Impact of particle aggregation on vertical fluxes of organic matter


Abstract

Particles sinking out of the euphotic zone are important vehicles of carbon export from the surface ocean. Most of the particles produce heavier aggregates by coagulating with each other before they sink. We implemented an aggregation model into the biogeochemical model of Regional Oceanic Modelling System (ROMS) to simulate the distribution of particles in the water column and their downward transport in the Northwest African upwelling region. Accompanying settling chamber, sediment trap and particle camera measurements provide data for model validation. In situ aggregate settling velocities measured by the settling chamber were around 55 m d⁻¹. Aggregate sizes recorded by the particle camera hardly exceeded 1 mm. The model is based on a continuous size spectrum of aggregates, characterised by the prognostic aggregate mass and aggregate number concentration. Phytoplankton and detritus make up the aggregation pool, which has an averaged, prognostic and size dependent sinking. Model experiments were performed with dense and porous approximations of aggregates with varying maximum aggregate size and stickiness as well as with the inclusion of a disaggregation term. Similar surface productivity in all experiments has been generated in order to find the best combination of parameters that produce measured deep water fluxes. Although the experiments failed to represent surface particle number spectra, in the deep water some of them gave very similar slope and spectrum range as the particle camera measurements. Particle fluxes at the mesotrophic sediment trap site off Cape Blanc (CB) have been successfully reproduced by the porous experiment with disaggregation term when particle remineralisation rate was 0.2 d⁻¹. The aggregation–disaggregation model improves the prediction capability of the original biogeochemical model significantly by giving much better estimates of fluxes for both upper and lower trap. The results also point to the need for more studies to enhance our knowledge on particle decay and its variation and to the role that stickiness play in the distribution of vertical fluxes.

1. Introduction

Particle fluxes from the ocean’s surface layers to its bottom are important means of carbon export and therefore have a crucial role in the global regulation of atmospheric CO₂. Many particles sinking into deep layers do so in the form of aggregates, which are produced by the coagulation of smaller particles. Coagulation does not only enhance the removal of material from euphotic zone, but it can also control the maximum phytoplankton concentration in the ocean (Jackson and Kiørboe, 2008). Among eastern boundary upwelling systems, the NW African Upwelling retains elevated concentrations of aggregates due to high biological productivity, which is distinguished by their enhanced export and belongs to the most productive ecosystems of the world’s ocean.

The efficiency of aggregate formation is regulated by factors like particle concentration, stickiness and collision rate. Although settling rates generally increase with aggregate size (Alldredge and Gotschalk, 1988, 1989), large size does not always guarantee fast sinking (Kiørboe et al., 1998) and sinking characteristics of aggregates depend on their composition, shape and porosity. The processes that can reduce the aggregate size are remineralisation, zooplankton feeding (Stemmann et al., 2004), fragmentation by zooplankton (Dilling and Alldredge, 2000) and disaggregation due to physical shear, which is caused by turbulence. The processes that aggregates go through during their sedimentation determine their vertical flux and distribution of elements they carry in the water column.

A number of models have been developed for a numerical definition of aggregation processes in the ocean with different levels of complexity. According to how collision between particles is described, Jackson (2005) classifies these models into two groups as...
those having rectilinear and curvilinear coagulation kernels. Rectilinear approximation belongs to the early formulations of coagulation, which assume that particles do not influence water motion and that chemical attraction and repulsion between particles can be ignored. Curvilinear kernels, on the contrary, take into account the effect of the particles on the surrounding fluid and on each other, i.e. van der Waals forces, and predict significantly less collision between particles of dissimilar sizes (Jackson and Burd, 1998). Rectilinear kernels appear, therefore, to generate a much stronger coagulation effect and vertical flux (Jackson, 2001).

Despite being the dominant process in controlling vertical carbon flux from biological production (Jackson et al., 2005) there are a function of particle diameter the particles are circular. We calculated the particle size spectrum equivalent diameter (ESD) of the each aggregate assuming that bit gray scale images. The analysis returned the area and abundance, Houston, USA). The color images were converted into 8 lyised using the image analysis software ‘Optimas’ (Meyer Instruments, Sub-Atlantic/Scotland. In order to measure in situ sinking speeds of marine snow aggregates, the vehicle was equipped with a settling chamber which was built in the context of a similar device used by Pillai et al. (1998). The chamber is made of a 30 cm × 30 cm × 40 cm plexiglass box that can be opened and closed sideways with the aid of the ROV’s manipulator. A cotillated light source, mounted on the port side of the vehicle, provides a slab of light of 12 cm width through the centre of the chamber. In order to measure the distance a particle travelled through time, a caliper was fixed in the middle of the box. Sinking aggregates in a sample volume of 20 cm × 12 cm × 17 cm or 4.08 l, were recorded with the aid of the ROV’s video camera stored on DV tapes. After reaching the depth of interest, the vehicle would fly a few meters straight forward, with opened chamber door. The vehicle would then stop and maintain depth while the door is closed. As described in Pillai et al. (1998), minor to moderate levels of turbulent motion of particles in the chamber were inevitable. Thus, we waited 10–15 min before we started to record vertically sinking particles, which took 20–40 min.

The sinking speed measurements were carried out at station GeoB 12914 (21°19.89 N; 18°49.60 W, hereafter referred to as SC) during RV Poseidon Cruise 365 off Cape Blanc/Mauritania in four depth levels: 50 m, 100 m, 250 m and 400 m. The depths were chosen after a particle abundance profile, acquired by the vertically profiling camera system ParCa. The 50 m depth level represents both the particle and chlorophyll maximum. At 100 m water depth, a distinct particle minimum is found. A small subsurface maximum can be found around 250 m while at 400 m, particle concentrations are comparably lower.

2.2. The model

We employed the Regional Oceanic Modelling System (ROMS) and its coupled ecosystem model to study aggregate fluxes in the NW African upwelling zone. ROMS uses a generalised terrain-following coordinates in vertical and orthogonal curvilinear coordinates in the horizontal to solve three-dimensional, free surface, hydrostatic, primitive equations (Shchepetkin and McWilliams, 2005). The ecosystem component of ROMS consists of seven state variables: nitrate, ammonium, phytoplankton, a dynamic phytoplankton chlorophyll/carbon ratio, zooplankton, and small and large detritus (Gruber et al., 2006). Large detritus in this original model is produced by the coagulation of phytoplankton and small detritus based on a simple particle density function. In order to implement the aggregation model we removed large detritus compartment and defined a new compartment representing aggregate number. The evolution of any state variable (Ci) follows the conservation equation:

$$\frac{\partial C_i}{\partial t} = -\nabla \cdot (u C_i) - A_p \nabla^2 C_i + \frac{\partial}{\partial z} \left( K_p \frac{\partial C_i}{\partial z} \right) + Q(C_i)$$

(1)

where $A_p$ is the horizontal eddy diffusion coefficient, $K_p$ is the vertical turbulent diffusion coefficient and $Q$ is the source minus sink term. The relationship between the different compartments of the model is outlined in Fig. 1. The parameter values of the model that are given in Gruber et al. (2006), represent a eutrophic coastal ecosystem and were unchanged in this study except for the particle remineralisation rate.
The aggregation processes and aggregate sinking are based on a continuous size spectrum of aggregates following Kriest (2002). Unlike Gehlen et al. (2006), not only detritus but also phytoplankton coagulate to produce aggregates. The total number of particles is treated as a separate state variable, which allows dynamical representation of average particle size and sinking rate. Aggregate size spectrum is defined by McCave (1984):

$$P(d) = Ad^{-f}$$

where \(d\) denotes aggregate diameter, \(A\) and \(f\) are evaluated from total particle mass and numbers (Kriest and Evans, 1999). The decrease in density with increasing aggregate size can be expressed by using fractal scaling in which the mass, \(M\), relates to the size of an aggregate by:

$$M = Bd^{-f}$$

where \(f\) is the fractal dimension of the aggregate (Jackson and Burd, 1998). The values of \(f\) change between 1.3 and 2.3 (Jackson, 2005), with small values indicating more porous structure. Similarly, particle sinking speed is also represented by a two parameter power law as a function of \(d\) (Kriest, 2002):

$$W = Cd^{\eta}$$

with \(\eta\) representing sinking exponent. Minimum mass and sinking rates are therefore prescribed depending on cell size.

Disaggregation is not considered in Kriest’s model but there exists a maximum size that an aggregate can reach, which also restricts aggregate settling rates to an upper limit. A universal formulation of disaggregation does not exist due to the variety of processes involved which are not completely understood, like physical or biological fragmentation, zooplankton feeding, and microbial activity. Stemmann et al. (2004) considered flux feeding zooplankton in their numerical study and found that it has a significant effect on particle fluxes above 500 m depth. In this study we kept the model as simple as possible and avoided involving another zooplankton compartment in order to make comparison to the original biogeochemical model (Gruber et al., 2006; Fischer and Karakas, 2009) possible. We therefore parameterised disaggregation by defining a disaggregation rate which is dependent on the number of aggregates and on the sinking velocity:

$$\psi(z) = NOS(z) \left[ \frac{1}{e(z) - 1 - \zeta} - 1 \right] k_0 e^{-2z}$$

where \(NOS\) is the total number concentration of aggregates, \(e\) is the slope of particle size distribution and \(k_0\) is an empirical rate constant. Similar to Dadou et al. (2001), disaggregation rate varies exponentially with depth, \(z\). The disaggregation term maintains the mass while forcing the model to produce more, smaller and slower aggregates.

Integration of Eqs. (3), (2), (4), and (2) over the size range gives average settling velocity of mass and number of particles. Aggregation equations due to turbulent shear and differential settlement are solved as described in Kriest (2002) over the entire range of size spectra.

The model area stretches between 5°N–41°N and 30°W–5.5°W, covering the entire region off NW Africa. The grid as well as forcing, initial and boundary data are produced by using ROMSTOOLS package (Penven et al., 2008). The topography is derived from 1-min GECO data and interpolated to a 20 km horizontal grid. The vertical grid has 32 sigma levels with resolution getting coarser at depth. Initial state and boundary fluxes for temperature, salinity, momentum and nutrients were derived from the World Ocean Atlas 2005 (Locarnini et al., 2006; Antonov et al., 2006; Garcia et al., 2006). Setting into motion from a cold start, the physical model was forced by monthly climatologies of Comprehensive Ocean–Atmosphere Data Set (Da Silva et al., 1994) during a spin-up period of 3 years, which was followed by the 6-hourly NCEP reanalysis-2 forcing (Kanamitsu et al., 2002) for the years 2002 and 2003.

As in Kriest (2002), prescribed particle mass and sinking factors and mass and sinking exponents in the simulations represent porous and dense aggregates, which are found in the ocean (Table 1). Remineralisation rate was constant but proportional to the sinking velocity of smallest aggregate size, i.e. 0.02 mm. Porous aggregates therefore remineralised four times faster than the dense aggregates. By setting remineralisation rate fixed to the aggregate sinking velocity a relatively similar productivity and export rate is provided in all experiments. Using these aggregate characteristics Table 2 shows the list of sensitivity experiments carried out with

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**Table 2**

<table>
<thead>
<tr>
<th>Aggregate porosity</th>
<th>Mass Scaling</th>
<th>Sinking Remineralisation rate (d⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(B)</td>
<td>(\zeta)</td>
</tr>
<tr>
<td>Dense</td>
<td>5700</td>
<td>2.28</td>
</tr>
<tr>
<td>Porous</td>
<td>273</td>
<td>1.62</td>
</tr>
</tbody>
</table>

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varying maximum aggregate size and stickiness values. The disaggregation term is switched on in one experiment to assess its effect on particle number spectra and on particle fluxes. While maximum aggregate size ranged between 0.4 and 5 mm, the stickiness coefficient was set to 0.5 and 0.05. Stickiness is a parameter which defines the probability of two colliding particles staying together, the value of which depends strongly on the concentration of mucus around particles (Dam and Drapeau, 1995). By reducing the stickiness one order of magnitude, we wanted to restrict the excessive collisions that the rectilinear kernel produces in comparison to a curvilinear formulation. In total five experiments were carried out employing: dense, and sticky aggregates with 5 mm maximum size (D5S), porous and sticky aggregates with 1 mm maximum size (P1S), porous and non-sticky aggregates with 1 mm maximum size (P1nS), dense and non-sticky aggregates with 0.4 mm maximum size (D04nS) and finally porous and non-sticky aggregates with 1 mm maximum size and disaggregation turned on (P1nS-disagg).

3. Results and discussion

3.1. Comparison of surface chlorophyll fields to the satellite data

The validation of the generated physical fields by the model has been discussed in Karakaş et al. (2006) and Marchesiello and Estrode (2007). In Fig. 2, we illustrate mean surface chlorophyll distribution from SeaWiFS and model experiments for the year 2002. The general pattern of chlorophyll distribution is similar in all simulations to the satellite data and there is very little discrepancy. This is not surprising because by setting the remineralisation rate proportional to the sinking velocity for dense and porous approximations, the remineralisation length scale is more or less maintained, which causes similar amounts of nitrogen to be recycled back to the nutrient pool for surface productivity.

Cape Blanc filament is reproduced successfully in all experiments. However, the model solution gives a diffusive gradient in the onshore–offshore direction. In general chlorophyll fields in dense experiments present slightly higher chlorophyll concentrations than porous experiments. Among the two dense experiments the one with smaller maximum aggregate (D04nS) size generated somewhat more chlorophyll along the coast. In the coastal transition zone (CTZ) the fields appear to be overestimated in the experiment D5S. The chlorophyll concentration in this simulation is almost two times higher (0.8 mg Chl m$^{-3}$) than the observed value (0.4 mg Chl m$^{-3}$) at the mesotrophic sediment trap site CB. Other experiments, on the other hand, give a good match at CB despite exaggerated values being reproduced within the CTZ to the north of Cape Bojador. The concentrations along the coast, on the other hand, are rather poorly represented in all modelled fields, which, to a considerable extent, resulted from the relatively coarse grid resolution.

3.2. Particle size spectrum and number distribution

Fig. 3 illustrates particle size spectrum against equivalent spherical diameter (ESD) at different depth levels as observed by the camera profiles and from the model experiments. Both observed and simulated plots show a decrease in abundance with increasing diameter, which is a typical pattern (Guidi et al., 2008; Stemmann et al., 2008). Note that the particle camera can capture particles of minimum 140 µm size and therefore particles of smaller size cannot be shown in Fig. 3a. Even though there does not seem to be a difference in observed particle abundances at different depths, the slope of curves varies. The slope at 500 m for instance is steeper than the one at 1000 m. At 200 m depth, however, strong oscillations are noticeable in particle abundance. The modelled size spectra present a very diffuse pattern compared to the observations and a diverse range of abundances. Almost in all experiments the slope of the curves increases with reducing depth. The dense approximation, nevertheless, appears to generate more moderate slopes. In fact we could have obtained a better match of size spectra by limiting the model fractal dimension to vary within a range which is found in observations because the fractal dimensions of particles are estimated from the measured slope of particle spectra (Burd and Jackson, 2002). In our experiments the fractal dimension was obtained from the total particle mass and numbers (Kriest and Evans, 1999).

Total particle numbers at this measurement site show a sharp decrease from 30 l$^{-1}$ at the surface to 2 l$^{-1}$ at around 175 m and record another maximum at 500 m with values around 8 l$^{-1}$ (Fig. 4). While modelled distributions of particles larger than 140 µm did not reproduce the peak abundance at the surface, the subsurface maximum was produced in all experiments, even if they were at different depths. This observed subsurface maximum is not uncommon in camera measurements (Nowald et al., 2006) and most probably this maxima indicates an Intermediate Nepheloid Layer (INL) which is generated by the particles eroded from the shelf and upper slope (Karakaş et al., 2006; Fischer et al., this volume). It cannot be justified to claim that this increase in particle numbers in the subsurface could also receive some contribution from aggregation processes because of the inability of the model to reproduce surface particle number concentrations as has been observed in the field. Therefore, whether aggregation could also contribute to this feature in the subsurface or have an impact on the oxygen minimum zone that is observed in similar depths (Fischer et al., this volume) remains an issue for further investigation.

Because particle aggregation in the model is controlled by particle collisions due to turbulent shear and differential settlement it could be also interesting to see the mean profile of shear against total particle numbers (Fig. 5). The mean shear at the site CB drops sharply under the surface and rises again at 50 m depth. Because 50 m corresponds to particle and chlorophyll maximum the influence of this shear increase is not obvious. Only in one experiment with dense aggregates there exists a slight decrease in particle numbers, which could be due to aggregation.

3.3. Aggregate settling velocity and mass

In Fig. 6, we show the observed sinking velocities of aggregates by using the settling chamber. A wide span of sinking velocities has been observed with majority around 55 m d$^{-1}$. Modelled aggregates are also transported into the deep ocean with a range of sinking velocities depending on their size and porosity. Fig. 7 shows averaged sinking velocities from the simulations for the year 2002 at the mesotrophic sediment trap site CB. Large, dense and sticky aggregates reach up to 400 m d$^{-1}$ velocity below 1000 m depth (D5S). The aggregates with 1 mm size sink a lot slower, i.e. with 30 m d$^{-1}$ at their fastest settling (P1S, P1nS and P1nS-disagg). Smaller aggregates, however, sink with 22 m d$^{-1}$ velocity (D04nS). The stickiness does not play any role in determining the maximum sinking velocity but it regulates the depth at which aggregates at-

![Table 2](image-url)
tain this velocity. Because of the smaller number of collisions that result in coagulation, non-sticky aggregates (P1nS) arrive at their peak size, as well as peak velocity, in deeper layers than sticky aggregates (P1S). It is interesting to note that when the disaggregation term is activated, sinking velocity curve presents a more linear pattern, which is similar to the one estimated by Berelson (2002). As shown by Kriest and Oschlies (2008), such a strong increase in sinking speeds that we observed with different model experiments appears to be a typical characteristic of power law size spectra, when it is described all along the water column. One should notice

Fig. 2. Mean surface chlorophyll distribution for the year 2002 as recorded by SeaWiFS and simulated by the model experiments. Location of the sediment trap site (CB), particle camera deployment site (PC) and settling chamber deployment site (SC) are also shown: (a) SeaWiFS, (b) D5S, (c) P1S, (d) P1nS, (e) D04nS and (f) P1nS-disagg.
that the sinking rates given here are the averaged rates for the entire particle size spectrum. We measured a similar range of sinking velocities, i.e. 34–43 m d$^{-1}$ by consecutive particle camera deployments in the region (Fischer et al., this volume).

The in situ measurements, nevertheless, do not show any indication of size dependency on particle sinking. A very weak or no relationship between diameter and sinking speed has been previously reported for in situ collected aggregates (Alldredge and Gotschalk, 1988). A stronger dependency, however, has been reported for aggregates that are produced on the roller table by differential settlement from that of aggregates produced by turbulent shear (Kriest, 2002). Our observations were carried out down to 400 m depth where turbulent shear is the dominant process, which could also explain why the model fails to reproduce particle size spectrum for the upper layers.

In Fig. 8, we show the distribution of total aggregate mass along the 21°N longitudinal cross section off Cape Blanc. Model simulations show significant differences regarding aggregate concentration. With dense aggregates of 5 mm size (D5S), concentrations of up to 2.5 mMol N m$^{-3}$ cover the entire water column due to the very high sinking velocity of these aggregates. Although not as much as D5S, smaller and non-sticky dense aggregates (D04nS) also generated enhanced mass. The simulations with porous aggregates resulted in much less aggregate mass, increasing towards surface and in onshore direction. The experiments with both sticky and non-sticky porous aggregates of 1 mm maximum size (P1S, P1nS and P1nS-disagg) had similar amounts of mass near the surface. However, the experiment P1S showed higher deep water concentration than P1nS due to its stickiness which allows faster aggregation and penetration to the deep ocean. Among all, the smallest aggregate mass in the deep layers was produced when the disaggregation term was switched on (P1nS-disagg).

3.4. Modelled organic carbon fluxes to the depth and their variation

Over the deployment period between April 2002 and May 2003 the mean observed organic carbon fluxes at the mesotrophic sediment trap site CB fall from 1.9 g m$^{-2}$ y$^{-1}$ to 1.7 g m$^{-2}$ y$^{-1}$ between
1228 m and 3606 m trap depths. This rate of reduction is comparable to previous observations of Bory et al. (2001), which were conducted as part of EUMELI program. These authors report a much lower decrease in POC fluxes with depth than the one calculated from the Martin et al. (1987) relationship. Fig. 9 shows simulated mean organic carbon fluxes with the model experiments. The experiments with dense aggregates (D5S and D04nS) give 2–4 order of magnitude higher fluxes, whereas porous aggregates could estimate the measured values better. The simulation with porous and non-sticky aggregates of 1 mm size (P1nS) for instance, gives 4 and 2.5 times larger fluxes for the upper and lower traps, respectively. The best estimate, however, is produced when the disaggregation was included. In this case the same type of aggregates gives almost the same value of flux at the upper trap and only 0.9 g less flux at the deep trap.

Kriest (2002) compared the results from her 1-D model to the observations and argued that porous parameterisation could represent the marine snow better. Because the remineralisation rates of dense and porous particles are different in our experiments, it is
difficult from our study to conclude which type of aggregate fits the flux observations better. Due to the unknowns and complexity involved in the validation of remineralisation we posed surface productivity as a constraint, and gave priority to the representation of surface chlorophyll fields. This is because independent from how well the simulated fluxes of a model match the observations, their validity is questionable unless surface productivity is also represented reasonably well by the model. We therefore tried to reproduce similar surface chlorophyll fields by using a similar remineralisation length scales for both dense and porous aggregates, i.e. by setting settling velocity proportional to the remineralisation rate. In this context looking at these results one can suggest that when disaggregation is included the best set of parameters which represent aggregate characteristics in this upwelling region

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**Fig. 8.** Modelled mean aggregate mass for the year 2002 along 21°N longitudinal cross section: (a) D5S, (b) P1S, (c) P1nS, (d) D04nS and (e) P1nS-disagg.
was the porous approximation with a remineralisation rate of 0.2 d⁻¹. In fact, as can be seen in Fig. 3, the porous aggregates with disaggregation give a very similar particle size spectrum and slope in deep water to the observation. It is also worth noting that observed aggregate sizes hardly exceed 1 mm (see Figs. 3 and 6). Because aggregation models with rectilinear kernels produce more collisions between particles and therefore higher fluxes than those with the curvilinear formulations (Jackson, 2001), one can argue that the curvilinear formulations have the potential to produce more realistic fluxes. In our simulations, we could get the best agreement to the observed fluxes with reduced stickiness, which decreased vertical fluxes as much as one order of magnitude.

The modelled fluxes with small porous, non-sticky aggregates produce a steep reduction of fluxes in subsurface waters due to particle remineralisation, which is followed by an increase of fluxes in deeper layers. Such an increase could be the result of lateral transport of organic matter or a transient pulse from above. Aggregation could therefore indirectly contribute to the observations of flux increase with depth. We were able to catch such a pulse of particles remineralisation with reduced stickiness, which decreased vertical fluxes as much as one order of magnitude.

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The reason why the model could produce a relatively good estimate of deep water fluxes although the surface particle size spectrum was in disagreement with camera measurements could be the stickiness. In most experiments we reduced the stickiness in order to avoid the exaggerated coagulation effect of rectilinear kernel. This however resulted in very small particles in the surface layers, which were unable to increase their size with collision. Particle flux exported out of surface layers was still sufficient to provide a good fit of deep fluxes. The concentration of transparent exopolymeric particles (TEP) affects the stickiness (Jackson, 1995; Passow, 2002) and the variation of stickiness during a bloom has
been reported elsewhere (Dam and Drapeau, 1995). Parameterising this variation has not been covered in our study but would modify the results.

4. Summary and conclusions

Various model experiments were carried out by applying an aggregation model into the phytoplankton and detritus compartments of a biogeochemical model. The model was based on a continuous size spectrum of aggregates. The simulations covered maximum aggregate sizes ranging between 0.4 and 5 mm. Both porous and dense aggregates were considered with reduced stickiness in order to yield limited collision between particles. One experiment also involved a disaggregation term to reduce the size of aggregates and produce more particles that sink slower. Setting the remineralisation rate proportional to the sinking velocity of smallest particles generated similar distributions in all experiments and a relatively good match of surface chlorophyll fields to the satellite data. The following conclusions can be drawn from the simulation results in the water column:

- The porous approximation with disaggregation and reduced stickiness gave the best agreement with the measurements at the mesotrophic sediment trap site CB off Cape Blanc provided that the particle decay rate is 0.2 d⁻¹.
- The model failed to reproduce observed particle size spectrum in particular for the upper layers. Simulation of particle size spectra could be improved by limiting the fractal dimension in the model.
- The rectilinear aggregation kernels could be less appropriate for flux predictions due to exaggerated collision rates that they generate.
- Disaggregation is a crucial mechanism in predicting the deep water fluxes and particle size spectra.

In order to improve the representation of aggregation dynamics, variation in stickiness and size dependent remineralisation could be the areas that should be focussed on in further numerical studies of aggregation.

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