Supplement: Model coupling approach

This supplement describes the coupling of the sediment transport and biogeochemical modules in more detail than the main text, focusing in particular on the partitioning of aggregates and detritus (S.1) and the seabed layering scheme (S.2).

S.1 Partitioning of aggregates and detritus

Exchange of particulate organic matter (POM) between the biogenic state variables (phytoplankton, small detritus, and large detritus), aggregate variables (refractory and labile aggregates) in the water column, and the seabed variables (labile and refractory seabed organic matter) forms a critical link for coupling the sediment transport and biogeochemical modules (Fig. 2). Here, we first describe how the model handles exchanges among the water column state variables, then describe the model's treatment of this material as it deposits on the seabed, and finally provide details for how the organic matter is treated upon resuspension as it is entrained into the water column.

In Fennel et al. (2006), small detritus and phytoplankton in the water column may coagulate to form large detritus. HydroBioSed builds on this framework by partitioning coagulated material into three types of particulate matter: (1) large detritus, (2) labile aggregates, and (3) refractory aggregates. Based on estimates that roughly half of the deposited particulate organic matter is refractory in the Gulf of Lions (Tesi et al., 2007; Pastor et al., 2011a), the model partitions coagulated material into 50% refractory aggregates and 50% labile material ($f_{lab} = 0.5$), which is divided evenly between labile aggregates (25%) and large detritus (25%) and ($f_{ldet} = 0.5$):

$$Agg_{ref} = (1 - f_{lab}) \times (L_{det} + Agg_{lab} + Agg_{ref}) \quad \text{(S1)}$$

$$Agg_{lab} = (f_{lab}) \times (1 - f_{ldet}) \times (L_{det} + Agg_{lab} + Agg_{ref}) \quad \text{(S2)}$$

$$L_{det} = (f_{lab}) \times (f_{ldet}) \times (L_{det} + Agg_{lab} + Agg_{ref}) \quad \text{(S3)}$$

Aggregates, similar to phytoplankton and detritus, were assigned settling velocities, remineralization rates and partitioning coefficients (see Table 3 for details).

Upon settling to the seabed, phytoplankton, detritus, and labile aggregates are incorporated into labile seabed organic matter. Refractory aggregates are added to the pool of refractory seabed organic matter. The seabed model stores the concentration (mmol m^{-2}) of each tracer within each bed layer, with newly deposited organic matter added to the top seabed layer. This organic matter may then undergo biodiffusion, burial, and cycles of erosion and deposition; and is subject to the biogeochemical processes described in the Soetaert et al. (1996a, 1996b) model.

Upon resuspension, labile and refractory seabed organic matter is incorporated into the pools of labile or refractory aggregates suspended in the water column, respectively. Like other coagulated material in the water column, this material may be re-partitioned based on Eq. (S1 – S3). Usually, the seabed organic matter is enriched in refractory material compared to the water column. Thus, this repartitioning reclassifies a fraction of the resuspended refractory organic matter, i.e. refractory aggregates, into the labile organic matter classes, i.e. large detritus, and labile aggregates. This formulation was chosen because organic matter resuspended from anoxic to oxic environments may be remineralized faster due to the availability of oxygen (Aller, 1994; Burdige, 2007) and because previous modeling studies on the Rhone shelf have used higher remineralization rates in the water column compared to the seabed (Pinazo et al., 1996; Pastor et al., 2011a).

S.2 Seabed layering scheme

This study modified the seabed layering scheme from Warner et al. (2008) to include biogeochemical tracers and diffusion of dissolved tracers between the seabed and water column (S.2.1), and to resolve millimeter-scale processes in surficial sediments while maintaining centimeter-scale resolution deeper in the seabed (S.2.2).

S.2.1 Inclusion of biogeochemical tracers and seabed-water column diffusion

To couple the sediment transport and biogeochemical modules, we incorporated tracers representing particulate organic carbon and dissolved chemical species including oxygen and nutrients into the seabed module. To elaborate on the information presented in the Methods (Sect. 2.1), this section details how the sediment transport module was adapted from Warner et al. (2008) to account for them. The inclusion of particulate organic carbon was relatively straightforward because the model treats it similarly to sediment classes, except that it decays in time. Inclusion of porewater chemistry in the model, however, necessitated accounting for the formation of porewater within newly deposited layers and the entrainment of porewater into the water column during erosion, as described in Sect. 2.1.3, as well as diffusion of dissolved chemical constituents across the seabed-water interface, which is described below.

Consistent with Soetaert et al. (1996a, 1996b), our model parameterizes diffusion across the seabed-water interface by assuming that concentrations of dissolved tracers in the bottom water column and surficial seabed layer are equal. At each step, dissolved tracers move into or out of the seabed so that concentrations in the surficial seabed layer match those in the bottom water column cell, while conserving tracer concentrations:

$$C_{w\_tnew} = \frac{z_{\mathrm{w1}}}{z_{\mathrm{w1}}+z_{\mathrm{a}}\times\Phi}\times\left(C_{w\_told}+C_{s\_told}\right) \tag{S4}$$

$$C_{s\_tnew} = \left(1-\frac{z_{\mathrm{w1}}}{z_{\mathrm{w1}}+z_{\mathrm{a}}\times\Phi}\right)\times\left(C_{w\_told}+C_{s\_told}\right) \tag{S5}$$

where symbols are defined in Table 1. Note that a second approach relying on a Fickian diffusion law and a diffusion coefficient of 1.09 x 10^9 m^2 s^{-1} based on Boudreau (1997) and Toussaint et al. (2014) was also tested as an alternative approach that more directly accounted for diffusion across the seabed-water interface. Yet, both approaches yielded nearly identical results at the Rhone study site, and so we kept the simpler approach, consistent with Soetaert et al. (1996a, 1996b).

S.2.2 Seabed resolution

Our seabed layering scheme was adopted from Warner et al. (2008), whose model includes a single, thin, active transport layer with thickness z_a, that represents the region of the seabed just below the sediment – water interface from which material can be entrained into the water column (Harris and Wiberg, 1997). This active transport layer, also called the surficial seabed layer, typically overlies a user-specified number of layers of uniform thickness, as well as a thick bottom layer that acts as a sediment repository. This scheme, however, can not resolve sub-millimeter scale changes in biogeochemical profiles near the seabed-water interface as well as cm-scale changes deeper in the seabed (e.g. Fig. 5), unless many seabed layers are used. To make the model more efficient, we modified Warner et al. (2008)'s scheme by including both high-resolution and medium-resolution layers in the middle of the seabed. Here, we describe the new layering scheme, and then discuss how model routines for erosion and deposition were adapted for this new scheme.

Specifically, below the active transport layer, we chose to include $N_{high\text{-}res}$ high-resolution layers with thickness $z_{high\text{-}res}$ immediately below the active transport layer, and then $N_{med\text{-}res}$ medium-resolution layers with thickness of $z_{med\text{-}res}$ in the middle of the seabed. After some experimentation, this study used 60 seabed layers, and z_a, $z_{high\text{-}res}$, $z_{med\text{-}res}$, $N_{high\text{-}res}$, and $N_{med\text{-}res}$ were set equal to 0.1 mm, 0.5 mm, 1 cm, 19 layers, and 39 layers (Table S1). The sediment mass contained in the bottom seabed layer evolved with deposition and erosion, but was initialized to be 4.5 * 10^4 kg m^{-2} , i.e. 333 m thick. As in Warner et al. (2008), the bed layering scheme was designed so that the total number of layers remains constant, and sediment mass is conserved; additionally, the number of "high" and "medium resolution" layers remains constant, although their thicknesses may change slightly with erosion and deposition.

Incorporating multiple types of layers within the seabed affected how the layering scheme handled erosion and deposition, and care was needed to ensure that the resolution remained high near the sediment – water interface and increased deeper in the seabed. During depositional periods, new sediment is incorporated into surficial seabed layer(s) as described in Warner et al. (2008). When deposition increases the thickness of the surficial layer so that it exceeds ~2*z_a, the surficial layer is split into two, forming a thinner active transport layer and a new high-resolution layer, so that the surface layer remains thin. Similarly, if a high-resolution layer becomes thicker than $z_{high\text{-}res}$, this layer is also split into two layers. To maintain a constant number of layers, the bottommost high-resolution layer is then absorbed into the topmost medium-resolution layer. If addition of material to the topmost medium-resolution layer causes it to exceed $z_{med\text{-}res}$ in thickness, the material from two medium-thick layers that are thinner than $z_{med\text{-}res}$ are combined or the bottommost medium-resolution layer is absorbed into the seabed repository. In contrast, during erosion, removal of one or more high-resolution surface layers causes new high-resolution layers to split off from the topmost medium-resolution layer(s). When the topmost medium-resolution layer(s) is fully depleted, a new medium-resolution layer(s) is shaved off of the deep repository.

We also modified how the thickness of the surficial seabed layer, z_a, was calculated in order to facilitate the representation of diffusive exchange across the seabed-water column interface and to maintain high vertical resolution in the seabed. The CSTMS assumes that z_a thickens with increasing bed shear stress, allowing sediment from deeper regions of the seabed to be entrained into the water column during energetic time periods (Harris and Wiberg, 1997; Warner et al., 2008). During a resuspension event with bed shear stress of 2 Pa, this default parameterization would have thickened the surficial seabed layer to ~1.3 cm. Alternatively, some studies have constrained the active transport layer to smaller constant values, including 1 mm in the western Gulf of Lions (Law et al., 2008). For this biogeochemical-sediment transport model, it was important that the surface layer remain thin in order to represent the high gradients of oxygen observed at the seabed-water interface, and so we chose z_a equal to 0.1 mm to get reasonable oxygen penetration into the seabed. Overall, these adaptations from Warner et al. (2008) allow the seabed module to resolve mm-scale changes in seabed properties near the surface, while maintaining cm-scale resolution deeper in the seabed.

Table S1: Parameters for new seabed layering scheme, as implemented for the Rhone study site. Dashed lines indicate that no symbol was assigned to that parameter.

Type of Layer	Symbol for Number of Layers	Number of Layers for Rhone model implementation	Symbol for Thickness of each layer	Thickness of Each Layer for Rhone model implementation (mm)
Active Transport Layer (i.e., the Surficial Layer)	--	1	z_a	0.1
High-Resolution Layers	$N_{high\text{-}res}$	19	$z_{high\text{-}res}$	0.5
Medium-Resolution Layers	$N_{med\text{-}res}$	39	$z_{med\text{-}res}$	10
Repository	--	1		Varies; 333 m at initialization