Supplementary Information

Quantifying the impact of anthropogenic atmospheric nitrogen deposition on the generation of hypoxia under future emission scenarios in Chinese coastal waters

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Text S1 Description of COOLBEANS

Coastal Ocean Oxygen Linked to Benthic Exchange And Nutrient Supply (COOLBEANS) is a biogeochemical model that links bottom water oxygen concentrations with nutrient loading. The change of oxygen concentration is controlled by the bottom oxygen demand (BOD) and vertical exchange of oxygen between surface and bottom, with the following equation as the backbone of the model,

$$\frac{dC}{dt} = \alpha(C_0 - C) - \frac{BOD}{L} \qquad \text{(S1)}$$

where C and C_0 are the concentrations of oxygen in surface waters and at the seafloor respectively (mol m^{-3}), t is the time (year), α is an exchange coefficient representing exchange between surface and bottom waters ($year^{-1}$), BOD is benthic oxygen demand (mol m^{-2} yr^{-1}) and L is the thickness of the bottom layer (m). Details of the equation and explanation of the model can be found in Reed and Harrison[2].

Bottom oxygen demand (BOD)

Oxygen in bottom waters is consumed mainly through the decomposition of organic matter in seafloor. The deposition of organic matter is controlled by the remineralization and burial rate of organic matter, which is expressed as

$$J_{SED} = J_{REM} - J_{BUR} \qquad \text{(S2)}$$

where J_{SED} is the flux of organic carbon to sediment (mol C m^{-2} yr^{-1}) , J_{REM} is the rate of organic matter remineralization, and J_{BUR} is the rate of organic carbon burial.

As not all the organic matters reaches bottom waters, the proportion of net primary productivity that is deposited on the sediment is qualified using a depth relationship[3], which is calculated as

$$J_{SED}\,(\mathrm{z}) = \left(0.83e^{-0.018z} + 0.17e^{-0.00046z}\right)P \qquad \text{(S3)}$$

where z is the water depth and P is the net primary productivity (mol C m^{-2} yr^{-1}).
The bottom oxygen demand accounts for oxygen consumption from the flux of organic carbon to the sediment and the effect of pyrite burial and iron and sulphate reduction.

$$BOD = \left(\frac{77}{60}\gamma - \frac{17}{60}\right)10F_{SED} \qquad \text{(S4)}$$

where γ is the proportion of organic matter that is remineralized in the sediment. We assume that the C:N ratio in the sediments in 10:1 because some organic matter will degrade before it reaches the bottom waters.

Maximum hypoxic area

After calculating the proportion of organic matter being deposit and the oxygen demand, maximum hypoxia area for a given COSCAT is calculated as follows,

$$A_{HY} = \frac{M_{SED}\left(\frac{77}{60}\gamma - \frac{17}{60}\right)}{\alpha(C_0 - 0.063)L} \qquad \text{(S5)}$$

where M_{SED} is the total deposition of organic matter in COSCAT (mol C yr^{-1}) and α is the proportion of organic matter remineralised, $C_0$is the surface oxygen concentration. It is assumed that the oxygen demand for hypoxic waters in bottom waters is 63 μmol O_2 L^{-1}.

Model Validation

Comparing model results with the observation can validate COOLBEANS. In our results, we modelled the maximum hypoxic area under present-day carbon fluxes in four major zones of China's coastal seas; the East Yellow Sea (23,200 km^2), Bohai Sea (7200 km^2), East China Sea (33,600 km^2) and South China Sea (57,500 km^2) (Table 1). The modelled hypoxic areas are larger than observed; Bohai Sea (4200 km2) in 2014 (Zhang et al 2016), East China Sea (15,400 km^2) in 2006 (Zhu et al 2011) and South China Sea (11,500 km^2) in 2013 (Zhu et al 2017). These results are slightly bigger than actual hypoxic areas because of the uncertainties in the input parameters, such as surface oxygen concentrations and primary productivity, which affect the accuracy of bottom-water oxygen and thus the hypoxic area. Moreover, in our model, the spatial resolution of COSCAT covers the whole coastal region. Thus, it cannot reproduce the localized hypoxic area within the zone. Therefore, this may affect the actual predictions made here. Also, hypoxia may last for only a short period of time, which cannot be captured in the model. Nonetheless, the modelled results are comparable with observed and generally validate the reliability and utility of COOLEBANS.

Table S1. Input used to run the COOLBEANS model to calculate the maximum hypoxic area by region[2]

Name	O_2 surface (mol/m^3)	O_2 bottom (mol/m^3)	Depth (m)	Net primary productivity (mol C/[m^2 y])	Temp (°C)	Salinity	Net primary productivity area (km^2)
East Yellow Sea	0.25	0.23	149.1	80.4	16.8	32.6	205000
Bohai Sea	0.27	0.30	20.4	150.0	13.5	30.1	54958
East China Sea	0.24	0.23	64.6	123.8	19.5	32.6	246000
South China Sea	0.21	0.16	97.4	119.6	25.6	33.4	186000

Table S2. The percentage change of total N deposition (wet and dry) relative to modern day deposition[4]

	RCP 4.5		RCP 8.5	
	2030	**2100**	**2030**	**2100**
East Yellow Sea	-19.0	-72.0	24.9	-58.9
Bohai Sea	11.8	-75.4	81.0	-64.2
East China Sea	1.1	-63.1	41.9	-59.4
South China Sea	39.1	-30.1	56.0	-42.6

Table S3. Modelled hypoxic areas (km^2) in Chinese coastal seas in modern-day and future N deposition under RCP 4.5 and RCP 8.5 emissions scenarios. Data are presented as mean ± standard deviation. Parentheses represent the percentage change compared to the modelled modern- day value.

		RCP 4.5		**RCP 8.5**	
Location	**Modern day**	**2030**	**2100**	**2030**	**2100**
East Yellow Sea	23152	22618 ± 166 (-2.3%)	21132 ± 80 (-8.7%)	23851 ± 222 (3%)	21499 ± 91 (-7.1%)
Bohai Sea	7167	7185 ± 9 (0.2%)	7056 ± 5 (-1.6%)	7287 ± 10 (1.7%)	7073 ± 8 (-1.3%)
East China Sea	33563	33579 ± 81 (0%)	32636 ± 72 (-2.8%)	34177 ± 79 (1.8%)	32690 ± 51 (-2.6%)
South China Sea	57521	59424 ± 271 (3.3%)	56057 ± 311 (-2.5%)	60247 ± 402 (4.7%)	55450 ± 236 (-3.6%)

Table S4. Rate of change of hypoxia (km^2/mg N m^{-2} yr^{-1})

Location	2030
East Yellow Sea	0.96
Bohai Sea	0.05
East China Sea	0.46
South China Sea	1.12

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