

$$\frac{dP_{S}}{dt} = \mu P_{S} - \tilde{\beta} P_{S} - \frac{\nu_{S}}{z} P_{S}$$
$$\frac{dP_{L}}{dt} = \tilde{\beta} P_{S} - \frac{\nu_{L}}{z} P_{L}$$

Coagulation Equation

$$\frac{\mathrm{d}n(\mathrm{m},\mathrm{t})}{\mathrm{d}\mathrm{t}} = \frac{\alpha}{2} \int_0^{\mathrm{m}} \beta(\mathrm{m}_j, \,\mathrm{m} - \mathrm{m}_j) n(\mathrm{m} - \mathrm{m}_j, \,\mathrm{t}) n(\mathrm{m}_j, \,\mathrm{t}) \,\mathrm{d}\mathrm{m}_j$$
$$- \alpha n(\mathrm{m}, \,\mathrm{t}) \int_0^{\infty} \beta(\mathrm{m}, \,\mathrm{m}_j) n(\mathrm{m}_j, \,\mathrm{t}) \,\mathrm{d}\mathrm{m}_j$$
$$- n(\mathrm{m}, \mathrm{t}) \frac{w_s(\mathrm{m})}{z} + I(\mathrm{m}, \mathrm{t})$$

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Two Size-Classes

$$\frac{\mathrm{d}\mathsf{P}_{\mathrm{S}}}{\mathrm{d}t} = \mu\mathsf{P}_{\mathrm{S}} - \beta_{1}\mathsf{P}_{\mathrm{S}}^{2} - \beta_{2}\mathsf{P}_{\mathrm{S}}\mathsf{P}_{\mathrm{L}} - \frac{\nu_{\mathrm{S}}}{z}\mathsf{P}_{\mathrm{S}}$$
$$\frac{\mathrm{d}\mathsf{P}_{\mathrm{L}}}{\mathrm{d}t} = \beta_{1}\mathsf{P}_{\mathrm{S}}^{2} + \beta_{2}\mathsf{P}_{\mathrm{S}}\mathsf{P}_{\mathrm{L}} - \frac{\nu_{\mathrm{L}}}{z}\mathsf{P}_{\mathrm{L}}$$

Two size classes, second order aggregation, large/small particle interactions

Full aggregation model

Burd, J. Geophys, Res., 2013

Burd & Jackson, Env. Sci. Technol., 36:323-327, 2002

Future Work

- Size resolved aggregation and flux models
 - Underway
- Better understanding of settling velocities
- Better understanding of biological processes
 - Particle repackaging, microbial processes

- What determines particle sinking velocities?
- Details matter!
- Are there simple relationships between degradation and physical parameters?
- How best to incorporate remineralization into models?

