

**Human Activities Caused Hypoxia Expansion in a Large Eutrophic
Estuary: Non-negligible Role of Riverine Suspended Sediments**

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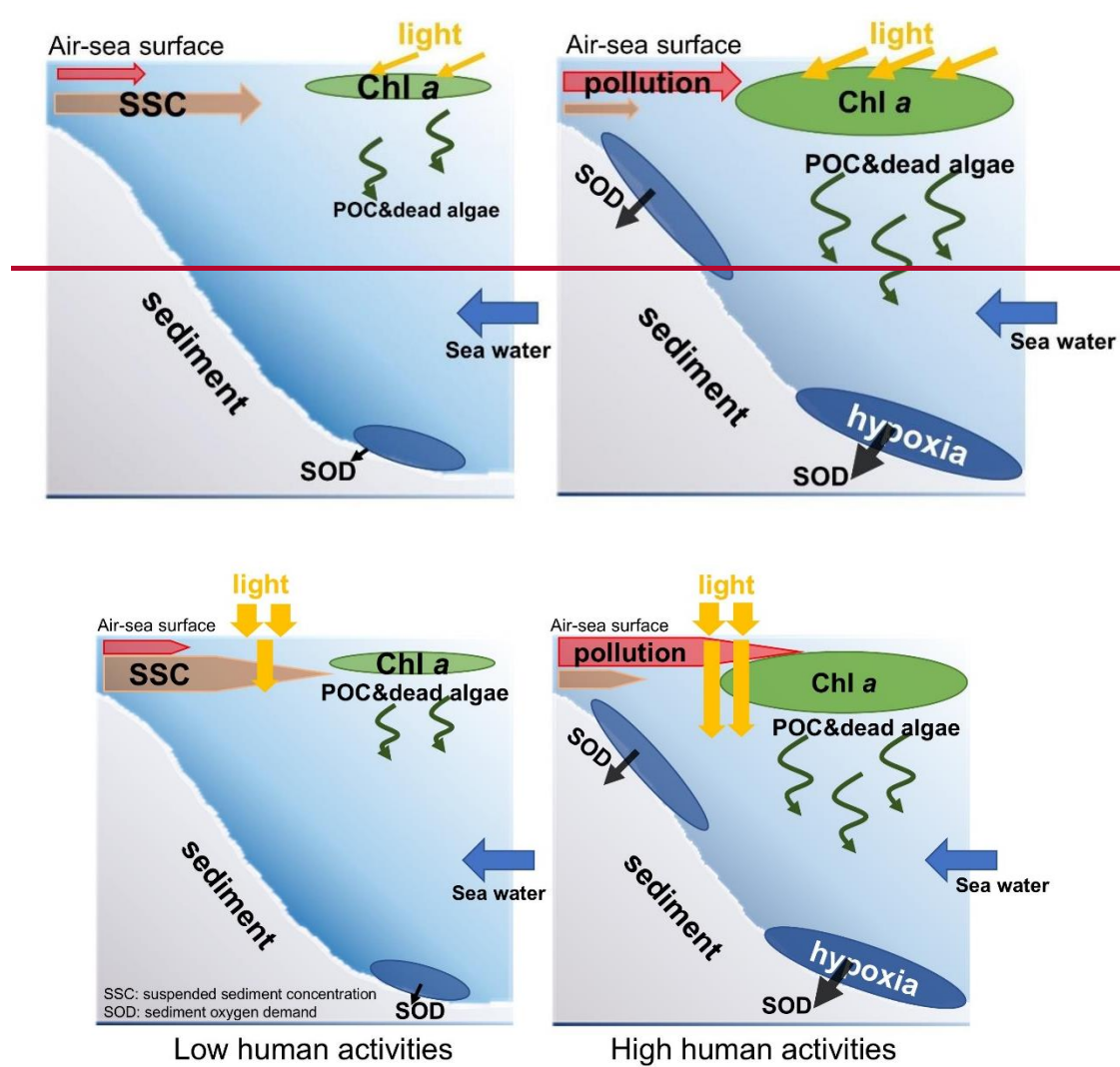
Abstract

Increase in riverine nutrient loads was generally recognized as the primary cause of coastal deoxygenation, whereas the role of other riverine factors, especially suspended sediments, has received less attention. This study aims to discern the impacts of anthropogenic alterations in various riverine inputs on the subsurface deoxygenation over the past three decades in a large river-dominated estuary, the Pearl River Estuary (PRE). By utilizing the physical-biogeochemical model, we reproduced the observed dissolved oxygen (DO) conditions off the PRE in the historical period (the 1990s with high-suspended sediments-DO and low-nutrient inputs) and the present period (the 2010s with low-suspended sediments-DO and high-nutrient inputs). Due to the decadal changes in riverine inputs, the PRE has witnessed more extensive and persistent low-oxygen events during summer in the 2020s, with larger spatial extents of $\sim 2926 \text{ km}^2$ for low oxygen ($\text{DO} < 4 \text{ mg/L}$, increased by $\sim 148\%$ relative to the 1990s) and 617 km^2 for hypoxia ($\text{DO} < 3 \text{ mg/L}$, by 192%) and longer duration (by $\sim 15\text{-}35$ days), evolving into three distinct hypoxic centers controlled by different factors. Model experiments suggested that the decreased riverine DO content (46%) has led to a low-oxygen expansion in the upper regions, accounting for 44% to the total increment. Meanwhile, the increased nutrient levels (100% in nitrogen and 225% in phosphorus) and the declined suspended sediment concentration (60%) have jointly promoted the primary production and bottom oxygen consumptions (dominated by sediment oxygen uptake), thus resulting in a substantial enlargement of low-oxygen area (104%) and hypoxic area (192%) in the lower reaches. Our results revealed a more critical role of the riverine suspended sediment decline in the exacerbation of eutrophication and deoxygenation off the PRE via improving light conditions to support higher local productivity, which could further amplify the effect combined with the growth in nutrients and confound the effectiveness of hypoxia mitigation under nutrient controls. Overall, in the context of global changes in riverine suspended sediments, it is imperative to reassess the contribution of riverine inputs to the coastal deoxygenation worldwide over the past

decades, given that the impact of suspended sediments has been constantly overlooked in relevant investigations.

Key words: Deoxygenation; suspended sediments; nutrient inputs; decadal changes; Pearl River Estuary

Graphical Abstract



1. Introduction

Hypoxia emerges when dissolved oxygen (DO) concentration drops below 3 mg/L in aquatic systems. It is an undesirable phenomenon which can lead to a series of

biological and ecological consequences, such as damaging the habitat for aquatic organisms and imposing detrimental effects on the ecosystem community structure (Diaz and Rosenberg, 2008; Roman et al., 2019). Due to the substantial impacts from human socioeconomic activities, coastal regions have become a hotspot for hypoxia (Breitburg et al., 2018; Pitcher et al., 2021). Moreover, long-term exacerbation of hypoxia with spatial expansion and increased intensity has been frequently reported in estuarine and coastal regions worldwide during the past decades, including the Baltic Sea (Carstensen et al., 2014), the northern Gulf of Mexico (Bianchi et al., 2010), Chesapeake Bay (Murphy et al., 2011), the Yangtze River Estuary (Chen et al., 2017), and the Pearl River Estuary (Hu et al., 2021).

Plenty of studies were conducted to reveal the mechanism of hypoxia formation and evolution in coastal regions. It has been widely recognized that coastal deoxygenation is largely attributed to the eutrophication-driven production of organic matters (Su et al., 2017; Wang et al., 2016; [Howarth et al., 2011](#)), which sink to the subsurface waters and bottom sediments, leading to intense oxygen depletion ([Wang et al., 2014](#); [Hagy et al., 2005](#)). This would induce hypoxia when the density stratification restricts DO replenishment from the surface waters (Wang et al., 2018; [Murphy et al., 2011](#)). One important reason underlying eutrophication and hypoxia is the excessive nutrients that are discharged into the water column and stimulate phytoplankton blooms (Cullen, 2015; Wang et al., 2021; [Cormier et al., 2023](#)). [Human activities, such as dam construction](#) (Bussi et al., 2021) [and soil-water conservation measures](#) (Yang et al., 2024) [can significantly reduce suspended sediment in estuaries](#). In addition, an improved light condition, e.g., due to the decreased suspended sediment loads, could also favor the enhancement of local production and hence hypoxia (Ge et al., 2020; Huang et al., 2022). The effects of nutrient and light conditions vary in coastal systems due to different hydrodynamic and topographic features, which makes the formulation of hypoxia mitigation strategies more challenging. Therefore, a quantitative assessment on the importance of these factors in generating hypoxia is crucial for understanding

the primary drivers of hypoxia evolution and for proposing effective countermeasures.

A case in point is the Pearl River Estuary (PRE), which is situated in the northern South China Sea and close to the Guangdong-Hong Kong-Macao Great Bay Area (Fig. 1a). Owing to the relatively large nutrient inputs and vertical stratification formed by freshwater plume, hypoxia typically occurs during summer in the bottom waters of the PRE. Before the 2000s, it was an episodic and small-scale issue because of the synergetic effect of shallow topography, high turbidity (Ma et al., 2022), and the intermittent stratification due to periodic disturbance by the tides. However, large-scale occurrences of low oxygen (when $DO < 4$ mg/L) and hypoxia were frequently reported in recent years. For example, it was estimated that the low-oxygen area within the PRE achieved 1000 km² and 1500 km² during summer in 2010 (Wen et al., 2020) and 2015 (Li et al., 2018), respectively, which were nearly double to that before the 2000s (Li et al., 2020b). Hu et al. (2021) compiled historical observations over four decades to investigate the long-term deoxygenation trend and its spatial expansion in the PRE. They highlighted the significant contributions of increased nutrient and decreased sediment fluxes from the Pearl River to the exacerbation of low-oxygen conditions in the region. Besides, the low-oxygen inflows from the Pearl River could also contribute to the low-oxygen area in the upper estuary (Hu et al., 2021). Nevertheless, a quantitative understanding of their relative contributions to the low-oxygen expansion in the PRE is lacking, particularly in different subregions (Fig.1b) where the mechanisms controlling the low-oxygen conditions are different (Li et al., 2020a). In the upper part of the PRE (Lingdingyang waters), aerobic respiration of terrestrial organic matter plays a greater role (Su et al., 2017; Yu et al., 2020); in the downstream regions of the PRE, deoxygenation is primarily controlled by eutrophication (Yu and Gan, 2022; Chen et al., 2024).

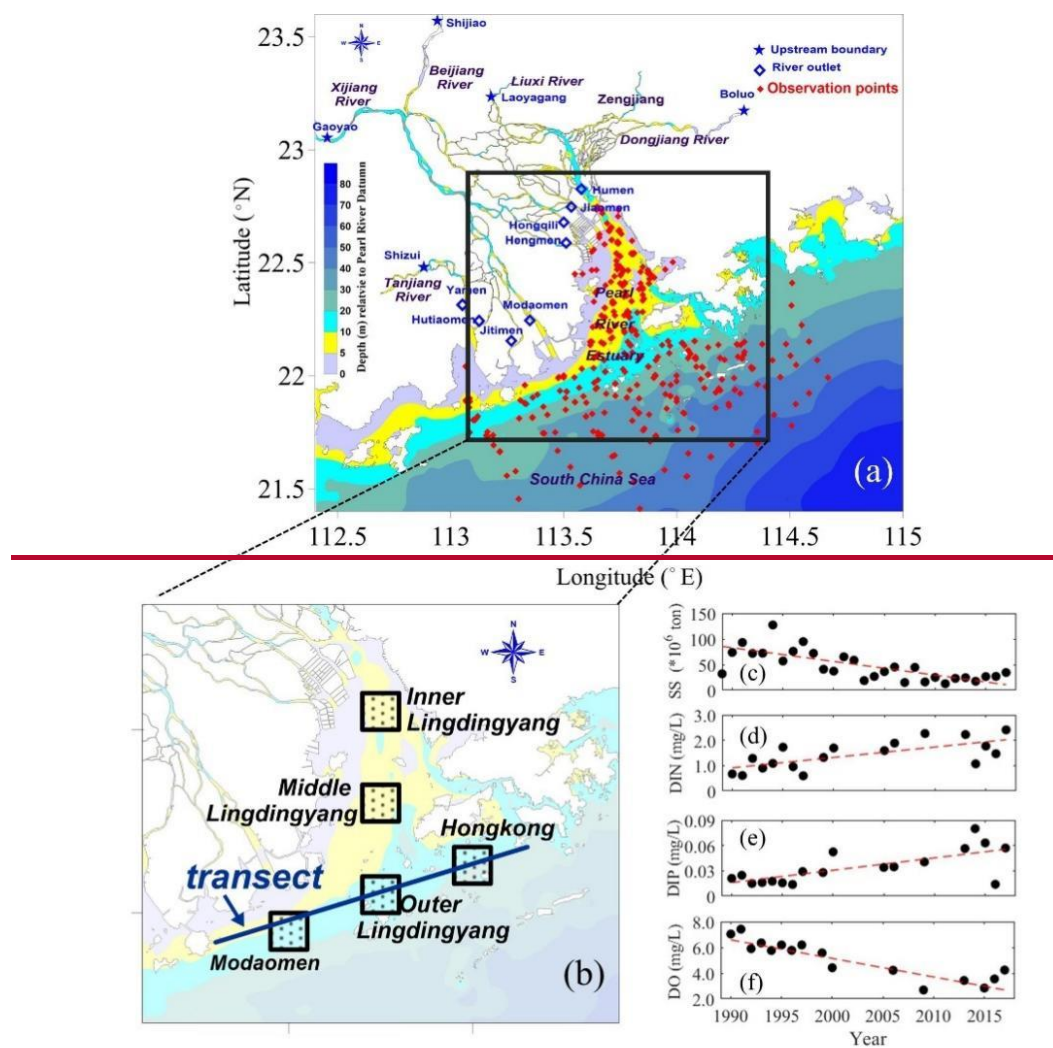
In this study, we used a coupled physical-biogeochemical model to investigate the decadal changes (the 1990s versus the 2010s) in summertime DO contents and related biogeochemical processes in the PRE and to quantify the relative contributions of the

changing riverine inputs (including nutrients, suspended sediments, and oxygen content; Fig. 1c-f) to the long-term expansion of low oxygen ($\text{DO} < 4 \text{ mg/L}$) and hypoxia ($\text{DO} < 3 \text{ mg/L}$) in the region.

2. Material and methods

2.1 Study area

The PRE and its adjacent shelf waters (Fig. 1a) represent an estuarine system under intensive human activities. One major anthropogenic impact in the PRE is the terrestrial substances fed by the Pearl River, which is the third largest river in China with an average annual runoff of $3.26 \times 10^{11} \text{ m}^3/\text{Year}$ (Luo et al., 2002), through eight river outlets, including Humen, Jiaomen, Hongqili, Hengmen, Modaomen, Jitimen, Hutiaomen, and Yamen (Fig. 1a). The long-term DO and water quality data used here were collected from open sources (e.g. government websites) and published studies (detailed in Data availability and Table S1 of Supplement). ~~(Table S1)~~. Over the past few decades, the terrestrial inputs from the Pearl River ~~has~~have experienced remarkable changes in oxygen content, sediment loads, and nutrients including dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) (Fig. 1c-f). Consequently, the ecological environments of the PRE have changed significantly.



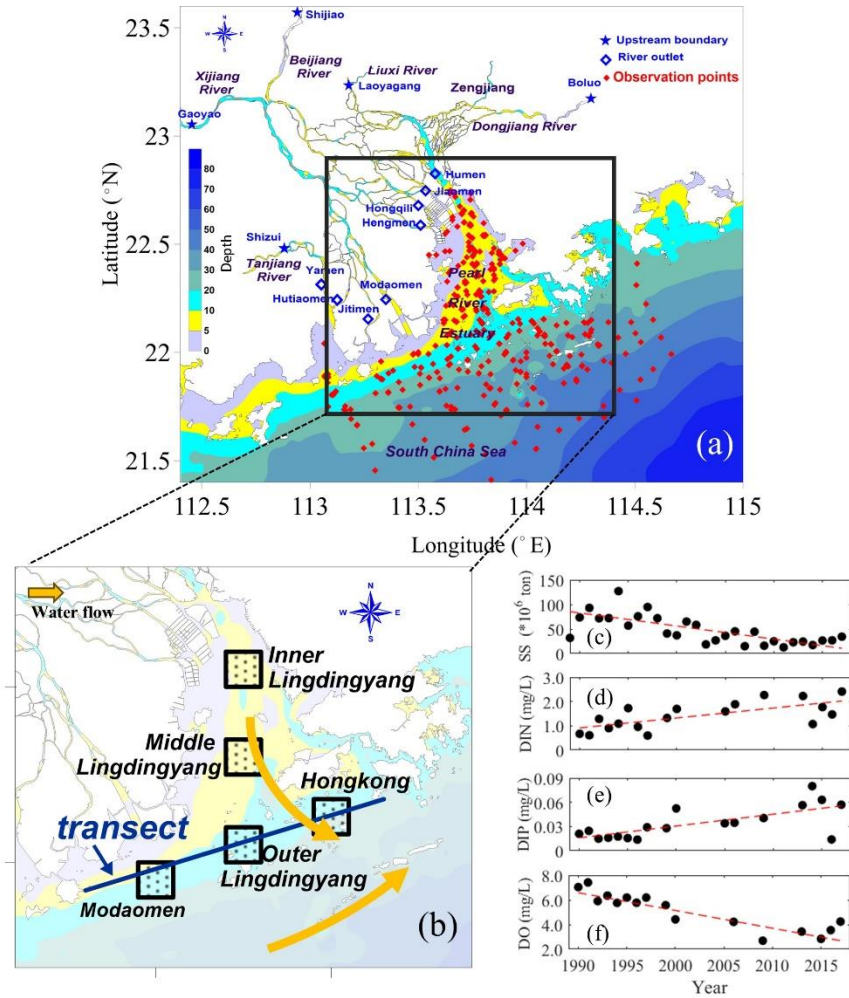


Fig. 1. (a) Study area of the PRE and sampling sites during 1985-2017; (b) five subregions and a transect along the coastal transition zone used for analysis and the water flow direction in the surface water; (c) annual loads of suspended sediments (SS) from the Pearl River; (d-f) the surface-layer (within the upper 2 m of water column) summertime concentrations of nutrients (DIN, DIP) and dissolved oxygen (DO) in the river outlets of the PRE.

In the 1990s, the PRE displayed a low level of eutrophication levels, reflecting limited upstream urbanization at that time. This period also witnessed extensive construction of water infrastructure projects, mostly completed around 2000 (Zhang et al., 2008), which led to a dramatic reduction in the riverine suspended sediment concentration (SSC). By the late 1990s, the Pearl River basin contained at least 8636 reservoirs. due to the weak urbanization in the upstream regions and high turbidity because of the absence of large-scale hydraulic facilities, e.g., dams, which could block

the suspended sediments from being transported into the estuary. Until the late 1990s, at least 8636 reservoirs were established in the Pearl River basin, the vast majority of which were built after China's reform and opening up in 1980 (Wu et al., 2016). After the 2000s, with the acceleration of urbanization and construction of hydraulic facilities, the PRE has undergone a significant increase in nutrients and decline in sediment loads (Fig. 1c-e), both of which are favorable for phytoplankton blooms and therefore for eutrophication and hypoxia. These long-term variations of riverine substances have also been reported by Lai et al. (2022) and Hu et al. (2021). In the meantime, the oxygen content in the PRE has exhibited a notable drawdown with significant expansions in low-oxygen extents in recent summers (Fig. 2), which has been revealed by the cruise observations in the PRE (Li et al., 2021; Su et al., 2017; Hu et al., 2021; Lu et al., 2018).

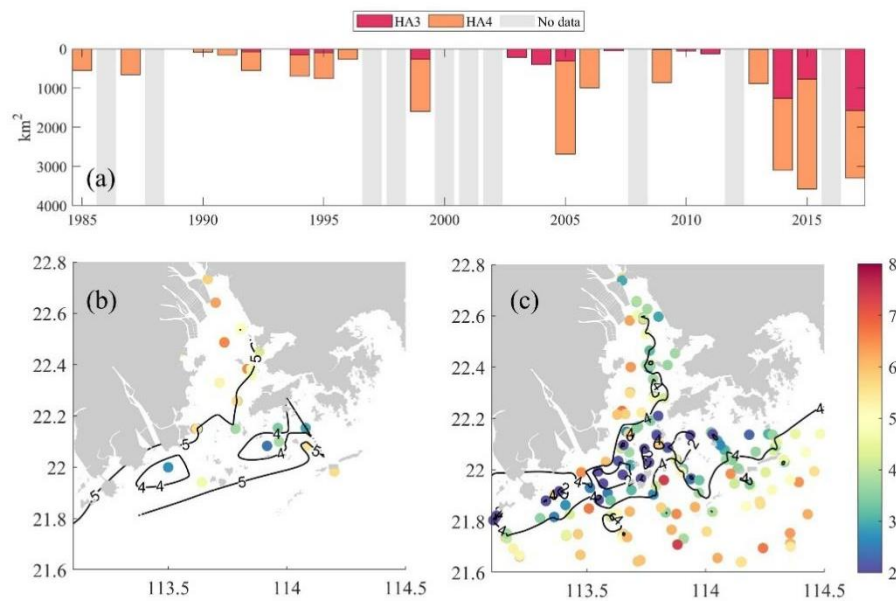


Fig. 2. (a) Interannual variations of low-oxygen area (HA4, DO < 4 mg/L) and hypoxic area (HA3, DO < 3 mg/L) in the bottom waters (~1-2 m above sediments) of the PRE during summer estimated from the cruise observations (note that the grey patches represent the lack of data); spatial distributions of summer-averaged DO concentrations during (b) 1991-1996 and (c) 2013-2017.

2.2 Model settings and validation

2.2.1 Model descriptions and settings

An online 1D-3D coupled physical-biogeochemical model, which has been extensively verified and applied in the PRE (Wang et al., 2017; Wang et al., 2018; Hu et al., 2011; Zhang et al., 2022), was utilized here to reproduce the oxygen dynamics under the long-term changes in riverine nutrients, suspended sediment concentration (SSC), and oxygen content (Fig. 1c-f). This 1D-3D modeling framework integrates a 1D representation of the Pearl River network with a 3D simulation of the Pearl River Estuary and adjacent shelf region, operating in an offline coupling mode. The 1D component numerically solves the Saint-Venant equations using a Preissmann scheme, discretizing the river network into 299 sections with five upstream boundaries (specified as either discharge or water level inputs). The 3D component employs the ECOM model with 16 vertical layers and adaptive horizontal resolution (400m to 3km), forced by tides, atmospheric forcing, and open boundary conditions. The two components exchange fluxes at eight river outlets: the 3D model incorporates river discharge from the 1D model as upstream boundary conditions, while the 1D model uses water levels computed by the 3D model as its downstream boundaries at each time step. This 1D-3D modeling framework was initially developed to investigate nutrient fluxes to the PRE and has been extended and validated to simulate oxygen dynamics and hypoxia in the PRE (Wang et al., 2017; Wang et al., 2018; Hu et al., 2011; Zhang et al., 2022; Chen et al., 2024). For the sake of conciseness in the main text, detailed descriptions on the physical and suspended sediment modules were provided in the Supplement (Text S1). Regarding the biogeochemical module, it is based on the Row-Column Aesop (RCA), which simulates interactive cycles of oxygen, carbon, nitrogen, phosphorus, and silicon in the water column (Fizpartick, 2004). As for the oxygen dynamics, it can be described as follows:

$$\frac{\partial DO}{\partial t} = -\mathbf{u} \cdot \nabla DO + \nabla \cdot (\mathbf{D} \nabla DO) + Rea + Phot + WCR + SOD \quad (1)$$

$$\frac{\partial DO}{\partial t} = -\left(u \frac{\partial DO}{\partial x} + v \frac{\partial DO}{\partial y} + w \frac{\partial DO}{\partial z}\right) + \frac{\partial}{\partial x} \left(A_H \frac{\partial DO}{\partial x}\right) + \frac{\partial}{\partial y} \left(A_H \frac{\partial DO}{\partial y}\right) + \frac{\partial}{\partial z} \left(K_H \frac{\partial DO}{\partial z}\right) + Rea + Phot + WCR + SOD \quad (1)$$

where DO represents the dissolved oxygen concentration (mg/L); $-\left(u \frac{\partial DO}{\partial x} + v \frac{\partial DO}{\partial y} + w \frac{\partial DO}{\partial z}\right)$ represents the horizontal and vertical advection of oxygen (mg O₂ L⁻¹ day⁻¹); $\frac{\partial}{\partial x} \left(A_H \frac{\partial DO}{\partial x}\right) + \frac{\partial}{\partial y} \left(A_H \frac{\partial DO}{\partial y}\right) + \frac{\partial}{\partial z} \left(K_H \frac{\partial DO}{\partial z}\right)$ represents the horizontal and vertical diffusion of oxygen (mg O₂ L⁻¹ day⁻¹) where the velocity vector $\mathbf{u} = (u, v, w)$, ∇DO represents the gradient operator (spatial derivative of dissolved oxygen concentration), and $\mathbf{D}$ is the diffusion coefficient tensor; Rea and $Phot$, WCR , and SOD represent the rates of air-water oxygen exchange, photosynthesis, water column respiration, and sediment oxygen demand, respectively (unit: mg O₂ L⁻¹ day⁻¹). The air-water oxygen exchange is parameterized as:

$$Rea = K_a \theta_a^{T-20} \cdot (DO_{sat} - DO) \quad (2)$$

where K_a is the surface mass transfer coefficient (m/day), θ_a is the temperature coefficient, T is the water temperature, and DO_{sat} is dissolve oxygen saturation concentration. The SOD is calculated by the sediment flux module (SFM) coupled to the RCA. The sediment module simulates the sedimentation and remineralization of organic carbon, nitrogen, and phosphorus, and dynamically estimates the oxygen and nutrient fluxes across the sediment-water interface (Fizpartick, 2004).

The growth of phytoplankton is co-limited by temperature, light, and nutrient conditions. The calculation of gross primary production (GPP , mg C L⁻¹ day⁻¹) of phytoplankton is determined as:

$$GPP = G_{Pmax} * e^{-\beta(T_{opt}-T)^2} * G_N(N) * G_I(I) * P_c \quad (32)$$

where G_{Pmax} is the maximum grow rate of phytoplankton at the optimum temperature (day⁻¹); T_{opt} is the optimum temperature (°C); β is the shaping coefficients; T is the water temperature (°C); $G_I(I)$ is the light limitation factor; $G_N(N)$ is the nutrient

limitation factor; P_c is the phytoplankton biomass (mg C L^{-1}).

The nutrient limitation factor $G_N(N)$ is parameterized as:

$$G_N(N) = \text{Min} \left(\frac{DIN}{K_{mN} + DIN}, \frac{DIP}{K_{mP} + DIP}, \frac{Si}{K_{mSi} + Si} \right) \quad (43)$$

where DIN , DIP , and Si represent the concentration (mg L^{-1}) of dissolved inorganic nitrogen (including NO_3^- and NH_4^+), dissolved inorganic phosphorus (PO_4^{3-}), and dissolved inorganic silicon (SiO_3^{2-}), respectively; K_{mN} , K_{mP} , and K_{mSi} represent the half-saturation constants (mg L^{-1}) for DIN , DIP , and Si , respectively. It should be noted that a higher nutrient limitation factor $G_N(N)$ indicates a weaker nutrient limitation effect on phytoplankton growth. Moreover, the nitrogen and phosphorus limitation are more significant than silicon limitation within the PRE, thus this study mainly focuses on the former.

The light limitation factor $G_I(I)$ is parameterized as:

$$G_I(I) = \frac{e}{k_e H} \left[\exp \left(\frac{-I_0(t)}{I_s} e^{-k_e H} \right) - \exp \left(\frac{-I_0(t)}{I_s} \right) \right] \quad (54)$$

$$k_e = k_{base} + k_c * a_{chl} * P_c + k_{sed} * SSC + k_{POC} * POC \quad (65)$$

$$I_0 = I_{surf} * e^{-k_e * H} \quad (7)(6)$$

where H is the depth of water column (m); I_0 is the incident light intensity at the segment surface (ly day^{-1}); I_s is the saturating light intensity (ly day^{-1}); k_e is the light extinction coefficient (m^{-1}); k_{base} is the background light extinction coefficient of water (m^{-1}); k_c is the phytoplankton-related extinction coefficient ($\text{m}^2 \text{mg}^{-1} \text{Chla}$); a_{chl} is the ratio of chlorophyll to phytoplankton carbon biomass; k_{sed} is the SSC-related extinction coefficient ($\text{m}^2 \text{mg}^{-1} \text{SSC}$); k_{POC} is the POC-related light extinction coefficient ($\text{m}^2 \text{mg}^{-1} \text{POC}$); I_{surf} is the ~~instant~~ instantaneous light radiation received at the water surface (ly day^{-1}).

To estimate the spatial characteristics of light conditions, we also calculated the eutrophic depth in the PRE (H_E , Equation 8), which is defined as the water depth reached by 1% of the surface light intensity ($I_{\frac{1}{100}} I_{surf}$). Basically, a larger eutrophic depth indicates a better light condition for phytoplankton growth.

$$I_{surf} * e^{-k_e * H_E} = I_{surf} * 1\% \quad (8)$$

247 where H_E represents the eutrophic depth (m).

248 **2.2.2 Model validation**

249 The coupled physical-biogeochemical model mentioned above has already been
250 validated against a variety of observations for several periods, which showed good
251 performance in reproducing the physical conditions, suspended sediment dynamics,
252 and biogeochemical cycles in the PRE. We briefly summarized the validation results
253 here. For the physical and suspended sediment modules, Hu and Li (2009) has applied
254 the 1D-3D coupled model to establish 30-day realistic simulations for July 1999 and
255 February 2001. The simulated water levels, discharges, salinity, and SSC agreed well
256 with the observations in the Pearl River network and the PRE for both periods, with
257 correlation coefficients all greater than 0.65 in summer. The simulated SSC at the
258 surface was also compared to satellite remote sensing data, which showed a fairly close
259 spatial pattern and comparable concentration magnitude. Furthermore, Wang et al.
260 (2017) provided an extensive model validation using field data collected from four
261 seasonal cruises in 2006, with high correlations for water levels (> 0.95), salinity ($>$
262 0.90) and temperature (> 0.80) and low root-mean-standard-errors between the
263 simulation and observations in summer.

264 Then, the biogeochemical module was established and used to explore the nutrient
265 and oxygen dynamics off the PRE in July 1999 and January-December 2006 (Hu and
266 Li, 2009; Wang et al., 2017). The point-to-point comparisons with the water quality
267 profiles indicated that the biogeochemical module was robust to reproduce the spatial
268 distributions of ammonia, nitrate, phosphorus, oxygen, and chlorophyll *a* in the PRE.

269 Our model demonstrated strong validation performance by accurately capturing the
270 observed temporal expansion of hypoxia, transitioning from localized bottom hypoxia
271 in the 1990s (Fig. 2b-c) to widespread occurrences in the 2010s (Fig. 5d-e). Initial
272 validation against 1994-1999 summer observations showed close agreement, with
273 simulated low-oxygen ($HA_4=1179.7 \text{ km}^2$) and hypoxic ($HA_3=211.3 \text{ km}^2$) areas
274 matching observational estimates ($802\pm437 \text{ km}^2$ and $131\pm84 \text{ km}^2$; Fig. 2a, Table 3). For

the 2013-2017 period, the model successfully replicated hypoxia intensification, as evidenced by HA4 expansion to 2925.5 km² aligning with observed 2715±1068 km². Projections to the 2020s indicated HA3 doubling to 617.2 km², remaining within observational uncertainty ranges (901±591 km²; 2013-2017 data), confirming the model's robustness in simulating both historical patterns and emerging hypoxia dynamics. In addition, Wang et al. (2017) has compared the simulated oxygen kinetic terms (including the air-sea re-aeration rate, water-column respiration and production rates, and sediment oxygen demand) with observations in summer, which demonstrated the model's capability in representing the important oxygen source-sink processes (e.g., oxygen consumptions across the sediment-water interface) in the PRE. Detailed model settings and parameters can be found in Wang et al. (2017).

2.3 Model experiments

Based on the well-validated model run in 2006 (Wang et al., 2017), the present study performed diagnostic simulations for two representative periods, characterized by low nutrients and high suspended sediments and oxygen content during 1991-1996 (referring as to the “1990s case”; Table 1) versus high nutrients and low suspended sediments and oxygen content during 2013-2017 (referring as to the “2010s case”). Each case was run from 1 January to 31 August, driven by climatological physical conditions (freshwater discharges and wind speeds detailed in Text S1 of the Supplement) averaged over 1990-2017 and by mean observed values of riverine water quality components in the corresponding period. Specifically in summertime (a period used for formal analysis here), the riverine concentrations were set to 1.0 mg/L (DIN), 0.02 mg/L (DIP), and 6.5 mg/L (DO) in the 1990s case, while they were set to 2.0 mg/L, 0.065 mg/L, and 3.5 mg/L in the 2010s case (Table 1). The riverine SSC was specified at 40 mg/L in the 2010s according to the in-situ observation near the Humen outlet in 2015 summer (Chen et al., 2020), and was set to 100 mg/L in the 1990s based on the ratio of the sediment loads between the 1990s and the 2010s (2.5 times). Long-term

monitoring at river outlets showed no significant temporal trend in COD compared to the marked increases in nutrients and decreases in DO, indicating stable oxygen-consuming OM inputs. We therefore maintained constant OM concentrations between study periods (organic carbon: 2 mg/L; organic nitrogen: 0.2 mg/L; organic phosphorus: 0.03 mg/L), consistent with published historical observations (Wang et al., 2018).

Furthermore, three additional model scenario simulations were conducted in order to disentangle the individual impact of each varying riverine input on the summer deoxygenation off the PRE. The setting of each scenario was identical to that of the 1990s case except that the riverine nutrients, SSC, and DO were separately replaced by the representative value in the 2010s (referring as to the “High-nutrient case”, “Low-SSC case”, and “DO-restore case”, respectively; Table 1).

Table 1. Riverine inputs (in unit of mg L⁻¹) for model experiments.

Cases	DIN	DIP	DO	SSC
1990s	1.0	0.020	6.5	100
2010s	2.0	0.065	3.5	40
High-nutrient	2.0	0.065	6.5	100
Low-SSC	1.0	0.020	6.5	40
DO-restore	2.0	0.065	6.5	40

3. Results

3.1 Responses of eutrophication to human-induced changes in the PRE

3.1.1 Long-term variations in water quality distributions

To examine changes in eutrophication (a key process affecting DO dynamics) and its influential factors during summer in the PRE, we compared the simulated distributions of SSC, nutrients, Chl *a*, and POC in the surface waters between the 1990s

and the 2010s cases (Fig. 3) as well as their vertical integrations in subregions (Table 2). Model results showed that the surface SSC within the PRE largely declined during the two periods. In the 1990s, SSC maintained at a high level in the inner Lingdingyang Bay (see its location in Fig. 1b), ranging from 70.0 to 100.0 mg/L (Fig. 3a). Due to the ~~particle sinking as waters advected downstream~~consecutive sinking along with water transport, SSC ~~dropped~~has decreased to ~10.0 mg/L in the lower reaches of the PRE in the 1990s. While in the 2010s, the riverine sediment loads have remarkably decreased, resulting in a corresponding drawdown in SSC downstream (Fig. 3b-c). Overall, the vertically-integrated SSC content in the inner Lingdingyang Bay and lower PRE dropped by 56.1% and 45.6%-47.3% to 244.5 mg/m² and 38.4-69.2 mg/m², respectively (Table 2).

In terms of nutrients, the variation induced by riverine inputs was also evident during the two periods, acting on the main estuary in association with the spreading of the river plume. As shown, the DIN content in the 1990s was mostly below 1.5 mg/L within the entire PRE (Fig. 3d). With respect to the 2010s, the DIN concentration has increased by 0.8 mg/L and 0.2 mg/L in the surface waters of the upper Lingdingyang Bay and the lower PRE, respectively (Fig. 3e-f). The vertically-integrated DIN mass has increased by 41.9%-102% in the PRE (Table 2). A similar situation occurred with respect to DIP, with its content increasing from 0.04 mg/L in the 1990s to 0.07 mg/L in the 2010s in the high-DIP area adjacent to the middle Lingdingyang Bay (Fig. 3g-i). In terms of vertical integration, DIP increased by 9%-108%, with the lowest increases located in the Hong Kong waters downstream of the estuary (Table 2).

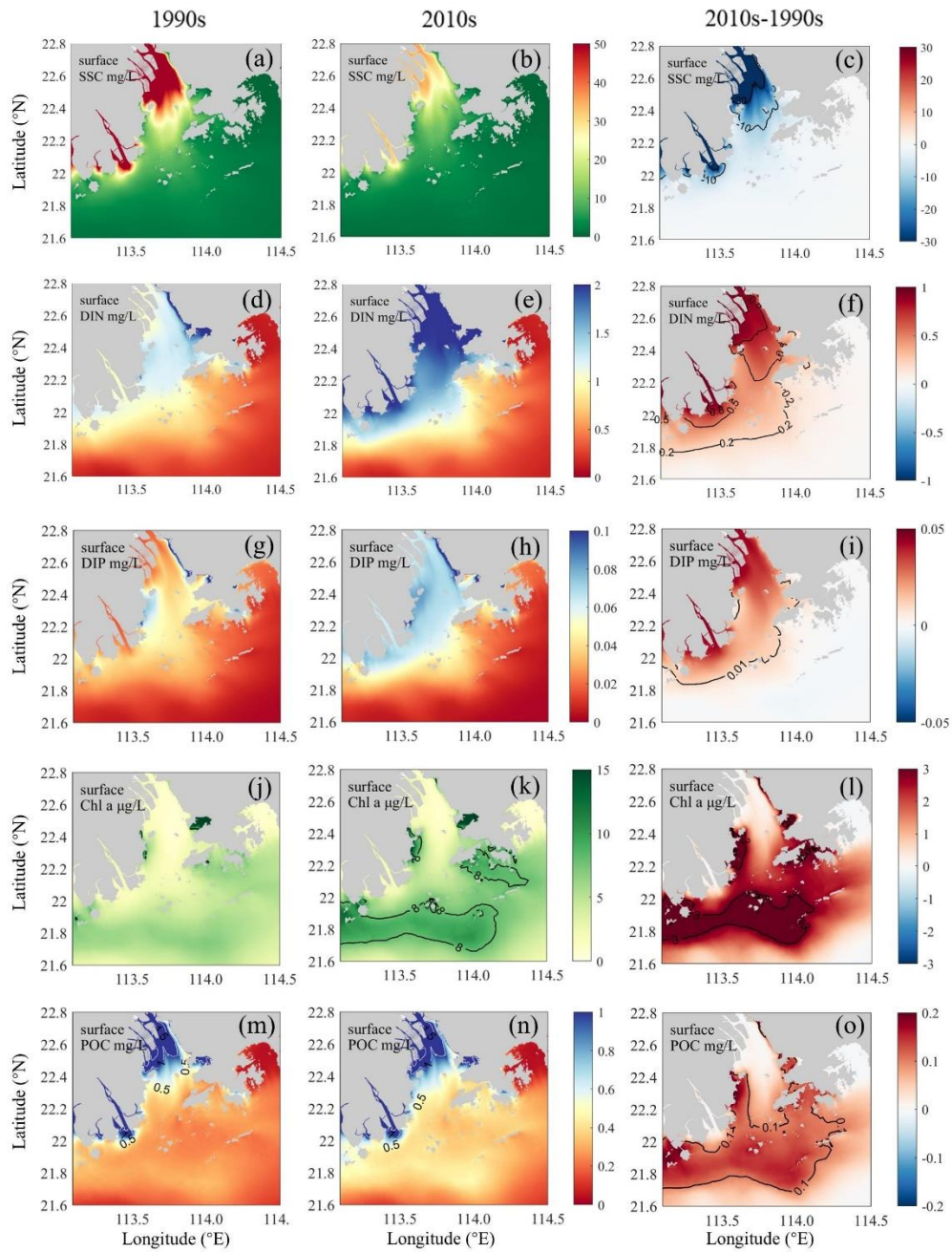


Fig. 3. Simulated distributions of (a-c) SSC, (d-f) DIN, (g-i) DIP, (j-l) Chl *a*, and (m-o) POC concentrations in the surface waters of the PRE for the 1990s (left panels) and the 2010s (middle panels) as well as their differences (right panels).

Table 2. Vertical integrations of DIN, DIP, SSC, Chl *a*, and POC contents; nutrient limitation index and euphotic depth; and DO concentrations, low-oxygen frequency (HF4), hypoxia frequency (HF3), and oxygen consumption rates in the bottom waters for subregions of the PRE (see locations in Fig. 1b) during the 1990s and the 2010s.

Subregions	Inner		Middle		Modaomen		Outer		Hong Kong waters	
	Lingdingyang Bay		Lingdingyang Bay		sub-estuary		Lingdingyang Bay			
Cases	1990s	2010s	1990s	2010s	1990s	2010s	1990s	2010s	1990s	2010s
DIN (mg m ⁻²)	6.58	12.24	5.42	9.20	4.89	7.62	5.17	7.92	3.62	5.14
DIP (mg m ⁻²)	0.23	0.48	0.34	0.48	0.55	0.71	0.56	0.66	0.51	0.56
Nutrient limitation index	0.94	0.97	0.95	0.97	0.92	0.94	0.91	0.93	0.83	0.85
SSC (mg m ⁻²)	556.5	244.5	332.9	164.6	120.4	63.4	127.7	69.2	70.6	38.4
Euphotic depth (m)	-1.3	-2.3	-2.0	-4.2	-9.5	-11.2	-11.8	-15.2	-20.7	-21.0
Chl <i>a</i> (µg m ⁻²)	5.0	7.1	11.7	22.9	39.4	70.4	40.7	72.9	74.3	108.9
POC (mg m ⁻²)	8.6	8.64	4.8	5.31	4.82	6.39	5.33	6.85	6.21	7.91
Bottom DO (mg L ⁻¹)	4.55	3.52	4.31	3.90	3.50	2.84	4.96	4.12	4.36	3.52
HF4	25.0%	79.7%	26.8%	65.2%	84.5%	99.1%	4.5%	49.3%	20.5%	61.1%
HF3	6.5%	27.6%	4.8%	10.1%	25.2%	56.5%	3.5%	9.1%	4.8%	21.4%
WCR (mg O ₂ L ⁻¹ day ⁻¹)	-0.38	-0.45	-0.20	-0.25	-0.09	-0.11	-0.07	-0.09	-0.06	-0.07
SOD (mg O ₂ L ⁻¹ day ⁻¹)	-1.72	-1.62	-0.89	-0.89	-0.24	-0.46	-0.28	-1.12	-0.91	-1.48

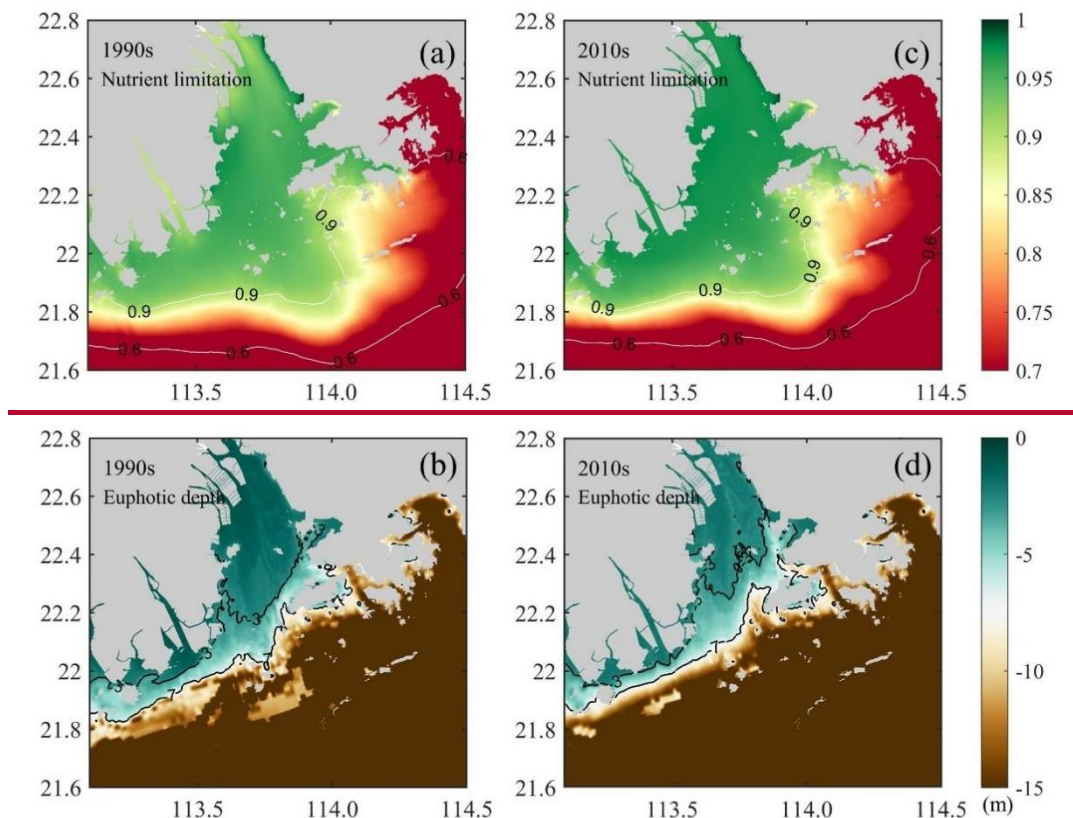
Note: HF4 (frequency of DO < 4 mg L⁻¹); HF3 (frequency of DO < 3 mg L⁻¹).

In response to changes in light (affected by the SSC content) and nutrient conditions, phytoplankton biomass has substantially grown in the 2010s, indicated by the increased Chl *a* concentration. In the 1990s, the phytoplankton biomass was at a low level, with the Chl *a* generally below 8.0 $\mu\text{g/L}$ in the surface waters (Fig. 3j). As for the 2010s, significant phytoplankton blooms were found along the Modaomen sub-estuary, outer Lingdingyang Bay, and Hong Kong waters (Fig. 3k-l), with the vertically-integrated Chl *a* content rising by 31.0 $\mu\text{g/m}^2$ (by 78.7% compared to the 1990s), 32.2 $\mu\text{g/m}^2$ (79.1%), and 34.6 $\mu\text{g/m}^2$ (46.6%), respectively (Table 2). As a result of the elevated primary production, a great amount of organic matter was produced in the PRE. Spatially coupled to the growth of Chl *a* (Fig. 3l), the POC content has significantly increased in the 2010s, especially in the lower PRE (Fig. 3m-o), with the vertically-integrated concentration increasing by 1.5-2.0 mg/m^2 (by 27.4%-32.6% compared to the 1990s) over the water column (Table 2).

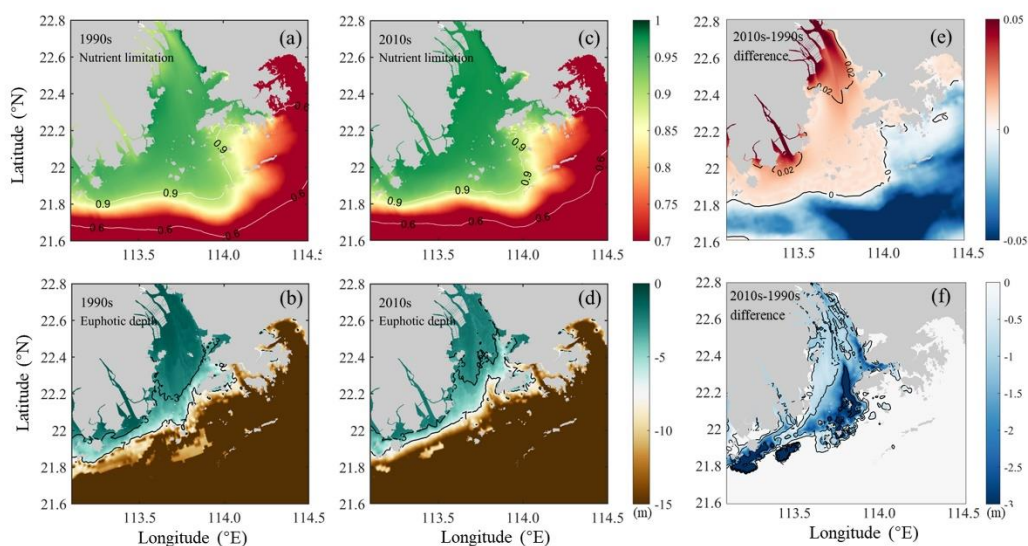
3.1.2 Long-term variations in nutrient and light limitations

The primary production in the PRE was controlled by the synergistic effects of nutrient and light conditions. We calculated the nutrient limitation factor and the eutrophic depth to quantify the intensity of nutrient limitation and light limitation on algae growth. It should be noted that a smaller nutrient limitation index and a shallower eutrophic depth represent a stronger nutrient limitation and a stronger light limitation, respectively. Results showed that the nutrient limitation exhibited a distinct estuary-shelf gradient, in which the Hong Kong waters experienced more severe nutrient limitation than the Modaomen sub-estuary and Lingdingyang Bay (Fig. 4a, c). Specifically, the nutrient limitation index decreased from the upper estuary (0.94) to the Hong Kong waters (0.83) in the 1990s. By contrast, the light limitation has attenuated along the river plume transport, largely ascribed to the decreased SSC (Fig. 3a-b). Compared to the Hong Kong waters, the regions adjacent to river outlets underwent more severe light limitation, shown by the eutrophic depth (Fig. 4b) increasing from the Lingdingyang Bay (1.3 m) and Modaomen sub-estuary (9.5 m) to the Hong Kong

380 waters (20.7 m).



381 **Fig. 4. Simulated distributions of (a, c) nutrient limitation index for the growth of**
 382 **phytoplankton and (b, d) euphotic depth (in unit of m) in the 1990s and the 2010s.**
 383



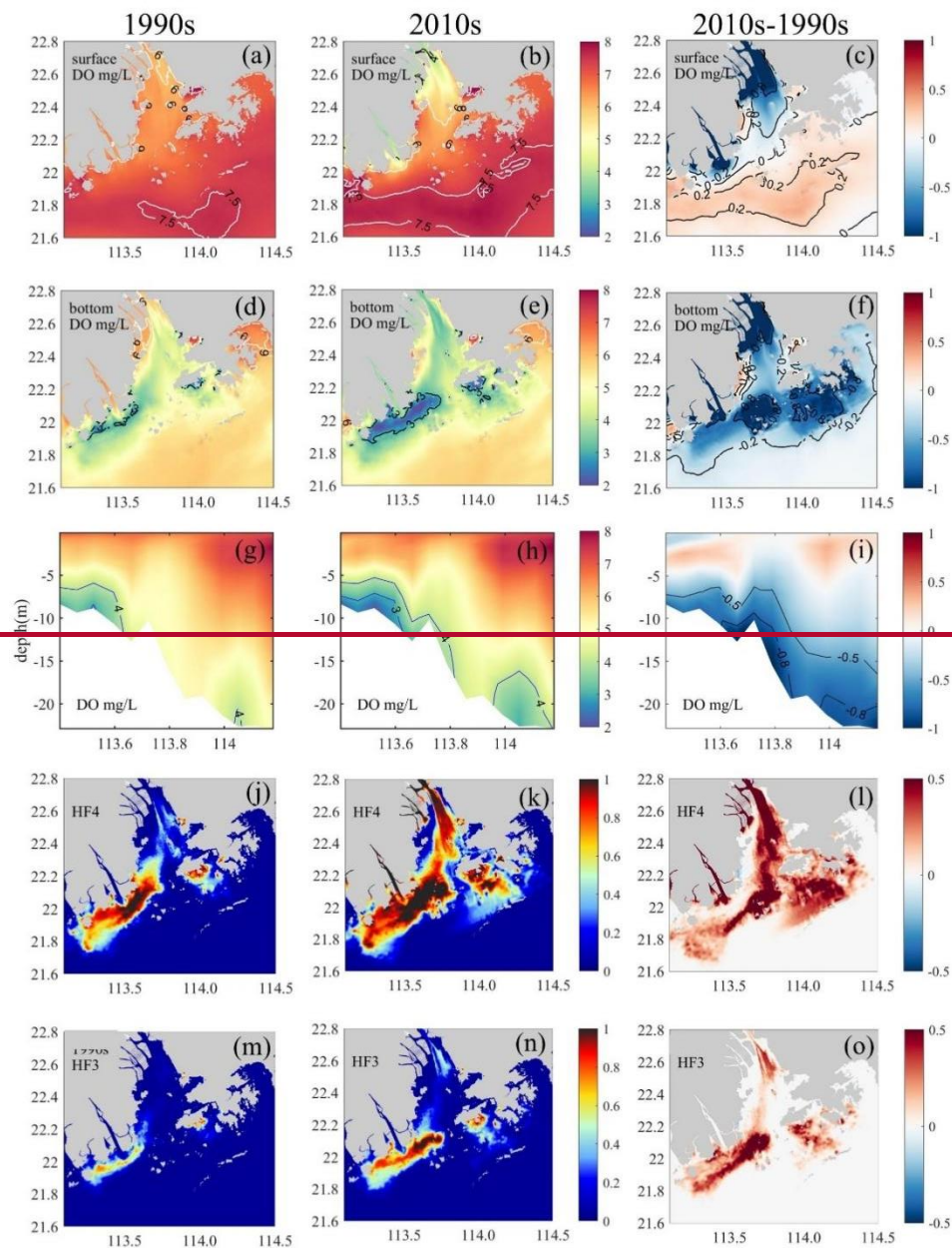
384 **Fig. 4. Simulated distributions (a, c) and difference (e) of nutrient limitation index for**
 385 **the growth of phytoplankton in the 1990s and the 2010s; (b, d) euphotic depth and its**
 386 **difference (e) (in unit of m) in the 1990s and the 2010s.**
 387
 388

389

390 Due to the growth in nutrient loads, nutrient limitation ~~has~~was -relieved in the
391 2010s. For instance, the nutrient limitation index in the Hong Kong waters has increased
392 to 0.85 (by 2.4% of the 1990s) in the 2010s (Table 2). In comparison, the relief of light
393 limitation was more evident with the reduced riverine suspended sediments. The
394 deepening of the euphotic depth in the Lingdingyang Bay was significantly greater than
395 that in the lower estuary (Fig. 4b, d). In the inner Lingdingyang and middle
396 Lingdingyang Bays, the euphotic depth increased by 1 m and 2.2 m (by 76.9% and
397 110.0% relative to the 1990s, Table2), respectively. The alterations in light conditions
398 in the remaining area were relatively minor, with the euphotic depth increasing to 11.2
399 m (by 17.9%) in the Modaomen sub-estuary and to 21 m (by 1.4%) in the Hong Kong
400 waters during the 2010s (Table 2).

3.2 Responses of DO dynamics to human-induced changes in the PRE

3.2.1 Variations in DO distributions and hypoxia occurrences



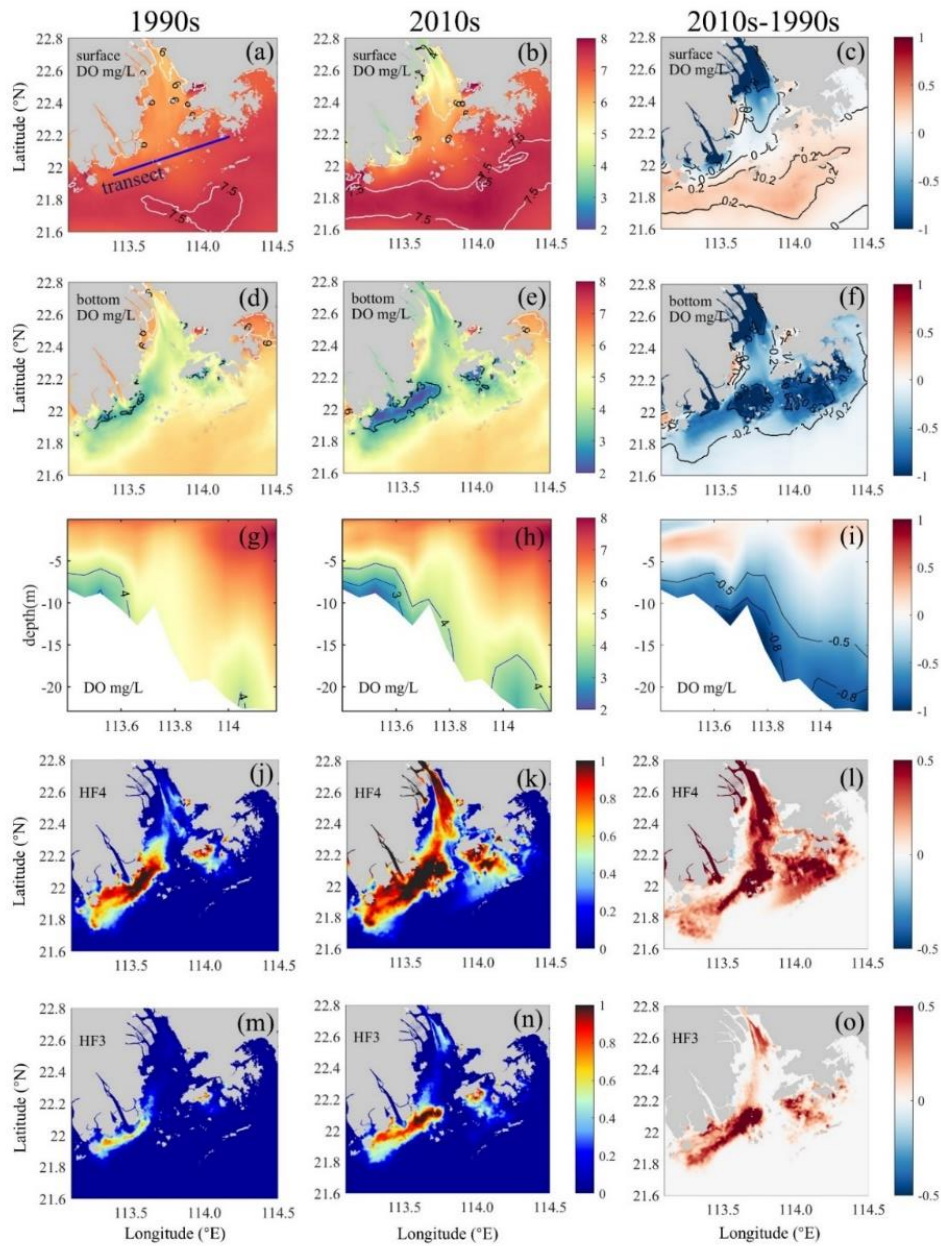


Fig. 5. (a-c) Surface DO and (d-f) bottom DO distributions, (g-i) vertical DO distributions along the transect (see its location in panel a)(see its location in Fig. 1b), and (j-l) low-oxygen frequency (HF4, DO < 4 mg/L) and (m-o) hypoxia frequency (HF3, DO < 3 mg/L) in the bottom waters of the PRE for the 1990s (left panels) and the 2010s (middle panels) as well as their differences (right panels). Note that hypoxia frequency is calculated as the number of hypoxic days divided by the total number of days in the study period, yielding a dimensionless ratio (range: 0–1).

Our model revealed distinct temporal shifts in summertime DO patterns and hypoxia distribution (Fig. 5). The surface DO in the 1990s was generally higher than 6

mg/L, increasing trend towards the shelf regions (Fig. 5a). By the 2010s, surface DO levels had increased by 0.2-0.3 mg/L (Fig. 5b-c), with an oxygen-enriched zone in the lower PRE correlating with high Chl a (Fig. 3k), though new low-oxygen zones (DO <4 mg/L) emerged near river outlets due to reduced Pearl River DO influx.

Bottom water simulations captured the hypoxia expansion from small-scale 1990s events (Fig. 2b-c) to widespread 2010s occurrences (Fig. 5d-e). Initial hypoxia clustered along the western PRE (Modaomen sub-estuary; Fig. 5d), with simulated HA4 (1179.7 km²) and HA3 (211.3 km²) (Table 3) matching observations (802±437 km² and 131±84 km²; 1994-1999 summers; Fig. 2a). By the 2010s, hypoxia intensified throughout Lingdingyang Bay and Hong Kong waters, with bottom DO declining to 2.8-4.1 mg/L (Table 2). Simulated HA4 expanded 1.5-fold to 2925.5 km² (Table 3), consistent with observed 2715±1068 km² (2013-2017; Fig. 2a). HA3 doubled to 617.2 km² by the 2020s, comparable to observed 901±591 km² (2013-2017).

~~Our model results demonstrated significant changes in the spatial pattern of summertime DO and hypoxia incidences from the past to the present (Fig. 5). The surface DO concentration in the 1990s was generally higher than 6 mg/L and exhibited an increasing trend towards the shelf regions (Fig. 5a). While in the 2010s, the surface DO has undergone an evident increase by 0.2-0.3 mg/L (Fig. 5b-c), with an oxygen-enriched zone in the lower PRE, which was closely coupled to the surface high Chl a value (Fig. 3k). However, low-oxygen events (DO < 4 mg/L) have appeared in the surface waters adjacent to the river outlets in the 2010s (Fig. 5b) due to the low DO influx from the Pearl River along with the freshwater discharge.~~

~~In the bottom waters, the observed shift from small-scale hypoxia in the 1990s to extensive hypoxia in the 2010s (Fig. 2b-c) was well reproduced by our model (Fig. 5d-e). In the 1990s, the low-oxygen events were primarily concentrated along the western side of the PRE (i.e. the Modaomen sub-estuary and adjacent waters; Fig. 5d). The simulated low-oxygen area (HA4) and hypoxic area (HA3) were approximately 1179.7 km² and 211.3 km² (Table 3), respectively, which is consistent with the observational~~

estimates of 802 ± 437 (mean $\pm$ standard deviation) and $131 \pm 84 \text{ km}^2$ during the summers of 1994–1999 (Fig. 2a). The low-oxygen conditions have considerably worsened over the estuary in the 2010s (Fig. 5e–f), especially evident in the inner Lingdingyang Bay, outer Lingdingyang Bay, and Hong Kong waters. The bottom DO levels have dropped to 2.8–4.1 mg/L on average in the five subregions (Table 2). Simultaneously, the simulated low-oxygen area (HA4) has increased to ~ 1.5 times larger than that in the 1990s, reaching 2925.5 km^2 (Table 3). The enlarged low-oxygen coverage in our model is consistent with the observational estimates of $2715 \pm 1068 \text{ km}^2$ during 2013–2017 (Fig. 2a). Besides, the simulated hypoxic area (HA3) has approximately increased by twofold and reached 617.2 km^2 in the 2020s, which is also comparable to the observational estimates of $901 \pm 591 \text{ km}^2$ during 2013–2017.

Table 3. Simulated low-oxygen (HA4, DO < 4 mg/L) and hypoxic (HA3, DO < 3 mg/L) areas in the bottom waters of the PRE and their changes relative to the 1990s.

Cases	HA4 (km ²)	Percentage of change	HA3 (km ²)	Percentage of change
1990s	1179.7	/	211.3	/
2010s	2925.5	+148%	617.2	+192%
High-nutrient	1542.6	+31%	282.5	+34%
Low-SSC	1737.0	+47%	412.4	+95%
DO-restore	2409.7	+104%	617.2	+192%

Note: The calculation in percentage of change is: $(HA_x - HA_{1990s}) / HA_{1990s}$, where x represents each case.

In addition, our model accurately replicated the two observed hypoxic centers along the coastal transition zone (Modaomen sub-estuary and Hong Kong waters; Fig. 2b-c), revealing distinct spatiotemporal deoxygenation patterns (Fig. 5g-o). During the 1990s, both centers exhibited limited low-oxygen zones, with Hong Kong waters showing <1 m thick DO <4 mg/L layers (Fig. 5g). Low-oxygen (HF4) and hypoxic (HF3) conditions persisted 18-76 days (20.5%-84.5% frequency) and 4-23 days (4.8%-25.2%) respectively during summer months (Fig. 5j,m; Table 2).

By the 2010s, hypoxic thickness increased substantially to ~1.5 m at Modaomen and ~5 m (~4 m thicker than 1990s) at Hong Kong waters (Fig. 5h). Event durations prolonged to 55-89 days (61.0%-99.1% HF4) and 19-51 days (21.4%-56.5% HF3) respectively (Fig. 5k, n; Table 2), demonstrating intensified and prolonged hypoxia.

In addition, the two observed hypoxic centers along the coastal transition zone (i.e., the Modaomen sub-estuary and Hong Kong waters; Fig. 2b-c) were also successfully reproduced by our model, showing heterogeneous deoxygenation features in terms of spatial extents and duration (Fig. 5g-o). In the 1990s, the low-oxygen conditions in these two centers were confined to a relatively small extent, especially in the Hong Kong waters, where the simulated thickness of low-oxygen (DO < 4 mg/L) was less than 1 m (Fig. 5g). The low-oxygen and hypoxic waters probably sustained for 18-76

~~days and 4–23 days within the hypoxic centers during the three summer months (June–August), respectively, synonymous with 20.5%–84.5% of low-oxygen occurrences (HF4) and 4.8%–25.2% of hypoxia occurrences (HF3) in summer (Fig. 5j, m; Table 2). As for the 2010s, the estimated thickness of hypoxia in the Modaomen sub-estuary has substantially increased to ~1.5 m, while the low-oxygen thickness in the Hong Kong waters has reached ~5 m (approximately 4 m thicker relative to the 1990s; Fig. 5h). Furthermore, the duration of the low-oxygen and hypoxic events in the 2010s was prolonged, roughly at 55–89 days (61.0%–99.1% of HF4) and 19–51 days (21.4%–56.5% of HF3) in the hypoxic centers (Fig. 5k, n; Table 2), respectively.~~

3.2.2 Variations in bottom oxygen consumption

To further explore the mechanism of long-term deoxygenation off the PRE, we investigated the oxygen consumption rates and their changes during the two periods (the 1990s versus the 2020s). We specifically focused on the oxygen consumption at the bottom layers covering the 20% of the water depth above the sediments, where the majority of hypoxic events in the PRE occurred (Fig. 5).

As shown in Table 2, the predominant oxygen sink in the bottom waters of the PRE was sediment oxygen demand (SOD) induced largely by the remineralization of organic matter in sediments, whereas water column respiration (WCR) only accounted for 15.2% of the bottom oxygen consumption on average. Over the past three decades, both the WCR and SOD have generally ~~enhanced~~increased in the PRE, primarily attributed to the growth in local production of organic matter associated with aggravated eutrophication (Fig. 3j-o). Particularly, the SOD in the outer Lingdingyang Bay and Hong Kong waters has remarkably increased from 0.28–0.92 mg O₂ L⁻¹ day⁻¹ in the 1990s to 1.12–1.48 mg O₂ L⁻¹ day⁻¹ in the 2010s (Table 2), which contributed to 80%~95% of the increment in total oxygen consumption. Although the absolute increase of SOD in the Modaomen sub-estuary was comparatively small, the SOD in the 2010s has almost doubled compared to the 1990s, leading to a substantial increase in the occurrence of hypoxic events in this region (Fig. 5d-o).

3.2.3 Disentangling contributions of riverine oxygen, suspended sediments, and nutrient changes on deoxygenation

As detailed in Section 2.3, three scenario simulations were performed to quantify the relative contributions of riverine changes to the decadal low-oxygen expansion in the PRE (Table 1). In general, the riverine impacts on DO and related biogeochemical factors varied significantly between subregions (Figs. 6-7). Specifically, increasing the riverine nutrient levels from the 1990s to the 2020s alone (High-nutrient case) led to a marked drawdown in the bottom DO around the lower PRE (by over 0.2 mg/L relative to the 1990s; Fig. 6a). The DO decline, extending from the Modaomen sub-estuary to the Hong Kong waters, was ascribed to the elevated phytoplankton biomass (Fig. 7b) facilitated by better nutrient conditions, which subsequently sustained stronger bottom oxygen depletions compared to the 1990s (Fig. 7c). Among the subregions, the Hong Kong waters was more susceptible to the changes in riverine nutrients as it was subject to comparatively severe nutrient limitation (Table 2). Therefore, with the improvement of nutrient utilization, this region experienced more pronounced deoxygenation in association with significant alterations in Chl *a* content and SOD (increased by 14.2 $\mu\text{g}/\text{m}^2$ and 0.26 $\text{mg O}_2 \text{ L}^{-1} \text{ day}^{-1}$, respectively, equivalent to 47.1% and 46.4% of their total increments over the past three decades; Fig. 7). While in the inner Lingdingyang Bay, the increased nutrient inputs only caused a slight change in Chl *a* content because the phytoplankton growth in this region was mostly light limited due to high water turbidity (Table 2). The concomitant changes in SOD and bottom DO were fairly small as well. Collectively, the high-nutrient scenario alone resulted in a 31% and 34% growth in the area affected by low oxygen (HA4) and hypoxia (HA3) relative to the 1990s, respectively (Table 3).

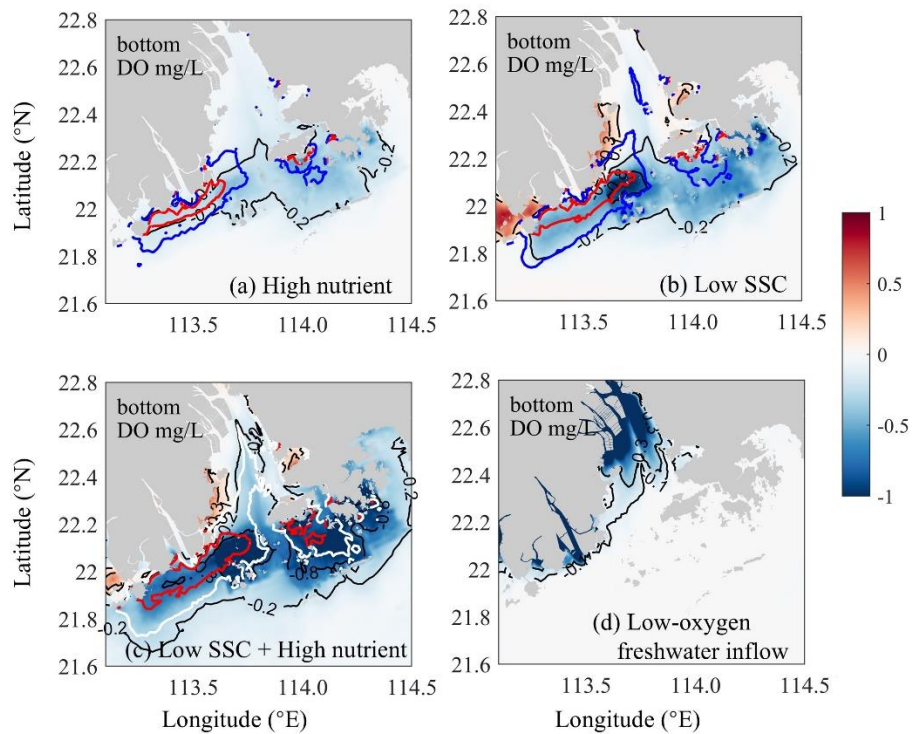
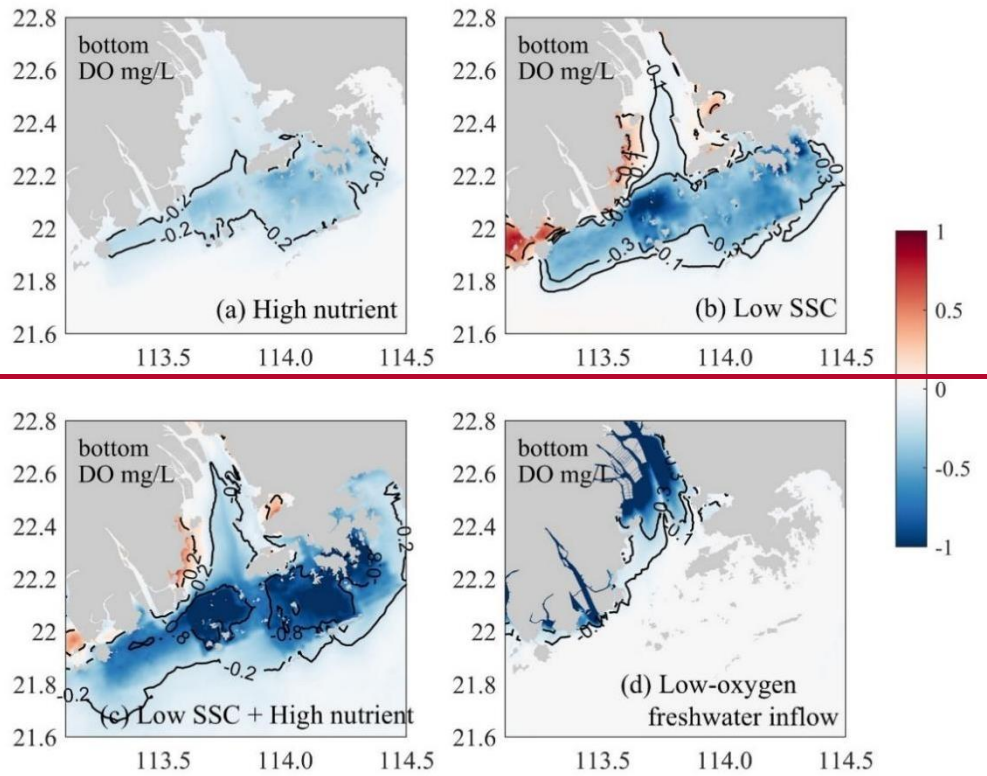
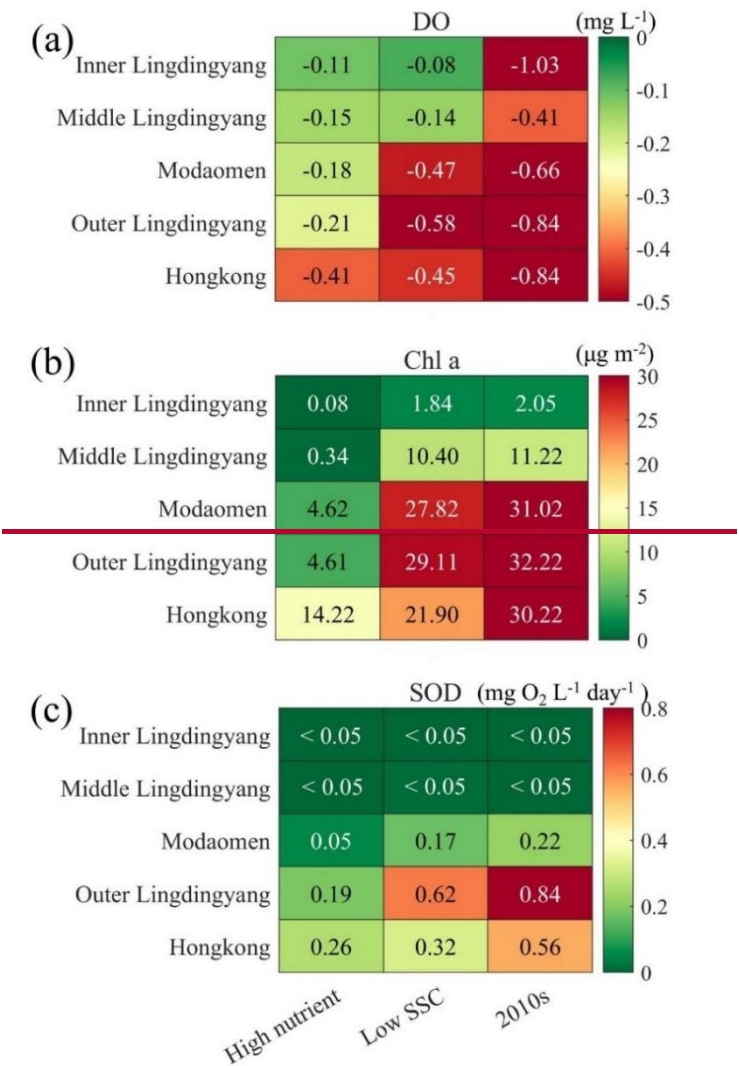


Fig. 6. Bottom DO changes induced by (a) riverine nutrient increases (the High-nutrient case minus the 1990s case), (b) riverine SSC declines (the Low-SSC case minus the 1990s case), (c) the combined effects of nutrient increases and SSC declines (the DO-restore case minus the 1990s case), and (d) riverine DO declines (the DO-restore case

minus the 2010s case), respectively. The blue and white contour lines represent DO = 4 mg/L for the respective cases, and the red contour lines represent DO = 3 mg/L.



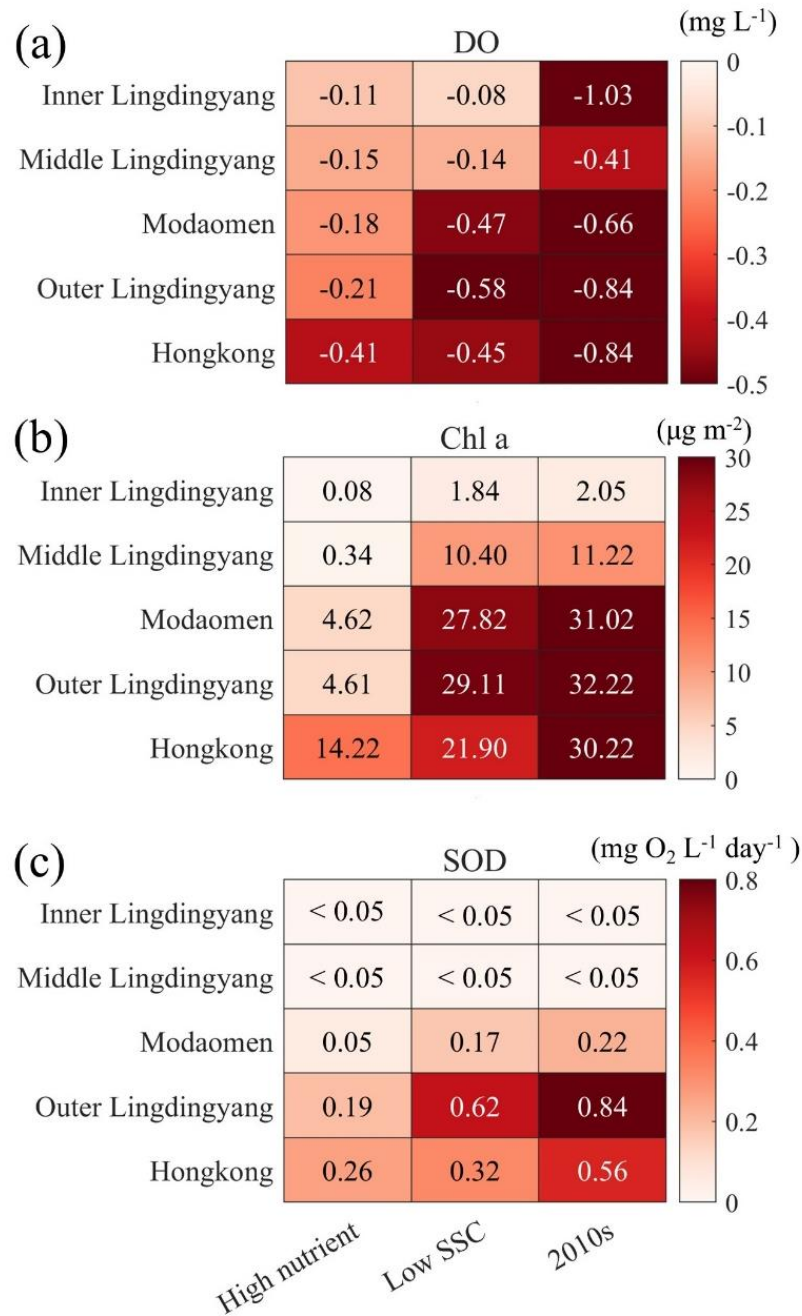


Fig. 7. Changes of (a) bottom DO concentration, (b) vertically-integrated Chl *a* content, and (c) SOD in subregions of the PRE for the High-nutrient, the Low-SSC, and the 2010s cases relative to the 1990s case.

Compared with the High-nutrient case, reducing the riverine suspended sediment loads from the 1990s to the 2020s alone (Low-SSC case) imposed a greater impact on the DO conditions, causing more extensive and intense deoxygenation through the PRE (Fig. 6b). Apparent DO decline (exceeding 0.3 mg/L relative to the 1990s) occurred

within the lower PRE, similar to that of the changing riverine nutrients described above. This is also attributed to the intensified SOD (with an increment of 0.17-0.62 mg O₂ L⁻¹ day⁻¹, accounting for 57.1%-77.3% of the total increment during the two periods; Fig. 7c), accompanied by a prominent increase in Chl *a* content (by 21.9-29.1 µg/m², accounting for 72.4%-90.3% of the total increment; Fig. 7b) due to the improved light condition (the relief of light limitation; Table 2). The SSC-induced changes in these biogeochemical factors were more pronounced in the outer Lingdingyang Bay and Modaomen sub-estuary than in other regions including the Hong Kong waters, which coincided with the alterations in deoxygenation among the subregions (Fig. 7). Overall, under the low-SSC scenario the low-oxygen area (HA4) and hypoxic area (HA3) expanded by 47% and 95% compared to the 1990s, respectively (Table 3). As shown in Figure 7 and Table 3, the combined effect of reducing SSC and increasing nutrient inputs (DO-restore case) led to a significant expansion of low-oxygen conditions, with hypoxic areas (HA4) and low-oxygen areas (HA3) reaching 2409.7 km² and 617.2 km², respectively. This combined effect exceeded the sum of changes induced by individual river inputs, highlighting the non-linear interaction between SSC and nutrient loading. In regions such as Outer Lingdingyang and Hong Kong, the combined effect was amplified, while in regions such as Inner and Middle Lingdingyang, the combined effect was less than the sum of individual effects. The growth of phytoplankton is not a linear process in response to various influencing factors; instead, these factors interact cumulatively. Therefore, when different factors are combined, their combined effect can exceed the impact of individual factors acting alone.~~In addition, it is important to note that the low-SSC induced exacerbation could be further escalated by superimposing with the effect of high nutrient inputs (Fig. 6e). As shown, the combined actions of decreasing SSC and increasing nutrients (DO-restore case) promoted a larger area of bottom waters off the lower PRE to develop into a low oxygen or hypoxic state, yielding a substantial expansion of low oxygen conditions (reaching 2409.7 km² of HA4 and 617.2 km² of HA3; Table 3) that eventually exceeded the sum of changes~~

~~induced by individual riverine input.~~

With respect to the influence of altered riverine DO influx, it could be deduced from the difference between the 2010s and the DO-restore cases (Fig. 6d). There was a considerable DO decrease (by over 0.8 mg/L) in the bottom waters adjacent to the river outlets (also in the surface waters) owing to the low-oxygen inflows from the upstream river channels. The impact of these low-oxygen waters was largely restricted within the upper Lingdingyang Bay under the effects of air-sea reoxygenation and water-column mixing along with the river plume transport. Collectively, reducing the riverine DO content from the 1990s to the 2020s alone resulted in an enlargement of low-oxygen area by nearly 515.8 km² (derived by subtracting the HA4 of the 2010s case from that of the DO-restore case; Table 3).

4. Discussion

4.1 Impacts of decadal changes in riverine inputs on deoxygenation off the PRE

By integrating long-term observations with physical-biogeochemical model simulations, we revealed significant bottom-water deoxygenation in the Pearl River Estuary over the past three decades, driven by changes in riverine inputs. From the 1990s to 2020s, summer inflows of DIN and DIP increased by ~100% and ~225%, while SSC decreased by ~60% due to human activities like dam construction (Liu et al., 2022) and reforestation (Cao et al., 2023). Concurrently, oxygen depletion from terrestrial pollutants reduced riverine DO concentrations by 46% (Ma et al., 2024). These shifts collectively intensified bottom-water low-oxygen conditions in PRE (Fig. 5), with model simulations showing a 148% expansion in summer low-oxygen areas (DO < 4 mg/L) and a 192% decrease in hypoxic areas (DO < 3 mg/L). Low-oxygen events also become more persistent, lasting longer (~15-35 days during June-August) and expanding vertically by ~1-4 m and (Table 3).~~By combining the long-term~~

606 ~~observations with simulations from the physical biogeochemical coupled model, we~~
607 ~~have elucidated the subsurface deoxygenation and associated mechanisms driven by~~
608 ~~changes in a variety of riverine inputs over the past three decades in a typical eutrophic~~
609 ~~estuarine system, namely the Pearl River Estuary (PRE). With the rapid socio-economic~~
610 ~~development, the inorganic nitrogen and phosphorus contents flowing into the PRE~~
611 ~~during summer have approximately increased by 100% and 225% from the historical~~
612 ~~period (1990s) to the present period (2020s), respectively (Table 1). Also, the riverine~~
613 ~~SSC has decreased by ~60%, consequent to the intense human activities such as dam~~
614 ~~construction (Liu et al., 2022) and reforestation (Cao et al., 2023). Besides, the~~
615 ~~amplified oxygen depletion fueled by terrestrial pollutants discharged into the upstream~~
616 ~~rivers has led to a lower riverine DO concentration (dropped by 46%) entering the~~
617 ~~estuary (Ma et al., 2024). These alterations have jointly triggered more extensive and~~
618 ~~persistent low oxygen conditions in the bottom waters of the PRE (Fig. 5). Based on~~
619 ~~our model estimation, the summertime low oxygen ($DO < 4$ mg/L) and hypoxic ($DO <$
620 3 mg/L) areas in the PRE have risen by 148% and 192% during the two periods,~~
621 ~~respectively (Table 3), together with a significant increase in the vertical thickness~~
622 ~~(expanding upwards by ~1.4 m) and the duration (extending by ~15–35 days during~~
623 ~~June–August) of low oxygen events.~~

624 More interestingly, the PRE has developed three distinct hypoxic centers
625 (including the inner Lingdingyang Bay, Modaomen sub-estuary, and Hong Kong waters)
626 controlled by different dominant factors, which renders the deoxygenation problem in
627 this region as a great reference for estuaries and coastal systems worldwide. Specifically,
628 the impact of riverine low-oxygen waters was confined within the upper estuary close
629 to the river outlets, leading to a ~44% increase in the low-oxygen area relative to the
630 1990s. Such local low-oxygen issue could be mitigated to a large extent if the riverine
631 DO recovered to a comparatively higher level (e.g., ~6.5 mg/L in the 1990s) according
632 to the DO-restore scenario (Fig. 6d). Reduced water turbidity downstream facilitates
633 the upstream transport of nutrients, promoting eutrophication and oxygen depletion in

634 the lower reaches, which is highly sensitive to changes in riverine nutrient and sediment
635 inputs. ~~By comparison, the deoxygenation in the lower estuary primarily followed the~~
636 ~~classic eutrophication-driven paradigm.~~ As indicated in the High-nutrient and the Low-
637 SSC cases, the increased nutrient inputs and declined suspended sediment loads have
638 separately alleviated the nutrient and light limitations on algae growth in the region,
639 thereby stimulating phytoplankton blooms and local production of organic matter to
640 support subsurface oxygen consumption (dominated by sediment oxygen uptake, SOD;
641 Fig. 7).

642 While previous studies have primarily examined the impacts of riverine inputs of
643 freshwater, nutrients and organic matter, this study provides a comprehensive
644 investigation of how suspended sediment reduction influences estuarine dissolved
645 oxygen dynamics. ~~In the PRE, Our results also indicated that~~ the riverine SSC reduction
646 played a more important role in driving the long-term low-oxygen expansion ~~in the~~
647 ~~PRE~~. Its synergistic effect with the riverine nutrient changes could further amplify the
648 exacerbation of eutrophication and subsequent deoxygenation, resulting in an enlarged
649 growth in the low-oxygen area (by 104%) and hypoxic area (by 192%) that was notably
650 larger than the total of their partial contributions (Table 3), and reached 70% of the total
651 impact from combined SSC, nutrient, and low-oxygen changes (148% low-oxygen
652 expansion).

653 It is worth mentioning that the relative importance of the riverine nutrient and SSC
654 changes were different between the two hypoxic centers in the lower PRE, depending
655 upon their distances and water flow conditions from the river outlets. Closer to the river
656 outlets, the Modaomen sub-estuary and its surrounding waters (located on the western
657 side of the coastal transition zone off the PRE) possessed a fairly high SSC level, which
658 imposed a stronger light limitation on the growth of phytoplankton in the region,
659 ultimately making the oxygen dynamics more susceptible to the decline in riverine SSC.
660 Suspended sediments were confined to the coastal area of Modaomen by water currents
661 (Fig. 1b), resulting in a significant decrease in sediment deposition in this region, which

greatly improved light availability, ultimately making the oxygen dynamics more susceptible to the decline in riverine SSC. On the contrary, the Hong Kong waters and adjacent coastal areas (located on the eastern side of the coastal transition zone) far from the river outlets were less affected by the riverine inputs, where the relatively low nutrient levels promoted more sensitive responses of biogeochemical processes (e.g. primary production and SOD) and hypoxia occurrences to nutrient variations. Besides, the complex island topography near Hong Kong (Fig1b) creates hydrodynamic barriers that restrict the offshore transport of suspended sediments.

4.2 Nutrient control and hypoxia mitigation in the context of sediment declines

Our results underscored the substantial spatial variability in the regulation of riverine inputs on deoxygenation, highlighting the need for which implies the necessity for establishing more refined and targeted strategies for hypoxia mitigation. Compared with the riverine nutrients, the regulatory effects influences of SSC on eutrophication and hypoxia have received less attention. It follows that there might be overestimations of the nutrient impacts in the previous studies without considering SSC to ensure the model simulation aligning with the observed deoxygenation. Such an overfitting problem could further lead to an optimistic assessment on the hypoxic mitigation effect under a certain nutrient control plan. Therefore, it is imperative to disentangle or re-evaluate the contribution of riverine nutrients and SSC to the coastal deoxygenation over the past decades. As exemplified in our study for the PRE, a more stringent nutrient reduction might be required to curb the deoxygenation issue given the low SSC status at present. This oversight suggests that previous studies may have overestimated nutrient impacts when failing to account for SSC-mediated processes required to align model simulations with observed deoxygenation patterns. Such model overcompensation could lead to potentially optimistic assessments of hypoxia mitigation effectiveness under proposed nutrient control plans. It is therefore critical to

689 disentangle and quantitatively re-evaluate the relative contributions of riverine nutrients
690 versus SSC changes to coastal deoxygenation dynamics over recent decades. As
691 demonstrated in the PRE case study, the current low-SSC regime suggests more
692 stringent nutrient reductions than previously estimated might be required to effectively
693 curb deoxygenation.

694 Furthermore, it should be noted that although the dam constructions in the Pearl
695 River Basin have mostly completed since the 2000s, it is still unclear whether the
696 declining trend of riverine SSC will persist in the future. For instance, the reforestation
697 in recent years has shown to be effective in reducing the summer freshwater discharges
698 and sediment loads in the Pearl River Basin (Cao et al., 2023). ~~Therefore, the role of~~
699 ~~riverine~~ This evolving context underscores that SSC variations ~~remains critical will~~
700 continue to play a defining role in future oxygen dynamics, introducing compounding
701 uncertainties ~~for oxygen dynamics in the future, which poses greater challenges and~~
702 ~~uncertainties for eutrophication and~~ hypoxia mitigation strategies. ~~Similar problems~~
703 ~~also exist in other estuaries and coastal systems suffering hypoxia. Notably, analogous~~
704 sediment-oxygen coupling mechanisms are emerging in other hypoxic systems. For
705 example, it was reported that the decrease of riverine SSC (by ~56%) appeared to be
706 the ~~predominated~~ predominant factor for the intensifying eutrophication (with a 61%
707 increase in the Chl *a* concentration) in the Yangtze River Estuary over the past decades
708 (Wang et al., 2019). In addition, several modelling studies have showed that the dam
709 constructions in the upper regions of Guadiana Estuary have significantly reduced the
710 water turbidity and exacerbated eutrophication in the lower estuary (Domingues et al.,
711 2012; Barbosa et al., 2010). A global-scale survey revealed that the sediment loads in
712 414 major rivers has approximately decreased by 51% since the 2000s due to human
713 activities (Dethier et al., 2022), suggesting that the deteriorating eutrophication and
714 deoxygenation in the context of sediment declines has become a global concern and
715 merits more attention and investigations in the future.

716 While our study emphasizes the impacts of reduced suspended sediments, human

activities may conversely increase sediment loads in estuaries. For example, land-use changes such as deforestation (Kasai et al., 2005) or industrialization (Syvitski and Kettner, 2011) may exacerbate soil erosion and sediment transport, leading to higher suspended sediment concentrations in the water. In such cases, light attenuation due to increased turbidity may suppress phytoplankton growth and reduce primary production, thereby mitigating hypoxia.

Some caveats to our work require further studies. First, our light attenuation parameterization builds upon the empirical formulation of Ditoro (2001), previously validated for the Pearl River Estuary (PRE) through biogeochemical consistency checks (Wang et al., 2018). While this approach successfully captured observed oxygen dynamics in our simulations, two key simplifications require explicit discussion. The current light attenuation parameterization in our model primarily accounts for the effects of chlorophyll and suspended sediments. Previous studies have demonstrated that CDOM (colored dissolved organic matter) also plays a significant role in light attenuation within the PRE (Cao et al., 2003; Wang et al., 2010), particularly during algal bloom periods. Although our model does not explicitly treat CDOM as an independent variable, its influence is indirectly accounted for within the existing parameterization. However, to accurately quantify CDOM's contribution to oxygen dynamics—including its long-term trends—future work should incorporate an explicit representation of CDOM's effects on light attenuation in the model, alongside sustained observational monitoring of CDOM. —For example, a Apart from anthropogenic activities, alterations in regional physical conditions aligning with climate changes such as wind and freshwater discharge could also regulate the long-term deoxygenation in coastal regions (Yu et al., 2015; Chen et al., 2024). Besides, t The impacts of ocean warming on deoxygenation (Laurent et al., 2018) remain unclear in the PRE as well, although warming has already been observed in the PRE (Cheung et al., 2021). Its compounding factors such as sea-level rise (Hong et al., 2020) may introduce additional complexity to hypoxia evolution through cascading ecosystem effects.

While these factors have not been considered in this study, the relative contributions of human activities and climate changes represent a significant topic for future investigations, which can facilitate a more comprehensive understanding of oxygen dynamics and hypoxia development in estuaries and coastal systems.

5. Conclusion

We applied a well-validated physical-biogeochemical model to reconstruct the summertime oxygen distributions in the PRE during two representative periods (the 1990s and the 2010s) and to disentangle the contribution of alterations in riverine inputs (i.e., suspended sediments, nutrients, and oxygen concentration) to the long-term deoxygenation off the PRE based on a suite of model experiments. We found that owing to the changes of riverine inputs over the past three decades, the low-oxygen and hypoxic areas in the bottom waters of the PRE have expanded by about 1.5 times and two-fold, respectively, with the duration time prolonged by ~15-35 days in summer. Concurrently, three hypoxic centers dominated by distinct factors were identified. Scenario simulations revealed that the decline in riverine oxygen concentration has caused a low-oxygen expansion (by ~44%) in the upper PRE. By comparison, the alterations in riverine nutrients and suspended sediments have separately provided better nutrient and light conditions to promote higher production of labile organic matter, which jointly maintained considerable oxygen depletions and exacerbated the low-oxygen conditions in the lower PRE. The relative importance of the changing riverine nutrients and suspended sediments to deoxygenation varied between subregions. The suspended sediment reduction was the predominated factor in the downstream regions close to the river outlets (e.g. the Modaomen sub-estuary), while the nutrient increase exerted a more substantial influence in the regions far from the river outlets (e.g. the Hong Kong waters). Our study highlights the significant role of the declined suspended sediments in the low-oxygen expansion off the PRE, which can further amplify the effect in association with the increasing nutrients. Therefore, in the

context of global regimes changes of riverine suspended sediments, we call for an urgent re-evaluation of the impacts of riverine inputs on deoxygenation in addition to nutrients in order to better understand the mechanism controlling hypoxia and thereby proposing effective mitigation strategies.

CRediT authorship contribution statement

Yue Nan: Investigation, Model experiments, Formal analysis, Visualization, Writing-original draft. **Zheng Chen:** Model experiments, Writing-review. **Bin Wang:** Writing-review. **Bo Liang:** Writing-review. **Jiatang Hu:** Project administration, Supervision, Conceptualization, Writing-review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The dissolved oxygen observation datasets off the Pearl River Estuary were obtained from published studies (Hu et al., 2021, DOI: 10.5194/bg-18-5247-2021; Su et al., 2017, DOI: 10.5194/bg-14-4085-2017; Li et al., 2021, DOI: 10.1029/2020JC016700) and the Hong Kong Environmental Protection Department (www.epd.gov.hk). The observed nutrients, oxygen, and suspended sediments data in the Pearl River are available from Hu et al. (2021) and publicly accessible databases maintained by China's Ministry of Ecology and Environment (<https://www.mee.gov.cn/>) and the China River Sediment Bulletin (<http://www.mwr.gov.cn/sj/tjgb/zghlnsgb/>).

799 ~~Data will be made available on request.~~
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802 **Reference**

- 803 Barbosa, A. B., Domingues, R. B., and Galvão, H. M.: Environmental Forcing of
804 Phytoplankton in a Mediterranean Estuary (Guadiana Estuary, South-western Iberia):
805 A Decadal Study of Anthropogenic and Climatic Influences, *Estuaries and Coasts*, 33,
806 324-341, 10.1007/s12237-009-9200-x, 2010.
- 807 Bianchi, T. S., DiMarco, S. F., Cowan, J. H., Hetland, R. D., Chapman, P., Day, J. W.,
808 and Allison, M. A.: The science of hypoxia in the Northern Gulf of Mexico: A review,
809 *Science of The Total Environment*, 408, 1471-1484,
810 <https://doi.org/10.1016/j.scitotenv.2009.11.047>, 2010.
- 811 Breitburg, D., Levin, L. A., Oschlies, A., Grégoire, M., Chavez, F. P., Conley, D. J.,
812 Garçon, V., Gilbert, D., Gutiérrez, D., Isensee, K., Jacinto, G. S., Limburg, K. E.,
813 Montes, I., Naqvi, S. W. A., Pitcher, G. C., Rabalais, N. N., Roman, M. R., Rose, K. A.,
814 Seibel, B. A., Telszewski, M., Yasuhara, M., and Zhang, J.: Declining oxygen in the
815 global ocean and coastal waters, *Science*, 359, eaam7240, 10.1126/science.aam7240,
816 2018.
- 817 Bussi, G., Darby, S. E., Whitehead, P. G., Jin, L., Dadson, S. J., Voepel, H. E.,
818 Vasilopoulos, G., Hackney, C. R., Hutton, C., Berchoux, T., Parsons, D. R., and
819 Nicholas, A.: Impact of dams and climate change on suspended sediment flux to the
820 Mekong delta, *Science of The Total Environment*, 755, 142468,
821 <https://doi.org/10.1016/j.scitotenv.2020.142468>, 2021.
- 822 Cao, W., Yang, Y., Xu, X., Huang, L., and Zhang, J.: Regional patterns of particulate
823 spectral absorption in the Pearl River estuary, *Chinese Science Bulletin*, 48, 2344-2351,
824 2003.
- 825 Cao, Z., Duan, H., Ma, R., Shen, M., and Yang, H.: Remarkable effects of greening
826 watershed on reducing suspended sediment flux in China's major rivers, *Science*
827 *Bulletin*, 68, 2285-2288, 2023.
- 828 Carstensen, J., Andersen, J. H., Gustafsson, B. G., and Conley, D. J.: Deoxygenation of
829 the Baltic Sea during the last century, *Proceedings of the National Academy of Sciences*
830 *of the United States of America*, 111, 5628-5633, 10.1073/pnas.1323156111, 2014.
- 831 Chen, J. Y., Pan, D. L., Liu, M. L., Mao, Z. H., Zhu, Q. K., Chen, N. H., Zhang, X. Y.,
832 and Tao, B. Y.: Relationships Between Long-Term Trend of Satellite-Derived
833 Chlorophyll-a and Hypoxia Off the Changjiang Estuary, *ESTUARIES AND COASTS*,
834 40, 1055-1065, 10.1007/s12237-016-0203-0, 2017.
- 835 Chen, L., Zhang, X., He, B., Liu, J., Lu, Y., Liu, H., Dai, M., Gan, J., and Kao, S.-J.:
836 Dark Ammonium Transformations in the Pearl River Estuary During Summer, *Journal*
837 *of Geophysical Research: Biogeosciences*, 125, e2019JG005596,
838 <https://doi.org/10.1029/2019JG005596>, 2020.
- 839 Chen, Z., Yu, L., and Hu, J.: Disentangling the contributions of anthropogenic nutrient
840 input and physical forcing to long-term deoxygenation off the Pearl River Estuary,
841 China, *Water Research*, 265, 122258, <https://doi.org/10.1016/j.watres.2024.122258>,
842 2024.

843 Cheung, Y. Y., Cheung, S., Mak, J., Liu, K., Xia, X., Zhang, X., Yung, Y., and Liu, H.:
 844 Distinct interaction effects of warming and anthropogenic input on diatoms and
 845 dinoflagellates in an urbanized estuarine ecosystem, *Global Change Biology*, 27, 3463-
 846 3473, 10.1111/gcb.15667, 2021.
 847 Cormier, J. M., Coffin, M. R. S., Pater, C. C., Knysh, K. M., Gilmour, R. F., Guyondet,
 848 T., Courtenay, S. C., and van den Heuvel, M. R.: Internal nutrients dominate load and
 849 drive hypoxia in a eutrophic estuary, *Environmental Monitoring and Assessment*, 195,
 850 1211, 10.1007/s10661-023-11621-y, 2023.
 851 Cullen, J. J.: Subsurface Chlorophyll Maximum Layers: Enduring Enigma or Mystery
 852 Solved?, in: *ANNUAL REVIEW OF MARINE SCIENCE*, VOL 7, edited by: Carlson,
 853 C. A., and Giovannoni, S. J., 207-239, 10.1146/annurev-marine-010213-135111, 2015.
 854 Dethier, E. N., Renshaw, C. E., and Magilligan, F. J.: Rapid changes to global river
 855 suspended sediment flux by humans, *Science*, 376, 1447-1452,
 856 10.1126/science.abn7980, 2022.
 857 Diaz, R. J. and Rosenberg, R.: Spreading dead zones and consequences for marine
 858 ecosystems, *Science*, 321, 926-929, 10.1126/science.1156401, 2008.
 859 DiToro, D. M.: *Sediment flux modeling*, John Wiley & Sons 2001.
 860 Domingues, R. B., Barbosa, A. B., Sommer, U., and Galvão, H. M.: Phytoplankton
 861 composition, growth and production in the Guadiana estuary (SW Iberia): Unraveling
 862 changes induced after dam construction, *Science of The Total Environment*, 416, 300-
 863 313, <https://doi.org/10.1016/j.scitotenv.2011.11.043>, 2012.
 864 Fizpartick, J.: *A user's guide for RCA (release 3.0)*, HydroQual Inc., New Jersey, USA.
 865 217p, 2004.
 866 Ge, J., Torres, R., Chen, C., Liu, J., Xu, Y., Bellerby, R., Shen, F., Bruggeman, J., and
 867 Ding, P.: Influence of suspended sediment front on nutrients and phytoplankton
 868 dynamics off the Changjiang Estuary: A FVCOM-ERSEM coupled model experiment,
 869 *Journal of Marine Systems*, 204, 103292,
 870 <https://doi.org/10.1016/j.jmarsys.2019.103292>, 2020.
 871 Hagy, J. D., Boynton, W. R., and Jasinski, D. A.: Modelling phytoplankton deposition
 872 to Chesapeake Bay sediments during winter-spring: interannual variability in relation
 873 to river flow, *ESTUARINE COASTAL AND SHELF SCIENCE*, 62, 25-40,
 874 10.1016/j.ecss.2004.08.004, 2005.
 875 Hong, B., Liu, Z., Shen, J., Wu, H., Gong, W., Xu, H., and Wang, D.: Potential physical
 876 impacts of sea-level rise on the Pearl River Estuary, China, *Journal of Marine Systems*,
 877 201, 103245, 10.1016/j.jmarsys.2019.103245, 2020.
 878 Howarth, R., Chan, F., Conley, D. J., Garnier, J., Doney, S. C., Marino, R., and Billen,
 879 G.: Coupled biogeochemical cycles: eutrophication and hypoxia in temperate estuaries
 880 and coastal marine ecosystems, *Frontiers in Ecology and the Environment*, 9, 18-26,
 881 <https://doi.org/10.1890/100008>, 2011.
 882 Hu, J. and Li, S.: Modeling the mass fluxes and transformations of nutrients in the Pearl
 883 River Delta, China, *Journal of Marine Systems*, 78, 146-167,
 884 <https://doi.org/10.1016/j.jmarsys.2009.05.001>, 2009.

885 Hu, J., Li, S., and Geng, B.: Modeling the mass flux budgets of water and suspended
886 sediments for the river network and estuary in the Pearl River Delta, China, *Journal of*
887 *Marine Systems*, 88, 252-266, <https://doi.org/10.1016/j.jmarsys.2011.05.002>, 2011.

888 Hu, J., Zhang, Z., Wang, B., and Huang, J.: Long-term spatiotemporal variations in and
889 expansion of low-oxygen conditions in the Pearl River estuary: a study synthesizing
890 observations during 1976–2017, *Biogeosciences*, 18, 5247-5264, [10.5194/bg-18-5247-](https://doi.org/10.5194/bg-18-5247-2021)
891 2021, 2021.

892 Huang, Y.-G., Yang, H.-F., Jia, J.-J., Li, P., Zhang, W.-X., Wang, Y. P., Ding, Y.-F., Dai,
893 Z.-J., Shi, B.-W., and Yang, S.-L.: Declines in suspended sediment concentration and
894 their geomorphological and biological impacts in the Yangtze River Estuary and
895 adjacent sea, *Estuarine, Coastal and Shelf Science*, 265, 107708,
896 <https://doi.org/10.1016/j.ecss.2021.107708>, 2022.

897 Kasai, M., Brierley, G. J., Page, M. J., Marutani, T., and Trustrum, N. A.: Impacts of
898 land use change on patterns of sediment flux in Weraamaia catchment, New Zealand,
899 *CATENA*, 64, 27-60, <https://doi.org/10.1016/j.catena.2005.06.014>, 2005.

900 Lai, Y., Jia, Z., Xie, Z., Li, S., and Hu, J.: Water quality changes and shift in mechanisms
901 controlling hypoxia in response to pollutant load reductions: A case study for Shiziyang
902 Bay, Southern China, *Science of The Total Environment*, 842, 156774,
903 <https://doi.org/10.1016/j.scitotenv.2022.156774>, 2022.

904 Laurent, A., Fennel, K., Ko, D. S., and Lehrter, J.: Climate change projected to
905 exacerbate impacts of coastal eutrophication in the northern Gulf of Mexico, *Journal of*
906 *Geophysical Research: Oceans*, 123, 3408-3426, 2018.

907 Li, D., Gan, J., Hui, R., Liu, Z., Yu, L., Lu, Z., and Dai, M.: Vortex and Biogeochemical
908 Dynamics for the Hypoxia Formation Within the Coastal Transition Zone off the Pearl
909 River Estuary, *Journal of Geophysical Research: Oceans*, 125, [10.1029/2020jc016178](https://doi.org/10.1029/2020jc016178),
910 2020a.

911 Li, D., Gan, J., Hui, C., Yu, L., Liu, Z., Lu, Z., Kao, S.-j., and Dai, M.: Spatiotemporal
912 Development and Dissipation of Hypoxia Induced by Variable Wind-Driven Shelf
913 Circulation off the Pearl River Estuary: Observational and Modeling Studies, *Journal*
914 *of Geophysical Research: Oceans*, 126, [e2020JC016700](https://doi.org/10.1029/2020JC016700),
915 <https://doi.org/10.1029/2020JC016700>, 2021.

916 Li, G., Liu, J., Diao, Z., Jiang, X., Li, J., Ke, Z., Shen, P., Ren, L., Huang, L., and Tan,
917 Y.: Subsurface low dissolved oxygen occurred at fresh- and saline-water intersection of
918 the Pearl River estuary during the summer period, *Marine Pollution Bulletin*, 126, 585-
919 591, [10.1016/j.marpolbul.2017.09.061](https://doi.org/10.1016/j.marpolbul.2017.09.061), 2018.

920 Li, X., Lu, C., Zhang, Y., Zhao, H., Wang, J., Liu, H., and Yin, K.: Low dissolved
921 oxygen in the Pearl River estuary in summer: Long-term spatio-temporal patterns,
922 trends, and regulating factors, *Marine Pollution Bulletin*, 151, 110814,
923 <https://doi.org/10.1016/j.marpolbul.2019.110814>, 2020b.

924 Liu, Z., Fagherazzi, S., Liu, X., Shao, D., Miao, C., Cai, Y., Hou, C., Liu, Y., Li, X., and
925 Cui, B.: Long-term variations in water discharge and sediment load of the Pearl River
926 Estuary: Implications for sustainable development of the Greater Bay Area, *Frontiers*

927 in Marine Science, 9, 983517, 10.3389/fmars.2022.983517, 2022.

928 Lu, Z., Gan, J., Dai, M., Liu, H., and Zhao, X.: Joint Effects of Extrinsic Biophysical
929 Fluxes and Intrinsic Hydrodynamics on the Formation of Hypoxia West off the Pearl
930 River Estuary, *Journal of Geophysical Research: Oceans*, 123, 6241-6259,
931 10.1029/2018jc014199, 2018.

932 Luo, X., Yang, Q., and Jia, L.: *The Riverbed Evolution of the River-Network System*
933 *in the Pearl River Delta*, Sun Yat-sen Univeristy Press, Guangzhou, China, 2002.

934 Ma, C., Zhao, J., Ai, B., Sun, S., and Yang, Z.: Machine Learning Based Long-Term
935 Water Quality in the Turbid Pearl River Estuary, China, *Journal of Geophysical*
936 *Research: Oceans*, 127, e2021JC018017, <https://doi.org/10.1029/2021JC018017>, 2022.

937 Ma, R., Chen, Z., Wang, B., Xu, C., Jia, Z., Li, L., and Hu, J.: Spatiotemporal variations
938 and controlling mechanism of low dissolved oxygen in a highly urbanized complex
939 river system, *Journal of Hydrology: Regional Studies*, 52, 101691,
940 <https://doi.org/10.1016/j.ejrh.2024.101691>, 2024.

941 Murphy, R. R., Kemp, W. M., and Ball, W. P.: Long-Term Trends in Chesapeake Bay
942 Seasonal Hypoxia, Stratification, and Nutrient Loading, *ESTUARIES AND COASTS*,
943 34, 1293-1309, 10.1007/s12237-011-9413-7, 2011.

944 Pitcher, G. C., Aguirre-Velarde, A., Breitburg, D., Cardich, J., Carstensen, J., Conley,
945 D. J., Dewitte, B., Engel, A., Espinoza-Morriberón, D., Flores, G., Garçon, V., Graco,
946 M., Grégoire, M., Gutiérrez, D., Hernandez-Ayon, J. M., Huang, H.-H. M., Isensee, K.,
947 Jacinto, M. E., Levin, L., Lorenzo, A., Machu, E., Merma, L., Montes, I., Swa, N.,
948 Paulmier, A., Roman, M., Rose, K., Hood, R., Rabalais, N. N., Salvanes, A. G. V.,
949 Salvattecí, R., Sánchez, S., Sifeddine, A., Tall, A. W., Plas, A. K. v. d., Yasuhara, M.,
950 Zhang, J., and Zhu, Z. Y.: System controls of coastal and open ocean oxygen depletion,
951 *Progress in Oceanography*, 197, 102613, <https://doi.org/10.1016/j.pocean.2021.102613>,
952 2021.

953 Roman, M. R., Brandt, S. B., Houde, E. D., and Pierson, J. J.: Interactive effects of
954 Hypoxia and temperature on coastal pelagic zooplankton and fish, *Frontiers in Marine*
955 *Science*, 6, 10.3389/fmars.2019.00139, 2019.

956 Su, J., Dai, M., He, B., Wang, L., Gan, J., Guo, X., Zhao, H., and Yu, F.: Tracing the
957 origin of the oxygen-consuming organic matter in the hypoxic zone in a large eutrophic
958 estuary: the lower reach of the Pearl River Estuary, China, *Biogeosciences*, 14, 4085-
959 4099, 10.5194/bg-14-4085-2017, 2017.

960 Syvitski, J. P. M. and Kettner, A.: Sediment flux and the Anthropocene, *Philosophical*
961 *Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*,
962 369, 957-975, doi:10.1098/rsta.2010.0329, 2011.

963 Wang, B., Hu, J., Li, S., and Liu, D.: A numerical analysis of biogeochemical controls
964 with physical modulation on hypoxia during summer in the Pearl River estuary,
965 *Biogeosciences*, 14, 2979-2999, 10.5194/bg-14-2979-2017, 2017.

966 Wang, B., Hu, J., Li, S., Yu, L., and Huang, J.: Impacts of anthropogenic inputs on
967 hypoxia and oxygen dynamics in the Pearl River estuary, *Biogeosciences*, 15, 6105-
968 6125, 10.5194/bg-15-6105-2018, 2018.

969 Wang, G., Cao, W., Yang, Y., Zhou, W., Liu, S., and Yang, D.: Variations in light
 970 absorption properties during a phytoplankton bloom in the Pearl River estuary,
 971 *Continental Shelf Research*, 30, 1085-1094, 2010.

972 Wang, H., Dai, M., Liu, J., Kao, S.-J., Zhang, C., Cai, W.-J., Wang, G., Qian, W., Zhao,
 973 M., and Sun, Z.: Eutrophication-Driven Hypoxia in the East China Sea off the
 974 Changjiang Estuary, *Environmental Science & Technology*, 50, 2255-2263,
 975 10.1021/acs.est.5b06211, 2016.

976 Wang, J. J., Bouwman, A. F., Liu, X. C., Beusen, A. H. W., Van Dingenen, R., Dentener,
 977 F., Yao, Y. L., Glibert, P. M., Ran, X. B., Yao, Q. Z., Xu, B. C., Yu, R. C., Middelburg,
 978 J. J., and Yu, Z. G.: Harmful Algal Blooms in Chinese Coastal Waters Will Persist Due
 979 to Perturbed Nutrient Ratios, *ENVIRONMENTAL SCIENCE & TECHNOLOGY*
 980 *LETTERS*, 8, 276-284, 10.1021/acs.estlett.1c00012, 2021.

981 Wang, K., Chen, J., Jin, H., Li, H., Gao, S., Xu, J., Lu, Y., Huang, D., Hao, Q., and
 982 Weng, H.: Summer nutrient dynamics and biological carbon uptake rate in the
 983 Changjiang River plume inferred using a three end-member mixing model, *Continental*
 984 *Shelf Research*, 91, 192-200, <https://doi.org/10.1016/j.csr.2014.09.013>, 2014.

985 Wang, Y., Wu, H., Lin, J., Zhu, J., Zhang, W., and Li, C.: Phytoplankton Blooms off a
 986 High Turbidity Estuary: A Case Study in the Changjiang River Estuary, *Journal of*
 987 *Geophysical Research: Oceans*, 124, 8036-8059, 10.1029/2019jc015343, 2019.

988 Wen, G., Liang, Z., Xu, X., Cao, R., Wan, Q., Ji, G., Lin, W., Wang, J., Yang, J., and
 989 Huang, T.: Inactivation of fungal spores in water using ozone: Kinetics, influencing
 990 factors and mechanisms, *Water Research*, 185, 116218,
 991 <https://doi.org/10.1016/j.watres.2020.116218>, 2020.

992 Wu, C. S., Yang, S., Huang, S., and Mu, J.: Delta changes in the Pearl River estuary and
 993 its response to human activities (1954–2008), *Quaternary International*, 392, 147-154,
 994 <https://doi.org/10.1016/j.quaint.2015.04.009>, 2016.

995 Yang, H., Wang, T., Yang, D., Yan, Z., Wu, J., and Lei, H.: Runoff and sediment effect
 996 of the soil-water conservation measures in a typical river basin of the Loess Plateau,
 997 *CATENA*, 243, 108218, <https://doi.org/10.1016/j.catena.2024.108218>, 2024.

998 Yu, L., Gan, J., 2022. Reversing impact of phytoplankton phosphorus limitation on
 999 coastal hypoxia due to interacting changes in surface production and shoreward bottom
 1000 oxygen influx. *Water Res.* 118094 <https://doi.org/10.1016/j.watres.2022.118094>.

1001 Yu, L., Fennel, K., Laurent, A., 2015. A modeling study of physical controls on hypoxia
 1002 generation in the northern Gulf of Mexico. *J. Geophys. Res. Oceans* 120, 5019–5039.
 1003 <https://doi.org/10.1002/2014JC010634>.

1004 Yu, L., Gan, J., Dai, M., Hui, C., Lu, Z., Li, D., 2020. Modeling the role of riverine
 1005 organic matter in hypoxia formation within the coastal transition zone off the Pearl
 1006 River Estuary. *Limnol. Oceanogr.* 9999, 1–17. <https://doi.org/10.1002/lno.11616>

1007 Zhang, S., Lu, X. X., Higgitt, D. L., Chen, C.-T. A., Han, J., and Sun, H.: Recent
 1008 changes of water discharge and sediment load in the Zhujiang (Pearl River) Basin,
 1009 China, *Global and Planetary Change*, 60, 365-380,
 1010 <https://doi.org/10.1016/j.gloplacha.2007.04.003>, 2008.

1011 Zhang, Z., Wang, B., Li, S., Huang, J., and Hu, J.: On the Intra-annual Variation of
1012 Dissolved Oxygen Dynamics and Hypoxia Development in the Pearl River Estuary,
1013 Estuaries and Coasts, 45, 1305-1323, 10.1007/s12237-021-01022-0, 2022.

1014

1015