

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

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19 **Key Points:**

- 20
- 21 • Sediment respire >60% of the organic matter produced in the water column of
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
25 conditions and timescales in the PRE and similar coastal systems.
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
30 stratification. Quantifying these biogeochemical and physical drivers is important for
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
33 a simple analysis to quantify both the biogeochemical and physical drivers of hypoxia.
34 We show that in the PRE region, sediment respire >60% of organic matter produced in
35 the water column, leading to high sediment oxygen uptake (average $41.1 \pm 16.3 \text{ mmol m}^{-2}$
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.
38 We then construct a generic mass-balance model to quantify oxygen loss, determine
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 $\text{O}_2 < 2 \text{ mg L}^{-1}$). 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
46 oxygen from the atmosphere and the surface water to the bottom water is blocked by
47 strong density stratification. To quantify these effects, we study a typical coastal system,
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
54 show that the model is generic and can be applied to other similar coastal systems, such
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
61 and weak ventilation, especially in bottom waters where oxygen depletion can be
62 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
65 reduce the oxygen resupply to the bottom. The increasing anthropogenic fertilization of
66 the coastal ocean, together with the stronger stratification caused by global warming,
67 therefore, can intensify hypoxia in both magnitude and duration (Diaz & Rosenberg,
68 2008).

69 Quantifying these physical and biogeochemical drivers of hypoxia is important for
70 management and predicting future trends. In addition to monitoring oxygen (Grégoire et
71 al., 2021), mechanistic modeling becomes very useful (Laurent & Fennel, 2017; Peña et
72 al., 2010). These models simulate the oxygen budget considering its source/sink
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
81 dynamics, and the reactions in the sediments and benthic-pelagic exchanges (Peña et
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
85 low transferability among systems (Peña et al., 2010). For cross-system comparison,
86 simple scale analyses are useful (Fennel & Testa, 2019). For example, the vulnerability
87 of the system can be understood by comparing the timescale of hypoxia formation to the
88 water residence time of the region (Fennel & Testa, 2019). However, while such an
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 mass-
94 balance model to understand oxygen loss without a detailed formulation of the physical
95 and biogeochemical complexity. The model can be used to understand the sensitivity of
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,

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

101 2. Field Methods

102 We study the Pearl River Estuary and adjacent shelf waters (PRE region) in the
103 summer of 2021 (Fig.1a and Table.S1; Li et al. 2024). We used a SeaBird-SBE17-plus
104 conductivity–temperature–depth (CTD) to measure the water column temperature,
105 density, salinity, O₂ concentrations and calculated the buoyancy frequency (N^2 ; s⁻²):

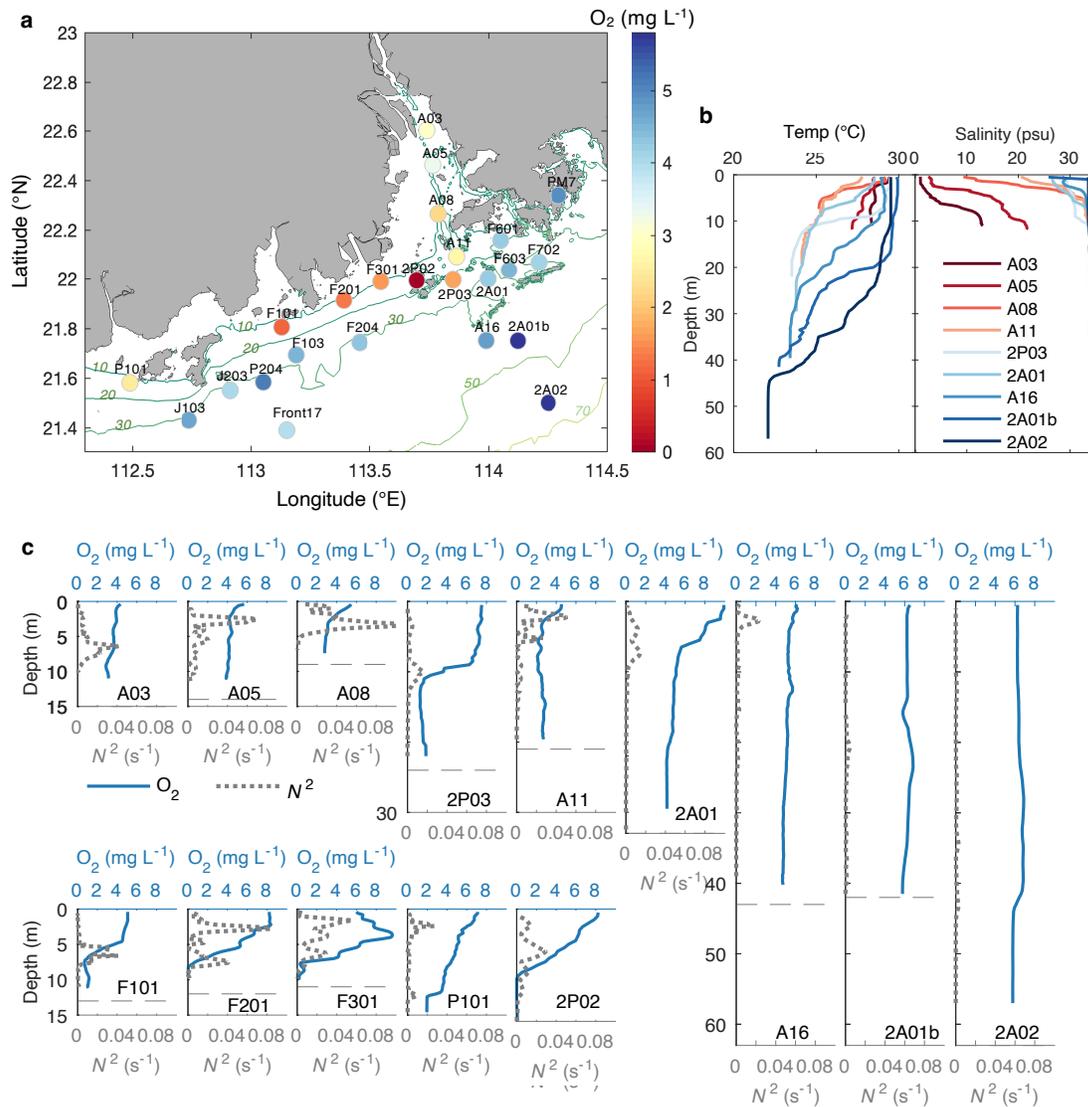
$$106 \quad N^2 = \frac{g}{\rho(z)} \frac{d\rho(z)}{dz} \quad \text{Eq.1}$$

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

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

121 3. Results

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

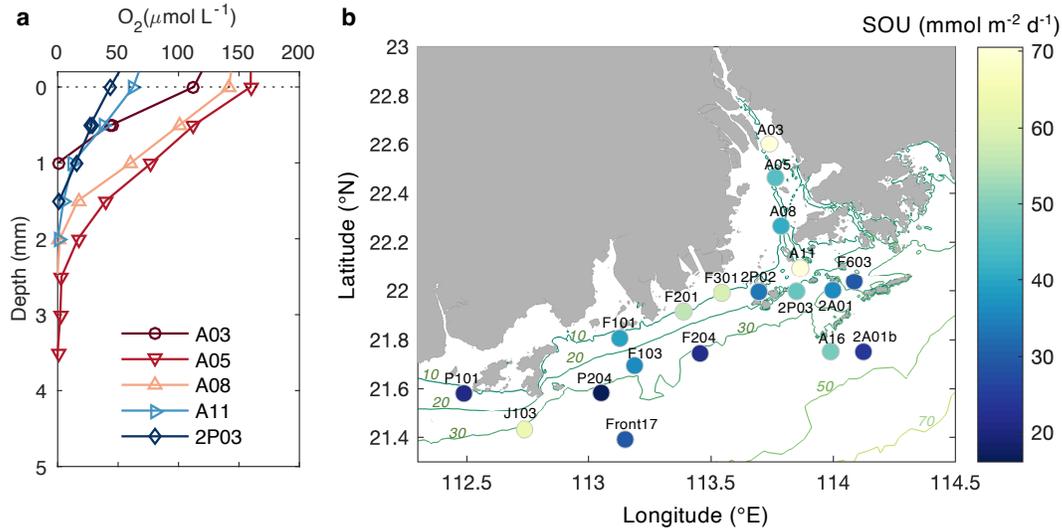


137

138 **Figure 1 Water column physiochemistry in the Pearl River Estuary region.** a) Sampling
 139 locations and bottom oxygen concentrations; b) Temperature and salinity profiles across the
 140 estuary to open ocean gradient c) Buoyancy frequency (N^2) and O_2 profiles across the
 141 salinity gradient and at the hypoxic sites. Horizontal dashed lines represent the bottom.
 142

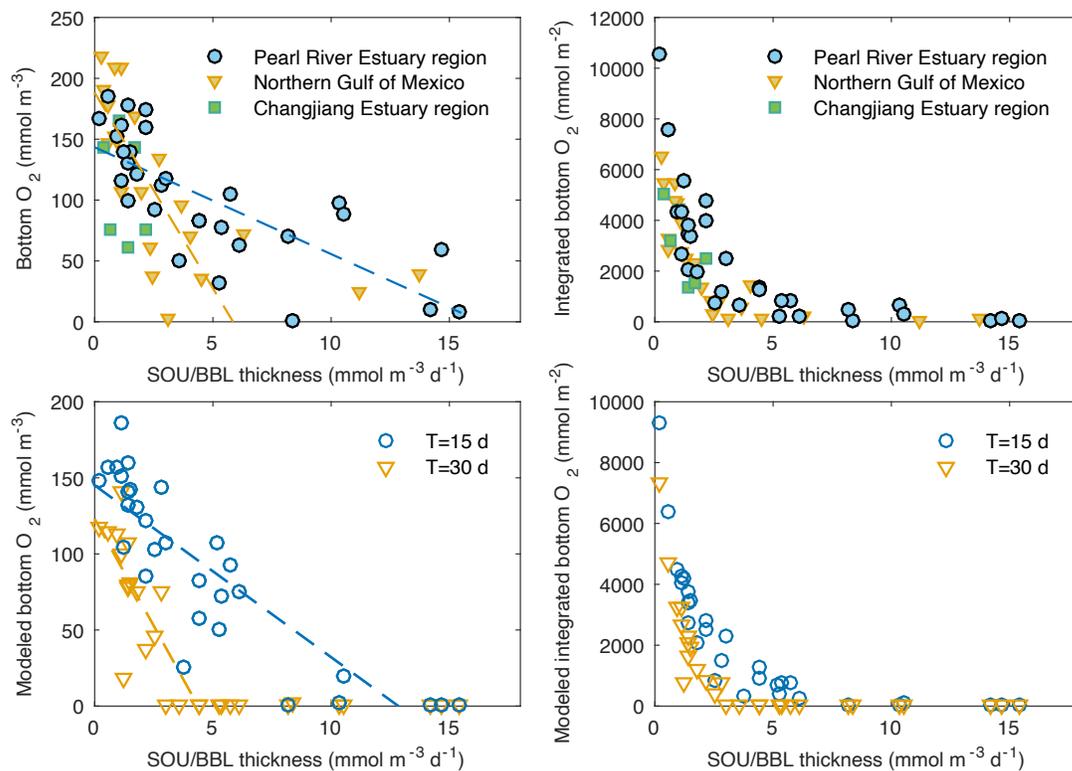
143 **3.2 Sediment oxygen uptake and bottom water oxygen** – Oxygen concentration in
 144 the BBL is controlled by the flux from the upper layer, which can be restricted by
 145 stratification, and the consumption in the water and sediments. In the sediments, oxygen
 146 drops sharply from 75-150 $\mu\text{mol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

151 $\text{mmol m}^{-2} \text{d}^{-1}$; 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
 153 assume oxygen is predominantly consumed via organic matter respiration, this
 154 consumption averages to $\sim 62 \pm 25\%$ of the organic matter produced in the water column
 155 of the region ($66 \text{ mmol m}^{-2} \text{d}^{-1}$) (Cai et al., 2004).



156
 157 **Figure 2 Sediment oxygen distribution and uptake. a)** O₂ profiles at selected sites; **b)**
 158 sediment oxygen uptake (SOU).
 159

160 High SOU would contribute significantly to the oxygen loss in the bottom water.
 161 However, the correlation between SOU and bottom oxygen is weak (Fig.S5 and Yu et al.
 162 (2015a)). This is because the thickness of the BBL would affect the sediment's impact: a
 163 thin layer would respond faster to SOU, while a thicker bottom reacts less with the effect
 164 of SOU being diluted. Indeed, the hypoxia sites have thin BBL (1.3 to <10 m), whereas
 165 the well-oxygenated sites have thicker BBL or entirely mixed water column (Figs.1c, S2,
 166 and Table.S1). By normalizing SOU to the thickness of the BBL (h), we obtain the
 167 oxygen depletion rate in the BBL by the sediments (SOU/h ; $\text{mmol m}^{-3} \text{d}^{-1}$), which exhibits
 168 a strong relationship with the bottom O₂ level (Fig.3a). A stronger correlation appears
 169 when considering the integrated O₂ over the BBL (mmol m^{-2}): oxygen decreases
 170 exponentially with increasing SOU/h (Fig.3b). The relationships exist in similar systems
 171 such as the northern Gulf of Mexico and the Changjiang Estuary region (Figs.3a and
 172 3b); both are estuary dominated shelves experiencing hypoxia (McCarthy et al., 2013;
 173 Zhu et al. 2016).). Similar relationships are also seen for the entire water column
 174 (Fig.S6).
 175



176

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

181

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
 187 SOU. This explains the curvature in Fig.3b: at the sites with low SOU/h, the BBL is thick
 188 and thus WOU becomes important, making the oxygen level sensitive to the apparent
 189 per-SOU change (steeper slopes at low SOU/h in Figs.3b).

190

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

196

197 **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

198 of the model are narrated in SI.2, which we briefly introduce here to facilitate discussion.
 199 The change of O₂ concentration in the BBL is caused by fluxes from above (assumed to
 200 be small and neglected here due to the large N₂ above the BBL) and the sediment (F_{s-O₂},
 201 which equals -SOU), and the reaction within the BBL (F_{BBL-O₂}, which equals -WOU_{BBL}):

$$202 \quad \frac{d\bar{C}_{\text{BBL-O}_2}}{dt} = \frac{F_{s\text{-O}_2}}{h} + \frac{F_{\text{BBL-O}_2}}{h} \quad \text{Eq.2}$$

203 Here, $\bar{C}_{\text{BBL-O}_2}$ is the average O₂ concentration in the BBL. Assuming oxygen is mostly
 204 consumed to respire organic matter (Zhang & Li, 2010), F_{BBL-O₂} depends on the amount
 205 of organic carbon settling into the BBL (C_{w-C}^{H-h} ; H is the total depth and h is the thickness
 206 of the BBL, hence the upper boundary of BBL is at $H-h$; the subscript 'w-C' stands for
 207 water-column carbon), the reaction rate (k_w), and the time the particles spend in the BBL
 208 ($t=h/u_w$; u_w is the particle settling velocity). Considering a 1C:1O₂ ratio and first-order
 209 reaction for simplicity, the reaction in the BBL is

$$210 \quad F_{\text{BBL-O}_2} = \int_{H-h}^H -k_w C_{w-C} dz_w = \int_{H-h}^H -k_w C_{w-C}^{H-h} e^{-\frac{k_w}{u_w}(z_w-H+h)} dz_w = u_w C_C^{H-h} \left(e^{-\frac{k_w}{u_w}h} - \right.$$

$$211 \quad \left. 1 \right) = -\text{WOU}_{\text{BBL}} \quad \text{Eq.3}$$

212 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 O₂ flux into the
 214 sediment equals the organic carbon flux ($u_w C_{w-C}^H$; C_{w-C}^H is the concentration at the
 215 sediment-water interface at depth H) corrected by a recycling efficiency (ε) for not all
 216 organic matter reaching sediments being reactive (Li et al., 2012):

$$217 \quad F_{s\text{-O}_2} = -\varepsilon u_w C_C^H = -\text{SOU} \quad \text{Eq.4}$$

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

$$220 \quad u_w C_{w-C}^H = u_w C_{w-C}^{H-h} + F_{\text{BBL-O}_2} \quad \text{Eq.5}$$

221 Combining Eqs.3, 4, and 5,

$$222 \quad F_{s\text{-O}_2} = -\varepsilon u_w C_{w-C}^H = -\varepsilon (u_w C_{w-C}^{H-h} + F_{\text{BBL-O}_2}) = -\varepsilon u_w C_{w-C}^{H-h} e^{-\left(\frac{k_w}{u_w}\right)h} \quad \text{Eq.6}$$

223 Therefore, from Eqs. 3 and 6,

$$224 \quad F_{\text{BBL-O}_2} = \frac{1}{\varepsilon} \left(e^{\left(\frac{k_w}{u_w}\right)h} - 1 \right) F_{s\text{-O}_2} = \frac{1}{\varepsilon} (e^{fh} - 1) F_{s\text{-O}_2} \quad \text{Eq.7.1}$$

$$225 \quad \text{or } \text{WOU}_{\text{BBL}} = \frac{1}{\varepsilon} (e^{fh} - 1) \text{SOU} \quad \text{Eq.7.2}$$

226 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
 229 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 $AOU_{\text{BBL}}h = T \left(1 + \frac{1}{\varepsilon} (e^{fh} - 1) \right) \text{SOU}$ Eq.8

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

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

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

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

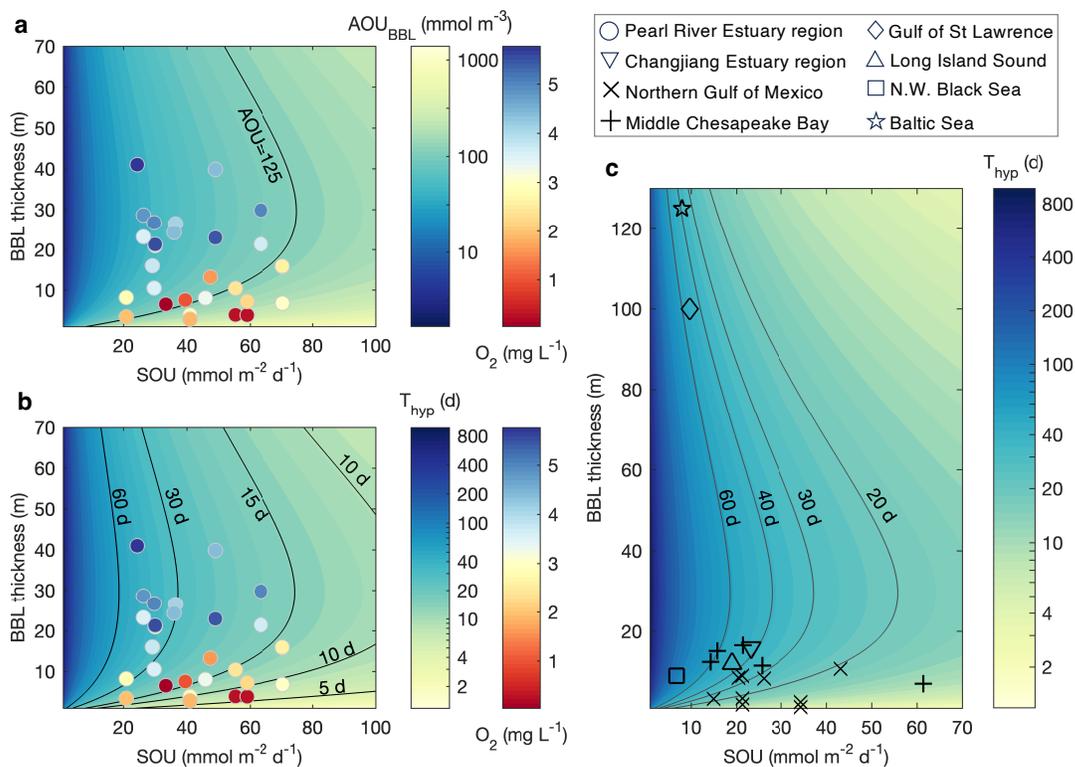
252 5. Discussion

253 **5.1 Conditions and time scales for hypoxia**— The model explains the relationships
 254 between the bottom O_2 level and SOU/h in the PRE region and other similar systems
 255 (Figs.3c and 3d). The duration of stratification determines the sensitivity of O_2 levels to
 256 SOU/h : the northern Gulf of Mexico has long periods of stratification (Bianchi et al.,
 257 2010; Dzwonkowski et al., 2018) and thus appears more sensitive to SOU: the bottom
 258 oxygen drops more with the same level of increase in SOU/h (Figs.3a and 3b). This is
 259 consistent with model results when the stratification period is set to be longer (e.g., $T=$
 260 30 versus 15 d; Figs.3c and 3d). Alternatively, the high sensitivity of oxygen can be
 261 achieved in systems with higher spatial reactivity of settling organic matter (f) (Fig.S8).

262 The model provides several quantitative insights. As expected, AOU_{BBL} increases
 263 with increasing SOU and the effect is more dramatic when BBL is thin (Fig.4a). In the
 264 PRE region, a BBL of <10 m is susceptible to hypoxia even at low SOU (Fig.4a). For
 265 thicker BBL to reach hypoxia, higher SOU is required, but the effect is not linear: in the
 266 PRE region, when SOU is above $\sim 75 \text{ mmol m}^{-2} \text{ d}^{-1}$, the bottom can easily develop
 267 hypoxia regardless of the BBL thickness (Fig.4a). This is because, in environments with

268 organic matter deposition supporting such high SOU, the WOU would be proportionally
 269 high (Eq.7.2).

270 We can estimate the time required for developing hypoxia (Figs.4b): waters with
 271 high SOU and thin BBL become hypoxic within a shorter time. In the PRE region, it
 272 requires $<\sim 15$ days for thin BBLs ($<\sim 10$ 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
 275 can estimate their hypoxia time scales (T_{hyp} ; Fig.4c), which can be compared to the
 276 stratification time scales to see if hypoxia can develop. For example, in the seasonally
 277 hypoxic northern Gulf of Mexico, most hypoxia sites have T_{hyp} of <30 - 40 days, which is
 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
 280 stable for several summer months (Boynton et al., 2022), thus hypoxia persistently
 281 develops even under low SOU (Fig.4c). More extreme cases are Gulf of St. Lawrence,
 282 the Black Sea, and the Baltic Sea, where persistent and even permanent stratification
 283 sustains thick hypoxia layers under low SOU (Fig.4c).

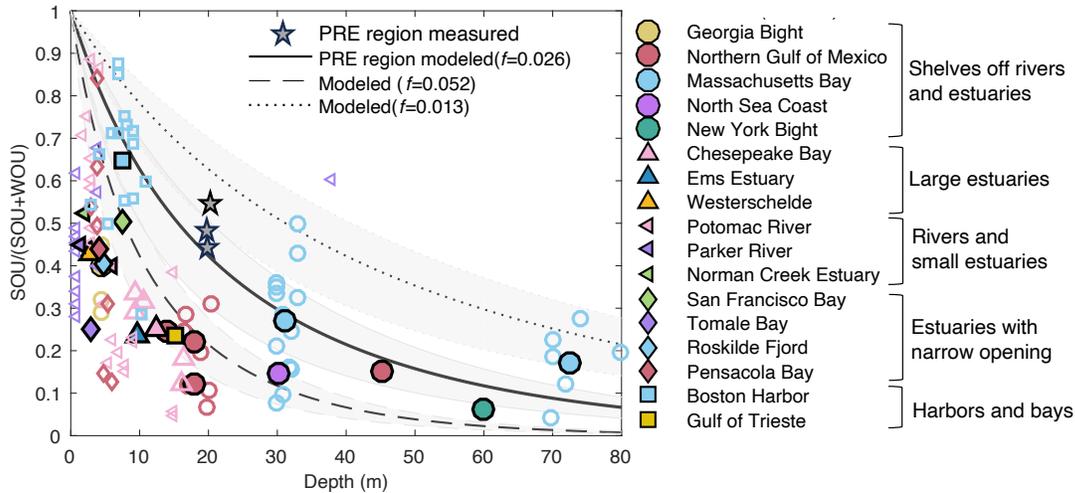


284

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*
291 *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*
293 *systems (Table S3) (Boynton et al., 2019, 2022; Fennel & Testa, 2019; McCarthy et al., 2013;*
294 *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
298 estuaries and coasts (Boynton et al., 2018) (Fig.5): %SOU declines exponentially with
299 the water layer thickness (for whole water column or BBL). Intuitively, the organic matter
300 spends more time in thicker waters consuming oxygen before reaching the sediments,
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
303 reactivity (f) and sediment recycling efficiency (ϵ). In systems with slowly settling
304 particles (low u_w), the large f (k_w/u_w) would lead to low %SOU (Fig.5). In contrast, SOU
305 contributes more when sedimentation is rapid (large u_w and thus small f ; Fig.5). Particle
306 settling velocity is controlled by particle concentrations (Archer & Devol, 1992), but more
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
309 when shear stress is too large (Manning, 2004). In rivers and estuaries, strong
310 turbulence also leads to particle resuspension (Boynton et al., 2018), increasing the time
311 the particles spend in the water column to consume oxygen (Moriarty et al. 2021). This
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
319 lesser extent (the shaded area in Fig.5), and the effect becomes smaller when the
320 organic matter spatial reactivity is high (see variability in the width of the shaded area in
321 Fig. 5), as there is less organic matter reaching the sediment for recycling efficiency to
322 make a difference.



323

324 **Figure 5** The contributions of SOU to total oxygen uptake (SOU +WOU) as a function of
 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
 328 different sediment recycling efficiency ($\varepsilon = 0.3-0.75$). Literature data are from (Boynton et al.,
 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
 331 measurements.

332

333 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
 336 in the BBL due to the sediment and water oxygen uptake (Eqs.8 and 9). While SOU
 337 needs to be measured, we show that bottom oxygen levels and water-column
 338 stratification can be used to parameterize SOU and increase the data size (Fig.3). WOU
 339 is linked to SOU in the model via their intrinsic mass-balance connection (Eqs.7.2 and
 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.

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

351 & Lehrter, 2011; Rowe et al., 2002). Therefore, for the model to work, SOU might need to
352 be measured under sufficient overlying-water oxygen (reaction not limited by oxygen) at
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
358 constraints, such as the reactivity and settling velocity of particles, to support other
359 mechanistic models.

360

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378

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390

391 **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
394 are from Zhang et al. 2017 and Chi et al. 2021; Data from the Northern Gulf of Mexico
395 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
398 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).

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