



*Supplement of*

## **Contribution of the open ocean to the nutrient and phytoplankton inventory in a semi-enclosed coastal sea**

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# 1 S1 Governing equations of the biogeochemical model

2 The biogeochemical model in this study was based on nitrogen (Fig. S1). Phosphate-related  
 3 variables were calculated based on a Redfield ratio of 16:1. The governing equations of the  
 4 biogeochemical model are as follows

5 
$$\frac{\partial DIN}{\partial t} + adv(DIN) - diff(DIN) = -Phyotosynthesis + Respiration + Excretion + Mineralization \quad (S1)$$

6 
$$\frac{\partial PHY}{\partial t} + adv(PHY) - diff(PHY) + S_{PHY} \frac{\partial PHY}{\partial z} = Phyotosynthesis - Respiration - Mortality of PHY - Grazing \quad (S2)$$

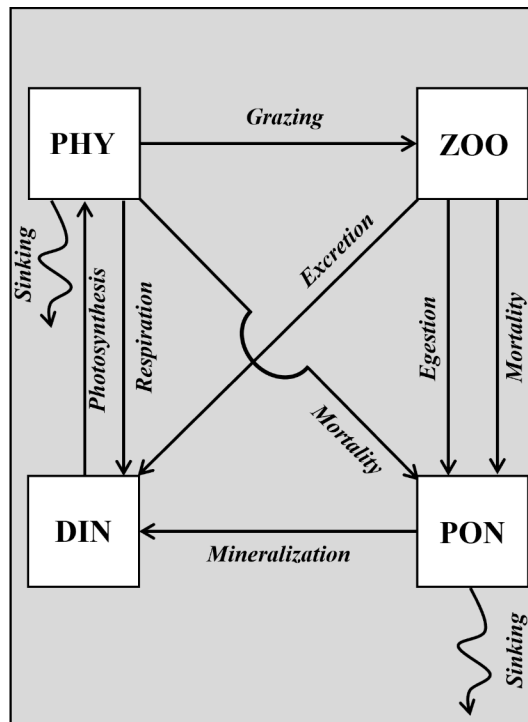
7 
$$\frac{\partial ZOO}{\partial t} + adv(ZOO) - diff(ZOO) = Grazing - Mortality of ZOO - Egestion - Excretion \quad (S3)$$

8 
$$\frac{\partial PON}{\partial t} + adv(PON) - diff(PON) + S_{PON} \frac{\partial PON}{\partial z} = Mortality of PHY + Mortality of ZOO + Egestion - Mineralization \quad (S4)$$

9 
$$\frac{\partial DIP}{\partial t} + adv(DIP) - diff(DIP) = (-Phyotosynthesis + Excretion + Mineralization + Respiration)/16 \quad (S5)$$

10 
$$adv( ) = u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} + w \frac{\partial}{\partial z} \quad (S6)$$

11 
$$diff( ) = \frac{\partial}{\partial x} \left( K_h \frac{\partial}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_h \frac{\partial}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_v \frac{\partial}{\partial z} \right) \quad (S7)$$



12

13 **Fig. S1.** Sketch of the biogeochemical model.

## 14 S2 Parameterized formulas of the biogeochemical model

15 The parameterized formulas for each biogeochemical process are as follows, and the parameter  
16 values are shown in Table S1.

$$17 \text{ Photosynthesis} = V_{\max} \cdot \min \left\{ \frac{DIN}{DIN + K_{DIN}}, \frac{DIP}{DIP + K_{DIP}} \right\} \cdot \frac{I}{I_{opt}} \exp \left( 1 - \frac{I}{I_{opt}} \right) \cdot \exp^{k_1 \cdot T} \cdot PHY \quad (S8)$$

$$18 I(z) = I_0 \exp^{-\int_0^z \kappa(z) dz} \quad (S9)$$

$$19 \kappa(z) = \kappa_1 + \kappa_2 PHY(z) \quad (S10)$$

20 Where  $I_0$  is the photosynthetically active solar radiation at the surface, which is 40% of the  
21 shortwave radiation at the surface. T is the water temperature.

$$22 \text{ Respiration} = P_{resp} \cdot \exp^{k_2 \cdot T} \cdot PHY \quad (S11)$$

$$23 \text{ Mortality of PHY} = P_{mor} \cdot \exp^{k_3 \cdot T} \cdot PHY^2 \quad (S12)$$

$$24 \text{ Grazing} = R_{\max} \cdot [1 - \exp^{\lambda(P_{lim} - PHY)}] \cdot \exp^{k_4 \cdot T} \cdot ZOO \quad (S13)$$

$$25 \text{ Mortality of ZOO} = Z_{mor} \cdot \exp^{k_5 \cdot T} \cdot ZOO^2 \quad (S14)$$

$$26 \text{ Egestion} = (1 - \alpha) \cdot R_{\max} \cdot [1 - \exp^{\lambda(P_{lim} - PHY)}] \cdot \exp^{k_4 \cdot T} \cdot ZOO \quad (S15)$$

$$27 \text{ Excretion} = (\alpha - \beta) \cdot R_{\max} \cdot [1 - \exp^{\lambda(P_{lim} - PHY)}] \cdot \exp^{k_4 \cdot T} \cdot ZOO \quad (S16)$$

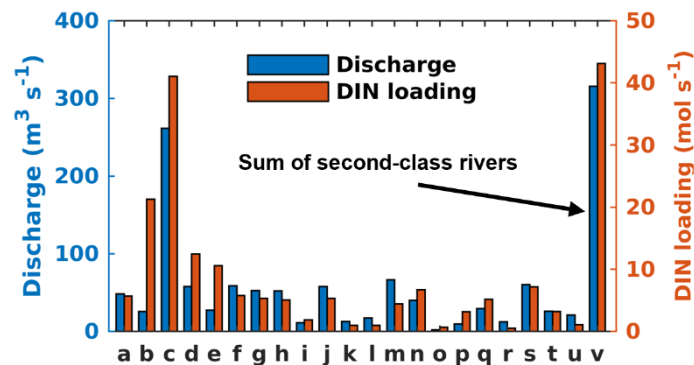
$$28 \text{ Decomposition} = D_{deco} \cdot \exp^{k_6 \cdot T} \cdot PON \quad (S17)$$

29 **Table S1.** Parameters for the biogeochemical model in this study

Symbol	Parameter	Value	Unit
$V_{\max}$	Phytoplankton maximum photosynthesis rate at 0°C	0.8	$day^{-1}$
$K_{DIN}$	Phytoplankton half saturation for DIN	3	$mmol N m^{-3}$
$K_{DIP}$	Phytoplankton half saturation for DIP	0.12	$mmol P m^{-3}$
$I_{opt}$	Phytoplankton optimum light intensity	104.7	$W m^{-2}$
$k_1$	Phytoplankton temperature coefficient for photosynthesis	0.0693	$^{\circ}C^{-1}$
$\kappa_1$	Light extinction coefficient of seawater	0.04	$m^{-1}$
$\kappa_2$	Self-shading coefficient of phytoplankton	0.04	$(mmol N m^{-3})^{-1}$
$P_{resp}$	Phytoplankton respiration rate at 0°C	0.03	$day^{-1}$
$k_2$	Phytoplankton temperature coefficient for respiration	0.0519	$^{\circ}C^{-1}$

$P_{mor}$	Phytoplankton mortality rate at 0°C	0.05	$day^{-1}$
$k_3$	Phytoplankton temperature coefficient for mortality	0.0693	$^{\circ}C^{-1}$
$R_{max}$	Zooplankton maximum grazing rate at 0°C	0.2	$day^{-1}$
$\lambda$	Zooplankton Ivlev constant	1.4	$(mmol\ N\ m^{-3})^{-1}$
$P_{lim}$	Zooplankton threshold value for grazing phytoplankton	0.043	$mmol\ N\ m^{-3}$
$k_4$	Zooplankton temperature coefficient for grazing	0.0693	$^{\circ}C^{-1}$
$Z_{mor}$	Zooplankton mortality rate at 0°C	0.0585	$mmol\ N\ m^{-3}$
$k_5$	Zooplankton temperature coefficient for mortality	0.0693	$^{\circ}C^{-1}$
$\alpha$	Assimilation efficiency of zooplankton	0.7	No dim
$\beta$	Growth efficiency of zooplankton	0.3	No dim
$D_{deco}$	Decomposition rate at 0°C	0.05	$mmol\ N\ m^{-3}$
$k_6$	Detritus temperature coefficient for decomposition	0.0693	$^{\circ}C^{-1}$
$S_{PHY}$	Sinking velocity of phytoplankton	1	$m\ day^{-1}$
$S_{PON}$	Sinking velocity of particulate organic nitrogen	0.1	$m\ day^{-1}$

### 30 S3 Annual mean discharge and DIN loading of each river



31

32 **Fig. S2.** Annual mean river discharge ( $m^3 s^{-1}$ ) and DIN loading ( $mol s^{-1}$ ). The letter a to u

33 represents the first-class rivers, and the letter v represents the sum of second-class rivers.

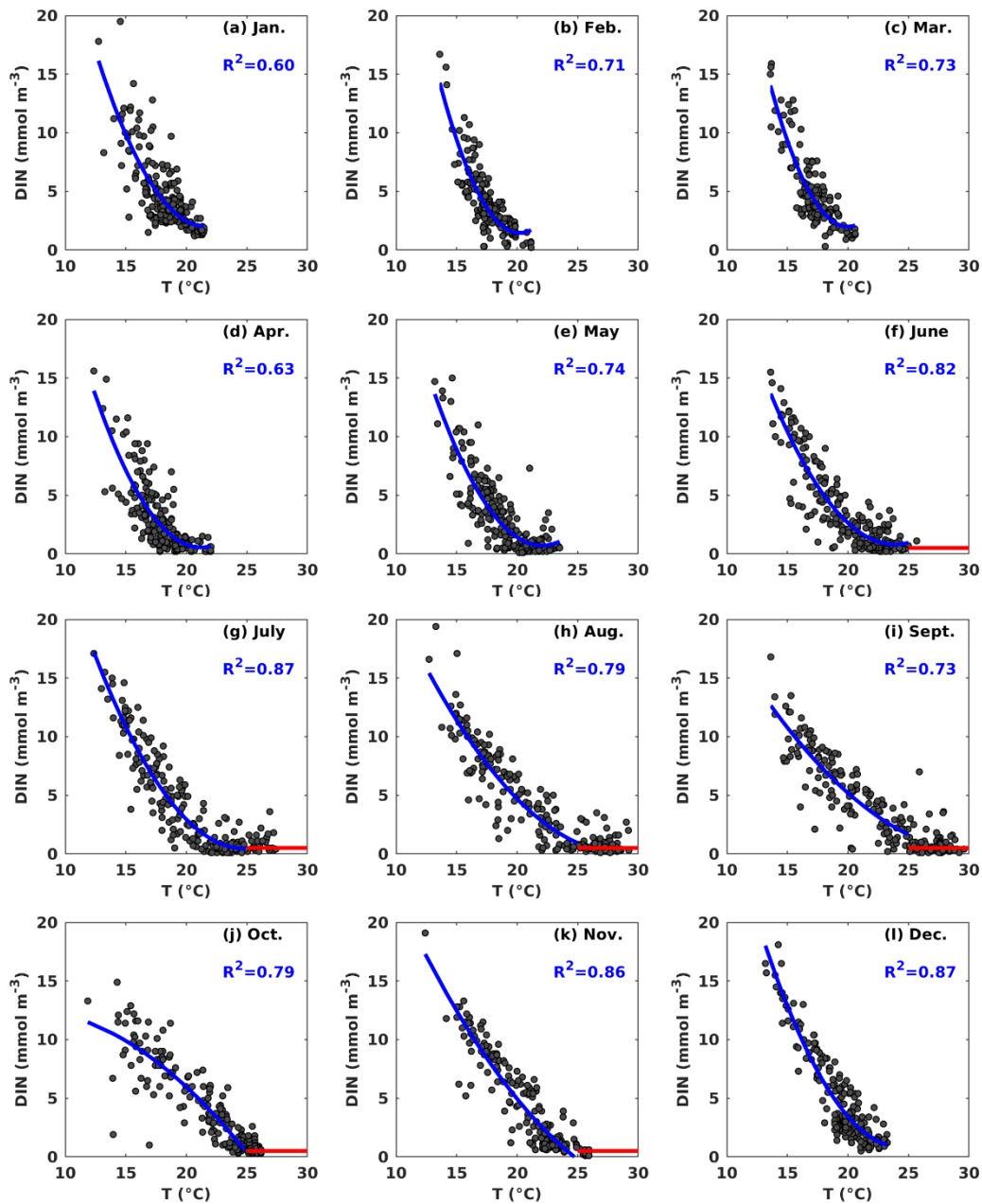
34 **Table S2.** 21 first-class rivers in this model. The label is in Fig. 1b and Fig. S2.

Label	River name
a	Kino River
b	Yamato River
c	Yodo River
d	Kako River
e	Ibo River
f	Yoshii River
g	Asahi River
h	Takahashi River

i Ashida River  
j Oota River  
k Oze River  
l Saba River  
m Naka River  
n Yoshino River  
o Doki River  
p Shigenobu River  
q Hiji River  
r Bansho River  
s Oono River  
t Oita River  
u Yamakuni River

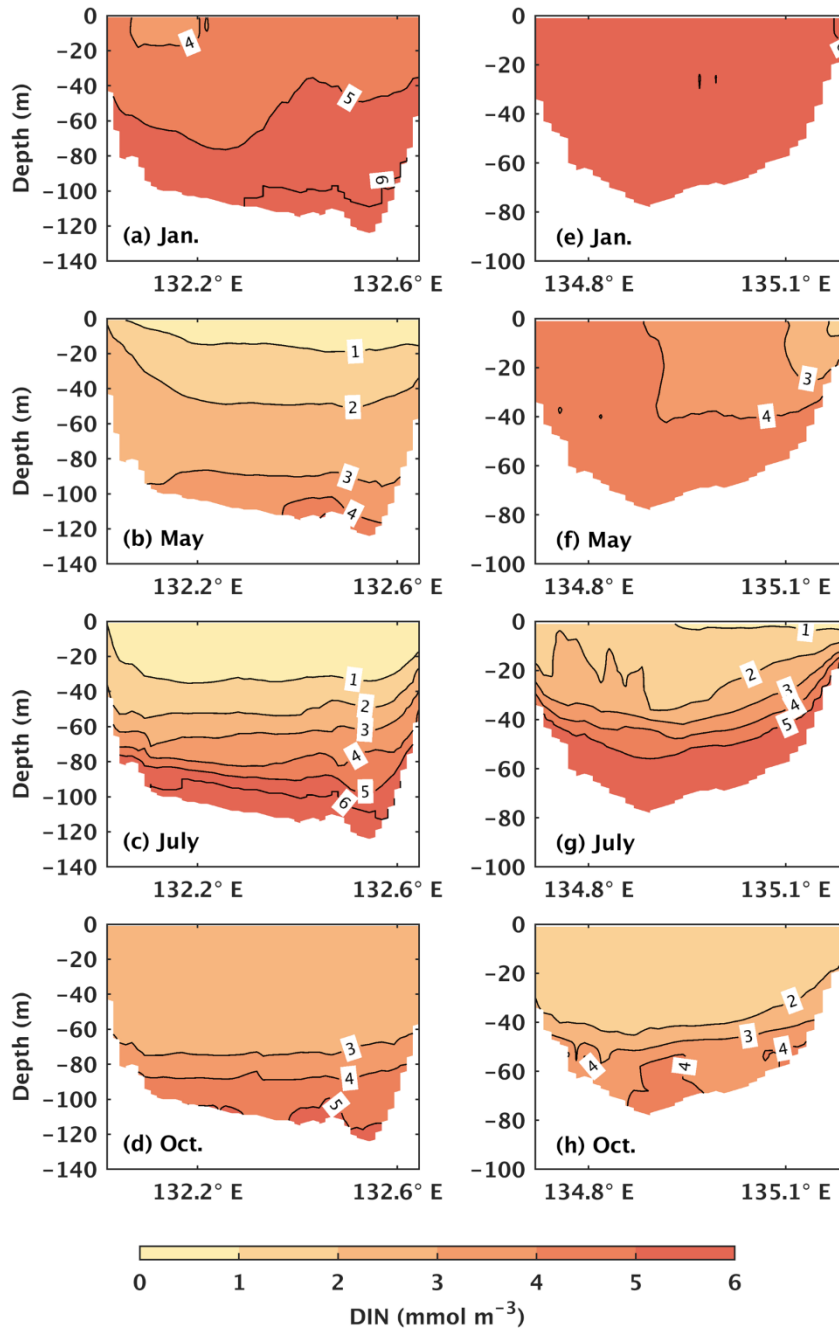
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35 **S4 DIN concentration at the open boundaries**



36

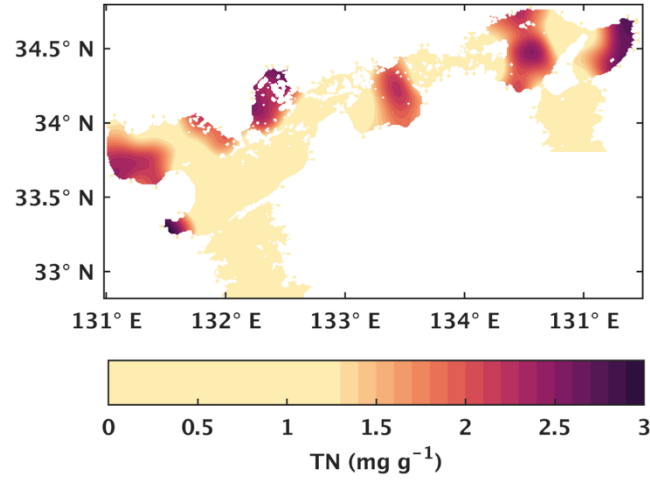
37 **Fig. S3.** Relationship between water temperature (°C) and DIN concentration ( $mmol m^{-3}$ ) at  
 38 Bungo Channel from 1991 to 2005. Blue line in each figure represents regression line for T lower  
 39 than 25 °C DIN concentration is equal to  $0.5 mmol m^{-3}$  for T larger than 25 °C from (f) June to  
 40 (k) Nov. represented by the red line.



41

42 **Fig. S4.** Vertical profiles of DIN concentration ( $mmol m^{-3}$ ) at the open boundary between the  
 43 Bungo Channel and the open ocean (**a to d**), and the open boundary between the Kii Channel and  
 44 the open ocean (**e to h**).

45 **S5 TN concentration at the surface of sediment**



46

47 **Fig. S5.** Annual mean TN concentration ( $mg\ g^{-1}$ ) at the surface of the sediment.

48 **S6 Governing equations of tracking technique**

49 The governing equations of tracking open ocean are as follows

$$50 \quad \frac{\partial DIN_{ocean}}{\partial t} + adv(DIN_{ocean}) - diff(DIN_{ocean}) = -Phytosynthesis \cdot \frac{DIN_{ocean}}{DIN} + Respiration \cdot$$

$$51 \quad \frac{PHY_{ocean}}{PHY} + Excretion \cdot \frac{ZOO_{ocean}}{ZOO} + Mineralization \cdot \frac{PON_{ocean}}{PON} \quad (S18)$$

$$52 \quad \frac{\partial PHY_{ocean}}{\partial t} + adv(PHY_{ocean}) - diff(PHY_{ocean}) + S_{PHY} \frac{\partial PHY_{ocean}}{\partial z} = Phytosynthesis \cdot \frac{DIN_{ocean}}{DIN} - Respiration \cdot$$

$$53 \quad \frac{PHY_{ocean}}{PHY} - Mortality\ of\ PHY \cdot \frac{PHY_{ocean}}{PHY} - Grazing \cdot \frac{PHY_{ocean}}{PHY} \quad (S19)$$

$$54 \quad \frac{\partial ZOO_{ocean}}{\partial t} + adv(ZOO_{ocean}) - diff(ZOO_{ocean}) = Grazing \cdot \frac{PHY_{ocean}}{PHY} - Mortality\ of\ ZOO \cdot \frac{ZOO_{ocean}}{ZOO} -$$

$$55 \quad Egestion \cdot \frac{ZOO_{ocean}}{ZOO} - Excretion \cdot \frac{ZOO_{ocean}}{ZOO} \quad (S20)$$

$$56 \quad \frac{\partial PON_{ocean}}{\partial t} + adv(PON_{ocean}) - diff(PON_{ocean}) + S_{PON} \frac{\partial PON_{ocean}}{\partial z} = Mortality\ of\ PHY \cdot \frac{PHY_{ocean}}{PHY} +$$

$$57 \quad Mortality\ of\ ZOO \cdot \frac{ZOO_{ocean}}{ZOO} + Egestion \cdot \frac{ZOO_{ocean}}{ZOO} - Mineralization \cdot \frac{PON_{ocean}}{PON} \quad (S21)$$

$$58 \quad adv( ) = u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} + w \frac{\partial}{\partial z} \quad (S22)$$

$$59 \quad diff( ) = \frac{\partial}{\partial x} \left( K_h \frac{\partial}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_h \frac{\partial}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_v \frac{\partial}{\partial z} \right) \quad (S23)$$



60 The governing equations of tracking rivers are as follows

$$61 \quad \frac{\partial DIN_{river}}{\partial t} + adv(DIN_{river}) - diff(DIN_{river}) = -Phytosynthesis \cdot \frac{DIN_{river}}{DIN} + Respiration \cdot \frac{PHY_{river}}{PHY} +$$

$$62 \quad Excretion \cdot \frac{ZOO_{river}}{ZOO} + Mineralization \cdot \frac{PON_{river}}{PON} \quad (S24)$$

$$63 \quad \frac{\partial PHY_{river}}{\partial t} + adv(PHY_{river}) - diff(PHY_{river}) + S_{PHY} \frac{\partial PHY_{river}}{\partial z} = Phytosynthesis \cdot \frac{DIN_{river}}{DIN} - Respiration \cdot$$

$$64 \quad \frac{PHY_{river}}{PHY} - Mortality of PHY \cdot \frac{PHY_{river}}{PHY} - Grazing \cdot \frac{PHY_{river}}{PHY} \quad (S25)$$

$$65 \quad \frac{\partial ZOO_{river}}{\partial t} + adv(ZOO_{river}) - diff(ZOO_{river}) = Grazing \cdot \frac{PHY_{river}}{PHY} - Mortality of ZOO \cdot \frac{ZOO_{river}}{ZOO} -$$

$$66 \quad Egestion \cdot \frac{ZOO_{river}}{ZOO} - Excretion \cdot \frac{ZOO_{river}}{ZOO} \quad (S26)$$

$$67 \quad \frac{\partial PON_{river}}{\partial t} + adv(PON_{river}) - diff(PON_{river}) + S_{PON} \frac{\partial PON_{river}}{\partial z} = Mortality of PHY \cdot \frac{PHY_{river}}{PHY} +$$

$$68 \quad Mortality of ZOO \cdot \frac{ZOO_{river}}{ZOO} + Egestion \cdot \frac{ZOO_{river}}{ZOO} - Mineralization \cdot \frac{PON_{river}}{PON} \quad (S27)$$

$$69 \quad adv( ) = u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} + w \frac{\partial}{\partial z} \quad (S28)$$

$$70 \quad diff( ) = \frac{\partial}{\partial x} \left( K_h \frac{\partial}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_h \frac{\partial}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_v \frac{\partial}{\partial z} \right) \quad (S29)$$

71 The governing equations of tracking sediment are as follows

$$72 \quad \frac{\partial DIN_{sediment}}{\partial t} + adv(DIN_{sediment}) - diff(DIN_{sediment}) = -Phytosynthesis \cdot \frac{DIN_{sediment}}{DIN} + Respiration \cdot$$

$$73 \quad \frac{PHY_{sediment}}{PHY} + Excretion \cdot \frac{ZOO_{sediment}}{ZOO} + Mineralization \cdot \frac{PON_{sediment}}{PON} \quad (S30)$$

$$74 \quad \frac{\partial PHY_{sediment}}{\partial t} + adv(PHY_{sediment}) - diff(PHY_{sediment}) + S_{PHY} \frac{\partial PHY_{sediment}}{\partial z} = Phytosynthesis \cdot \frac{DIN_{sediment}}{DIN} -$$

$$75 \quad Respiration \cdot \frac{PHY_{sediment}}{PHY} - Mortality of PHY \cdot \frac{PHY_{sediment}}{PHY} - Grazing \cdot \frac{PHY_{sediment}}{PHY} \quad (S31)$$

$$76 \quad \frac{\partial ZOO_{sediment}}{\partial t} + adv(ZOO_{sediment}) - diff(ZOO_{sediment}) = Grazing \cdot \frac{PHY_{sediment}}{PHY} - Mortality of ZOO \cdot$$

$$77 \quad \frac{ZOO_{sediment}}{ZOO} - Egestion \cdot \frac{ZOO_{sediment}}{PHY} - Excretion \cdot \frac{ZOO_{sediment}}{PHY} \quad (S32)$$

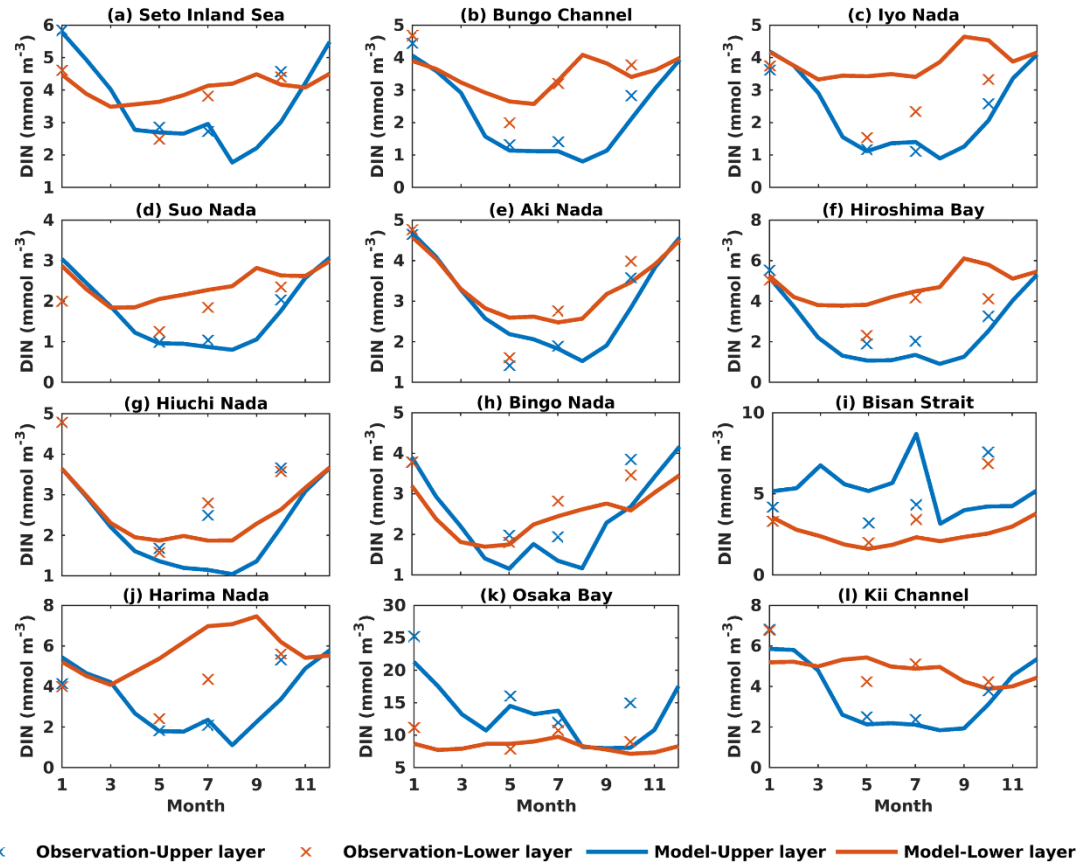
$$78 \quad \frac{\partial PON_{sediment}}{\partial t} + adv(PON_{sediment}) - diff(PON_{sediment}) + S_{PON} \frac{\partial PON_{sediment}}{\partial z} = Mortality of PHY \cdot$$

$$79 \quad \frac{PHY_{sediment}}{PHY} + Mortality of ZOO \cdot \frac{ZOO_{sediment}}{ZOO} + Egestion \cdot \frac{ZOO_{sediment}}{ZOO} - Mineralization \cdot \frac{PON_{sediment}}{PON} \quad (S33)$$

$$80 \quad adv( ) = u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} + w \frac{\partial}{\partial z} \quad (S34)$$

$$diff(\quad) = \frac{\partial}{\partial x} \left( K_h \frac{\partial}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_h \frac{\partial}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_v \frac{\partial}{\partial z} \right) \quad (S35)$$

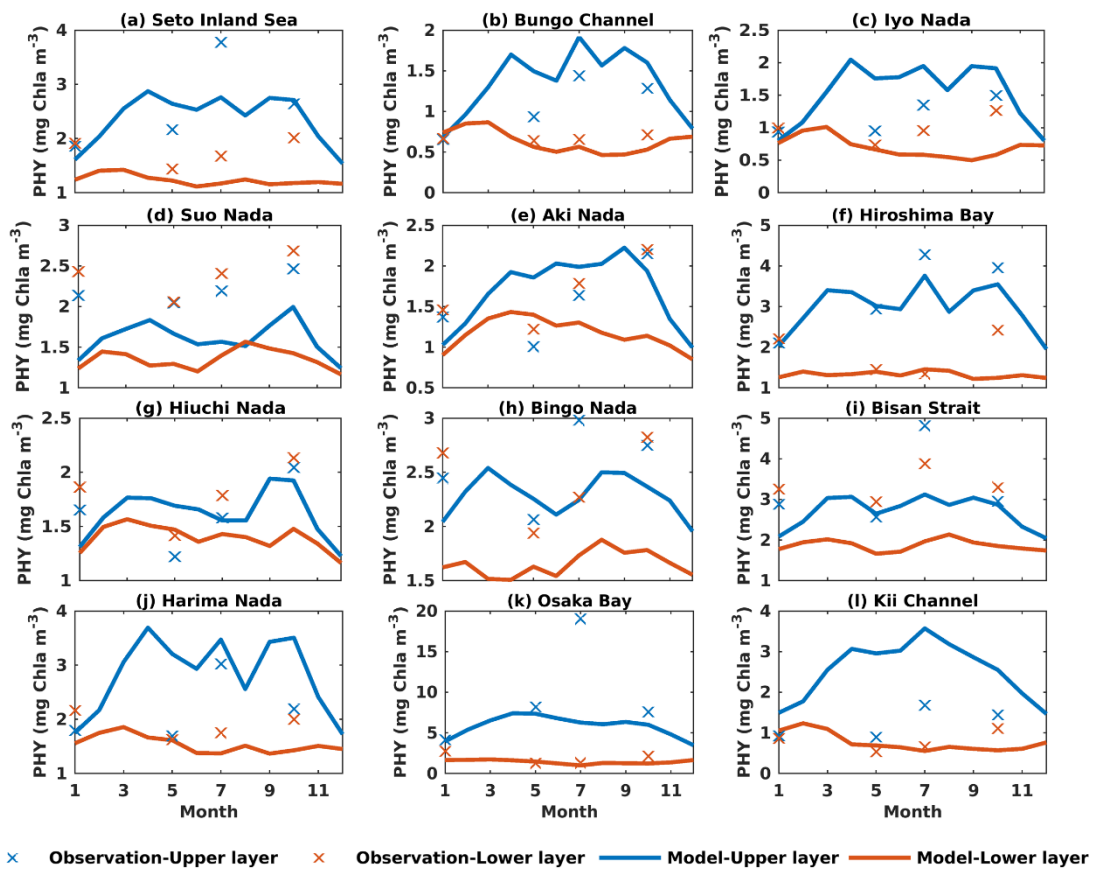
## 82 S7 Seasonal variations of DIN and PHY



83

84 **Fig. S6.** Monthly mean observed and simulated DIN ( $mmol\ m^{-3}$ ) for the upper and lower years

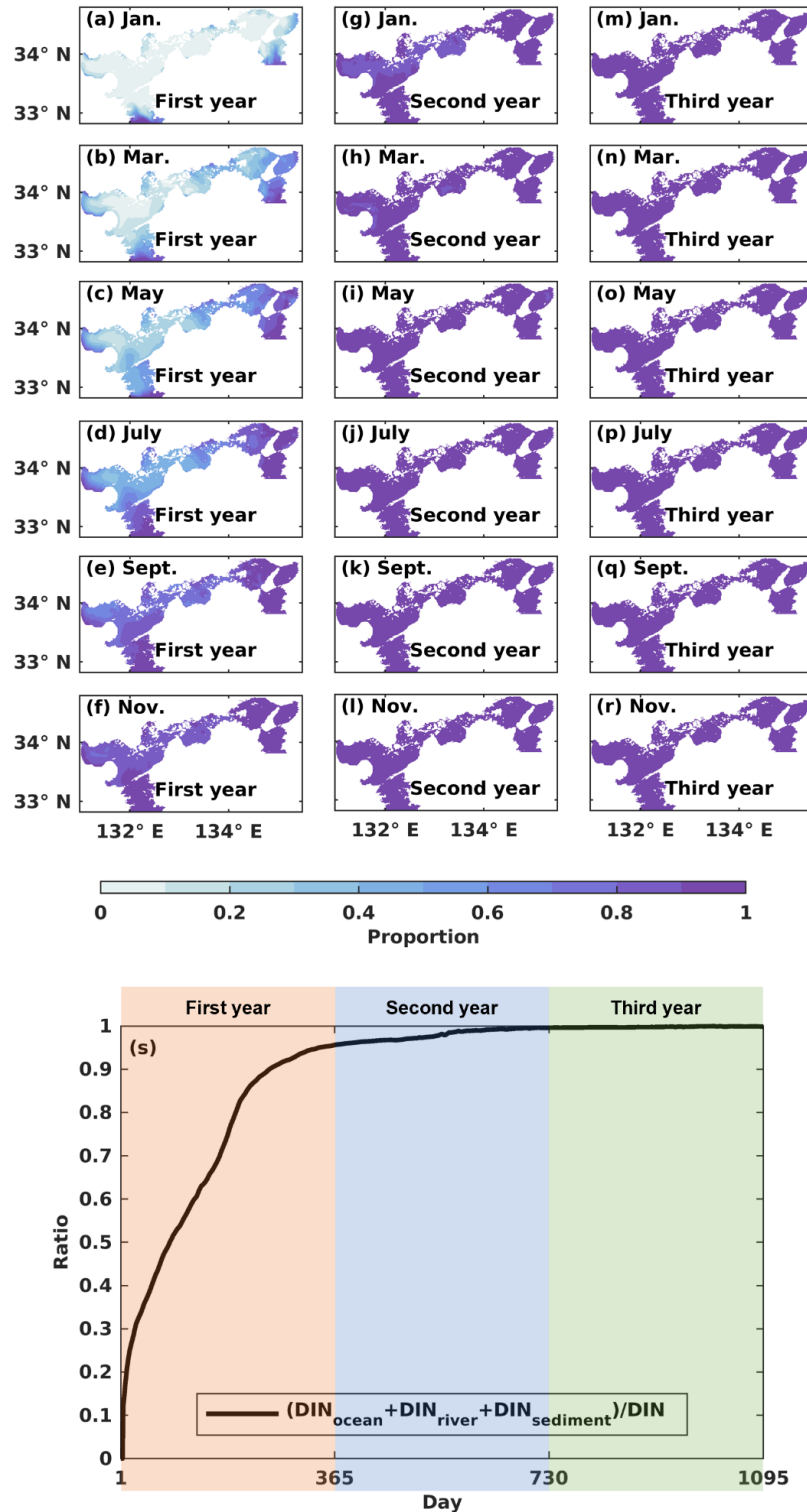
85 of each subregion of SIS. The observation stations in each subregion are presented in Fig. 1(c).



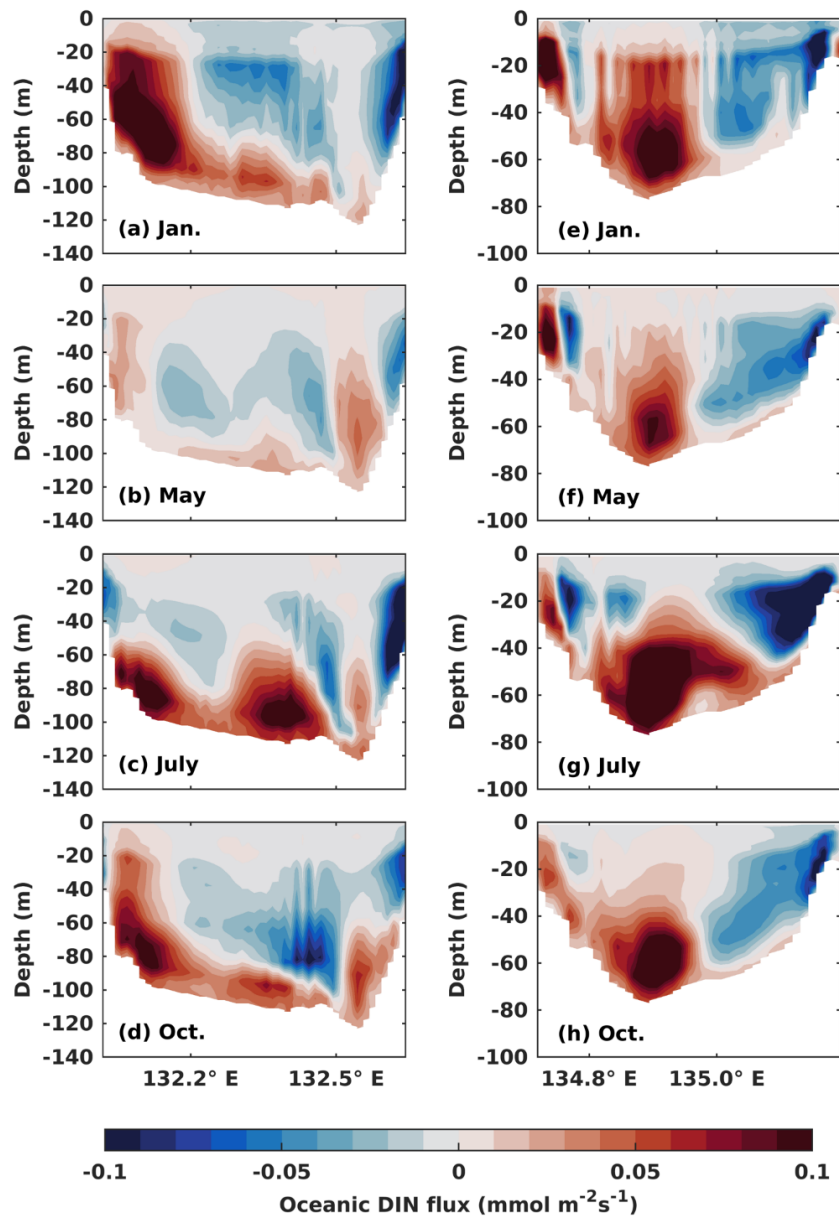
86

87 **Fig. S7.** Monthly mean observed and simulated PHY concentration ( $mg\ Chla\ m^{-3}$ ) for the upper  
 88 and lower layers of each subregion of SIS. The observation stations in each subregion are  
 89 presented in Fig. 1(c).

90 **S8** Temporal variation of  $(DIN_{ocean} + DIN_{river} +$   
 91  $DIN_{sediment})/DIN$



92  
 93 **Fig. S8.** (a-r) The monthly mean ratio of water column averaged  $(DIN_{ocean} + DIN_{river} +$   
 94  $DIN_{sediment})/DIN$  over the first three years. (s) The daily mean ratio of volume averaged  
 95  $(DIN_{ocean} + DIN_{river} + DIN_{sediment})/DIN$  over the first three years.

97 **S9 Oceanic DIN flux at the open boundaries**

98

99 **Fig. S9.** Monthly mean of oceanic DIN flux ( $mmol\ m^{-2}s^{-1}$ ) at the open boundary between the  
 100 Bungo Channel and the open ocean (a-d) and at the open boundary between the Kii Channel and  
 101 the open ocean (e-h). The red colors represent the oceanic DIN transported from the open ocean  
 102 into the Seto Inland Sea, and the blue colors represent the oceanic DIN transported from the Seto  
 103 Inland Sea into the open ocean.