Sediment oxygen uptake and hypoxia: a simple mass-balance model for estuaries and coastal oceans

Jing Sun¹, Liuqian Yu², Xingyu Yang¹, Jianping Gan¹, Hongbin Yin³, and Jiying Li¹

¹The Hong Kong University of Science and Technology ²The Hong Kong University of Science and Technology (Guangzhou) ³Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences

March 14, 2024

Abstract

Hypoxia is increasing in coastal oceans. This is because eutrophication has increased oxygen consumption, while less oxygen is replenished to the bottom under stronger stratification. Quantifying these biogeochemical and physical drivers is important for management and predicting future trends. By using observations from the Pearl River Estuary (PRE) region (10-70 m deep) and similar coastal systems, this paper introduces a simple analysis to quantify both the biogeochemical and physical drivers of hypoxia. We show that in the PRE region, sediment respires >60% of organic matter produced in the water column, leading to high sediment oxygen uptake (average 41.1 ± 16.3 mmol m-2 d-1) and shallow oxygen penetrations (2-7 mm). The sediment's effect on the bottom oxygen loss becomes stronger with the reducing thickness of the bottom boundary layer. We then construct a generic mass-balance model to quantify oxygen loss, determine timescales of hypoxia formation, and explain within- and cross-system variabilities.

Sediment oxygen uptake and hypoxia: a simple mass-balance model for estuaries and coastal oceans

- 3 Jing Sun^{1,2}, Liugian Yu^{2,3*}, Xingyu Yang^{1,2}, Jianping Gan^{1,2}, Hongbin Yin⁴, and Jiying 4 Li^{1,2*} 5 6 7 ¹Department of Ocean Science, The Hong Kong University of Science and Technology, 8 Clear Water Bay, Kowloon, Hong Kong SAC, P. R. China 9 ²Center for Ocean Research in Hong Kong and Macau, Hong Kong SAC, P. R. China ³Earth, Ocean and Atmospheric Sciences Thrust, The Hong Kong University of Science 10 11 and Technology (Guangzhou), Guangdong, P.R. China 12 ⁴Nanjing Institute of Geography and Limnology, Chinese Academy of Science, Nanjing, 13 Jiangsu, P. R. China 14 15 Corresponding author: Jiying Li (jiyingli@ust.hk; OCRID: 0000-0003-1677-6922) 16 Liugian Yu (liugianyu@hkust-gz.edu.cn; OCRID: 0000-0002-5492-8213) 17 18 19 Key Points: 20 • Sediment respires >60% of the organic matter produced in the water column of 21 the Pearl River Estuary (PRE) region, leading to high sediment oxygen uptake. 22 • The sediment's effect on the bottom oxygen loss is controlled by the thickness of 23 the bottom boundary layer. 24 • We develop a simple and generic mass-balance model to understand hypoxia conditions and timescales in the PRE and similar coastal systems. 25
- 26

27 Abstract

28 Hypoxia is increasing in coastal oceans. This is because eutrophication has increased 29 oxygen consumption, while less oxygen is replenished to the bottom under stronger stratification, Quantifying these biogeochemical and physical drivers is important for 30 31 management and predicting future trends. By using observations from the Pearl River 32 Estuary (PRE) region (10-70 m deep) and similar coastal systems, this paper introduces a simple analysis to quantify both the biogeochemical and physical drivers of hypoxia. 33 34 We show that in the PRE region, sediment respires >60% of organic matter produced in 35 the water column, leading to high sediment oxygen uptake (average 41.1±16.3 mmol m⁻² 36 d⁻¹) and shallow oxygen penetrations (2-7 mm). The sediment's effect on the bottom 37 oxygen loss becomes stronger with the reducing thickness of the bottom boundary layer. We then construct a generic mass-balance model to quantify oxygen loss, determine 38 39 timescales of hypoxia formation, and explain within- and cross-system variabilities. 40

41 Plain language summary

42 Coastal oceans, especially those off rivers and estuaries, frequently experience low-43 oxygen conditions such as hypoxia (dissolved $O_2 < 2 \text{ mg L}^{-1}$). This is because the 44 nutrient-rich coastal ocean produces high amount of organic matter, which settles to the 45 bottom waters to consume oxygen. Hypoxia becomes more severe if the resupply of oxygen from the atmosphere and the surface water to the bottom water is blocked by 46 strong density stratification. To quantify these effects, we study a typical coastal system, 47 48 the Pearl River Estuary and the adjacent shelf, combining field and lab observations and 49 mass-balance modeling. We find that sediment consumes a substantial amount of 50 oxygen, and its contribution to hypoxia can be predicted if we know how thick the 51 stratified bottom layer is. We derive some simple equations to understand oxygen loss, 52 which can tell us what level of oxygen consumption can render the system hypoxia, and 53 for how long the stratification needs to be maintained for hypoxia to develop. We also show that the model is generic and can be applied to other similar coastal systems, such 54 55 as the northern Gulf of Mexico and the Changjiang Estuary region, to explain the 56 variability in hypoxia conditions and timescales.

57 **1 Introduction**

58 Low oxygen conditions are becoming more frequent in coastal oceans, affecting

59 biogeochemical cycles and marine life (Katsev et al., 2007; Levin et al., 2009;

60 Middelburg & Levin, 2009). These conditions are a result of high oxygen consumption

and weak ventilation, especially in bottom waters where oxygen depletion can be

severe, leading to hypoxia ($O_2 < 2 \text{ mg L}^{-1}$). In estuaries and coastal shelves, oxygen is

63 rapidly consumed due to the high organic matter production driven by terrestrial and/or

64 upwelling nutrients; freshwater inputs also enhance vertical density stratification and

reduce the oxygen resupply to the bottom. The increasing anthropogenic fertilization ofthe coastal ocean, together with the stronger stratification caused by global warming,

therefore, can intensify hypoxia in both magnitude and duration (Diaz & Rosenberg,2008).

Quantifying these physical and biogeochemical drivers of hypoxia is important for 69 management and predicting future trends. In addition to monitoring oxygen (Grégoire et 70 71 al., 2021), mechanistic modeling becomes very useful (Laurent & Fennel, 2017; Peña et al., 2010). These models simulate the oxygen budget considering its source/sink 72 73 components, including physical transports, air-sea exchanges, photosynthesis, and 74 biogeochemical consumption in the water column and sediments (Peña et al., 2010; 75 Testa et al., 2017). Among models of various complexity, coupled-physical-76 biogeochemical models are the most comprehensive, for they simulate the interactions 77 between nutrient-driven organic matter productivity and physical transport, the two major 78 drivers of oxygen variability (Fennel et al., 2016; Yu et al., 2015a, 2021). These models, 79 however, rely on parametrizations of many processes, for example, the relationships 80 between lights, temperature, nutrients, organic matter production, respiration, food-web dynamics, and the reactions in the sediments and benthic-pelagic exchanges (Peña et 81 82 al., 2010; Yu et al., 2015a, b, 2021). Moreover, parametrizations can be system-specific 83 and need to be well constrained by a large matrix of observations (e.g., dynamics in 84 biomass indicators, nutrients, and physical properties). Thus, the models usually have low transferability among systems (Peña et al., 2010). For cross-system comparison. 85 86 simple scale analyses are useful (Fennel & Testa, 2019). For example, the vulnerability of the system can be understood by comparing the timescale of hypoxia formation to the 87 water residence time of the region (Fennel & Testa, 2019). However, while such an 88 89 approach provides regional order-of-magnitude understanding, it is inadequate for 90 describing local heterogeneity, which is important for estuarine coastal systems. 91 This paper introduces a simple analysis that can describe regional heterogeneity 92 and also enables cross-system comparison. By using water column and sediment 93 oxygen data across a typical estuary and coastal shelf, we derive a simple massbalance model to understand oxygen loss without a detailed formulation of the physical 94 and biogeochemical complexity. The model can be used to understand the sensitivity of 95 96 the system to both the biogeochemical and physical drivers of hypoxia. We then discuss 97 how the model can be generalized to understand within-and cross-system variability.

using examples from similar coastal systems including the Northern Gulf of Mexico, theChangjiang Estuary region, and the Chesapeake Bay.

100

101 **2. Field Methods**

We study the Pearl River Estuary and adjacent shelf waters (PRE region) in the summer of 2021 (Fig.1a and Table.S1; Li et al. 2024). We used a SeaBird-SBE17-plus conductivity–temperature–depth (CTD) to measure the water column temperature, density, salinity, O_2 concentrations and calculated the buoyancy frequency (N^2 ; s⁻²):

106 $N^2 = \frac{g}{\rho(z)} \frac{d\rho(z)}{dz}$ Eq.1

107 *g* is gravity acceleration; z is water depth; ρ is potential density. High N^2 means high 108 stability of the water column.

Sediment cores with undisturbed overlying waters were collected using a Uwitec 109 corer. Oxygen micro-profiles were obtained using a Unisense O₂ electrode. The 110 111 sediment-water interface has the sharpest oxygen gradient. Oxygen penetration depth was defined as the depth where oxygen is under the detection limit of ~0.3 μ mol L⁻¹. 112 Total sediment oxygen uptake (SOU; mmol m⁻² d⁻¹), defined as the downward flux of 113 114 oxygen into the sediment, was determined using onboard whole-core incubations: sediment cores were stabilized, sealed, and monitored for the oxygen concentrations in 115 the overlying waters, which were gently stirred to generate the water movement and 116 117 create a diffusive boundary layer (Bowman & Delfino, 1980; Glud, 2008). SOU was calculated from the linear decrease of oxygen. The incubation typically lasts 2-3 hours. 118 119 Detailed methods are described in SI.1.

120

121 **3. Results**

3.1 Stratification and hypoxia in the water column – The water column develops 122 hypoxia within the nearshore waters (10-20 m) off the estuary during the summer 123 (Fig.1a), whereas offshore sites (>30 m) are well oxygenated. Such local seasonal 124 125 hypoxia has been observed for several recent years (Li et al., 2020; Yu et al., 2021). At most sites, the water column is stratified by vertical gradients of temperature and salinity 126 127 (Figs.1b and S1): the surface water from the upstream is warmer and fresher, while the bottom seawater is colder and saltier. In the stratified waters, the surface mixed layers 128 are thin, with the density drastically increasing below 5-10 m forming a pycnocline 129 (Fig.S1). This parallels the changes of buoyancy frequency (N^2) (Fig.1c), which peaks 130 within the pycnocline and decreases downward, until the density has little variation, 131 forming a stable bottom boundary layer (BBL; Figs.1c and S1) (Trowbridge & Lentz, 132 2018). We defined the upper boundary of BBL as the depth where N^2 increases 133 drastically above (i.e., $N^2 > 0.01 \text{ s}^{-2}$). The BBL has homogenously lower oxygen and 134 reaches hypoxia at some sites (Figs.1a and 1c). 135





Figure 1 Water column physiochemistry in the Pearl River Estuary region. a) Sampling locations and bottom oxygen concentrations; b) Temperature and salinity profiles across the estuary to open ocean gradient c) Buoyancy frequency (N^2) and O_2 profiles across the salinity gradient and at the hypoxic sites. Horizontal dashed lines represent the bottom.

3.2 Sediment oxygen uptake and bottom water oxygen – Oxygen concentration in 143 the BBL is controlled by the flux from the upper layer, which can be restricted by 144 stratification, and the consumption in the water and sediments. In the sediments, oxygen 145 drops sharply from 75-150 μ mol L⁻¹ near the interface to nondetectable (<0.3 μ mol L⁻¹) 146 147 within a few millimeters downcore (1-7 mm; Figs.2a and S3). Oxygen penetration decreases with decreasing water depths, consistent with global observations but more 148 dramatically compared to the open ocean (Figs. S4b and S4c). The drastic depletion of 149 oxygen in sediments is a result of high SOU (16.5-70.5 mmol m⁻² d⁻¹, average 41.1±16.3 150

151 mmol m⁻² d⁻¹; Fig.2b and Table.S1), consistent with typical coastal sediments (Fig.S4d).

152 Nearshore sediments have relatively higher SOU compared to offshore (Fig.2b). If we

assume oxygen is predominantly consumed via organic matter respiration, this

154 consumption averages to ~62±25% of the organic matter produced in the water column

155 of the region (66 mmol $m^{-2} d^{-1}$) (Cai et al., 2004).



156

Figure 2 Sediment oxygen distribution and uptake. a) O₂ profiles at selected sites; b)
sediment oxygen uptake (SOU).

159

High SOU would contribute significantly to the oxygen loss in the bottom water. 160 However, the correlation between SOU and bottom oxygen is weak (Fig.S5 and Yu et al. 161 162 (2015a)). This is because the thickness of the BBL would affect the sediment's impact: a thin layer would respond faster to SOU, while a thicker bottom reacts less with the effect 163 of SOU being diluted. Indeed, the hypoxia sites have thin BBL (1.3 to <10 m), whereas 164 the well-oxygenated sites have thicker BBL or entirely mixed water column (Figs.1c, S2, 165 and Table.S1). By normalizing SOU to the thickness of the BBL (h), we obtain the 166 oxygen depletion rate in the BBL by the sediments (SOU/*h*; mmol m⁻³ d⁻¹), which exhibits 167 a strong relationship with the bottom O₂ level (Fig.3a). A stronger correlation appears 168 when considering the integrated O_2 over the BBL (mmol m⁻²): oxygen decreases 169 exponentially with increasing SOU/h (Fig.3b). The relationships exist in similar systems 170 such as the northern Gulf of Mexico and the Changjiang Estuary region (Figs.3a and 171 3b); both are estuary dominated shelves experiencing hypoxia (McCarthy et al., 2013; 172 Zhu et al. 2016).). Similar relationships are also seen for the entire water column 173 174 (Fig.S6).





Figure 3 Bottom oxygen vs SOU normalized to BBL thickness (SOU/h). a and b) Bottom
oxygen vs SOU/h in the PRE region, North Gulf of Mexico (McCarthy et al., 2013), and
Changjiang Estuary region (Zhang et al., 2017); c and d) Modeled bottom oxygen vs SOU/h,
using water stability periods of T= 15 and 30 days.

182 The water column oxygen uptake (WOU) is not explicitly considered, but it does not 183 mean WOU is not important and omitted. Instead, the robust relationships suggest an 184 intrinsic connection between SOU and WOU, which are both driven by the degradation 185 of organic matter. Their proportions are determined by the water thickness, which 186 determines the time settling particles spend in the water and thus their leftovers to drive SOU. This explains the curvature in Fig.3b: at the sites with low SOU/h, the BBL is thick 187 and thus WOU becomes important, making the oxygen level sensitive to the apparent 188 per-SOU change (steeper slopes at low SOU/h in Figs.3b). 189

The strong correlations between oxygen level and SOU/*h* also suggest the possibility of parameterizing SOU. SOU is important in controlling the water column oxygen budget and sediment geochemistry and fluxes and rates (e.g., denitrification, sulfate reduction) (Li et al., 2018a, b; Li & Katsev, 2014), but published SOC data is scarce due to measurement challenges. The potential parameterization of SOU using more obtainable water column CTD data is useful.

4. The Mass-Balance Model — Inspired by the observations above, we construct a
 mass-balance model to explore their physical meanings and quantitative insights. Details

of the model are narrated in SI.2, which we briefly introduce here to facilitate discussion. The change of O_2 concentration in the BBL is caused by fluxes from above (assumed to

- be small and neglected here due to the large N_2 above the BBL) and the sediment (F_{s-O2} ,
- which equals –SOU), and the reaction within the BBL (F_{BBL-O2} , which equals –WOU_{BBL}):

202
$$\frac{\mathrm{d}\bar{C}_{\mathrm{BBL-O2}}}{\mathrm{d}t} = \frac{F_{\mathrm{S-O2}}}{h} + \frac{F_{\mathrm{BBL-O2}}}{h}$$
Eq.2

Here, C_{BBL-O2} is the average O₂ concentration in the BBL. Assuming oxygen is mostly consumed to respire organic matter (Zhang & Li, 2010), F_{BBL-O2} depends on the amount of organic carbon settling into the BBL (C_{W-C}^{H-h} ; *H* is the total depth and *h* is the thickness of the BBL, hence the upper boundary of BBL is at *H-h*; the subscript 'w-C' stands for water-column carbon), the reaction rate (k_w), and the time the particles spend in the BBL ($t=h/u_w$; u_w is the particle settling velocity). Considering a 1C:1O₂ ratio and first-order reaction for simplicity, the reaction in the BBL is

210
$$F_{\text{BBL}-\text{O2}} = \int_{H-h}^{H} -k_{\text{w}}C_{\text{w}-\text{C}} \, \mathrm{d}z_{\text{w}} = \int_{H-h}^{H} -k_{\text{w}}C_{\text{w}-\text{C}}^{H-h} e^{-\frac{k_{\text{w}}}{u_{\text{w}}}(z_{\text{w}}-H+h)} \, \mathrm{d}z_{\text{w}} = u_{\text{w}}C_{\text{C}}^{H-h} \left(e^{-\frac{k_{\text{w}}}{u_{\text{w}}}h} - \frac{k_{\text{w}}}{u_{\text{w}}}\right) \, \mathrm{d}z_{\text{w}} = u_{\text{w}}C_{\text{W}}^{H-h} \left(e^{-\frac{k_{\text{w}}}{u_{\text{w}}}h} - \frac{k_{\text{w}}}{u_{\text{w}}}h}\right) \, \mathrm{d}z_{\text{w}} = u_{\text{w}}C_{\text{w}}^{H-h} \left(e^{-\frac{k_{\text{w}}}{u_{\text{w}}}h} - \frac{k_{\text{w}}}{u_{\text{w}}}h}\right) \, \mathrm{d}z_{\text{w}} = u_{\text{w}}C_{\text{w}}^{H-h} \left(e^{-\frac{k_{\text{w}}}{u_{\text{w}}}h} - \frac{k_{\text{w}}}{u_{\text{w}}}h}\right) \, \mathrm{d}z_{\text{w}} = u_{\text{w}}C_{\text{w}}^{H-h} \left(e^{-\frac{k_{w}}}{u_{\text{w}}}h} - \frac{k_{w}}{u_{\text{w}}}h}\right) \, \mathrm{d}z_{\text{w}} = u_{\text{w}}^{H-h} \left(e^{-\frac{k_{w}}}{u_{\text{w}}}h\right)$$

211 1) =
$$-WOU_{BBL}$$
 Eq.3

where C_{w-C} is the concentration of organic matter in the water column; z_w is the vertical

- 213 displacement. Similarly, for pseudo-steady-state consideration, the O_2 flux into the
- sediment equals the organic carbon flux ($u_w C_{w-C}^H$; C_{w-C}^H is the concentration at the
- sediment-water interface at depth H) corrected by a recycling efficiency (ε) for not all
- organic matter reaching sediments being reactive (Li et al., 2012):

217
$$F_{s-O2} = -\varepsilon u_w C_c^H = -SOU$$
 Eq.4

Because sedimentation $(u_w C_c^H)$ is from the leftover of remineralization in the water column:

220
$$u_{w}C_{w-C}^{H} = u_{w}C_{w-C}^{H-h} + F_{BBL-O2}$$
 Eq.5

221 Combining Eqs.3, 4, and 5,

222
$$F_{s-O2} = -\varepsilon u_w C_{w-C}^H = -\varepsilon \left(u_w C_{w-C}^{H-h} + F_{BBL-O2} \right) = -\varepsilon u_w C_{w-C}^{H-h} e^{-\left(\frac{\kappa_w}{u_w}\right)h}$$
Eq.6

(]- \

223 Therefore, from Eqs. 3 and 6,

224
$$F_{\text{BBL}-02} = \frac{1}{\varepsilon} \left(e^{\left(\frac{k_{\text{W}}}{u_{\text{W}}}\right)h} - 1 \right) F_{\text{s}-02} = \frac{1}{\varepsilon} \left(e^{fh} - 1 \right) F_{\text{s}-02}$$
 Eq.7.1

- 225 or WOU_{BBL} = $\frac{1}{\varepsilon} (e^{fh} 1)$ SOU Eq.7.2
- For simplicity, we introduce a parameter, spatial reactivity ($f = k_w/u_w$, m⁻¹), which

227 describes the reaction proceeded per-unit distance the particles move downwards.

- 228 Eq.7.2 shows how WOU_{BBL} and SOU are related (see observations above). We then
- rewrite the oxygen budget by combining Eq.7 and Eq.2 and integrating it over a period
- 230 (*T*), during which the present oxygen level develops:

231 AOU_{BBL}
$$h = T\left(1 + \frac{1}{\varepsilon}(e^{fh} - 1)\right)$$
SOU Eq.8

AOU_{BBL} is the apparent oxygen utilization in the BBL. In summary, oxygen utilization in the BBL is determined by the SOU, the spatial reactivity of organic matter (*f*), the thickness of BBL (*h*), the recycling efficiency in sediments (ε), and the duration (*T*) of stratification to develop the AOU. Similarly, for the whole water column,

236 AOU ×
$$H = T\left(1 + \frac{1}{\varepsilon}(e^{fH} - 1)\right)$$
SOU Eq.9

237 and WOU = $\frac{1}{s} (e^{fH} - 1)$ SOU Eq.10

One may fit the data (SOU, h, H, and AOU) to estimate the parameters (f, ε , and T). 238 239 However, as the data is limited and scattered, fitting them to a model with multiple parameters will lead to overfitting producing wrong results. As we are interested in the 240 physical insights rather than definite values (also not realistic as they are naturally 241 242 variable), we choose to fix the sediment recycling efficiency as $\varepsilon = 0.5$, for that the deep sediments bury about half of the organic matter reaching the seafloor (Zhou, 2022), 243 244 consistent with observations in shallow-oxygenated sediments (Li et al., 2018b). We use 245 T=15 days for the lack of information, but also constrained by observations that stratification and hypoxia take two weeks to redevelop after the water column is mixed 246 up (Zhao et al., 2021). Under these constraints, we obtain an organic matter spatial 247 reactivity of $f = 0.026 \text{ m}^{-1}$ for the PRE region, and the model reproduces the water column 248 AOU well (Fig.S7). The estimate is consistent with the rate of organic matter 249 remineralization estimated for water depth (H) of 10-20 m and that 62% of the organic 250 251 matter reaches the seafloor: $f = (1-0.62)/H = 0.014-0.028 \text{ m}^{-1}$ (details in SI.3).

252 **5. Discussion**

5.1 Conditions and time scales for hypoxia— The model explains the relationships between the bottom O_2 level and SOU/*h* in the PRE region and other similar systems (Figs.3c and 3d). The duration of stratification determines the sensitivity of O_2 levels to SOU/*h*: the northern Gulf of Mexico has long periods of stratification (Bianchi et al., 2010; Dzwonkowski et al., 2018) and thus appears more sensitive to SOU: the bottom oxygen drops more with the same level of increase in SOU/*h* (Figs.3a and 3b). This is

consistent with model results when the stratification period is set to be longer (e.g., T= 30 versus 15 d; Figs.3c and 3d). Alternatively, the high sensitivity of oxygen can be

achieved in systems with higher spatial reactivity of settling organic matter (*f*) (Fig.S8). The model provides several quantitative insights. As expected, AOU_{BBL} increases with increasing SOU and the effect is more dramatic when BBL is thin (Fig.4a). In the PRE region, a BBL of <10 m is susceptible to hypoxia even at low SOU (Fig.4a). For thicker BBL to reach hypoxia, higher SOU is required, but the effect is not linear: in the PRE region, when SOU is above ~75 mmol m⁻² d⁻¹, the bottom can easily develop hypoxia regardless of the BBL thickness (Fig.4a). This is because, in environments with organic matter deposition supporting such high SOU, the WOU would be proportionallyhigh (Eq.7.2).

270 We can estimate the time required for developing hypoxia (Figs.4b): waters with high SOU and thin BBL become hypoxic within a shorter time. In the PRE region, it 271 272 requires <~15 days for thin BBLs (<~10 m) to develop hypoxia; the thicker BBLs require 273 longer, but in general not longer than 60 days (Fig.4b). Assuming similar organic matter 274 spatial reactivity (f) in other coastal waters (but see discussion later for variability), we can estimate their hypoxia time scales (T_{hyp} ; Fig.4c), which can be compared to the 275 276 stratification time scales to see if hypoxia can develop. For example, in the seasonally hypoxic northern Gulf of Mexico, most hypoxia sites have T_{hyp} of <30-40 days, which is 277 278 generally shorter than the duration of stratification (30 days to several months) (Bianchi 279 et al., 2010). In the Chesapeake Bay mid-stem central channel, the pycnocline remains stable for several summer months (Boynton et al., 2022), thus hypoxia persistently 280 develops even under low SOU (Fig.4c). More extreme cases are Gulf of St. Lawrence, 281 282 the Black Sea, and the Baltic Sea, where persistent and even permanent stratification sustains thick hypoxia layers under low SOU (Fig.4c). 283





285 Figure 4 Modeled apparent oxygen utilization (AOU) and time scales for developing

286 **hypoxia** (T_{hyp}). a) AOU_{BBL} as a function of SOU and BBL thickness in the PRE region (f=

287 0.026 m^{-1} and T= 15 d). Higher AOU indicates higher oxygen loss and hypoxia occurs when 288 AOU_{BBL} > 125 mmol m^{-3} (observed bottom O₂ levels are shown with filled colors for

289 comparison); **b**) the time required for the BBL to become hypoxia (T_{hyp}) (f= 0.026 m⁻¹). If

290 stratification sustains longer than T_{hyp}, the bottom water becomes hypoxic. The sites with

thick BBL and low SOU need a longer time to develop hypoxia thus the oxygen

292 concentrations remain high. **c**) same as **b** but hypoxia sites from other estuarine and coastal

systems (Table S3) (Boynton et al., 2019, 2022; Fennel & Testa, 2019; McCarthy et al., 2013;
 Zhang et al., 2017).

295

296 5.2 Sediments vs water column oxygen uptake— The model can estimate the 297 contribution of SOU to total oxygen loss (%SOU) and explain the global observations in estuaries and coasts (Boynton et al., 2018) (Fig.5): %SOU declines exponentially with 298 299 the water layer thickness (for whole water column or BBL). Intuitively, the organic matter spends more time in thicker waters consuming oxygen before reaching the sediments, 300 301 thus reducing the %SOU. The model (Eqs.7.2 and 10) formulates this understanding 302 and explains the possible variabilities: %SOU is regulated by the organic matter spatial reactivity (f) and sediment recycling efficiency (ε). In systems with slowly settling 303 304 particles (low u_w), the large f (k_w/u_w) would lead to low %SOU (Fig.5). In contrast, SOU contributes more when sedimentation is rapid (large u_w and thus small f, Fig.5). Particle 305 settling velocity is controlled by particle concentrations (Archer & Devol, 1992), but more 306 307 importantly by turbulence intensity, which can either accelerates settling by promoting 308 particle collisions and flocculation (Ruiz et al., 2004) or decrease it by breaking up floc when shear stress is too large (Manning, 2004). In rivers and estuaries, strong 309 310 turbulence also leads to particle resuspension (Boynton et al., 2018), increasing the time the particles spend in the water column to consume oxygen (Moriaty et al. 2021). This 311 312 might explain why rivers and estuaries have low %SOU compared to shelves (Fig.5), 313 where the reactivity of organic matter (k_w) is likely similar if not higher because the 314 organic matter is more planktonic-origin. Likewise, low spatial reactivity in shelf waters 315 may be due to higher particle settling velocity for reasons we can only speculate: salinity 316 increase (Abolfazli & Strom, 2023) and blooming of typically dominated elongated or 317 chains-forming phytoplankton species can promote flocculation and fast settling 318 (Arguedas-Leiva et al., 2022). Sediment recycling efficiency regulates %SOC but to a lesser extent (the shaded area in Fig.5), and the effect becomes smaller when the 319 320 organic matter spatial reactivity is high (see variability in the width of the shaded area in Fig. 5), as there is less organic matter reaching the sediment for recycling efficiency to 321 322 make a difference.



Figure 5 The contributions of SOU to total oxygen uptake (SOU +WOU) as a function of 324 325 water layer thickness (for the entire water column or BBL). The solid line represents model 326 results for the PRE region ($\varepsilon = 0.5$; f= 0.026). Results obtained using different spatial 327 reactivities (f) are shown in dotted and dashed lines; shaded areas show variability with different sediment recycling efficiency (ε = 0.3-0.75). Literature data are from (Boynton et al., 328 329 2018; Chi et al., 2021; Kemp et al., 1992; Murrell & Lehrter, 2011). Solid markers indicate 330 average values and the open markers of the corresponding colors are individual measurements. 331

332

6. Summary, caveats, and outlooks

334 Using data in the PRE region, we construct and test a simple mass balance model 335 to understand bottom hypoxia in coastal waters. The model describes oxygen utilization in the BBL due to the sediment and water oxygen uptake (Eqs.8 and 9). While SOU 336 needs to be measured, we show that bottom oxygen levels and water-column 337 stratification can be used to parameterize SOU and increase the data size (Fig.3). WOU 338 is linked to SOU in the model via their intrinsic mass-balance connection (Eqs.7.2 and 339 340 10). Therefore, by having data on the water column physical and oxygen conditions 341 across a region (easily obtained from CTD) and some estimates of SOU, the model can 342 estimate other determinants of oxygen loss and quantitatively describe the conditions 343 and time scales for hypoxia formation, as well as the contributions from water column 344 versus sediments.

There are several caveats to using the model. It should be used within areas with similar particle settling velocity and organic matter reactivity. These parameters can vary significantly across regions. Ideally, parameters can be chosen or fitted more locally (e.g., differentiating the inner estuary and the offshore shelf). Moreover, SOU is assumed to be stable during the development of the observed oxygen level, but SOU can decrease when oxygen becomes very limited (<1.5–3.2 mg L⁻¹) (Chi et al., 2021; Murrell

- & Lehrter, 2011; Rowe et al., 2002). Therefore, for the model to work, SOU might need to 351 be measured under sufficient overlying-water oxygen (reaction not limited by oxygen) at 352 353 sites with very low oxygen levels. Other complications of the physical conditions need to 354 be considered, for example, when stratification is disrupted by a typhoon. Despite these 355 limitations, the model provides intuitive and quantitative estimates of hypoxia and can be 356 used to understand the variability among systems and changes under future scenarios 357 (e.g., longer stratification under climate change). The model can also help estimate key constraints, such as the reactivity and settling velocity of particles, to support other 358 359 mechanistic models.
- 360

361 Acknowledgment

362 The work is substantially supported by grants from the Research Grant Council (RGC) of the Hong Kong Special Administrative Region, China (Project Reference Numbers: 363 16303022 and 26305621 to JL, a grant from the National Natural Science Foundation of 364 365 China to LY (Project No. 42206160), and grants from RGC to JG and LY (Project Reference Numbers: 16307423 and AoE/P-601/23-N to JG). The work is also funded by 366 367 the Center for Ocean Research in Hong Kong and Macau (CORE). CORE is a joint 368 research center for ocean research between Laoshan Laboratory and Technology and 369 the Hong Kong University of Science and Technology (HKUST). We thank the captain 370 and crew of the R/V Haike 68 and Chief Scientists Zhongming Lu and Isaac Cheung for assisting in sample collection. Lei Zhou is acknowledged for assistance in sediment 371 sample collection and field analysis. We thank Mark J. McCarthy (Estonian University of 372 373 Life Sciences) and Wayne S. Gardner (University of Texas at Austin) for providing CTD 374 data from the Northern Gulf of Mexico. These data were collected aboard the R/V Pelican (Louisiana University Marine Consortium) supported by the NOAA/CSCOR 375 376 Grant (#NA07NOS4780225) to Wayne Gardner. We thank Weicong Cheng and Dou Li 377 for their technical and intellectual support.

378

379 Author contributions:

- 380 Conceptualization: Jiying Li
- 381 Investigation: Jing Sun, Jiying Li, and Xingyu Yang
- 382Data curation: Jing Sun, Jiying Li, and Xingyu Yang
- 383 Formal analysis: Jing Sun, Jiying Li, and Liuqian Yu
- 384 Methodology: Jing Sun, Jiying Li, Liuqian Yu, and Jianping Gan
- 385 Funding acquisition: Jiying Li, Liuqian Yu, and Jianping Gan
- 386 Project administration: Jiying Li and Jianping Gan
- 387 Supervision: Jiying Li
- 388 Writing—original draft: Jing Sun and Jiying Li
- 389 Writing—review& editing: Jiying Li, Liuqian Yu, Hongbin Yin, and Jianping Gan
- 390
- **Data Availability Statement**

- 392 Data presented in the paper are available at DataSpace@HKUST via
- 393 doi:10.14711/dataset/KCLUQW (Li et al. 2024). Data from the Changjiang estuary region
- are from Zhang et al. 2017 and Chi et al. 2021; Data from the Northern Gulf of Mexico
- are from McCarthy et al. 2013; Data from the Chesapeake Bay are from Boynton et al.
- 396 (2018), Boynton et al. (2022), Boynton and Ceballos (2019), Kemp et al. (1992), and the
- 397 Chesapeake Bay Program Datahub (https://datahub.chesapeakebay.net). Additional
- data from other systems are also compiled in Fennel and Testa (2019), Boynton et al.
- 399 (2018), Boynton et al. (2022), and Kemp et al. (1992).
- 400

401 **References**

- 402
- Abolfazli, E., & Strom, K. (2023). Salinity Impacts on Floc Size and Growth Rate With and Without
 Natural Organic Matter. *Journal of Geophysical Research: Oceans*, *128*(7).
- 405 https://doi.org/10.1029/2022jc019255
- 406 Archer, D., & Devol, A. (1992). Benthic oxygen fluxes on the Washington shelf and slope: A
 407 comparison of in situ microelectrode and chamber flux measurements. *Limnology and*
- 408 Oceanography, 37(3), 614–629. <u>https://doi.org/10.4319/lo.1992.37.3.0614</u>
- Arguedas-Leiva, J.-A., Słomka, J., Lalescu, C. C., Stocker, R., & Wilczek, M. (2022). Elongation
 enhances encounter rates between phytoplankton in turbulence. *Proceedings of the National Academy of Sciences*, *119*(32), e2203191119. https://doi.org/10.1073/pnas.2203191119
- 412 Bianchi, T. S., DiMarco, S. F., Cowan, J. H., Hetland, R. D., Chapman, P., Day, J. W., & Allison,
- M. A. (2010). The science of hypoxia in the Northern Gulf of Mexico: A review. *Science of The Total Environment*, 408(7), 1471–1484. <u>https://doi.org/10.1016/j.scitotenv.2009.11.047</u>
- Bowman, G. T., & Delfino, J. J. (1980). Sediment oxygen demand techniques: A review and
 comparison of laboratory and in situ systems. *Water Research*, *14*(5), 491–499.
- 417 <u>https://doi.org/10.1016/0043-1354(80)90215-8</u>
- Boynton, Fraser, W. C., & Alejandra, M. (2019). Chesapeake Bay and Maryland Coastal Bays
 Sediment-Water Oxygen and Nutrient Flux Data Set. *Mendeley Data*, (V1).
 https://doi.org/10.17632/jpwvc5jytk.1
- Boynton, W. R., Ceballos, M. A. C., Bailey, E. M., Hodgkins, C. L. S., Humphrey, J. L., & Testa, J.
 M. (2018). Oxygen and Nutrient Exchanges at the Sediment-Water Interface: a Global
- 423 Synthesis and Critique of Estuarine and Coastal Data. *Estuaries and Coasts*, *41*(2), 301–333.
 424 https://doi.org/10.1007/s12237-017-0275-5
- 425 Boynton, W. R., Ceballos, M. A. C., Hodgkins, C. L. S., Liang, D., & Testa, J. M. (2022). Large-
- Scale Spatial and Temporal Patterns and Importance of Sediment–Water Oxygen and
 Nutrient Fluxes in the Chesapeake Bay Region. *Estuaries and Coasts*, 1–20.
- 428 https://doi.org/10.1007/s12237-022-01127-0
- 429 Cai, W.-J., Dai, M., Wang, Y., Zhai, W., Huang, T., Chen, S., et al. (2004). The biogeochemistry
- 430 of inorganic carbon and nutrients in the Pearl River estuary and the adjacent Northern South
- 431 China Sea. *Continental Shelf Research*, 24(12), 1301–1319.
- 432 <u>https://doi.org/10.1016/j.csr.2004.04.005</u>

433 Chi, L., Song, X., Ding, Y., Yuan, Y., Wang, W., Cao, X., et al. (2021). Heterogeneity of the 434 sediment oxygen demand and its contribution to the hypoxia off the Changjiang estuary and 435 its adjacent waters. Marine Pollution Bulletin, 172, 112920. 436 https://doi.org/10.1016/j.marpolbul.2021.112920 437 Diaz, R. J., & Rosenberg, R. (2008). Spreading Dead Zones and Consequences for Marine 438 Ecosystems. Science, 321(5891), 926–929. https://doi.org/10.1126/science.1156401 Dzwonkowski, B., Fournier, S., Reager, J. T., Milroy, S., Park, K., Shiller, A. M., et al. (2018). 439 440 Tracking sea surface salinity and dissolved oxygen on a river-influenced, seasonally stratified 441 shelf, Mississippi Bight, northern Gulf of Mexico. Continental Shelf Research, 169, 25-33. 442 https://doi.org/10.1016/j.csr.2018.09.009 443 Fennel, K., & Testa, J. M. (2019). Biogeochemical Controls on Coastal Hypoxia. Annual Review 444 of Marine Science, 11(1), 105–130. https://doi.org/10.1146/annurev-marine-010318-095138 445 Fennel, K., Laurent, A., Hetland, R., Justić, D., Ko, D. S., Lehrter, J., et al. (2016). Effects of 446 model physics on hypoxia simulations for the northern Gulf of Mexico: A model intercomparison. Journal of Geophysical Research: Oceans, 121(8), 5731-5750. 447 448 https://doi.org/10.1002/2015jc011577 449 Glud, R. N. (2008). Oxygen dynamics of marine sediments. Marine Biology Research, 4(4), 243-450 289. https://doi.org/10.1080/17451000801888726 451 Grégoire, M., Garcon, V., Garcia, H., Breitburg, D., Isensee, K., Oschlies, A., et al. (2021). A 452 Global Ocean Oxygen Database and Atlas for Assessing and Predicting Deoxygenation and 453 Ocean Health in the Open and Coastal Ocean. Frontiers in Marine Science, 8, 724913. 454 https://doi.org/10.3389/fmars.2021.724913 455 Katsev, S., Chaillou, G., Sundby, B., & Mucci, A. (2007). Effects of progressive oxygen depletion 456 on sediment diagenesis and fluxes: A model for the lower St. Lawrence River Estuary. Limnology and Oceanography, 52(6), 2555–2568. https://doi.org/10.4319/lo.2007.52.6.2555 457 458 Kemp, W., Sampou, P., Garber, J., Turtle, J., & Boynton, W. (1992). Seasonal depletion of 459 oxygen from bottom waters of Chesapeake Bay: roles of benthic and planktonic respiration 460 and physical exchange processes. Marine Ecology Progress Series, 85, 137–152. 461 https://doi.org/10.3354/meps085137 462 Laurent, A., & Fennel, K. (2017). Modeling Coastal Hypoxia, Numerical Simulations of Patterns, 463 Controls and Effects of Dissolved Oxygen Dynamics, 149–171. https://doi.org/10.1007/978-3-464 319-54571-4 7 465 Levin, L. A., Ekau, W., Gooday, A. J., Jorissen, F., Middelburg, J. J., Nagvi, S. W. A., et al. 466 (2009). Effects of natural and human-induced hypoxia on coastal benthos. *Biogeosciences*, 467 6(10), 2063–2098. https://doi.org/10.5194/bg-6-2063-2009 468 Li, D., Gan, J., Hui, R., Liu, Z., Yu, L., Lu, Z., & Dai, M. (2020). Vortex and Biogeochemical 469 Dynamics for the Hypoxia Formation Within the Coastal Transition Zone off the Pearl River 470 Estuary. Journal of Geophysical Research: Oceans, 125(8). https://doi.org/10.1029/2020jc016178 471

- Li, J., & Katsev, S. (2014). Nitrogen cycling in deeply oxygenated sediments: Results in Lake
- 473 Superior and implications for marine sediments. *Limnology and Oceanography*, 59(2), 465–
 474 481. <u>https://doi.org/10.4319/lo.2014.59.2.0465</u>
- Li, J., Crowe, S. A., Miklesh, D., Kistner, M., Canfield, D. E., & Katsev, S. (2012). Carbon
- 476 mineralization and oxygen dynamics in sediments with deep oxygen penetration, Lake
 477 Superior. *Limnology and Oceanography*, 57(6), 1634–1650.
- 478 https://doi.org/10.4319/lo.2012.57.6.1634
- Li, J., Zhang, Y., & Katsev, S. (2018a). Phosphorus recycling in deeply oxygenated sediments in
- 480 Lake Superior controlled by organic matter mineralization. *Limnology and Oceanography*,
- 481 63(3), 1372–1385. <u>https://doi.org/10.1002/lno.10778</u>
- Li, J., Brown, E. T., Crowe, S. A., & Katsev, S. (2018b). Sediment geochemistry and contributions
 to carbon and nutrient cycling in a deep meromictic tropical lake: Lake Malawi (East Africa). *Journal of Great Lakes Research*, 44(6), 1221–1234. https://doi.org/10.1016/j.jglr.2017.12.001
- Li, J., Sun, J, Yu, L., Gan, J., & Yang, X. (2024). Sediment oxygen uptake and hypoxia in the Pearl River Estuary Region [Dataset]. DataSpace@HKUST,
- 487 https://doi:10.14711/dataset/KCLUQW
- Manning, A. J. (2004). The Observed Effects of Turbulence on Estuarine Flocculation. *Journal of Coastal Research. Sediment Transport in European Estuarine Environments: Proceedings of the STRAEE Workshop (WINTER 2004):*, (Special Issue No. 41), 90–104. Retrieved from
 https://www.jstor.org/stable/25736634
- 492 McCarthy, M. J., Carini, S. A., Liu, Z., Ostrom, N. E., & Gardner, W. S. (2013). Oxygen
- 493 consumption in the water column and sediments of the northern Gulf of Mexico hypoxic zone.
- 494 Estuarine, Coastal and Shelf Science, 123, 46–53. <u>https://doi.org/10.1016/j.ecss.2013.02.019</u>
- 495 Middelburg, J. J., & Levin, L. A. (2009). Coastal hypoxia and sediment biogeochemistry.
- 496 Biogeosciences, 6(7), 1273–1293. <u>https://doi.org/10.5194/bg-6-1273-2009</u>
- 497 Moriarty, J. M., Friedrichs, M. A. M., & Harris, C. K. (2021). Seabed Resuspension in the
- Chesapeake Bay: Implications for Biogeochemical Cycling and Hypoxia. *Estuaries and Coasts*, 44(1), 103–122. <u>https://doi.org/10.1007/s12237-020-00763-8</u>
- Murrell, M. C., & Lehrter, J. C. (2011). Sediment and Lower Water Column Oxygen Consumption
 in the Seasonally Hypoxic Region of the Louisiana Continental Shelf. *Estuaries and Coasts*,
 34(5), 912–924. https://doi.org/10.1007/s12237-010-9351-9
- Peña, M. A., Katsev, S., Oguz, T., & Gilbert, D. (2010). Modeling dissolved oxygen dynamics and
 hypoxia. *Biogeosciences*, 7(3), 933–957. https://doi.org/10.5194/bg-7-933-2010
- Rowe, G. T., Kaegi, M. E. C., Morse, J. W., Boland, G. S., & Briones, E. G. E. (2002). Sediment
 community metabolism associated with continental shelf hypoxia, Northern Gulf of Mexico.
 Estuaries, 25(6), 1097–1106. <u>https://doi.org/10.1007/bf02692207</u>
- 508 Ruiz, J., Macías, D., & Peters, F. (2004). Turbulence increases the average settling velocity of
- 509 phytoplankton cells. Proceedings of the National Academy of Sciences, 101(51), 17720–
- 510 17724. <u>https://doi.org/10.1073/pnas.0401539101</u>

511 Testa, J. M., Li, Y., Lee, Y. J., Li, M., Brady, D. C., Toro, D. M. D., & Kemp, W. M. (2017). 512 Modeling Coastal Hypoxia, Numerical Simulations of Patterns, Controls and Effects of 513 Dissolved Oxygen Dynamics, 95–118. https://doi.org/10.1007/978-3-319-54571-4 5 514 Trowbridge, J. H., & Lentz, S. J. (2018). The Bottom Boundary Layer. Annual Review of Marine 515 Science, 10(1), 397-420. https://doi.org/10.1146/annurev-marine-121916-063351 516 Wulff, F., & Stigebrandt. A. (1989). A time-dependent budget model for nutrients in the Baltic Sea. 517 Glob. Biogeochem. Cycles 3: 63-78. https://doi:10.1029/gb003i001p00063 Yu, L., Fennel, K., Laurent, A., Murrell, M. C., & Lehrter, J. C. (2015a), Numerical analysis of the 518 519 primary processes controlling oxygen dynamics on the Louisiana shelf. *Biogeosciences*, 520 12(7), 2063–2076. https://doi.org/10.5194/bg-12-2063-2015 521 Yu, Liuqian, Fennel, K., & Laurent, A. (2015b). A modeling study of physical controls on hypoxia generation in the northern Gulf of Mexico: Physical Controls on Hypoxia. Journal of 522 523 Geophysical Research: Oceans, 120(7), 5019–5039. https://doi.org/10.1002/2014jc010634 524 Yu, Liuqian, Gan, J., Dai, M., Hui, C. R., Lu, Z., & Li, D. (2021). Modeling the role of riverine 525 organic matter in hypoxia formation within the coastal transition zone off the Pearl River 526 Estuary. Limnology and Oceanography, 66(2), 452-468. https://doi.org/10.1002/lno.11616 527 Zhang, Haiyan, Zhao, L., Sun, Y., Wang, J., & Wei, H. (2017). Contribution of sediment oxygen 528 demand to hypoxia development off the Changjiang Estuary. Estuarine, Coastal and Shelf 529 Science, 192, 149–157. https://doi.org/10.1016/j.ecss.2017.05.006 530 Zhang, Heng, & Li, S. (2010). Effects of physical and biochemical processes on the dissolved 531 oxygen budget for the Pearl River Estuary during summer. Journal of Marine Systems, 79(1-532 2), 65-88. https://doi.org/10.1016/j.jmarsys.2009.07.002 533 Zhao, Y., Uthaipan, K., Lu, Z., Li, Y., Liu, J., Liu, H., et al. (2021). Destruction and reinstatement 534 of coastal hypoxia in the South China Sea off the Pearl River estuary. *Biogeosciences*, 18(8), 535 2755-2775. https://doi.org/10.5194/bg-18-2755-2021 536 Zhou, L. (2022). Sediment oxygen uptake and carbon mineralization in the Pearl River Estuary and adjacent coastal waters. https://doi.org/10.14711/thesis-991013088359403412 537 Zhu, J., Zhu, Z., Lin, J., Wu, H., & Zhang, J. (2016). Distribution of hypoxia and pychocline off the 538 539 Changjiang Estuary, China. Journal of Marine Systems, 154, 28-40. 540 https://doi.org/10.1016/j.jmarsys.2015.05.002 541

542 **References From the Supporting Information**

- APHA (1998) Standard Methods for the Examination of Water and Wastewater. 20th Edition,
 American Public Health Association, American Water Works Association and Water
 Environmental Federation, Washington DC.
- Boynton, W. R., Ceballos, M. A. C., Hodgkins, C. L. S., Liang, D., & Testa, J. M. (2022). Large-546 547 Scale Spatial and Temporal Patterns and Importance of Sediment–Water Oxygen and Nutrient 548 Fluxes in the Chesapeake Bay Region. Estuaries and Coasts, 1–20. 549 https://doi.org/10.1007/s12237-022-01127-0
- 550 Cai, W. J., Dai, M., Wang, Y., Zhai, W., Huang, T., Chen, S., et al. (2004). The biogeochemistry
- of inorganic carbon and nutrients in the Pearl River estuary and the adjacent Northern South

- 552 China Sea. Continental Shelf Research, 24(12), 1301–1319.
- 553 <u>https://doi.org/10.1016/j.csr.2004.04.005</u>
- 554 Cannaby, H., Fach, B. A., Arkin, S. S., & Salihoglu, B. (2015). Climatic controls on biophysical
- interactions in the Black Sea under present day conditions and a potential future (A1B) climate
 scenario. *Journal of Marine Systems*, *141*, 149–166.

557 <u>https://doi.org/10.1016/j.jmarsys.2014.08.005</u>

- 558 Capet, A., Beckers, J.-M., & Grégoire, M. (2013). Drivers, mechanisms and long-term variability 559 of seasonal hypoxia on the Black Sea northwestern shelf – is there any recovery after
- 560 eutrophication? *Biogeosciences*, *10*(6), 3943–3962. https://doi.org/10.5194/bg-10-3943-2013
- 561 Capet, Arthur, Meysman, F. J. R., Akoumianaki, I., Soetaert, K., & Grégoire, M. (2016).
- 562 Integrating sediment biogeochemistry into 3D oceanic models: A study of benthic-pelagic 563 coupling in the Black Sea. *Ocean Modelling*, *101*, 83–100.
- 564 <u>https://doi.org/10.1016/j.ocemod.2016.03.006</u>
- Fennel, K., & Testa, J. M. (2019). Biogeochemical Controls on Coastal Hypoxia. *Annual Review of Marine Science*. Retrieved from https://doi.org/10.1146/annurev-marine-010318-095138
- 567 Glud, R. N. (2008). Oxygen dynamics of marine sediments. *Marine Biology Research*, 4(4), 243–
 568 289. <u>https://doi.org/10.1080/17451000801888726</u>
- Jørgensen, B. B., & Revsbech, N. P. (1985). Diffusive boundary layers and the oxygen uptake of
 sediments and detritus1. *Limnology and Oceanography*, 30(1), 111–122.
 https://doi.org/10.4319/lo.1985.30.1.0111
- 572 Lehmann, M. F., Barnett, B., Gélinas, Y., Gilbert, D., Maranger, R. J., Mucci, A., et al. (2009).
- Aerobic respiration and hypoxia in the Lower St. Lawrence Estuary: Stable isotope ratios of
 dissolved oxygen constrain oxygen sink partitioning. *Limnology and Oceanography*, 54(6),
 2157–2169. https://doi.org/10.4319/lo.2009.54.6.2157
- Li, J., Crowe, S. A., Miklesh, D., Kistner, M., Canfield, D. E., & Katsev, S. (2012). Carbon
- 577 mineralization and oxygen dynamics in sediments with deep oxygen penetration, Lake 578 Superior. *Limnology and Oceanography*, 57(6), 1634–1650.
- 579 https://doi.org/10.4319/lo.2012.57.6.1634
- McCarthy, M. J., Carini, S. A., Liu, Z., Ostrom, N. E., & Gardner, W. S. (2013a). Oxygen
 consumption in the water column and sediments of the northern Gulf of Mexico hypoxic zone.
- 582 *Estuarine, Coastal and Shelf Science, 123, 46–53.* <u>https://doi.org/10.1016/j.ecss.2013.02.019</u>
- McCarthy, M. J., Carini, S. A., Liu, Z., Ostrom, N. E., & Gardner, W. S. (2013b). Oxygen
 consumption in the water column and sediments of the northern Gulf of Mexico hypoxic zone.
- 585 Estuarine, Coastal and Shelf Science, 123, 46–53. <u>https://doi.org/10.1016/j.ecss.2013.02.019</u>
- McDougall, T. J., & Barker, P. M. (2011). *Getting started with TEOS-10 and the Gibbs Seawater* (GSW) Oceanographic Toolbox (Vol. SCOR/IAPSO WG127). SCOR/IAPSO WG127.
- 588 Middelburg, J. J. (1989). A simple rate model for organic matter decomposition in marine 589 sediments. *Geochimica et Cosmochimica Acta*, 53(7), 1577–1581.

590 https://doi.org/10.1016/0016-7037(89)90239-1

- 591 Noffke, A., Sommer, S., Dale, A. W., Hall, P. O. J., & Pfannkuche, O. (2016). Benthic nutrient
- 592 fluxes in the Eastern Gotland Basin (Baltic Sea) with particular focus on microbial mat

- 593 ecosystems. *Journal of Marine Systems*, 158, 1–12.
- 594 <u>https://doi.org/10.1016/j.jmarsys.2016.01.007</u>
- 595 Welsh, B. L., & Eller, F. C. (1991). Mechanisms controlling summertime oxygen depletion in
- 596 western Long Island Sound. *Estuaries*, 14(3), 265–278. <u>https://doi.org/10.2307/1351661</u>
- Wulff, F., & Stigebrandt, A. (1989). A time-dependent budget model for nutrients in the Baltic Sea.
 Global Biogeochemical Cycles, *3*(1), 63–78. <u>https://doi.org/10.1029/gb003i001p00063</u>
- 599 Zhang, H., Zhao, L., Sun, Y., Wang, J., & Wei, H. (2017). Contribution of sediment oxygen
- demand to hypoxia development off the Changjiang Estuary. *Estuarine, Coastal and Shelf Science*, *192*, 149–157. https://doi.org/10.1016/j.ecss.2017.05.006
- 602 Zhou, L. (2022). Sediment oxygen uptake and carbon mineralization in the Pearl River Estuary
- 603 and adjacent coastal waters. Master's Thesis, The Hong Kong University of Science and
- 604 Technology. doi: 10.14711/thesis-991013088359403412.
- 605

Sediment oxygen uptake and hypoxia: a simple mass-balance model for estuaries and coastal oceans

- 3 Jing Sun^{1,2}, Liugian Yu^{2,3*}, Xingyu Yang^{1,2}, Jianping Gan^{1,2}, Hongbin Yin⁴, and Jiying 4 Li^{1,2*} 5 6 7 ¹Department of Ocean Science, The Hong Kong University of Science and Technology, 8 Clear Water Bay, Kowloon, Hong Kong SAC, P. R. China 9 ²Center for Ocean Research in Hong Kong and Macau, Hong Kong SAC, P. R. China ³Earth, Ocean and Atmospheric Sciences Thrust, The Hong Kong University of Science 10 11 and Technology (Guangzhou), Guangdong, P.R. China 12 ⁴Nanjing Institute of Geography and Limnology, Chinese Academy of Science, Nanjing, 13 Jiangsu, P. R. China 14 15 Corresponding author: Jiying Li (jiyingli@ust.hk; OCRID: 0000-0003-1677-6922) 16 Liugian Yu (liugianyu@hkust-gz.edu.cn; OCRID: 0000-0002-5492-8213) 17 18 19 Key Points: 20 • Sediment respires >60% of the organic matter produced in the water column of 21 the Pearl River Estuary (PRE) region, leading to high sediment oxygen uptake. 22 • The sediment's effect on the bottom oxygen loss is controlled by the thickness of 23 the bottom boundary layer. 24 • We develop a simple and generic mass-balance model to understand hypoxia conditions and timescales in the PRE and similar coastal systems. 25
- 26

27 Abstract

28 Hypoxia is increasing in coastal oceans. This is because eutrophication has increased 29 oxygen consumption, while less oxygen is replenished to the bottom under stronger stratification, Quantifying these biogeochemical and physical drivers is important for 30 31 management and predicting future trends. By using observations from the Pearl River 32 Estuary (PRE) region (10-70 m deep) and similar coastal systems, this paper introduces a simple analysis to quantify both the biogeochemical and physical drivers of hypoxia. 33 34 We show that in the PRE region, sediment respires >60% of organic matter produced in 35 the water column, leading to high sediment oxygen uptake (average 41.1±16.3 mmol m⁻² 36 d⁻¹) and shallow oxygen penetrations (2-7 mm). The sediment's effect on the bottom 37 oxygen loss becomes stronger with the reducing thickness of the bottom boundary layer. We then construct a generic mass-balance model to quantify oxygen loss, determine 38 39 timescales of hypoxia formation, and explain within- and cross-system variabilities. 40

41 Plain language summary

42 Coastal oceans, especially those off rivers and estuaries, frequently experience low-43 oxygen conditions such as hypoxia (dissolved $O_2 < 2 \text{ mg L}^{-1}$). This is because the 44 nutrient-rich coastal ocean produces high amount of organic matter, which settles to the 45 bottom waters to consume oxygen. Hypoxia becomes more severe if the resupply of oxygen from the atmosphere and the surface water to the bottom water is blocked by 46 strong density stratification. To quantify these effects, we study a typical coastal system, 47 48 the Pearl River Estuary and the adjacent shelf, combining field and lab observations and 49 mass-balance modeling. We find that sediment consumes a substantial amount of 50 oxygen, and its contribution to hypoxia can be predicted if we know how thick the 51 stratified bottom layer is. We derive some simple equations to understand oxygen loss, 52 which can tell us what level of oxygen consumption can render the system hypoxia, and 53 for how long the stratification needs to be maintained for hypoxia to develop. We also show that the model is generic and can be applied to other similar coastal systems, such 54 55 as the northern Gulf of Mexico and the Changjiang Estuary region, to explain the 56 variability in hypoxia conditions and timescales.

57 **1 Introduction**

58 Low oxygen conditions are becoming more frequent in coastal oceans, affecting

59 biogeochemical cycles and marine life (Katsev et al., 2007; Levin et al., 2009;

60 Middelburg & Levin, 2009). These conditions are a result of high oxygen consumption

and weak ventilation, especially in bottom waters where oxygen depletion can be

severe, leading to hypoxia ($O_2 < 2 \text{ mg L}^{-1}$). In estuaries and coastal shelves, oxygen is

63 rapidly consumed due to the high organic matter production driven by terrestrial and/or

64 upwelling nutrients; freshwater inputs also enhance vertical density stratification and

reduce the oxygen resupply to the bottom. The increasing anthropogenic fertilization ofthe coastal ocean, together with the stronger stratification caused by global warming,

therefore, can intensify hypoxia in both magnitude and duration (Diaz & Rosenberg,2008).

Quantifying these physical and biogeochemical drivers of hypoxia is important for 69 management and predicting future trends. In addition to monitoring oxygen (Grégoire et 70 71 al., 2021), mechanistic modeling becomes very useful (Laurent & Fennel, 2017; Peña et al., 2010). These models simulate the oxygen budget considering its source/sink 72 73 components, including physical transports, air-sea exchanges, photosynthesis, and 74 biogeochemical consumption in the water column and sediments (Peña et al., 2010; 75 Testa et al., 2017). Among models of various complexity, coupled-physical-76 biogeochemical models are the most comprehensive, for they simulate the interactions 77 between nutrient-driven organic matter productivity and physical transport, the two major 78 drivers of oxygen variability (Fennel et al., 2016; Yu et al., 2015a, 2021). These models, 79 however, rely on parametrizations of many processes, for example, the relationships 80 between lights, temperature, nutrients, organic matter production, respiration, food-web dynamics, and the reactions in the sediments and benthic-pelagic exchanges (Peña et 81 82 al., 2010; Yu et al., 2015a, b, 2021). Moreover, parametrizations can be system-specific 83 and need to be well constrained by a large matrix of observations (e.g., dynamics in 84 biomass indicators, nutrients, and physical properties). Thus, the models usually have low transferability among systems (Peña et al., 2010). For cross-system comparison. 85 86 simple scale analyses are useful (Fennel & Testa, 2019). For example, the vulnerability of the system can be understood by comparing the timescale of hypoxia formation to the 87 water residence time of the region (Fennel & Testa, 2019). However, while such an 88 89 approach provides regional order-of-magnitude understanding, it is inadequate for 90 describing local heterogeneity, which is important for estuarine coastal systems. 91 This paper introduces a simple analysis that can describe regional heterogeneity 92 and also enables cross-system comparison. By using water column and sediment 93 oxygen data across a typical estuary and coastal shelf, we derive a simple massbalance model to understand oxygen loss without a detailed formulation of the physical 94 and biogeochemical complexity. The model can be used to understand the sensitivity of 95 96 the system to both the biogeochemical and physical drivers of hypoxia. We then discuss 97 how the model can be generalized to understand within-and cross-system variability.

using examples from similar coastal systems including the Northern Gulf of Mexico, theChangjiang Estuary region, and the Chesapeake Bay.

100

101 **2. Field Methods**

We study the Pearl River Estuary and adjacent shelf waters (PRE region) in the summer of 2021 (Fig.1a and Table.S1; Li et al. 2024). We used a SeaBird-SBE17-plus conductivity–temperature–depth (CTD) to measure the water column temperature, density, salinity, O_2 concentrations and calculated the buoyancy frequency (N^2 ; s⁻²):

106 $N^2 = \frac{g}{\rho(z)} \frac{d\rho(z)}{dz}$ Eq.1

107 *g* is gravity acceleration; z is water depth; ρ is potential density. High N^2 means high 108 stability of the water column.

Sediment cores with undisturbed overlying waters were collected using a Uwitec 109 corer. Oxygen micro-profiles were obtained using a Unisense O₂ electrode. The 110 111 sediment-water interface has the sharpest oxygen gradient. Oxygen penetration depth was defined as the depth where oxygen is under the detection limit of ~0.3 μ mol L⁻¹. 112 Total sediment oxygen uptake (SOU; mmol m⁻² d⁻¹), defined as the downward flux of 113 114 oxygen into the sediment, was determined using onboard whole-core incubations: sediment cores were stabilized, sealed, and monitored for the oxygen concentrations in 115 the overlying waters, which were gently stirred to generate the water movement and 116 117 create a diffusive boundary layer (Bowman & Delfino, 1980; Glud, 2008). SOU was calculated from the linear decrease of oxygen. The incubation typically lasts 2-3 hours. 118 119 Detailed methods are described in SI.1.

120

121 **3. Results**

3.1 Stratification and hypoxia in the water column – The water column develops 122 hypoxia within the nearshore waters (10-20 m) off the estuary during the summer 123 (Fig.1a), whereas offshore sites (>30 m) are well oxygenated. Such local seasonal 124 125 hypoxia has been observed for several recent years (Li et al., 2020; Yu et al., 2021). At most sites, the water column is stratified by vertical gradients of temperature and salinity 126 127 (Figs.1b and S1): the surface water from the upstream is warmer and fresher, while the bottom seawater is colder and saltier. In the stratified waters, the surface mixed layers 128 are thin, with the density drastically increasing below 5-10 m forming a pycnocline 129 (Fig.S1). This parallels the changes of buoyancy frequency (N^2) (Fig.1c), which peaks 130 within the pycnocline and decreases downward, until the density has little variation, 131 forming a stable bottom boundary layer (BBL; Figs.1c and S1) (Trowbridge & Lentz, 132 2018). We defined the upper boundary of BBL as the depth where N^2 increases 133 drastically above (i.e., $N^2 > 0.01 \text{ s}^{-2}$). The BBL has homogenously lower oxygen and 134 reaches hypoxia at some sites (Figs.1a and 1c). 135





Figure 1 Water column physiochemistry in the Pearl River Estuary region. a) Sampling locations and bottom oxygen concentrations; b) Temperature and salinity profiles across the estuary to open ocean gradient c) Buoyancy frequency (N^2) and O_2 profiles across the salinity gradient and at the hypoxic sites. Horizontal dashed lines represent the bottom.

3.2 Sediment oxygen uptake and bottom water oxygen – Oxygen concentration in 143 the BBL is controlled by the flux from the upper layer, which can be restricted by 144 stratification, and the consumption in the water and sediments. In the sediments, oxygen 145 drops sharply from 75-150 μ mol L⁻¹ near the interface to nondetectable (<0.3 μ mol L⁻¹) 146 147 within a few millimeters downcore (1-7 mm; Figs.2a and S3). Oxygen penetration decreases with decreasing water depths, consistent with global observations but more 148 dramatically compared to the open ocean (Figs. S4b and S4c). The drastic depletion of 149 oxygen in sediments is a result of high SOU (16.5-70.5 mmol m⁻² d⁻¹, average 41.1±16.3 150

151 mmol m⁻² d⁻¹; Fig.2b and Table.S1), consistent with typical coastal sediments (Fig.S4d).

152 Nearshore sediments have relatively higher SOU compared to offshore (Fig.2b). If we

assume oxygen is predominantly consumed via organic matter respiration, this

154 consumption averages to ~62±25% of the organic matter produced in the water column

155 of the region (66 mmol $m^{-2} d^{-1}$) (Cai et al., 2004).



156

Figure 2 Sediment oxygen distribution and uptake. a) O₂ profiles at selected sites; b)
sediment oxygen uptake (SOU).

159

High SOU would contribute significantly to the oxygen loss in the bottom water. 160 However, the correlation between SOU and bottom oxygen is weak (Fig.S5 and Yu et al. 161 162 (2015a)). This is because the thickness of the BBL would affect the sediment's impact: a thin layer would respond faster to SOU, while a thicker bottom reacts less with the effect 163 of SOU being diluted. Indeed, the hypoxia sites have thin BBL (1.3 to <10 m), whereas 164 the well-oxygenated sites have thicker BBL or entirely mixed water column (Figs.1c, S2, 165 and Table.S1). By normalizing SOU to the thickness of the BBL (h), we obtain the 166 oxygen depletion rate in the BBL by the sediments (SOU/*h*; mmol m⁻³ d⁻¹), which exhibits 167 a strong relationship with the bottom O₂ level (Fig.3a). A stronger correlation appears 168 when considering the integrated O_2 over the BBL (mmol m⁻²): oxygen decreases 169 exponentially with increasing SOU/h (Fig.3b). The relationships exist in similar systems 170 such as the northern Gulf of Mexico and the Changjiang Estuary region (Figs.3a and 171 3b); both are estuary dominated shelves experiencing hypoxia (McCarthy et al., 2013; 172 Zhu et al. 2016).). Similar relationships are also seen for the entire water column 173 174 (Fig.S6).





Figure 3 Bottom oxygen vs SOU normalized to BBL thickness (SOU/h). a and b) Bottom
oxygen vs SOU/h in the PRE region, North Gulf of Mexico (McCarthy et al., 2013), and
Changjiang Estuary region (Zhang et al., 2017); c and d) Modeled bottom oxygen vs SOU/h,
using water stability periods of T= 15 and 30 days.

182 The water column oxygen uptake (WOU) is not explicitly considered, but it does not 183 mean WOU is not important and omitted. Instead, the robust relationships suggest an 184 intrinsic connection between SOU and WOU, which are both driven by the degradation 185 of organic matter. Their proportions are determined by the water thickness, which 186 determines the time settling particles spend in the water and thus their leftovers to drive SOU. This explains the curvature in Fig.3b: at the sites with low SOU/h, the BBL is thick 187 and thus WOU becomes important, making the oxygen level sensitive to the apparent 188 per-SOU change (steeper slopes at low SOU/h in Figs.3b). 189

The strong correlations between oxygen level and SOU/*h* also suggest the possibility of parameterizing SOU. SOU is important in controlling the water column oxygen budget and sediment geochemistry and fluxes and rates (e.g., denitrification, sulfate reduction) (Li et al., 2018a, b; Li & Katsev, 2014), but published SOC data is scarce due to measurement challenges. The potential parameterization of SOU using more obtainable water column CTD data is useful.

4. The Mass-Balance Model — Inspired by the observations above, we construct a
 mass-balance model to explore their physical meanings and quantitative insights. Details

of the model are narrated in SI.2, which we briefly introduce here to facilitate discussion. The change of O_2 concentration in the BBL is caused by fluxes from above (assumed to

- be small and neglected here due to the large N_2 above the BBL) and the sediment (F_{s-O2} ,
- which equals –SOU), and the reaction within the BBL (F_{BBL-O2} , which equals –WOU_{BBL}):

202
$$\frac{\mathrm{d}\bar{C}_{\mathrm{BBL-O2}}}{\mathrm{d}t} = \frac{F_{\mathrm{S-O2}}}{h} + \frac{F_{\mathrm{BBL-O2}}}{h}$$
 Eq.2

Here, C_{BBL-O2} is the average O₂ concentration in the BBL. Assuming oxygen is mostly consumed to respire organic matter (Zhang & Li, 2010), F_{BBL-O2} depends on the amount of organic carbon settling into the BBL (C_{W-C}^{H-h} ; *H* is the total depth and *h* is the thickness of the BBL, hence the upper boundary of BBL is at *H-h*; the subscript 'w-C' stands for water-column carbon), the reaction rate (k_w), and the time the particles spend in the BBL ($t=h/u_w$; u_w is the particle settling velocity). Considering a 1C:1O₂ ratio and first-order reaction for simplicity, the reaction in the BBL is

210
$$F_{\text{BBL}-\text{O2}} = \int_{H-h}^{H} -k_{\text{w}}C_{\text{w}-\text{C}} \, \mathrm{d}z_{\text{w}} = \int_{H-h}^{H} -k_{\text{w}}C_{\text{w}-\text{C}}^{H-h} e^{-\frac{k_{\text{w}}}{u_{\text{w}}}(z_{\text{w}}-H+h)} \, \mathrm{d}z_{\text{w}} = u_{\text{w}}C_{\text{C}}^{H-h} \left(e^{-\frac{k_{\text{w}}}{u_{\text{w}}}h} - \frac{k_{\text{w}}}{u_{\text{w}}}\right) \, \mathrm{d}z_{\text{w}} = u_{\text{w}}C_{\text{W}}^{H-h} \left(e^{-\frac{k_{\text{w}}}{u_{\text{w}}}h} - \frac{k_{\text{w}}}{u_{\text{w}}}h}\right) \, \mathrm{d}z_{\text{w}} = u_{\text{w}}C_{\text{w}}^{H-h} \left(e^{-\frac{k_{\text{w}}}{u_{\text{w}}}h} - \frac{k_{\text{w}}}{u_{\text{w}}}h}\right) \, \mathrm{d}z_{\text{w}} = u_{\text{w}}C_{\text{w}}^{H-h} \left(e^{-\frac{k_{\text{w}}}{u_{\text{w}}}h} - \frac{k_{\text{w}}}{u_{\text{w}}}h}\right) \, \mathrm{d}z_{\text{w}} = u_{\text{w}}C_{\text{w}}^{H-h} \left(e^{-\frac{k_{w}}}{u_{\text{w}}}h} - \frac{k_{w}}{u_{\text{w}}}h}\right) \, \mathrm{d}z_{\text{w}} = u_{\text{w}}^{H-h} \left(e^{-\frac{k_{w}}}{u_{\text{w}}}h\right)$$

211 1) =
$$-WOU_{BBL}$$
 Eq.3

where C_{w-C} is the concentration of organic matter in the water column; z_w is the vertical

- 213 displacement. Similarly, for pseudo-steady-state consideration, the O_2 flux into the
- sediment equals the organic carbon flux ($u_w C_{w-C}^H$; C_{w-C}^H is the concentration at the
- sediment-water interface at depth H) corrected by a recycling efficiency (ε) for not all
- organic matter reaching sediments being reactive (Li et al., 2012):

217
$$F_{s-O2} = -\varepsilon u_w C_c^H = -SOU$$
 Eq.4

Because sedimentation $(u_w C_c^H)$ is from the leftover of remineralization in the water column:

220
$$u_{w}C_{w-C}^{H} = u_{w}C_{w-C}^{H-h} + F_{BBL-O2}$$
 Eq.5

221 Combining Eqs.3, 4, and 5,

222
$$F_{s-O2} = -\varepsilon u_w C_{w-C}^H = -\varepsilon \left(u_w C_{w-C}^{H-h} + F_{BBL-O2} \right) = -\varepsilon u_w C_{w-C}^{H-h} e^{-\left(\frac{\kappa_w}{u_w}\right)h}$$
Eq.6

(]- \

223 Therefore, from Eqs. 3 and 6,

224
$$F_{\text{BBL}-02} = \frac{1}{\varepsilon} \left(e^{\left(\frac{k_{\text{W}}}{u_{\text{W}}}\right)h} - 1 \right) F_{\text{s}-02} = \frac{1}{\varepsilon} \left(e^{fh} - 1 \right) F_{\text{s}-02}$$
 Eq.7.1

- 225 or WOU_{BBL} = $\frac{1}{\varepsilon} (e^{fh} 1)$ SOU Eq.7.2
- For simplicity, we introduce a parameter, spatial reactivity ($f = k_w/u_w$, m⁻¹), which

227 describes the reaction proceeded per-unit distance the particles move downwards.

- 228 Eq.7.2 shows how WOU_{BBL} and SOU are related (see observations above). We then
- rewrite the oxygen budget by combining Eq.7 and Eq.2 and integrating it over a period
- 230 (*T*), during which the present oxygen level develops:

231 AOU_{BBL}
$$h = T\left(1 + \frac{1}{\varepsilon}(e^{fh} - 1)\right)$$
SOU Eq.8

AOU_{BBL} is the apparent oxygen utilization in the BBL. In summary, oxygen utilization in the BBL is determined by the SOU, the spatial reactivity of organic matter (*f*), the thickness of BBL (*h*), the recycling efficiency in sediments (ε), and the duration (*T*) of stratification to develop the AOU. Similarly, for the whole water column,

236 AOU ×
$$H = T\left(1 + \frac{1}{\varepsilon}(e^{fH} - 1)\right)$$
SOU Eq.9

237 and WOU = $\frac{1}{s} (e^{fH} - 1)$ SOU Eq.10

One may fit the data (SOU, h, H, and AOU) to estimate the parameters (f, ε , and T). 238 239 However, as the data is limited and scattered, fitting them to a model with multiple parameters will lead to overfitting producing wrong results. As we are interested in the 240 physical insights rather than definite values (also not realistic as they are naturally 241 242 variable), we choose to fix the sediment recycling efficiency as $\varepsilon = 0.5$, for that the deep sediments bury about half of the organic matter reaching the seafloor (Zhou, 2022), 243 244 consistent with observations in shallow-oxygenated sediments (Li et al., 2018b). We use 245 T=15 days for the lack of information, but also constrained by observations that stratification and hypoxia take two weeks to redevelop after the water column is mixed 246 up (Zhao et al., 2021). Under these constraints, we obtain an organic matter spatial 247 reactivity of $f = 0.026 \text{ m}^{-1}$ for the PRE region, and the model reproduces the water column 248 AOU well (Fig.S7). The estimate is consistent with the rate of organic matter 249 remineralization estimated for water depth (H) of 10-20 m and that 62% of the organic 250 251 matter reaches the seafloor: $f = (1-0.62)/H = 0.014-0.028 \text{ m}^{-1}$ (details in SI.3).

252 **5. Discussion**

5.1 Conditions and time scales for hypoxia— The model explains the relationships between the bottom O_2 level and SOU/*h* in the PRE region and other similar systems (Figs.3c and 3d). The duration of stratification determines the sensitivity of O_2 levels to SOU/*h*: the northern Gulf of Mexico has long periods of stratification (Bianchi et al., 2010; Dzwonkowski et al., 2018) and thus appears more sensitive to SOU: the bottom oxygen drops more with the same level of increase in SOU/*h* (Figs.3a and 3b). This is

consistent with model results when the stratification period is set to be longer (e.g., T= 30 versus 15 d; Figs.3c and 3d). Alternatively, the high sensitivity of oxygen can be

achieved in systems with higher spatial reactivity of settling organic matter (*f*) (Fig.S8). The model provides several quantitative insights. As expected, AOU_{BBL} increases with increasing SOU and the effect is more dramatic when BBL is thin (Fig.4a). In the PRE region, a BBL of <10 m is susceptible to hypoxia even at low SOU (Fig.4a). For thicker BBL to reach hypoxia, higher SOU is required, but the effect is not linear: in the PRE region, when SOU is above ~75 mmol m⁻² d⁻¹, the bottom can easily develop hypoxia regardless of the BBL thickness (Fig.4a). This is because, in environments with organic matter deposition supporting such high SOU, the WOU would be proportionallyhigh (Eq.7.2).

270 We can estimate the time required for developing hypoxia (Figs.4b): waters with high SOU and thin BBL become hypoxic within a shorter time. In the PRE region, it 271 272 requires <~15 days for thin BBLs (<~10 m) to develop hypoxia; the thicker BBLs require 273 longer, but in general not longer than 60 days (Fig.4b). Assuming similar organic matter 274 spatial reactivity (f) in other coastal waters (but see discussion later for variability), we can estimate their hypoxia time scales (T_{hyp} ; Fig.4c), which can be compared to the 275 276 stratification time scales to see if hypoxia can develop. For example, in the seasonally hypoxic northern Gulf of Mexico, most hypoxia sites have T_{hyp} of <30-40 days, which is 277 278 generally shorter than the duration of stratification (30 days to several months) (Bianchi 279 et al., 2010). In the Chesapeake Bay mid-stem central channel, the pycnocline remains stable for several summer months (Boynton et al., 2022), thus hypoxia persistently 280 develops even under low SOU (Fig.4c). More extreme cases are Gulf of St. Lawrence, 281 282 the Black Sea, and the Baltic Sea, where persistent and even permanent stratification sustains thick hypoxia layers under low SOU (Fig.4c). 283





285 Figure 4 Modeled apparent oxygen utilization (AOU) and time scales for developing

286 **hypoxia** (T_{hyp}). a) AOU_{BBL} as a function of SOU and BBL thickness in the PRE region (f=

287 0.026 m^{-1} and T= 15 d). Higher AOU indicates higher oxygen loss and hypoxia occurs when 288 AOU_{BBL} > 125 mmol m^{-3} (observed bottom O₂ levels are shown with filled colors for

289 comparison); **b**) the time required for the BBL to become hypoxia (T_{hyp}) (f= 0.026 m⁻¹). If

290 stratification sustains longer than T_{hyp}, the bottom water becomes hypoxic. The sites with

thick BBL and low SOU need a longer time to develop hypoxia thus the oxygen

292 concentrations remain high. **c**) same as **b** but hypoxia sites from other estuarine and coastal

systems (Table S3) (Boynton et al., 2019, 2022; Fennel & Testa, 2019; McCarthy et al., 2013;
 Zhang et al., 2017).

295

296 5.2 Sediments vs water column oxygen uptake— The model can estimate the 297 contribution of SOU to total oxygen loss (%SOU) and explain the global observations in estuaries and coasts (Boynton et al., 2018) (Fig.5): %SOU declines exponentially with 298 299 the water layer thickness (for whole water column or BBL). Intuitively, the organic matter spends more time in thicker waters consuming oxygen before reaching the sediments, 300 301 thus reducing the %SOU. The model (Eqs.7.2 and 10) formulates this understanding 302 and explains the possible variabilities: %SOU is regulated by the organic matter spatial reactivity (f) and sediment recycling efficiency (ε). In systems with slowly settling 303 304 particles (low u_w), the large f (k_w/u_w) would lead to low %SOU (Fig.5). In contrast, SOU contributes more when sedimentation is rapid (large u_w and thus small f, Fig.5). Particle 305 settling velocity is controlled by particle concentrations (Archer & Devol, 1992), but more 306 307 importantly by turbulence intensity, which can either accelerates settling by promoting 308 particle collisions and flocculation (Ruiz et al., 2004) or decrease it by breaking up floc when shear stress is too large (Manning, 2004). In rivers and estuaries, strong 309 310 turbulence also leads to particle resuspension (Boynton et al., 2018), increasing the time the particles spend in the water column to consume oxygen (Moriaty et al. 2021). This 311 312 might explain why rivers and estuaries have low %SOU compared to shelves (Fig.5), 313 where the reactivity of organic matter (k_w) is likely similar if not higher because the 314 organic matter is more planktonic-origin. Likewise, low spatial reactivity in shelf waters 315 may be due to higher particle settling velocity for reasons we can only speculate: salinity 316 increase (Abolfazli & Strom, 2023) and blooming of typically dominated elongated or 317 chains-forming phytoplankton species can promote flocculation and fast settling 318 (Arguedas-Leiva et al., 2022). Sediment recycling efficiency regulates %SOC but to a lesser extent (the shaded area in Fig.5), and the effect becomes smaller when the 319 320 organic matter spatial reactivity is high (see variability in the width of the shaded area in Fig. 5), as there is less organic matter reaching the sediment for recycling efficiency to 321 322 make a difference.



Figure 5 The contributions of SOU to total oxygen uptake (SOU +WOU) as a function of 324 325 water layer thickness (for the entire water column or BBL). The solid line represents model 326 results for the PRE region ($\varepsilon = 0.5$; f= 0.026). Results obtained using different spatial 327 reactivities (f) are shown in dotted and dashed lines; shaded areas show variability with different sediment recycling efficiency (ε = 0.3-0.75). Literature data are from (Boynton et al., 328 329 2018; Chi et al., 2021; Kemp et al., 1992; Murrell & Lehrter, 2011). Solid markers indicate 330 average values and the open markers of the corresponding colors are individual measurements. 331

332

6. Summary, caveats, and outlooks

334 Using data in the PRE region, we construct and test a simple mass balance model 335 to understand bottom hypoxia in coastal waters. The model describes oxygen utilization in the BBL due to the sediment and water oxygen uptake (Eqs.8 and 9). While SOU 336 needs to be measured, we show that bottom oxygen levels and water-column 337 stratification can be used to parameterize SOU and increase the data size (Fig.3). WOU 338 is linked to SOU in the model via their intrinsic mass-balance connection (Eqs.7.2 and 339 340 10). Therefore, by having data on the water column physical and oxygen conditions 341 across a region (easily obtained from CTD) and some estimates of SOU, the model can 342 estimate other determinants of oxygen loss and quantitatively describe the conditions 343 and time scales for hypoxia formation, as well as the contributions from water column 344 versus sediments.

There are several caveats to using the model. It should be used within areas with similar particle settling velocity and organic matter reactivity. These parameters can vary significantly across regions. Ideally, parameters can be chosen or fitted more locally (e.g., differentiating the inner estuary and the offshore shelf). Moreover, SOU is assumed to be stable during the development of the observed oxygen level, but SOU can decrease when oxygen becomes very limited (<1.5–3.2 mg L⁻¹) (Chi et al., 2021; Murrell

- & Lehrter, 2011; Rowe et al., 2002). Therefore, for the model to work, SOU might need to 351 be measured under sufficient overlying-water oxygen (reaction not limited by oxygen) at 352 353 sites with very low oxygen levels. Other complications of the physical conditions need to 354 be considered, for example, when stratification is disrupted by a typhoon. Despite these 355 limitations, the model provides intuitive and quantitative estimates of hypoxia and can be 356 used to understand the variability among systems and changes under future scenarios 357 (e.g., longer stratification under climate change). The model can also help estimate key constraints, such as the reactivity and settling velocity of particles, to support other 358 359 mechanistic models.
- 360

361 Acknowledgment

362 The work is substantially supported by grants from the Research Grant Council (RGC) of the Hong Kong Special Administrative Region, China (Project Reference Numbers: 363 16303022 and 26305621 to JL, a grant from the National Natural Science Foundation of 364 365 China to LY (Project No. 42206160), and grants from RGC to JG and LY (Project Reference Numbers: 16307423 and AoE/P-601/23-N to JG). The work is also funded by 366 367 the Center for Ocean Research in Hong Kong and Macau (CORE). CORE is a joint 368 research center for ocean research between Laoshan Laboratory and Technology and 369 the Hong Kong University of Science and Technology (HKUST). We thank the captain 370 and crew of the R/V Haike 68 and Chief Scientists Zhongming Lu and Isaac Cheung for assisting in sample collection. Lei Zhou is acknowledged for assistance in sediment 371 sample collection and field analysis. We thank Mark J. McCarthy (Estonian University of 372 373 Life Sciences) and Wayne S. Gardner (University of Texas at Austin) for providing CTD 374 data from the Northern Gulf of Mexico. These data were collected aboard the R/V Pelican (Louisiana University Marine Consortium) supported by the NOAA/CSCOR 375 376 Grant (#NA07NOS4780225) to Wayne Gardner. We thank Weicong Cheng and Dou Li 377 for their technical and intellectual support.

378

379 Author contributions:

- 380 Conceptualization: Jiying Li
- 381 Investigation: Jing Sun, Jiying Li, and Xingyu Yang
- 382Data curation: Jing Sun, Jiying Li, and Xingyu Yang
- 383 Formal analysis: Jing Sun, Jiying Li, and Liuqian Yu
- 384 Methodology: Jing Sun, Jiying Li, Liuqian Yu, and Jianping Gan
- 385 Funding acquisition: Jiying Li, Liuqian Yu, and Jianping Gan
- 386 Project administration: Jiying Li and Jianping Gan
- 387 Supervision: Jiying Li
- 388 Writing—original draft: Jing Sun and Jiying Li
- 389 Writing—review& editing: Jiying Li, Liuqian Yu, Hongbin Yin, and Jianping Gan
- 390
- **Data Availability Statement**

- 392 Data presented in the paper are available at DataSpace@HKUST via
- 393 doi:10.14711/dataset/KCLUQW (Li et al. 2024). Data from the Changjiang estuary region
- are from Zhang et al. 2017 and Chi et al. 2021; Data from the Northern Gulf of Mexico
- are from McCarthy et al. 2013; Data from the Chesapeake Bay are from Boynton et al.
- 396 (2018), Boynton et al. (2022), Boynton and Ceballos (2019), Kemp et al. (1992), and the
- 397 Chesapeake Bay Program Datahub (https://datahub.chesapeakebay.net). Additional
- data from other systems are also compiled in Fennel and Testa (2019), Boynton et al.
- 399 (2018), Boynton et al. (2022), and Kemp et al. (1992).
- 400

401 **References**

- 402
- Abolfazli, E., & Strom, K. (2023). Salinity Impacts on Floc Size and Growth Rate With and Without
 Natural Organic Matter. *Journal of Geophysical Research: Oceans*, *128*(7).
- 405 https://doi.org/10.1029/2022jc019255
- 406 Archer, D., & Devol, A. (1992). Benthic oxygen fluxes on the Washington shelf and slope: A
 407 comparison of in situ microelectrode and chamber flux measurements. *Limnology and*
- 408 Oceanography, 37(3), 614–629. <u>https://doi.org/10.4319/lo.1992.37.3.0614</u>
- Arguedas-Leiva, J.-A., Słomka, J., Lalescu, C. C., Stocker, R., & Wilczek, M. (2022). Elongation
 enhances encounter rates between phytoplankton in turbulence. *Proceedings of the National Academy of Sciences*, *119*(32), e2203191119. https://doi.org/10.1073/pnas.2203191119
- 412 Bianchi, T. S., DiMarco, S. F., Cowan, J. H., Hetland, R. D., Chapman, P., Day, J. W., & Allison,
- M. A. (2010). The science of hypoxia in the Northern Gulf of Mexico: A review. *Science of The Total Environment*, 408(7), 1471–1484. <u>https://doi.org/10.1016/j.scitotenv.2009.11.047</u>
- Bowman, G. T., & Delfino, J. J. (1980). Sediment oxygen demand techniques: A review and
 comparison of laboratory and in situ systems. *Water Research*, *14*(5), 491–499.
- 417 <u>https://doi.org/10.1016/0043-1354(80)90215-8</u>
- Boynton, Fraser, W. C., & Alejandra, M. (2019). Chesapeake Bay and Maryland Coastal Bays
 Sediment-Water Oxygen and Nutrient Flux Data Set. *Mendeley Data*, (V1).
 https://doi.org/10.17632/jpwvc5jytk.1
- Boynton, W. R., Ceballos, M. A. C., Bailey, E. M., Hodgkins, C. L. S., Humphrey, J. L., & Testa, J.
 M. (2018). Oxygen and Nutrient Exchanges at the Sediment-Water Interface: a Global
- 423 Synthesis and Critique of Estuarine and Coastal Data. *Estuaries and Coasts*, *41*(2), 301–333.
 424 https://doi.org/10.1007/s12237-017-0275-5
- 425 Boynton, W. R., Ceballos, M. A. C., Hodgkins, C. L. S., Liang, D., & Testa, J. M. (2022). Large-
- Scale Spatial and Temporal Patterns and Importance of Sediment–Water Oxygen and
 Nutrient Fluxes in the Chesapeake Bay Region. *Estuaries and Coasts*, 1–20.
- 428 https://doi.org/10.1007/s12237-022-01127-0
- 429 Cai, W.-J., Dai, M., Wang, Y., Zhai, W., Huang, T., Chen, S., et al. (2004). The biogeochemistry
- 430 of inorganic carbon and nutrients in the Pearl River estuary and the adjacent Northern South
- 431 China Sea. *Continental Shelf Research*, 24(12), 1301–1319.
- 432 <u>https://doi.org/10.1016/j.csr.2004.04.005</u>

433 Chi, L., Song, X., Ding, Y., Yuan, Y., Wang, W., Cao, X., et al. (2021). Heterogeneity of the 434 sediment oxygen demand and its contribution to the hypoxia off the Changjiang estuary and 435 its adjacent waters. Marine Pollution Bulletin, 172, 112920. 436 https://doi.org/10.1016/j.marpolbul.2021.112920 437 Diaz, R. J., & Rosenberg, R. (2008). Spreading Dead Zones and Consequences for Marine 438 Ecosystems. Science, 321(5891), 926–929. https://doi.org/10.1126/science.1156401 Dzwonkowski, B., Fournier, S., Reager, J. T., Milroy, S., Park, K., Shiller, A. M., et al. (2018). 439 440 Tracking sea surface salinity and dissolved oxygen on a river-influenced, seasonally stratified 441 shelf, Mississippi Bight, northern Gulf of Mexico. Continental Shelf Research, 169, 25-33. 442 https://doi.org/10.1016/j.csr.2018.09.009 443 Fennel, K., & Testa, J. M. (2019). Biogeochemical Controls on Coastal Hypoxia. Annual Review 444 of Marine Science, 11(1), 105–130. https://doi.org/10.1146/annurev-marine-010318-095138 445 Fennel, K., Laurent, A., Hetland, R., Justić, D., Ko, D. S., Lehrter, J., et al. (2016). Effects of 446 model physics on hypoxia simulations for the northern Gulf of Mexico: A model intercomparison. Journal of Geophysical Research: Oceans, 121(8), 5731-5750. 447 448 https://doi.org/10.1002/2015jc011577 449 Glud, R. N. (2008). Oxygen dynamics of marine sediments. Marine Biology Research, 4(4), 243-450 289. https://doi.org/10.1080/17451000801888726 451 Grégoire, M., Garcon, V., Garcia, H., Breitburg, D., Isensee, K., Oschlies, A., et al. (2021). A 452 Global Ocean Oxygen Database and Atlas for Assessing and Predicting Deoxygenation and 453 Ocean Health in the Open and Coastal Ocean. Frontiers in Marine Science, 8, 724913. 454 https://doi.org/10.3389/fmars.2021.724913 455 Katsev, S., Chaillou, G., Sundby, B., & Mucci, A. (2007). Effects of progressive oxygen depletion 456 on sediment diagenesis and fluxes: A model for the lower St. Lawrence River Estuary. Limnology and Oceanography, 52(6), 2555–2568. https://doi.org/10.4319/lo.2007.52.6.2555 457 458 Kemp, W., Sampou, P., Garber, J., Turtle, J., & Boynton, W. (1992). Seasonal depletion of 459 oxygen from bottom waters of Chesapeake Bay: roles of benthic and planktonic respiration 460 and physical exchange processes. Marine Ecology Progress Series, 85, 137–152. 461 https://doi.org/10.3354/meps085137 462 Laurent, A., & Fennel, K. (2017). Modeling Coastal Hypoxia, Numerical Simulations of Patterns, 463 Controls and Effects of Dissolved Oxygen Dynamics, 149–171. https://doi.org/10.1007/978-3-464 319-54571-4 7 465 Levin, L. A., Ekau, W., Gooday, A. J., Jorissen, F., Middelburg, J. J., Nagvi, S. W. A., et al. 466 (2009). Effects of natural and human-induced hypoxia on coastal benthos. *Biogeosciences*, 467 6(10), 2063–2098. https://doi.org/10.5194/bg-6-2063-2009 468 Li, D., Gan, J., Hui, R., Liu, Z., Yu, L., Lu, Z., & Dai, M. (2020). Vortex and Biogeochemical 469 Dynamics for the Hypoxia Formation Within the Coastal Transition Zone off the Pearl River 470 Estuary. Journal of Geophysical Research: Oceans, 125(8). https://doi.org/10.1029/2020jc016178 471

- Li, J., & Katsev, S. (2014). Nitrogen cycling in deeply oxygenated sediments: Results in Lake
- 473 Superior and implications for marine sediments. *Limnology and Oceanography*, 59(2), 465–
 474 481. <u>https://doi.org/10.4319/lo.2014.59.2.0465</u>
- Li, J., Crowe, S. A., Miklesh, D., Kistner, M., Canfield, D. E., & Katsev, S. (2012). Carbon
- 476 mineralization and oxygen dynamics in sediments with deep oxygen penetration, Lake
 477 Superior. *Limnology and Oceanography*, 57(6), 1634–1650.
- 478 https://doi.org/10.4319/lo.2012.57.6.1634
- Li, J., Zhang, Y., & Katsev, S. (2018a). Phosphorus recycling in deeply oxygenated sediments in
- 480 Lake Superior controlled by organic matter mineralization. *Limnology and Oceanography*,
- 481 63(3), 1372–1385. <u>https://doi.org/10.1002/lno.10778</u>
- Li, J., Brown, E. T., Crowe, S. A., & Katsev, S. (2018b). Sediment geochemistry and contributions
 to carbon and nutrient cycling in a deep meromictic tropical lake: Lake Malawi (East Africa). *Journal of Great Lakes Research*, 44(6), 1221–1234. https://doi.org/10.1016/j.jglr.2017.12.001
- Li, J., Sun, J, Yu, L., Gan, J., & Yang, X. (2024). Sediment oxygen uptake and hypoxia in the Pearl River Estuary Region [Dataset]. DataSpace@HKUST,
- 487 https://doi:10.14711/dataset/KCLUQW
- Manning, A. J. (2004). The Observed Effects of Turbulence on Estuarine Flocculation. Journal of
 Coastal Research. Sediment Transport in European Estuarine Environments: Proceedings of
 the STRAEE Workshop (WINTER 2004):, (Special Issue No. 41), 90–104. Retrieved from
 https://www.jstor.org/stable/25736634
- 492 McCarthy, M. J., Carini, S. A., Liu, Z., Ostrom, N. E., & Gardner, W. S. (2013). Oxygen
- 493 consumption in the water column and sediments of the northern Gulf of Mexico hypoxic zone.
- 494 Estuarine, Coastal and Shelf Science, 123, 46–53. <u>https://doi.org/10.1016/j.ecss.2013.02.019</u>
- 495 Middelburg, J. J., & Levin, L. A. (2009). Coastal hypoxia and sediment biogeochemistry.
- 496 Biogeosciences, 6(7), 1273–1293. <u>https://doi.org/10.5194/bg-6-1273-2009</u>
- 497 Moriarty, J. M., Friedrichs, M. A. M., & Harris, C. K. (2021). Seabed Resuspension in the
- Chesapeake Bay: Implications for Biogeochemical Cycling and Hypoxia. *Estuaries and Coasts*, 44(1), 103–122. <u>https://doi.org/10.1007/s12237-020-00763-8</u>
- Murrell, M. C., & Lehrter, J. C. (2011). Sediment and Lower Water Column Oxygen Consumption
 in the Seasonally Hypoxic Region of the Louisiana Continental Shelf. *Estuaries and Coasts*,
 34(5), 912–924. https://doi.org/10.1007/s12237-010-9351-9
- Peña, M. A., Katsev, S., Oguz, T., & Gilbert, D. (2010). Modeling dissolved oxygen dynamics and
 hypoxia. *Biogeosciences*, 7(3), 933–957. https://doi.org/10.5194/bg-7-933-2010
- Rowe, G. T., Kaegi, M. E. C., Morse, J. W., Boland, G. S., & Briones, E. G. E. (2002). Sediment
 community metabolism associated with continental shelf hypoxia, Northern Gulf of Mexico.
 Estuaries, 25(6), 1097–1106. <u>https://doi.org/10.1007/bf02692207</u>
- 508 Ruiz, J., Macías, D., & Peters, F. (2004). Turbulence increases the average settling velocity of
- 509 phytoplankton cells. Proceedings of the National Academy of Sciences, 101(51), 17720–
- 510 17724. <u>https://doi.org/10.1073/pnas.0401539101</u>

511 Testa, J. M., Li, Y., Lee, Y. J., Li, M., Brady, D. C., Toro, D. M. D., & Kemp, W. M. (2017). 512 Modeling Coastal Hypoxia, Numerical Simulations of Patterns, Controls and Effects of 513 Dissolved Oxygen Dynamics, 95–118. https://doi.org/10.1007/978-3-319-54571-4 5 514 Trowbridge, J. H., & Lentz, S. J. (2018). The Bottom Boundary Layer. Annual Review of Marine 515 Science, 10(1), 397-420. https://doi.org/10.1146/annurev-marine-121916-063351 516 Wulff, F., & Stigebrandt. A. (1989). A time-dependent budget model for nutrients in the Baltic Sea. 517 Glob. Biogeochem. Cycles 3: 63-78. https://doi:10.1029/gb003i001p00063 Yu, L., Fennel, K., Laurent, A., Murrell, M. C., & Lehrter, J. C. (2015a), Numerical analysis of the 518 519 primary processes controlling oxygen dynamics on the Louisiana shelf. *Biogeosciences*, 520 12(7), 2063–2076. https://doi.org/10.5194/bg-12-2063-2015 521 Yu, Liuqian, Fennel, K., & Laurent, A. (2015b). A modeling study of physical controls on hypoxia generation in the northern Gulf of Mexico: Physical Controls on Hypoxia. Journal of 522 523 Geophysical Research: Oceans, 120(7), 5019–5039. https://doi.org/10.1002/2014jc010634 524 Yu, Liuqian, Gan, J., Dai, M., Hui, C. R., Lu, Z., & Li, D. (2021). Modeling the role of riverine 525 organic matter in hypoxia formation within the coastal transition zone off the Pearl River 526 Estuary. Limnology and Oceanography, 66(2), 452-468. https://doi.org/10.1002/lno.11616 527 Zhang, Haiyan, Zhao, L., Sun, Y., Wang, J., & Wei, H. (2017). Contribution of sediment oxygen 528 demand to hypoxia development off the Changjiang Estuary. Estuarine, Coastal and Shelf 529 Science, 192, 149–157. https://doi.org/10.1016/j.ecss.2017.05.006 530 Zhang, Heng, & Li, S. (2010). Effects of physical and biochemical processes on the dissolved 531 oxygen budget for the Pearl River Estuary during summer. Journal of Marine Systems, 79(1-532 2), 65-88. https://doi.org/10.1016/j.jmarsys.2009.07.002 533 Zhao, Y., Uthaipan, K., Lu, Z., Li, Y., Liu, J., Liu, H., et al. (2021). Destruction and reinstatement 534 of coastal hypoxia in the South China Sea off the Pearl River estuary. *Biogeosciences*, 18(8), 535 2755-2775. https://doi.org/10.5194/bg-18-2755-2021 536 Zhou, L. (2022). Sediment oxygen uptake and carbon mineralization in the Pearl River Estuary and adjacent coastal waters. https://doi.org/10.14711/thesis-991013088359403412 537 Zhu, J., Zhu, Z., Lin, J., Wu, H., & Zhang, J. (2016). Distribution of hypoxia and pychocline off the 538 539 Changjiang Estuary, China. Journal of Marine Systems, 154, 28-40. 540 https://doi.org/10.1016/j.jmarsys.2015.05.002 541

542 **References From the Supporting Information**

- APHA (1998) Standard Methods for the Examination of Water and Wastewater. 20th Edition,
 American Public Health Association, American Water Works Association and Water
 Environmental Federation, Washington DC.
- Boynton, W. R., Ceballos, M. A. C., Hodgkins, C. L. S., Liang, D., & Testa, J. M. (2022). Large-546 547 Scale Spatial and Temporal Patterns and Importance of Sediment–Water Oxygen and Nutrient 548 Fluxes in the Chesapeake Bay Region. Estuaries and Coasts, 1–20. 549 https://doi.org/10.1007/s12237-022-01127-0
- 550 Cai, W. J., Dai, M., Wang, Y., Zhai, W., Huang, T., Chen, S., et al. (2004). The biogeochemistry
- of inorganic carbon and nutrients in the Pearl River estuary and the adjacent Northern South

- 552 China Sea. Continental Shelf Research, 24(12), 1301–1319.
- 553 <u>https://doi.org/10.1016/j.csr.2004.04.005</u>
- 554 Cannaby, H., Fach, B. A., Arkin, S. S., & Salihoglu, B. (2015). Climatic controls on biophysical
- interactions in the Black Sea under present day conditions and a potential future (A1B) climate
 scenario. *Journal of Marine Systems*, *141*, 149–166.

557 <u>https://doi.org/10.1016/j.jmarsys.2014.08.005</u>

- 558 Capet, A., Beckers, J.-M., & Grégoire, M. (2013). Drivers, mechanisms and long-term variability 559 of seasonal hypoxia on the Black Sea northwestern shelf – is there any recovery after
- 560 eutrophication? *Biogeosciences*, *10*(6), 3943–3962. https://doi.org/10.5194/bg-10-3943-2013
- 561 Capet, Arthur, Meysman, F. J. R., Akoumianaki, I., Soetaert, K., & Grégoire, M. (2016).
- 562 Integrating sediment biogeochemistry into 3D oceanic models: A study of benthic-pelagic 563 coupling in the Black Sea. *Ocean Modelling*, *101*, 83–100.
- 564 <u>https://doi.org/10.1016/j.ocemod.2016.03.006</u>
- Fennel, K., & Testa, J. M. (2019). Biogeochemical Controls on Coastal Hypoxia. *Annual Review of Marine Science*. Retrieved from https://doi.org/10.1146/annurev-marine-010318-095138
- 567 Glud, R. N. (2008). Oxygen dynamics of marine sediments. *Marine Biology Research*, 4(4), 243–
 568 289. <u>https://doi.org/10.1080/17451000801888726</u>
- Jørgensen, B. B., & Revsbech, N. P. (1985). Diffusive boundary layers and the oxygen uptake of
 sediments and detritus1. *Limnology and Oceanography*, 30(1), 111–122.
 https://doi.org/10.4319/lo.1985.30.1.0111
- 572 Lehmann, M. F., Barnett, B., Gélinas, Y., Gilbert, D., Maranger, R. J., Mucci, A., et al. (2009).
- Aerobic respiration and hypoxia in the Lower St. Lawrence Estuary: Stable isotope ratios of
 dissolved oxygen constrain oxygen sink partitioning. *Limnology and Oceanography*, 54(6),
 2157–2169. https://doi.org/10.4319/lo.2009.54.6.2157
- Li, J., Crowe, S. A., Miklesh, D., Kistner, M., Canfield, D. E., & Katsev, S. (2012). Carbon
- 577 mineralization and oxygen dynamics in sediments with deep oxygen penetration, Lake 578 Superior. *Limnology and Oceanography*, 57(6), 1634–1650.
- 579 https://doi.org/10.4319/lo.2012.57.6.1634
- McCarthy, M. J., Carini, S. A., Liu, Z., Ostrom, N. E., & Gardner, W. S. (2013a). Oxygen
 consumption in the water column and sediments of the northern Gulf of Mexico hypoxic zone.
- 582 *Estuarine, Coastal and Shelf Science, 123, 46–53.* <u>https://doi.org/10.1016/j.ecss.2013.02.019</u>
- McCarthy, M. J., Carini, S. A., Liu, Z., Ostrom, N. E., & Gardner, W. S. (2013b). Oxygen
 consumption in the water column and sediments of the northern Gulf of Mexico hypoxic zone.
- 585 Estuarine, Coastal and Shelf Science, 123, 46–53. <u>https://doi.org/10.1016/j.ecss.2013.02.019</u>
- McDougall, T. J., & Barker, P. M. (2011). *Getting started with TEOS-10 and the Gibbs Seawater* (GSW) Oceanographic Toolbox (Vol. SCOR/IAPSO WG127). SCOR/IAPSO WG127.
- 588 Middelburg, J. J. (1989). A simple rate model for organic matter decomposition in marine 589 sediments. *Geochimica et Cosmochimica Acta*, 53(7), 1577–1581.

590 https://doi.org/10.1016/0016-7037(89)90239-1

- 591 Noffke, A., Sommer, S., Dale, A. W., Hall, P. O. J., & Pfannkuche, O. (2016). Benthic nutrient
- 592 fluxes in the Eastern Gotland Basin (Baltic Sea) with particular focus on microbial mat

- 593 ecosystems. *Journal of Marine Systems*, 158, 1–12.
- 594 <u>https://doi.org/10.1016/j.jmarsys.2016.01.007</u>
- 595 Welsh, B. L., & Eller, F. C. (1991). Mechanisms controlling summertime oxygen depletion in
- 596 western Long Island Sound. *Estuaries*, 14(3), 265–278. <u>https://doi.org/10.2307/1351661</u>
- Wulff, F., & Stigebrandt, A. (1989). A time-dependent budget model for nutrients in the Baltic Sea.
 Global Biogeochemical Cycles, *3*(1), 63–78. <u>https://doi.org/10.1029/gb003i001p00063</u>
- 599 Zhang, H., Zhao, L., Sun, Y., Wang, J., & Wei, H. (2017). Contribution of sediment oxygen
- demand to hypoxia development off the Changjiang Estuary. *Estuarine, Coastal and Shelf Science*, *192*, 149–157. https://doi.org/10.1016/j.ecss.2017.05.006
- 602 Zhou, L. (2022). Sediment oxygen uptake and carbon mineralization in the Pearl River Estuary
- 603 and adjacent coastal waters. Master's Thesis, The Hong Kong University of Science and
- 604 Technology. doi: 10.14711/thesis-991013088359403412.
- 605

1	
2	Geophysical Research Letters
3	
4	Supporting Information for
5 6	Sediment oxygen uptake and hypoxia: a simple mass-balance model for estuaries and coastal oceans
7	
8	Jing Sun ^{1,2} , Liuqian Yu ^{2,3*} , Xingyu Yang ^{1,2} , Jianping Gan ^{1,2} , Hongbin Yin ⁴ , and Jiying Li ^{1,2*}
9	
10 11	¹ Department of Ocean Science, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong SAC, P. R. China
12	² Center for Ocean Research in Hong Kong and Macau, Hong Kong SAC, P. R. China
13 14	³ Earth, Ocean and Atmospheric Sciences Thrust, The Hong Kong University of Science and Technology (Guangzhou), Guangdong, P.R. China
15 16	⁴ Nanjing Institute of Geography and Limnology, Chinese Academy of Science, Nanjing, Jiangsu, P. R. China
17	
18 19 20 21 22 23 24 25	Contents of this file Text S1 to S3 S1 Methods S2 The mass balance model for oxygen S3 Spatial reactivity of organic matter in the water column
25 26	Table S1 to S8

27 Introduction

28 The supporting information (SI) includes a detailed description of the methods (S1), the 29 mass balance model (S2), and how the data is used to obtain the fitted parameter spatial 30 reactivity (S3). The SI also includes a table summarizing the physicochemical properties 31 of all sites (Table S1), a table listing all the parameters used in the model and their 32 descriptions (Table S2), a table including data from other coastal systems (Table S3), 33 and eight figures (Figs. S1-S8) supporting the discussion in the main text.

34 S1. Methods

35 Samples were collected during the summer of 2021 from the Pearl River Estuary and its 36 adjacent continental shelf waters (PRE region) (Li et al. 2024). We used a Sea-Bird 37 SBE17 plus conductivity-temperature-depth (CTD) probe to measure the temperature, 38 density, salinity, and dissolved O₂ concentrations. Chlorophyll (Chl-a) fluorescence 39 obtained from the CTD probe was calibrated by measuring Chl-a fluorometrically (APHA, 40 1998) in the water samples taken from various depths by using Niksin bottles attached 41 on the CTD. We calculate the buoyancy frequency (N^2 (s⁻²)) to indicate the stratification 42 of the water column:

43
$$N^2 = \frac{g}{\rho(z)} \frac{d\rho(z)}{dz}$$
 Eq. S1

44 where g is the gravity acceleration (9.80665 m s⁻²), z is the water depth (m) with zero at 45 the sea surface and positive downwards; ρ is the potential density (kg m⁻³) calculated using the Gibbs-SeaWater Oceanographic Toolbox (GSWOT) and data obtained by the 46 47 CTD probes, including temperature, salinity, depth, pressure, and geographic coordinates (McDougall & Barker, 2011). Higher N^2 implies high stability of the water 48 49 column.

50 Sediment cores were collected with undisturbed overlying waters of around 15-20 51 cm using a Uwitec corer (core liners of 86 mm ID and 60 cm length). The sediment's 52 oxygen micro-profiles (of 0.5-1 mm resolution) were obtained using a micro-profiling 53 system equipped with a Unisense O₂ electrode, calibrated using the air-saturated 54 seawater and zero oxygen solution at in-situ temperature. The sediment-water interface 55 was defined as the depth where the sharpest oxygen gradient was observed, which was 56 consistent with our visual observation of the interface. Oxygen penetration depth (OPD) 57 was defined as the depth where the oxygen concentration under the detection limit of ~ 58 0.3 μ mol L⁻¹. The sediment physical properties, including water content and densities, 59 were guantified and reported in (Zhou, 2022).

60 The total sediment oxygen uptake (SOU) was determined using whole-core 61 incubations: sediment cores were stabilized, and the overlying water was gently bubbled 62 with air to compensate for the oxygen lost between sample collection and incubation. 63 The sediment cores were then tightly sealed with rubber stoppers to start the incubation, 64 during which the overlying waters were gently stirred with a stir bar located at ~ 5 cm 65 above the sediment-water interface to generate the movement of overlying water and 66 create a diffusive boundary layer (Jørgensen & Revsbech, 1985). The cores were 67 covered with aluminum foil to avoid the potential disturbance from light, and the oxygen 68 concentration in the overlying water was monitored using an oxygen optical probe 69 (Pyroscience). The incubation typically lasts around 2-3 hours, during which ~ 20% 70 dissolved oxygen in the overlying water was consumed. The SOU (mmol $O_2 \text{ m}^{-2} \text{ d}^{-1}$) was 71 obtained from the linear decrease of oxygen in the overlying waters. Onboard 72

73 **S2.** The mass balance model for oxygen

The paper focuses on oxygen budget in the bottom waters (or BBL). For clarity, we will first introduce the mass balance model for the entire water column, followed by the

first introduce the mass balance model for the entire water column, follmodel in the BBL that can be understood using similar logic.

77 **S2.1** The oxygen mass balance

78 The O₂ budget of the entire water column can be written as changes in oxygen

concentrations contributed by fluxes from the atmosphere, sediments, and net

80 consumption within the water column:

81
$$\frac{d\bar{c}_{w-O2}}{dt} = \frac{F_{AWI-O2}}{H} - \frac{F_{SWI-O2}}{H} + \frac{\int_{0}^{H} R_{w-O2} dz_{w}}{H}$$
 Eq. S2

82 Here, \overline{C}_{w-O2} is the oxygen concentration (C_{w-O2}) integrated over the entire water column

83 divided by the total depth of the water column (*H*): $\bar{C}_{w-02} = (\int_0^H C_{w-02} dz_w)/H$, which is

also the average O_2 concentration in the water column. F_{AWI-O2} and F_{SWI-O2} are the O_2

fluxes at the air-water interface (AWI) and sediment-water interface (SWI), respectively (positive means downward flux, thus F_{AWI-O2} describes oxygen entering the water column

and $F_{\text{SWI-O2}}$ describes oxygen leaving the water column); $R_{\text{w-O2}}$ is the rate of oxygen in

the water column (negative means consumption); z_w is the downward vertical

89 displacement in the water column reference to the air-sea interface (positive indicates

90 going downwards). All parameters are described in Table S2.

91 The integration of the O_2 rate over the entire water column can be defined as the O_2 92 reaction flux in the water column (F_{w-O2}):

93
$$\int_0^H R_{w-O2} dz_w = F_{w-O2}$$
 Eq. S3

- Here, negative F_{w-O2} means oxygen consumption in the water column. Similarly,
- 95 integrating the O₂ rate in the sediments (R_{s-O2}) can be defined as the O₂ reaction flux in 96 the sediment (F_{s-O2}):

97
$$\int_0^{+\infty} R_{s-02} dz_s = F_{s-02}$$
 Eq. S4

Here, z_s is the vertical displacement in the sediment column ($z_s = 0$ at the sediment-water interface, and positive indicates going downwards) and negative F_{s-02} means oxygen

100 consumption in the sediments. The sediment oxygen consumption (negative F_{s-02}) is

equivalent to downward fluxes (positive F_{SWI-O2}):

102
$$F_{s-O2} = -F_{SWI-O2}$$
 Eq. S5

103 This can also be understood by considering the mass balance of O_2 for the entire

sediment column, as total oxygen consumption (F_{s-O2}) should cancel out the amount of oxygen coming into the sediment from the water column (F_{SWI-O2}): $F_{s-O2} + F_{SWI-O2} = 0$.

106 Combing Eqs. S2-5 yields:

107
$$\frac{d\bar{C}_{w-O2}}{dt} = \frac{F_{AWI-O2}}{H} + \frac{F_{s-O2}}{H} + \frac{F_{w-O2}}{H}$$
 Eq. S6

108 S2.2 Oxygen consumption and flux in the sediment

109 The fluxes (integrated rates) of oxygen (F_{w-O2} and F_{s-O2}) can be approximated as the

110 integrated rates of carbon mineralization for water and sediment columns, respectively,

assuming oxygen in the water and sediments is mostly consumed by remineralization of

112 organic matter and its reduced products and a close to 1:1 ratio between organic carbon

remineralization and oxygen consumption. The reaction rates of O_2 in sediments (R_{s-O2}) can then be described using a first-order kinetic model:

115
$$R_{s-02} = \frac{dC_{s-C}}{dt} = -k_s C_{s-C}$$
 Eq.S7

Here, C_{s-c} and k_s are the concentration and reactivity of organic carbon in the sediment, respectively. The solution of Eq.S7 is

118
$$C_{s-C} = C_{s-C}^0 e^{-k_s t}$$
 Eq.S8

119 where C_{s-C}^0 is organic carbon concentration at the sediment-water interface; *t* is the age 120 of the sediment layer reference to its initial deposition on the seafloor, which is also the 121 time for sediment to be buried from the sediment surface to its current depth (*z*_s) with a 122 sediment burial velocity of *u*_s. Therefore,

123
$$t = \frac{z_s}{u_s}$$
 Eq.S9

124 and Eq.S8 becomes

125
$$C_{s-C} = C_{s-C}^0 e^{-k_s (\frac{z_s}{u_s})} = C_{s-C}^0 e^{-(\frac{k_s}{u_s})z_s}$$
 Eq. S10

126 Combining Eqs. S4, 5, and 10,

127
$$F_{s-02} = \int_0^{+\infty} R_{s-02} dz_s = -\int_0^{+\infty} k_s C_{s-C}^0 e^{-\left(\frac{k_s}{u_s}\right) z_s} dz_s = -C_{s-C}^0 u_s$$
 Eq. S11

128 Intuitively, oxygen is consumed due to the downward flux of organic carbon into the

sediments ($C_{s-C}^0 u_s$), which is also the flux from the water column ($C_{w-C}^H u_w$) considering the mass balance:

131
$$F_{s-O2} = -C^0_{s-C} u_s = -C^H_{w-C} u_w$$
 Eq. S12

132 Here, C_{w-C}^{H} is the organic carbon concentration in the water column at the seafloor $(z_w=H)$ and u_w is the particle settling velocity in the water column. However, Eqs. S11 133 134 and S12 assume a constant reactivity of the organic matter in the sediments (k_s), and all 135 the organic carbon can be eventually decomposed. In reality, reactivity should decrease 136 as the organic matter becomes older (Li et al., 2012; Middelburg, 1989), and at a certain 137 depth, the organic matter would be too old and refractory (k_s becomes too small). For 138 simplicity, Eqs. S11 and S12 can be corrected using an efficiency (ϵ) of organic carbon 139 remineralization in the sediments:

140
$$F_{s-02} = -\varepsilon C_{s-C}^0 u_s = -\varepsilon C_{w-C}^H u_w$$
 Eq.S13

141 S2.3 Oxygen consumption and flux in the water column

Similarly, in the water column, if we assume the decay of organic matter follows a firstorder model as in the sediments:

144
$$R_{w-O2} = \frac{dC_{w-C}}{dt} = -k_w C_{w-C}$$
 Eq.S14

- Here, C_{w-C} and k_w are the concentration and reactivity of organic carbon in the water
- column, respectively. The concentration of organic carbon can then be describedsimilarly to Eq. S10:

148
$$C_{w-C} = C_{w-C}^0 e^{-k_w (\frac{z_w}{u_w})} = C_{w-C}^0 e^{-(\frac{k_w}{u_w})z_w}$$
 Eq.S15

- 149 where C_{w-C}^{0} is the organic carbon concentration in the surface water ($z_{w}=0$). The
- 150 concentration of organic matter on the seafloor (C_{w-C}^{H}) is

151
$$C_{w-C}^{H} = C_{w-C}^{0} e^{-(\frac{k_{w}}{u_{w}})H}$$
 Eq.S16

152 Therefore, combining Eqs.S3, S14, S15, and S16 yields the oxygen reaction flux in the 153 water column:

154
$$F_{w-02} = \int_0^H -k_w C_{w-C} dz_w = \int_0^H -k_w C_{w-C}^0 e^{-k_w (\frac{z_w}{u_w})} dz_w = C_{w-C}^0 u_w (e^{-(\frac{k_w}{u_w})H} - 1) \quad \text{Eq.S17}$$

155 Combining Eqs.S13 and 16 yields

156
$$F_{s-02} = -\varepsilon C_{w-C}^H u_w = -\varepsilon C_{w-C}^0 e^{-(\frac{\kappa_w}{u_w})H} u_w$$
Eq.S18

157 Therefore, from Eqs. S17 and S18, the oxygen flux in the water column and sediments 158 has an intrinsic relationship:

159
$$F_{w-02} = \frac{1}{\varepsilon} (e^{(\frac{K_w}{u_w})H} - 1)F_{s-02}$$
 Eq.S19

160 For simplicity, we introduce a rate parameter termed spatial reactivity (*f*, or spatial

161 frequency) to characterize the reaction of oxygen in the water column, by normalizing 162 the temporal frequency (temporal reactivity k_w , in the unit of d⁻¹) to the particles settling 163 velocity (u_w):

Similar to temporal reactivity (k_w) that refers to the reaction proceeded per unit of time (see Eq. S14), the spatial frequency (f; in unit of m⁻¹) describes the reaction proceeded

167 per unit distance the particles settle downwards. In other words, Eq. S14 becomes

168
$$R_{w-O2} = \frac{dC_{w-C}}{dz_w} = -fC_{w-C}$$
 Eq. S21

169 Eq. S19 can then be simplified as

170
$$F_{w-02} = \frac{1}{\varepsilon} (e^{fH} - 1) F_{s-02}$$
 Eq. S22

171 S2.4 Apparent oxygen utilization (AOU) in the water column

172 Now consider the water column experiencing oxygen loss from its equilibrium saturation 173 concentration to the current state over a period of *T*. From Eq. S6,

174
$$\int_{0}^{T} \frac{\mathrm{d}\bar{c}_{w-O2}}{\mathrm{d}t} \mathrm{d}t = \int_{0}^{T} \left(\frac{F_{AWI-O2}}{H} + \frac{F_{s-O2}}{H} + \frac{F_{w-O2}}{H} \right) \mathrm{d}t \qquad \text{Eq. S23}$$

Assuming the fluxes (F_{AWI-O2} , F_{s-O2} , and F_{w-O2}) do not change significantly during this period (pseudo steady state), Eq. S23 becomes

177
$$\bar{C}_{w-02} - \bar{C}_{w-02}^{sat} = \left(\frac{F_{AWI-02}}{H} + \frac{F_{s-02}}{H} + \frac{F_{w-02}}{H}\right)T$$
 Eq. S24

- 178 Where \bar{C}_{w-02}^{sat} is the average saturation oxygen concentration in the water column at in-
- 179 situ temperatures. Thus, the LHS of Eq. S24 equals the negative average water column
- 180 apparent oxygen utilization (AOU):

181
$$(\bar{C}_{w-02} - \bar{C}_{w-02}^{sat}) = (\int_0^H -AOU \, dz_w)/H = -\overline{AOU}$$
 Eq. S25

182 Eqs. S24, S25 and S22 can then be combined:

183
$$-\overline{AOU} \times H = F_{AWI-O2}T + T\left(1 + \frac{1}{\varepsilon}(e^{fH} - 1)\right)F_{s-O2}$$
 Eq. S26

184 and

185
$$\overline{\text{AOU}} \times H = F_{\text{AWI}-\text{O2}}T + T\left(1 + \frac{1}{\varepsilon}(e^{fH} - 1)\right)$$
SOU Eq. S27

186 S2.5 Oxygen mass balance in the bottom boundary layer (BBL)

Similar to the oxygen mass balance in the whole water column (Eq. S6), the changes in
 O₂ concentrations in the BBL is contributed by fluxes from the upper water column,

189 sediments, and consumption within the BBL:

190
$$\frac{d\bar{c}_{BBL-O2}}{dt} = \frac{F_{BI-O2}}{h} + \frac{F_{s-O2}}{h} + \frac{F_{BBL-O2}}{h}$$
 Eq. S28

Here, \overline{C}_{BBL-O2} is the integrated oxygen concentration in the BBL divided by the thickness the BBL (*h*): $\overline{C}_{BBL-O2} = (\int_{H-h}^{h} C_{BBL-O2} dz_w)/h$, which is also the average O₂ concentration in the BBL. F_{BI-O2} is the flux of O₂ across the interface (boundary) between the BBL and the upper waters (positive means downward flux, and oxygen enters the BBL); F_{BBL-O2} is the oxygen reaction flux in the BBL, defined as the integrated O₂ rate in the BBL.

Similar to Eq. S15, by using the upper boundary of the BBL ($z_w = H-h$) as the reference, the concentration of organic matter in the BBL is

198
$$C_{w-C} = C_{w-C}^{H-h} e^{-k_w (\frac{z_w - (H-h)}{u_w})} = C_{w-C}^{H-h} e^{-(\frac{k_w}{u_w})(z_w - (H-h))}$$
 Eq. S29

199 where C_{w-C}^{H-h} is the concentration of organic carbon at depth *H*-*h* (the boundary of the 200 upper boundary of the BBL). Organic carbon concentration at the SWI is

201
$$C_{w-c}^{H} = C_{w-c}^{H-h} e^{-\left(\frac{k_{w}}{u_{w}}\right)h}$$
 Eq. S30

202 Therefore, by combining Eq. S13 and Eq. S30, the sediment oxygen flux becomes

203
$$F_{s-02} = -\varepsilon C_{w-C}^{H} u_{w} = -\varepsilon C_{w-C}^{H-h} e^{-\left(\frac{k_{w}}{u_{w}}\right)h} u_{w}$$
Eq. S31

204 Similar to Eq. S17, O₂ reaction flux in the BBL is defined as

205
$$F_{\text{BBL-O2}} = \int_{H-h}^{H} -k_{\text{w}}C_{\text{w-C}} dz_{\text{w}}$$
 Eq. S32

206 By combining Eqs. S32 and S29,

207
$$F_{\text{BBL}-\text{O2}} = \int_{H-h}^{H} -k_{\text{w}} C_{\text{w}-\text{C}}^{H-h} e^{-(\frac{k_{\text{w}}}{u_{\text{w}}})(z_{\text{w}}-(H-h))} dz_{\text{w}} = C_{\text{w}-\text{C}}^{H-h} u_{\text{w}} (e^{-(\frac{k_{\text{w}}}{u_{\text{w}}})h} - 1)$$
Eq. S33

Therefore, combining Eqs. S33 and S31 we can get the relationship between the flux of oxygen in the BBL and the sediments:

210
$$F_{\text{BBL}-\text{O2}} = \frac{1}{\varepsilon} \left(e^{\left(\frac{k_{\text{W}}}{u_{\text{W}}}\right)h} - 1 \right) F_{\text{s}-\text{O2}} = \frac{1}{\varepsilon} \left(e^{fh} - 1 \right) F_{\text{s}-\text{O2}}$$
 Eq. S34

Similar to Eq. S26, we can obtain the O_2 budget for the BBL the loss of O_2 from saturation concentration to the current state over a period of *T*:

213
$$-\overline{AOU}_{BBL} \times h = F_{BI-O2}T + T\left(1 + \frac{1}{\varepsilon}(e^{fh} - 1)\right)F_{s-O2}$$
 Eq. S35
214 and

215
$$\overline{\text{AOU}}_{\text{BBL}} \times h = F_{\text{BI}-\text{O2}}T + T\left(1 + \frac{1}{\varepsilon}(e^{fh} - 1)\right)$$
SOU Eq. S36
216

217 In **<u>summary</u>**, the oxygen mass balance in the whole water column can be simplified as:

218
$$\overline{AOU} \times H = F_{AWI-O2}T + T\left(1 + \frac{1}{s}(e^{fH} - 1)\right)$$
SOU Eq. S27

219 The oxygen mass balance in the bottom boundary layer can be simplified as:

220
$$\overline{\text{AOU}}_{\text{BBL}} \times h = F_{\text{BI-O2}}T + T\left(1 + \frac{1}{\varepsilon}(e^{fh} - 1)\right)$$
SOU Eq. S36

221 Where *T* is the time needed to develop the current AOU; ε is the efficiency of organic 222 matter remineralization in sediments; *f* is the spatial frequency of organic matter 223 remineralization in the water column.

224 S3. Spatial reactivity (f) of organic matter in the water column

225 The spatial reactivity ($f = k_w/u_w$) describes the reaction proceeded per-unit distance 226 the particles settle downwards. By fitting the observation (F_{s-O2} , h, H, and AOU 227 calculated) to the model (Eqs. S27 and S36) using a sediment recycling efficiency of ε = 228 0.5 and a reaction time (also time for stratification to sustain) of T = 15 d, we obtain an 229 organic matter spatial reactivity of f = 0.026 m⁻¹ for the PRE region. During our sampling 230 period, there was a typhoon that had potentially disrupts the water column stratification. 231 Therefore, the water column CTD data obtained right after the typhoon were excluded 232 when fitting the model. A comparison of observation and model is shown in Figure S7.

We can check the order of magnitude of *f* using a separate estimation of the rate of organic matter remineralization in the water column. For an organic matter production rate of 66 mmol m⁻² d⁻¹ in the region (Cai et al., 2004) and an average SOU of 41.1±16.3 mmol m⁻² d⁻¹, about 28% of the organic matter remineralization occurs in the water column (100%- 41.1/66*100% = 28%). Therefore, from Eq. S21,

$$238 \qquad f = \frac{-\mathrm{uc}_{\mathrm{w-C}}}{c_{\mathrm{w-C}} \,\mathrm{d}z_{\mathrm{w}}} \qquad \qquad \text{Eq. S37}$$

For water column total depth ($H = dz_w$) of 10-20 m, the spatial reactivity is f=0.28/H =

240 0.014-0.028 m⁻¹. This is an order of magnitude consistent with the model fitting results.



242

Figure S1 Vertical distributions of temperature, salinity, sigma density (σ_{θ}), chlorophyl a 244 (chl-a), and oxygen concentrations in the water column.



- 252
- Figure S2 Vertical distributions of buoyance frequency (N²) and oxygen concentrations in the water column. Horizontal dash lines represent the seafloor.





Figure S3 Oxygen profiles in the sediments.



260 261

262 Figure S4 a) Spatial distribution of sediment oxygen penetration depth (OPD) in the 263 Pearl River Estuary and adjacent shelf; b) OPD vs total water depth in the PRE region; 264 c) OPD vs total water depth in the global ocean (Glud, 2008); d) Sediment oxygen 265 uptake in the PRE region compared to that of global marine sediments (Glud, 2008). 266



- Figure S5 Bottom oxygen concentration vs sediment oxygen uptake from PRE region,
- 269 northern Gulf of Mexico (McCarthy et al., 2013a), and the Changjiang Estuary region





Figure S6 a) Average oxygen concentration and B) integrated O₂ concentrations in the 273 whole water column vs SOU normalized to total water depth (SOU/Depth) in the Pearl 274 River Estuary region, northern Gulf of Mexico (McCarthy et al., 2013a), and the 275 Changjiang Estuary region (Zhang et al., 2017).









280 the BBL and the whole water column.







Date	Station	Latitude	Longitude	Depth	BBL	Bottom	Average	AOU	AOUBBL	OPD	SOU
(mm/dd/yy)		(°N)	(°E)	(m)	thickness	O2 (µmol	O ₂	(mmol m⁻³)	(mmol m⁻³)	(mm)	(mmol m⁻²
					(m)	L ⁻¹)	(µmol L ⁻¹)				d ⁻¹)
04/09/2021*	PM7	114.211	22.340	19						2.0	
06/03/2021*	A03	113.741	22.602	15	6.8	97.3	102.0	125.5	120.1	1.0	70.5
06/03/2021*	A05	113.765	22.463	14	8.0	105.0	118.7	107.1	113.2	2.5	45.8
06/04/2021*	A08	113.788	22.266	9	3.9	87.9	110.6	103.8	122.9	2.0	41.0
06/21/2021		113.78	22.279	8	2.8	59.7	115.9	93.8	149.3		
06/04/2021*	A11	113.866	22.093	21	15.8	83.3	85.0	123.8	134.1	3.0	70.4
06/21/2021		113.866	22.095	21	15.9	82.5	99.7	109.7	127.2		
06/04/2021*	A16	113.99	21.752	43	39.9	139.3	155.6	54.7	50.7	3.5	49.0
06/22/2021		113.99	21.752	43	23.0	173.6	176.6	32.5	42.6		
06/05/2021*	P101	112.488	21.581	16	3.4	62.7	128.3	74.6	121.7	3.0	20.9
06/19/2021		112.581	21.584	15	8.2	92.2	136.3	66.6	109.7		
06/07/2021*	F103	113.189	21.694	29	21.3					3.0	35.9
06/19/2021		113.189	22.694	29	24.3	140.2	150.8	63.3	72.8		
06/07/2021*	F101	113.129	21.937	13	5.6					2.0	39.4
06/19/2021		113.128	21.806	15	7.6	31.6	70.0	130.9	168.4		
06/08/2021*	F201	113.389	21.914	12	3.9	9.1	147.1	65.4	199.9	2.0	55.4
06/20/2021		113.388	21.912	12	10.0	77.4	90.0	124.7	140.2		
06/15/2021*	F301	113.548	21.990	11	3.8	8.9	126.3	87.6	197.5	1.8	59.0
06/21/2021		113.547	21.991	10	7.2	70.5	128.4	76.3	88.6		
06/06/2021	J203	112.913	21.551	34	30.3	108.2	118.6	91.1	94.2		
06/17/2021*		112.919	21.551	34	19.7	147.8	144.1	63.8	77.5	5.5	
06/17/2021*	Front17	113.150	21.390	30	16.0	120.6	143.8	65.6	94.4	5.0	29.2
06/06/2021	J103	112.740	21.430	36	21.4	117.0	120.4	87.6	100.6		
06/18/2021*		112.738	21.431	36	29.8	160.3	179.1	31.6	34.1	4.5	63.5
06/06/2021	P204	113.052	21.592	33	20.9	100.0	123.0	77.8	93.4		
06/19/2021*		113.052	21.584	33	21.3	108.8	172.7	32.9	36.9	3.0	30.0
06/08/2021	F204	113.463	21.746	33	23.2	115.6	113.1	94.2	115.1		
06/20/2021*		113.456	21.744	33	28.6	153.1	163.9	48.4	54.4	4.0	26.3
06/11/2021	F603	114.084	22.038	31	10.5	113.1	132.5	77.2	100.3		
06/22/2021*		114.085	22.037	31	26.7	161.3	169.4	36.7	43.4	2.5	29.7
06/11/2021	F702	114.213	22.070	31	12.0	100.0	143.8				
06/22/2021*		114.124	22.412	31	26.5	156.3	168.8				
06/11/2021	F601	114.050	22.159	21	20.0	173.0	173.0	30.2	30.2		
06/22/2021*		114.050	22.159	21	14.7	93.8	124.7	85.6	105.3	4.0	
07/01/2021*	2A01	113.998	22.001	33	26.5	131.0	157.6	48.5	71.0	2.5	36.4
07/04/2021*	2A02	114.252	21.501	63	63	166.9	191.3	10.2	36.3	4.5	14.0
07/06/2021*	2P03	113.851	21.997	24	13.3	50.3	112.8	86.3	70.0	3.0	47.4
07/06/2021*	2P02	113.698	21.994	16	6.5	1.4	97.2	112.0	221.9	1.0	33.4
07/08/2021*	2A01b	114.123	21.751	41	41	184.5	196.4	8.6	13.6	7.0	24.4

Table S1. Sampling locations, water depth, thickness of the BBL, bottom water O₂, oxygen penetration depth (OPD), sediment
 oxygen uptake (SOU), apparent oxygen utilization in the water column and BBL (AOU and AOU_{BBL}).

Table S2 List parameters and variables

Н	Total depth of the water column [m]
7	The vertical displacement in the water column with the sea surface as zero
ZW	and positive going downward [m]
7	The vertical displacement in the acdiment column with the acdiment water
Zs	interface as zero and positive going downward [m]
0	Interface as zero and positive going downward [ing.
Cw-02	O_2 concentration in the water column [mmor m ⁻¹]
\bar{C} on $= \left(\int_{-\infty}^{\infty} C \cos dz \right) / H$	Average O_2 concentration in the water column [mmoi m°], defined as C_{w-O2}
$U_{W-02} = \left(\int_{0}^{0} U_{W-02} U U_{W}\right) / H$	integrated along the entire water column divided by the total depth H.
$=$ sat $\left(\int_{-\infty}^{H} sat \right)$ (12)	Average saturation O ₂ concentration in the water column at in-situ
$C_{w-02}^{sat} = (\int C_{w-02}^{sat} dz_w) / H$	temperature [mmol m ⁻³], defined as the saturation O_2 concentration C_{w-O2}
	integrated along the entire water column divided by the total depth H.
Cs-O2	O ₂ concentration in the sediment [mmol m ⁻³]
R _{w-O2}	Reaction rate of O ₂ in the water column [mmol m ⁻³ d ⁻¹]
Rs-02	Reaction rate of O ₂ in sediments [mmol m ⁻³ d ⁻¹]
Fawi-02	O ₂ fluxes at the air-water interface [mmol m ⁻² d ⁻¹]
Fswil-02	Ω_2 fluxes at the sediment-water interface [mmol m ⁻² d ⁻¹] positive
1 300-02	downwards, also defined as sediment oxygen uptake (SOU)
$\mathbf{E} = \int_{-\infty}^{H} \mathbf{D} d\mathbf{r}$	Ω_2 reaction flux in the water column [mmo] m ⁻² d ⁻¹] defined as the
$r_{w-02} - J_0 \kappa_{w-02} dz_w$	integration of the Ω_2 rate (R_{w,Ω_2}) over the entire water column
$\Gamma = - \int_{-\infty}^{+\infty} D = \frac{1}{2}$	Ω_2 reaction flux in the sediment [mmo] m ⁻² d ⁻¹] defined as the integration of
$r_{s-02} = J_0 \kappa_{s-02} dz_s$	the O_2 rate (R_{e,O_2}) over the entire sediment column
C- 0	Ω
	Organic carbon concentration in the sediments at the sediment water
C s-C	interface $(z = 0)$ [mmol m ⁻³]
<u>^</u> -	$\frac{1}{2} \frac{1}{2} \frac{1}$
<u>Cw-c</u>	Organic carbon concentration in the surface water $(7, -0)$ [mmol m ⁻³]
	Organic carbon concentration in the sodiments at the sodiment water $(2w-0)$ [mmorms]
C ^m w-C	Organic carbon concentration in the sediments at the sediment-water interface $(\pi, \pi/4)$ [merel m ⁻³]
1.	$\frac{1}{10000000000000000000000000000000000$
Ks	Reactivity of organic carbon in Sectiments [d ⁻¹]
Kw	
Us	Burial velocity of sediments [m d ']
U _w	Settling velocity of particles in the water column [m d ⁻¹]
$f = k_{\rm W}/u_{\rm W}$	Spatial frequency $[m^{-1}]$, defined as the temporal frequency (rates k_w) divided
	by the settling velocity <i>u</i> _w .
t	lime (d)
3	The efficiency of organic carbon remineralization in sediments
Т	The time needed for the water column to reach the current level of oxygen
	from an oxygen-saturated condition.
$AOU = C_{w-02}^{sat} - C_{w-02}$	Apparent oxygen utilization in the water column [mmol m ⁻³], defined as the
	difference between oxygen concentration at saturation and the measured
	oxygen concentration in the water.
$\int_{0}^{H} (C_{w-02}^{sat} - C_{w-02}) dz_{w}$	Average AOU in the water column [mmol m ⁻³], defined as AOU integrated
$AOU = \frac{V_0 + V_0 + V_0}{H}$	over the entire water column divided by the total depth <i>H</i> .
$= \overline{C}_{w_{-02}}^{sat} - \overline{C}_{w_{-02}}$	
h	The thickness of the bottom boundary layer [m].
(c^h)	Average O_2 concentration in BBL [mmol m ⁻³], defined as O_2 concentration
$\overline{C}_{BBL-O2} = \left(\begin{array}{c} C_{W-O2} dz_W \end{array} \right) / h$	$(C_{w,o2})$ integrated over the BBL divided by the thickness of the BBL h.
<u> </u>	
F BI-02	The flux of O_2 across the interface (boundary) between the BBL and the
	upper waters (positive means downward flux, and oxygen enters the BBL)
2 ^H	[IIIIII0I III ⁻ U ⁻].
$F_{\rm RBL} = \int_{-\infty}^{\infty} R_{\rm HL} \cos dz_{\rm HL}$	the oxygen reaction flux in the BBL, defined as the integrated O ₂ rate in the
$\int_{H-h}^{H-h} \int_{H-h}^{H-h} $	BBL.
-AOU _{BBL}	Average AOLL in the BBL [mmol m ⁻³] defined as AOLL integrated over the
$\int_{U_{w}}^{H} (C_{w=02}^{\text{sat}} - C_{w=02}) dz_{w}$	BBL divided by the thickness of the layer h
$=\frac{H-h^2}{H}$	
$= \overline{C}_{\text{RPL}}^{\text{sat}} \circ \overline{C}_{\text{RPL}}^{\text{II}} \circ \overline{C}_{\text{RPL}}^{\text{II}}$	
ART-05 ART-05	

290 **Table S3** Water column oxygen and sediment oxygen uptake from other coastal

291

systems

Region	Site ID	Depth (m)	BBL*/hypoxia*/ pycnocline [^]	Bot. O ₂	Aver. O ₂	SOU (mmol	Ref
		50		(mg/L)	(mg/L)	<u>m-a-)</u>	_
Changliang Estuary region	H18_Aug	58	35.7 25.0*	2.40	3.59	24.0	a
Changliang Estuary region		20	35.U 15.0*	4.60	5.48 4 70	13.5	a
Changliang Estuary region	H9_Aug	34	15.9	1.90	4.70	23.2	a
Changliang Estuary region		34 57	14.0	4.57	0.08	18.2	a
Changliang Estuary region	HI5_Aug	57	29.0	2.40	2.50	02.0	a
Northorn Culf of Movies		57 10	21.1 0.2*	0.30	0.03	20.0	a h
Northern Gulf of Maxico	CT2 Aug09	19	0.0	0.10	3.0Z	20.1	D h
Northern Gulf of Mexico		20	14.0 0.7*	4.52	5.90 5.64	10.7	D h
Northern Gulf of Mexico	F5_Aug09	29	9.7 16.0*	3.44 2.44	5.04 5.64	19.3	D h
Northern Gulf of Mexico	F5_Aug09	29	10.9 E 0*	3.44	0.04 4.40	19.3	D h
Northern Gulf of Mexico	MRM_Aug09	10	0.8 1.0*	3.09	4.49	21.3	D h
Northern Gulf of Maxico	MDM Aug09	10	1.9	0.70	4.49	21.3	D h
Northern Gulf of Mexico	MRM_AUg09	10	3.4 40.7*	2.30	4.49	21.3	D
Northern Gulf of Mexico		18	10.7	2.27	5.60	43.2	D
Northern Gulf of Mexico		28	8.5	1.22	4.13	20.4	D
Northern Gulf of Mexico	F5_May10	29	9.0	1.93	5.03	21.2	D
Northern Gulf of Mexico		10	1.3	1.11	4.09	34.3	D
Northern Gulf of Mexico		19	3.3	1.15	5.15	15.0	D
Northern Gulf of Mexico	C12_May11	33	28.0	4.74	5.58	26.4	D
Northern Gulf of Mexico	F5_May11	29	12.7	5.43	0.35	21.4	D
Northern Gulf of Mexico		19	19.0	4.70	5.55	11.5	D
Northern Gulf of Mexico	CIZ_Sep08	29	19.0	5.69	5.33	9.9	D
Northern Gulf of Mexico	F5_Sep08	28	28.0	6.10	0.28	11.0	D
Northern Gulf of Mexico	B7_Janu9	21	21.0	4.80	1.24	18.5	D
Northern Gulf of Mexico		18	6.U	4.31	0.02	16.5	D
Northern Gulf of Mexico	CT2_Jan09	25	18.7	6.70	6.87	20.4	D
Northern Gulf of Mexico	CIZ_Janu9	25	25.3	6.70	0.87	20.4	D
Northern Gulf of Mexico	F5_Janu9	30	30.0	6.98	6.70	9.8	D
Northern Gulf of Mexico	MRM_May11	10	2.5	1.28	5.15	34.3	D
Middle Chesapeake Bay	CB3.2C	13	7.0	0.80		61.4	С
Middle Chesapeake Bay	CB4.1C	32	11.5	0.10		25.7	С
Middle Chesapeake Bay	CB4.3C	27	12.4	0.23		14.3	С
Middle Chesapeake Bay	CB5.1	28	16.5	0.90		21.4	С
Middle Chesapeake Bay	CB5.2	30	15.1	1.01		15.8	C
Gult of St Lawrence			100*	< 2.0		9.7	d
Long Island Sound			12*	< 2.0		19	e
Northwestern Black Sea			9*	< 2.0		6.8	f
Baltic Sea			125*	< 2.0		8	g

292 Note:

a) Sediment oxygen uptake (SOU) are from Zhang et al., (2017) and the water column

294 parameters are calculated from CTD profiles provided by the author H. Zhang.

b) SOU data are from McCarthy et al., (2013) and water column parameters are calculated from CTD profiles provide by the author M. J. McCarthy.

297 c) SOU data are from Boynton et al., (2022); water column data for the corresponding sites are from the Chesapeake Bay Program (CBP, https://datahub.chesapeakebay.net).

299 d) Fennel and Testa 2019 (originally from Lehmann et al., (2009))

300 e) Fennel and Testa 2019 (originally from Welsh & Eller, (1991))

301f)Fennel and Testa 2019 (originally from Cannaby et al., (2015), Capet et al., (2013), and302Capet et al., (2016))

303 g) Fennel and Testa 2019 (originally from Noffke et al., (2016) and Wulff & Stigebrandt (1989))

304

306 **Reference**

- APHA (1998) Standard Methods for the Examination of Water and Wastewater. 20th
 Edition, American Public Health Association, American Water Works Association and
 Water Environmental Federation, Washington DC.
- Boynton, W. R., Ceballos, M. A. C., Hodgkins, C. L. S., Liang, D., & Testa, J. M. (2022).
 Large-Scale Spatial and Temporal Patterns and Importance of Sediment–Water
 Oxygen and Nutrient Fluxes in the Chesapeake Bay Region. *Estuaries and Coasts*,
 1–20. https://doi.org/10.1007/s12237-022-01127-0
- Cai, W. J., Dai, M., Wang, Y., Zhai, W., Huang, T., Chen, S., et al. (2004). The
 biogeochemistry of inorganic carbon and nutrients in the Pearl River estuary and the
 adjacent Northern South China Sea. *Continental Shelf Research*, 24(12), 1301–1319.
 https://doi.org/10.1016/j.csr.2004.04.005
- Cannaby, H., Fach, B. A., Arkin, S. S., & Salihoglu, B. (2015). Climatic controls on
 biophysical interactions in the Black Sea under present day conditions and a potential
 future (A1B) climate scenario. *Journal of Marine Systems*, *141*, 149–166.
 https://doi.org/10.1016/j.jmarsys.2014.08.005
- Capet, A., Beckers, J.-M., & Grégoire, M. (2013). Drivers, mechanisms and long-term
 variability of seasonal hypoxia on the Black Sea northwestern shelf is there any
 recovery after eutrophication? *Biogeosciences*, *10*(6), 3943–3962.
 <u>https://doi.org/10.5194/bg-10-3943-2013</u>
- Capet, Arthur, Meysman, F. J. R., Akoumianaki, I., Soetaert, K., & Grégoire, M. (2016).
 Integrating sediment biogeochemistry into 3D oceanic models: A study of benthic pelagic coupling in the Black Sea. *Ocean Modelling*, *101*, 83–100.
 https://doi.org/10.1016/j.ocemod.2016.03.006
- Fennel, K., & Testa, J. M. (2019). Biogeochemical Controls on Coastal Hypoxia. Annual
 Review of Marine Science. Retrieved from <u>https://doi.org/10.1146/annurev-marine-</u>
 010318-095138
- Glud, R. N. (2008). Oxygen dynamics of marine sediments. *Marine Biology Research*,
 4(4), 243–289. <u>https://doi.org/10.1080/17451000801888726</u>
- Jørgensen, B. B., & Revsbech, N. P. (1985). Diffusive boundary layers and the oxygen
 uptake of sediments and detritus1. *Limnology and Oceanography*, *30*(1), 111–122.
 <u>https://doi.org/10.4319/lo.1985.30.1.0111</u>
- Lehmann, M. F., Barnett, B., Gélinas, Y., Gilbert, D., Maranger, R. J., Mucci, A., et al.
 (2009). Aerobic respiration and hypoxia in the Lower St. Lawrence Estuary: Stable
 isotope ratios of dissolved oxygen constrain oxygen sink partitioning. *Limnology and Oceanography*, *54*(6), 2157–2169. https://doi.org/10.4319/lo.2009.54.6.2157
- Li, J., Crowe, S. A., Miklesh, D., Kistner, M., Canfield, D. E., & Katsev, S. (2012). Carbon
 mineralization and oxygen dynamics in sediments with deep oxygen penetration,
 Lake Superior. *Limnology and Oceanography*, 57(6), 1634–1650.
- 345 https://doi.org/10.4319/lo.2012.57.6.1634
- McCarthy, M. J., Carini, S. A., Liu, Z., Ostrom, N. E., & Gardner, W. S. (2013a). Oxygen
 consumption in the water column and sediments of the northern Gulf of Mexico
 hypoxic zone. *Estuarine, Coastal and Shelf Science, 123*, 46–53.
 https://doi.org/10.1016/j.ecss.2013.02.019
- McCarthy, M. J., Carini, S. A., Liu, Z., Ostrom, N. E., & Gardner, W. S. (2013b). Oxygen
 consumption in the water column and sediments of the northern Gulf of Mexico

- 352 hypoxic zone. *Estuarine, Coastal and Shelf Science, 123, 46–53.*
- 353 <u>https://doi.org/10.1016/j.ecss.2013.02.019</u>
- McDougall, T. J., & Barker, P. M. (2011). *Getting started with TEOS-10 and the Gibbs Seawater (GSW) Oceanographic Toolbox* (Vol. SCOR/IAPSO WG127).
 SCOR/IAPSO WG127.
- Middelburg, J. J. (1989). A simple rate model for organic matter decomposition in marine
 sediments. *Geochimica et Cosmochimica Acta*, *53*(7), 1577–1581.
 https://doi.org/10.1016/0016-7037(89)90239-1
- Noffke, A., Sommer, S., Dale, A. W., Hall, P. O. J., & Pfannkuche, O. (2016). Benthic
 nutrient fluxes in the Eastern Gotland Basin (Baltic Sea) with particular focus on
 microbial mat ecosystems. *Journal of Marine Systems*, *158*, 1–12.
 https://doi.org/10.1016/j.jmarsys.2016.01.007
- Welsh, B. L., & Eller, F. C. (1991). Mechanisms controlling summertime oxygen
 depletion in western Long Island Sound. *Estuaries*, *14*(3), 265–278.
 https://doi.org/10.2307/1351661
- Wulff, F., & Stigebrandt, A. (1989). A time-dependent budget model for nutrients in the
 Baltic Sea. *Global Biogeochemical Cycles*, *3*(1), 63–78.
 <u>https://doi.org/10.1029/gb003i001p00063</u>
- Zhang, H., Zhao, L., Sun, Y., Wang, J., & Wei, H. (2017). Contribution of sediment
 oxygen demand to hypoxia development off the Changjiang Estuary. *Estuarine, Coastal and Shelf Science*, *192*, 149–157. https://doi.org/10.1016/j.ecss.2017.05.006
- Zhou, L. (2022). Sediment oxygen uptake and carbon mineralization in the Pearl River
 Estuary and adjacent coastal waters. Master's Thesis, The Hong Kong University of
- 375 Science and Technology. doi: 10.14711/thesis-991013088359403412.