Particle Dynamics in the Ocean:

Marine Particle Processes and their Representation

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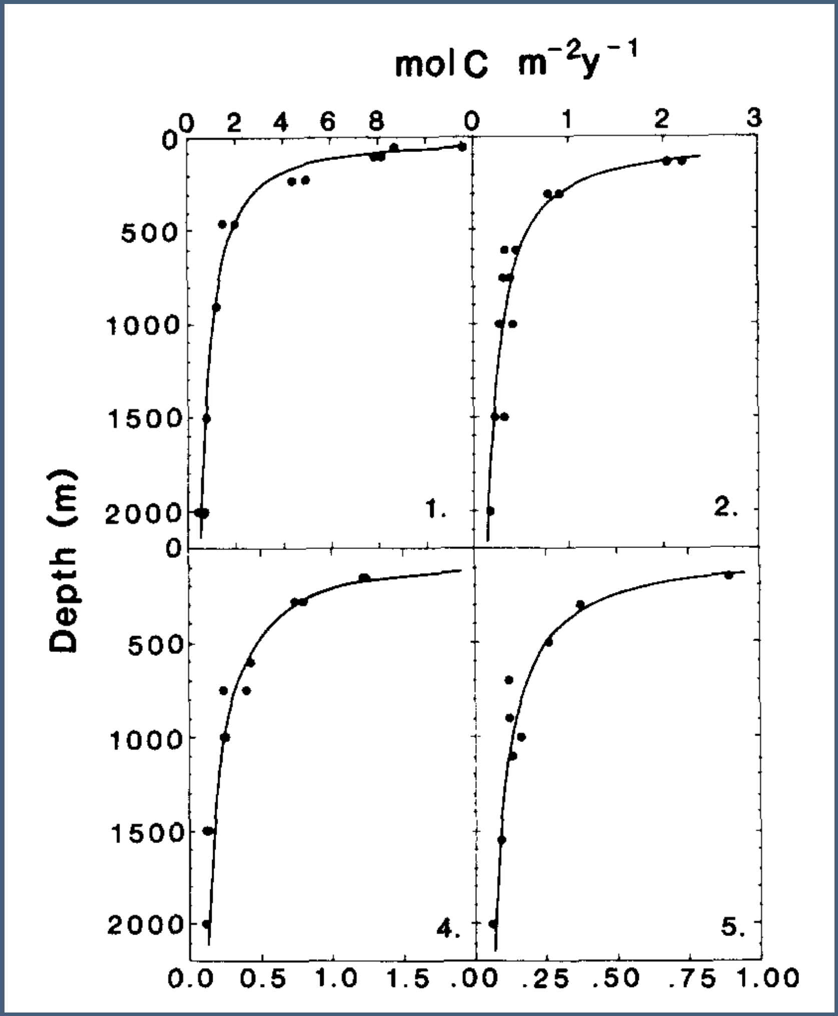
Thanks to: George Jackson, Iris Kriest, Hyung-Tek Oh, Uta Passow, Aisling Metcalfe, Serge Stoll

Outline

- How do we describe particles?
- How do we represent particle dynamics?

Martin Curve

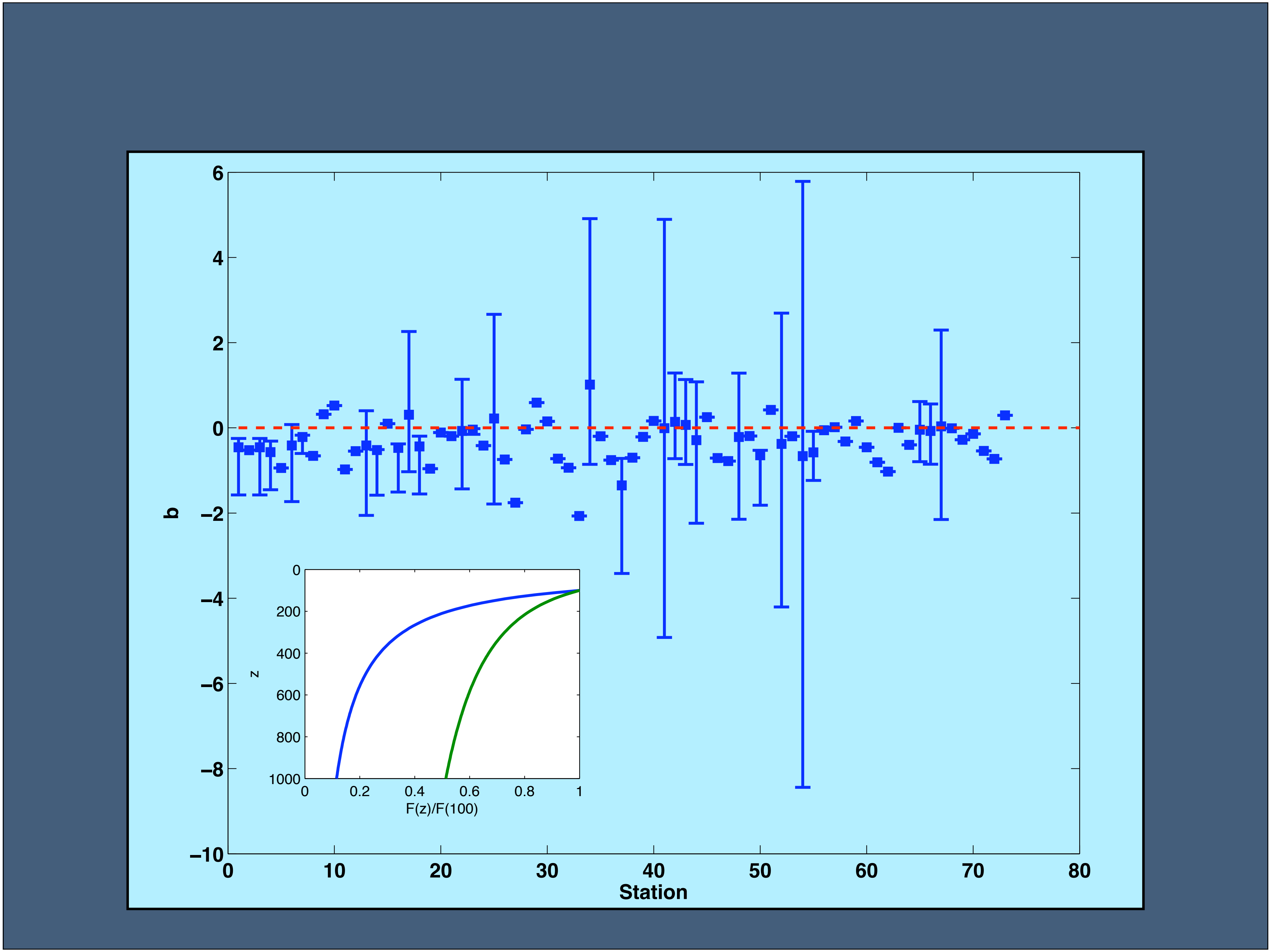


Martin et al., 1987

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

$$b = -0.973 \rightarrow -0.319$$

$$b = -0.858$$



6
4
2
0
−2
−4
−6
−8
−10
b
0
10
20
30
40
50
60
70
80
Station
0
200
400
600
800
1000
z
0
0.2
0.4
0.6
0.8
1
F(z)/F(100)

Some Philosophy

- **Modeling as simulation**
  - *Reproduce the data*
  - *Fit simple functions*
- **Modeling as theory**
  - *Use first principles to make predictions*
  - *Allow for spatial & temporal variability*
- **Suite of models at different scales**

How to classify particles?

Biogeochemical function

Particle Size

Flux contribution

Particle Settling Speed

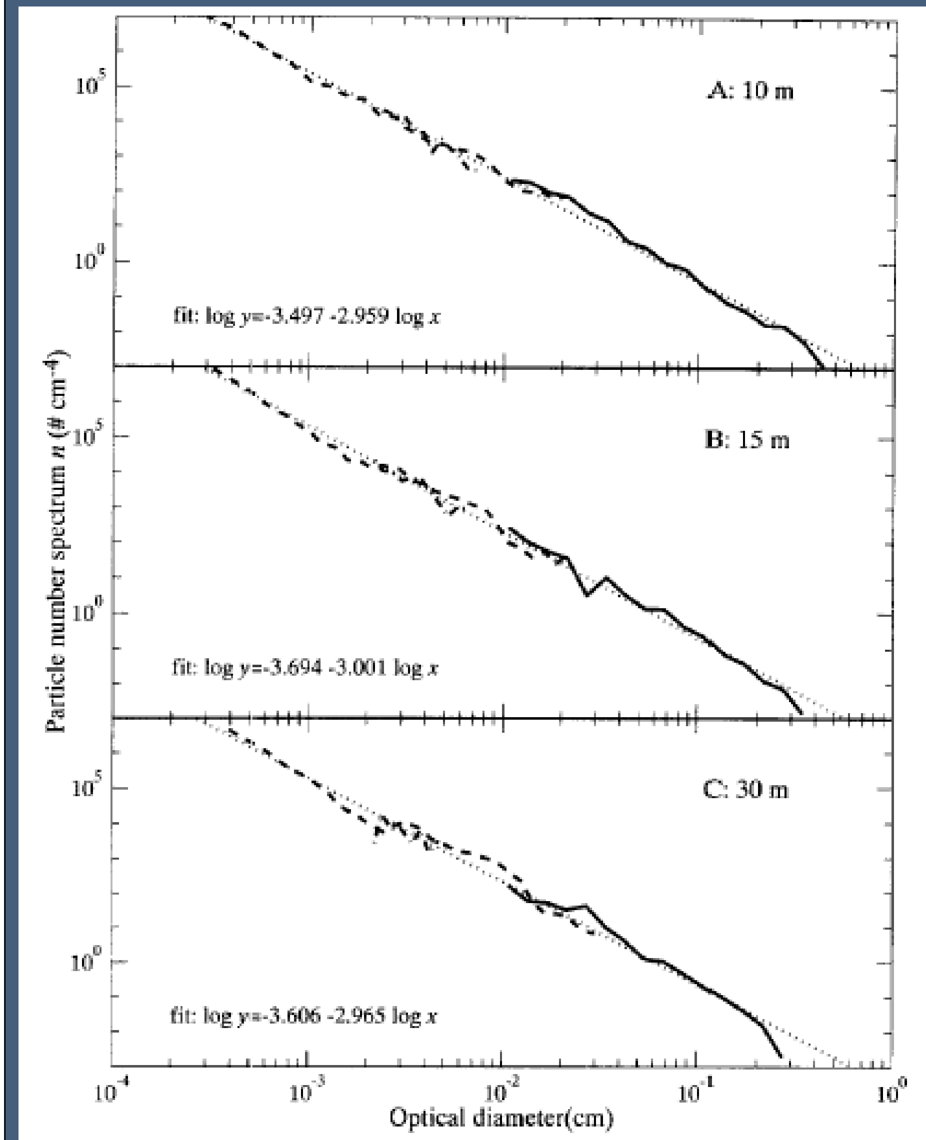
Ecosystem function

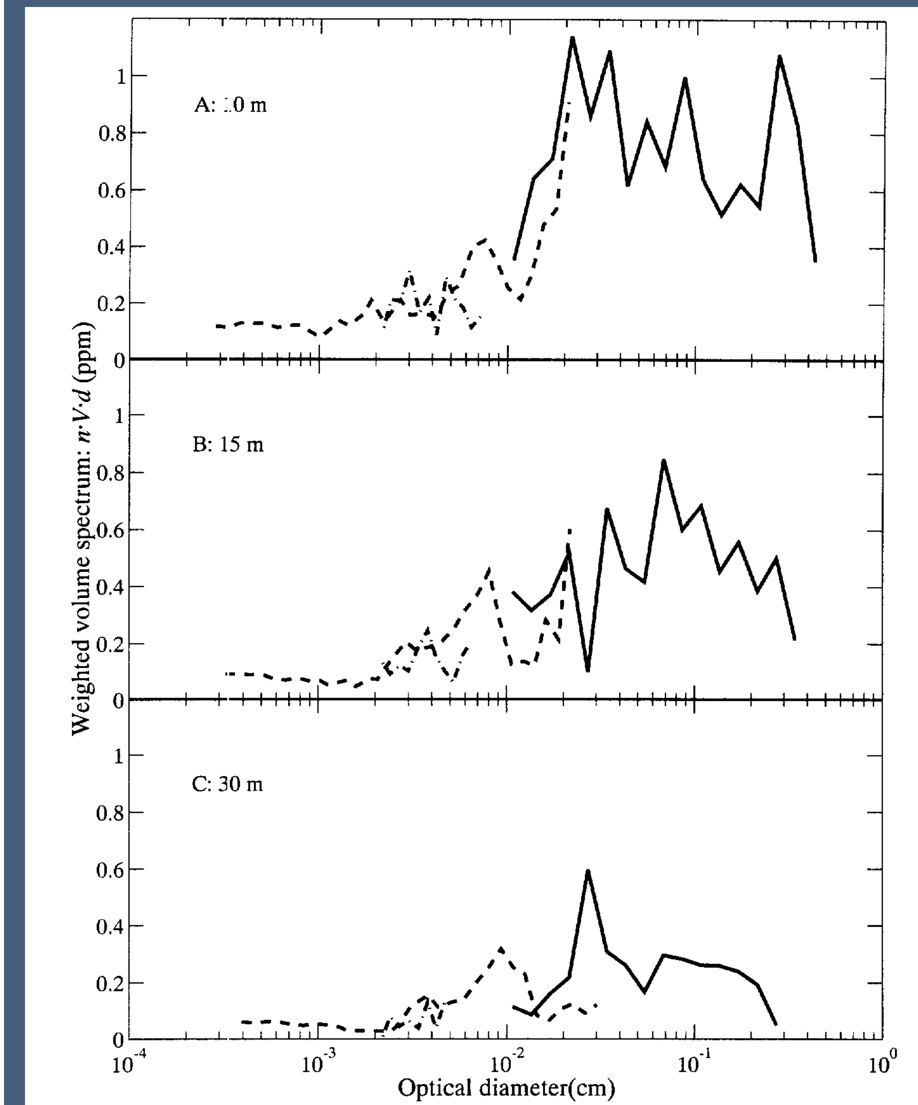
Particle Type

???

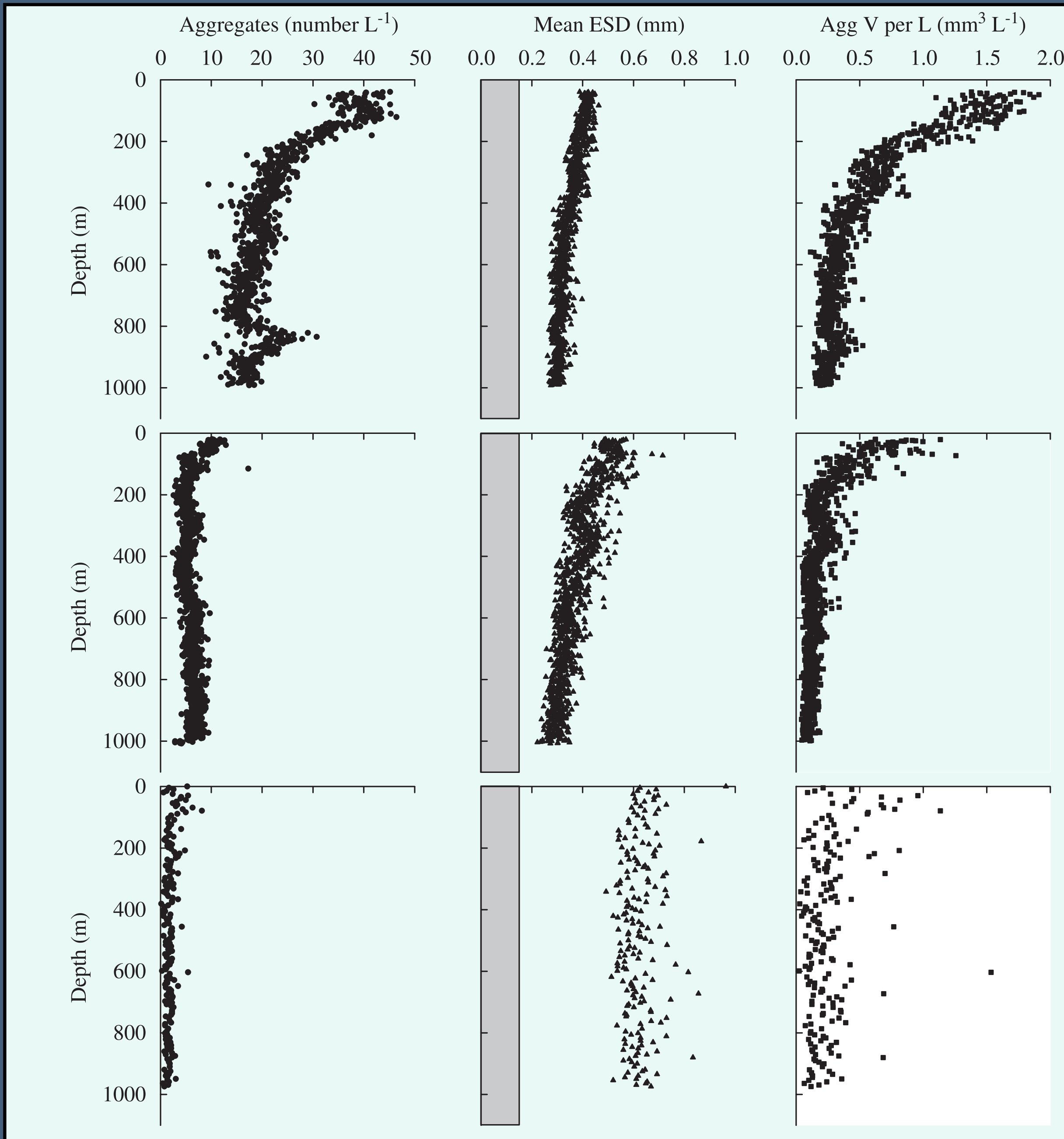
???

Particle Size Spectra





Jackson et al., 1997



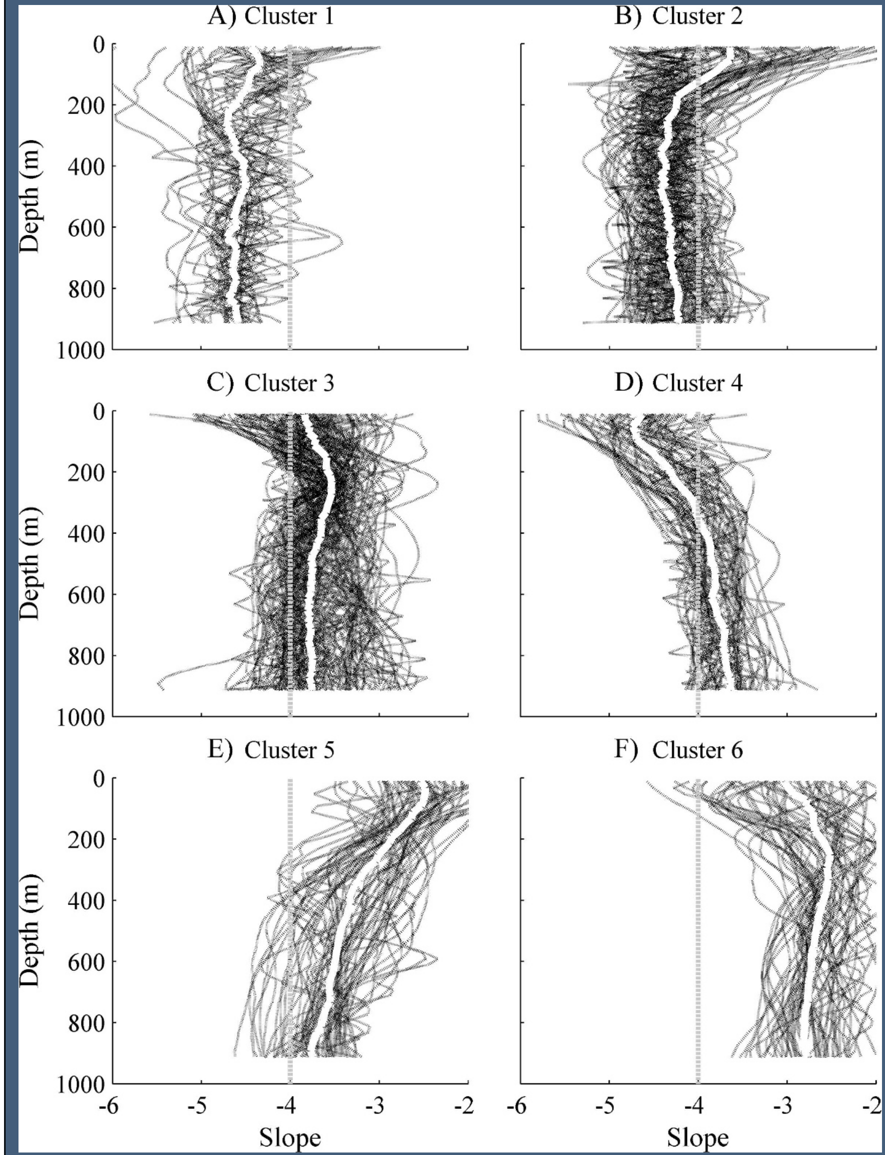
Southern Ocean

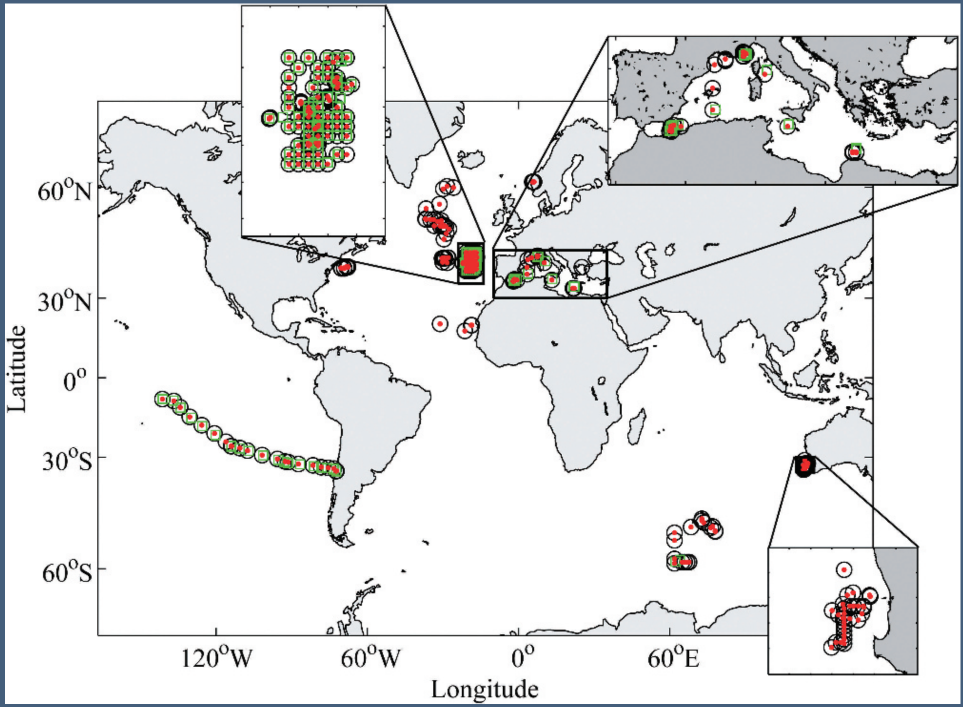
Eastern Atlantic

Equatorial Pacific

De La Roch & Passow, 2007 (Data from Guidi et al.)

Variations in spectral slope





Guidi et al., 2009

Coagulation Equation

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

Coagulation kernels

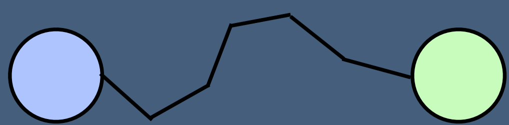
$$\frac{dn(m,t)}{dt} = \frac{\alpha}{2}\int_0^m \boxed{\beta(m_j,\, m-m_j)}\, n(m-m_j,\, t)\, n(m_j,\, t)\, dm_j$$

$$-\, \alpha n(m,\, t)\int_0^\infty \boxed{\beta(m,\, m_j)}\, n(m_j,\, t)\, dm_j$$

$$-\, n(m,t)\frac{w_s(m)}{z} + I(m,t)$$

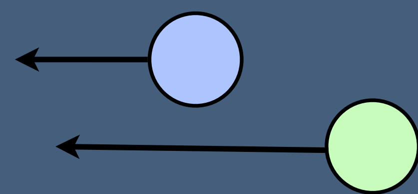
Coagulation Mechanisms

Brownian Motion



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

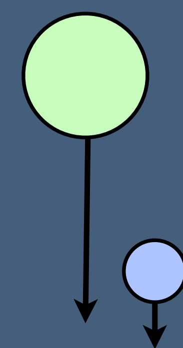
Fluid Shear



$$\beta(r_i, r_j) = 1.3\left(\frac{\epsilon}{\nu}\right)^{1/2}(r_i + r_j)^3$$

$$\beta(r_i, r_j) = \frac{p^2}{1 + 2p^2}\left(\frac{\epsilon}{\nu}\right)^{1/2}(r_i + r_j)^3$$

Differential Sedimentation



$$\beta(r_i, r_j) = \pi(r_i + r_j)^2|w_j - w_i|$$

$$\beta(r_i, r_j) = 0.5\pi r_j^2\,|w_j - w_i|$$

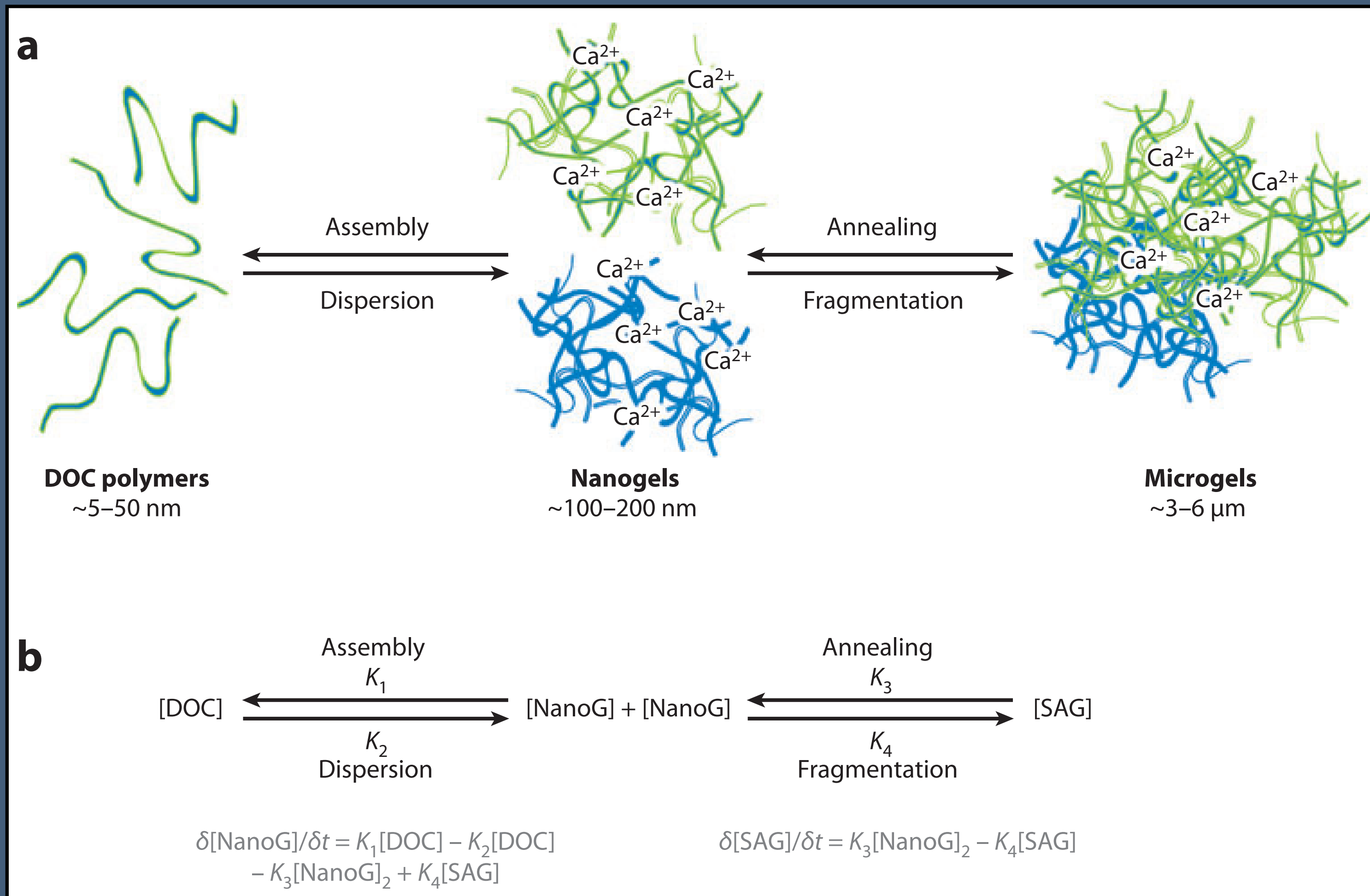
Stickiness

$$
\begin{aligned}
\frac{dn(m,t)}{dt} &= \frac{\alpha}{2}\int_0^m \beta(m_j,\, m - m_j)n(m - m_j,\, t)n(m_j,\, t)\, dm_j \\
&- \alpha n(m,\, t)\int_0^\infty \beta(m,\, m_j)n(m_j,\, t)\, dm_j \\
&- n(m,t)\frac{w_s(m)}{z} + I(m,t)
\end{aligned}
$$

Stickiness: largely biological & chemical?

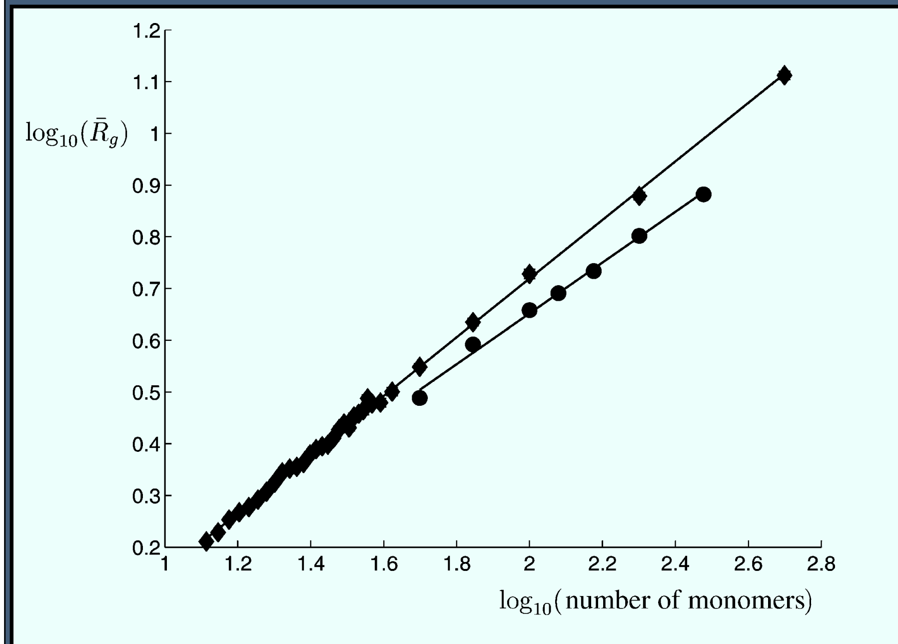
Transparent exopolymer particles - nanogels?

Nanoparticles



Verdugo, *Ann. Rev. Mar. Sci.*, 2012

Nano-gels



Metcalfe et al., *J. Coll. Int. Sci.*, 2006

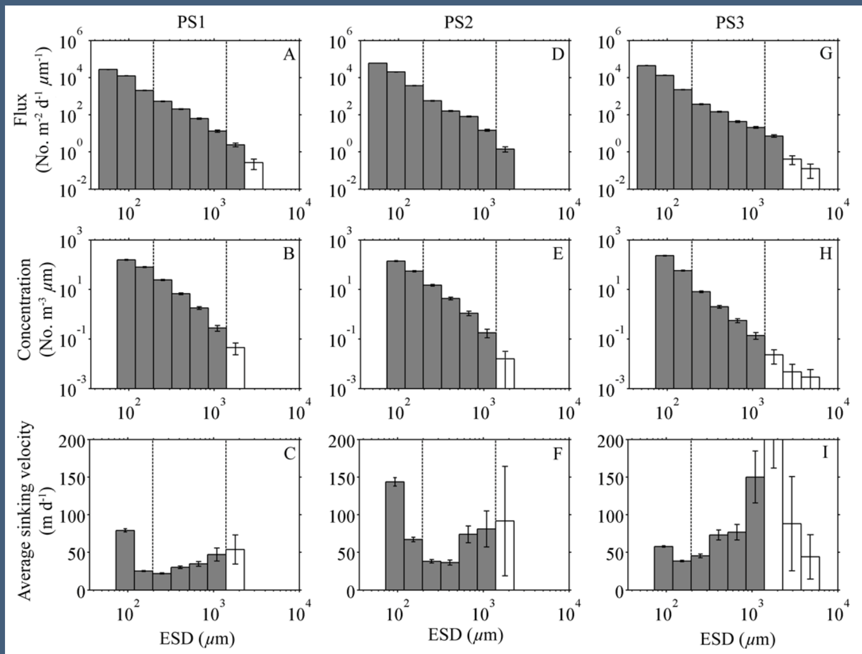
Polymers with stickinesss varying along their length

Distribution of stickiness and polymer rigidity affects fractal dimension, gel size, aggregation times

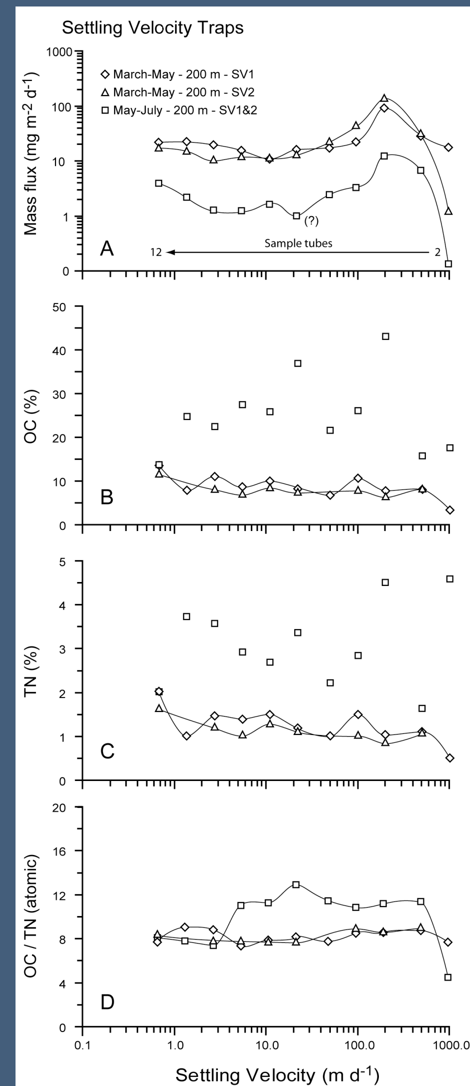
Settling

$$
\begin{aligned}
\frac{dn(m,t)}{dt} = & \frac{\alpha}{2}\int_0^m \beta(m_j,\, m - m_j)n(m - m_j,\, t)n(m_j,\, t)\, dm_j \\
& - \alpha n(m,\, t)\int_0^\infty \beta(m,\, m_j)n(m_j,\, t)\, dm_j \\
& - \boxed{n(m,t)\frac{w_s(m)}{z}} + I(m,t)
\end{aligned}
$$

Settling Speed



McDonnell & Buesseler, *Limnol. Oceanogr.*, 2011

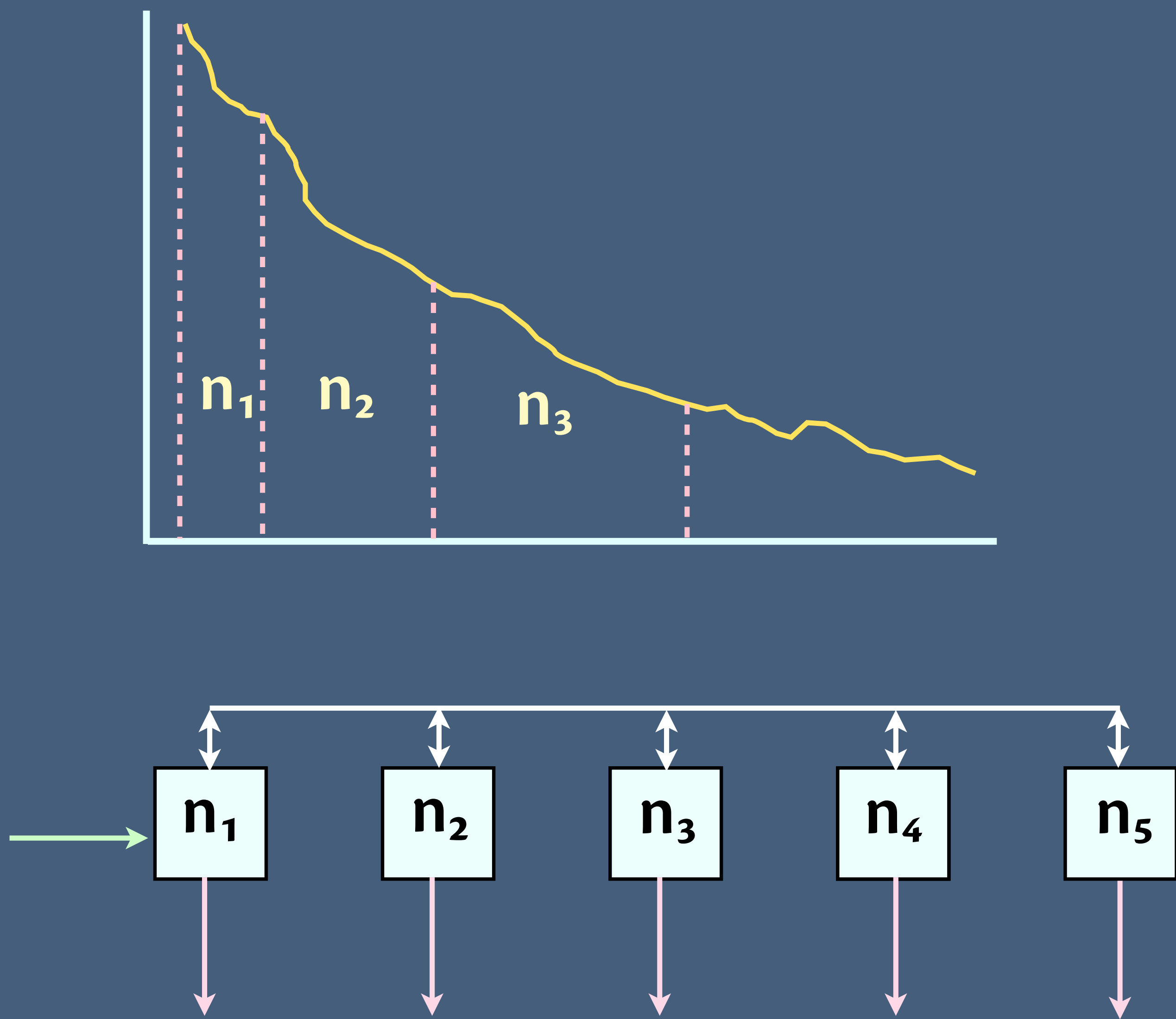


Peterson et al., *Limnol. Oceanogr. Methods*, 2005

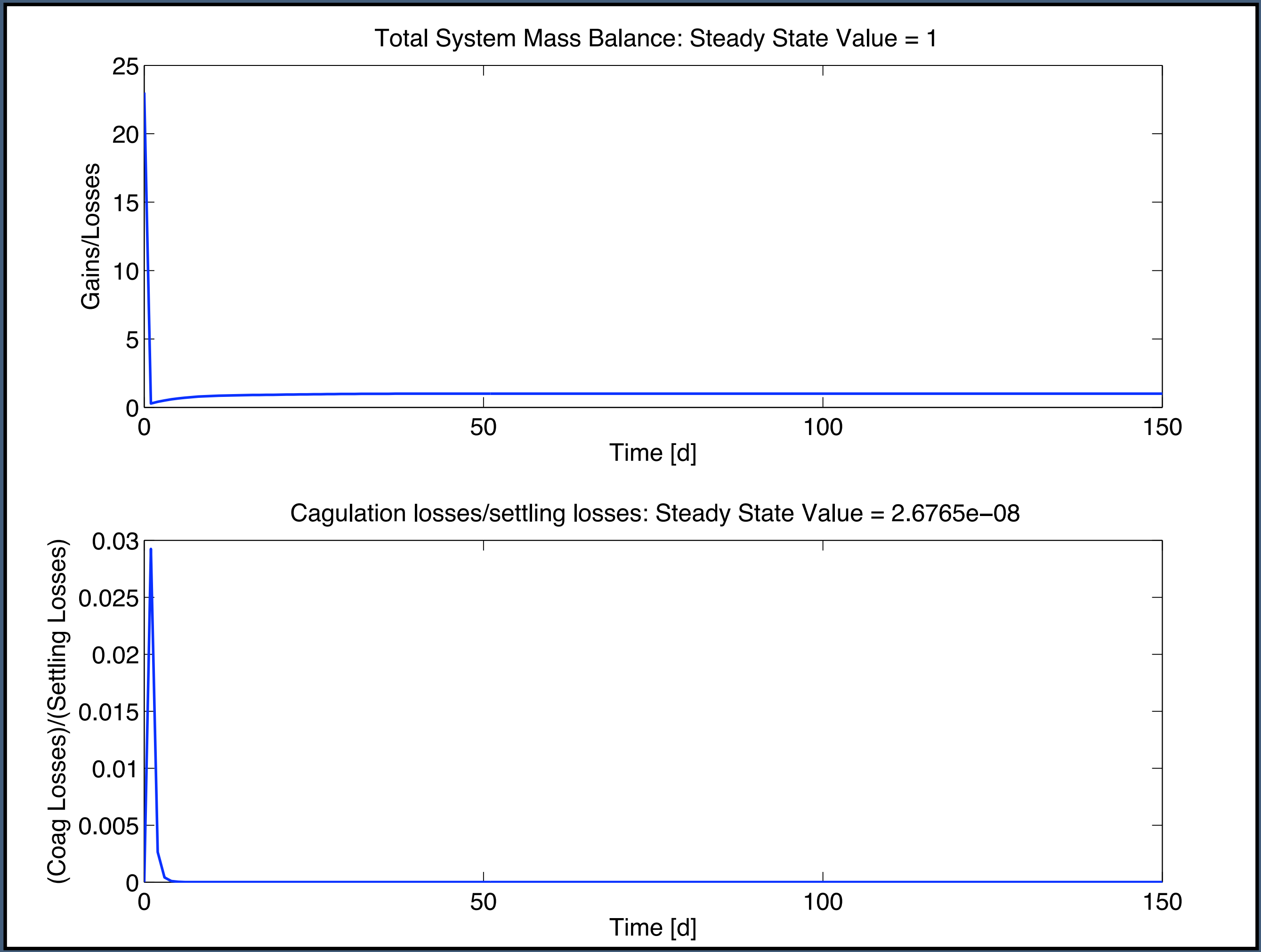
Input/Growth

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

Sectional Approach



Mass Balance



Integral Models

Mass concentration $$\frac{d\phi}{dt} = \mu\phi - \frac{F_\phi}{Z}$$

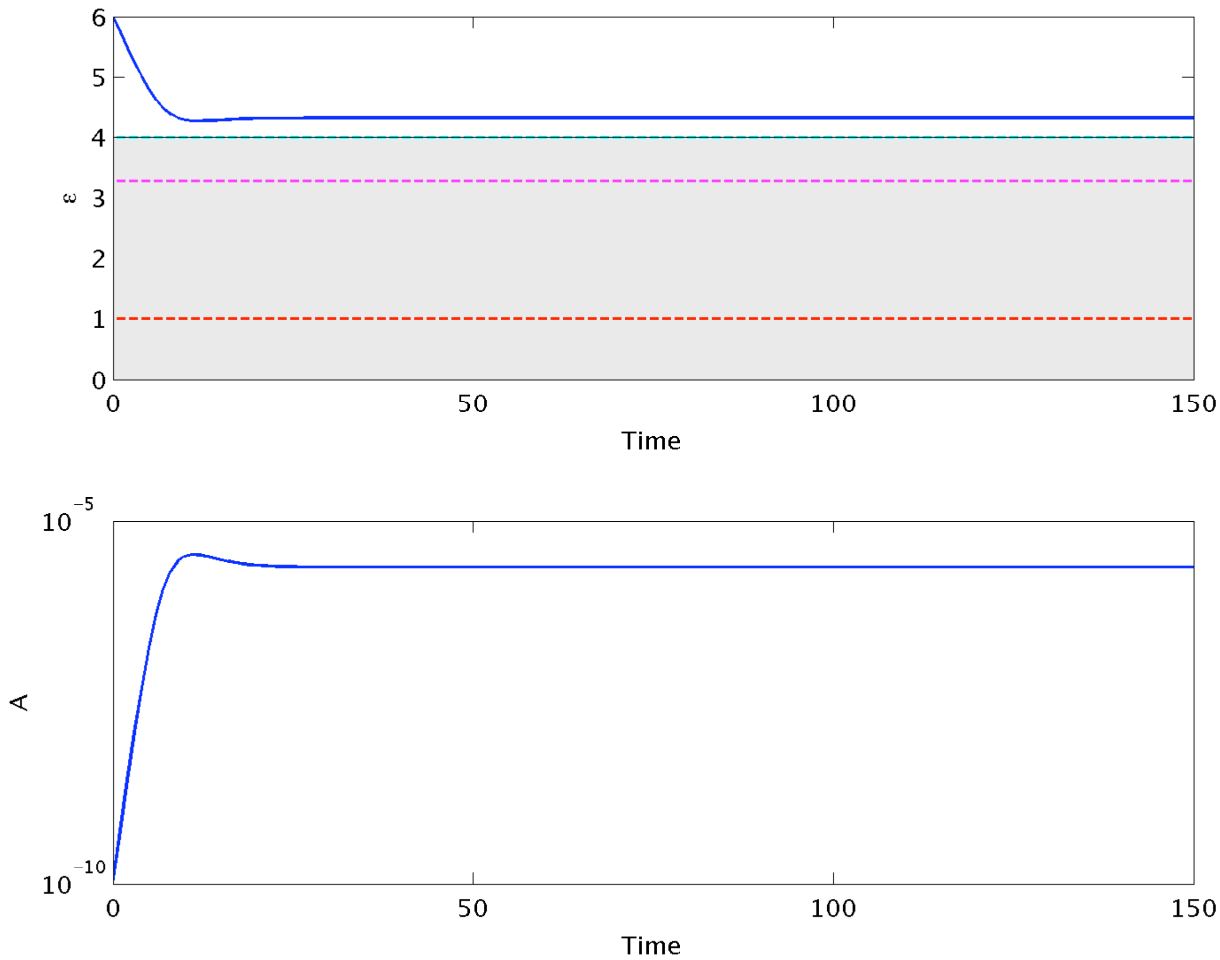
Number concentration $$\frac{d\psi}{dt} = \mu\psi - \frac{F_\psi}{Z} - \xi$$

$$F_\psi = \int_{d_0}^{\infty} w(d)n(d)\,dd \qquad F_\phi = \int_{d_0}^{\infty} C(d)w(d)n(d)\,dd$$

$$\xi = \frac{\alpha}{2}\int_{d_0}^{\infty}\int_{d_0}^{\infty} \left(\beta_{\mathrm{shear}}(d_1, d_2) + \beta_{\mathrm{ds}}(d_1, d_2)\right) n(d_1)n(d_2)\,dd_1\,dd_2$$

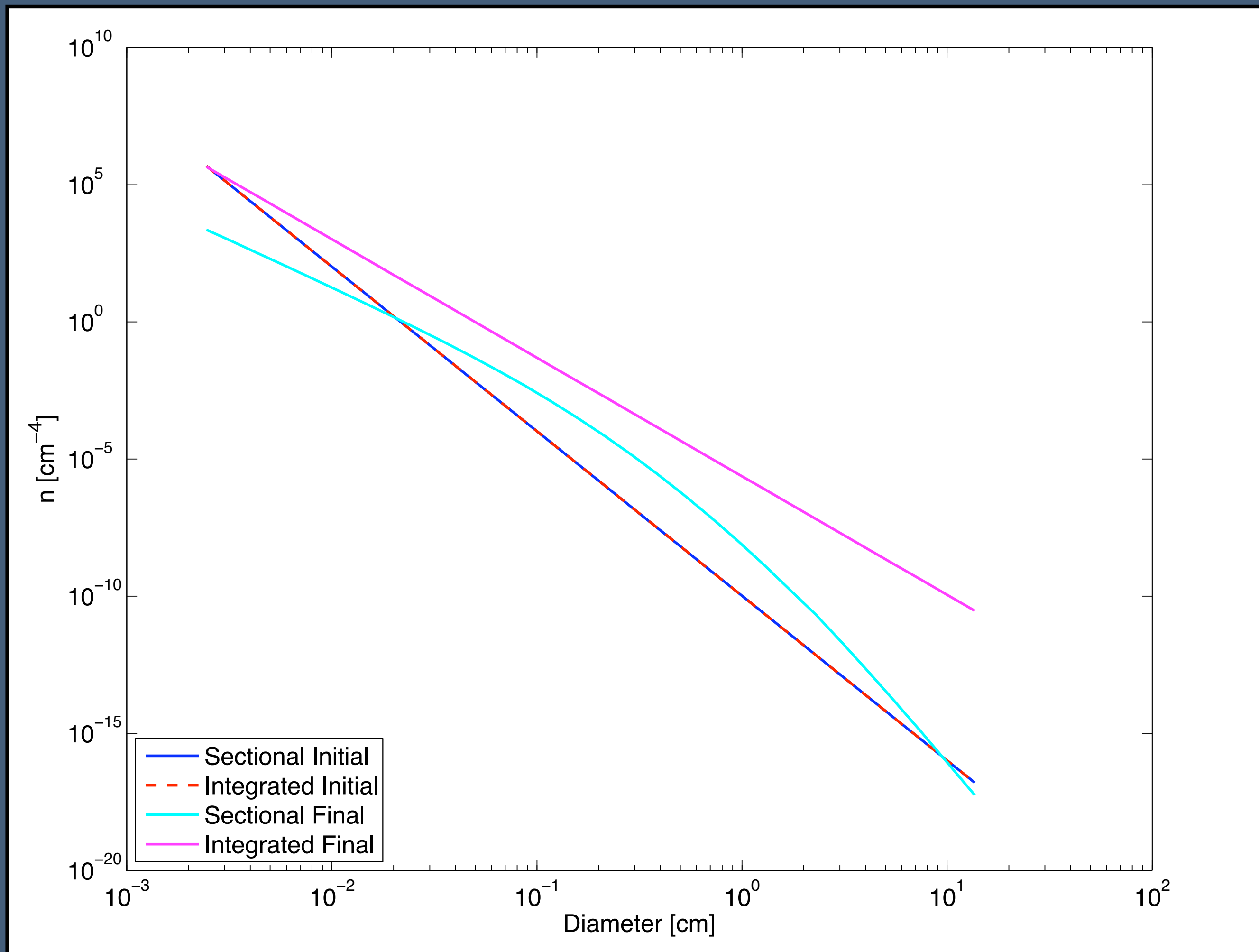
$$n(d) = Ad^{-\epsilon}$$

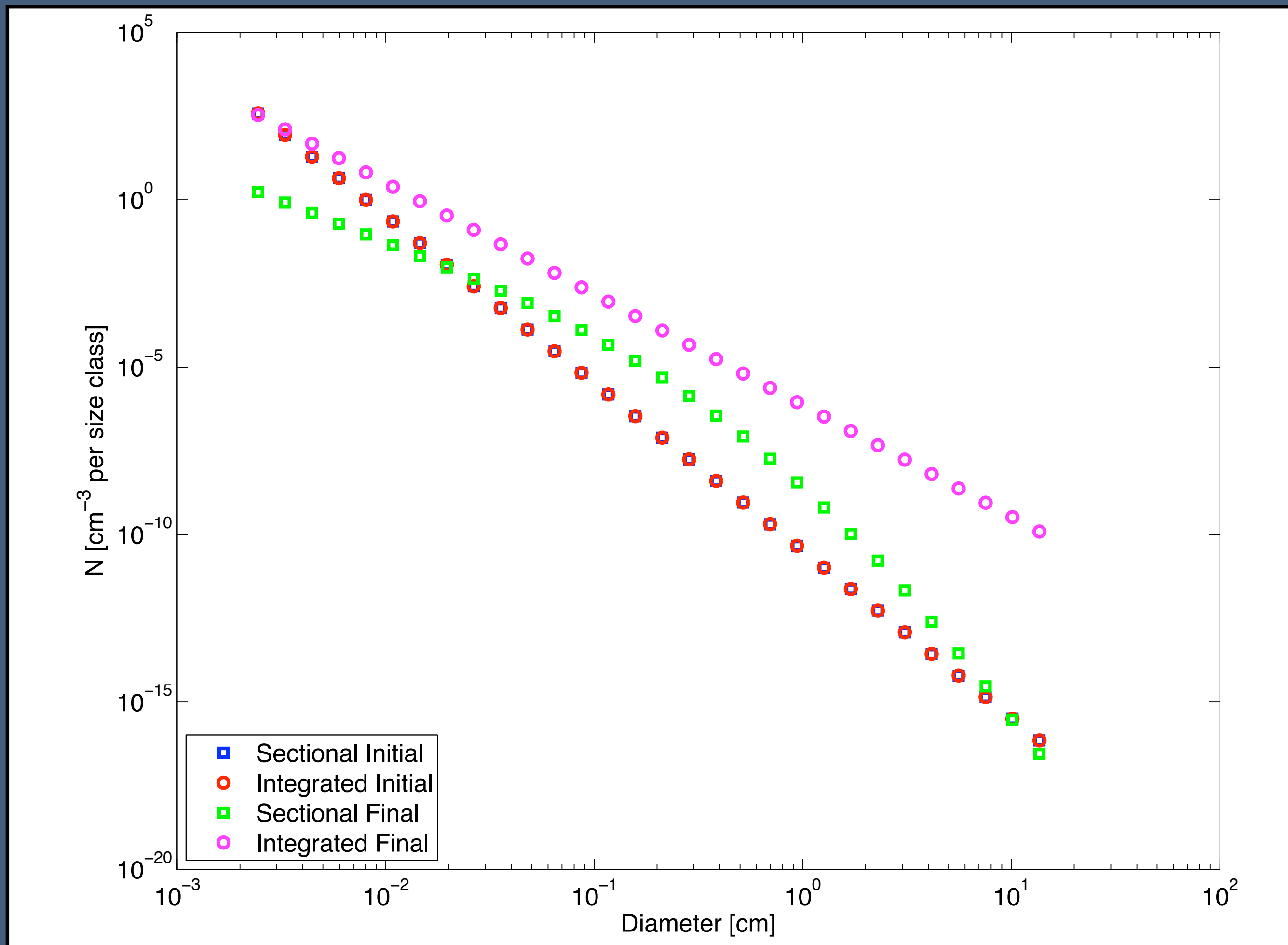
Based on Kriest & Evans, *Earth & Planetary Sciences, 2000*



6
5
4
3
2
1
0
ε
0
50
100
150
Time
10^−5
10^−10
A
0
50
100
150
Time

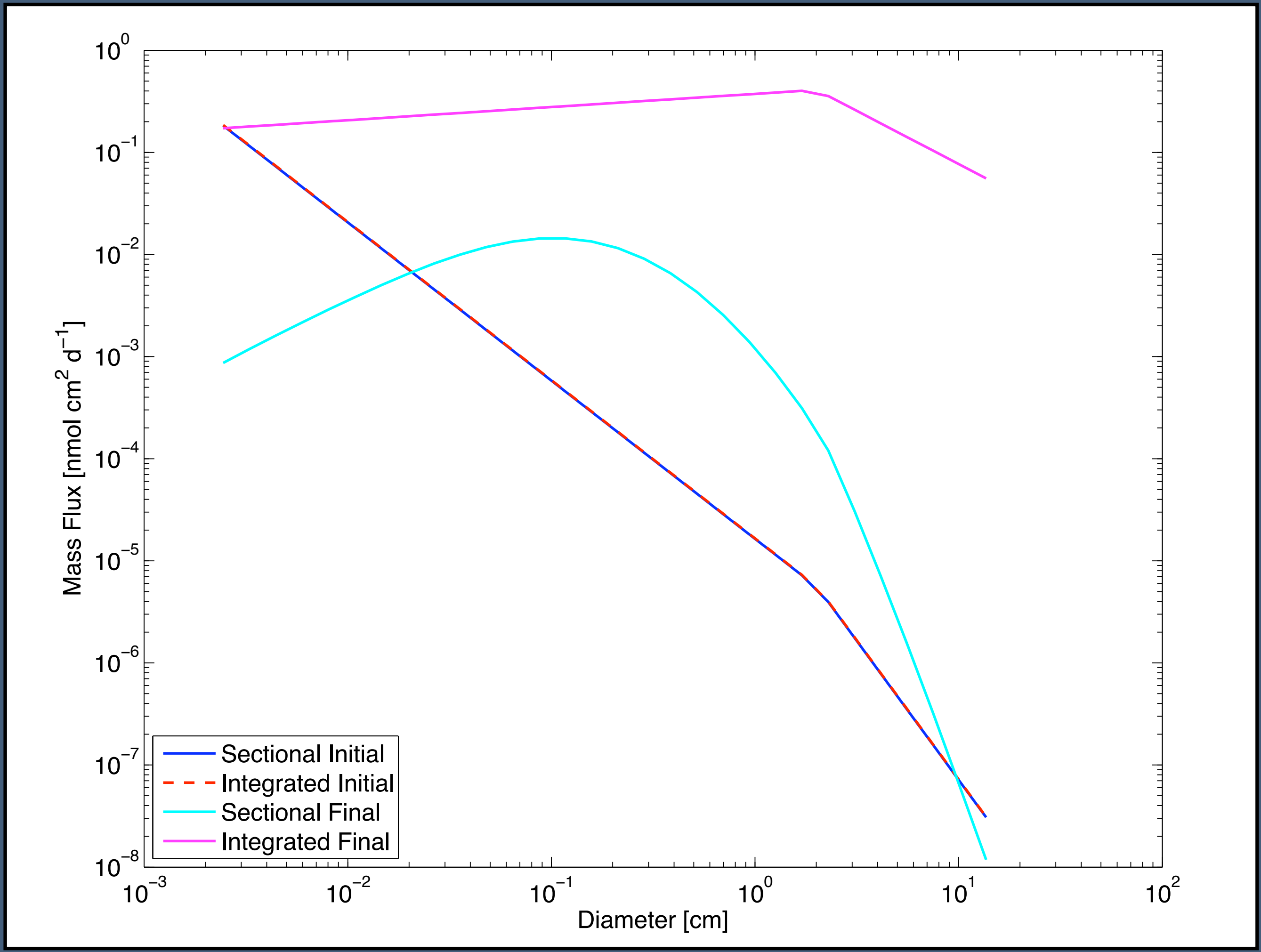
Size spectrum comparison



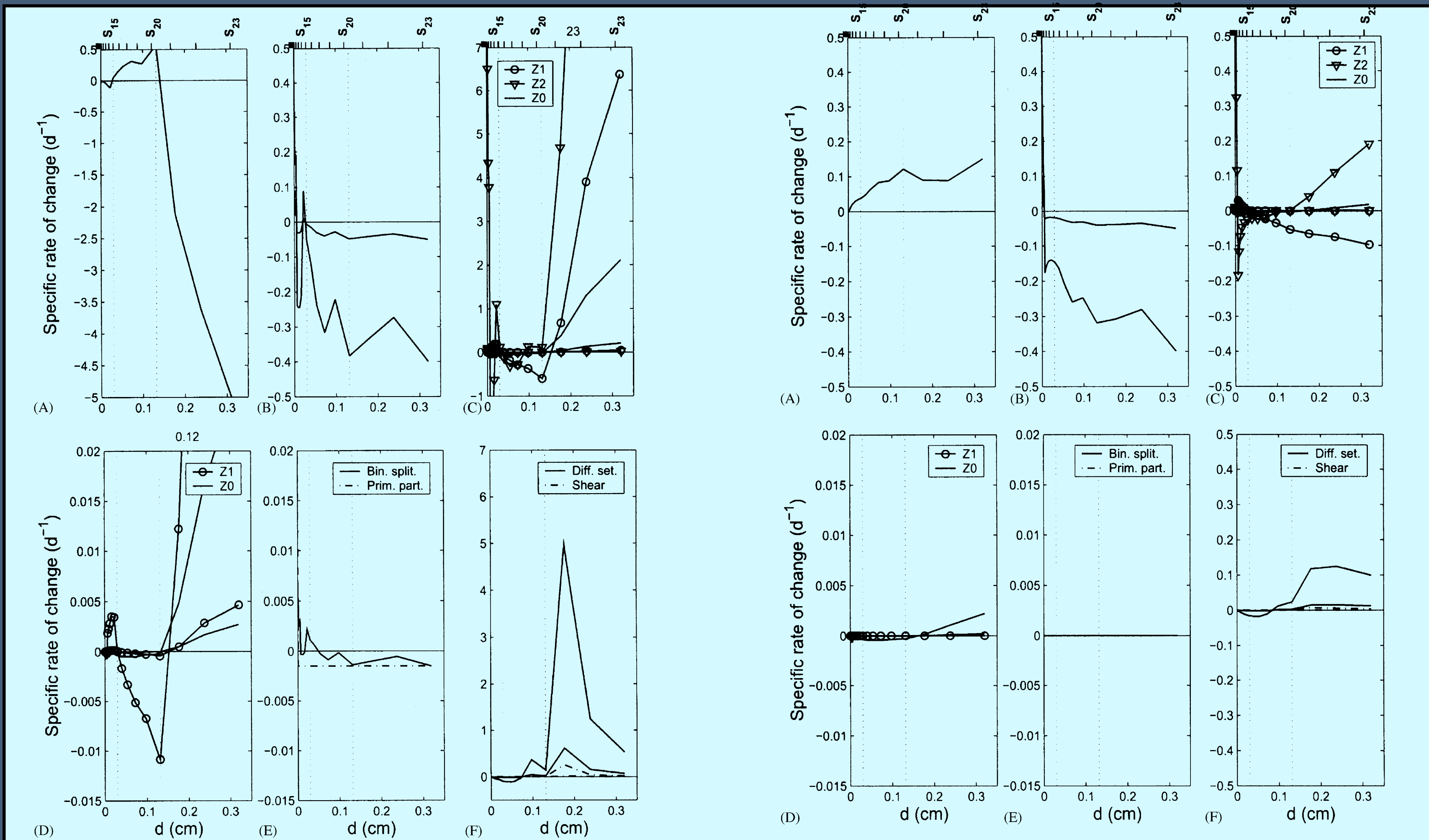


N [cm^{-3} per size class]
Diameter [cm]
10^{5}
10^{0}
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Sectional Initial
Integrated Initial
Sectional Final
Integrated Final

Flux Comparison

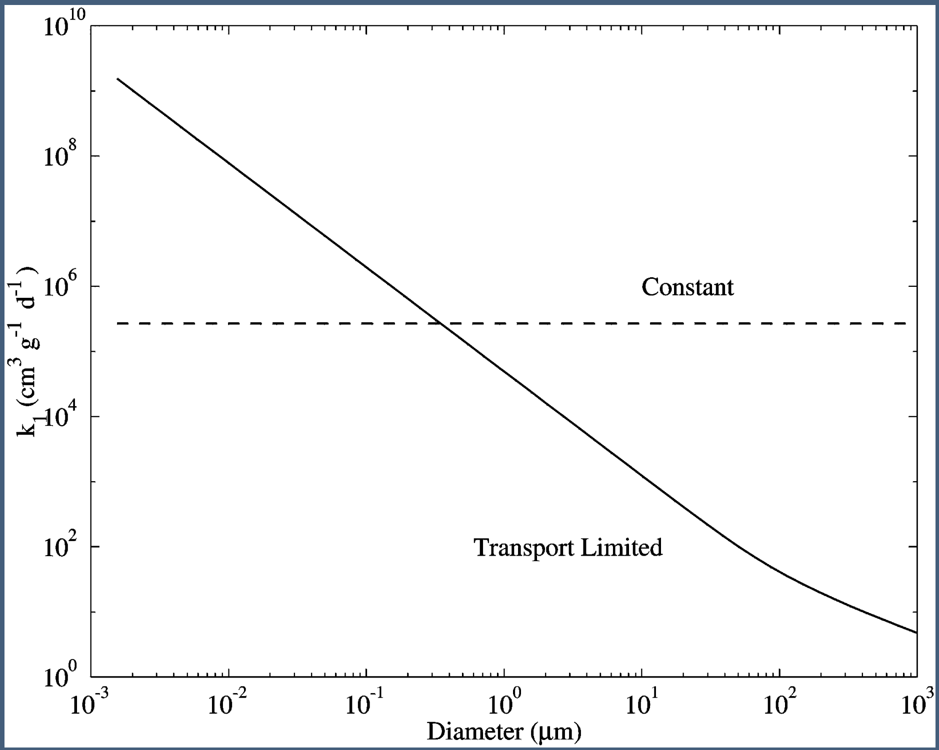


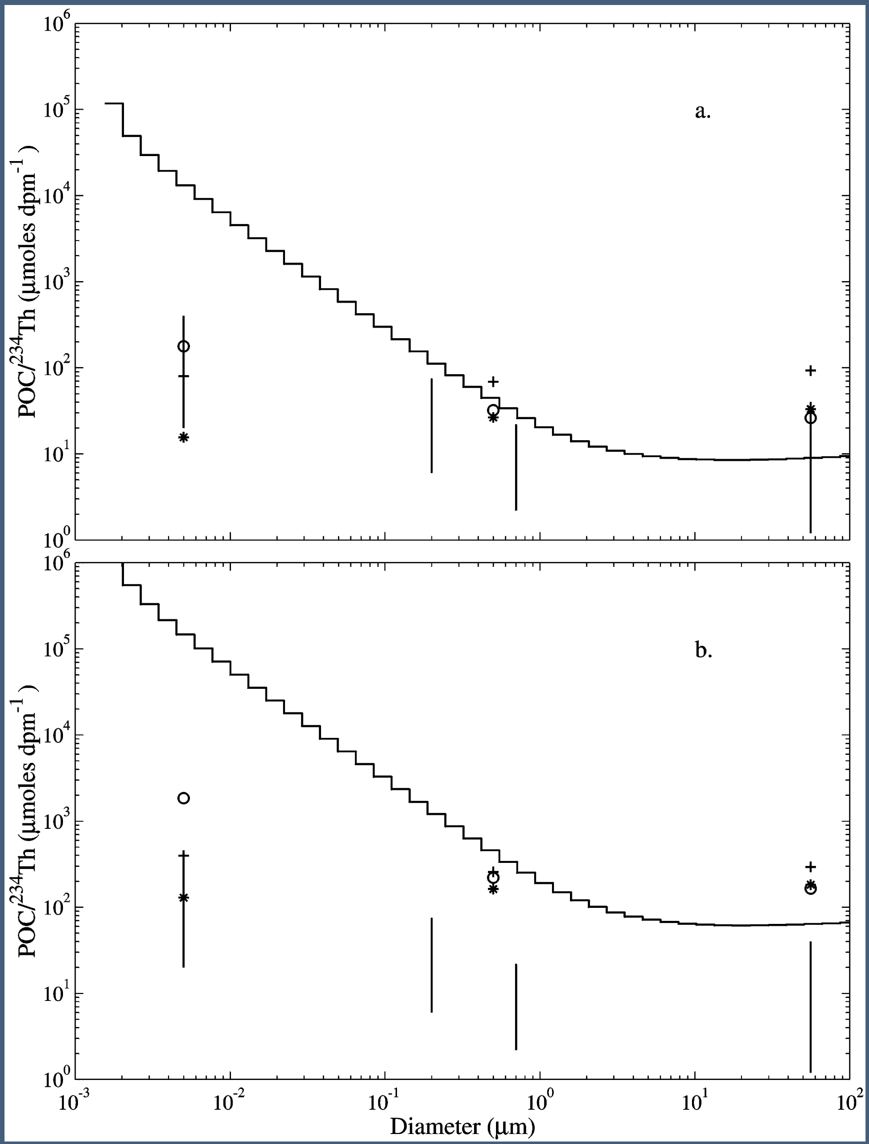
Biological Processes



Stemmann et al., *Deep-Sea Research I*, 2004

Chemical Processes

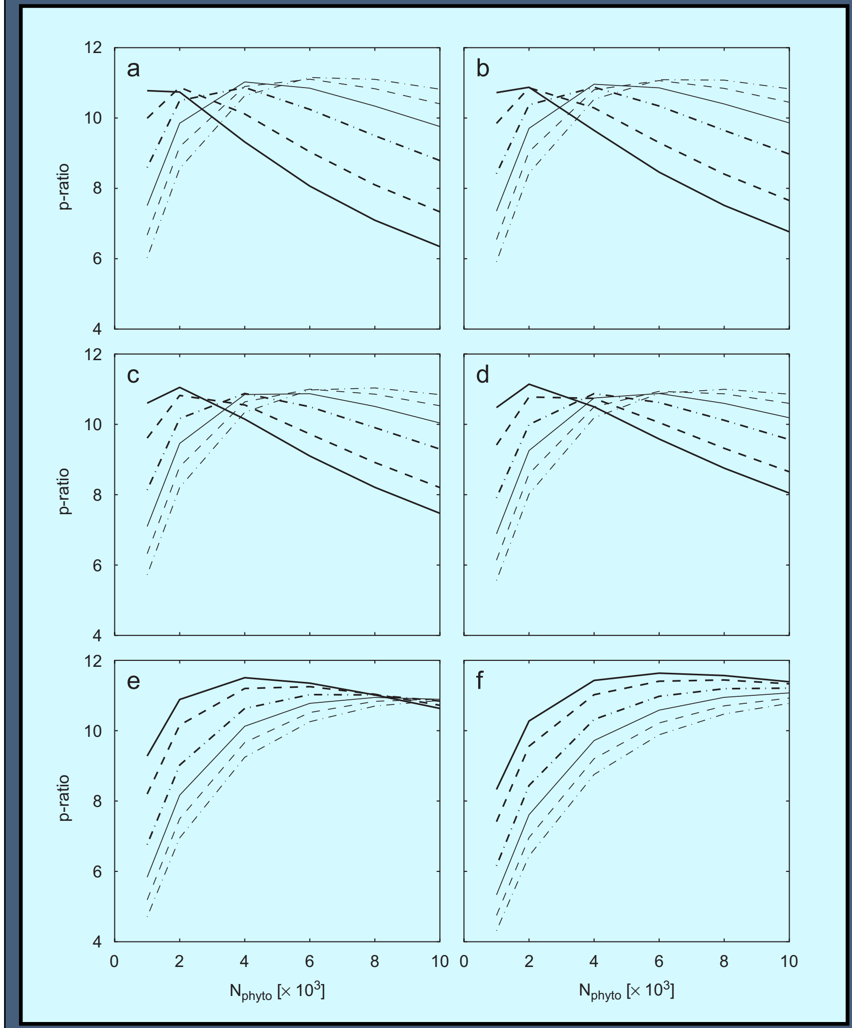




Extension of Honeyman & Santschi (1989)

Burd et al., *Deep-Sea Research I*, 2000

Multiple Particle Types



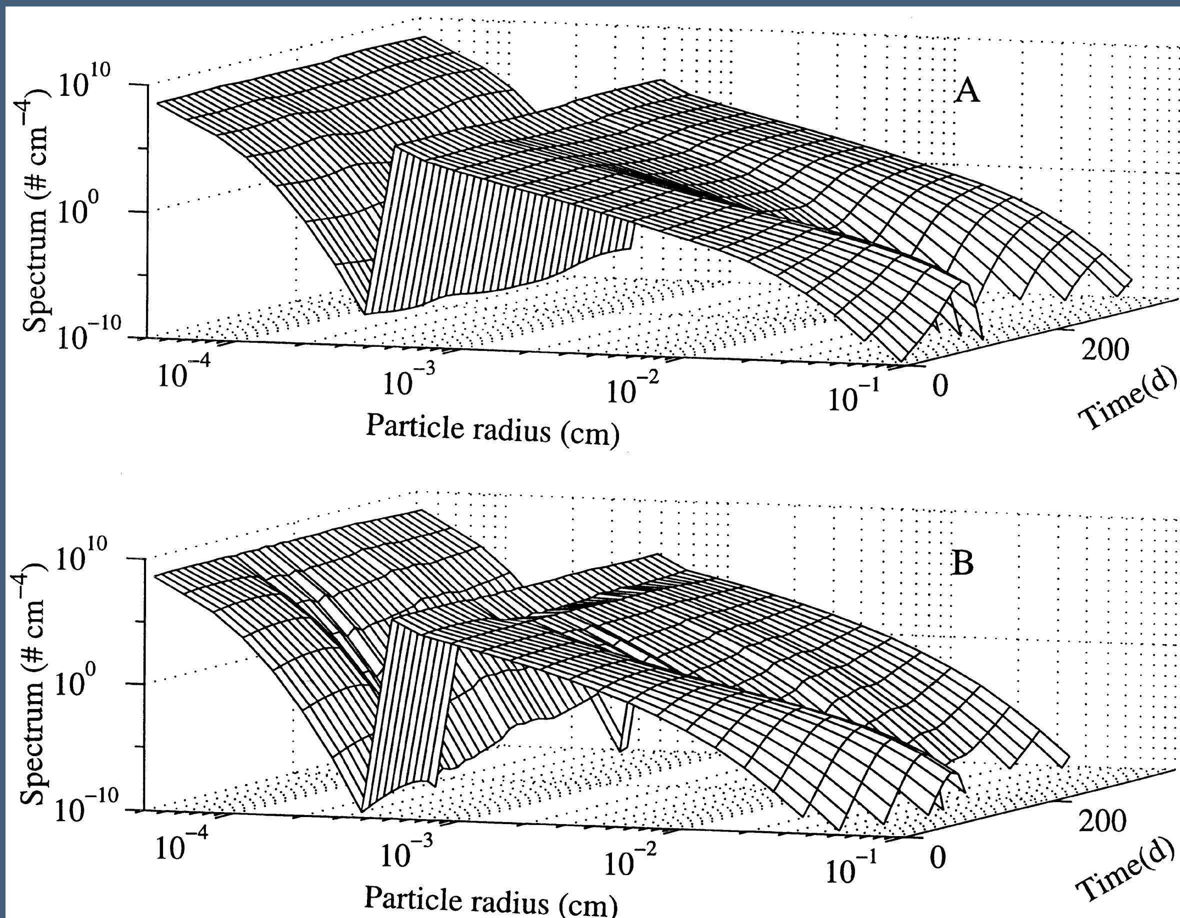
Burd et al., *Deep-Sea Research I*, 2007

Three particle types (algal cells, fecal pellets, aggregates)

Each follows a separate log-normal distribution.

Each particle type has settling velocity law, carbon content etc.

Multiple Particle Types



Coagulation coupled to an ecosystem model

Jackson, *Deep-Sea Research I*, 2001

Conclusions

- Need a combination of modeling approaches
  - *Detailed mechanistic models & data comparisons on the same scales & same information*
  - *Computationally efficient models that capture the dynamics and can run in large scale models*
- Need to assess the assumptions built into the models
  - *How do assumptions (scientific & numerical) affect interpretation of results?*
- Models & data need to inform each other