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The Role of Seabed Resuspension on Oxygen and Nutrient Dynamics in Coastal Systems: A Numerical Modeling Study

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The Role of Seabed Resuspension on Oxygen and Nutrient Dynamics in Coastal Systems: A Numerical Modeling Study

A Dissertation
Presented to
The Faculty of the School of Marine Science
The College of William and Mary in Virginia

In Partial Fulfillment
of the Requirements for the Degree of
Doctor of Philosophy

by
Julia Miege Moriarty
August 2017
APPROVAL PAGE

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the requirements for the degree of
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# TABLE OF CONTENTS

Acknowledgements ........................................................................................................ vi
List of Tables .................................................................................................................. vii
List of Figures .................................................................................................................. viii
Abstract ........................................................................................................................... ix

## 1. Introduction

References for Chapter 1 ................................................................................................. 2

## 2. The roles of resuspension, diffusion and biogeochemical processes on oxygen
dynamics offshore of the Rhône River, France: a numerical modeling study ........ 13

Abstract for Chapter 2 .................................................................................................... 14

### 2.1 Introduction

### 2.2 Methods

- 2.2.1 Study site .............................................................................................................. 19
- 2.2.2 Model development ............................................................................................ 21
  - 2.2.2.1 Sediment transport module ........................................................................... 21
  - 2.2.2.2 Water-column biogeochemistry module ....................................................... 23
  - 2.2.2.3 Seabed biogeochemistry module .................................................................. 24
- 2.2.3 Model implementation and sensitivity tests ....................................................... 27

### 2.3 Results

- 2.3.1 Model evaluation ............................................................................................... 31
  - 2.3.2 Response of oxygen dynamics to resuspension .............................................. 33
    - 2.3.2.1 Seabed oxygen consumption ..................................................................... 34
    - 2.3.2.2 Bottom-water oxygen consumption ......................................................... 36
  - 2.3.3 Sensitivity tests ................................................................................................. 37
    - 2.3.3.1 Seabed oxygen consumption: Sensitivity tests ......................................... 38
    - 2.3.3.2 Bottom-water oxygen consumption: Sensitivity tests ............................... 40

### 2.4 Discussion

- 2.4.1 Resuspension-induced increases in oxygen consumption ............................... 41
  - 2.4.1.1 Why does resuspension change oxygen consumption on the Rhône Delta? 41
  - 2.4.1.2 How does resuspension-induced O₂ consumption compare to seasonal variability? ................................................................. 43
- 2.4.2 Modeling resuspension-induced changes in oxygen dynamics ....................... 45
- 2.4.3 Implications of model development and future work ...................................... 48

### 2.5 Summary and conclusions .................................................................................. 50

## Appendix 2.A

- 2.4.3.1 Inclusion of biogeochemical tracers and seabed-water-column diffusion ........ 53
- 2.4.3.2 Seabed resolution ............................................................................................ 54

Acknowledgements for Chapter 2 .................................................................................. 56

References for Chapter 2 ................................................................................................. 58

Tables for Chapter 2 ........................................................................................................ 69
4. The Impact of Seabed Resuspension on Primary Productivity and Remineralization: A Numerical Modeling Study of the Chesapeake Bay

4.1. Introduction

4.1.1. The role of resuspension on biogeochemical processes in Chesapeake Bay

4.1.2. Objective

4.2. Methods

4.2.1. Standard Model Formulation and Implementation

4.2.2. Model Runs and Analysis

4.3. Results

4.3.1. Evaluation of July 2000 standard model run

4.3.2. Effect of resuspension on primary production and remineralization along the Bay

4.4. Discussion

4.4.1. Along-estuary variability in the response of primary productivity and remineralization

4.4.2. Implications for oxygen and nitrogen dynamics

4.4.3. Role of sediment transport processes
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LIST OF TABLES

Table 2.1: Description of symbols ................................................................. 69
Table 2.2: Description of phrases, acronyms, and abbreviations ..................... 71
Table 2.3: Environmental conditions and parameters for the standard model implementation ........................................................................................................ 72
Table 2.4: List of sensitivity tests ..................................................................... 75
Table 2.5: Statistics for model-observation comparison ..................................... 76
Table 2.6: Oxygen consumption rates ............................................................ 77
Table 2.A.1: Parameters for the new seabed layering scheme .......................... 78
Table 3.1: Model forcing for the standard model run ......................................... 125
Table 3.2: Table of model runs ................................................................... 130
Table 3.3: Statistics for model-observation comparison .................................... 131
Table 4.1: Selected parameters for the standard model run in Chapter 4 .......... 181
LIST OF FIGURES

Figure 2.1: Study Site .................................................................................................................. 79
Figure 2.2: Model Schematic ...................................................................................................... 80
Figure 2.3: Model-observation comparison ................................................................................ 81
Figure 2.4: Oxygen consumption time-series ............................................................................. 82
Figure 2.5: Seabed profiles of biogeochemical tracers ................................................................. 83
Figure 2.6: Sources and sinks of oxygen in the seabed ............................................................... 84
Figure 2.7: Estimates of oxygen consumption for each sensitivity test ...................................... 85
Figure 2.8: Oxygen consumption averaged over different timescales ......................................... 86
Figure 3.1: Study site .................................................................................................................. 132
Figure 3.2: Time-series of model forcing .................................................................................. 133
Figure 3.3: Seabed oxygen consumption ................................................................................... 134
Figure 3.4: Time-series of model estimates for June 2006 ......................................................... 135
Figure 3.5: Time-series of model estimates for July 2006 .......................................................... 136
Figure 3.6: Box and whisker charts of model estimates for different sensitivity tests ............... 137
Figure 3.7: Maps of estimates from the standard model run, and the difference between the standard and no-resuspension model runs .......................................................... 138
Figure 3.8: Estimates from the standard model run for a transect westward of Atchafalaya Bay ........................................................................................................................................ 139
Figure 4.1: Study site .................................................................................................................. 184
Figure 4.2: Time-series of model forcing .................................................................................. 185
Figure 4.3: Model comparison to satellite-derived estimates ..................................................... 186
Figure 4.4: Along-estuary transects of biogeochemical rates and concentrations ..................... 187
Figure 4.5: Bed stresses in Chesapeake Bay .............................................................................. 188
Figure 4.6: Maps of biogeochemical rates and concentrations .................................................. 189
Figure 4.7: Regional Averages of biogeochemical rates and concentrations ............................... 190
Seabed resuspension can impact organic matter fate and water column biogeochemistry in coastal environments. Cycles of erosion and deposition can, for example, affect remineralization rates, seabed-water column fluxes of dissolved oxygen and nutrients, and light attenuation. Yet, models that incorporate both sediment transport and biogeochemical processes are rare, and nearly all neglect the effect of resuspension on oxygen and nutrient dynamics. Development of a novel tool, i.e. a coupled hydrodynamic-sediment transport-biogeochemical model, allowed for an investigation of the role of resuspension on oxygen and nitrogen dynamics within three distinct coastal environments. Called HydroBioSed, the coupled model was built within the Regional Ocean Modeling System and accounted for physical processes including the deposition and erosion of inorganic sediment and particulate organic matter from the seabed, as well as the flux of dissolved inorganic chemical species at the seabed-water column interface. The model also considered biogeochemical reactions including the remineralization of organic matter and oxidation of reduced chemical species, in both the seabed and the water column. HydroBioSed was first implemented as a one-dimensional vertical model for the Rhône River subaqueous delta. Results indicated that cycles of erosion and deposition altered rates of diffusion between the seabed and water column. This process increased fluxes of oxygen into the seabed during erosional periods, and the effect remained significant when results were averaged over time scales longer than individual events. The coupled model was next implemented in three-dimensions for the riverine-influenced northern Gulf of Mexico shelf. In this environment, resuspension-induced effects on bottom water biogeochemistry were dominated by increases in remineralization. Specifically, remineralization of resuspended organic matter increased oxygen consumption and ammonium production, especially in shallow areas where bed stresses were typically high. Finally, HydroBioSed was implemented for the Chesapeake Bay estuary and adapted to account for light attenuation by sediment and resuspended particulate organic matter. Here, resuspension-induced turbidity caused a down-stream shift in primary production. This shift, combined with remineralization of resuspended seabed organic matter, caused oxygen concentrations to decrease and ammonium concentrations to increase throughout the estuary. Overall, use of a novel coupled hydrodynamic-sediment transport-biogeochemical model, showed that cycles of erosion and deposition impact water column biogeochemistry, but the specific effects of resuspension varied across the three distinct environments studied.
The Role of Seabed Resuspension on Oxygen and Nutrient Dynamics in Coastal Systems: A Numerical Modeling Study
Chapter 1:

1. Introduction
The primary management strategy for many coastal water quality issues focuses on reducing terrestrial inputs of nutrients and sediment (e.g. Bricker et al., 2007; Kemp et al., 2009). Physical and sedimentary processes within the coastal ocean, however, such as water column mixing and either temporary or permanent burial of material in the seabed, complicate the relationship between terrestrial inputs and budgets of oxygen, nutrients, carbon, and sediment. For example, temporal lags between nutrient reductions and water quality improvements and increased cycling of nutrients within coastal systems have indicated that sedimentary processes can affect hypoxia and nutrient levels in some environments (e.g. Kemp et al., 2009; Testa and Kemp, 2012). As a result, sedimentary processes can confound the evaluation of management strategies because they are often poorly constrained or ignored. Quantifying the role of sedimentary processes is therefore important for improving our understanding of issues such as hypoxia, and for enabling managers to make sound decisions relating to ecosystem health (Bricker et al., 1999; McKee et al., 2004; Kemp et al., 2009; Bianchi et al., 2010; Committee on Environment and Natural Resources, 2010).

In coastal systems, waves and currents frequently entrain particles, as well as porewater and associated nutrients, from the seabed into the water column. The physical processes of erosion and deposition may therefore substantially impact the fate of sediment, organic matter, nutrient and oxygen. For example, seabed and bottom boundary layer observations indicate that resuspension can enhance organic matter remineralization (Aller, 1998; Hartnett et al., 1998; Arzayus and Canuel, 2004; Ståhlberg et al., 2006). Entrainment of particles into the water column creates turbidity that can reduce the penetration of light into the water column, reducing rates of photosynthesis and primary
production (Cloern, 1987; Malone et al., 1988; Schallenberg and Burns, 2004; Lohrenz et al., 2008). At the seabed-water interface, cycles of erosion and deposition can also alter diffusive fluxes of oxygen and nutrients between the seabed and water column (Toussaint et al., 2014; Glud, 2008). Once particulates and the nutrients dissolved in porewater are entrained into the water column during periods of resuspension, they may also be transported and redistributed around the system or exported, impacting the spatial and temporal gradients in biogeochemical processes (Lampitt et al., 1995; Abril et al., 1999).

Numerical models that account for both physical and biogeochemical processes may enhance our understanding of how resuspension affects oxygen, nutrient, organic matter and sediment dynamics. Models complement observational and laboratory studies that are typically limited by technological constraints and cost, and often focus on point measurements. Numerical models may help interpolate and extrapolate information from more limited field or lab studies to larger spatial and temporal scales, and can also be applied to time periods when no observations are available. For example, hydrodynamic models have long been used to elucidate circulation patterns in coastal areas (Haidvogel et al., 2000; Chen et al., 2003; Zhang and Baptista, 2008). Over the past few decades, sediment transport processes have been incorporated into hydrodynamic models to better represent sediment erosion and redistribution in coastal areas (e.g. Warner et al., 2008; Ulses et al., 2008; Xu et al., 2011; Cheng et al., 2013). Similarly, coupled biogeochemical and hydrodynamic models have been used to study oxygen, nutrient, organic matter, and plankton dynamics, as well as other processes (e.g. Fennel et al., 2006; Yu et al., 2015; Feng et al., 2015; Liu et al., 2007).
However, these previous regional-scale biogeochemical models have ignored or greatly simplified seabed and sediment transport processes (Rose et al., 2017; Hofmann et al., 2011). Many models assume that organic matter that settles to the seabed is instantaneously remineralized, buried, or resuspended (e.g. Cerco et al., 2013; Feng et al., 2015; Bruce et al., 2014; Liu et al., 2015; Fennel et al., 2013). Others account for the storage of organic matter in the seabed, but neglect erosion (e.g. Laurent et al., 2016; Testa et al., 2014). Similarly, many biogeochemical models parameterize turbidity-induced light attenuation based on salinity (e.g. Fennel et al., 2011; Fennel et al., 2016); ignore light attenuation due to resuspended sediment and organic matter (Liu et al., 2007); or use a temporally and spatially constant light attenuation coefficient (e.g. Bruce et al., 2014). A few recent regional-scale modeling efforts have considered both sediment transport and biogeochemical processes to focus on the transport of particulate organic carbon across shelves (Capet et al., 2016) or the impact of resuspension on light attenuation (McSweeney et al., 2016). To our knowledge, no previous modeling study has directly accounted for the impact of sediment transport processes, including resuspension, on organic matter remineralization, oxidation of reduced chemical species, diffusion across the seabed-water column interface, and light attenuation. However, the studies cited above motivate full consideration of both sediment transport and biogeochemical processes within a numerical model.

Development of a regional-scale model that can represent seabed resuspension, suspended sediment transport, and as well as biogeochemical processes, is further motivated by the impact that parameterization of seabed and sediment processes can have on estimates of water column biogeochemistry and water quality. In the northern Gulf of
Mexico, model estimates of hypoxic area, i.e. area of the seabed that is overlain by water less than 2 mg L\(^{-1}\), varied from almost zero to more than 3 times the observed value, depending how seabed-water column fluxes of oxygen and nitrogen were parameterized (Fennel et al., 2013). In the South China Sea, model estimates of primary production varied by up to factor of eight, depending how seabed-water column fluxes were parameterized (Liu et al., 2007). Finally, a Black Sea model that accounted for resuspension of particulate organic matter showed that increasing their threshold for erosion from 0.02 Pa to 0.05 Pa altered model estimates of primary production by about 60\%, and seabed remineralization of carbon by up to about 40\% (Capet et al., 2016).

As demonstrated above, motivation for this dissertation stems from the fact that both observations and model results indicate that seabed and sediment processes substantially effect biogeochemistry in many coastal systems, yet biogeochemical modeling tools have long neglected to directly account for sediment processes. Previous incorporation of sediment and biogeochemical modules into a community hydrodynamic modeling framework implies that development of a fully coupled model is timely, as well as important. Development of such a modeling tool will enable me to address the following questions within this dissertation:

1. To what extent does resuspension affect fluxes of dissolved oxygen and nitrogen between the seabed and the water column?

2. How does entrainment of particulate organic matter into the water column, and its subsequent remineralization, during cycles of erosion and deposition alter the oxygen and nitrogen dynamics in the water column?
3. How does increased turbidity in the water column, due to resuspension, alter oxygen and nitrogen dynamics?

The numerical model will also enable me to evaluate how the role of resuspension changes depending on the timescale considered, i.e. from time scales that span about a day to a month. Furthermore, the numerical model can be used to consider the role of resuspension in disparate settings, i.e. a subaqueous delta, a river-dominated shelf, and a large estuary.

To address these questions, this dissertation research included development of a coupled hydrodynamic-sediment transport-biogeochemical model and used the model to better understand and quantify the role of resuspension on oxygen and nitrogen dynamics in different locations. Each of the following three chapters focuses on a different study site, as well as a subset of the research questions listed above.

Specifically, Chapter 2 describes the development of a one-dimensional (vertical) version of the coupled model, and explores the extent to which cycles of erosion and deposition alter seabed-water column fluxes and water column oxygen consumption. This coupled model was applied to represent a site on the Rhône River subaqueous delta. Results indicated that accounting for cycles of erosion and deposition in the coupled model was necessary to represent the observed oxygen dynamics, i.e. that fluxes of oxygen into the seabed increased during resuspension events. Note that Chapter 2 has been published as Moriarty et al. (2017).

Chapters 3 and 4 build on Chapter 2 by implementing three-dimensional versions of the coupled model. Chapter 3 focuses on the extent to which resuspension in the northern Gulf of Mexico, a river-dominated shelf, affected seabed and near-bed
biogeochemical processes. Results indicated that remineralization of resuspended organic matter substantially increased both oxygen consumption and ammonium production on the shelf. Chapter 4 focuses on the relative impacts of resuspension on primary productivity and water column organic matter remineralization in Chesapeake Bay, a large estuary. Results indicated that the resuspension in the Upper Bay decreased photosynthesis, reducing oxygen production and nutrient uptake. Resuspension also increased near-bed remineralization rates, which increased oxygen consumption and ammonium production, especially in the Lower Bay.

Finally, Chapter 5 briefly summarizes the results from this dissertation, and synthesizes the model results presented in previous chapters. Together, these chapters examine the role resuspension can play on water column biogeochemistry in different environments, and through various processes.
References for Chapter 1


Chapter 2

2. The roles of resuspension, diffusion and biogeochemical processes on oxygen dynamics offshore of the Rhône River, France: a numerical modeling study

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Abstract for Chapter 2

Observations indicate that resuspension and associated fluxes of organic material and porewater between the seabed and overlying water can alter biogeochemical dynamics in some environments, but measuring the role of sediment processes on oxygen and nutrient dynamics is challenging. A modeling approach offers a means of quantifying these fluxes for a range of conditions, but models have typically relied on simplifying assumptions regarding seabed-water-column interactions. Thus, to evaluate the role of resuspension on biogeochemical dynamics, we developed a coupled hydrodynamic, sediment transport, and biogeochemical model (HydroBioSed) within the Regional Ocean Modeling System (ROMS). This coupled model accounts for processes including the storage of Particulate Organic Matter (POM) and dissolved nutrients within the seabed; fluxes of this material between the seabed and the water column via erosion, deposition, and diffusion at the sediment-water interface; and biogeochemical reactions within the seabed. A one-dimensional version of HydroBioSed was then implemented for the Rhône subaqueous delta, France. To isolate the role of resuspension on biogeochemical dynamics, this model implementation was run for a two-month period that included three resuspension events; also, the supply of organic matter, oxygen and nutrients to the model was held constant in time. Consistent with time-series observations from the Rhône Delta, model results showed that erosion increased the diffusive flux of oxygen into the seabed by increasing the vertical gradient of oxygen at the seabed-water interface. This enhanced supply of oxygen to the seabed, as well as resuspension-induced increases in ammonium availability in surficial sediments, allowed seabed oxygen consumption to increase via nitrification. This increase in nitrification compensated for
the decrease in seabed oxygen consumption due to aerobic remineralization that occurred as organic matter was entrained into the water column. Additionally, entrainment of POM into the water column during resuspension events, and the associated increase in remineralization there, also increased oxygen consumption in the region of the water column below the pycnocline. During these resuspension events, modeled rates of oxygen consumption increased by up to factors of ~2 and ~8 in the seabed and below the pycnocline, respectively. When averaged over two months, the intermittent cycles of erosion and deposition led to a ~16 % increase of oxygen consumption in the seabed, as well as a larger increase of ~140 % below the pycnocline. These results imply that observations collected during quiescent periods, and biogeochemical models that neglect resuspension or use typical parameterizations for resuspension, may underestimate net oxygen consumption at sites like the Rhône delta. Local resuspension likely has the most pronounced effect on oxygen dynamics at study sites with a high oxygen concentration in bottom waters, only a thin seabed oxic layer, and abundant labile organic matter.

2.1 Introduction

Understanding and quantifying the role that physical processes play on coastal water quality remains a scientific and management concern. Management solutions to hypoxia, the occurrence of low oxygen concentrations, as well as other water quality issues, have focused on reducing riverine delivery of nutrients and sediments (Bricker et al., 2007). Yet temporal lags between these reductions and water quality improvements (Kemp et al., 2009), and increased cycling of nutrients within coastal systems (e.g. Testa and Kemp, 2012), indicate that temporary storage of nutrients in the seabed and subsequent release to the water column via diffusion and/or resuspension can affect water
quality in some coastal environments. Neglecting these processes impairs managers’ ability to develop and evaluate strategies for improving coastal water quality (e.g. Artioli et al., 2008).

Resuspension-induced fluxes of sediment, Particulate Organic Matter (POM), and dissolved chemical species between the seabed and water-column can significantly affect biogeochemistry in coastal waters, including oxygen dynamics (Glud, 2008). Entrainment of seabed organic matter and reduced chemical species into the water-column can increase remineralization and oxidation rates, thereby decreasing oxygen concentrations in bottom-waters (BW) in some environments. For example, Abril et al. (1999) observed that oxygen concentrations were inversely correlated with tidal fluctuations of suspended particulate matter concentrations in the Gironde Estuary, France. Recently, Toussaint et al. (2014) collected high-resolution time-series of microelectrode oxygen profiles on the Rhône River subaqueous delta that showed resuspension may also increase oxygen consumption in the seabed. This experiment revealed increases in diffusive fluxes of oxygen from the water-column to the seabed during erosional events. Other observational studies have estimated resuspension-induced increases in oxygen consumption within the seabed and bottom-waters using measurements of turbulent oxygen fluxes (Berg and Huettel, 2008) and erodibility experiments (e.g., Sloth et al., 1996). Yet, it remains difficult to distinguish and quantify the relative influences of different biogeochemical (e.g. remineralization, oxidation) and physical (e.g. diffusion, resuspension) processes on oxygen dynamics in both the seabed and bottom-waters.

Hydrodynamic-biogeochemical models often complement observational studies of water quality (e.g. Moll and Radach, 2003; Aikman et al., 2014), but these simulations
usually neglect or simplify sebed-water-column fluxes. Water quality models often assume that organic matter and nutrients reaching the seabed are permanently buried, instantaneously remineralized, resuspended without remineralization, or a combination thereof (e.g. Cerco et al., 2013; Fennel et al., 2013; Feng et al., 2015; Bruce et al., 2014; Liu et al., 2015). Yet, numerical experiments showed that switching among relatively simple parameterization methods for sebed-water-column fluxes can alter the estimated area of low-oxygen regions by about -50 % to +100 % in the Gulf of Mexico (Fennel et al., 2013). This sensitivity of modeled oxygen concentrations to the choice of parameterization, as well as the observations of temporally variable oxygen fluxes discussed above, motivate development of a process-based model for sebed-water-column fluxes.

We therefore developed a modeling approach that accounts for physical and biogeochemical processes at the sebed-water interface, including resuspension of POM and porewater, and implemented it for the dynamic Rhône Delta. Previously, one-dimensional box models with a few vertical levels have been used to study the role of organic matter resuspension on oxygen (Wainright and Hopkinson, 1997) and contaminant levels (Chang and Sanford, 2005). Additionally, three-dimensional circulation models have been coupled to biogeochemical models with a single sebed layer and implemented to investigate the role of POM resuspension on Baltic Sea carbon budgets (Almroth-Rosell et al., 2011) and Black Sea biogeochemistry (Capet et al., 2016). To the best of our knowledge, however, no previously existing models have sufficient vertical resolution to resolve changes in the vertical biogeochemical profiles.
that drive diffusive seabed-water-column fluxes, or the ability to account for the entrainment of reduced chemical species into the water column.

This paper presents a model called *HydroBioSed* that can reproduce the mm-scale changes in seabed profiles of oxygen, nitrogen and carbon, as well as the resuspension-induced changes in seabed-water-column fluxes observed on the Rhône River subaqueous delta, by coupling hydrodynamic, biogeochemical and sediment transport modules. This process-based numerical model was implemented for the Rhône River subaqueous delta and used to evaluate how episodic erosion and deposition affect millimeter-scale seabed biogeochemistry and overall oxygen consumption in a dynamic coastal environment. Specific research questions for this paper include: (1) How do erosion and deposition affect the timing and magnitude of seabed and bottom-water oxygen consumption? (2) What are the relative roles of local resuspension, organic matter remineralization, and oxidation of reduced chemical species in controlling oxygen consumption in the seabed and bottom waters? (3) How sensitive is oxygen consumption to resuspension frequency and magnitude, sedimentation rate, organic matter lability and availability, rate of diffusion within the seabed, and seabed nitrification rate? (4) What characteristics of the study site lead to the dependence of oxygen dynamics on local resuspension?

### 2.2 Methods

This section describes the Rhône Delta (Sec. 2.2.1), and *HydroBioSed* (Sect. 2.2.2), before explaining how the model was implemented to address the research questions (Sect. 2.2.3). Tables 2.2.1 and 2.2.2 list related symbols and vocabulary.
2.2.1 Study site

Located in the Gulf of Lions at the northwest end of the Mediterranean Sea, the Rhône River subaqueous delta in France is an excellent study site for these research questions in part because of the available observations (Fig. 2.1). Our study is co-located with the site from Toussaint et al. (2014) at the “Mesurho” station (Pairaud et al., 2016) and is only a few km away from Site A in Pastor et al. (2011a); both locations are at ~25 m water depth and are characterized by similar biogeochemical characteristics (e.g. Rassmann et al., 2016), and so data from both sites were used for model input, validation and evaluation. Importantly, data from Toussaint et al. (2014) included a time-series of oxygen profiles with sub-millimeter scale resolution within the seabed and bottom centimeter of the water column. By resolving changes that occurred during resuspension events, Toussaint et al. (2014) showed that diffusion of oxygen into the seabed increased during resuspension events.

This site experiences frequent seabed disturbance due to centimeters of erosion superimposed on rapid fluvial deposition. Over timescales of decades, due to its proximity to the Rhône River (Fig. 2.1), accumulation rates at this site are ~10 cm y\(^{-1}\) for sediment and 657 g m\(^{-2}\) y\(^{-1}\) of carbon (Radakovitch et al., 1999; Pastor et al., 2011a), although deposition varies in response to seasonal and episodic changes in river discharge and wave energy (Pont, 1997; Miralles et al., 2006; Ulses et al., 2008; Cathalot et al., 2010). Deposition is punctuated by erosional events, and our study period, April-May 2012, included three instances when wave energy resuspended 1-2 cm of material from the seabed (Toussaint et al., 2014). At this site, erosion and deposition are the main sources of seabed disturbance; little bioturbation has been observed (Pastor et al., 2011b).
The delivery of organic matter to the shelf drives oxygen consumption directly via aerobic remineralization, and indirectly, as reduced chemical species produced during remineralization are oxidized (Lansard et al., 2009). Organic material comprises about 2-12 % and <1-5 % of water-column and seabed particulate matter, respectively, and about four-fifths of it originates from a terrestrial source, with little marine influence at the study site (Bourgeois et al., 2011; Pastor et al., 2011a; Lorthiois et al., 2012; Cathalot et al., 2013). Yet, the material settling to the seabed at this site is relatively labile, and has been estimated to have remineralization rate constants of 11 - 33 y\(^{-1}\) in the water column (Pinazo et al., 1996) and 0.31–11 y\(^{-1}\) in the seabed (Pastor et al., 2011a). Despite the large input of organic matter to the Gulf of Lions, oxygen concentrations remain near saturation and hypoxia has not been reported, likely because the system is physically dynamic (Rabouille et al., 2008), suggesting that most organic matter is aerobically remineralized. In contrast, ~85% of seabed organic matter remineralization is anaerobic at our study site (Pastor et al., 2011a). This remineralization produces high ammonium concentrations that diffuse upwards and cause nitrification to account for an unusually large amount (over half) of the site’s seabed oxygen consumption, which is about 10-30 mmol O\(_2\) m\(^{-2}\) d\(^{-1}\) in the prodelta where our site is located (Lansard et al., 2009; Pastor et al., 2011a, Toussaint et al., 2014). Yet, seabed fluxes of oxygen, carbon, and dissolved nutrients vary during resuspension events, complicating efforts to quantify the importance of different biogeochemical processes at this site (Lansard et al., 2009; Toussaint et al., 2014) and motivating this study.
2.2.2 Model development

The fully coupled HydroBioSed numerical model was developed within the Regional Ocean Modeling System (ROMS), a community-based and well-used ocean modeling framework (Haidvogel et al., 2000, 2008; Shchepetkin, 2003; Shchepetkin and McWilliams, 2009). In addition to its core hydrodynamic components, ROMS includes widely-used modules for sediment transport (CSTMS; Community Sediment Transport Modeling System; Warner et al., 2008), and water-column biogeochemistry (e.g. Fennel et al., 2006, 2013). We built on those previous studies by coupling the sediment transport and water-column biogeochemistry components (Fig. 2.2a), enabling the model to account for storage of POM and nutrients in the seabed, and subsequent resuspension and redistribution of the organic matter and nutrients. As part of the coupling, we also incorporated aggregation of detritus, seabed-water-column diffusion, and a multi-layer seabed biogeochemical model based on Soetaert et al. (1996a, 1996b). Below, we briefly describe the sediment transport and water-column biogeochemistry modules used, highlighting differences from standard ROMS implementations and the addition of the seabed biogeochemistry model.

2.2.2.1 Sediment transport module

Suspended sediment tracers in the ROMS-CSTMS module are transported by ocean currents, experience downward settling, may be deposited and eroded from the multi-layer seabed model, and are subject to source and sink terms such as river discharge (Warner et al., 2008). As discussed in Warner et al. (2008), the rates of
deposition, $D_{\text{ised}}$, and erosion, $E_{\text{ised}}$, for each sediment class $\text{ised}$, are calculated as follows (parameters are defined in Table 2.1):

$$D_{\text{ised}} = -\frac{\partial (w_{5,\text{ised}}c_{\text{ised},z=1})}{\partial z_w}$$

$$E_{\text{ised}} = M (1 - \Phi) f_{\text{ised}} \left( \frac{\tau_{\text{bed}} - \tau_{\text{crit,ised}}}{\tau_{\text{crit,ised}}} \right) \quad \text{when } \tau_{\text{bed}} \geq \tau_{\text{crit,ised}}$$

$$= 0 \quad \text{when } \tau_{\text{bed}} < \tau_{\text{crit,ised}}$$

Resuspension from the seabed is parameterized such that erosion may only occur when the modeled bed stress, $\tau_{\text{bed,ised}}$, exceeds the critical shear stress, $\tau_{\text{crit,ised}}$. Because erosion and deposition can co-occur, “erosional” and “depositional” time periods refer to times of net erosion, i.e. when $E_{\text{ised}} - D_{\text{ised}} > 0$, and net deposition, i.e. when $E_{\text{ised}} - D_{\text{ised}} < 0$, respectively. Previous CSTMS applications accounted only for inert particulates; however, here we adapted the model to link sediment transport and biogeochemical processes. In HydroBioSed, POM from the water-column biogeochemical module provides an additional source of particulates to the seabed (Sect. 2.2.2.3), and POM can be deposited, eroded, and buried along with the sediment in its seabed layer. Note that POM comprises only ~3% of the seabed by mass on the Rhône Delta and so it was considered negligible for calculating fluxes within the seabed layering scheme. Additionally, the seabed layering scheme of Warner et al. (2008) was modified so that the seabed has sufficient resolution (<1 mm) near the seabed-water interface where vertical gradients in biogeochemical constituents such as dissolved oxygen can be high (see Appendix 2.A). Finally, while versions of CSTMS already accounted for diffusion of sediment within the seabed (Sherwood et al., in prep), HydroBioSed uses the same methods to account for the diffusion of porewater and POM.
2.2.2.2 Water-column biogeochemistry module

ROMS water-column biogeochemistry modules have typically included variables for multiple nutrient, plankton and detrital classes and accounted for processes such as growth, grazing and remineralization (e.g. Fennel et al., 2006). Here, the ROMS biogeochemical model from Fennel et al. (2013) was modified so that HydroBioSed converts some of the large detritus into faster-sinking aggregates in the water column. In Fennel et al. (2013), small detritus and phytoplankton in the water column may coagulate to form large detritus. HydroBioSed builds on the Fennel et al. (2013) framework by partitioning coagulated material into three types of particulate matter: (1) large detritus, (2) labile aggregates, and (3) refractory aggregates (Fig. 2.2b). 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 ($f_{det} = 0.5$) between labile aggregates (25 %) and large detritus (25 %):

$$A_{g g_{r e f}} = (1 - f_{lab}) \times (L_{det} + A_{g g_{lab}} + A_{g g_{ref}})$$  \hspace{1cm} (2.3)

$$A_{g g_{lab}} = (f_{lab}) \times (1 - f_{det}) \times (L_{det} + A_{g g_{lab}} + A_{g g_{ref}})$$ \hspace{1cm} (2.4)

$$L_{det} = (f_{lab}) \times (f_{det}) \times (L_{det} + A_{g g_{lab}} + A_{g g_{ref}})$$ \hspace{1cm} (2.5)

Aggregates, similar to phytoplankton and detritus, are assigned settling velocities and remineralization rate constants (Table 2.3; Fennel et al., 2006), and are transported within the water column by the hydrodynamic module. Upon sinking to the bed, aggregates, as well as phytoplankton and detritus, are added to the pool of seabed organic matter within the seabed module, as described in the next section.
2.2.2.3 Seabed biogeochemistry module

A seabed biogeochemistry module (Soetaert et al., 1996a, 1996b) was added to ROMS to account for changes in oxygen, dissolved nitrogen, and POM due to remineralization, oxidation of reduced chemical species, and diffusion across the seabed-water interface. This model has performed well in many environments including areas near river deltas (Wijsman et al., 2002; Pastor et al., 2011a), on the continental shelf and slope (Soetaert et al., 1998; Epping et al., 2002), and in the deep ocean (Middelburg et al., 1996). To incorporate the Soetaert et al. (1996a, 1996b) model into HydroBioSed, we used the code developed by Wilson et al. (2013), and adapted it for the ROMS framework and the Rhône Delta. Calculations use the first-order accurate Euler method.

This seabed biogeochemistry model specifically tracks degradable particulate organic carbon (POC), oxygen, nitrate, ammonium, and oxygen demand units (ODUs), defined as the moles of reduced chemical species that react with one mole of $O_2$ when oxidized. Like Soetaert et al.’s early diagenetic model (1996a, 1996b), HydroBioSed uses ODUs to represent a combination of reduced chemical species that are produced during anoxic remineralization, including iron and manganese ions, sulfide, and methane. Modeled POC includes both labile and refractory (or semi-labile) classes. For a full model description, see Soetaert et al. (1996a, 1996b), but here we present the rate equations for oxic remineralization (Eq. 2.6), denitrification (Eq. 2.7), anoxic remineralization (Eq. 2.8), nitrification (Eq. 2.9) and oxidation of ODUs (Eq. 2.10) to provide context for the Results and Discussion (see Table 2.1 for parameter definitions):

$$R_{aerobic} = POC \times R_{POC} \left( \frac{q_2}{q_2 + k_{O_2} \cdot l_{tot}} \right)$$

(2.6)
\[ R_{DNF} = POC \times R_{POC} \left( \frac{l_{O_2}}{O_2 + l_{O_2} NO_3 + k_{NO_3} L_{tot}} \right) \]  
\[ R_{anoxic} = POC \times R_{POC} \left( \frac{l_{O_2, anoxic}}{O_2 + l_{O_2, anoxic} NO_3 + l_{NO_3, anoxic} L_{tot}} \right) \]  
\[ R_{nit} = NH_4 \times R_{nit,max} \left( \frac{O_2}{O_2 + k_{O_2, nit}} \right) \]  
\[ R_{oduox} = ODU \times R_{odu,max} \left( \frac{O_2}{O_2 + k_{O_2, oduox}} \right) \]  

where \( L_{tot} \), the non-dimensional sum of the limitation factors on remineralization processes, is:

\[ L_{tot} = \left( \frac{O_2}{O_2 + k_{O_2}} \right) + \left( \frac{l_{O_2}}{O_2 + l_{O_2} NO_3 + k_{NO_3}} \right) + \left( \frac{l_{O_2, anoxic}}{O_2 + l_{O_2, anoxic} NO_3 + l_{NO_3, anoxic}} \right) \]  

Adaptations to the Soetaert et al. (1996a, 1996b) early diagenesis model which were made to merge it with the CSTMS and Fennel modules include neglecting seabed consolidation and temperature-induced changes to biogeochemical rates. Specifically, HydroBioSed neglects changes in porosity with depth in the sediment bed because this study focused on the frequently resuspended surficial centimeter of the seabed and seabed-water-column interactions. Also, we neglected the effect of temperature on remineralization and diffusion because temperature was held constant for this implementation of HydroBioSed (see Sect. 2.2.3).

Merging the Soetaert et al. (1996a, 1996b) seabed biogeochemical model with the sediment transport and water-column biogeochemistry modules allows HydroBioSed to account for exchanges of biogeochemical tracers across the seabed-water interface due to deposition, erosion, and diffusion (Fig. 2.2b). Upon settling to the seabed, phytoplankton, detritus, and labile aggregates are incorporated into labile seabed organic matter in the surficial seabed layer. Refractory aggregates are added to the pool of refractory seabed organic matter.
organic matter in that layer. Porewater in newly deposited sediments is assumed to initially have concentrations of dissolved nutrients and oxygen equal to those in the overlying water column. This material may be re-entrained into the water column when bed shear stress exceeds the critical shear stress of the seabed. Specifically, any POM or dissolved chemical species in the porewater within an eroded layer(s) of sediment is also entrained into the bottom water-column layer. The flux of sediment entrained into the water column is determined by the CSTMS module (see Sect. 2.2.2.1). In addition to erosion and deposition, dissolved oxygen and nutrients may be transported across the seabed-water interface by diffusion as described in Appendix 2.A.1.

During erosional periods, resuspended 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 repartitioned based on Eqs. (2.3–2.5). 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 modeling approach is supported by laboratory experiments by Stahlberg et al. (2006) indicating that organic matter remineralization rates increased during and in the days following resuspension events, and that changes in remineralization rates were not only due to changes in oxygen availability. Due to the limited availability of pertinent research, we also considered literature related to the effect of redox oscillations on organic matter remineralization (e.g. Gilbert et al., 2016; Sun et al., 2003; Caradec et al., 2004; Aller, 1994; Wakeham and Canuel, 2006; Arzayus and Canuel, 2004). Yet,
because guidance from this literature was inconclusive, we chose the simple approach described above for the partitioning of organic matter that mimics the changes in remineralization described in Stahlberg et al. (2006). We also tested an alternative, ‘no-repartitioning’ approach that did not repartition resuspended organic matter, but this approach caused decreases in oxygen gradients across the seabed-water interface during depositional periods, inconsistent with observations from Toussaint et al. (2014) (Fig. 2.2c).

Overall, HydroBioSed represents POM in the seabed until it is resuspended, remineralized, or buried. Similarly, dissolved chemical species in the porewater may undergo biogeochemical transformations, diffuse into or out of the seabed, or be exchanged with the water column during periods of erosion and deposition. Thus, unlike Soetaert et al. (1996a, 1996b) and other classical seabed biogeochemistry models (e.g. Berner, 1980; Boudreau, 1997; Soetaert et al., 2000; DiToro, 2001), HydroBioSed can quantify the effect of resuspension on biogeochemical dynamics (Fig. 2.2).

2.2.3 Model implementation and sensitivity tests

To evaluate the coupled model and explore the role of local resuspension on oxygen dynamics, we implemented a one-dimensional version of HydroBioSed for the Rhône Delta. This section describes the standard model run and sensitivity tests, and summarizes our methods for model evaluation and analysis. See Table 2.3 for a list of model input and parameters.

“Standard” Model Run: A one-dimensional (vertical) version of HydroBioSed was implemented for a 24-m deep site on the Rhône subaqueous delta (Fig. 2.1) for April-May 2012. This time period coincided with Toussaint et al. (2014)’s observational
study and included three resuspension events as well as quiescent periods characterized by low bed stress. To implement a quasi one-dimensional model within the ROMS framework, a 5-cell x 6-cell model grid with spatially uniform forcing and periodic open boundary conditions was used. Vertical stratification in the model was maintained by strongly nudging temperature and salinity to climatological values; a pycnocline at 4 m above the seabed separated the colder saltier bottom waters from the warmer fresher upper water column. Wave- and current-induced bed stresses were estimated using the Sherwood, Signell and Warner (SSW) bottom boundary layer parameterization based on Madsen (1994) and described in Warner et al., (2008).

To isolate the effect of resuspension on seabed-water-column fluxes, water-column concentrations of oxygen, nitrogen, and ODU, as well as the supply of POM (excluding that from resuspension) were strongly nudged to temporally constant values. Hourly to daily oxygen observations from the bottom boundary layer (Toussaint et al., 2014) were used to constrain modeled concentrations in the water-column. These observations indicated that oxygen concentrations 1 m above the bed varied between 216 - 269 mmol O$_2$ m$^{-3}$, but that resuspension events did not appear to impact near-bed O$_2$ fluctuations. A constant value of 253 mmol O$_2$ m$^{-3}$ was therefore used for water-column O$_2$ concentrations (Pastor et al., 2011a). Values for water-column nitrate, ammonium, and ODU concentrations were chosen based on Pastor et al. (2011a)’s Site A data because no observations were available from our study site (Fig. 2.1). Additionally, small detritus concentrations were strongly nudged to provide a constant supply of degradable POM to the water-column equivalent to 657 gC m$^{-2}$ y$^{-1}$, based on Pastor et al. (2011a)’s estimate for organic sedimentation rate, S$_{organic}$. Nudging the small detritus concentrations did not
affect those of the large detritus and aggregates that were resuspended from and deposited onto the seabed.

Model forcing and parameters were chosen based on a combination of observed values (wave height, bottom-water oxygen concentrations), climatology (inorganic sedimentation rate, salinity, temperature), and values used in previously implemented models (fraction of labile material, nitrification rate, rates of diffusion within the seabed). See Table 2.3 for more details. A few parameters, i.e. critical shear stress for erosion and erosion rate parameter, were tuned to reproduce the 1-2 cm of observed erosion. For initialization, the model was run without resuspension until it reached steady state. As the biogeochemical profiles reached a state of quasi-equilibrium within days following perturbations, using alternative initialization techniques primarily affected estimates for the first resuspension event and did not have a large effect on our results. The model used a 30 second time-step, the MPDATA advection scheme (Smolarkiewicz and Margolin, 1998), the Generic Length Scale turbulence closure (Umlauf and Burchard, 2009), and a Piecewise Parabolic Method (Colella and Woodward, 1984) with a weighted essentially non-oscillatory scheme (Liu et al., 1994) to estimate particle settling. It saved output in three-hour increments, and took ~6 hours to run on a single processor for a 2-month simulation.

*Sensitivity Tests*: In addition to the standard model run, seven sets of sensitivity tests examined the response of oxygen consumption to different parameters and processes (Table 2.4). These tests modified parameters related to resuspension and seabed processes, including the critical shear stress for erosion ($\tau_{\text{crit}}$), erosion rate parameter ($M$), inorganic and organic sedimentation rates ($S_{\text{inorganic}}$ and $S_{\text{organic}}$), lability of aggregated
organic matter ($f_{lab}$) and the partitioning of organic matter (see Fig. 2.2b), rate of diffusion within the seabed ($D_i$), and nitrification rate in the seabed ($R_{nit,max}$). Additional tests modifying the ODU oxidation rate and the parameterization scheme for seabed-water-column diffusion had a negligible effect on model results and so are not presented here.

Additionally, “no-resuspension” model runs were completed to evaluate the role of cycles of erosion and deposition on biogeochemical dynamics. Specifically, for each sensitivity test and the standard model run, a corresponding simulation was conducted that was identical to the original, except that erosion was prevented by increasing the critical shear stress to $\tau_{crit} = 10$ Pa and decreasing the erosion rate parameter to $M= 0$ kg m$^{-2}$ s$^{-1}$. For conciseness, however, references to the “no-resuspension” model run refer to the no-resuspension version of the standard model, unless otherwise noted.

**Model Analysis:** We focused on seabed and bottom-water oxygen consumption and on fluxes of oxygen at the seabed-water interface. Bottom water was defined as the region of the water column within 4 m of the seabed, i.e. below the pycnocline, where suspended sediment concentrations were high during resuspension events. Concentrations and rates for analyses were saved in the model output. The fraction of oxygen consumption due to resuspension was calculated by dividing the difference between each sensitivity test and its no-resuspension model run by the value from the sensitivity test. Additionally, note that all POM estimates presented in this paper are for degradable organic matter. Although some studies add concentrations of inert POM to model estimates of degradable POM for comparison to observations, we plot only degradable POM for simplicity. Finally, depths of erosion into the seabed, which depend on both the
duration of the event and bed stresses, were calculated by comparing the thickness of the seabed before versus during a time period of net erosion.

2.3 Results

This section evaluates the skill of the standard model run by comparing it to observations (Sect. 2.3.1), analyzes the effect of resuspension on oxygen dynamics (Sect. 2.3.2), and evaluates the results’ sensitivity to model parameters (Sect. 2.3.3).

2.3.1 Model evaluation

Comparison of the standard version of HydroBioSed to Toussaint et al. (2014)’s time-series of oxygen profiles showed that model results were consistent with measured concentrations, and changed during resuspension events in a manner similar to the observations (Fig. 2.3). During quiescent conditions when bed shear stress was low, modeled and observed oxygen concentrations decreased with depth into the seabed, falling from about 250 mmol O$_2$ m$^{-3}$ in the bottom water column to 0 mmol O$_2$ m$^{-3}$ within 1-2 mm below the seabed surface. Similarly, both the modeled and observed oxygen penetration depths decreased to about <1 mm in the seabed during times of erosion, before returning to a quasi-steady state within hours of bed stresses returning to background values.

To quantify the changes in seabed oxygen profiles, the oxygen gradient near the seabed-water interface was calculated from both the observed and modeled profiles (Table 2.5). Specifically, the slope of the oxygen profile was averaged over the oxygen penetration depth (OPD; variables are defined in Table 2.1):
\[
\frac{DO_2}{dz_{OPD}} = -\frac{O_{2,SWI} + O_{2,OPD}}{z_{SWI} + z_{OPD}}
\]  

(2.13)

Overall, \(dO_2/dz_{OPD}\) increased during erosional periods (Fig. 2.3). During times when the seabed was not mobilized, \(dO_2/dz_{OPD}\) maintained a baseline of \(\sim 100\) mol O\(_2\) m\(^{-4}\), in both the modeled results and the observed values. In contrast, resuspension decreased the oxygen penetration depth, increasing \(dO_2/dz_{OPD}\) to about 500 mol O\(_2\) m\(^{-4}\) (observed by Toussaint et al., 2014) and 900 mol O\(_2\) m\(^{-4}\) (modeled).

Differences in the modeled and observed oxygen profiles derive at least partially from differences in estimating seabed elevation (i.e. erosion and deposition). As a one-dimensional vertical model, HydroBioSed assumed uniform conditions in the horizontal, and so all resuspended material was re-deposited in the same location within a few days following an event. Yet, at the actual study site, it is likely that some material was carried out of the area and that deposition following the erosional periods was more gradual than estimated in the model (e.g. see the late April/early May event in Fig. 2.3c). Also, the model provided higher temporal resolution than possible with the sampling gear, and may capture peaks in \(dO_2/dz_{OPD}\) that are missed by the sampling frequency (Fig. 2.3d). Yet, in spite of these differences, HydroBioSed reproduced the general behavior of oxygen profiles as observed on the Rhône subaqueous delta (Fig. 2.3e,f,g). In contrast to previous models that could not account for resuspension-induced temporal variations (Pastor et al., 2011a), both observed and modeled \(dO_2/dz_{OPD}\) increased by factors of approximately 4-9 during erosional periods.
2.3.2 Response of oxygen dynamics to resuspension

Overall, the combined seabed-bottom-water oxygen consumption increased from ~40 mmol O$_2$ m$^{-2}$ d$^{-1}$ to over 200 mmol O$_2$ m$^{-2}$ d$^{-1}$ during resuspension events (Fig. 2.4b,c). Averaged over two months, resuspension roughly doubled the combined seabed-bottom-water oxygen consumption to >70 mmol O$_2$ m$^{-2}$ d$^{-1}$. Although the seabed and bottom waters contributed about equally to oxygen consumption during quiescent periods, the large increase in combined seabed-bottom-water oxygen consumption during resuspension events was primarily driven by remineralization of POM in bottom waters (Table 2.6). For both the seabed and bottom waters, resuspension added variability to oxygen dynamics, so that about one-half of the total oxygen consumption occurred within the 30 % of the two-month study period that included the resuspension events.

The cycles of erosion and deposition that affected biogeochemical cycles are illustrated by time-series of seabed profiles (Fig. 2.5). Before resuspension events, the porewater in surface sediments was typically equilibrated with the overlying water column, with oxygen penetrating ~1-2 mm into the seabed (Fig. 2.5a). As energetic waves increased bed stresses, however, particulate matter from the seabed was eroded into overlying water, with typical erosion depths of ~5-20 mm. This erosion of the surficial seabed exposed low-oxygen, high-ammonium, high-ODU porewater to the sediment-water interface. This exposure changed profiles by, for example, sharpening the oxygen and ammonium gradients at the seabed-water interface and resuspending POM (Fig. 2.5b,h,k). As wave energy subsided and bed stresses decreased hours to a few days later, previously resuspended sediment and POM was re-deposited on the seabed (Fig. 2.5l). This re-deposited organic matter was particularly enriched in labile organic matter.
compared to the material that had remained on the seabed, due to repartitioning in the water column (Fig. 2.2b). As new seabed layers formed from re-deposited sediments, dissolved constituents from the overlying water were incorporated into the porewater of these new layer(s). This altered profiles by, for example, briefly increasing the thickness of the oxic layer up to ~5 mm during depositional periods.

The next two sections provide a more detailed and quantitative analysis of how these exchanges of porewater and particulate matter between the seabed and the overlying water increased oxygen consumption and affected related biogeochemical processes within the seabed (Sect. 2.3.2.1) and bottom waters (Sect. 2.3.2.2).

2.3.2.1 Seabed oxygen consumption

Resuspension directly altered the supply of oxygen to the seabed. In this environment, where oxygen penetration was limited to the top few millimeters of the seabed, resuspension events typically removed the entire seabed oxic layer; the oxygen that had been in the porewater was entrained into the water column. Similarly during deposition, incorporation of oxygen within the porewater of newly deposited sediment provided a source of oxygen to the seabed, accounting for up to a quarter of oxygen input to the seabed on a timescale of hours to days. Overall, this “pumping” of oxygen into and out of the seabed when sediments were deposited or eroded provided a small net source of oxygen to the seabed during a typical resuspension cycle; based on time-integrated fluxes of oxygen across the seabed-water interface for the two-month period (Fig. 2.6a), these exchanges accounted for 4 % of the net oxygen supply to the seabed.

The remaining supply of oxygen (96 %) was delivered to the seabed via diffusion across the seabed-water interface. Although these diffusive fluxes of oxygen were always
directed into the seabed, erosion and deposition caused fluctuations in the rate of
diffusion. During periods of resuspension, erosion of the oxic layer sharpened the oxygen
gradient at the seabed-water interface, thus increasing diffusion of oxygen into the seabed
by about 77 % (Fig. 2.6a). In contrast, during periods of deposition, incorporation of
oxygen-rich porewater into newly deposited surficial seabed layers reduced the oxygen
gradient at the seabed-water interface, decreasing diffusion of oxygen into the seabed by
about 71 %. However, “erosional oxygen profiles” with thin oxygen penetration depths
persisted longer and induced larger changes in the rate of diffusion, compared to
“depositional oxygen profiles” with thick oxygen penetration depths. This imbalance
occurred because the additional oxygen available in the seabed during periods of re-
deposition (i.e., oxygen available due to the incorporation of oxic water into the
porewater of newly-deposited sediments) was rapidly consumed by aerobic organic
matter remineralization and nitrification, and so oxygen profiles returned to their quasi-
steady state condition within hours to ~1 day after a resuspension event. In contrast,
during erosional periods, steep oxygen gradients and increased rates of diffusion into the
seabed persisted for ~2-5 days because of high nitrification rates (Fig. 2.6). Overall,
averaged over two months, these resuspension-induced variations increased the rate of
oxygen diffusion into the seabed by 12 %.

In addition to impacting the supply of oxygen to the seabed, resuspension altered
the magnitude of various biogeochemical oxygen sinks within the seabed (Table 2.6, Fig.
2.6b). For example, erosion of organic matter, and labile organic matter in particular,
decreased rates of oxic remineralization in the seabed from about 5 to <1 mmol O₂ m⁻² d⁻¹
(e.g. compare the mid-April quiescent period to the late April resuspension event). This
decrease was offset by nitrification, which increased from \( \sim 10-15 \) to \( \sim 30 \text{ mmol O}_2 \text{ m}^2 \text{ d}^{-1} \) during resuspension events. Nitrification rates increased because of the greater supply of oxygen to the seabed from erosion-enhanced diffusion. Nitrification also increased due to the larger ammonium concentrations in surficial sediments that occurred as erosion exposed relatively ammonium-rich seabed layers and due to the erosion-induced increase in the rate of diffusion of ammonium from deeper regions of the seabed towards the seabed-water interface. Overall, these changes increased the fraction of oxygen consumed via nitrification from about 60-70 % during quiescent periods to \( \sim 85 \) % during erosional periods. At the same time, the fraction of oxygen consumed via aerobic remineralization decreased from about 30-40 % during quiescent periods to 15 % during erosion. In contrast, following resuspension events, remineralization of redeposited organic matter, especially labile organic matter, briefly increased oxic remineralization rates. Also, low ammonium concentrations in newly deposited sediments limited nitrification during depositional periods. Together, these changes briefly altered the fraction of oxygen consumed via nitrification vs. remineralization to about 17 % and 83 %, respectively, during periods of re-deposition. Averaged over two months, however, resuspension-induced changes in the availability of oxygen, organic matter, and nutrients had little effect on the fraction of oxygen consumption due to nitrification (74 %) and remineralization (26 %).

2.3.2.2 Bottom-water oxygen consumption

Resuspension primarily affected oxygen dynamics within the water column by entraining POM into the layer of water below the pycnocline, i.e. bottom waters, which increased remineralization rates there (Table 2.6). Turbulence entrained this material as
high as ~3-4 m above the seabed during resuspension events, with near-bed concentrations of POM reaching up to $5 \times 10^4$ mmol C m$^{-3}$ in the model. Aerobic remineralization of resuspended material consumed up to 170 mmol O$_2$ m$^{-2}$ d$^{-1}$, although the average rate during erosional periods was 63 mmol O$_2$ m$^{-2}$ d$^{-1}$.

In addition to entraining POM into the water column, resuspension increased fluxes of reduced chemical species from the seabed into bottom waters, further increasing oxygen consumption in the water column (Table 2.6). During quiescent periods, oxidation of ammonium (nitrification) resulted in a background level of oxygen consumption of ~23 mmol O$_2$ m$^{-2}$ d$^{-1}$ in bottom waters. During erosion, the steepening of gradients at the seabed-water interface increased the diffusive flux of ammonium from the seabed to bottom waters from near zero to up to about 25 mmol m$^{-2}$ d$^{-1}$ of NH$_4$. Direct entrainment of ammonium into the water column provided an additional ~5-10 mmol m$^{-2}$ d$^{-1}$ of NH$_4$. The greater supply of NH$_4$ increased bottom-water nitrification rates to up to ~34 mmol O$_2$ m$^{-2}$ d$^{-1}$ during resuspension events, with an average of 26 mmol O$_2$ m$^{-2}$ d$^{-1}$ during erosional periods. Comparing this oxygen demand with the estimates of remineralization-related demand calculated above, nitrification accounted for ~30 % of oxygen consumption in bottom waters during erosional periods. The remaining ~70 % percent came from the remineralization of organic matter.

2.3.3 Sensitivity tests

Like the standard model run, results from every sensitivity test showed that resuspension increased bottom-water oxygen consumption during both individual resuspension events and when estimates were averaged over two months (Fig. 2.7d). All sensitivity tests except one showed that resuspension also increased seabed oxygen
consumption (Fig. 2.7b). In all model runs, oxygen consumption in bottom waters was larger than that in the seabed for every sensitivity test by at least a factor of ~5 during resuspension events and ~2 when results were averaged over two months. However, altering various parameters affected the model estimates of oxygen consumption in both the seabed and bottom waters, as explored below. This analysis focuses on the two-month average of oxygen consumption rate and the maximum rate of oxygen consumption from erosional periods (Fig. 2.7a,c). For both of these quantities we also computed the fraction of oxygen consumption induced by resuspension (Fig. 2.7b,d).

2.3.3.1 Seabed oxygen consumption: Sensitivity tests

Over timescales ranging from hours to two months, seabed oxygen consumption was more sensitive to changes in the rate of diffusion within the seabed ($D_i$, Cases B1 and B2; Fig. 2.7a) than any other parameter considered in the sensitivity tests (Table 2.4). Halving and doubling the diffusion coefficients changed the seabed oxygen consumption by -28 % and 39 %, respectively, when integrated over the two-month model run, and by -22 % and 24 % during individual resuspension events. These changes occurred because faster diffusion rates within the seabed more quickly transported oxygen deeper into the seabed, reducing oxygen levels in surface sediments, and thereby increasing the diffusion of oxygen through the seabed-water interface. Additionally, faster diffusion rates within the seabed transported ammonium upwards, toward the seabed-water interface. Increasing $D_i$ thus increased the amount of oxygen and ammonium at the oxic-anoxic interface within the seabed, allowing for more seabed oxygen consumption via nitrification. In contrast, lower diffusion rates within the seabed lowered the supply of
oxygen and ammonium to this region of the seabed, reducing seabed oxygen consumption.

Within the standard model run and most sensitivity tests, resuspension accounted for about 14% of the cumulative seabed oxygen consumption when integrated over two months. The role of resuspension, however, was especially sensitive to the partitioning and delivery of organic matter because POM entrained into the water column was subject to repartitioning (see Sect. 2.2.2.3; Fig. 2.2b) and so resuspension increased the amount of labile material available to re-deposit on the seabed. This additional source of seabed labile organic matter increased seabed oxygen consumption directly, due to oxic remineralization, and indirectly, as ammonium produced during this process was oxidized via nitrification. Overall, altering the partitioning of organic matter between labile and refractory classes changed the effect of resuspension on seabed oxygen consumption by up to 60% over two months (Cases L1 and L2; Fig. 2.7b). Specifically, decreasing (increasing) the fraction of organic matter that is labile, $f_{lab}$, by 30% decreased (increased) the resuspension-induced fraction of the seabed oxygen consumption to 5% (22%), compared to 14% in the standard model run. Furthermore, the sensitivity test without repartitioning of POM in the water column was the only sensitivity test for which resuspension caused a marginal (negative) effect on seabed oxygen consumption when results were averaged over two months (Case C1; Fig. 2.2c, 7b). In this case, resuspension-induced increases in the supply of oxygen and seabed nitrification were about equal to the decrease in oxic remineralization that occurred when POM was entrained into the water column.
2.3.3.2 Bottom-water oxygen consumption: Sensitivity tests

Oxygen consumption in bottom waters averaged over two months was more sensitive to changes in the critical shear stress for erosion, $\tau_{\text{crit}}$, than other parameters (Fig. 2.7c; Cases T1 and T2). Halving and doubling the critical shear stress changed time-averaged bottom-water oxygen consumption by 50 % and -35 %, respectively. During individual resuspension events, the effect of halving and doubling this parameter was more moderate and resulted in 7 % and -20 % changes, respectively. These changes in oxygen consumption occurred because halving and doubling the critical stress for erosion changed the frequency of resuspension, i.e. the amount of time that $\tau_{\text{bed}} > \tau_{\text{crit}}$, from 36 % of the time in the standard model run to 53 % and 15 %, respectively. Thus, decreasing the critical shear stress prolonged resuspension events, which caused more seabed organic matter and porewater to be entrained into the water column, increasing oxygen consumption in bottom waters. In contrast, a larger critical shear stress shortened resuspension events, decreasing oxygen consumption there.

Within the standard model run and most sensitivity tests, resuspension accounted for about 57 % of bottom-water oxygen consumption when averaged over two months (Fig. 2.7d). Similar to the above analysis, the extent to which resuspension affected oxygen consumption was especially sensitive to the critical shear stress (Cases T1, T2). Over the two-month model run, halving (doubling) the critical shear stress changed the fraction of bottom-water oxygen consumption that occurred due to resuspension to 34 % (71 %).
2.4 Discussion

This discussion focuses on the importance of resuspension-induced changes in oxygen budgets in different environments (Sect. 2.4.1); compares our approach to other modeling techniques (Sect. 2.4.2); and suggests future research (Sect. 2.4.3).

2.4.1 Resuspension-induced increases in oxygen consumption

Resuspension-induced oxygen consumption that occurred during short time periods (hours to days) increased model estimates of oxygen consumption integrated over longer timescales of weeks to months for all model runs (Fig. 2.7, 2.8). In other words, erosion and deposition did not just add variability to the time-series of oxygen consumption; resuspension impacted the oxygen budget of the Rhône subaqueous delta. This section discusses the environmental conditions that caused this effect and the extent to which we expect resuspension to increase oxygen consumption in other coastal systems (Sect. 2.4.1.1); and the importance of these changes relative to seasonal variability (Sect. 2.4.1.2).

2.4.1.1 Why does resuspension change oxygen consumption on the Rhône Delta?

Several characteristics of the Rhône subaqueous delta favor the increased rates of oxygen consumption due to local resuspension. First, frequent resuspension, e.g. three events in two months (Fig. 2.3c), ensures that the entrainment of seabed organic matter into the water column and erosional seabed profiles occur often, increasing resuspension-induced oxygen consumption in both bottom waters and the seabed. Second, oxygen concentrations in bottom waters and near the seabed-water interface are relatively high,
i.e. over 200 mmol O$_2$ m$^{-3}$ (Fig. 2.3e,f,g), ensuring that oxygen is available to be consumed. Third, the seabed at this site on the Rhône Delta experiences little biological mixing (Pastor et al., 2011a). This encourages the formation of a relatively thin oxic layer that can be completely resuspended, allowing erosional seabed profiles that increase seabed oxygen consumption to form frequently. Fourth, organic matter and/or reduced chemical species concentrations are high in surficial sediments relative to the water column (e.g. Pastor et al., 2011a,b; Cathalot et al., 2010). This ensures that erosion provides a significant supply of organic matter to the water column for remineralization, increasing oxygen consumption in bottom waters during resuspension. Also, the large amount of labile organic matter and reduced chemical species in the seabed facilitates resuspension-induced seabed oxygen consumption by quickly consuming oxygen via remineralization or oxidation during resuspension events. The speed of oxygen consumption is important for the maintenance of erosional seabed profiles and destruction of depositional profiles throughout the entire resuspension event. Fifth, remineralization rates in bottom waters are fast compared to the residence time of suspended particles in the water column, ensuring oxygen can be consumed in bottom waters before organic matter settles back to the seabed. The rates used in the model imply that as much as 170 mmol O$_2$ m$^{-2}$ d$^{-1}$ is consumed via organic matter remineralization during resuspension events, which often last for days on the Rhône Delta (Table 2.6, Fig. 2.4). Finally, resuspension can increase rates of organic matter remineralization during and following resuspension events due to changes in redox conditions and other processes, increasing oxygen consumption (e.g. Stahlberg et al., 2006). Such changes can
increase aerobic remineralization rates, and were particularly important for enhancing
time-averaged seabed oxygen consumption.

We expect that the effect of local resuspension on oxygen dynamics in other
systems that share characteristics of the Rhône subaqueous delta would be similar to our
results. For seabed oxygen dynamics, this implies that the importance of local
resuspension increases in energetic, oxic, and coastal areas with high organic matter
input, but relatively little bioturbation, including other river deltas (Aller, 1998; e.g.
Amazon Delta, Brazil: Aller et al., 1996). For water-column oxygen dynamics, the above
criteria suggest that local resuspension is most important in similar coastal areas with
organic-rich, muddy seabeds, but relatively low background concentrations of organic
matter in the water column. These characteristics may be found in regions with
historically high nutrient loading and where organic matter has accumulated in the seabed
(e.g. Gulf of Finland: Almroth et al., 2009). In sites that meet some, but not all of the
above criteria, local resuspension may have a reduced effect on oxygen dynamics
compared to the Rhône subaqueous delta.

2.4.1.2 How does resuspension-induced \( O_2 \) consumption compare to seasonal
variability?

The model estimated that resuspension increased seabed and bottom-water
oxygen consumption by about 16 % and 140 %, respectively, when integrated over April-
May 2012 (Fig. 2.7); however, seasonal variations in environmental conditions such as
temperature may change the importance of resuspension for oxygen dynamics. The two-
month model run presented here assumed a constant bottom-water temperature of 15°C,
but observed values vary from ~12–20 °C over the course of a year on the Rhône Delta
(Millot, 1990; Fuchs and Pairaud, 2014; C. Rabouille, pers. comm.). A common method for estimating temperature-induced changes in biogeochemical processes is the “Q_{10} rule” (van’t Hoff, 1898), which predicts that oxygen consumption increases by a factor of ~2-3 for each temperature increase of 10°C in coastal areas (e.g. Thamdrup et al., 1998; Dedieu et al., 2007; Cardoso et al., 2014). Based on the 16±4°C temperature range expected at this site over a year, this suggests that resuspension-induced changes in oxygen consumption are as important as the factor of 2 change estimated due to temperature-induced variability. Thus, although temperature effects have been widely studied, resuspension can cause similar variations in oxygen consumption.

Seasonal variations in resuspension frequency and magnitude may have a similarly large effect on oxygen consumption. During the winter when easterly storms are more frequent (Guillén et al., 2006; Palanques et al., 2006), resuspension-induced oxygen consumption could be more important than was estimated for the April-May period in this study. At the 32 m deep “Sète” site in the central coastal region of the Gulf of Lions, significant wave heights exceeding 2 m were observed an average of 3.5, 1 and 2 times per month in November-December 2003, January-February 2004, and March-April 2004, respectively (Ulses et al., 2008). Approximately doubling the resuspension frequency during the winter storm season could roughly double resuspension-induced oxygen consumption, counteracting reductions in wintertime oxygen consumption due to colder temperatures. Overall, accounting for the effect of erosional and depositional cycles on oxygen consumption may vary in importance throughout the year on the Rhône subaqueous delta, but it is likely more important during Fall compared to the Springtime period that was analyzed for this study.
Finally, oxygen dynamics may vary in response to seasonal or episodic variations in organic matter availability and lability. Following a flood in 2008, sebed oxygen consumption on the Rhône Delta decreased by one-third to one-half when riverine inputs of relatively refractory organic matter lowered remineralization rates in surficial sebed sediments, reducing sebed oxygen consumption (Cathalot et al., 2010). This result is consistent with results from our L1 sensitivity test indicating that reducing the ratio of labile to refractory organic matter lowered sebed oxygen consumption (Fig. 2.7a). Thus, although variability in the amount and quality of organic matter delivered to the delta could be episodic, it may also substantially affect estimates of sebed oxygen consumption oxygen, similar to temperature and resuspension.

2.4.2 Modeling resuspension-induced changes in oxygen dynamics

HydroBioSed differs from other models by accounting for resuspension-induced changes in millimeter-scale biogeochemistry, a feature that was necessary to reproduce Toussaint et al. (2014)’s observed temporal variations in sebed oxygen consumption on the Rhône subaqueous delta. In contrast, other models neglect resuspension-induced changes in biogeochemical dynamics or assume that increases in water-column oxygen consumption due to remineralization of resuspended organic matter during erosion are at least partially offset by decreases in remineralization and associated oxygen consumption in the sebed (e.g. Feng et al., 2015; Capet et al., 2016). Results from these model parameterizations therefore conflict with our HydroBioSed results that show that both water-column and sebed oxygen consumption increase during resuspension events (Fig. 2.4, 2.6), consistent with observations for the Rhône subaqueous delta (Fig. 2.4, 2.6; Toussaint et al., 2014). This implies that the parameterizations from other models such as
those cited above underestimate oxygen consumption during resuspension events when applied to environments with similar characteristics to the Rhône Delta, as described in Sect. 2.4.1.1. The remainder of this section explores which sediment processes were most critical for modeling the effect of resuspension on Rhône Delta oxygen dynamics.

First, resuspension increased the importance of bottom waters relative to the seabed for oxygen consumption. During quiescent conditions, bottom waters and the seabed each accounted for similar rates of oxygen consumption. However, when POM and porewater were entrained into the water column via resuspension, bottom-water oxygen consumption increased by a factor of 8, while seabed oxygen consumption only doubled. This disproportionate increase of oxygen consumption within bottom waters affirmed the importance of observing and modeling oxygen dynamics within bottom waters during resuspension events. Also, only accounting for quiescent time periods would underestimate the role of bottom waters, which accounted for 75 % of the total oxygen consumption over the two-month model run for the Rhône Delta site, but only accounted for about 50 % when resuspension was neglected.

Second, diffusion of oxygen across the sediment-water interface dominated the supply of oxygen to the seabed in the model, regardless of the timescale or time period considered. The other transport mechanism, the “pumping” of oxygen into and out of the seabed as layers of sediment were deposited or eroded, provided at most a third of the instantaneous flux to the seabed (during depositional time periods; Fig. 2.5). Also, pumping contributed much less to seabed oxygen supply over time, primarily because the entrainment of porewater from the seabed into the water column during erosional periods partially offset the depositional flux of oxygen (Fig. 2.5). Over the two-month simulation,
diffusion across the seabed-water interface accounted for 96% of the seabed oxygen supply, whereas pumping via erosion and deposition accounted for only 4% of seabed oxygen fluxes. Thus, for environments like the Rhône Delta, future observational and modeling efforts should include resuspension-induced changes to diffusive fluxes across the seabed water interface (Jørgensen and Revsbech, 1985).

Although resuspension can affect oxygen dynamics in coastal environments, the large spatial or temporal scale of some biogeochemistry models may make incorporating a full sediment model undesirable. For environments similar to the Rhône Delta, we suggest parameterizations for bottom-water and seabed oxygen consumption that focus on the role of resuspended organic matter and seabed-water-column diffusion. For example, various approaches have been used to parameterize the effect of resuspension on particulate organic matter fluxes (e.g. Cerco et al., 2013; Feng et al., 2015). Approaches accounting for temporal lags between deposition and re-entrainment of organic matter into the water column seem especially promising for modeling oxygen dynamics in episodically energetic environments like the Rhône Delta (e.g. Almroth-Rosell, 2011; Capet et al., 2016). In addition, future parameterizations for seabed-water-column fluxes should focus on diffusion of oxygen across the seabed-water interface as well as the supply of organic matter and reduced chemical species (e.g. Findlay and Watling, 1997; De Gaetano et al., 2008; Hetland and DiMarco, 2008; Murrell and Lehrter, 2011; Testa et al., 2013; Laurent et al., 2016). Methods combining parameterizations for seabed-water-column fluxes and seabed resuspension may be particularly helpful for environments similar to the Rhône Delta where erosion and deposition may affect these processes.
2.4.3 Implications of model development and future work

This study focused on oxygen dynamics while holding the supply of organic matter and sediment; water-column concentrations of nutrients and oxygen; and temperature constant in time based on conditions observed on the Rhône subaqueous delta. Future work should therefore include analyzing the role of resuspension on oxygen dynamics for a variety of environmental conditions and investigating how temporal variability in environmental conditions affects the relative importance of resuspension for oxygen dynamics. Additionally, applying HydroBioSed for a three-dimensional system would further facilitate its application to additional scientific and water quality concerns. For example, transport of organic matter from regions near the Mississippi and Atchafalaya river mouths, shallow autotrophic waters, and wetlands to “Dead Zones” has been speculated to encourage the depletion of oxygen in bottom waters there (Bianchi et al., 2010). However, the importance of organic matter transport within a single season of hypoxia, and on inter-annual timescales, is difficult to quantify with observations and has been debated on the northern shelf of the Gulf of Mexico (Rowe and Chapman, 2002; Boesch, 2003; Turner et al., 2008; Forrest et al., 2012; Eldridge and Morse, 2008) and other locations (Kemp et al., 2009 and references therein). Modeling efforts that account for resuspension of organic matter, as well as oxygen and nutrients, can help quantify the extent to which organic matter supply, resuspension and transport affect biogeochemistry in these dynamic coastal environments (e.g. Almroth-Rosell et al., 2011; Capet et al., 2016).

Our analysis focused on oxygen, but resuspension also affected model estimates of nitrogen dynamics. For example, during quiescent periods, nitrification roughly
balanced production of ammonium from remineralization of organic matter in the seabed, consistent with Pastor et al. (2011a). Yet, during erosional periods, the exposure of ammonium-rich porewater to oxygen increased seabed nitrification, enhancing fluxes of nitrate out of the seabed, consistent with observations from other systems (e.g. Fanning et al., 1982; Sloth et al., 1996; Tengberg et al., 2003). Overall, resuspension roughly doubled nitrate fluxes out of the seabed during resuspension, which led to about a 10% increase overall for the two-month model run.

HydroBioSed did not represent all processes that occur near the seabed-water-column interface. For example, future work could include accounting for turbulence-induced changes in diffusion, advective fluxes through the seabed, and variations in seabed porosity; as well as improving the model’s representation of organic matter. Within HydroBioSed, for example, the steepening of the oxygen gradient at the seabed-water interface occurred because of changes in oxygen concentrations within the seabed and bottom waters (Fig. 2.3). HydroBioSed did not account for the thinning of the viscous layer at the seabed-water interface in response to wave-induced turbulence, which would act to further increase the oxygen gradient during erosional time periods (Gundersen and Jorgensen, 1990; Chatelain and Guizien, 2010; Wang et al., 2013). This implies that our current model estimates of oxygen diffusion into the seabed during resuspension events are conservative. Additionally, the model could be adapted for locations where waves and currents drive flows of water through non-cohesive seabeds, stimulating biogeochemical reactions (Huettel et al., 2014), or to account for vertical gradients in seabed porosity (Soetaert et al., 1996a, 1996b). Finally, the uncertainty about both how to partition organic matter into classes for numerical modeling efforts and the
effect of resuspension on remineralization rates, as noted in Sect. 2.2.2.3, has a large
effect on model estimates (Fig. 2.7, Cases L1, L2, C1) and deserves attention from both
the modeling and observational research communities.

Finally, this modeling effort incorporated time-dependent reactions into the
ROMS sediment transport module and could be adapted for other research applications
for which both resuspension and time-dependent tracers are important. For example, the
model has been adapted to account for short-lived radioisotopes (Birchler, 2014) and
could be adapted to include time-dependent particulate tracers including the following:
(1) particle-reactive nutrients and contaminants (Wiberg and Harris, 2002; Chang and
Sanford, 2005); (2) other “particulates” such as cysts of harmful algal blooms species
(Beaulieu et al., 2005; Giannakourou et al., 2005; Butman et al., 2014; Kidwell, 2015) or
fecal pellets (Gardner et al., 1985; Walsh et al., 1988); and (3) temporal variability in
organic matter lability, oxygen exposure time and carbon budgets (Aller, 1998; Hartnett
et al., 1998; Burdige, 2007).

2.5 Summary and conclusions

A model called HydroBioSed was developed that couples hydrodynamics,
sediment transport, and both water-column and seabed biogeochemistry. A one-
dimensional (vertical) version of the model was then implemented for the Rhône River
subaqueous delta. This work expanded on the commonly used ROMS framework by
accounting for non-conservative tracers, the resuspension of organic matter and
entrainment of porewater into the water column, diffusion of dissolved tracers across the
seabed-water interface, and feedbacks between resuspension and diffusion across the
seabed-water interface. Including these processes created a new model capable of
reproducing previously observed changes in seabed profiles that occurred during resuspension events on the Rhône River subaqueous delta.

Resuspension increased model estimates of oxygen consumption over the range of timescales considered (hours to two months). In the seabed, resuspension increased the exposure of anoxic, ammonium-rich sediment to oxic, ammonium-poor bottom waters, thus stimulating seabed oxygen consumption via nitrification during erosional periods. This oxygen consumption compensated for or exceeded the decrease in oxic remineralization rates that occurred as organic matter was resuspended into the water column. Additionally, entrainment of seabed organic matter and reduced chemical species from the porewater into the bottom portion of the water column, i.e. below the pycnocline, increased oxygen consumption there. Overall, resuspension increased peak oxygen consumption rates more in bottom waters (factor of 8) than in the seabed (factor of 2). When averaged over a two-month period that included intermittent periods of erosion and deposition, accounting for resuspension increased oxygen consumption by ~16 % in the seabed and ~140 % in bottom waters. Overall, the combined seabed and bottom-water oxygen consumption increased by a factor of ~5 during wave resuspension events and roughly doubled the two-month average.

These results imply that observations collected during quiescent periods, and models based on steady-state assumptions, may underestimate net oxygen consumption. This finding is consistent with results from laboratory erodibility experiments (e.g. Sloth et al., 1996), observations using eddy correlation techniques (Berg and Huettel, 2008), and microelectrode profiles (Toussaint et al., 2014). While all of these studies showed increased oxygen consumption during resuspension events, they each had limitations; i.e.,
erodibility experiments are limited to low levels of erosion and timescales of hours, eddy-correlation methods can only be used for time periods without abrupt shifts in hydrodynamic and oxygen conditions (Lorrai et al., 2010), and microelectrodes can only be deployed in soft muddy seabeds. Thus, models like HydroBioSed that resolve both biogeochemical processes and resuspension may help observational studies quantify oxygen dynamics over longer time periods, during storms, and in a variety of environments.

Certain characteristics of the Rhône subaqueous delta study site, including its oxic water column, shallow oxygen penetration into the seabed compared to the thickness of eroded layers, fast rates of oxygen consumption, and the high concentrations of labile seabed organic matter, enhance the effect of resuspension on oxygen dynamics. Together, these characteristics ensure the following: oxygen consumption in bottom waters is limited by the supply of organic matter and reduced chemical species, as opposed to oxygen availability; resuspended material is rich in organic matter and reduced chemical species that increases oxygen demand in the water column; oxygen consumption in the seabed is dependent on the supply of oxygen, as opposed to the rate of consumption; oxygen is available to be supplied to the seabed during resuspension; and erosion exposes anoxic regions of the seabed to oxic regions of the water column. The dependence of oxygen dynamics on those environmental conditions caused modeled estimates of oxygen consumption to be particularly sensitive to the supply and lability of organic carbon, rates of diffusion within the seabed, nitrification rate, and the frequency of resuspension. Our results imply that local resuspension may affect oxygen dynamics in other environments with similar characteristics.
Appendix 2.A

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 (2.A.1), and to resolve millimeter-scale processes in surficial sediments while maintaining centimeter-scale resolution deeper in the seabed (2.A.2).

2.A.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. 2.2.2), 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 dissolved oxygen, nitrogen and ODU 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. 2.2.2.3, as well as diffusion of dissolved chemical constituents across the seabed-water interface, which is described below.

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 (symbols defined in Table 2.1):
\[ C_{w,tnew} = \frac{z_{w1}}{z_{w1} + z_a \Phi} \times (C_{w,told} \times z_{w1} + C_{s,told} \times z_a \times \Phi) \]  \hspace{1cm} (2.A1)

\[ C_{s,tnew} = \left(1 - \frac{z_{w1}}{z_{w1} + z_a \Phi}\right) \times (C_{w,told} \times z_{w1} + C_{s,told} \times \Phi) \]  \hspace{1cm} (2.A2)

Note that we also tested a second approach relying on a Fickian diffusion law with a diffusion coefficient of \(1.09 \times 10^9\) m\(^2\) s\(^{-1}\) based on Boudreau (1997) and Toussaint et al. (2014) to more directly account for diffusion across the seabed-water interface. Yet, both approaches yielded nearly identical results at the Rhône study site, and so we kept the simpler approach.

### 2.A.2 Seabed resolution

Our seabed layering scheme is based on 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, cannot 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. 2.5), unless many seabed layers are used. Modifications to Warner et al. (2008)’s scheme therefore include incorporating both high-resolution and medium-resolution layers in the middle of the seabed.

Specifically, the layering scheme includes \(N_{\text{high-res}}\) high-resolution layers with thickness \(z_{\text{high-res}}\) immediately below the active transport layer, and then \(N_{\text{med-res}}\) medium-resolution layers with thickness of \(z_{\text{med-res}}\) in the middle of the seabed. After some
experimentation, this study used 60 seabed layers, and $z_a$, $z_{high-res}$, $z_{med-res}$, $N_{high-res}$, and $N_{med-res}$ were set equal to 0.1 mm, 0.5 mm, 1 cm, 19 layers, and 39 layers, respectively (Table 2.A.1). As in Warner et al. (2008), the bed layering scheme required that the number of layers remains constant; for this study, the number of “high” and “medium resolution” layers also remains constant, although their thicknesses may change slightly with erosion and deposition.

Incorporating multiple types of layers within the seabed and maintaining high resolution near the sediment–water interface affects how the layering scheme handles erosion and deposition. 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 $\sim 2z_a$, 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 $z_{high-res}$, 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 adding material to the topmost medium-resolution layer causes it to exceed $z_{med-res}$ in thickness, the material from two medium-thick layers that are thinner than $z_{med-res}$ are combined or the bottommost medium-resolution layer is absorbed into the seabed repository. In contrast, during erosion, removal of 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 depleted, a new medium-resolution layer(s) is shaved off of the deep repository.
Additionally, the method of calculating the thickness of the surficial seabed layer, $z_a$, was changed 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 is important that the surface layer remain thin in order to represent the high gradients of oxygen observed at the seabed-water interface, and so $z_a$ is set 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.

**Acknowledgements for Chapter 2**

Observations from the Rhône River delta observatory (Mesurho) were provided by F. Toussaint (Laboratoire des Sciences du Climat et de l’Environnement). R. Wilson (formerly Dalhousie University) provided model code from Wilson et al. (2013). Feedback from E. Canuel, C. Friedrichs (Virginia Institute of Marine Science; VIMS), two anonymous reviewers, and Biogeosciences Associate Editor Jack Middelburg improved this paper. A. Miller, D. Weiss (VIMS), and E. Walters (the College of William & Mary; W&M) provided computational support and access to W&M’s computing
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References for Chapter 2


Tables for Chapter 2

Table 2.1: Description of symbols

Description of symbols used in this paper. Note that concentrations are porewater or bottom-water concentrations, not bulk concentrations, unless otherwise noted, but units of length and area (i.e., m and m²) refer to the dimensions of the grid cell, and were not corrected for porosity.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agglab</td>
<td>Concentration of labile aggregates</td>
<td>mmol N m⁻³</td>
</tr>
<tr>
<td>Aggrref</td>
<td>Concentration of refractory aggregates</td>
<td>mmol N m⁻³</td>
</tr>
<tr>
<td>C_ised</td>
<td>Concentration of sediment from class <em>ised</em></td>
<td>kg m⁻²</td>
</tr>
<tr>
<td>C_s_tnew</td>
<td>Concentration of dissolved tracer in the surficial seabed layer, for the new time step</td>
<td>mmol m⁻³</td>
</tr>
<tr>
<td>C_s_told</td>
<td>Concentration of dissolved tracer in the surficial seabed layer from the old time step</td>
<td>mmol m⁻³</td>
</tr>
<tr>
<td>C_w_tnew</td>
<td>Concentration of dissolved tracer in the bottom water-column layer, for the new time step</td>
<td>mmol m⁻³</td>
</tr>
<tr>
<td>C_w_told</td>
<td>Concentration of dissolved tracer in the bottom water-column layer from the old timestep</td>
<td>mmol m⁻³</td>
</tr>
<tr>
<td>dO₂/dzOPD</td>
<td>the slope of the vertical oxygen profile, averaged over the oxygen penetration depth, z_OPD</td>
<td>mmol O₂ m⁻⁴</td>
</tr>
<tr>
<td>Dᵢ</td>
<td>Coefficient for diffusion within the seafloor for seabed constituent i</td>
<td>m² s⁻¹</td>
</tr>
<tr>
<td>D_ised</td>
<td>Rate of deposition for sediment from class <em>ised</em></td>
<td>kg m⁻² s⁻¹</td>
</tr>
<tr>
<td>D_w</td>
<td>Diffusion coefficient at the seabed-water interface</td>
<td>m² s⁻¹</td>
</tr>
<tr>
<td>dz</td>
<td>Grid cell thickness</td>
<td>m</td>
</tr>
<tr>
<td>E_ised</td>
<td>Rate of erosion for sediment from class <em>ised</em></td>
<td>kg m⁻² s⁻¹</td>
</tr>
<tr>
<td>f_bur</td>
<td>Fraction of organic matter that is buried in the seabed</td>
<td>---</td>
</tr>
<tr>
<td>f_ised</td>
<td>Fraction of the surficial seabed layer composed of sediment class <em>ised</em></td>
<td>---</td>
</tr>
<tr>
<td>f_lab</td>
<td>Fraction of coagulated organic matter that is labile within the water column</td>
<td>---</td>
</tr>
<tr>
<td>f_det</td>
<td>Fraction of labile coagulated organic matter that is large detritus within the water column</td>
<td>---</td>
</tr>
<tr>
<td><em>ised</em></td>
<td>Index used for different sediment classes.</td>
<td>---</td>
</tr>
<tr>
<td>kO₂</td>
<td>Half-saturation constant for O₂ limitation of aerobic remineralization</td>
<td>mmol O₂ m⁻³</td>
</tr>
<tr>
<td>kO₂_nit</td>
<td>Half-saturation constant for O₂ limitation of nitrification</td>
<td>mmol O₂ m⁻³</td>
</tr>
<tr>
<td>kO₂_odaux</td>
<td>Half-saturation constant for O₂ limitation of O2U oxidation</td>
<td>mmol O₂ m⁻³</td>
</tr>
<tr>
<td>kNO₃</td>
<td>Half-saturation constant for NO₃ limitation of nitrate</td>
<td>mmol N m⁻³</td>
</tr>
<tr>
<td>lO₂</td>
<td>Half-saturation constant for O₂ inhibition of nitrate remineralization</td>
<td>mmol O₂ m⁻³</td>
</tr>
<tr>
<td>lO₂_anoxic</td>
<td>Half-saturation constant for O₂ inhibition of anoxic remineralization</td>
<td>mmol O₂ m⁻³</td>
</tr>
<tr>
<td>lNO₃_anoxic</td>
<td>Half-saturation constant for NO₃ inhibition of anoxic remineralization</td>
<td>mmol N m⁻³</td>
</tr>
<tr>
<td>L_BO</td>
<td>Limitation of seabed oxygen consumption due to bottom-water O₂ availability</td>
<td>---</td>
</tr>
<tr>
<td>L_det</td>
<td>Concentration of large detritus</td>
<td>mmol N m⁻³</td>
</tr>
<tr>
<td>L_sat</td>
<td>Sum of the limitation factors on remineralization processes</td>
<td>---</td>
</tr>
<tr>
<td>M</td>
<td>Erosion rate parameter representing seabed erodibility</td>
<td>kg m⁻² s⁻¹</td>
</tr>
<tr>
<td>NO₃</td>
<td>Nitrate concentration</td>
<td>mmol N m⁻³</td>
</tr>
<tr>
<td>N_high-res</td>
<td>Number of high-resolution seabed layers</td>
<td>---</td>
</tr>
<tr>
<td>N_med-res</td>
<td>Number of medium-resolution seabed layers</td>
<td>---</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Units</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>-------</td>
</tr>
<tr>
<td>NH$_4$</td>
<td>Ammonium concentration</td>
<td>mmol N m$^{-3}$</td>
</tr>
<tr>
<td>$R_{anoxic}$</td>
<td>Anaerobic Remineralization Rate in the seabed</td>
<td>mmol C m$^{-3}$ d$^{-1}$</td>
</tr>
<tr>
<td>$R_{aerobic}$</td>
<td>Aerobic Remineralization Rate in the seabed</td>
<td>mmol C m$^{-3}$ d$^{-1}$</td>
</tr>
<tr>
<td>$R_{DNF}$</td>
<td>Denitrification Rate in the seabed</td>
<td>mmol C m$^{-3}$ d$^{-1}$</td>
</tr>
<tr>
<td>$R_{nitr}$</td>
<td>Nitrification Rate in the seabed</td>
<td>mmol N m$^{-3}$ d$^{-1}$</td>
</tr>
<tr>
<td>$R_{nitr,max}$</td>
<td>Maximum Nitrification Rate in the seabed</td>
<td>d$^{-1}$</td>
</tr>
<tr>
<td>$R_{odux}$</td>
<td>Oxidation Rate of ODUs in the seabed</td>
<td>mmol O$_2$ m$^{-3}$ d$^{-1}$</td>
</tr>
<tr>
<td>$R_{odux,max}$</td>
<td>Maximum Oxidation Rate of ODUs in the seabed</td>
<td>d$^{-1}$</td>
</tr>
<tr>
<td>$R_{POC}$</td>
<td>Remineralization rate constant for particulate organic matter in the seabed</td>
<td></td>
</tr>
<tr>
<td>$S_{inorganic}$</td>
<td>Inorganic sedimentation rate</td>
<td>m y$^{-1}$ or kg m$^{-2}$ y$^{-1}$</td>
</tr>
<tr>
<td>$S_{organic}$</td>
<td>Particulate organic matter sedimentation rate</td>
<td>gC m$^{-2}$ y$^{-1}$</td>
</tr>
<tr>
<td>$O_2$</td>
<td>Dissolved oxygen concentration</td>
<td>mmol O$_2$ m$^{-3}$</td>
</tr>
<tr>
<td>$O_2,OPD$</td>
<td>Dissolved O$_2$ concentration at the oxygen penetration depth; equals zero by definition</td>
<td>mmol O$_2$ m$^{-3}$</td>
</tr>
<tr>
<td>$O_2,SWI$</td>
<td>Dissolved oxygen concentration at the seabed-water interface</td>
<td>mol O$_2$ m$^{-3}$</td>
</tr>
<tr>
<td>ODU</td>
<td>Oxygen Demand Unit concentration</td>
<td>mmol O$_2$ m$^{-3}$</td>
</tr>
<tr>
<td>POC</td>
<td>Particulate organic carbon concentration</td>
<td>mmol C m$^{-3}$</td>
</tr>
<tr>
<td>POM</td>
<td>Particulate organic matter concentration</td>
<td>mmol N m$^{-3}$</td>
</tr>
<tr>
<td>$w_{s,ised}$</td>
<td>Settling velocity of sediment from class $ised$</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$z$</td>
<td>Vertical level in the water column modules, ranging from 1 (near the seabed) to 20 (near the water-air interface)</td>
<td>--</td>
</tr>
<tr>
<td>$z_a$</td>
<td>Thickness of seabed active transport layer</td>
<td>m</td>
</tr>
<tr>
<td>$z_{high-res}$</td>
<td>Thickness of high-resolution seabed layers</td>
<td>m</td>
</tr>
<tr>
<td>$z_{med-res}$</td>
<td>Thickness of medium-resolution seabed layers</td>
<td>m</td>
</tr>
<tr>
<td>$z_{newdep}$</td>
<td>Thickness of new deposition</td>
<td>m</td>
</tr>
<tr>
<td>$z_{ODP}$</td>
<td>Oxygen penetration depth into the seabed; this is negative in our coordinate system</td>
<td>m</td>
</tr>
<tr>
<td>$z_{SWI}$</td>
<td>Depth at the seabed water interface (SWI); equals zero in our coordinate system</td>
<td>m</td>
</tr>
<tr>
<td>$z_{w1}$</td>
<td>Thickness of bottom water-column grid cell</td>
<td>m</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>Seabed porosity</td>
<td>---</td>
</tr>
<tr>
<td>$\tau_{bed}$</td>
<td>Bed shear stress from waves and currents</td>
<td>Pa</td>
</tr>
<tr>
<td>$\tau_{crit}$</td>
<td>Critical shear stress, assumed to be the same for all sediment classes.</td>
<td>Pa</td>
</tr>
<tr>
<td>$\tau_{crit,ised}$</td>
<td>Critical shear stress for sediment class $ised$</td>
<td>Pa</td>
</tr>
</tbody>
</table>

$^a$ m$^3$ = m$^3$ (of liquid) x m$^{-1}$ (bulk distance)
$^b$ For this variable, m$^3$ indicates volume of particulates in the grid cell, not water
Table 2.2: Description of phrases, acronyms, and abbreviations

<table>
<thead>
<tr>
<th>Name / Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active transport layer</td>
<td>Region of the seabed from which material can be entrained into the water column; synonymous with the phrase ‘active layer’ in sediment transport papers (Harris and Wiberg, 1997; Warner et al., 2008). In the model, the active transport layer is the same as the surficial seabed layer.</td>
</tr>
<tr>
<td>Anoxic remineralization</td>
<td>Includes iron, manganese, and sulfur remineralization of organic matter, and methanogenesis, but not denitrification.</td>
</tr>
<tr>
<td>Bottom water</td>
<td>The region of the water column within 4 m of the seabed where suspended sediment concentrations were high during resuspension events</td>
</tr>
<tr>
<td>CSTMS</td>
<td>Community Sediment Transport Modeling System</td>
</tr>
<tr>
<td>Diagenesis</td>
<td>Within this paper, ‘diagenesis’ is used to refer to models that account for organic matter remineralization and associated biogeochemical processes within the seabed. We note, however, that diagenesis is commonly used to refer to any physical, chemical, geological, or biological changes in sediment or sediment rock following deposition, prior to metamorphism.</td>
</tr>
<tr>
<td>Diffusion at (or across) the seabed-water interface</td>
<td>Molecular diffusion of dissolved chemicals across the seabed-water interface. In the context of HydroBioSed, this refers to exchanges between the bottom water-column grid cell and surficial seabed layer so that they are in equilibrium (see Appendix).</td>
</tr>
<tr>
<td>Diffusion within the seabed</td>
<td>Molecular diffusion within the seabed; Referred to as ‘biodiffusion’ in other modeling papers when bioturbation is modeled as a diffusive process.</td>
</tr>
<tr>
<td>HydroBioSed</td>
<td>The coupled hydrodynamic–sediment transport–water-column and seabed biogeochemistry model developed and implemented in this study</td>
</tr>
<tr>
<td>Local resuspension</td>
<td>“One-dimensional” (vertical) resuspension, i.e. neglecting horizontal transport processes.</td>
</tr>
<tr>
<td>Module</td>
<td>Refers to a ‘sub-model’ within a model, e.g. the sediment transport module within ROMS</td>
</tr>
<tr>
<td>Nitrate remineralization</td>
<td>In this paper, synonymous with denitrification</td>
</tr>
<tr>
<td>Nutrient(s)</td>
<td>Refers to refer to nitrogen and/or phosphorus. Does not include ODUs</td>
</tr>
<tr>
<td>ODU</td>
<td>Oxygen Demand Unit; one ODU is the number of moles of reduced chemical species that react with one mole of O₂ when oxidized.</td>
</tr>
<tr>
<td>OPD</td>
<td>Oxygen Penetration Depth; Depth in the seabed at which oxygen decreased to zero.</td>
</tr>
<tr>
<td>POM</td>
<td>Particulate Organic Matter</td>
</tr>
<tr>
<td>Quiescent</td>
<td>Characterized by low-energy environmental conditions; i.e. used to refer to time periods with low waves and no resuspension in this paper</td>
</tr>
<tr>
<td>Re-deposition</td>
<td>Deposition of particulates previously resuspended from the same location</td>
</tr>
<tr>
<td>Resuspend, Resuspended</td>
<td>(verb, adjective) Refers to the entrainment of seabed material into the water column via erosion, or to the material that was eroded from the seabed</td>
</tr>
<tr>
<td>Resuspension (event)</td>
<td>(noun) Refers to cycle of erosion and deposition</td>
</tr>
<tr>
<td>ROMS</td>
<td>Regional Ocean Modeling System</td>
</tr>
<tr>
<td>Seabed</td>
<td>Region beneath the water column</td>
</tr>
<tr>
<td>Sediment</td>
<td>Inorganic particles</td>
</tr>
<tr>
<td>Steady state</td>
<td>Refers to models that do not change in time, e.g. due to wave-induced resuspension</td>
</tr>
</tbody>
</table>
Table 2.3: Environmental conditions and parameters for the standard model implementation

<table>
<thead>
<tr>
<th>Model Input/Parameter</th>
<th>Modeled Value</th>
<th>Literature Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hydrodynamic and Sediment Transport Parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Depth</td>
<td>24 m</td>
<td>Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Wave Height</td>
<td>Observed time-series</td>
<td>Toussaint et al. (2014)</td>
</tr>
<tr>
<td>Wave Period</td>
<td>10 s</td>
<td>Ulsses et al. (2008), Palanques et al. (2006), Guillen et al. (2006)</td>
</tr>
<tr>
<td>Bottom-water Temperature</td>
<td>15 °C</td>
<td>Millot et al. (1990)</td>
</tr>
<tr>
<td>Surface Water Temperature</td>
<td>20 °C</td>
<td>Millot et al. (1990)</td>
</tr>
<tr>
<td>Bottom-water Salinity</td>
<td>35 psu</td>
<td>Panlanques et al., 2006; Cruzado and Velasquez, 1990</td>
</tr>
<tr>
<td>Surface Water Salinity</td>
<td>33 psu</td>
<td>Panlanques et al., 2006; Cruzado and Velasquez, 1990</td>
</tr>
<tr>
<td>Inorganic Sedimentation Rate</td>
<td>$S_{\text{inorganic}} = 10 \text{ cm } y^{-1}$</td>
<td>Pastor et al. (2011a)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fraction of Sediment that is Muddy Flocs</td>
<td>80 %</td>
<td>Roussiez et al. (2006), Ferre et al. (2005), Radkovitch et al. (1999)</td>
</tr>
<tr>
<td>Fraction of Sediment that is Sand</td>
<td>20 %</td>
<td>Roussiez et al. (2006), Ferre et al. (2005), Radkovitch et al. (1999)</td>
</tr>
<tr>
<td>Settling Velocity of Muddy Flocs</td>
<td>0.19 mm s$^{-1}$</td>
<td>Curran et al. (2007)</td>
</tr>
<tr>
<td>Settling Velocity of Sand</td>
<td>30 mm s$^{-1}$</td>
<td>Curran et al. (2007)</td>
</tr>
<tr>
<td>Critical Bed Shear Stress</td>
<td>$\tau_{\text{crit}} = 0.3 \text{ Pa}$</td>
<td>Pastoussaint et al. (2014)</td>
</tr>
<tr>
<td>Erosion Rate Parameter</td>
<td>$M = 0.01 \text{ kg m}^{-2} \text{s}^{-1}$</td>
<td>Pastoussaint et al. (2014)</td>
</tr>
<tr>
<td>Porosity</td>
<td>$\Phi = 0.9$</td>
<td>Unpublished data</td>
</tr>
<tr>
<td>Sediment Density of Muddy Flocs</td>
<td>$\approx 1048 \text{ kg m}^{-3}$</td>
<td>Curran et al. (2007)</td>
</tr>
<tr>
<td>Sediment Density of Sand</td>
<td>$\approx 2650 \text{ kg m}^{-3}$</td>
<td>Curran et al. (2007)</td>
</tr>
<tr>
<td><strong>Water-column Biogeochemical Parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen Concentration</td>
<td>253 mmol O$_2$ m$^{-3}$</td>
<td>Pastoussaint et al. (2014), Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Nitrate Concentration</td>
<td>0.5 mmol N m$^{-3}$</td>
<td>Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Ammonium Concentration</td>
<td>5.8 mmol N m$^{-3}$</td>
<td>Pastor et al. (2011a)</td>
</tr>
<tr>
<td>ODU Concentration</td>
<td>0 mmol O$_2$ m$^{-3}$</td>
<td>Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Phytoplankton Concentration</td>
<td>0.03 mmol N m$^{-3}$</td>
<td>Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Zooplankton Concentration</td>
<td>1.17 mmol N m$^{-3}$</td>
<td>Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Small Detritus Concentrations</td>
<td>0.03 mmol N m$^{-3}$</td>
<td>Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Maximum Nitrification Rate</td>
<td>0.7 d$^{-1}$</td>
<td>Pinazo et al. (1996)</td>
</tr>
<tr>
<td>Coagulation Rate of Phytoplankton and Small Detritus</td>
<td>182 d$^{-1}$</td>
<td>Pastoussaint et al. (2011a)</td>
</tr>
<tr>
<td>Detritus and Aggregate Remineralization Rate Constant</td>
<td>11 y$^{-1}$</td>
<td>Pinazo et al. (1996)</td>
</tr>
<tr>
<td>Settling (Sinking) Velocity of Phytoplankton</td>
<td>0.1 m d$^{-1}$</td>
<td>Pastoussaint et al. (2014), Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Settling (Sinking) Velocity of Large detritus</td>
<td>1.0 m d$^{-1}$</td>
<td>Pastoussaint et al. (2014), Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Settling (Sinking) Velocity of Small detritus</td>
<td>0.1 m d$^{-1}$</td>
<td>Pastoussaint et al. (2014), Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Settling (Sinking) Velocity of Labile</td>
<td>16.416 m d$^{-1}$</td>
<td>Curran et al. (2007)</td>
</tr>
</tbody>
</table>
### Aggregates

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Settling (Sinking) Velocity of Refractory Aggregates</td>
<td>16.416 m d^{-1}</td>
<td>Curran et al. (2007)</td>
</tr>
<tr>
<td>Nudging Parameter for Large detritus, Aggregates, Sediment</td>
<td>0 d^{-1}</td>
<td>None</td>
</tr>
<tr>
<td>Nudging Parameter for NO\textsubscript{3}, Phytoplankton, Small Detritus</td>
<td>0.02 d^{-1}</td>
<td>None</td>
</tr>
<tr>
<td>Nudging Parameter for NH\textsubscript{4}, Oxygen, ODU, Zooplankton</td>
<td>0.2 d^{-1}</td>
<td>None</td>
</tr>
<tr>
<td>POM Sedimentation Rate</td>
<td>( S_{\text{organic}} = 657 ) gC m(^{-2}) y(^{-1})</td>
<td>Pastor et al. (2011a)</td>
</tr>
</tbody>
</table>

### Nudging Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nudging Parameter for Large detritus</td>
<td>0 d^{-1}</td>
<td>None</td>
</tr>
<tr>
<td>Nudging Parameter for NO\textsubscript{3}, Phytoplankton, Small Detritus</td>
<td>0.02 d^{-1}</td>
<td>None</td>
</tr>
<tr>
<td>Nudging Parameter for NH\textsubscript{4}, Oxygen, ODU, Zooplankton</td>
<td>0.2 d^{-1}</td>
<td>None</td>
</tr>
</tbody>
</table>

### POM Sedimentation Rate

\[ S_{\text{organic}} = 657 \) gC m\(^{-2}\) y\(^{-1}\) | Pastor et al. (2011a) |

### Partitioning

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partitioning of Refractory vs. Labile Organic Matter</td>
<td>( f_{\text{lab}} = 0.5 )</td>
<td>Pastor et al. (2011a), Tesi et al. (2007)</td>
</tr>
<tr>
<td>Partitioning of Labile Aggregates vs. Large Detritus</td>
<td>( f_{\text{ldet}} = 0.5 )</td>
<td>Pastor et al. (2011a), Tesi et al. (2007)</td>
</tr>
</tbody>
</table>

### Seabed Biogeochemical Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labile Organic Matter Remineralization Rate Constant</td>
<td>11 y(^{-1})</td>
<td>Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Refractory Organic Matter Remineralization Rate Constant</td>
<td>0.31 y(^{-1})</td>
<td>Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Ratio of mol C: mol N in Labile Organic Matter</td>
<td>7.10</td>
<td>Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Ratio of mol C: mol N in Refractory Organic Matter</td>
<td>14.3</td>
<td>Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Half-Saturation Constant for O\textsubscript{2} Limitation of Aerobic Remineralization</td>
<td>( k_{O2} = 1 ) mmol O\textsubscript{2} m(^{-3})</td>
<td>Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Half-Saturation Constant for NO\textsubscript{3} Limitation of Nitrate Remineralization (Denitrification)</td>
<td>( k_{NO3} = 20 ) mmol N m(^{-3})</td>
<td>Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Half-Saturation Constant for O\textsubscript{2} Limitation of Nitrification</td>
<td>( k_{O2, nit} = 10 ) mmol O\textsubscript{2} m(^{-3})</td>
<td>Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Half-Saturation Constant for O\textsubscript{2} Limitation in ODU Oxidation</td>
<td>( k_{O2, oduox} = 1 ) mmol O\textsubscript{2} m(^{-3})</td>
<td>Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Half-Saturation Constant for O\textsubscript{2} Inhibition of Nitrate Remineralization (Denitrification)</td>
<td>( I_{O2} = 1 ) mmol O\textsubscript{2} m(^{-3})</td>
<td>Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Half-Saturation Constant for O\textsubscript{2} Inhibition of Anoxic Remineralization</td>
<td>( I_{O2, anoxic} = 1 ) mmol O\textsubscript{2} m(^{-3})</td>
<td>Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Half-Saturation Constant for NO\textsubscript{3} Inhibition of Anoxic Remineralization</td>
<td>( I_{NO3, anoxic} = 10 ) mmol NO\textsubscript{3} m(^{-3})</td>
<td>Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Maximum Nitrification Rate</td>
<td>( R_{\text{nit, max}} = 100 ) d(^{-1})</td>
<td>Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Maximum Oxidation Rate of Oxygen Demand Units</td>
<td>( R_{\text{ofox, max}} = 20 ) d(^{-1})</td>
<td>Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Fraction of ODU's Produced that are Solid and Inert</td>
<td>99.5%</td>
<td>Pastor et al. (2011a)</td>
</tr>
<tr>
<td>Diffusion Coefficient for Across Seabed-Water Interface</td>
<td>( D_{\text{sw}} = 1.08 \cdot 10^{-9} ) m(^{2}) s(^{-1})</td>
<td>Toussaint et al. (2014)</td>
</tr>
<tr>
<td>Coefficients for Diffusion Within the Seabed</td>
<td>( D_{\text{particulates}} = 2.55 \cdot 10^{-10} ) m(^{2}) s(^{-1})</td>
<td>( a ) Pastor et al. (2011a)</td>
</tr>
<tr>
<td></td>
<td>( D_{O2} = 11.99 \cdot 10^{-10} ) m(^{2}) s(^{-1})</td>
<td>( b ) Units are m(^{3}) sediment, not m(^{3}) water</td>
</tr>
<tr>
<td></td>
<td>( D_{NO3} = 9.80 \cdot 10^{-10} ) m(^{2}) s(^{-1})</td>
<td>( c ) Chosen based on organic sedimentation rate</td>
</tr>
<tr>
<td></td>
<td>( D_{NH4} = 10.04 \cdot 10^{-10} ) m(^{2}) s(^{-1})</td>
<td>( d ) Chosen based on time series of seabed elevation in Toussaint et al. (2014)</td>
</tr>
<tr>
<td></td>
<td>( D_{ODU} = 4.01 \cdot 10^{-10} ) m(^{2}) s(^{-1})</td>
<td>( e ) Chosen based on organic sedimentation rate</td>
</tr>
</tbody>
</table>
*No local data
*Derived from the molecular diffusion rates, but adjusted for the porosity and tortuosity of the seabed as described in Pastor et al., 2011a.
Table 2.4: List of sensitivity tests

Additionally, for each simulation listed here, an identical model run was completed that neglected resuspension (i.e. with $M = 0 \text{ kg/m}^2\text{s}$; $\tau_{\text{crit}} = 10 \text{ Pa}$).

<table>
<thead>
<tr>
<th>Sensitivity Test Abbreviation</th>
<th>Sensitivity Test Name</th>
<th>Changed Parameters and/or Parameterizations Relative to the Standard Model Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>Low Erosion Rate Parameter</td>
<td>$M = 0.005 \text{ kg m}^{-2}\text{s}^{-1}$</td>
</tr>
<tr>
<td>R2</td>
<td>High Erosion Rate Parameter</td>
<td>$M = 0.02 \text{ kg m}^{-2}\text{s}^{-1}$</td>
</tr>
<tr>
<td>T1</td>
<td>Low Critical Shear Stress</td>
<td>$\tau_{\text{crit}} = 0.15 \text{ Pa}$</td>
</tr>
<tr>
<td>T2</td>
<td>High Critical Shear Stress</td>
<td>$\tau_{\text{crit}} = 0.6 \text{ Pa}$</td>
</tr>
<tr>
<td>S1</td>
<td>Low Inorganic Sedimentation</td>
<td>$S_{\text{inorganic}} = 0.05 \text{ m y}^{-1} = 7 \text{ kg m}^{-2}\text{y}^{-1}$</td>
</tr>
<tr>
<td>S2</td>
<td>High Inorganic Sedimentation</td>
<td>$S_{\text{inorganic}} = 0.20 \text{ m y}^{-1} = 28 \text{ kg m}^{-2}\text{y}^{-1}$</td>
</tr>
<tr>
<td>P1</td>
<td>Low Particulate Organic Sedimentation</td>
<td>$S_{\text{organic}} = 328.5 \text{ gC m}^{-2}\text{y}^{-1}$</td>
</tr>
<tr>
<td>P2</td>
<td>High Particulate Organic Sedimentation</td>
<td>$S_{\text{organic}} = 1314 \text{ gC m}^{-2}\text{y}^{-1}$</td>
</tr>
<tr>
<td>L1</td>
<td>Low Lability</td>
<td>$f_{\text{lab}} = 0.20$</td>
</tr>
<tr>
<td>L2</td>
<td>High Lability</td>
<td>$f_{\text{lab}} = 0.80$</td>
</tr>
<tr>
<td>B1</td>
<td>Low Seabed Diffusion</td>
<td>$D_i = \text{original values} \times 0.5$</td>
</tr>
<tr>
<td>B2</td>
<td>High Seabed Diffusion</td>
<td>$D_i = \text{original values} \times 2.0$</td>
</tr>
<tr>
<td>N1</td>
<td>Low Nitrification Rate</td>
<td>$R_{\text{nit,max}} = 50 \text{ d}^{-1}$</td>
</tr>
<tr>
<td>N2</td>
<td>High Nitrification Rate</td>
<td>$R_{\text{nit,max}} = 200 \text{ d}^{-1}$</td>
</tr>
<tr>
<td>C1</td>
<td>No-Repartitioning</td>
<td>See Fig. 2.2c; Sect. 2.2.2.3</td>
</tr>
</tbody>
</table>
Table 2.5: Statistics for model-observation comparison

Statistics for model-observation comparison, including the root mean square difference (RMSD) and the correlation coefficient (R). The mean and standard deviation of estimates from both the model and observations are also shown.

<table>
<thead>
<tr>
<th></th>
<th>RMSD</th>
<th>R</th>
<th>Mean ± Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Model</strong></td>
</tr>
<tr>
<td><strong>Seabed Height</strong></td>
<td>1.39 cm</td>
<td>0.21</td>
<td>-0.52 ± 0.82 cm</td>
</tr>
<tr>
<td><strong>O₂ Gradient</strong></td>
<td>105 mol O₂ m⁻¹</td>
<td>0.48</td>
<td>180 ± 118 mol O₂ m⁻¹</td>
</tr>
</tbody>
</table>
Table 2.6: Oxygen Consumption

O$_2$ Consumption (mmol O$_2$ m$^{-2}$ d$^{-1}$) in the seabed, bottom water, and combined seabed-bottom water due to various processes over the two-month model run, and during periods of deposition and erosion. Abbreviations include: POM Rem. (particulate organic matter remineralization); ODU Ox (Oxidation of ODUs); Nit (nitrification); and “Seabed + BW” (the combined seabed-bottom-water region).

<table>
<thead>
<tr>
<th></th>
<th>Seabed</th>
<th>Bottom Waters</th>
<th>Seabed + BW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>POM Rem.</td>
<td>Nit.</td>
</tr>
<tr>
<td>2-Month Average</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum Values</td>
<td>12</td>
<td>0.56</td>
<td>3.7</td>
</tr>
<tr>
<td>over 2 Months</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Values</td>
<td>35</td>
<td>18</td>
<td>33</td>
</tr>
<tr>
<td>over 2 Months</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>18</td>
<td>5.5</td>
<td>12</td>
</tr>
<tr>
<td>During Depositional Periods</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>21</td>
<td>3.3</td>
<td>18</td>
</tr>
<tr>
<td>During Erosional Periods</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2.A.1: Parameters for new seabed layering scheme

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

<table>
<thead>
<tr>
<th>Type of Layer</th>
<th>Symbol for Number of Layers</th>
<th>Number of Layers for Rhône model implementation</th>
<th>Symbol for Thickness of Each Layer</th>
<th>Thickness of Each Layer for Rhône model implementation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Transport Layer (i.e., the Surficial Layer)</td>
<td>--</td>
<td>1</td>
<td>$z_a$</td>
<td>0.1</td>
</tr>
<tr>
<td>High-Resolution Layers</td>
<td>$N_{\text{high-res}}$</td>
<td>19</td>
<td>$z_{\text{high-res}}$</td>
<td>0.5</td>
</tr>
<tr>
<td>Medium-Resolution Layers</td>
<td>$N_{\text{med-res}}$</td>
<td>39</td>
<td>$z_{\text{med-res}}$</td>
<td>10</td>
</tr>
<tr>
<td>Repository</td>
<td>--</td>
<td>1</td>
<td></td>
<td>Varies; 333 m at initialization</td>
</tr>
</tbody>
</table>
Figures for Chapter 2

Figure 2.1: Study Site

a) Red box indicates location of panel (b) in the Gulf of Lions. b) Dots indicate our study site (SS; blue), i.e. the Mesurho station (Pairaud et al., 2016), and Pastor et al. (2014)'s Site A (green) offshore of the Rhône River. Bathymetric data (black lines) were obtained from the European Marine Observation and Data Network. Coastline data were obtained from the U.S. National Oceanic and Atmospheric Administration.
Figure 2.2: Model Schematic

(a) Schematic of links between the seabed biogeochemical module and other modules, and detailed schematics of particulate organic matter partitioning for the (b) standard model run and (c) no-repartitioning sensitivity test. The colors of the boxes and labels indicate processes associated with sediment transport (brown), water-column biogeochemistry (green) and seabed biogeochemistry and model coupling (black). Abbreviations for this figure represent sediment (Sed.), biogeochemistry (Biogeochem.), phytoplankton (Phyt.), zooplankton (Zoop.), detritus (Det.), seabed organic matter (S.O.M.), aggregates (Agg.), labile (Lab.) and refractory (Ref.).
Figure 2.3: Model-observation comparison

Time series of modeled (blue lines and x’s) and observed (red dots; Toussaint et al., 2014) bed stress, near-bed suspended sediment concentrations (SSC), seabed height, and vertical oxygen gradient averaged over the oxic layer of the seabed (top 4 panels), and three examples of oxygen profiles before (6 April 2012), during (9 April 2012), and after (12 April 2012) an erosional event in early April (bottom panels). The dashed black lines in the bottom panels indicate the seabed-water interface. Shading in the top panels indicates resuspension events, i.e. cycles of erosion and re-deposition, including 6–13 April, 23 April–3 May, and 18–25 May 2012.
Time series of bed stress and oxygen consumption in the seabed and bottom water (BW) for both the standard (blue solid line) and no-resuspension model runs (pink line). Shading indicates resuspension events, i.e. cycles of erosion and re-deposition, as listed in Fig. 2.3. The red dashed line indicates the critical shear stress for erosion, and the black dashed lines indicate the times at which profiles in Fig. 2.5 were estimated.

Figure 2.4: Oxygen consumption time-series
Figure 2.5: Seabed profiles of biogeochemical tracers

Seabed profiles of oxygen (top row; mmol O$_2$ m$^{-3}$), nitrate (second row; mmol N m$^{-3}$), ammonium (third row; mmol N m$^{-3}$), and degradable particulate organic carbon (POC; bottom row; dry weight (%)) from the standard model run for times immediately preceding the mid-April resuspension event (6 April 2012, left column), during the erosional period (10 April 2012, center column), and during the depositional period (13 April 2012, right column). Fig. 2.4 shows the times at which the profiles were estimated. Tickmarks on the blue lines indicate the location of each seabed layer. The black dashed lines indicate the seabed water interface, and all seabed depths are given relative to this interface. The ‘x’s indicate near-bed values for the water column.
Figure 2.6: Sources and sinks of oxygen in the seabed

Physical (top) and biogeochemical (bottom) sources and sinks of oxygen within the seabed for the standard model run. Sources and sinks of oxygen to the seabed are positive and negative, respectively. Small biogeochemical sinks <1 mmol O₂ m⁻² d⁻¹ (ODU oxidation and remineralization of refractory POM) are not shown. Shading indicates resuspension events, i.e. cycles of erosion and deposition, including 6–13 April, 23 April–3 May, and 18–25 May, 2012.
Figure 2.7: Estimates of oxygen consumption for each sensitivity test

Rate of oxygen consumption in the (a) sebed and (c) bottom waters for each sensitivity test listed in Table 2.4. Fraction of (b) sebed and (d) bottom-water oxygen consumption induced by resuspension, calculated by dividing the difference between each sensitivity test and its no-resuspension model run by the value from the sensitivity test. In both panels, bars represent averages over two months. Dots indicate the maximum values during this two-month period (which occurred during resuspension events). The dashed lines represent values from the standard model run, with the color of the line consistent with the type of data it represents (i.e. two-month average or maximum value).
Figure 2.8: Oxygen consumption averaged over different timescales

Box and whisker plot indicating the 0\textsuperscript{th}, 25\textsuperscript{th}, 50\textsuperscript{th}, 75\textsuperscript{th}, and 100\textsuperscript{th} percentiles of combined seabed-bottom-water (BW) oxygen consumption averaged over different timescales for the standard model run. The pink lines indicate estimates from the no-resuspension model run.
Chapter 3

3. Role of seabed resuspension on nitrogen and oxygen dynamics for the northern Gulf of Mexico: A numerical modeling study
Key Points for Chapter 3

1. A hydrodynamic-sediment transport-biogeochemical model shows that resuspension exacerbates hypoxia in the northern Gulf of Mexico.

2. Resuspension of seabed organic matter intensifies water column remineralization rates, thereby increasing oxygen consumption and ammonium production.

3. The effect of resuspension on oxygen and ammonium dynamics is nearly continuous in shallow regions and episodic in deeper waters.

Abstract for Chapter 3

Resuspension affects water quality in coastal environments by entraining seabed organic matter and porewater into the water column, which can increase remineralization and alter seabed fluxes. Seabed and bottom boundary layer processes are often simplified in numerical models of water column biogeochemistry, however, and resuspension is typically neglected. Here, we implemented HydroBioSed, a coupled hydrodynamic-sediment transport-biogeochemical model to examine the role of resuspension on oxygen and nitrogen dynamics for timescales of a day to a month. The model was implemented for the northern Gulf of Mexico, where the extent of summertime hypoxia is known to be sensitive to seabed and bottom boundary layer processes. Results indicated that particulate organic matter remineralization in the bottom water column, and therefore oxygen consumption and ammonium production, increased by an order of magnitude during resuspension events. Altered fluxes of oxygen and ammonium between the seabed and water column, as well as changes in oxidation of reduced chemical species, also
impacted biogeochemical dynamics, but to a lesser extent than the resuspension–induced increases in remineralization. The role of resuspension in the numerical model also varied depending on water depth. In shallow waters where resuspension occurred most of the time, the effect of resuspension on bottom water biogeochemical dynamics was persistent and nearly constant in time. In contrast, resuspension events in deeper areas caused less frequent, episodic changes in biogeochemical processes. Overall, when averaged over the shelf and for timescales of a month in the numerical model, cycles of erosion and deposition accounted for about two-thirds of bottom water oxygen consumption and ammonium production.

3.1 Introduction

Seabed and bottom boundary layer processes modulate biogeochemical cycles and water quality in coastal waters (McKee et al., 2004; Aller, 1998). In these environments, understanding these processes, which include seabed-water column fluxes of oxygen, nutrients, organic matter and sediments, is especially important as they can affect water column oxygen and nutrient levels (e.g. Connolly et al., 2010; Conley et al., 2009). Quantifying the role of such fluxes on water quality can therefore be important for understanding ecosystem responses to management efforts (Kemp et al., 2009).

Resuspension of particulate organic matter and sediment, i.e. inorganic particles, can modulate biogeochemical dynamics in the seabed and bottom boundary layer through a variety of processes. Observational and laboratory studies show that resuspension may alter rates of organic matter remineralization (e.g., Aller, 1998; Hartnett et al., 1998; Ståhlberg et al., 2006; Ziervogel et al., 2015), seabed-nutrient fluxes (e.g., Toussaint et
al., 2014; Porter et al., 2010; Almroth et al., 2009; Fanning et al., 1982), and light attenuation (e.g., Cloern, 1987; Salisbury et al., 2004). In addition to local effects, resuspension and subsequent redistribution of material within coastal waters can alter the spatial and temporal distribution of particulate organic matter, which may then affect biogeochemical dynamics (e.g., Goñi et al., 2007; Christiansen et al., 1997; Lampitt et al., 1995; Abril et al., 1999). However, observational and laboratory approaches for understanding and quantifying the role of seabed and near-bed processes on water column biogeochemistry are often limited by technological, safety, and/or cost constraints, and thus models are important for interpolating and extrapolating results in space and time.

3.1.1 The Role of Seabed and Near-Bed Processes in the Northern Gulf of Mexico

This study focused on the northern Gulf of Mexico, which is a river-dominated shelf system characterized by a seasonally varying dynamic physical environment. The Mississippi River and its distributary, the Atchafalaya River (Figure 3.1), deliver freshwater, sediment, and nutrients to the northern Gulf of Mexico shelf, where terrestrial inputs are generally transported westward and offshore by shelf currents (e.g. Wright and Nittrouer, 1995; Bianchi et al., 2010; Zhang et al., 2012; Wysocki et al., 2006; Fry et al., 2015). Material deposited in shallow areas of the shelf (~0-20 m water depth) is subjected to high bed stresses and may be resuspended and redistributed across the shelf throughout the year, while hurricanes and storms can rework deposited sediments and particulate organic matter in deeper regions (Goñi et al., 2006; Xu et al., 2011; Allison et al., 2000; Corbett et al., 2004).
Seasonally high temperatures and riverine freshwater and nutrient inputs enable development of hypoxia in the summer when vertical stratification, enhanced by westerly winds that cause the river plume to spread across the shelf, limit oxygen supply to bottom waters (e.g. Wiseman et al., 1997; Bianchi et al., 2010; Forrest et al., 2012). Unlike many regions where the location, extent and fragmentation of hypoxia is constrained by bathymetry (e.g. Conley et al., 2009; Kemp et al., 2005), hypoxia in the northern Gulf of Mexico is typically observed near the Mississippi Delta where persistent stratification occurs, as well as in fragmented patches across the shelf that vary inter-annually in location and area, and possibly on shorter timescales as well (Rabalais et al., 2002). The hypoxic layer on this shelf is thin, typically about 1 – 2 m thick (Fennel et al., 2016 and references therein), which makes it particularly sensitive to seabed and bottom boundary layer processes.

Previously developed conceptual models for the formation and maintenance of hypoxia on the northern Gulf of Mexico shelf acknowledge that the processes affecting the formation of these low-oxygen areas vary spatially. Rowe and Chapman (2002)’s conceptual diagram consists of three regions. Near the Mississippi delta and along the coast, the high turbidity in their “Brown Water” limits phytoplankton growth and so hypoxia is fueled by remineralization of allochthonous particulate organic matter. Further off- and along-shore, high levels of primary production in their “Green Water” region, and remineralization of this autochthonous particulate organic matter, cause hypoxia. Finally, the “Blue Water” region occurs even further off- and along-shore where reduced nitrogen concentrations limit phytoplankton growth and hypoxia can occurs due to advection of low-oxygen waters into the area and remineralization of organic matter.
In the last decade, many papers have built on Rowe and Chapman (2002)’s conceptual diagram by showing the importance of benthic processes, including remineralization, for oxygen consumption, especially in shallow areas and the western region of the hypoxic zone (e.g. Hetland and DiMarco, 2008; Lehrter et al., 2012; McCarthy et al., 2013; Fennel et al., 2013; Yu et al., 2015b; Feist et al., 2016). Even weeks after particulate organic matter deposition, nutrient fluxes from the seabed may further stimulate production, remineralization, and future oxygen demand, especially at the onset and end of hypoxic events (Eldridge and Morse, 2008).

Seabed and bottom boundary layer biogeochemical processes respond to cycles of erosion and deposition, although the effects have been less frequently studied than those due to factors such as temperature, redox conditions and organic matter lability. Episodes of resuspension may entrain millimeters to centimeters of previously deposited sediment and particulate organic matter into the water column (e.g. Xu et al., 2011; Goñi et al., 2007). A single study, Fanning et al. (1982), examined the role of resuspension on bottom water nutrient concentrations, and their observations indicated that dissolved inorganic nitrogen concentrations in the bottom boundary layer approximately doubled during erosional periods on the northern Gulf of Mexico continental shelf.

Previous modeling efforts focused on the northern Gulf of Mexico have corroborated that oxygen and nitrogen dynamics are sensitive to seabed-water column fluxes, but these studies have simplified or parameterized these processes (Fennel et al., 2013; Feist et al., 2016; Yu et al., 2015a, 2015b; Laurent et al., 2016; Hetland and DiMarco, 2008). Model estimates of hypoxic area, for example, are sensitive to the manner in which the model represents seabed-water column fluxes. Fennel et al. (2013)
found that using different parameterizations for seabed-water column fluxes of oxygen and nutrients altered the estimated hypoxic area by over 100%. This sensitivity of the model results suggests that more realistic representation of the seabed and related processes in biogeochemical models may be important for understanding and predicting biogeochemical budgets, and the formation of hypoxic areas, in the northern Gulf of Mexico. To our knowledge, nearly all biogeochemical models implemented for this region have neglected the role of resuspension. Exceptions include a one-dimensional model for carbon dynamics (Wainright and Hopkinson, 1997), and a three-dimensional study that accounted for the effect of resuspended sediment on light attenuation (Justić and Wang, 2014). However, no study has focused on the effect of resuspension on remineralization, seabed-water column fluxes, and the distribution of particulate organic matter on the shelf, or how changes in these processes affect oxygen and nitrogen dynamics, in the northern Gulf of Mexico.

3.1.2 Objectives

This study therefore uses a numerical modeling approach that accounts for both sediment transport and biogeochemical processes to address the following questions:

1. On timescales of a single resuspension event, how do erosion and deposition affect oxygen and ammonium dynamics in water below the pycnocline due to different processes, including: altered seabed-water column fluxes; the remineralization of resuspended particulate organic matter; and oxidation of reduced chemical species that were entrained into the water column?
2. How does the biogeochemical response to cycles of erosion and deposition vary depending on the characteristics of the event (e.g. magnitude of resuspension) and environmental conditions (e.g. particulate organic matter concentrations)?

3. What is the cumulative effect of short episodes of resuspension on oxygen and ammonium dynamics over month-long timescales for different areas of the shelf?

3.2 Materials and Methods

To address the research questions listed above, a series of model runs using HydroBioSed, i.e. the coupled hydrodynamic-sediment transport-biogeochemical model, were completed for the northern Gulf of Mexico for 2006-2007. The following sub-sections describe how the coupled model was modified from Chapter 2 (Section 3.2.1) and implemented for the northern Gulf of Mexico (Section 3.2.2), before describing the seven different model runs (Section 3.2.3) and model analysis (Section 3.2.4).

3.2.1 Standard model formulations

Model formulations for HydroBioSed were described in some detail for the one-dimensional model used in Chapter 2 to represent the Rhône shelf. Briefly, modeled processes account for advection of water, biogeochemical tracers, and sediment; sinking and deposition of particulate organic matter to the seabed; subsequent resuspension or storage of particulate organic matter in the seabed; remineralization of particulate organic matter and oxidation of reduced chemical species in both the water column and seabed; and diffusion of dissolved chemical species across the seabed-water interface. This coupled model (Chapter 2) builds on the Regional Ocean Modeling System (ROMS) framework (Haidvogel et al., 2000, 2008; Shchepetkin, 2003; Shchepetkin and
To represent the northern Gulf of Mexico, the formulations described in Chapter 2 were adapted for use in a three-dimensional model and for a site having different environmental conditions. Specific modifications include open boundary conditions appropriate for the three-dimensional model, and slight alterations to the seabed-layering scheme to account for a wider range of erosional and depositional conditions. Additionally, whereas the version of the model in Chapter 2 nudged water column nutrient and oxygen concentrations toward observed values, this model implementation allowed all state variables to evolve freely as prescribed by the water column biogeochemical model of Fennel et al. (2006; 2008; 2011). Chapter 2 also assumed that a certain fraction of deposited organic matter was labile versus refractory. In the current model, for the Gulf of Mexico, all particulate organic matter produced on the shelf was assumed to be labile, while the rivers delivered both labile and refractory particulate organic matter. Finally, rates of remineralization and biodiffusion (i.e. vertical mixing within the seabed, including bioturbation as described in Sherwood et al. (in prep)) were parameterized to vary with temperature, as described in Laurent et al. (2016), who optimized a steady-state one-dimensional version of the Soetaert et al. (1996a; 1996b) model for a couple sites on the northern Gulf of Mexico shelf.
3.2.2 Standard model implementation

Model configuration, forcing, and parameters are provided in Table 3.1, but are summarized here. The model grid and hydrodynamic forcing for the coupled northern Gulf of Mexico model were based on Hetland and DiMarco (2012), but also accounted for wave-induced bed stress. The model grid specifically focused on the area west of the Mississippi River delta where seasonal hypoxia develops and has been used for multiple modeling studies of sediment transport and hypoxia (e.g. Xu et al., 2011, 2015; Fennel et al., 2013, 2016; Laurent et al., 2016). Lateral open boundary conditions were consistent with Hetland and DiMarco (2012), and were based on Chapman (1985) for sea surface height, Flather (1976) for depth-averaged momentum, and Marchesiello et al. (2001)’s radiation conditions for depth-varying momentum and tracers. Tracers were also nudged to climatological data at the open boundaries. Wave Watch III (WW3; Tolman et al., 2002) model estimates of significant wave height, dominant surface wave period, and dominant wave direction were used to estimate representative bottom wave period and representative bottom orbital velocity, following methods from Wiberg and Sherwood (2008). Bed stress was calculated using the bottom boundary layer parameterization based on Madsen (1994), as described in Warner et al. (2008), consistent with previous Gulf of Mexico sediment transport models (Xu et al., 2011, 2015).

The sediment transport inputs and parameters were configured based on Xu et al. (2011; 2015), while the water column biogeochemistry module was based on Fennel et al. (2013). Table 3.1 provides details, which are summarized here. Sediment classes were distinguished by source (i.e. seabed, Mississippi River, or Atchafalaya River). Particle properties, i.e. settling velocity and critical shear stress for erosion, were based on Xu et
al. (2011; 2015). Sediment concentrations affected the density equation of state (Warner et al., 2008) and bioturbation was accounted for as in Chapter 2 and Sherwood et al. (in prep). Particulate organic matter classes were characterized by source; their properties were based on the literature, in that remineralization rate constants came from Fry et al. (2015) and Fennel et al. (2013); and settling velocities came from Wakeham et al. (2009).

Implementation of the seabed biogeochemistry model was guided by Laurent et al. (2016). For implementation over multiple years and the entire model grid, a couple of rate constants were adjusted to better match observations of seabed-water column fluxes (Table 3.1). Relative to the values used by Laurent et al. (2016), the nitrification rate constant was doubled from 50 to 100 d⁻¹, and the labile particulate organic matter remineralization rate constant was increased from 0.01 to 0.1 d⁻¹. Additional information regarding the model implementation can be found in Table 3.1.

3.2.3 Model runs

The coupled model described above was run for 2006-2007, which were relatively typical years for river discharge, wave energy, and winds. Compared to 2007, 2006 had lower discharge, more easterly winds, and higher wave energy based on data from NDBC buoys 42040 and 42007 and the Army Corps of Engineers (Figure 3.2; Table 3.1). Although these years may not completely represent the inter-annual variability of the northern Gulf of Mexico, they are adequate for looking at the impact of short-term events over month-long timescales. Model initial fields were obtained by repeating the 2006-2007 model run three times, until temporal variations between spatially averaged data
were minimal, and then the final timestep of the “spin-up” simulation was used as the initial condition for the “standard model run”. Model output was saved every 12 hours.

In addition to the standard model run, sensitivity tests were used to estimate how various parameters choices affected modeled biogeochemical dynamics. Sensitivity tests were identical to the standard model, except as noted in Table 3.2, and focused on resuspension, remineralization rate constants, and particulate organic matter settling velocities to explore the effect of resuspended particulate organic matter on bottom water biogeochemistry. Sensitivity tests were initialized with modeled fields from the standard model from June 1, 2006 or July 1, 2006. Each sensitivity test was run for one month. Model analysis focused on these time periods because Gulf of Mexico hypoxia is typically observed in July (e.g. Rabalais et al., 2002). June 2006 had similar environmental conditions to July 2006, but included a large wave-induced resuspension event (Figure 3.2).

3.2.4 Model analysis

Model analysis focused on how seabed resuspension affected biogeochemical processes within the bottom water column, and their effect on oxygen and ammonium dynamics. These processes included seabed-water column fluxes of oxygen and ammonium, and oxidation of ammonium and other reduced chemical species, but these were not especially sensitive to resuspension (data not shown). In contrast, POC remineralization was characterized by large, episodic changes during resuspension events, and so the Results and Discussion primarily focus this process.
First, the standard model was evaluated by comparing it to observations from the northern Gulf of Mexico of concentrations of particulate organic carbon (POC), O₂, NH₄, and NO₃ in the seabed and bottom water column, as well as seabed-water column fluxes and bulk water column respiration rates. Following model evaluation, analysis focused primarily on wave events in June and July 2006, but time-averaged estimates over month-long periods throughout 2006-2007 are also discussed. Except when the text explicitly states otherwise, model estimates were averaged over the “shelf region”, defined as the area west of the Mississippi delta and shallower than 50 m water depth (i.e. all of the shaded areas in Figure 3.1c). For this analysis, “bottom water” concentrations and rates included calculations for the bottom grid cell of the model, which was ~0.5 and 3 m in 10 and 50 m deep areas, respectively. Also, the “remineralization rate constant” is a temporally and spatially constant model input parameter with units of time⁻¹. In contrast, the text will use the terms “effective remineralization rate” and “remineralization” to refer to the temporal rate of change in particulate organic matter concentrations due to remineralization, with units of carbon concentration x time⁻¹.

To estimate the effect of resuspension on the biogeochemical processes listed above, we analyzed results from the standard model and the sensitivity tests. Specifically, estimates from the standard model run during cycles of erosion and deposition were compared to those from quiescent time periods. The role of resuspension was further quantified by comparing results from the standard model run to those from the no-resuspension sensitivity tests for June and July 2006. Finally, calculations from the sensitivity tests were compared to those from the standard model run to indicate the
sensitivity of the results to parameters affecting remineralization and the residence time of particles in the water column.

3.3 Results

3.3.1 Comparison of standard model to observations

This section evaluates the representation of near-bed POC concentrations, as well as rates of remineralization and seabed-water column fluxes, in the standard model. Overall, the model captured the observed spatial and temporal variations in POC concentrations. For example, on the mid-shelf the coupled model estimated elevated concentrations of POC in the bottom water column relative to the middle of the water column as has been previously observed (Fry et al., 2015). In shallow areas, modeled concentrations of POC were similar throughout the water column because it was vertically well mixed, similar to observations from Goñi et al. (2006).

The coupled model also reproduced observed patterns of seabed-water column fluxes and bottom water respiration. For example, model estimates of seabed-water column oxygen fluxes ranged from -40.4 to 3.79 mmol m$^{-2}$ d$^{-1}$, similar to the range of observed values of -56.4 to 0 mmol m$^{-2}$ d$^{-1}$ (Figure 3.3; Table 3.3 and references therein). Note that negative values are defined to be directed into the seabed. Additionally, the model reproduced the range of estimates for seabed-water column nitrogen fluxes, including the bi-directional fluxes of nitrate and ammonium (Table 3.3). Finally, observed estimates of bottom water respiration, i.e. the rate of oxygen consumption in bottom waters, ranged from below detection limits to 106 mmol O$_2$ m$^{-3}$ d$^{-1}$, which encompassed the majority of model estimates, which averaged 6.14 mmol O$_2$ m$^{-3}$ d$^{-1}$ with
a standard deviation of 14.9 mmol O$_2$ m$^{-3}$ d$^{-1}$ in water depths of 0-50 m west of the Mississippi delta (Table 3.3).

Model estimates of seabed fluxes and respiration generally had larger ranges than those derived from field data, which is not surprising because the model covered a longer time period, a wider range of spatial locations, and a broader range of environmental conditions (e.g. storms versus quiescent periods), compared to observational studies. For example, in some instances, the model estimated that oxygen fluxes were directed out of the seabed (Table 3.3) during the beginning of erosional periods when layers of oxic porewater from surficial sediments were entrained into the water column. However, this process is unlikely to be observed during field studies due to limitations in sampling methods. Similarly, model estimates of respiration in the bottom grid cells at times exceeded the maximum observed values (Table 3.3). This is not surprising, because modeled POC concentrations in these grid cells also exceeded observed values (Table 3.3), at least in part due to differences between the vertical resolution and sampling strategies of observational techniques and the model.

3.3.2. Effect of resuspension over event timescales

Entrainment of seabed organic matter into the overlying water increased remineralization in the bottom meter of the water column during resuspension events by an order of magnitude (Figure 3.4). Although much of June 2006 was characterized by low-energy hydrodynamic conditions and modest levels of erosion, energetic waves caused widespread resuspension to occur from June 10 - 23, 2006. During this thirteen-day period, bed shear stresses reached as high as 2 Pa (Figure 3.4), and exceeded the 0.13
Pa threshold for resuspension, in water depths up to about 30 m. Seabed organic matter was entrained into the water column, increasing estimated concentrations of POC from near zero to 100-700 mmol C m\(^{-3}\) (Figure 3.4). Averaging over the shelf region, this additional source of particulate organic matter resulted in effective remineralization rates increasing from about 0.5 to 1-15 mmol C m\(^{-3}\) d\(^{-1}\) during this June 2006 event (data not shown). In contrast to June, most of July was characterized by a few mild resuspension events when bed stresses were sufficiently high to resuspend sediment, but erosion remained relatively small, about an order of magnitude less than those in June (Figure 3.5). Consistent with the June resuspension event, however, effective remineralization rates during these smaller events increased from 0-2 to 0-7 mmol C m\(^{-3}\) d\(^{-1}\) (Figure 3.5).

Resuspension also increased nitrification and seabed-water column fluxes of ammonium. During resuspension events in June and July 2006, resuspension increased median nitrification rates from ~0.02 to 0.05 mmol NH\(_4\) m\(^{-3}\) (data not shown). Seabed-water column fluxes of ammonium varied from ~0.2 mmol NH\(_4\) m\(^{-2}\) d\(^{-1}\) during quiescent times to up to 0.5 mmol NH\(_4\) m\(^{-2}\) d\(^{-1}\) during resuspension events. Resuspension-induced changes in seabed fluxes of oxygen, in contrast, were negligible in most areas of the grid. Overall, these resuspension-induced changes in nitrification and seabed fluxes were small compared to changes in remineralization, so the remainder of the Results section focuses on the latter process, as well as oxygen and nitrogen dynamics.

The resuspension-induced changes in remineralization and other biogeochemical processes increased sinks of oxygen and sources of ammonium in the bottom water column (Figures 3.4, 3.5). In the bottom meter of the water column during the June and July 2006 resuspension events, the rate of oxygen consumption, defined as the sum of
oxygen consumed via remineralization, nitrification, and oxidation of ODUs, increased from about zero during quiescent periods to a median value of ~7 mmol O$_2$ m$^{-3}$ d$^{-1}$ during resuspension events for the shelf region. Similarly, net ammonium production, i.e. NH$_4$ produced via remineralization minus that consumed via nitrification, increased from about zero to ~1 mmol O$_2$ m$^{-3}$ d$^{-1}$ during resuspension events in June and July 2006.

A comparison of model estimates between the standard and no-resuspension simulations also indicated that cycles of erosion and deposition increased remineralization, oxygen consumption and ammonium production. Median estimates of remineralization in the standard model exceeded that in the no-resuspension model by ~7 mmol O$_2$ m$^{-3}$ d$^{-1}$ during the June and July 2006 resuspension events (Figures 3.4, 3.5). This resuspension–induced modification of biogeochemical dynamics caused oxygen concentrations to decrease by up to ~20 mmol O$_2$ m$^{-3}$ during the June and July 2006 resuspension events. Similarly, ammonium concentrations increased by up to ~5 mmol NH$_4$ m$^{-3}$ during periods of resuspension (Figures 3.4, 3.5).

3.3.3. **Time-averaged effects of resuspension**

In addition to causing variability in biogeochemical dynamics over timescales of hours to days, cycles of erosion and deposition altered remineralization, and concentrations of oxygen and ammonium, when results were averaged over month-long time periods. Compared to the no-resuspension model run, estimates of effective remineralization rates in the bottom meter of the water column increased from ~1 to 4 mmol O$_2$ m$^{-3}$ d$^{-1}$ in the standard model run when averaged over the shelf regions for June 1-30, 2006 (Figure 3.6a). For those same months, accounting for resuspension in the
model decreased average oxygen concentrations in the bottom meter of the water column by ~10 mmol O$_2$ m$^{-3}$ and increased average ammonium concentrations by ~2 mmol NH$_4$ m$^{-3}$ in June 2006 (Figure 3.6b,c).

The result that remineralization of resuspended seabed organic matter increased oxygen consumption and ammonium production is further supported by sensitivity tests that examined the effect of altering particulate organic matter settling velocity and remineralization rate constants. For example, increasing the settling velocity of resuspended particulate organic matter by a factor of 5 decreased the residence time of resuspended particulate organic matter in the water column (data not shown). This reduced remineralization compared to the standard model run; and oxygen and ammonium concentrations were changed by about +10 mmol O$_2$ m$^{-3}$ and -2 mmol NH$_4$ m$^{-3}$, respectively, when averaged over the shelf regions in June 2006 (Figure 3.6). Likewise, decreasing the settling velocities by a factor of 5 increased remineralization, changing oxygen and ammonium concentrations by about -60 mmol O$_2$ m$^{-3}$ and +7 mmol NH$_4$ m$^{-3}$, respectively, during this time period (Figure 3.6). Similarly, decreasing the remineralization rate constants reduced remineralization, whereas increasing these constants enhanced remineralization, in a manner similar to the settling velocity sensitivity tests (Figure 3.6). For all sensitivity tests, however, the factor of 5 changes in parameters resulted in about a factor of 2 change in average effective remineralization rates, and smaller changes to oxygen and ammonium levels (Figure 3.6).
3.4 Discussion

3.4.1 Across- and Along- Shelf Variability of the Role of Resuspension on Remineralization, Oxygen, and Ammonium

The result that resuspension of particulate organic matter increased remineralization is consistent with previous observational (Aller, 1998; Ståhlberg et al., 2006) and modeling studies (Wainright and Hopkinson, 1997; Capet et al., 2016), but utilizing a coupled sediment transport and biogeochemical model allowed us to examine the spatial and temporal variability of different processes. This section examines variations in the model results due to environmental factors including bathymetry, stratification, and the concentrations of particulate organic matter and oxygen.

Across-shelf gradients of the effects of resuspension on biogeochemical dynamics on the northern Gulf of Mexico shelf contributed heavily to spatial variations in the model results (Figure 3.7). In contrast to deeper areas, regions shallower than about 20 m experienced stronger wave-induced bed stresses that caused frequent and more intense periods of resuspension (Figure 3.7a). In these shallow areas, where bed stresses were sufficiently strong to resuspend sediment almost all of the time, persistent mixing between the seabed and bottom boundary layer had a nearly continuous effect on biogeochemical signals including remineralization, in the bottom of the water column (data not shown). In deeper waters, resuspension persisted for only a few days and produced distinct perturbations in remineralization (data not shown), but the effects were less substantial compared to shallower areas when results were averaged over month-long periods (Figure 3.7b). For example, in the standard model, effective remineralization
rates during July 2006 ranged up to ~20 mmol O\textsubscript{2} m\textsuperscript{-3} in water depths 0-20 m (Figure 3.7b). When erosion was prevented in the no-resuspension sensitivity test, remineralization was reduced by about 50% compared to the standard model (Figure 3.7b). In contrast, in regions 30-50 m deep, time-averaged rates of remineralization were similar in both the standard and no-resuspension models (Figure 3.7b).

This intense vertical mixing throughout shallow water columns, especially during times of resuspension, increased remineralization, and the associated oxygen consumption and ammonium production, throughout the water column (Figure 3.8). Resuspension, triggered by energetic waves and currents, tended to occur during times of strong winds (Figure 3.2), which enhanced vertical mixing. This was especially true in shallow waters, where resuspended particulate organic matter became relatively evenly distributed throughout the water column during resuspension events, until stratification was re-established after the event (Figure 3.8). For example, Figure 3.8 shows results for an across-shelf transect west of Atchafalaya Bay. At this location during the June 2006 resuspension event, surface water POC concentrations increased relative to quiescent periods from ~100 mmol C m\textsuperscript{-3} to ~300 mmol C m\textsuperscript{-3} at ~10 m depth (Figure 3.8). In contrast, along the same transect, but at 50 m water depth, resuspension-induced changes in surface water POC concentrations were negligible. This across-shore variability in the vertical distribution of particulate organic matter concentrations is consistent with observations showing that peaks in surface and bottom water POC and total suspended solids are generally co-located in water less than 20 m deep (Goñi et al., 2006). Overall, these across-shelf variations in vertical mixing, and therefore particulate organic matter profiles, explain why resuspension-induced changes in biogeochemical dynamics
affected nearly all of the water column in areas shallower than about 20 m, but only the near-bed layer, i.e. within about 5 m above the seabed, in deeper areas.

In the along-shelf direction, persistent stratification of the river plume immediately west of the Mississippi Delta reduced the influence of resuspension on the formation and maintenance of hypoxia there, compared to areas west of Atchafalaya Bay. Near the delta, persistent stratification caused the biogeochemical sinks of oxygen to exceed the supply of oxygen to bottom waters via vertical diffusion and other transport processes for both the standard and no-resuspension model runs. In contrast, regions west of Atchafalaya Bay experienced more variable stratification and the extent of hypoxia was more sensitive to estimated rates of oxygen consumption, consistent with Hetland and DiMarco (2008). Thus, resuspension-induced changes in seabed and bottom water oxygen consumption had an increased effect on hypoxia west of Atchafalaya Bay. For example, although POC concentrations were similar in both regions (Figure 3.7f), resuspension caused oxygen concentrations to decrease by ~25 mmol O$_2$ m$^{-3}$ in waters adjacent to the Mississippi delta, but by over 50 mmol O$_2$ m$^{-3}$ west of Atchafalaya Bay, when averaged over a month (Figure 3.7c). Overall, the maximum hypoxic area in August 2006 estimated for the different sensitivity tests varied from 12 x10$^3$ km$^2$ to 21 x 10$^3$ km$^2$, primarily due to changes in oxygen concentrations in the western region of the shelf (data not shown).

The resuspension-induced gradients in biogeochemical processes in the numerical model (Figure 3.7) were generally consistent with previous conceptual models of hypoxia in the northern Gulf of Mexico. Namely, the numerical model showed that water column biogeochemistry on the western region of the shelf is more sensitive to seabed and near-
bed processes compared to the region adjacent to the Mississippi River plume. For example, convergence of shelf currents caused particulate organic matter to accumulate in bottom waters west of Atchafalaya Bay offshore the Chenier Plains and along the 20 m isobaths (Figure 3.7f). This accumulation, as well as local resuspension, enhanced near-bed POC concentrations and effective remineralization rates, lowering oxygen concentrations in these regions (Figure 3.7b,c). This region of POC accumulation is also co-located with the area where oxygen concentrations were sensitive to benthic respiration in Hetland and DiMarco (2008)’s modeling effort, and is similar in location to Rowe and Chapman (2002)’s “Green Water” zone, where hypoxia is controlled by organic matter availability and stratification. Compared to these previous studies, our results emphasize that remineralization of resuspended and redistributed particulate organic matter, in addition to seabed respiration, can help to explain the observed spatial patterns of hypoxia in this region.

The coupled model results similarly support the hypothesis that across-shelf transport of particulate organic matter produced on the shelf, enhanced by resuspension, can affect where and when hypoxia develops. In the coupled model, resuspension augmented both offshore and onshore fluxes of particulate organic matter, depending on hydrodynamic conditions (data not shown). Seaward transport is consistent with previously published hypotheses that offshore transport of particulate organic matter from the inner- to mid-shelf could help fuel hypoxia on the mid-shelf, based on observations of particulate organic matter concentrations (Fry et al., 2015) and sediment transport modeling studies (Xu et al., 2011). In addition to offshore fluxes, comparison of the standard and the no-resuspension model runs indicated that resuspension increased
shoreward fluxes of particulate organic matter towards the inner shelf, consistent with observations of sediment transport during storms and cold fronts (Kineke et al., 2006; Goñi et al., 2007) and sediment accretion on mudflats west of Atchafalaya Bay (Draut et al., 2005). This result, that the direction of across-shelf particulate organic matter fluxes varies, could help explain the interannual variability in the location of hypoxia observed in shallow regions west of Atchafalaya Bay (Rabalais et al., 2002).

3.4.2 Resuspension-induced changes to seabed fluxes

The primary effect in the model of resuspension on water column biogeochemistry was to increase remineralization, as described above, but cycles of erosion and deposition also impacted seabed-water column fluxes, especially in shallow areas (Figure 3.7e, g, h). In water shallower than ~30 m, resuspension enhanced remineralization and therefore ammonium concentrations in bottom waters, which increased diffusive fluxes of ammonium into the seabed and net nitrification rates (Figure 3.7d,h). Averaged over June 2006, in water depths of less than 20 m, resuspension was frequent and ammonium concentrations increased by up 10 mmol NH₄ m⁻² d⁻¹, increasing fluxes of ammonium into the seabed by up to 1 mmol NH₄ m⁻² d⁻¹ (Figure 3.7d,h). Not surprisingly, little to no effect on seabed fluxes from resuspension was estimated for regions having water deeper than ~30 m where resuspension was minimal (Figure 3.7h).

In contrast to ammonium, the effect of resuspension on seabed oxygen fluxes was more variable in space, but was also more important in shallow waters. Erosion of the surficial oxic layer of the sediments exposed the anoxic region of the seabed to oxygen, which increased the diffusive flux of oxygen from the water column into the seabed,
consistent with other studies (Glud, 2008; Toussaint et al., 2014), including a one-dimensional (vertical) version of our coupled model implemented for the Rhône Delta (Chapter 2). Compared to these previous studies, which focused on oxic environments, however, the effect of resuspension on seabed oxygen fluxes was relatively small in the coupled model for the northern Gulf of Mexico. Also, the coupled model estimated that resuspension caused seabed oxygen fluxes to decrease in some locations (Figure 3.7g). These differences from results of previous studies likely occurred because the model focused on a hypoxic time period when less oxygen was available in bottom waters to be diffused into the seabed. Remineralization of organic matter during resuspension events consumed oxygen during these time periods, further reducing the availability of O\(_2\) to diffuse into the seabed. Finally, unlike the previous studies cited above, the coupled model accounted for redistribution of resuspended seabed POC (Figure 3.7f). This redistribution of POC, in addition to the resuspension-induced depletion of oxygen in the bottom water column and the hypoxic study period, can help explain the decrease in seabed oxygen flux when resuspension is accounted for in the model (Figure 3.7g).

### 3.4.3 Implications for future studies

Accounting for resuspension-induced increases in bottom water oxygen consumption improved model estimates of seabed and near-bed processes. For example, Yu et al. (2015) showed that parameterizations used by previous Gulf of Mexico model implementations often overestimated seabed oxygen consumption, but underestimated water column oxygen consumption. For example, their model estimates of seabed oxygen consumption generally ranged from \(~30\)-50 mmol O\(_2\) m\(^{-2}\) d\(^{-1}\), while observations ranged from \(~0\)-50 mmol O\(_2\) m\(^{-2}\) d\(^{-1}\) (Yu et al., 2015b’s Figure 7 and references therein). By
implementing a more process-based representation of the seabed biogeochemistry that depended on biogeochemical rates within the seabed, as well as diffusion across the seabed water interface, the coupled model better represented the range of values observed on the shelf (Figure 3.3; Table 3.3). Additionally, the increased rates of bottom water remineralization induced by resuspension can help explain why Gulf of Mexico models that neglect cycles of erosion and deposition may underestimate oxygen consumption in the water column, leading to overestimated oxygen concentrations (Yu et al., 2015b; Laurent et al., 2016). Future work could include parameterizing the effect of resuspension on bottom water and seabed processes using proxies such as bed stress and organic content of the seabed for organic-rich shelves that experience resuspension such as the Gulf of Mexico.

Our results indicated that resuspension-induced seabed fluxes were small, i.e. they accounted for no more than a third of the total flux, and primarily affected waters shallower than 20 m (Figure 3.7g,h). In comparison, resuspension increased bottom water remineralization by up to 100% over large swaths of the shelf (Figure 3.7b). This difference implies that the effect of resuspension on oxygen and ammonium seabed fluxes may be less important than the influence of erosion and deposition on bottom water remineralization. The secondary importance of resuspension-induced changes to seabed fluxes indicates that numerical models of water column biogeochemistry in the northern Gulf of Mexico should prioritize accounting for the effect of erosion and deposition on bottom water remineralization. For example, models that simply include particulate organic matter storage in the seabed, and subsequent erosion (e.g. Capet et al., 2016) may be sufficient some time periods, especially for studies focusing on the mid-
shelf where resuspension-induced changes in seabed-water column fluxes are small. However, it may be helpful to account for resuspension-induced changes in seabed fluxes in shallow areas where resuspension has a larger effect (Figure 3.7a, g,h). Note, however, that this conclusion is limited to the timeframe of our study, i.e. summer months, when bottom water oxygen concentrations are low and likely limit seabed oxygen fluxes.

Accounting for resuspension also improved the biogeochemical module’s ability to represent POC concentrations, especially near the seabed. In all model runs considered here, and in previous studies, particulate organic matter created in surface waters or delivered via river inputs was remineralized as it sank through the water column, which created a local maxima of POC near the surface (e.g. Fennel et al., 2013; Figure 3.8). In contrast, in our model run with resuspension, particulate organic matter could also be re-entrained into the water column following deposition, which created a second local maxima of POC near the seabed (Figure 3.8). By accounting for resuspension and this additional source of particulate organic matter, the standard model run could better represent vertical profiles of POC, as presented in the comparison of model estimates to observations (Section 3.3.1). Correctly accounting for particulate organic matter dynamics in this near-bed region would be particularly important for future models focused on quantifying the role of the shelf as a sink for carbon and nitrogen (McKee et al., 2004; Hofmann et al., 2011).

Our results also underscore the importance of sampling during resuspension events for improving our understanding of bottom boundary layer and seabed processes, and their role in water column biogeochemistry, including the development and
maintenance of hypoxia. For example, resuspension and remineralization of particulate organic matter shifted the locus of oxygen consumption from the seabed to the water column in many locations, especially in shallow waters where resuspension nearly always occurred. Specifically, while seabed oxygen fluxes increased moderately during resuspension events, water column oxygen consumption increased an order of magnitude during these times (Figure 3.7), consistent with estimates for the Rhône subaqueous delta in Chapter 2. These results imply that biogeochemical observations within the bottom boundary layer and surficial sediments (e.g. Abril et al., 1999), as well as lab experiments focused on the effects of resuspension (e.g. Fanning et al., 1982; Sloth et al., 1996), may be particularly informative.

Future work should also include more consideration of how particulate organic matter remineralization and settling velocities are determined in numerical models, as well as the observations to support that model development. A continuing challenge is the question of how to relate particulate organic matter composition and environmental conditions to the remineralization rate constants required by biogeochemical models. Incubation experiments, which observe rates of change of particulate organic matter concentration in laboratory settings, may offer an alternative approach for measuring this constant (e.g. Fry et al., 2015). Similarly, estimating hydrodynamic properties of particulate organic matter, e.g. settling velocity and critical shear stress, remains challenging, but utilizing acoustic measurements to estimate the settling velocity of particles and erodibility experiments to estimate the critical shear stress may offer alternative approaches (e.g. Friedrichs et al., 2008; Schaaff et al., 2006; Fall et al., 2014). However, remineralization rate constants and hydrodynamic sediment properties have a
large effects on model estimates both in our study (Figure 3.6) and previous work in various settings (Cerco et al., 2013; Laurent et al., 2016; Liu et al., 2007). In our model sensitivity tests, the factor of 5 changes in settling velocity and remineralization rate constant resulted in about a factor of 2 change in net remineralization rates, although changes to oxygen and ammonium levels were smaller (Figure 3.6). Future work that evaluates methods of parameterizing remineralization and particle settling would be helpful for further constraining model results.

Implementing coupled hydrodynamic-sediment transport-biogeochemical models for different environmental settings would also be useful for better understanding how the resuspension affects biogeochemical dynamics in other systems. Oxygen concentrations on the northeast Atlantic shelf, for example, have been shown to vary with particulate organic matter supply (Lampitt et al., 1995). Additionally, resuspension on the shoals of Chesapeake Bay is believed to increase light attenuation and enhance delivery of organic matter to the channel, fueling hypoxia (Cerco and Noel, 2013), but the magnitude, timing, and impact of these fluxes is not well understood. Implementation of the coupled model for other shelves, as well as estuaries, would improve our understanding of how resuspension affects biogeochemical processes in different kinds of systems.

3.5 Conclusions

The role of resuspension on bottom water oxygen and nitrogen dynamics was investigated using a coupled hydrodynamic-sediment transport-biogeochemical model for the northern Gulf of Mexico. Although resuspension altered seabed fluxes, as well as rates of nitrification and oxidation of other reduced chemical species, increased net
remineralization was the primary driver of increased oxygen consumption and ammonium production during resuspension events. Specifically, resuspension entrained particulate organic matter from the seafloor into the water column, and model results indicated that this increased remineralization rates in the bottom water column from near \(-0.5\) to up to \(-15\) mmol C m\(^{-3}\). During individual resuspension events, oxygen consumption and ammonium production increased by up to a factor of 30 when results were averaged over the shelf for water depths of 0 – 50 m. When averaged over two months, resuspension increased oxygen consumption and ammonium production by a factor of \(-2.5\). Overall, entrainment of particulate organic matter into the water column and its subsequent remineralization were sufficient to shift the locus of oxygen consumption from the seabed to the bottom boundary layer.

The effect of resuspension on bottom water oxygen and nitrogen dynamics varied in time and space, responding to across-shelf variations in the frequency of resuspension and vertical mixing, and along-shelf variations in stratification. The largest effects of resuspension on biogeochemical rates were estimated to occur in water depths up to about 20 m where resuspension was frequent and particulate organic matter was vertically well mixed. Additionally, larger resuspension-induced changes in rates of oxygen consumption and ammonium production were estimated to occur in the western region of the shelf, i.e. west of Atchafalaya Bay, where stratification was less persistent and in convergence zones where more particulate organic matter accumulated in the seabed and bottom boundary layer, compared to other regions.

Resuspension-induced increases in net remineralization rate enlarged the modeled hypoxic area, with the largest expansion estimated for the region offshore of and west of
Atchafalaya Bay. Without resuspension, hypoxic area in the model decreased by over 70% in June and July 2006. Moreover, resuspension caused the region of hypoxic area to shift landward and persist for a longer time period. This result underscores the sensitivity of water column biogeochemistry, including hypoxia, to seabed and bottom boundary layer processes.

Acknowledgements for Chapter 3

Dr. Arnaud Laurent (Dalhousie University) provided model code for the light attenuation parameterization in ROMS. Justin Birchler (now at U.S. Geological Survey) and Dr. Tara Kniskern (VIMS) provided information for river and wave forcing. Discussions with Robert Hetland (Texas A&M University) improved the model analysis. Computational support was provided by Dave Forrest, Adam Miller (VIMS), and the College of William & Mary (W&M)’s HPC team. W&M computational facilities were supported by the National Science Foundation, Commonwealth of Virginia Equipment Trust Fund, and Office of Naval Research. The U.S. National Oceanic and Atmospheric Administration Center for Sponsored Coastal Ocean Research (NA09NOS4780229, NA09NOS4780231) and the VIMS graduate program provided funding.
References for Chapter 3


Justić, D., Wang, L., 2014. Assessing temporal and spatial variability of hypoxia over the inner Louisiana-upper Texas shelf: Application of an unstructured-grid three-
dimensional coupled hydrodynamic-water quality model. Cont. Shelf Res. 72, 163–179. doi:10.1016/j.csr.2013.08.006


### Tables for Chapter 3

#### Table 3.1: Model forcing and parameters for the standard model run

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Modeled Value</th>
<th>Source for Observed/Literature Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model Forcing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wave Forcing (Height, Period, Direction)</td>
<td>Time-series of model estimates</td>
<td>NOAA’s WaveWatch III model (Tolman et al., 2002)</td>
</tr>
<tr>
<td>Atmospheric Forcing (Winds, Temperature, etc.)</td>
<td>Wind: NARR Model Atmospheric Forcing: climatological surface heat and freshwater fluxes</td>
<td>Wind: Fennel et al. (2013) Atmospheric Forcing: from da Silva et al. (1994a, b), as described by Fennel et al. (2013)</td>
</tr>
<tr>
<td>Hydrodynamic Data for nudging at Open Boundaries</td>
<td>Horizontally uniform climatology of vertical profiles for temperature and salinity; Sediment concentrations assumed to equal zero.</td>
<td>Boyer et al. (2006) as described by Yu et al. (2015b)</td>
</tr>
<tr>
<td>Nudging Timescale for Velocity (Depth-averaged &amp; Depth-varying), Free-surface, Salinity, Temperature, Sediment, and Biogeochemical Tracers</td>
<td>10 days (outgoing) 1 (incoming)</td>
<td>Fennel et al. (2013)</td>
</tr>
<tr>
<td>Model Timestep</td>
<td>15 seconds</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Hydrodynamic &amp; Sediment Transport Parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical Stretching Parameters</td>
<td>θs = 5  θb=0.7  Tcline = 5</td>
<td>Fennel et al. (2013)</td>
</tr>
<tr>
<td>Partitioning of Sediment into Classes</td>
<td>MI River Small Flocs: 50% Large Flocs: 50%</td>
<td>Xu et al. (2011)</td>
</tr>
<tr>
<td></td>
<td>Atchafalaya River Small Flocs: 90% Large Flocs: 10%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Seabed Large Flocs: spatially variable Sand: spatially variable</td>
<td></td>
</tr>
<tr>
<td>Settling Velocity</td>
<td>MI River Small Flocs: 0.1 mm s(^{-1}) Large Flocs: 1.0 mm s(^{-1})</td>
<td>Xu et al. (2015)</td>
</tr>
<tr>
<td></td>
<td>Atchafalaya River Small Flocs: 0.1 mm s(^{-1}) Large Flocs: 1.0 mm s(^{-1})</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Seabed Large Flocs: 0.1 mm s(^{-1}) Sand: 1.0 mm s(^{-1})</td>
<td></td>
</tr>
<tr>
<td>Critical Bed Shear Stress for Erosion</td>
<td>MI River</td>
<td>Small Flocs: 0.11 Pa</td>
</tr>
<tr>
<td>--------------------------------------</td>
<td>----------</td>
<td>----------------------</td>
</tr>
<tr>
<td>Atchafalaya River</td>
<td>Small Flocs: 0.03 Pa</td>
<td>Large Flocs: 0.03 Pa</td>
</tr>
<tr>
<td>Seabed</td>
<td>Large Flocs: 0.11 Pa</td>
<td>Sand: 0.13 Pa</td>
</tr>
<tr>
<td>Erosion Rate Parameter</td>
<td>$3 \times 10^{-4}$ kg m$^{-2}$ s$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>Porosity</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Sediment Density</td>
<td>2650 kg m$^{-3}$</td>
<td></td>
</tr>
</tbody>
</table>

| Shortwave Radiation Parameterization | | | | Fennel et al. (2016) |

### Biogeochemical Parameters

#### Water Column Rates

<p>| Light attenuation due to: | Seawater | Chlorophyll | | Fennel et al. (2006, 2013) |
|--------------------------|----------|-------------||--------------------------|
| Chlorophyll attenuation | 0.04 l/m | 0.02486 l/(mg Chl m2) | | Fennel et al. (2006; 2013) |
| Fraction of shortwave radiation that is photosynthetically active | 0.43 | | | Fennel et al. (2006; 2013) |
| Radiation threshold for nitrification inhibition | 0.0095 Watts/m$^2$ | | | Fennel et al. (2006; 2013) |
| Half-saturation coefficient of radiation for nitrification | 0.1 Watts/m$^2$ | | | Fennel et al. (2006; 2013) |
| Maximum nitrification rate | 0.05 d$^{-1}$ | | | Fennel et al. (2006; 2013) |
| Temperature-limited phytoplankton growth parameter | 0.59 | | | Fennel et al. (2006; 2013) |
| Inverse half-saturation coefficient for NH4 uptake by phytoplankton | 2.0 d$^{-1}$ | | | Fennel et al. (2011, 2013) |
| Zooplankton half-saturation constant for ingestion | 2.0 d$^{-1}$ | | | Fennel et al. (2011; 2013) |
| Maximum chlorophyll to carbon ratio | 0.0535 mg Chl (mg C)$^{-1}$ | | | Fennel et al. (2006; 2013) |
| Chlorophyll minimum threshold value | 0.001 mg Chl m$^{-3}$ | | | Fennel et al. (2006; 2013) |
| Phytoplankton Carbon: Nitrogen ratio | 6.625 mol C (mol N)$^{-1}$ | | | Redfield ratio; Fennel et al. (2006, 2013) |
| Initial slope of Photosynthesis-Irradiance curve | 0.025 mg C (mg Chl Watts m$^{-2}$ day)$^{-1}$ | | | Fennel et al. (2011; 2013) |
| Phytoplankton minimum threshold value | 0.001 mmol N m$^{-3}$ | | | Fennel (pers. comm.) |
| Phytoplankton mortality rate | 0.15 d$^{-1}$ | | | Fennel et al. (2011; 2013) |
| Nitrogen assimilation efficiency for zooplankton | 0.75 | | | Fennel et al. (2006; 2013) |
| Zooplankton basal metabolism | 0.1 d$^{-1}$ | | | Fennel et al. (2006; 2013) |
| Zooplankton Carbon: Nitrogen ratio | 6.625 mol C (mol N)$^{-1}$ | | | Redfield ratio; Fennel et al. (2006, 2013) |
| Zooplankton specific excretion rate | 0.1 d$^{-1}$ | | | Fennel et al. (2006; 2013) |
| Zooplankton maximum growth rate | 0.6 d$^{-1}$ | | | Fennel et al. (2006; 2013) |
| Zooplankton minimum threshold value | 0.001 mmol N m$^{-3}$ | | | Fennel (pers. comm.) |</p>
<table>
<thead>
<tr>
<th><strong>Zooplankton mortality rate</strong></th>
<th>0.025 d⁻¹</th>
<th>Fennel et al. (2006; 2013)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coagulation rate of</strong></td>
<td>0.005 (mmol N m⁻³)⁻¹ d⁻¹</td>
<td>Fennel et al. (2006; 2013)</td>
</tr>
<tr>
<td>phytoplankton and small</td>
<td></td>
<td></td>
</tr>
<tr>
<td>detritus</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Organic matter</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>remineralization rates</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small Detritus</td>
<td>0.3 d⁻¹</td>
<td>Yu et al. (2015b), Fry et al. (2015), Devereux et al. (2015), Wainright and Hopkinson (1997) and references therein</td>
</tr>
<tr>
<td>Large Detritus</td>
<td>0.1 d⁻¹</td>
<td></td>
</tr>
<tr>
<td>Labile Aggregates</td>
<td>0.1 d⁻¹</td>
<td></td>
</tr>
<tr>
<td>Refractory Aggregates</td>
<td>0.1 d⁻¹</td>
<td></td>
</tr>
<tr>
<td><strong>Settling (sinking) velocity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phytoplankton</td>
<td>0.1 m d⁻¹</td>
<td>Fennel et al. (2006; 2013)</td>
</tr>
<tr>
<td>Small Detritus</td>
<td>0.1 m d⁻¹</td>
<td>Fennel et al. (2006; 2013)</td>
</tr>
<tr>
<td>Large Detritus</td>
<td>1.0 m d⁻¹</td>
<td>Fennel et al. (2006; 2013)</td>
</tr>
<tr>
<td>Labile Aggregates</td>
<td>8.64 m d⁻¹ (0.0001 m s⁻¹)</td>
<td>Wakeham et al. (2009)</td>
</tr>
<tr>
<td>Refractory Aggregates</td>
<td>8.64 m d⁻¹ (0.0001 m s⁻¹)</td>
<td>Wakeham et al. (2009)</td>
</tr>
<tr>
<td><strong>Critical Bed Shear Stress</strong></td>
<td>0.11 Pa</td>
<td>No data, assumed to be similar to seabed flocs</td>
</tr>
<tr>
<td>of Particulate Organic Matter</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Erosion Rate Parameter</strong></td>
<td>3 × 10⁻³ kg/m²/s</td>
<td>No data, assumed to be similar to seabed flocs</td>
</tr>
<tr>
<td>for Particulate Organic Matter</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Partitioning of particulate</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>organic matter in river input</td>
<td>16 % small detritus</td>
<td>Fry et al. (2015) - 16% is labile</td>
</tr>
<tr>
<td></td>
<td>84 % refractory aggregates</td>
<td>Laurent et al. (2016) – 74% of deposited OC is labile (original and optimized value)</td>
</tr>
</tbody>
</table>

### Seabed Rates

<table>
<thead>
<tr>
<th><strong>Base Remineralization rates of Seabed Organic Matter</strong></th>
<th>Labile Organic Matter</th>
<th>0.1 d⁻¹</th>
<th>Laurent et al. (2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Refractory Organic Matter</td>
<td>5.8 × 10⁻³ d⁻¹</td>
<td>Laurent et al. (2016)</td>
</tr>
<tr>
<td><strong>Coefficients for Q₁₀</strong></td>
<td>Base temperature</td>
<td>30 °C</td>
<td>Laurent et al. (2016)</td>
</tr>
<tr>
<td>temperature - remineralization relationship</td>
<td>Q₁₀ parameter</td>
<td>3</td>
<td>Laurent et al. (2016)</td>
</tr>
<tr>
<td></td>
<td>Labile</td>
<td>0.15</td>
<td>Laurent et al. (2016)</td>
</tr>
<tr>
<td></td>
<td>Refractory</td>
<td>0.1</td>
<td>Laurent et al. (2016)</td>
</tr>
<tr>
<td><strong>Half saturation constant for O₂</strong></td>
<td>20 µmol O₂ L⁻¹</td>
<td>Laurent et al. (2016)</td>
<td></td>
</tr>
<tr>
<td>limitation in oxic respiration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Half saturation constant for NO₃</strong></td>
<td>1 µmol NO₃ L⁻¹</td>
<td>Laurent et al. (2016)</td>
<td></td>
</tr>
<tr>
<td>limitation in denitrification</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Half saturation constant for O₂</strong></td>
<td>0.1 µmol O₂ L⁻¹</td>
<td>Laurent et al. (2016)</td>
<td></td>
</tr>
</tbody>
</table>
| Limitation in nitrification | Half saturation constant for O2 limitation in oxidation of ODUs | Half saturation constant for O2 inhibition in denitrification | Half saturation constant for O2 inhibition in anoxic mineralization | Half saturation constant for NO3 inhibition in anoxic mineralization | Maximum nitrification rate | Maximum oxidation rate of oxygen demand units | Fraction of ODUs produced in the seabed that are solid and inert | Base biodiffusion coefficients
<table>
<thead>
<tr>
<th>Sediment and Particulate Organic Matter</th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>O2</td>
<td>2.785e-11 m^2 s^-1</td>
<td>0 m^2 s^-1</td>
</tr>
<tr>
<td>NO3</td>
<td>9.78e-10 m^2 s^-1</td>
<td>9.803e-10 m^2 s^-1</td>
</tr>
<tr>
<td>NH4</td>
<td>9.745e-11 m^2 s^-1</td>
<td>9.745e-11 m^2 s^-1</td>
</tr>
<tr>
<td>ODU</td>
<td>9.745e-11 m^2 s^-1</td>
<td>9.745e-11 m^2 s^-1</td>
</tr>
<tr>
<td>Coefficients for Q10 temperature – biodiffusion relationship (for particulates)</td>
<td>Base temperature</td>
<td>Q10 parameter</td>
</tr>
<tr>
<td>------------------------------------------</td>
<td>----------------</td>
<td>-----</td>
</tr>
<tr>
<td>O2</td>
<td>30°C</td>
<td>2</td>
</tr>
<tr>
<td>NO3</td>
<td>3.507e-11 m^2 s^-1</td>
<td>3.507e-11 m^2 s^-1</td>
</tr>
<tr>
<td>NH4</td>
<td>3.889e-11 m^2 s^-1</td>
<td>3.889e-11 m^2 s^-1</td>
</tr>
<tr>
<td>ODU</td>
<td>2.801e-11 m^2 s^-1</td>
<td>2.801e-11 m^2 s^-1</td>
</tr>
<tr>
<td>Bioturbation Depth into seabed</td>
<td>Maximum biodiffusion coefficient is used</td>
<td>Minimum biodiffusion coefficient is used</td>
</tr>
<tr>
<td>------------------------------------------</td>
<td>----------------</td>
<td>-----</td>
</tr>
<tr>
<td></td>
<td>0-1 cm deep</td>
<td>Over 3 cm deep</td>
</tr>
<tr>
<td></td>
<td>Laurent et al. (2016)</td>
<td>Laurent et al. (2016)</td>
</tr>
<tr>
<td>Biodiffusion coefficient linearly interpolated from maximum to minimum value</td>
<td>1-3 cm deep</td>
<td>Laurent et al. (2016)</td>
</tr>
</tbody>
</table>
### Table 3.2: Model runs

<table>
<thead>
<tr>
<th>Name of Model Run (Abbreviation)</th>
<th>Change Compared to the Standard Model Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard (ST)</td>
<td>N/A</td>
</tr>
<tr>
<td>No-resuspension (NR)</td>
<td>Resuspension was prevented from occurring by changing the erosion rate parameter to zero and the critical shear stress for erosion to 10 Pa for both sediment and particulate organic matter</td>
</tr>
<tr>
<td>Fast-settling (FS)</td>
<td>Increased settling velocities of sediment, organic aggregates, and large detritus by 50%</td>
</tr>
<tr>
<td>Slow-settling (SS)</td>
<td>Decreased settling velocities of sediment, organic aggregates, and large detritus by 50%</td>
</tr>
<tr>
<td>Fast-remineralization (FR)</td>
<td>Increased remineralization rate constants of large detritus, organic aggregates and labile seabed organic matter by 50%</td>
</tr>
<tr>
<td>Slow-remineralization (SR)</td>
<td>Decreased remineralization rate constants of large detritus, organic aggregates and labile seabed organic matter by 50%</td>
</tr>
</tbody>
</table>
Table 3.3: Statistics for model-observation comparison

Statistics for model-observation comparison. Fluxes are positive for values that are out of the seabed.

<table>
<thead>
<tr>
<th></th>
<th>Standard Model</th>
<th></th>
<th>Observation</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean +/- Standard Deviation</td>
<td>Range</td>
<td>Range</td>
<td></td>
</tr>
<tr>
<td><strong>Bottom Water POC</strong> (mmol m⁻³)</td>
<td>123 ± 349</td>
<td>0 – 18,822</td>
<td>0 - 225</td>
<td>Fry et al. (2015)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0-417</td>
<td>Goñi et al. (2006)</td>
</tr>
<tr>
<td><strong>Seabed-Water Column O₂ Flux</strong> (mmol m⁻² d⁻¹)</td>
<td>-4.40 ± 3.70</td>
<td>-40.4 – 3.79</td>
<td>~ -25 - 0</td>
<td>Lehrter et al. (2012)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-14.05 – 0</td>
<td>Devereux et al. (2015)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-56.4 – -0.82</td>
<td>Rowe et al. (2002)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-43.3 – -9.94</td>
<td>McCarthy et al. (2013)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-23.3 – -1.3</td>
<td>Murrell and Lehrter (2011)</td>
</tr>
<tr>
<td><strong>Seabed-Water Column NH₄ Flux</strong> (mmol m⁻² d⁻¹)</td>
<td>-0.60 ± 0.72</td>
<td>-9.90 – 1.96</td>
<td>-0.17 – 3.84</td>
<td>Lehrter et al. (2012)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-4.4 – -0.8</td>
<td>Rowe et al. (2002)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-0.11 – 4.92</td>
<td>McCarthy et al. (2015)</td>
</tr>
<tr>
<td><strong>Seabed-Water Column NO₃ Flux</strong> (mmol m⁻² d⁻¹)</td>
<td>1.05 ± 1.37</td>
<td>-8.73 – 20.2</td>
<td>-1.01 – 1.03</td>
<td>Lehrter et al. (2012)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.1 – 2</td>
<td>Rowe et al. (2002)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-3.58 – 0.75</td>
<td>McCarthy et al. (2015)</td>
</tr>
<tr>
<td><strong>Bottom water oxygen respiration</strong> (mmol m⁻³ d⁻¹)</td>
<td>6.14 ± 14.9</td>
<td>0 - 955</td>
<td>3.84-106</td>
<td>McCarthy et al. (2013)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.4 – 14.0</td>
<td>Murrell and Lehrter (2011)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>~0 – 46.6</td>
<td>Murrell et al. (2013)</td>
</tr>
</tbody>
</table>
Figure 3.1: Study site

Study site maps showing (a) location within the Gulf of Mexico, (b) model grid, and (c) regions considered in the Discussion. In (b), grid lines show every 5 grid cells. Atchafalaya Bay and the Mississippi River Delta are denoted by “AB” and “MRD”, respectively. In (c), yellow shading indicates the “shelf region”. Black lines in (b) and (c) are bathymetric contours for every 20 m. The red and black line indicates the location of the transect in Figure 3.8.
Figure 3.2: Time-series of model forcing

Time-series of model forcing, including (a) the combined water discharge of the Mississippi and Atchafalaya Rivers; (b) wind speed (blue line; left axis) and direction (red dots; right axis) toward which winds are blowing (in degrees clockwise from east); and (c) significant wave height; and (d) air temperature (blue solid line) and depth-averaged temperature at the open boundary (red dashed line). Wind and wave data were provided for a location on the mid-shelf at 20 m water depth. Shading indicates the time period on which this paper focuses, i.e. June and July 2006. Data sources are listed in Table 3.1.
Seabed oxygen consumption (SOC), i.e. seabed-water column fluxes, versus oxygen concentration. (a) Scatter plot of field experiments after Yu et al. (2015b). Colors indicate different sources of estimates. Shaded region and blue and red lines indicate estimates of seabed oxygen consumption based on parameterizations used in Yu et al. (2015b). (b) Histogram of estimates from the coupled numerical model. Estimates of bottom water oxygen concentration were from the bottom grid cells in the model. Colors indicate the frequency of estimates that fell within the indicated level of bottom water oxygen (x-axis) and seabed oxygen consumption (y-axis). Black line indicates the maximum estimate of seabed oxygen consumption for a given bottom water oxygen concentration.
Figure 3.4: Time-series of model estimates for June 2006

Time-series of (a) bed stress, bottom water concentrations of (b) POC, (c) O$_2$, and (d) NH$_4$, and bottom water remineralization rate for June 1-30, 2006. Model estimates were shown for the bottom grid cell of the model from the shelf region for both the standard (grey and black lines) and no-resuspension (red line) model runs. Shaded areas indicate the 5th-95th percentiles of estimates; the dark lines indicate the median values.
Figure 3.5: Time-series of model estimates for July 2006

Same as Figure 3.4, but for July 1-31, 2006.
Figure 3.6: Box and whisker charts of model estimates for different sensitivity tests

Box and whisker charts of estimated (a) remineralization rate, (b) O2 concentration, and (c) NH4 concentration in the bottom grid cell of the model. Red lines indicate the median value; red dots indicates the mean value for each model run. For each plot, estimates are provided for the standard (ST), no-resuspension (NR), fast-settling (FS), slow-settling (SS), fast-remineralization (FR), and slow-remineralization (SR) model runs (see Table 3.2). All estimates were averaged over June 2006 and the shelf region.
Figure 3.7: Maps of estimates from the standard model run, and the difference between the standard and no-resuspension model runs

Maps of estimates from the standard model run (left column) and the difference between the standard and no-resuspension model runs (right column), averaged over June 1-30, 2006. Estimates are given for (a) frequency of resuspension (fraction of time bed stress exceeded 0.1 Pa); bottom water (b) remineralization rate (Remin. R; mmol O$_2$ m$^{-3}$ d$^{-1}$), (c) O$_2$ and (d) NH$_4$ concentration (mmol m$^{-3}$); (e) nitrification rate (Nitri R; mmol O$_2$ m$^{-3}$ d$^{-1}$); and (f) POC concentration (mmol m$^{-3}$); and seabed-water column (S-W) fluxes (Fl.) of (g) O$_2$ and (h) NH$_4$ (mmol m$^{-2}$ d$^{-1}$). Legends for the colored shading is given by the scale bars in the bottom right of each plot.
Figure 3.8: Estimates from the standard model run for a transect westward of Atchafalaya Bay

Estimates from the standard model run for a transect west of Atchafalaya Bay (location given in Figure 3.1). Left, center and right columns show POC concentrations (mmol C m$^{-3}$); rate of oxygen consumption (mmol O$_2$ m$^{-3}$ d$^{-1}$); and oxygen concentrations (mmol O$_2$ m$^{-3}$). Each row of panels represents a time before (June 12), during (June 18-19), or after (June 22, July 2) the June resuspension event.
Chapter 4

4. The Impact of Seabed Resuspension on Primary Productivity and Remineralization: A Numerical Modeling Study of the Chesapeake Bay
**Key Points for Chapter 4**

1. A coupled hydrodynamic-sediment transport-biogeochemistry model was implemented for the Chesapeake Bay to evaluate the effect of resuspension of sediment and particulate organic matter on oxygen and nitrogen dynamics.

2. Resuspension of sediment and organic matter increased light attenuation, reducing primary productivity in the surface waters of the Upper Bay, where total suspended solid concentrations were highest.

3. Remineralization of resuspended organic matter increased oxygen consumption and ammonium production, especially in the Mid-to Lower-Bay where particulate organic matter accumulated.

4. The overall effects of resuspension, including both increased remineralization and reduced primary productivity, combined to increase ammonium concentrations and decrease oxygen concentrations throughout Chesapeake Bay.

**Abstract for Chapter 4**

Sediment processes including resuspension and subsequent redistribution of particles may affect water quality in large estuaries like the Chesapeake Bay by altering light attenuation and organic matter remineralization. The degree to which these processes affect biogeochemical dynamics varies in response to riverine inputs, degree of stratification, and other factors; thus, it can be difficult to isolate the role of individual processes. This difficulty motivated the implementation of a coupled hydrodynamic-sediment transport-biogeochemical model for Chesapeake Bay to evaluate the impact of resuspension on oxygen and nitrogen dynamics. Results show that resuspension increased
light attenuation, thereby decreasing surface-water primary productivity by up to ~70% in
the main channel of the Upper Bay over the timescale of a month. Entrainment of seabed
organic matter into the water column also increased remineralization rates near the
seabed by more than a factor of two. Averaged over timescales ranging from a day to a
month, the resuspension-induced increase in near-bed remineralization and reduction in
surface-water primary productivity decreased oxygen concentrations. Similarly, the
reduced nutrient uptake by phytoplankton and the enhancement in remineralization both
increased ammonium concentrations. Overall, the effect of resuspension on bottom water
oxygen and ammonium concentrations was greatest in the Mid- to Lower- Bay where
organic matter accumulated and in the Upper Bay where turbidity limited primary
production.

4.1. Introduction

Seabed and sediment processes can modulate biogeochemistry and impact water
quality issues such as low oxygen concentrations in coastal systems. In many estuaries,
for example, growth of phytoplankton and vegetation is limited by high concentrations of
suspended particles that attenuate light within the water column (Cloern, 1987; Xu et al.,
2005). Water column biogeochemistry can also be modified by fluxes of oxygen,
nutrients and organic matter between the seabed and overlying water (McKee et al.,
2004). Quantifying the above processes can be important for understanding variations in
biogeochemical dynamics and water quality (Kemp et al., 2009; Artioli et al., 2008).

Resuspension can be a dominant control on the seabed and sediment processes
that affect water column biogeochemistry in coastal systems. By definition, resuspension
entrains inorganic particulates and organic matter into the water column, increasing
turbidity and light attenuation (e.g. Shi et al., 2013). Temporary transference of material from the seabed to the water column may also enhance remineralization rates due to the increased organic matter concentrations in bottom waters as well as the exposure of that organic matter to an oxic water column (Aller, 1998; Hartnett et al., 1998). Fluxes of dissolved oxygen and nutrients through the seabed-water interface may also be affected by resuspension (e.g. Toussaint et al., 2014; Glud, 2008). Finally, once particulates and porewater are entrained into the water column, they may be redistributed around the system, altering spatial and temporal gradients in biogeochemical processes (e.g. Chapter 2; Lampitt et al., 1995; Goñi et al., 2007; Christiansen et al., 1997; Abril et al., 1999).

Field and laboratory approaches, however, are often constrained by technology and cost, and have limited spatial or temporal coverage. It is often especially difficult to observe processes during storms, when seabed resuspension may increase substantially. This can make the relative magnitude of the impact of these various processes on water column and seabed biogeochemistry difficult to quantify, motivating a numerical modeling approach.

Recent developments in numerical modeling have made investigations into the impact of resuspension on water column biogeochemistry feasible and timely. In the last decade, open-source hydrodynamic models have been coupled to both sediment transport and water column biogeochemistry modules (e.g. Warner et al., 2008; Fennel et al., 2006). Recent studies have also begun to link sediment and biogeochemical processes in coupled models by accounting for subsets of the set of processes described above (e.g. McSweeney et al., 2016; Capet et al., 2016; Feng et al., 2015; Testa et al., 2014). The development of HydroBioSed, which uses a novel approach to couple sediment transport
and biogeochemical processes, however, allows for the effect of resuspension on light attenuation, remineralization, and seabed fluxes to be analyzed for different coastal systems. HydroBioSed was previously implemented for the Rhône River subaqueous delta (Chapter 2) and the northern Gulf of Mexico shelf (Chapter 3). These past implementations of HydroBioSed did not account for resuspension-induced effects on light attenuation, and both targeted river-influenced continental shelves rather than an estuarine system. In contrast, this chapter focuses on quantifying the role of resuspension on light attenuation, remineralization, and oxygen and nitrogen dynamics in a single estuary, the Chesapeake Bay.

4.1.1 The role of resuspension on biogeochemical processes in Chesapeake Bay

Chesapeake Bay, the largest estuary in the United States, receives seasonally varying inputs of freshwater, sediment and nutrients and is characterized by a deep channel and broad shoals (Figure 4.1). Springtime delivery of nutrients stimulates primary productivity by phytoplankton, especially in the Mid- to Lower- Bay, i.e. the meso- to poly-haline regions (e.g. Malone et al., 1996). This phytoplankton growth is enhanced by both nutrients and light availability, i.e. it is both nutrient- and light-limited, despite eutrophication of the Bay in recent decades (Harding et al., 2002 and references therein). The seasonal enhancement in production and eventual decomposition of organic matter, combined with stratification over the main channel that is induced by the large springtime input of freshwater, causes low oxygen levels and high ammonium concentrations to occur in the channel of the Chesapeake Bay during summer months, especially in the mesohaline region (Kemp et al., 2005). In contrast, the shoals are generally vertically mixed. As a result, hypoxia is typically constrained to the main
channel, although the volume of low-oxygen water varies depending on stratification and circulation, e.g. due to wind, as well as changes in oxygen consumption, e.g. due to variations in nutrient and organic matter availability (Scully, 2010; Murphy et al., 2011; Testa and Kemp, 2012).

Previous observational studies indicate that the biogeochemistry of Chesapeake Bay and its tributaries may be affected by seabed and sediment processes. On timescales of years to decades, observations in the York River estuary, a tributary to the Chesapeake Bay, show that resuspension enhances remineralization rates and reduces accumulation of organic matter in the seabed (Arzayus and Canuel, 2004). Other studies have shown an increase in ammonium levels and hypoxic volume over the last few decades, which has been linked to an increase in both westerly winds (Scully, 2010) and accumulation of organic matter in the seabed (Testa and Kemp, 2012). On daily to seasonal timescales, observations have indicated that primary productivity is limited by light attenuation in the water column, especially in the oligohaline Upper Bay (Harding et al., 2002). Finally, observations show that resuspension facilitates the maintenance of the estuarine turbidity maximum (ETM) in the Upper Bay, and redistribution of seabed particulates from the shoals to other regions (Sanford, 1994; Sanford et al., 2001); although these studies focus on inorganic sediments, they likely also affect particulate organic matter (POM).

Together, these studies indicate that resuspension may affect remineralization rates, phytoplankton growth, as well as nutrient and oxygen levels, in Chesapeake Bay.

Seabed and sediment transport processes, including resuspension, have also been invoked to explain differences between observations and modeling results within Chesapeake Bay, further motivating analysis of the extent to which these processes affect
water column biogeochemistry. For example, Cerco et al. (2013) suggested that transport of particulate organic matter from the shoals to the channel may help explain why their model overestimated oxygen concentrations in the channel. Xu and Hood (2006) similarly suggested that underestimating this lateral transport, or underestimating light attenuation due to resuspended sediments, may be responsible for their overestimation of chlorophyll on the Bay’s shoals. Finally, Li et al. (2015) indicated that changes in primary productivity by phytoplankton had a large effect on the volume of hypoxic water that developed in their model. Primary productivity is limited by light attenuation in much of the Bay (Harding et al., 2002), and so Li et al. (2015)’s result implies that accurately representing particulate concentrations is important for quantifying oxygen cycling in Chesapeake Bay. Although the above studies hypothesize that seabed and sediment processes can affect the representation of water column biogeochemistry in models, they rely on parameterizations of these processes. This motivated the implementation of a coupled hydrodynamic-sediment transport-biogeochemical model to evaluate the role of resuspension on oxygen and nitrogen dynamics in Chesapeake Bay.

4.1.2 Objective

In summary, seabed and sediment transport processes, including resuspension, may be important for understanding variations in water column biogeochemistry in Chesapeake Bay and other coastal systems. Spatial and temporal variability in these processes, and how they affect water column biogeochemistry, have remained difficult to quantify, however, motivating this study. Specific research questions focus on the uncertainty of modeled water column biogeochemistry to resuspension, and include:
1. How does resuspension affect primary productivity and remineralization on the timescale of days to a month, and how do the resulting changes in these biogeochemical processes affect concentrations of oxygen and ammonium?

2. How does the biogeochemical response to resuspension vary spatially, depending on factors including proximity to tributaries and turbidity?

These research questions will be investigated using a coupled hydrodynamic-sediment transport-biogeochemical model, as described below.

4.2. Methods

4.2.1. Standard Model Formulation and Implementation

Model formulations were built on HydroBioSed, the coupled hydrodynamic-sediment transport-biogeochemical model described in Chapters 2 and 3. The coupled model was developed within the Regional Ocean Modeling System (ROMS) framework (Haidvogel et al., 2000, 2008; Shchepetkin, 2003; Shchepetkin and McWilliams, 2005), which had previously been coupled to modules for sediment transport (Warner et al., 2008) and water column biogeochemistry (e.g. Feng et al., 2015). As with previous versions of HydroBioSed, the coupled model accounts for the advection of water, sediment and biogeochemical tracers; the sinking and deposition of sediment and organic matter to the seabed; subsequent resuspension or storage of sediment and organic matter in the seabed; remineralization of organic matter and oxidation of reduced chemical species in both the water column and seabed; and diffusion of dissolved chemical species across the seabed-water interface.
Model formulations for HydroBioSed were detailed in Chapters 2 and 3, but equations for erosion and deposition are also summarized here. As in Warner et al. (2008), the model accounts for multiple sediment classes, denoted using the index \( ised \), and net fluxes of particulates across the seabed-water interface were estimated as the difference between erosion and deposition, which occur simultaneously. Rates of deposition, \( D_{ised} \), and erosion, \( E_{ised} \), for each sediment class \( ised \), were calculated as follows:

\[
D_{ised} = -\frac{\partial (w_s ised C_{ized,z=1})}{\partial z_{w1}} \quad (4.1)
\]

\[
E_{ised} = M (1 - \Phi) f_{ised} \left( \frac{\tau_{bed} - \tau_{crit,ised}}{\tau_{crit,ised}} \right) \quad \text{when} \ \tau_{bed} \geq \tau_{crit,ised} \quad (4.2)
\]

\[
= 0 \quad \text{when} \ \tau_{bed} < \tau_{crit,ised}
\]

Note that erosion may only occur in the model when the bed shear stress, \( \tau_{bed} \) (Pa), exceeds the critical shear stress, \( \tau_{crit,ised} \) (Pa). The formulations above depend on the settling velocity of the sediment class, \( w_{s,ised} \) (m s\(^{-1}\)); concentration of sediment class \( ised \) in the bottom grid cell of the model, \( C_{ized,z=1} \) (kg m\(^{-2}\)); the erosion rate parameter, \( M \) (kg m\(^{-2}\) s\(^{-1}\)); seabed porosity, \( \phi \) (non-dimensional); and the fraction of the seabed composed of sediment class \( ised \), \( f_{ised} \) (non-dimensional). As in previous versions of HydroBioSed, particulate organic matter is deposited in the same manner as inorganic particles, and is eroded with the sediment classes representing mud.

HydroBioSed has previously been coupled to the Fennel et al. (2006, 2013) water column biogeochemistry module, but was re-coupled to the similar Estuarine-Carbon-Biogeochemistry (ECB) water column biogeochemistry module for application to Chesapeake Bay. The ECB model was chosen because it was specifically developed for estuaries, and had previously been implemented within ROMS for the Chesapeake Bay
(Feng et al., 2015; Irby et al., 2016). Note that HydroBioSed includes a seabed biogeochemistry module (Soetaert et al., 1996a, 1996b) and relies on the sediment transport model within ROMS to calculate resuspension, and so our implementation used different bottom boundary conditions than Feng et al. (2015), who incorporated simpler parameterizations of resuspension and seabed biogeochemical processes.

For application to Chesapeake Bay, HydroBioSed was also modified so that inorganic sediment and resuspended organic matter affected light attenuation in the water column. Specifically, concentrations of multiple classes of inorganic sediment were estimated by the sediment transport module and used by the water column biogeochemical model in its estimate of light attenuation. The diffuse light attenuation coefficient, $K_D$, was estimated following Feng et al. (2015). Specifically, the light attenuation coefficient for most of the Bay, $K_{D,Bay}$, depended on $[TSS]$, i.e. the concentration of total suspended solids (TSS; includes inorganic and organic particulates), including inorganic and organic particles; and $[Salt]$, i.e. salinity. Near the Bay mouth, this formulation for $K_{D,Bay}$ could become negative, however, and so a shelf parameterization was used that depended on $[Chl]$, i.e. the concentration of chlorophyll; and $[DON]$, i.e. the dissolved organic nitrogen concentration, which includes contributions from nitrate and ammonium in the model. Thus, $K_D$ was estimated as follows:

$$K_D = \begin{cases} 
K_{D,Bay} & \text{when } K_{D,Bay} > 0 \\
= K_{D,Shelf} & \text{when } K_{D,Shelf} < 0 
\end{cases}$$

$$K_{D,Bay} = 1.4 + 0.063 [TSS] - 0.057 [Salt]$$

$$K_{D,Shelf} = 0.4 + 0.02486 [Chl] + 0.003786 \times \max \{0 ; 6.62 [DON] - 70.819\}$$
Use of the Warner et al. (2008) sediment transport module and multiple inorganic sediment classes also allowed HydroBioSed to account for more processes that affect suspended concentrations, compared to previous versions of ChesROMS-ECB. The coupled model, for example, accounted for seabed armoring and related changes in erodibility, as well as spatial and temporal variations in grain size. HydroBioSed also treated seabed organic matter particles as a sediment class that could later be re-entrained into the water column. This approach differs from previous versions of ECB that only accounted for one class of inorganic sediment within the water column (Feng et al., 2015). Additionally, previous versions of ECB parameterized resuspension of organic particulates by assuming that a fraction of the organic material settling to the seabed was instantaneously resuspended as small detritus, depending on the estimated bed stress (Feng et al., 2015). The remaining fraction reaching the seabed was either instantaneously remineralized or permanently buried and could not be resuspended back into the water column (Feng et al., 2015).

Forcing for the coupled model for Chesapeake Bay was based on a previously published hydrodynamic-biogeochemical model, ChesROMS-ECB (Feng et al., 2015; Irby and Friedrichs, 2017; Scully, 2016). ChesROMS-ECB used the curvilinear horizontal ChesROMS grid (Xu et al., 2012), which had an average resolution of 1.7 km inside the Bay. The vertical grid had 20 layers and was vertically stretched to have increased resolution in surface waters and near the seabed. Advection schemes included MPDATA for tracers, a third-order upstream scheme for depth-varying horizontal
momentum, and a fourth-order centered difference scheme for vertical momentum. Our implementation of ChesROMS-ECB was forced by spatially and temporally variable winds from NCEP’s North American Regional Reanalysis (NARR) dataset. Open boundary conditions at the mouth of the Bay accounted for tides and sub-tidal changes in water level using data from the Advanced Circulation Model (ADCIRC) EC2001 tidal database (Mukai et al., 2002) and observationally based estimates of water level from NOAA stations at Lewes, Delaware and Duck, North Carolina. These data were incorporated into the model through a Chapman (1985) open boundary condition. Water velocities and tracers at the open boundary at the Bay mouth were estimated using a Flather (1976) condition for depth-averaged velocity and radiation conditions based on Marchesiello et al. (2001) for depth-varying velocity and tracers. Temperature and salinity were also nudged to climatological values from the 2001 World Ocean Atlas, while oxygen was nudged to be at 100% saturation at the open boundary. The model forcing described above is consistent with previous studies (e.g. Feng et al., 2015; Scully, 2016; Irby and Friedrichs, 2017).

Inputs of water, sediment, organic matter and nutrients from the watershed to the Bay were based on model output from the Chesapeake Bay Program’s Watershed Model (USEPA, 2010; Shenk and Linker, 2013), as in Irby and Friedrichs (2017) (Table 4.1). These inputs included riverine sources of water and both dissolved and particulate tracers, as well as inputs of water and dissolved tracers from overland flow. Terrestrial inputs of organic matter were partitioned based on Irby and Friedrichs (2017), except that some small detritus, up to 3%, was assumed to enter the Bay as terrestrial aggregates. The magnitude of this aggregated component was based on estimates of organic matter
accumulation from Zimmerman and Canuel (2001) at riverine-influenced sites near the Susquehanna River mouth.

Unlike previous versions of ChesROMS-ECB, this study also accounted for locally generated wind-waves and open ocean swell because wave energy is important for suspended sediment within Chesapeake Bay (e.g. Sanford, 1994; Harris et al., 2011). To account for the effect of waves on modeled bed shear stresses, this ROMS implementation used the Madsen (1994) bottom boundary layer formulation as described by Warner et al. (2008). Spatially and temporally varying estimates of wave height, period, direction, and orbital velocity were estimated using the Simulating WAves Nearshore model (SWAN; Booij et al., 1999). This study built on a previous implementation of SWAN for Chesapeake Bay by Lin et al., 2002) by accounting for waves propagating into the Bay from the ocean by using estimates from the National Oceanic and Atmospheric Administration’s Wave Watch III model (Tolman, 2009) at the open boundary at the Bay mouth.

Parameters in the water column biogeochemistry, seabed biogeochemistry and sediment transport modules were primarily based on Feng et al. (2015), Testa et al. (2014) and Cerco et al. (2010, 2013), respectively. Parameters that are new to this ChesROMS-ECB implementation or are important for interpretation of our results are listed in Table 4.1, but are also briefly discussed here. Classes of inorganic sediment included sand, two classes of aggregated mud, and one class of unaggregated mud to represent the washload. Parameters were chosen to be the same as Cerco et al. (2010, 2013), except for the erosion rate parameter and critical shear stress for sand (defined in eqs. 4.1 and 4.2), which were adjusted to match estimates of TSS from Son and Wang.
The need to adjust parameters is not unexpected because Cerco et al. (2010; 2013) and HydroBioSed use different parameterization for sand erosion. In addition to the plankton and detrital tracers included in previous implementations of ChesROMS-ECB, the coupled model also accounted for additional classes of organic matter aggregates. Specifically, as phytoplankton and detritus were deposited on the seabed, they were incorporated into an estuarine particulate organic matter class in the seabed, which could later be entrained into the water column by resuspension. This estuarine particulate organic matter was assumed to have the same remineralization rate constant as large detritus when it was suspended, but it settled more quickly (Table 4.1). Additionally, the small fraction of riverine load assumed to be terrestrial aggregates could also be stored in the seabed or suspended within the water column; this material was assigned the same properties as estuarine organic matter, except for a lower N:C ratio (Table 4.1).

4.2.2. Model Runs and Analysis

The coupled model described above was run for the year 2000, which was characterized by low-to-average riverine discharge and wave energy in the Chesapeake Bay (Figure 4.2). Initialization of hydrodynamic and water column biogeochemical fields were taken from a multi-decadal model run from Irby and Friedrichs (submitted). Initialization of the seabed was based on observations of grain size, fraction of particulates that is organic, and organic matter composition (Cerco et al., 2010; Zimmerman and Canuel, 2001; Table 4.1). The model was run with a 15 second time step and daily averages of model estimates were saved as output. Previous publications have focused on the evaluation of modeled hydrodynamics, oxygen and nitrogen using un-
coupled versions of the ChesROMS-ECB model (e.g. Feng et al., 2015; Irby et al., 2016). Evaluation of our “standard” model run, described above, therefore focused on sediment dynamics, as well as representation of the dominant biogeochemical processes affected by resuspension including light attenuation, primary productivity, and remineralization. Note that only phytoplankton, and not vegetation, were accounted for in the model and influenced its estimates of primary productivity. Also, organic matter included both allochthonous and autochthonous sources, but it was impossible to distinguish between the sources in the model calculations.

Model analysis focused on how seabed resuspension affected primary productivity and remineralization, i.e. the uncertainty in these processes due to resuspension, as well as how changes in these processes affected oxygen and nitrogen dynamics. Analysis focused on the month of July 2000 (Figure 4.2) because oxygen concentrations are generally lowest in mid-summer (e.g. Bever et al., 2013). To evaluate the role of resuspension, an additional “no-resuspension” simulation was run for July 2000. The sensitivity test was initialized based on output from July 1, 2000 from the standard model run, but resuspension was prevented from occurring by changing the erosion rate parameter, M, to zero and by increasing the critical shear stress, $\tau_{\text{crit, sed}}$, to 50 Pa., which exceeded estimates of bed stress in the standard model run by an order of magnitude (eqs. 4.1, 4.1; Table 4.1). Differences between this “no-resuspension run” and the “standard model run” were used to indicate how the entrainment of seabed material into the overlying water column affected primary productivity and remineralization, as well as oxygen and nutrient concentrations. Note that “bottom water” and “surface water” estimates refer to values in the surficial or bottom grid cell of the model.
4.3. Results

4.3.1. Evaluation of July 2000 standard model run

The spatial patterns of TSS from the standard model run were similar to those inferred from satellite data (Son and Wang, 2012). Both the satellite-derived and modeled TSS estimate higher concentrations near tributary mouths and in shoal regions (Figure 4.3a,b). Moving from the Susquehanna River towards the mouth of the Bay along the main estuarine channel, surface water TSS concentrations decreased by about one order of magnitude in satellite data and by two orders of magnitude in the model. Similarly, on the eastern shoals, the satellite and numerical model estimates indicated that surface total TSS was ~1 and 2-3 orders of magnitude higher, respectively, compared to surface waters in the main channel. In general, estimates from the standard model run were higher than satellite-derived estimates where TSS concentrations were high, and were lower than satellite-derived estimates where TSS concentrations were low (Figure 4.3a,b). This result was not surprising as the satellite estimates of TSS generally underestimate the range of values derived from in-situ measurements (Son and Wang, 2012).

Estimates of sub-surface TSS concentrations and the location of the estuarine turbidity maximum from the standard model run were also compared to in-situ data from Sanford et al. (2001). The standard model run estimated the time-averaged location of the highest TSS concentrations in the estuarine turbidity maximum in July 2000 to occur at about 10 m water depth at 39.3-39.4 °N (Figure 4.4). This is similar to the observed location of the estuarine turbidity maximum in February to October 1996, which was 20-55 km downstream from Havre de Grace, Maryland (about 39.15-39.4 °N with distance
calculated along the channel) in about 12 m water depth (Sanford et al., 2001). Sanford et al. (2001) also observed TSS concentrations ranging from less than 30 to over 200 mg L\(^{-1}\) in this region, consistent with our time-averaged concentration of \(\sim 100\) mg L\(^{-1}\) in July 2000.

Modeled light attenuation (Figure 4.3d) and primary production (Figure 4.4c) were also compared to values from previous studies. The modeled diffuse light attenuation coefficient (\(K_D\)) was compared to satellite-derived values from Son and Wang (2012) (Figure 4.3c). Both the modeled and satellite-derived \(K_D\) in surface waters decreased from over 3 m\(^{-1}\) near tributary mouths to less than 1 m\(^{-1}\) near the Bay mouth (Figure 4.3c,d). Model estimates of primary productivity were compared to values derived from bottle incubations by Harding et al. (2002), who estimated that maximum summertime production occurred in their Region 4, located at \(\sim 38.4 - 38.75\)°N, with a mean of 2354 ± 188 mg C m\(^{-2}\) d\(^{-1}\) based on research cruises from 1982-2000. The model similarly estimated a depth-integrated Mid-Bay maximum in primary productivity of about 2600 mg C m\(^{-2}\) d\(^{-1}\) in the same location (Figure 4.4c).

Finally, model estimates of oxygen consumption, calculated by summing rates of aerobic remineralization (Figure 4.4d) and nitrification, were compared to estimates derived from bottom incubation experiments at three locations along the Bay in the summers of 1989-1990 (Smith and Kemp, 1995). Observational estimates of summertime bottom water oxygen consumption increased from approximately 0.01 mg O\(_2\) L\(^{-1}\) h\(^{-1}\) in the Upper Bay and about zero in the Mid Bay, to 0.04 mg O\(_2\) L\(^{-1}\) h\(^{-1}\) in the Lower Bay. The model similarly estimated a down-estuary increase, with estimates changing from about 0.01 mg O\(_2\) L\(^{-1}\) h\(^{-1}\) in the Upper bay, to 0.02-0.03 mg O\(_2\) L\(^{-1}\) h\(^{-1}\) in...
the Mid Bay, to 0.04 mg O₂ L⁻¹ h⁻¹ in the Lower Bay. Differences in the Mid Bay likely occurred due to the finer spatial and temporal resolution afforded by the model, as well as variations in oxygen concentrations, which were anoxic during the observational period but hypoxic in the model in July 2000.

4.3.2. Effect of resuspension on primary production and remineralization along the Bay

Spatial variation in tidal energy, river influence, and waves caused bed stresses in the standard model run in July 2000 to be highest in the Upper Bay and Lower Bay, with a minimum in the Mid Bay (Figure 4.5). In the Upper Bay, fast tidal currents and riverine-influenced flows caused bed stresses throughout most of July 2000 to exceed 0.03 Pa, the threshold for erosion of mud and organic matter (Figure 4.5b,d). Near-bed current speeds decreased in the Mid Bay, however, and bed stresses were reduced such that the 0.03 Pa threshold was only exceeded about half of the time. In the Lower Bay, tidal and wave energy were higher, producing current- and wave- induced bed shear stresses that exceeded 0.1 Pa in much of this region (Figure 4.5a,b). Overall, the combined current- and wave-induced bed stresses exceeded 0.03 Pa almost all of the time in the Lower Bay in the standard model run (Figure 4.5d).

Comparing results from the standard and no-resuspension model runs revealed that resuspension induced by these energetic bed stresses increased TSS concentrations throughout the Bay in July 2000 (Figure 4.4a, 4.6a). In the Upper Bay, for example, surface TSS concentrations in the Bay’s surface waters reached up to ~80 mg L⁻¹ in the standard model run, but only about 5 mg L⁻¹ in the no-resuspension simulation (Figure
4.4a, 4.6a). Similarly, bottom water TSS concentrations in the Upper Bay exceeded 100 mg L\(^{-1}\) in the standard model run, but only reached about 10 mg L\(^{-1}\) in the model run that prevented resuspension (Figure 4.4a). The response of the Mid and Lower Bay to resuspension was smaller than that of the Upper Bay, but resuspension enhanced near-bed TSS concentrations in this southern region by up to about 30-40 mg L\(^{-1}\) (Figure 4.4a).

This resuspension-enhanced turbidity increased light attenuation throughout the water column, reducing primary productivity throughout much of the Bay (Figure 4.4c, 4.6c). In surface waters during July 2000, the diffuse light attenuation coefficient, \(K_D\), reached up to 5 m\(^{-1}\) in the standard model run (Figure 4.3), but remained below 2 m\(^{-1}\) in surface waters of the no-resuspension model run (not shown). The largest response of primary productivity to resuspension occurred north of 39\(^o\)N, where primary production in the channel was reduced by over a half, i.e. from over 80 mmol C m\(^{-3}\) d\(^{-1}\) in the no-resuspension model run to below 30 mmol C m\(^{-3}\) d\(^{-1}\) in the standard simulation, when results were averaged over July 2000 (Figure 4.4c, 4.6c). In the surface waters of the Mid-to-Lower Bay, in contrast, primary production approximately doubled from about 20 mmol C m\(^{-3}\) d\(^{-1}\) in the no-resuspension model run to about 40 mmol C m\(^{-3}\) d\(^{-1}\) in the standard simulation, when averaged over July 2000 (Figure 4.4c, 4.6c). The resuspension-induced effect on primary productivity was less significant below the surface waters; from ~5-10 m below the surface to the seabed, resuspension induced a slight decrease in primary production all along the main channel (Figure 4.4c).

The effect of resuspension on particulate organic matter concentrations and remineralization also varied along the length of the Bay in July 2000 (Figure 4.4b,d; Figure 4.4b,d). In the Upper Bay, resuspension caused bottom water particulate organic
carbon (POC) concentrations to decrease from up to 100 mmol C m$^{-3}$ in the no-resuspension model run to ~30 mmol C m$^{-3}$ in the standard model run in the Upper Bay channel (Figure 4.4b, 4.6b). In contrast, resuspension about doubled bottom water POC concentrations in the Lower Bay channel in the standard model run, compared to the no-resuspension simulation (Figure 4.4b, 4.6b). Similar to resuspension-induced changes in particulate organic matter concentrations, resuspension caused model estimates of remineralization to decrease in the Upper Bay and increase in the Lower Bay. In the channel of the Upper Bay, bottom water remineralization decreased from about 3 mmol C m$^{-3}$ d$^{-1}$ in the no-resuspension simulation to about 1 mmol C m$^{-3}$ d$^{-1}$ in the standard model run (Figures 4.4d, 4.6d). In the channel of the Lower Bay, bottom water remineralization almost doubled from about 3 mmol C m$^{-3}$ d$^{-1}$ in the no-resuspension simulation to about 5 mmol C m$^{-3}$ d$^{-1}$ in the standard model run (Figures 4.4d, 4.6d).

Oxygen concentrations responded to resuspension by decreasing throughout almost the entire Bay (Figures 4.4e, 4.6e). The largest reduction in oxygen levels occurred in the surface waters of the Upper Bay, where concentrations decreased by over 100 mmol O$_2$ m$^{-3}$, in the standard model run compared to the no-resuspension simulation in July 2000 (Figures 4.4e). Resuspension also decreased oxygen concentrations to a lesser extent throughout the bottom portion of the water column throughout the Bay (Figures 4.4e, 4.6e). The only location where resuspension increased oxygen levels was in the surface waters of the Lower Bay, where concentrations increased by up to ~50 mmol O$_2$ m$^{-3}$, when averaged over July 2000 (Figure 4.4e).

In contrast to oxygen, accounting for resuspension in the model caused ammonium concentrations to increase throughout the Bay when averaged over July 2000.
(Figures 4.4f, 4.6f). The largest increases were estimated to occur in the surface waters of the Upper Bay, where ammonium concentrations increased by up to 5-10 mmol N m$^{-3}$ in the standard model run compared to the no-resuspension model run (Figure 4.4f, 4.6f). Bottom water ammonium levels also increased, particularly in the Lower Bay where concentrations in the channel increased by up to about 5 mmol N m$^{-3}$ when averaged over July 2000 (Figure 4.4f, 4.6f).

4.4. Discussion

When averaged over the entire Bay for the month of July 2000, the model indicated that the effect of resuspension on primary productivity and remineralization was small (Figure 4.7c,d). Despite the subtle effect of resuspension on these spatially averaged biogeochemical rates, the regional response varied and was substantial in some regions, causing dramatic local changes in POC, oxygen and nutrient concentrations (Figure 4.7b,e,f). This Discussion explores the along-estuary variability in primary production and remineralization presented above (Section 4.4.1), considers the effect of resuspension on oxygen and ammonium concentrations (4.4.2), analyzes the role of sediment transport mechanisms (4.4.3), and then reflects on implications for future studies (Section 4.4.4).

4.4.1. Along-estuary variability in the response of primary productivity and remineralization

The response of water column biogeochemistry in Chesapeake Bay to resuspension varied along the estuary. In the Upper Bay, resuspension kept particles delivered from the rivers and those caught in the estuarine turbidity maximum in
suspension, as opposed to being deposited on the seabed (Figure 4.4a, 4.6a). The
resuspension-enhanced turbidity in the Upper Bay, combined with the high
concentrations of riverine-delivered nutrients there, caused phytoplankton growth to be
primarily light-limited in this region. Thus, the resuspension-induced turbidity decreased
primary productivity (Figures 4.4c, 4.6c). This lower rate of phytoplankton growth also
reduced nutrient uptake in the Upper Bay, so that more dissolved inorganic nitrogen
flowed downstream to the surface waters of the Mid-to-Lower Bay. As surface water TSS
and nutrient concentrations decreased downstream, phytoplankton growth gradually
transitioned from being light-limited in the Upper Bay to nutrient-limited in the Mid-to-
Lower Bay. Therefore, the resuspension-induced increase in ammonium in the Mid-to-
Lower Bay was able to stimulate primary productivity in this region (Figures 4.4, 4.6).

Concentrations of POC and remineralization responded to changes in primary
productivity, as well as patterns of resuspension. In the Upper Bay channel, the increases
in POC concentrations due to entrainment of seabed material into the water column were
more than offset by the resuspension-induced decrease in organic matter production from
reduced primary productivity. This offset led to an overall reduction in POC
concentrations and effective remineralization rates in this region (Figures 4.4, 4.6). In the
Mid-to-Lower Bay channel, in contrast, resuspension increased POC concentrations
through three mechanisms. Specifically, resuspension enhanced primary production,
entrained material from the seabed into the water column, and facilitated fluxes of POC
from the across the Lower Bay to the Mid Bay, as well as the Lower Bay’s channel (see
Section 4.4.3). This enhanced supply of POC to the Mid-to-Lower Bay channel increased
remineralization in this region (Figures 4.4, 4.6).
The location of the transition from the Upper Bay, where resuspension decreased primary production and remineralization, to the Mid and Lower Bay, where resuspension increased these rates, may shift depending on environmental conditions. In July 2000 in the standard model run, this transition gradually occurred as surface water TSS and ammonium concentrations decreased (Figure 4.4), and so phytoplankton growth changed from being light-limited to being nutrient-limited. The location of the transition could therefore shift up- or down-stream due to episodic, seasonal or inter-annual variations in freshwater input that cause particulate or nutrient concentrations to change. For example, either higher riverine loads of TSS or nitrogen, or faster currents that more quickly transport this material downstream, could cause this transition to shift downstream toward the Lower Bay. Indeed, seasonal and inter-annual shifts in the location and magnitude of the phytoplankton bloom have been observed to vary with river discharge in Chesapeake Bay (e.g Harding, 1994; Harding et al., 2005; Roman et al., 2005; and references therein).

By changing TSS concentrations, seasonal patterns in resuspension magnitude or frequency can also affect the extent to which phytoplankton growth is primarily light-limited, thereby impacting the location of this transition. For example, in our no-resuspension model run, riverine sediment settled to the seabed within a couple of days of delivery to the Bay, greatly increasing light levels in the Upper Bay. As a result, in the no-resuspension model run, primary productivity peaked near the Susquehanna River mouth and decreased downstream (Figures 4.4, 4.6), demonstrating that even without altering riverine inputs, the transition from primarily light-limited to primarily nutrient-limited phytoplankton growth can shift along the estuary due to changes in resuspension.
Although such extreme changes in resuspension are unlikely to occur, TSS concentrations in the Upper Bay can change in response to resuspension, sediment properties, and seasonally varying wave energy (Sanford et al., 2001; Sanford, 1994; Harris et al., 2011). These resuspension-induced changes in TSS concentrations are most likely to affect turbidity and phytoplankton growth where the ETM develops in the Upper Chesapeake Bay. Additionally, resuspension may alter how much sediment is entrained into the surface waters of the Upper Bay and transported downstream, thereby affecting where the gradient from light-limited to nutrient-limited productivity occurs. Overall, resuspension-induced changes are likely to have the most impact on the location of this transition during times of low river discharge, such as late summer, or during storms, when there are large changes in TSS concentrations.

4.4.2. Implications for oxygen and nitrogen dynamics

The effect of resuspension on primary productivity and remineralization varied along the estuary, but changes in both processes acted to decrease oxygen concentrations and increase ammonium concentrations in the model result for July 2000 (Figure 4.6, 4.7). In the Upper Bay, resuspension reduced photosynthesis, lowering the supply of oxygen and oxygen concentrations. At the same time, throughout the Bay, aerobic remineralization of resuspended seabed organic matter increased oxygen consumption, which also acted to decrease oxygen concentrations. Consistent with patterns of oxygen dynamics, ammonium concentrations in the Upper Bay increased in response to reduced phytoplankton growth, which lowered nutrient uptake rates. Also, throughout the Bay, both remineralization of resuspended organic matter produced ammonium, increasing concentrations throughout the Bay.
Although it was expected that remineralization of resuspended organic matter would lower oxygen concentrations and raise ammonium concentrations, it was somewhat surprising that decreases in primary production in the Upper Bay would exacerbate this effect. Reductions in phytoplankton productivity and organic matter concentrations are generally expected to increase oxygen levels due to the decreased remineralization rates (e.g. Bricker et al., 2007; Kemp et al., 2009; and references therein). In fact, this expectation has motivated management programs across the globe to focus on reducing nutrient inputs to coastal watersheds (e.g. Bricker et al., 2007; Kemp et al., 2009).

However, the decrease in oxygen concentrations due to reduced primary productivity in the Upper Bay can at least partially be explained by the temporal lag between the production of organic matter and its remineralization. Specifically, differences between production and remineralization rates, as well as the time needed for particulate organic matter to settle to the seabed, may explain why our results showed that decreased primary productivity lowered oxygen concentrations in this one-month-long study in the Upper Bay. First, variations in photosynthesis occurred over much shorter timescales than changes in organic matter remineralization. The modeled rate constant for phytoplankton growth, 2.15 d\(^{-1}\), was 1 – 2 orders of magnitude faster than the rate constants for remineralization, which ranged from 0.01 – 0.3 d\(^{-1}\), consistent with literature values (e.g. Lomas et al., 2002). This effectively delayed the response of remineralization to changes in primary productivity. Second, it takes time for phytoplankton blooms in surface water to produce detritus that sinks below the pycnocline. In the model, particulate organic matter settling velocities ranged over three
orders of magnitude, from 0.1 – 10 m d\(^{-1}\) and the surface layer was approximately 5 – 10 m thick. The time required for particulate organic matter to sink below the pycnocline therefore ranged from about 0.5 – 100 days, depending on the settling velocity and vertical mixing. These lags could therefore delay the response of bottom water remineralization rates to reductions in surface primary productivity by as long as a season. This analysis implies that the resuspension-induced reduction in Upper Bay primary productivity, and associated reduction in POC concentrations, could cause a larger decrease in remineralization over longer timescales. This could cause oxygen concentrations to increase in the Upper Bay, supporting management practices focused on reducing phytoplankton growth and production of organic matter (e.g. Bricker et al., 2007; Kemp et al., 2009).

4.4.3. Role of sediment transport processes

By changing sediment and particulate organic matter concentrations within the water column, resuspension substantially impacted biogeochemical processes in the numerical model. This motivated further analysis of how resuspension and subsequent redistribution of particulates affected sediment and particulate organic matter concentrations, focusing on mechanisms by which resuspension increased POC concentrations in the channel and how these processes might be parameterized in biogeochemical modeling efforts.

Along-estuary redistribution of resuspended particulate organic matter increased effective remineralization rates in the Mid-to-Lower Bay, altering oxygen and ammonium concentrations. Primary production peaked near 38.7°N, but the resulting phytoplankton and detritus was initially deposited over large portions of the Mid and
Lower Bay, as evidenced by POM deposition patterns in the no-resuspension model run (data not shown). In the standard model, much of the material that had been deposited in the Lower Bay and the shoals was subsequently resuspended due to energetic currents and waves (Figure 4.5) and transported northward towards the Mid-Bay and the channel of the Lower Bay (data not shown). These modeled transport patterns are consistent with previous studies that demonstrated up-estuary flows on the shoals of the Lower Bay (Valle-Levinson and Lwiza, 1995), and mud accumulation in the channel of the Mid-to-Lower Bay (Hobbs et al., 1992). Remineralization of this resuspended particulate organic matter as it was transported, and once it reached the channel in the Mid-to-Lower Bay, decreased oxygen concentrations and increased ammonium concentrations in this region, although additional modeling studies would be needed to quantify the role of this material compared to locally resuspended particulates.

The resuspension-induced transport of organic matter towards low-energy regions in the Mid-to-Lower Bay, including the channel, and the resulting increase in remineralization in these regions, is similar to previously developed hypotheses. Cerco et al. (2013) and Xu and Hood (2006), for example, suggest that accumulation of organic matter in the main channel of the Chesapeake Bay may affect water column biogeochemistry, including oxygen concentrations. Our results differed slightly from these hypotheses because the dominant transport direction was up-estuary, although lateral fluxes delivered particulates to the channel to a lesser extent.

A few Chesapeake Bay biogeochemistry models already account for some processes relating to resuspension and subsequent redistribution of particulate organic matter, but our results can help refine their parameterizations. For example, Cerco et al.
(2013)’s model used water-depth-dependent values for particulate organic matter settling velocities so that particulates were slower in shallow areas compared to deeper areas in order to facilitate accumulation of organic matter in the channel. Also, the model developed by Feng et al. (2015) prevented particulate organic matter deposition and burial when bed stresses were high. These parameterizations may have underestimated transport of particulate organic matter, however, because they did not allow all organic material to be resuspended once it was deposited. Also, Feng et al. (2015) did not account for wave-induced bed stress, which often exceeded the threshold for resuspension (0.03 Pa), in the Lower Bay (Figure 4.5b,c). Future parameterizations could consider adjusting particulate organic matter settling velocities based on bed stress patterns, as opposed to water depth; account for wave-induced bed stresses; and allow seabed organic matter to be resuspended, e.g. similar to Feng et al. (2015)’s parameterization for inorganic sediment. In lieu of using a coupled model like HydroBioSed, an alternate approach is to use a single seabed layer to account for the storage of POM in the seabed (Capet et al., 2016).

4.4.4. Implications for Future Studies

Our model results showed that oxygen concentrations in Chesapeake Bay are sensitive to both oxygen consumption and production, in addition to physical processes such as stratification. Similar sensitivities of oxygen concentration to rates of consumption and production have been noted in other modeling studies. For example, Scully (2013) indicated that a 25% decrease in the oxygen consumption rate in their Chesapeake Bay model reduced hypoxic volume by a factor of three; similarly, increasing the oxygen consumption rate by 25% doubled their estimate of hypoxic
volume. In addition, Li et al., (2015) showed that neglecting primary production in their hydrodynamic-biogeochemical model increased hypoxic volume by a factor of ~5 in July-September, 1999, in Chesapeake Bay. Unlike these other studies, however, our results illustrated that accounting for resuspension impacts the calculations of both consumption and production. This motivates further work to constrain processes related to resuspension, and its effect on oxygen production (i.e. primary production) and consumption (i.e. remineralization), as well as oxygen concentrations.

Accounting for resuspension improved the model’s representation of observed patterns of turbidity and primary production. When our model neglected resuspension, riverine sediments were quickly deposited and no estuarine turbidity maximum formed, causing primary production to peak near the Susquehanna River mouth (Figure 4.4, 4.6). Including resuspension in the model allowed an estuarine turbidity maximum to form and increased turbidity, especially in the Upper Bay. This caused primary productivity to shift downstream, allowing the model to better represent observations (Sanford et al., 2001; Harding et al., 2002). Accounting for resuspension is likely also important in other estuaries or coastal regions where resuspension-induced turbidity affects primary production (e.g. Delaware Bay: Pennock and Sharp, 1986; McSweeney et al., 2016).

The model indicated that redistribution of resuspended particulate organic matter influenced spatial patterns of remineralization and seabed accumulation, but additional model runs could help quantify these transport processes and their implications for water quality. This study focused on a relatively calm summer period, but wave and wind energy are typically at their lowest during the summer, so model studies of other seasons would be informative (Figure 4.2). Other studies have indicated that storms may rework
and redistribute centimeters of seabed sediments and organic matter (e.g. Sanford, 1994; Cheng et al., 2013; Harris et al., 2011; Brasseur et al., 2005), but the largest storm during July 2000 was characterized by moderate wave and wind energy (Figure 4.2). Model runs for other, larger storm events might improve understanding of how the role of resuspension on water column biogeochemistry varies seasonally.

Refining model parameterizations and accounting for additional processes in the coupled model could also enhance our ability to quantify the effects of resuspension on biogeochemical dynamics. Our results were especially sensitive to changes in light attenuation, but we used a fairly simplistic, empirical approach. Using a more process-based formulation to estimate light attenuation, for example, could be helpful for better constraining model estimates of primary productivity (e.g. del Barrio et al., 2014; Gallegos et al., 2011).

The model could also be refined to account for sediment supplied by shoreline erosion along the Bay and tributary processes. Shoreline erosion, including material from marshes, accounts for over half of the terrestrial inputs of TSS into the Bay (Cerco, pers. comm., 2017), and neglecting this supply of sediment and particulate organic matter could cause our model to underestimate particulate fluxes and turbidity. Predicting fluxes of particulates between estuaries and coastal environments such as wetlands and beaches can be complicated (Cerco et al., 2010) and is often neglected (e.g. this study; Cheng et al., 2013). However, these fluxes of sediment and particulate organic matter can affect biogeochemical dynamics and budgets in Chesapeake Bay and other coastal systems (Cerco, pers. comm., 2017; Vonk et al., 2012).
Finally, implementation of the coupled model for different environments (e.g. this Chapter; Chapters 2, 3) and observational studies from different locations (e.g. Lampitt et al., 1995; Abril et al., 1999) have indicated that the impact of resuspension on biogeochemical processes may vary among systems. This implies that consideration of additional sites, as well as time periods characterized by different environmental conditions, will increase understanding of how resuspension may affect water column biogeochemistry in other locations. This understanding will also lead towards a better understanding of when a coupled hydrodynamic-sediment transport-biogeochemistry model is necessary to reproduce observations, and will facilitate development of parameterizations for the effect of resuspension on biogeochemical dynamics.

4.5. Conclusions

Results from our coupled hydrodynamic-sediment transport-biogeochemical model indicated that resuspension substantially altered spatial patterns of primary productivity and remineralization in Chesapeake Bay in July 2000, even though there was little net effect when results were averaged over the entire Bay. In the Upper Bay, the increased turbidity due to resuspension limited phytoplankton productivity, which generated less organic matter and reduced remineralization. The reduction in primary production allowed more riverine nutrients to flow farther downstream to the Mid- and Lower-Bay, stimulating phytoplankton growth and remineralization there. Throughout the Bay, resuspension of seabed organic matter also enhanced remineralization in the bottom portion of the water column. Overall, in the Upper Bay, the resuspension-induced decrease in primary production exceeded the increase in remineralization of resuspended organic matter, and so particulate organic matter concentrations and net remineralization
rates decreased there. In the Mid-to-Lower Bay, in contrast, remineralization of resuspended organic matter exceeded resuspension-induced changes primary production, and so particulate organic matter concentrations and net remineralization rates increased.

The resuspension-induced changes in primary production and remineralization both caused oxygen concentrations to decrease and ammonium concentrations to increase during the modeled time period of July 2000. Specifically, aerobic remineralization of resuspended organic matter consumed oxygen, while reduced rates of photosynthesis decreased the production of oxygen in the water column. Similarly, remineralization of resuspended organic matter produced ammonium, and reduced rates of primary production also decreased the uptake of ammonium by phytoplankton in the Upper Bay. These changes in biogeochemical processes caused decreased oxygen concentrations and increased ammonium concentrations throughout the Bay, in spite of resuspension-induced decreases in organic matter production that were estimated for the Upper Bay, on timescales of a day to a month. Overall, these results imply resuspension may substantially affect spatial patterns of primary production and remineralization, as well as oxygen and nitrogen dynamics, in estuaries similar to the Chesapeake Bay.

Acknowledgements for Chapter 4

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173
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USEPA, [US Environmental Protection Agency], 2010. Chesapeake Bay total maximum daily load for nitrogen, phosphorus and sediment.


Tables for Chapter 4

Table 4.1: Selected parameters for the standard model run

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Modeled Value</th>
<th>Source for Observed/Literature Values</th>
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<tbody>
<tr>
<td><strong>Sediment Transport Parameters</strong></td>
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<tr>
<td>Partitioning of Sediment into Classes</td>
<td>Unaggregated Mud: 4 mg L(^{-1}) Small Flocs, Large Flocs, and Sand: Ranges based on estimates from EPA’s Watershed Model</td>
<td>Cerco et al. (2010; 2013)</td>
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<td>Settling Velocity, (w_{s,\text{sed}})</td>
<td>Unaggregated Mud: 0.012 mm s(^{-1}) Small Flocs: 0.03 mm s(^{-1}) Large Flocs: 0.1 mm s(^{-1}) Sand: 1.0 mm s(^{-1})</td>
<td>Cerco et al. (2010; 2013);</td>
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<td>Critical Bed Shear Stress for Erosion, (\tau_{\text{crit,\text{sed}}})</td>
<td>Unaggregated Mud: 0.03 Pa Small Flocs: 0.03 Pa Large Flocs: 0.03 Pa Sand: 20.0 Pa</td>
<td>Cerco et al. (2010; 2013); Value for sand chosen to match Son and Wang (2012) data.</td>
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<tr>
<td>Erosion Rate Parameter, (M)</td>
<td>(3 \times 10^{-5}) kg m(^{-2}) s(^{-1})</td>
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<td>Porosity, (\phi)</td>
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<td>Sediment Density</td>
<td>Unaggregated Mud: 1350 kg/m(^3) Small Flocs: 1350 kg/m(^3) Large Flocs: 2000 kg/m(^3) Sand: 2650 kg/m(^3)</td>
<td>Cerco et al. (2010)</td>
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<td>Seabed Initialization for Different Sediment Classes</td>
<td>Spatially variable, based on maps of observed grain size</td>
<td>Nichols et al. (1991), as presented in Cerco et al. (2010)</td>
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<td><strong>Biogeochemical Parameters</strong></td>
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<td><strong>Selected Water Column Rates</strong></td>
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<td>Phytoplankton growth rate constant</td>
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<td>Particulate organic matter solubilization rate constant</td>
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<td>Feng et al. (2015)</td>
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<td>Terrestrial Aggregates</td>
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</tr>
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<td>Assumed to be similar to seabed flocs; Cerco et al. (2010; 2013)</td>
</tr>
<tr>
<td>Erosion Rate Parameter for Organic Matter</td>
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<td>Assumed to be similar to seabed flocs; Cerco et al. (2010; 2013)</td>
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<td>Partitioning of organic matter in river input</td>
<td>Varies in time based on output from EPA Watershed Model</td>
<td>Based on Irby et al. (in prep), but assumed that up to 3% of small detritus was terrestrial aggregates.</td>
</tr>
<tr>
<td>Seabed Rates</td>
<td>Base Remineralization rates of Seabed Organic Matter</td>
<td>Coefficients for Q&lt;sub&gt;10&lt;/sub&gt; temperature — remineralization relationship</td>
</tr>
<tr>
<td>----------------------------------------------------------------------------</td>
<td>------------------------------------------------------</td>
<td>--------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Estuarine Organic Matter</td>
<td>5.23 × 10&lt;sup&gt;-4&lt;/sup&gt; d&lt;sup&gt;-1&lt;/sup&gt;</td>
<td>Base temperature</td>
</tr>
<tr>
<td>Terrestrial Organic Matter</td>
<td>5.23 × 10&lt;sup&gt;-4&lt;/sup&gt; d&lt;sup&gt;-1&lt;/sup&gt;</td>
<td>Q&lt;sub&gt;10&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base temperature</td>
<td>20 °C</td>
<td></td>
</tr>
<tr>
<td>Q&lt;sub&gt;10&lt;/sub&gt;</td>
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</tr>
<tr>
<td>Ratio of mol N: mol C in seabed organic matter</td>
<td>Estuarine</td>
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</tr>
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<td></td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>Terrestrial</td>
<td>0.1</td>
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<tr>
<td>Half saturation constant for O&lt;sub&gt;2&lt;/sub&gt; limitation in oxic respiration</td>
<td>6.25 µmol O&lt;sub&gt;2&lt;/sub&gt; L&lt;sup&gt;-1&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Half saturation constant for NO&lt;sub&gt;3&lt;/sub&gt; limitation in denitrification</td>
<td>1.0 µmol NO&lt;sub&gt;3&lt;/sub&gt; L&lt;sup&gt;-1&lt;/sup&gt;</td>
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</tr>
<tr>
<td>Half saturation constant for O&lt;sub&gt;2&lt;/sub&gt; limitation in nitrification</td>
<td>31.25 µmol O&lt;sub&gt;2&lt;/sub&gt; L&lt;sup&gt;-1&lt;/sup&gt;</td>
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<td>Half saturation constant for O&lt;sub&gt;2&lt;/sub&gt; inhibition in denitrification</td>
<td>0.312 µmol O&lt;sub&gt;2&lt;/sub&gt; L&lt;sup&gt;-1&lt;/sup&gt;</td>
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<td>Half saturation constant for O&lt;sub&gt;2&lt;/sub&gt; inhibition in anoxic mineralization</td>
<td>0.1 µmol O&lt;sub&gt;2&lt;/sub&gt; L&lt;sup&gt;-1&lt;/sup&gt;</td>
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<tr>
<td>Half saturation constant for NO&lt;sub&gt;3&lt;/sub&gt; inhibition in anoxic mineralization</td>
<td>0.1 µmol NO&lt;sub&gt;3&lt;/sub&gt; L&lt;sup&gt;-1&lt;/sup&gt;</td>
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<tr>
<td>Maximum nitrification rate</td>
<td>0.1 d&lt;sup&gt;-1&lt;/sup&gt;</td>
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<tr>
<td>Maximum oxidation rate of oxygen demand units</td>
<td>0.05 d&lt;sup&gt;-1&lt;/sup&gt;</td>
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<td>Fraction of ODU&lt;sub&gt;s&lt;/sub&gt; produced in the seabed that are solid and inert</td>
<td>0%</td>
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<td>Base biodiffusion coefficients</td>
<td>Sediment and Particulate Organic Matter</td>
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<td>Surficial Sediments: 4.4 × 10&lt;sup&gt;-11&lt;/sup&gt; m&lt;sup&gt;2&lt;/sup&gt; s&lt;sup&gt;-1&lt;/sup&gt;</td>
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<td>Deep Sediments: 0 m&lt;sup&gt;2&lt;/sup&gt; s&lt;sup&gt;-1&lt;/sup&gt;</td>
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<td>O2</td>
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<td>NO&lt;sub&gt;3&lt;/sub&gt;</td>
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<td>9.78 × 10&lt;sup&gt;10&lt;/sup&gt; m&lt;sup&gt;2&lt;/sup&gt; s&lt;sup&gt;-1&lt;/sup&gt;</td>
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<td>NH&lt;sub&gt;4&lt;/sub&gt;</td>
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<td>ODU</td>
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<td>Coefficients for Q&lt;sub&gt;10&lt;/sub&gt; temperature — biodiffusion</td>
<td>Base temperature</td>
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<td>20 °C</td>
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<tr>
<td>Q&lt;sub&gt;10&lt;/sub&gt; (particulates)</td>
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<td>Q&lt;sub&gt;10&lt;/sub&gt; (solutions)</td>
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Zimmerman and Canuel (2000)
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<th>Depth</th>
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<td>Depths in the seabed where different bioturbation coefficients are used for particulates</td>
<td>0-1 cm deep</td>
<td>Laurent et al. (2016)</td>
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<td>Surficial biodiffusion coefficient</td>
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<tr>
<td>Deep biodiffusion coefficient</td>
<td>Over 3 cm deep</td>
<td>Laurent et al. (2016)</td>
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<tr>
<td>Linear interpolation between surficial and deep values</td>
<td>1-3 cm deep</td>
<td>Laurent et al. (2016)</td>
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1Note that most water column biogeochemistry parameters are the same as Feng et al. (2015) and are not re-printed here, unless they are critical for the text.
Figures for Chapter 4

**Figure 4.1: Study site**

Maps show the (a) model grid and (b) different spatial regions considered in this study. In (a), grid lines show every 5 grid cells and black lines are bathymetric contours for every 10 m. Red dots indicate the location of the along-estuary transects for Figures 4.4. In (b), each color indicates a different region used in Figure 4.7. Regions were divided by latitude and water depth ($h<10$ m vs. $h>10$ m).
Figure 4.2: Time-series of model forcing

Panels include (a) combined water discharge from tributaries and overland flow into Chesapeake Bay from the EPA Watershed Model (USEPA, 2010; Shenk and Linker, 2013); (b) wind speed (blue line; left axis) and direction (red dots; right axis) toward which winds are blowing (in degrees clockwise from east) from NARR; and (c) significant wave height for a location outside the Bay at 20 m water depth estimated using SWAN (Booij et al., 1999). Shading indicates July 2000, the time period of focus for this paper.
Figure 4.3: Model comparison to satellite-derived estimates

Monthly averaged surface TSS (a,b; mg L\(^{-1}\)) and K\(_D\) (c,d; m\(^{-1}\)) based on climatologies derived from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data for July 2002-2013 (a,c; Son and Wang, 2012; Wang et al., 2009) and the standard model run (b,d) for July 2000.
Figure 4.4: Along-estuary transects of biogeochemical rates and concentrations

Estimates from the standard (left) and no-resuspension (center) model runs for a transect along the main channel of the Bay (location given in Figure 4.1). The change induced by resuspension (right) is calculated by subtracting estimates from the no-resuspension model run from those from the standard model run. All estimates were averaged over July 2000. Panels include (a) total suspended solids (b) POC concentration (c) primary productivity (Prod), (d) particulate organic matter remineralization rate (Remin), and concentrations of (e) oxygen and (f) ammonium.
Figure 4.5: Bed stresses in Chesapeake Bay

(a) Wave-induced bed shear stress, (b) current-induced bed shear stress, and (c) combined wave- and current-induced bed shear stresses, all averaged over July 2000. (d) Fraction of time in July 2000 when the combined wave- and current-induced bed shear stresses exceeded 0.03 Pa, the critical threshold for resuspension of mud and particulate organic matter.
Figure 4.6: Maps of biogeochemical rates and concentrations

Estimates from the (left) standard and (center) no-resuspension model runs; as well as the difference between the model runs (right), all averaged over July 2000. Panels include concentrations of (a) surface water TSS, (b) bottom water POC, (c) surface water primary productivity, (d) bottom water remineralization, and bottom water concentrations of (e) oxygen and (f) ammonium.
Figure 4.7: Regional Averages of biogeochemical rates and concentrations

Bar charts of biogeochemical rates and concentrations estimated by the standard (blue bars and lines) and no-resuspension (turquoise bars and lines) model runs. Estimates are for (a) surface TSS concentration, (b) bottom POC concentration, (c) surface primary productivity, (d) bottom remineralization, (e) bottom O2 concentration, and (f) bottom NH$_4$ concentration. Surface values were averaged over the top two grid cells and bottom water estimates were averages over the bottom two grid cells. All estimates were temporally averaged over July 2000 and spatially averaged for the grid cells within different regions of the Bay (Figure 4.1), including parts of the channel (left of the black dashed line) and parts of the shoals (right of the black dashed line). Bars represent the Upper Bay channel (UC; Region 2); Mid-to-Upper Bay channel (MUC; Region 4); Mid-to-Lower Bay channel (MLC; Region 6); Lower Bay channel (LC; Region 8); Upper Bay shoal (US; Region 1); Mid-to-Upper Bay shoal (MUS; Region 3); Mid-to-Lower Bay shoal (MLS; Region 5); Lower Bay shoal (LS; Region 7). Blue and turquoise lines represent estimates averaged over the entire Bay. Red error bars indicate the standard error of estimates over July 2000 and each specific region, but are small compared to the bars, and are not always visible.
Chapter 5

5. Conclusions
This dissertation evaluated the role of resuspension on oxygen and nitrogen dynamics in coastal environments utilizing a numerical modeling approach. To represent both physical and biogeochemical processes, a novel coupled hydrodynamic-sediment transport-biogeochemistry model called HydroBioSed was developed. This coupled model accounts for seabed and sediment transport processes including erosion, deposition, and diffusive fluxes across the seabed-water interface. HydroBioSed also accounts for biogeochemical processes including organic matter remineralization and oxidation of reduced chemical species, in both the seabed and the water column. To analyze the role of resuspension on oxygen and nitrogen dynamics in different coastal environments, the coupled model was then implemented for three different locations: the Rhône River subaqueous delta (Chapter 2), the Northern Gulf of Mexico (Chapter 3), and Chesapeake Bay (Chapter 4). The remainder of this chapter synthesizes the results from all three locations and discusses implications for future research.

5.1 Synthesis of Results

This modeling effort focused on a variety of coastal systems, but the results from all three sites considered here indicated that resuspension can substantially impact water column biogeochemical processes in coastal environments. In particular, this study focused on: (1) the well-mixed Rhône River subaqueous delta where the waters remained oxic; (2) the riverine-influenced northern Gulf of Mexico shelf where a thin hypoxic layer overlying the seabed develops during the summer; and (3) the large estuarine Chesapeake Bay where the location of low oxygen levels is largely constrained by bathymetry. To complement the main chapters of this dissertation, which were organized by study site, this section synthesizes the effect of resuspension on three different
processes including: remineralization of particulate organic matter, fluxes of dissolved oxygen and ammonium across the seabed-water interface, and light attenuation.

First, modeling results from all three locations showed that remineralization of resuspended organic matter could be a substantial sink of oxygen and source of ammonium to the bottom water column. Specifically, the enhancement in remineralization that occurred due to resuspension increased the production of ammonium. Aerobic remineralization of resuspended particulate organic matter also increased oxygen consumption. Additionally, resuspension-induced remineralization increased ammonium concentrations in the bottom portion of the water column, which stimulated nitrification. However, this increase in nitrification had a smaller effect on oxygen and ammonium concentrations compared to resuspension-induced changes in remineralization rates.

For the two study sites that experience summertime hypoxia, the northern Gulf of Mexico and Chesapeake Bay, remineralization of resuspended organic matter helped increase the expanse of these low-oxygen areas. Stratification and a large nutrient supply were sufficient to form low-oxygen regions near large sources of riverine input in these systems; i.e. near the Mississippi River Delta and in the Upper Bay, near the Susquehanna River; but accounting for resuspension-induced changes in organic matter concentrations contributed to the formation of low-oxygen regions further downstream. This result is consistent with previous studies showing that water column biogeochemistry in these downstream areas is relatively sensitive to sediment processes (Hetland and DiMarco, 2008; Testa and Kemp, 2012).
Our model results also showed that cycles of erosion and deposition can alter the timing and magnitude of seabed-water column fluxes. At all three locations, the model indicated that erosion altered the vertical profiles of dissolved oxygen by exposing the anoxic portion of the seabed to the overlying water column, which was usually more oxic than the erosional surface of the seabed. This increased the vertical gradient of oxygen at the seabed-water interface, thereby enhancing the associated diffusive flux of oxygen into the seabed. In contrast, the response of seabed-water column fluxes to deposition varied, depending on the lability assumed for deposited organic matter and the rate at which biogeochemical processes consumed oxygen in the seabed. As a result, when averaged over one or more resuspension events, fluxes of oxygen into the seabed often increased slightly, compared to time periods and model runs without resuspension. This allowed seabed oxygen consumption to increase or remain about constant when episodes of resuspension occurred, despite the temporary transfer of organic matter from the seabed to the water column that occurred during these time periods. This result explains the changes in oxygen profiles observed on the Rhône delta during resuspension events (Toussaint et al., 2014), and can help explain the resuspension-induced increase in oxygen consumption that is observed in laboratory experiments (e.g. Sloth et al., 1996).

The response of seabed-water column fluxes of ammonium to resuspension was more variable among the three sites in this modeling effort, compared to the response of oxygen fluxes. On the Rhône delta, exposure of the ammonium-rich seabed to the ammonium-poor water column during erosional periods caused a net increase in the flux of ammonium from the seabed to the water column. Although this exposure also occurred on the Gulf of Mexico shelf, resuspension there also further increased
ammonium concentrations in the water column due to enhanced rates of remineralization, as discussed above. In the Gulf of Mexico, this caused the model to estimate a net increase of ammonium fluxes into the seabed. Similarly, resuspension reduced the flux of ammonium out of the seabed in the Chesapeake Bay. This response highlights the increased variability in ammonium dynamics, compared to oxygen dynamics, which arises because ammonium may be formed in either the seabed or the water column. In contrast, oxygen is sourced to the surface water column from air-sea exchange or photosynthesis. The differences among different sites in the response of seabed fluxes of ammonium to resuspension at least partially explains the variability in estimates from laboratory experiments (e.g. Tengberg et al., 2003; Almroth et al., 2009; Sloth et al., 1996).

In addition to near bed processes induced by particulate and dissolved fluxes across the seabed-water interface, results from the Chesapeake Bay model showed that turbidity caused by resuspension can affect primary production. The results varied spatially, along the length of the Bay. In the Upper Bay, where phytoplankton growth was light-limited due to river inputs and the estuarine turbidity maximum, the resuspension-induced turbidity reduced photosynthesis. This reduction allowed more nitrogen to flow to the Mid- to Lower- Bay, stimulating primary production there. This shift in phytoplankton growth from primarily light-limited to nutrient-limited has also been observed to occur in the Gulf of Mexico (e.g. Quigg et al., 2011; Fennel et al., 2011), and so accounting for the effect of resuspension on light attenuation could result in a similar shift there.
Over timescales of a day to a month, the resuspension-induced reduction in primary productivity in the Upper Chesapeake Bay contributed to the reduction in oxygen concentrations and the increase in ammonium concentrations throughout the water column there. This sensitivity of model estimates of oxygen to primary production is consistent with previous modeling efforts, which showed that neglecting primary productivity increased the volume of hypoxic waters in Chesapeake Bay over the course of a season (Li et al., 2015). However, our result that reductions in primary productivity and photosynthesis contributed to reductions in oxygen concentrations differs from the result expected for longer timescales, i.e. that the decreased availability of organic matter would lower remineralization rates and increase oxygen levels (e.g., Kemp et al., 2009).

5.2 Implications for Future Research

Overall, the results of this numerical modeling effort indicated that cycles of erosion and deposition can impact estimates of remineralization rates, primary production and seabed-water column fluxes, even when model estimates were integrated over time periods longer than individual resuspension events, i.e. over one to two months. This result implies that these resuspension-induced biases should be considered when designing future modeling and observational studies, and when interpreting observations, in coastal marine environments.

For example, our results may inform future parameterizations of seabed and sediment processes in water column biogeochemistry models. For example, current parameterizations either ignore the role of resuspension, or assume that seabed oxygen consumption decreases during resuspension events (Capet et al., 2016) or when bed stresses are high (Feng et al., 2015). In contrast, this study, which represented seabed and
sediment processes more explicitly than in previous models, indicated that fluxes of oxygen into the seabed and seabed oxygen consumption often slightly increased when the model accounted for resuspension in coastal systems that were rich in organic matter. This result implies that future modeling efforts should adapt their parameterizations of seabed and sediment processes accordingly. Additionally, most models assume that organic matter cannot be resuspended once it has been deposited, but results from all three sites highlight that resuspended sediment can influence water column processes including remineralization and primary production.

In particular, the coupled model offers a method for developing parameterizations for the role of seabed and sediment processes that account for the role of resuspension on water column biogeochemistry. Statistical analyses, e.g. regressions of biogeochemical rates versus variables representing physical processes such as bed stress, may be useful for developing future parameterizations. A similar approach has been used, for example, to develop simple formulations to estimate the location of the salinity front on the Amazon shelf (Molinas et al., 2014); and to estimate the effect of inorganic sediment concentrations on light attenuation on the U.K. shelf (van der Molen et al., 2016). Although site-specific parameterizations are likely most accurate, using the coupled model to derive a general formulation that depends on environmental conditions could also be helpful. Overall, improving parameterizations of seabed and sediment processes will be especially useful for studies that must prioritize efficient computations, such as forecasting efforts; or model runs that represent long time periods or large areas.

Regarding observational and laboratory studies, results from this modeling effort imply that limiting sampling to quiescent time periods, with no data taken during episodic
resuspension events, may produce biases in observational estimates of biogeochemical processes. Care should be used when extrapolating observations from one study to new time periods characterized by different environmental conditions. Observing episodic events can be difficult due to cost and safety concerns, but approaches such as adaptive sampling, tripod-based measurements, and laboratory studies may offer approaches for obtaining data representative of storm and resuspension periods (e.g. Sloth et al., 1996; Berg and Huettel, 2008; Toussaint et al., 2014). Studies that compare time periods and sites that are similar, but are characterized by different hydrodynamic and sediment transport conditions, may also be helpful for further constraining the role of resuspension on water column biogeochemistry (e.g. Arzayus and Canuel, 2004; Pusceddu et al., 2005).

Additionally, the model estimates were sensitive to settling velocities and remineralization rate constants for particulate organic matter, but these values are difficult to constrain, motivating future observational and laboratory studies. It is relevant to note that our coupled model is likely more sensitive to these parameters than non-coupled water column biogeochemistry models. This is because many water column biogeochemistry models assume that organic matter cannot be resuspended and/or that organic matter is instantaneously remineralized or buried once it is deposited. These assumptions can make the model sensitive to the choice of the bottom boundary condition, but less sensitive to parameters that affect the transport and fate of organic matter over long periods of time, i.e. following deposition. In contrast, estimates from the coupled model were sensitive to these parameters in all three locations considered here. Although changes in parameters did not affect the general conclusions of modeling
effort, additional work to constrain these parameters would help to reduce the uncertainty in future studies.

The spatial and temporal variability of our results within individual systems highlights the importance of considering different environmental conditions and locations in future studies. In both the Chesapeake Bay and northern Gulf of Mexico, for example, the effects of resuspension differed in shallow versus deeper areas, and in regions closer to the river mouth versus farther downstream. This variability implied that application of the coupled model to different coastal systems would further increase our understanding of how resuspension affects biogeochemical processes, as well as oxygen and nutrient dynamics. Future studies, for example, could focus on regions without large riverine influences, or on systems where vegetation plays a role in sediment transport and biogeochemical processes.

In conclusion, our development of HydroBioSed, a coupled hydrodynamic-sediment transport-biogeochemical model, represents a novel method to address interdisciplinary research questions. This dissertation used the coupled model to focus on the role of seabed resuspension on biogeochemical dynamics in coastal environments. However, the framework developed here is especially powerful because it can be adapted to represent the transport of any particle-reactive or particulate material, such as hydrophobic contaminants or nutrients, or the cysts of harmful algal bloom species.

Development of this coupled model relied on open-source well-accepted models that were previously created within different scientific disciplines. Implementation and evaluation of the model also relied on observations from multiple disciplines, as well as recent technological advances such as adaptive sampling. Overall, this connectivity
among different scientific communities, combined with the successful development and use of HydroBioSed, demonstrates how community-developed open-source models, as well as collaborations between modelers and observational scientists, can advance scientific research.
References for Chapter 5


201


VITA

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