Acceleration of Hydrological cycle with climate warming disrupts marine ecosystem function in the Arctic Ocean

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Outline

- Background
- Model and methods
- Physical changes with warming
- Marine biogeochemical responses
- Summary

With climate warming, major global changes in the Arctic include: high rate of warming; loss of sea ice; acceleration of hydrological cycle.

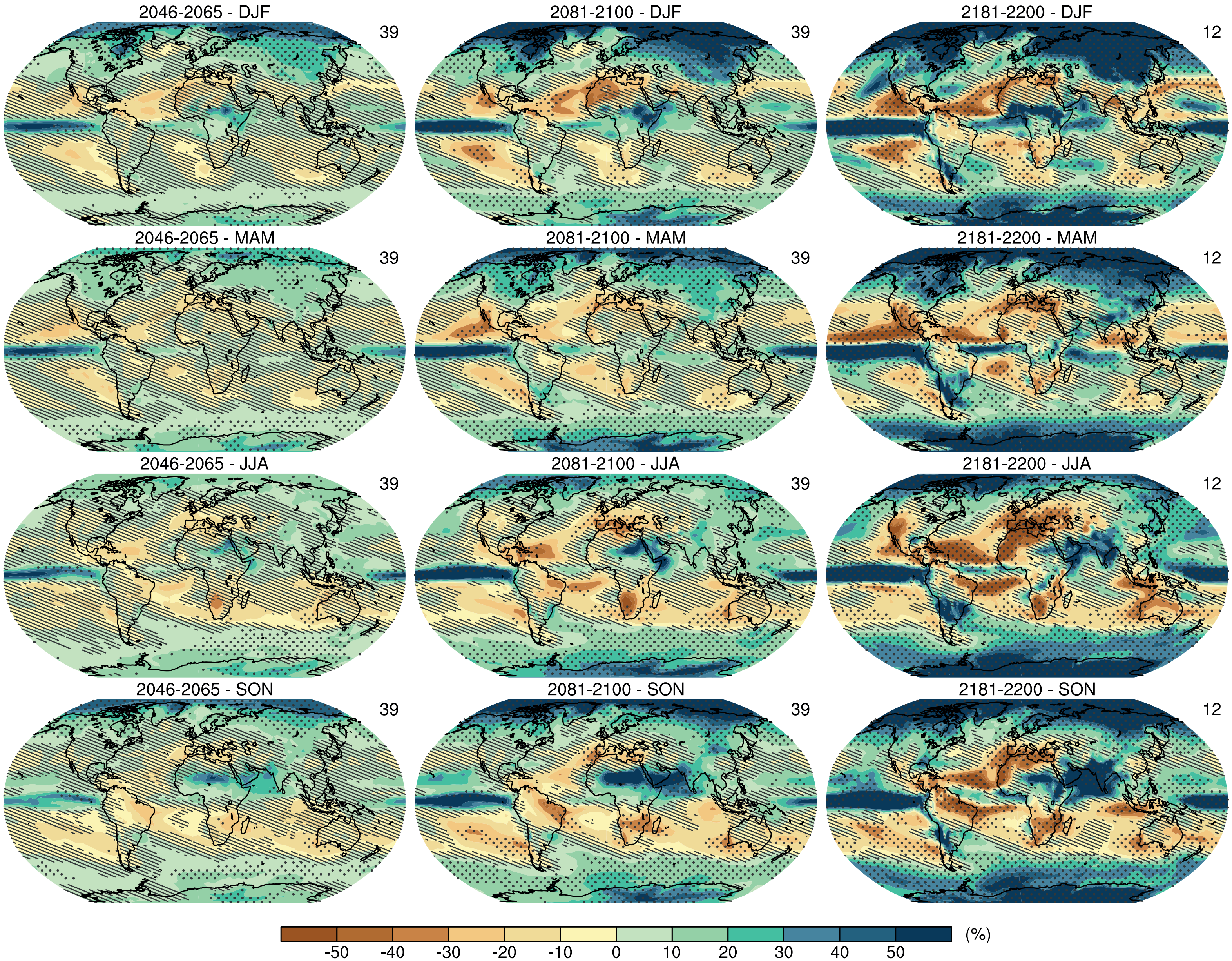
Continued increase in Arctic Ocean net primary production (Arrigo and Van Dijken (2015)

Net primary production (NPP, Tg C yr^{-1}) in different sectors of the Arctic Ocean, 1998–2012. Also included are the percent change in NPP estimated from the linear regression of the 15-year time series and the *p*-value for the regression of NPP against year. Significant changes are in bold.

	Greenland	Barents	Kara	Laptev	Siberian	Chukchi	Beaufort	Baffin
1998	150.2	102.3	49.3	39.6	23.7	28.7	43.3	30.5
1999	159.4	101.5	50.7	45.3	30.0	30.3	30.1	30.2
2000	140.7	124.0	59.9	48.4	31.9	24.1	22.5	32.3
2001	130.2	134.3	70.9	31.1	30.3	27.7	25.9	29.7
2002	145.9	118.0	48.5	44.1	35.2	30.9	25.6	30.1
2003	129.9	116.2	40.6	48.9	38.3	29.9	26.3	29.4
2004	140.5	130.2	66.7	26.2	41.1	34.9	34.1	26.6
2005	127.3	115.6	58.8	43.3	35.9	34.1	29.6	26.0
2006	143.0	148.2	61.1	43.3	30.1	25.1	31.8	33.4
2007	121.1	134.5	83.9	73.4	61.6	39.9	38.2	31.7
2008	137.2	122.1	88.7	44.1	49.2	36.8	40.5	29.3
2009	133.1	127.0	70.6	61.1	38.9	40.0	34.6	36.3
2010	141.4	143.9	74.5	70.3	47.4	29.9	35.9	34.4
2011	131.5	151.0	93.8	80.4	41.1	38.5	43.2	28.5
2012	113.6	129.8	81.3	73.3	42.8	30.5	48.9	32.4
Mean	136.3	126.6	66.6	51.5	38.5	32.1	34.0	30.7
% change	**–15.2**	**28.3**	**79.1**	**112.4**	**67.7**	**42.1**	**53.1**	8.3
p-value	0.013	0.006	0.001	0.002	0.008	0.042	0.019	0.310

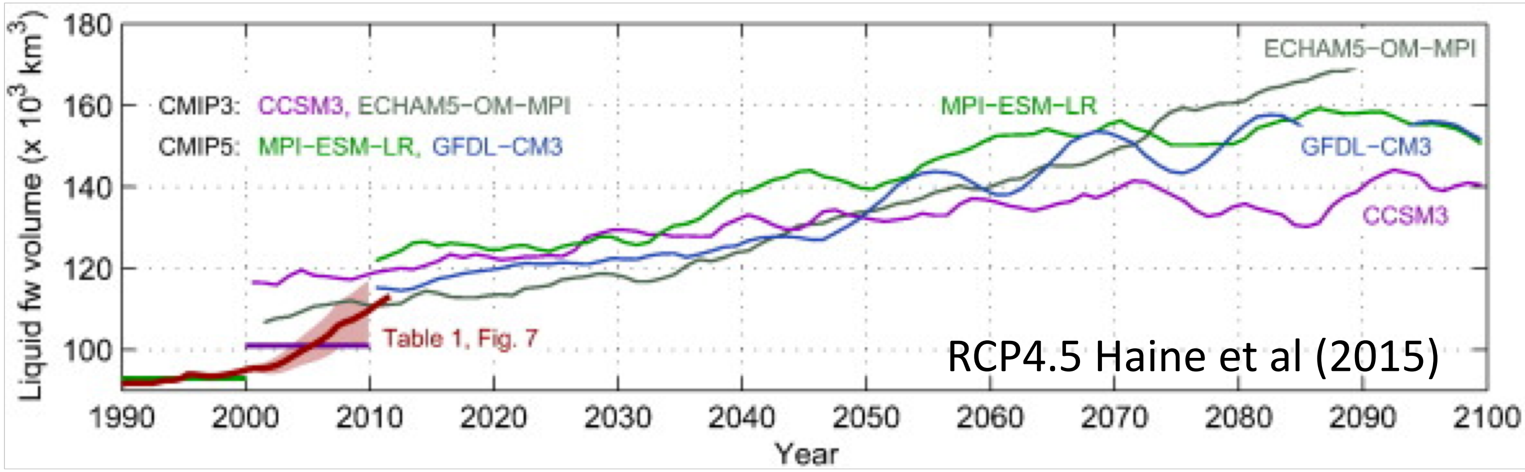
Dramatic declines in sea-ice cover in the Arctic Ocean in recent decades have the potential to fundamentally alter marine ecosystems.

Seasonal mean percentage precipitation change (RCP8.5)

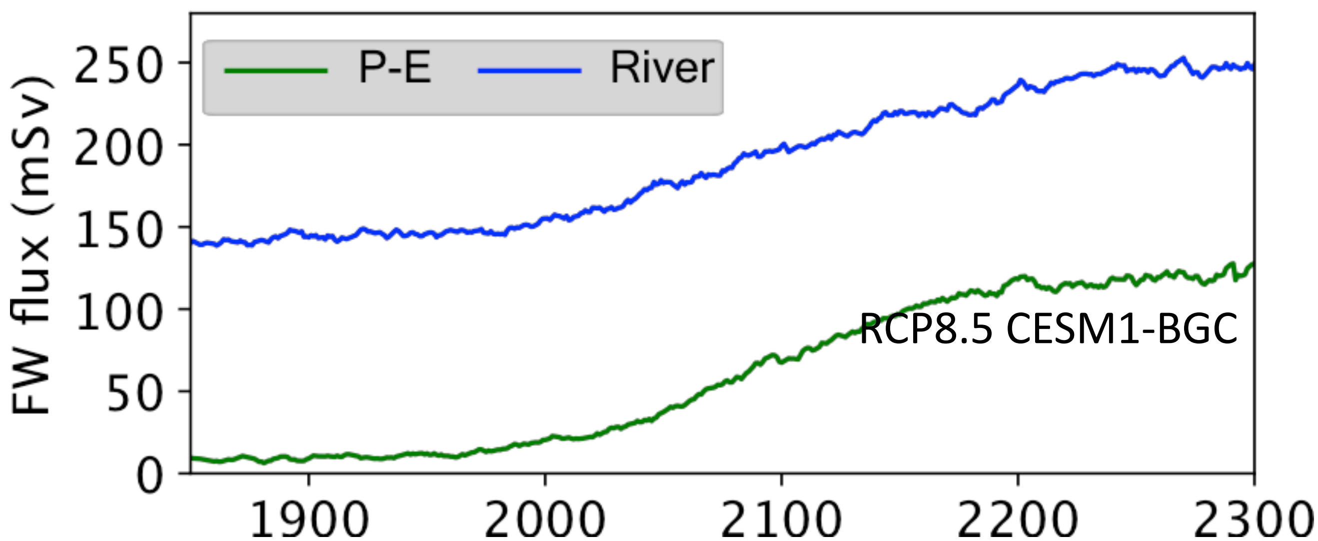


IPCC AR5

Liquid freshwater volume change in the Arctic Ocean



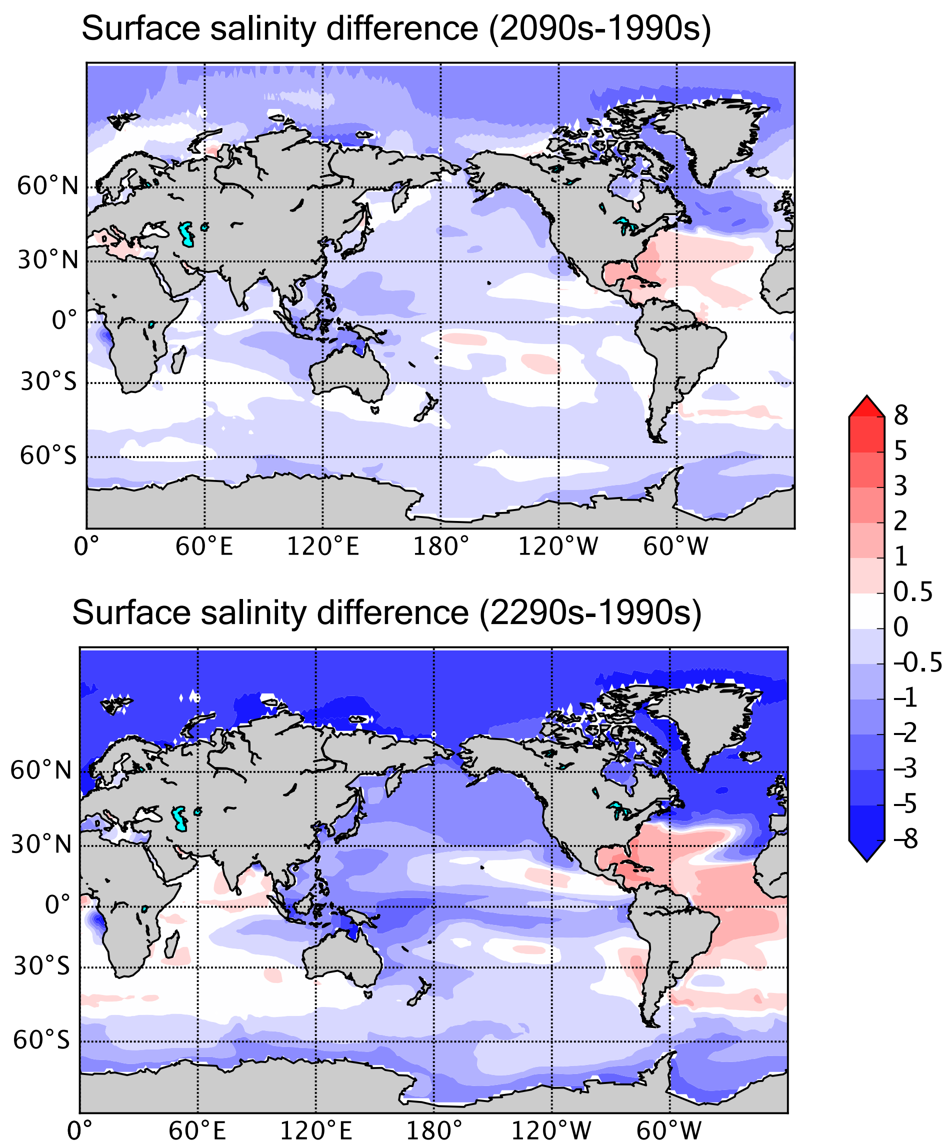
freshwater flux from river and P-E



What is the effect of the accelerating land and atmosphere hydrological cycles on the Arctic marine ecosystem?

Ocean salinity change is the clearest evidence of the change of hydrological cycle.

Arctic Ocean is freshened more than other basins



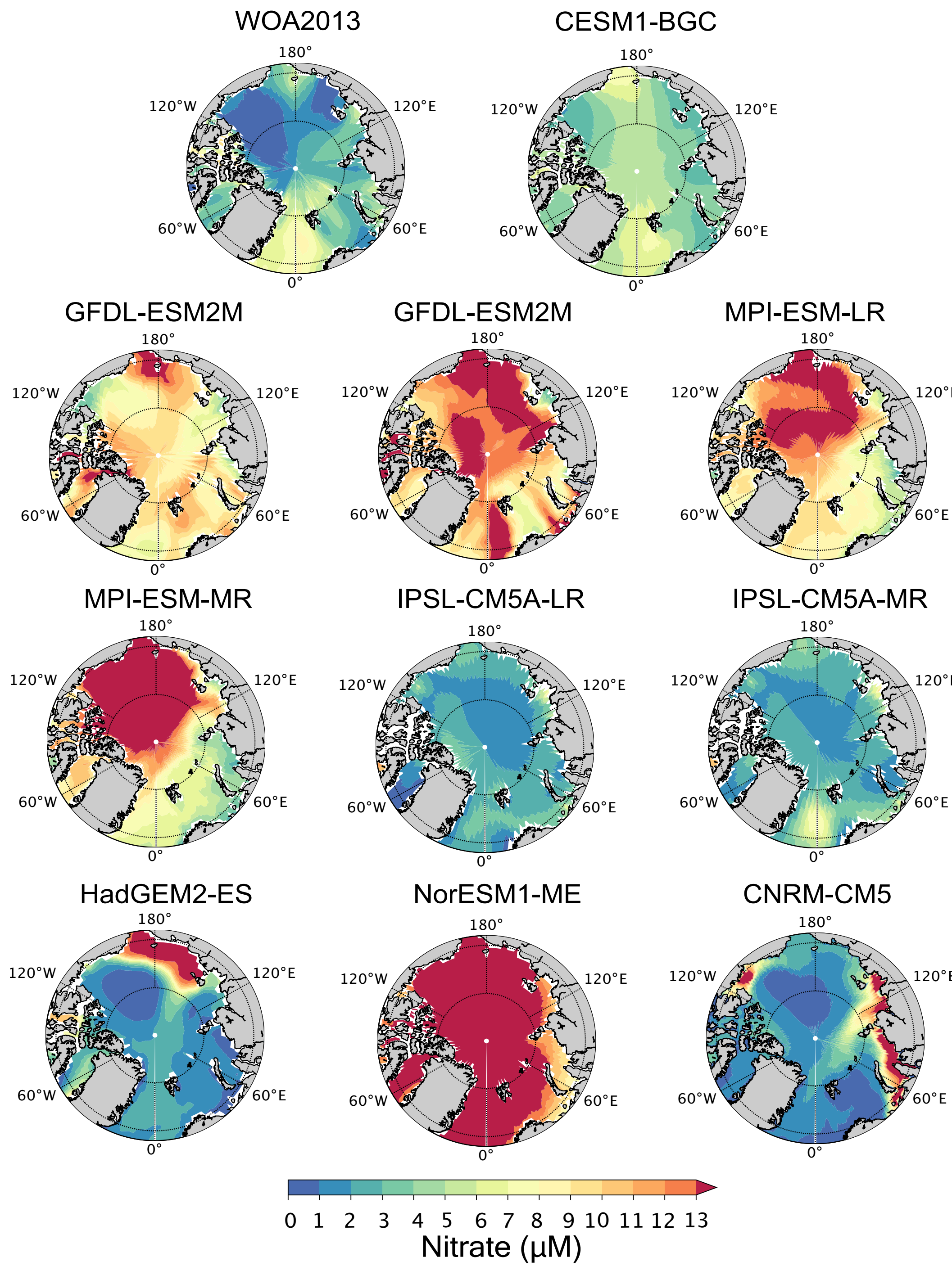
Model and Methods

Model simulation: CESM1-BGC (historical+RCP8.5)

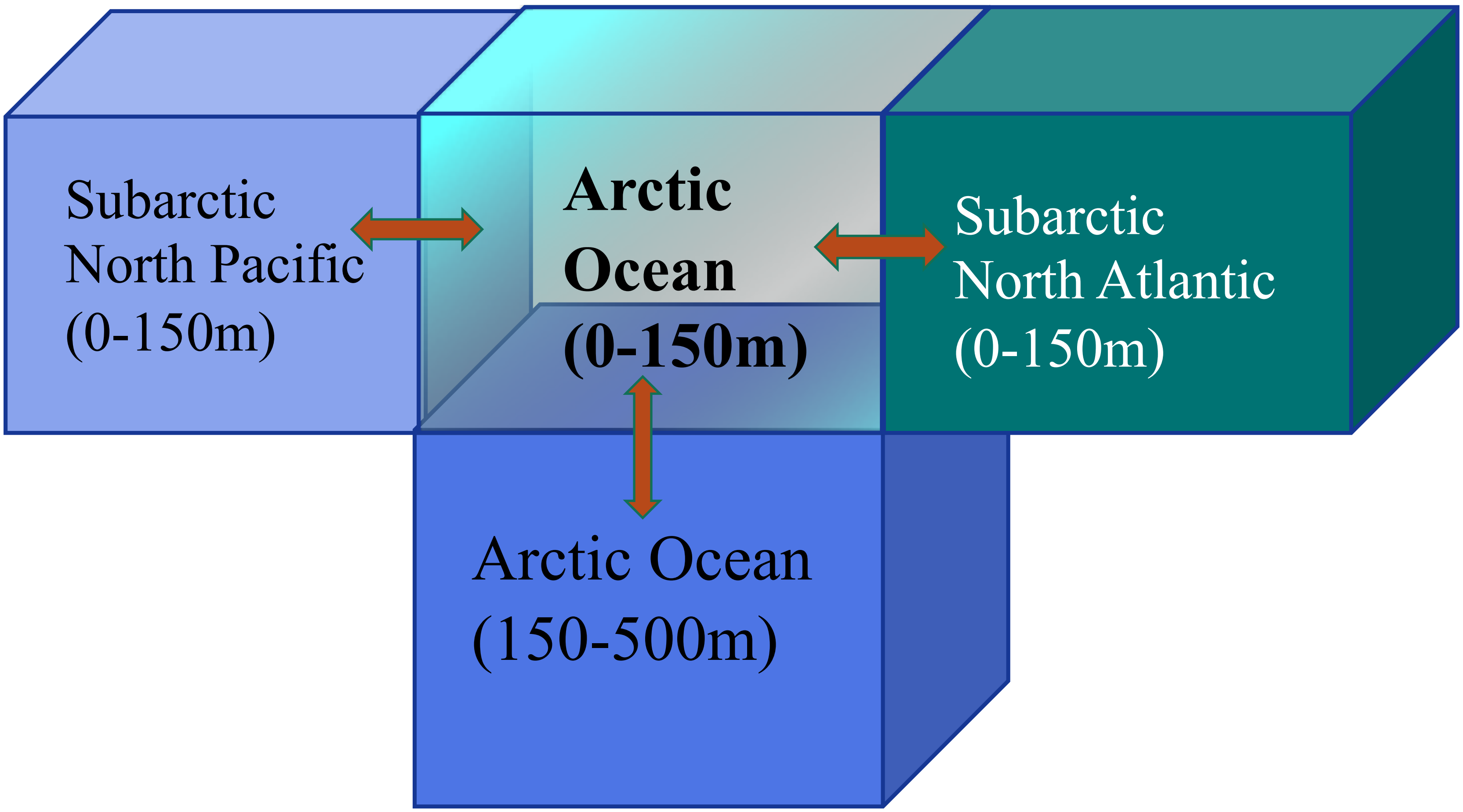
Box model: to complement the full ESM simulation

Regression model

- Annual mean data from CESM1-BGC long term simulation from 1850 to 2300 under the RCP8.5 scenario.



Box model

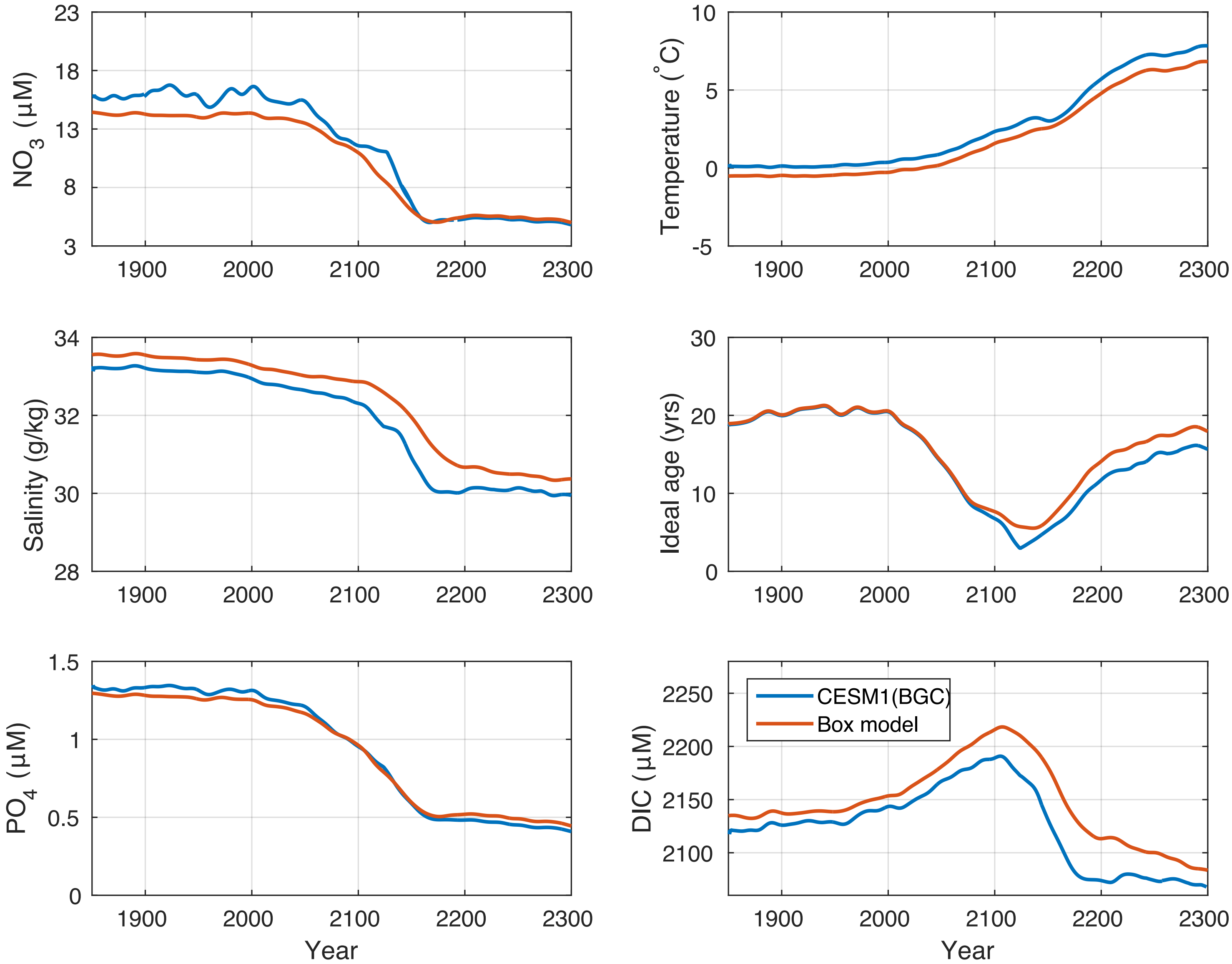

Subarctic
North Pacific
(0-150m)
Arctic
Ocean
(0-150m)
Subarctic
North Atlantic
(0-150m)
Arctic Ocean
(150-500m)

Box model equations

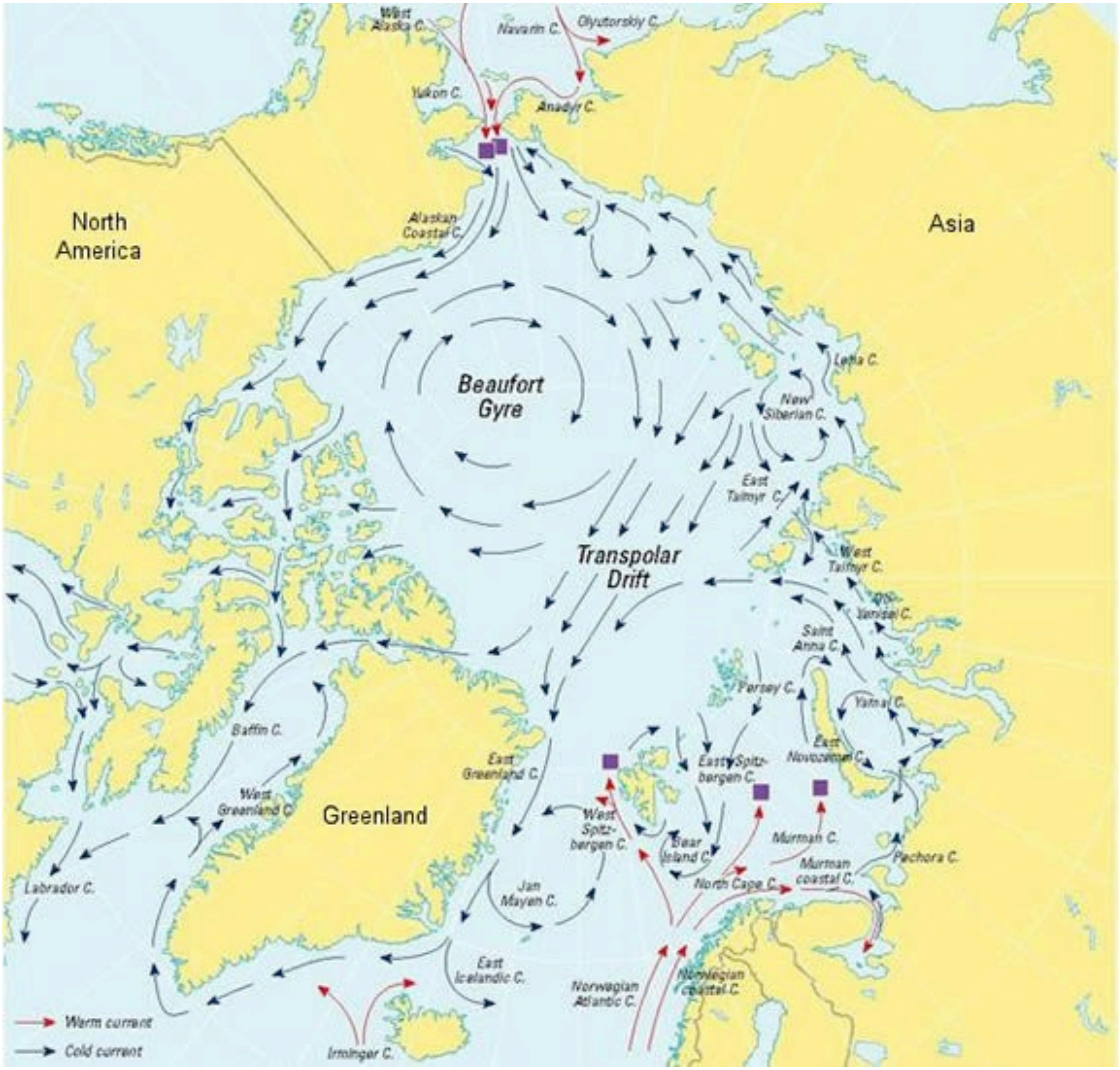
$$\begin{bmatrix} [O_2]-[O_2]_1 & [O_2]-[O_2]_2 & [O_2]-[O_2]_3 & [O_2]-[O_2]_4 \\ T-T_1 & T-T_2 & T-T_3 & T-T_4 \\ S-S_1 & S-S_2 & S-S_3 & S-S_4 \\ A-A_1 & A-A_2 & A-A_3 & A-A_4 \\ [PO_4]-[PO_4]_1 & [PO_4]-[PO_4]_2 & [PO_4]-[PO_4]_3 & [PO_4]-[PO_4]_4 \end{bmatrix} \begin{bmatrix} k_1 \\ k_2 \\ k_3 \\ k_4 \end{bmatrix} =$$

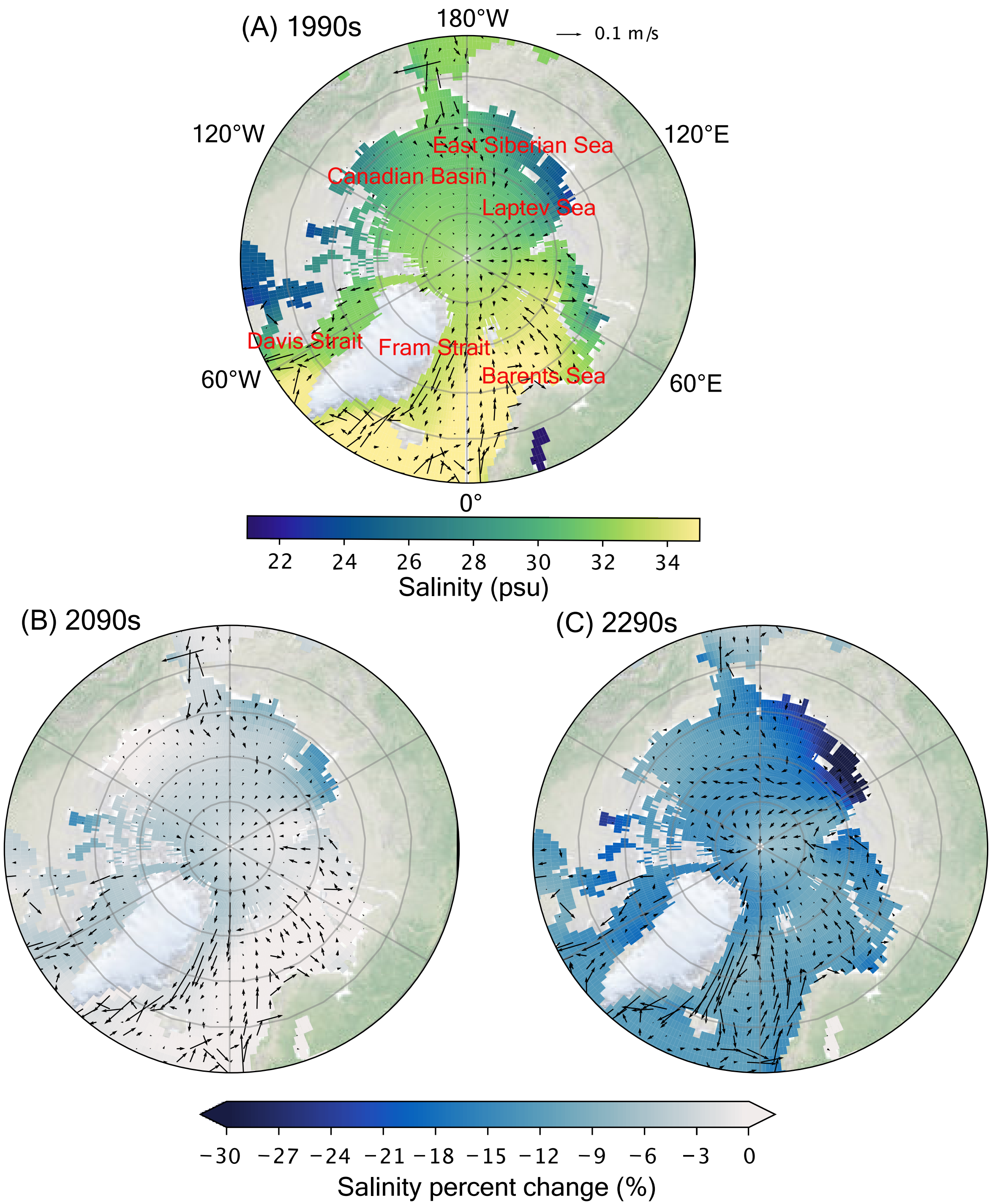
$$\frac{d}{dt}\begin{bmatrix} [O_2] \\ T \\ S \\ A \\ PO_4 \end{bmatrix} + \begin{bmatrix} -R \\ 0 \\ 0 \\ 0 \\ R/r_{O_2P} + D/r_{NO_3P} \end{bmatrix}$$

Box model validation

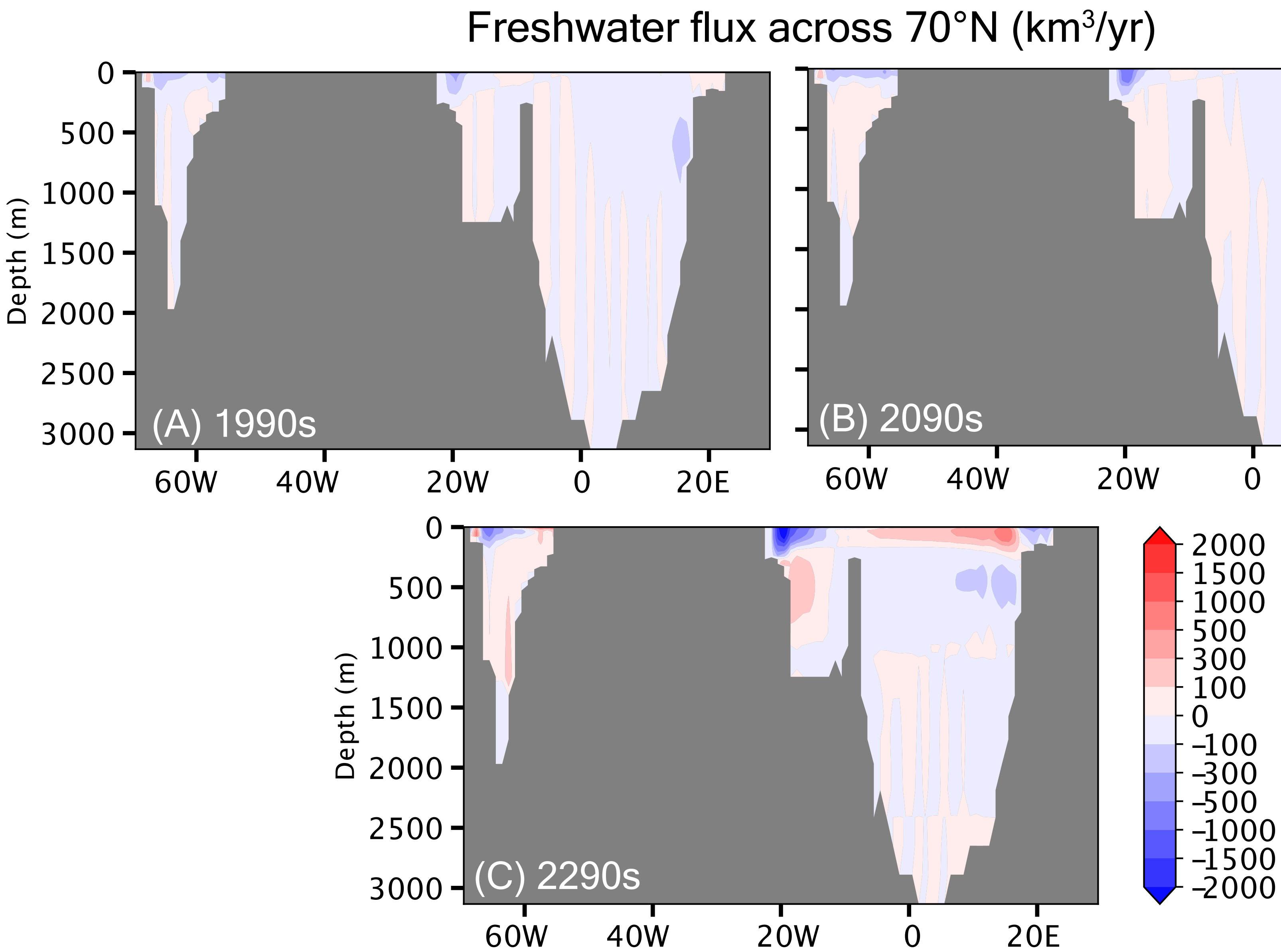


Arctic Ocean surface circulation



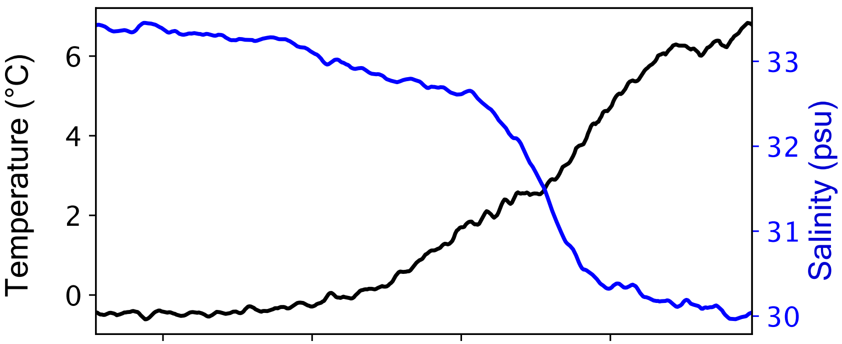


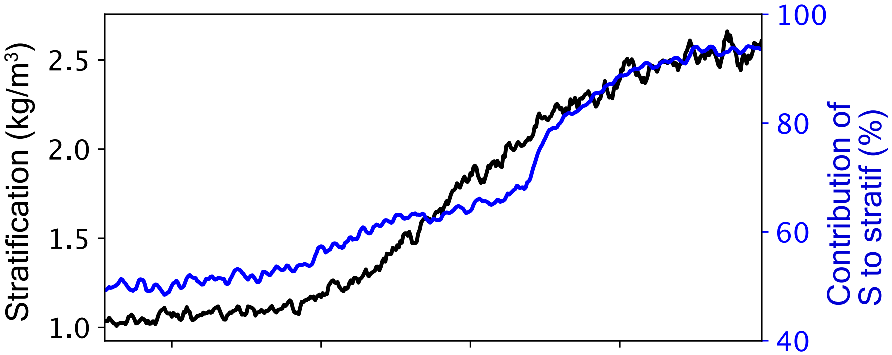
(A) 1990s
180°W
0.1 m/s
120°W
120°E
East Siberian Sea
Canadian Basin
Laptev Sea
Davis Strait
Fram Strait
Barents Sea
60°W
60°E
0°
22
24
26
28
30
32
34
Salinity (psu)
(B) 2090s
(C) 2290s
−30
−27
−24
−21
−18
−15
−12
−9
−6
−3
0
Salinity percent change (%)



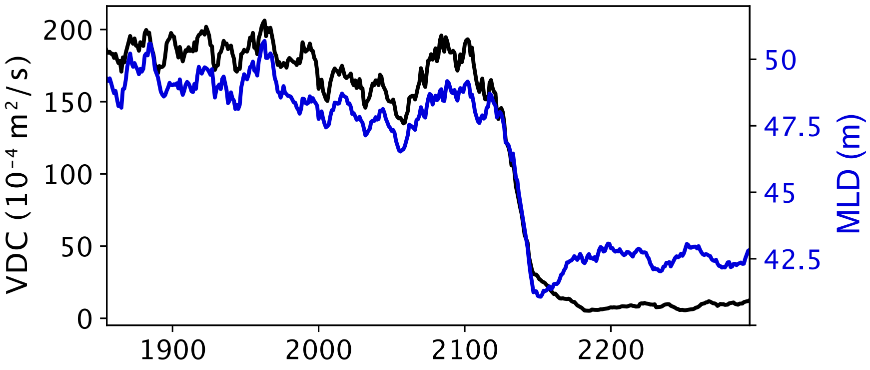
Freshwater flux across 70°N (km³/yr)
Depth (m)
0
500
1000
1500
2000
2500
3000
60W
40W
20W
0
20E
(A) 1990s
(B) 2090s
(C) 2290s
2000
1500
1000
500
300
100
0
–100
–300
–500
–1000
–1500
–2000

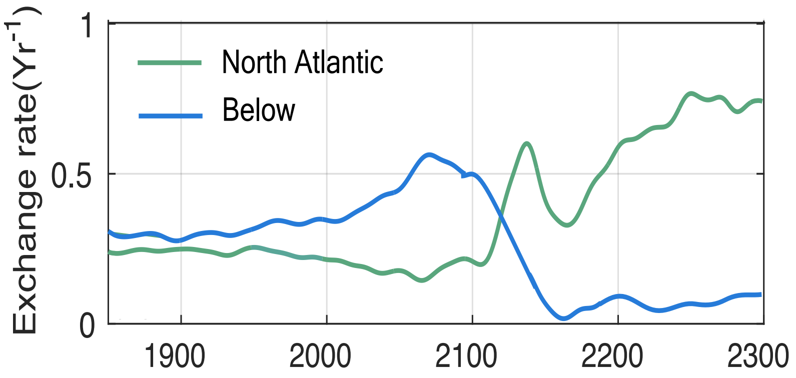
Growing freshwater inputs increase stratification



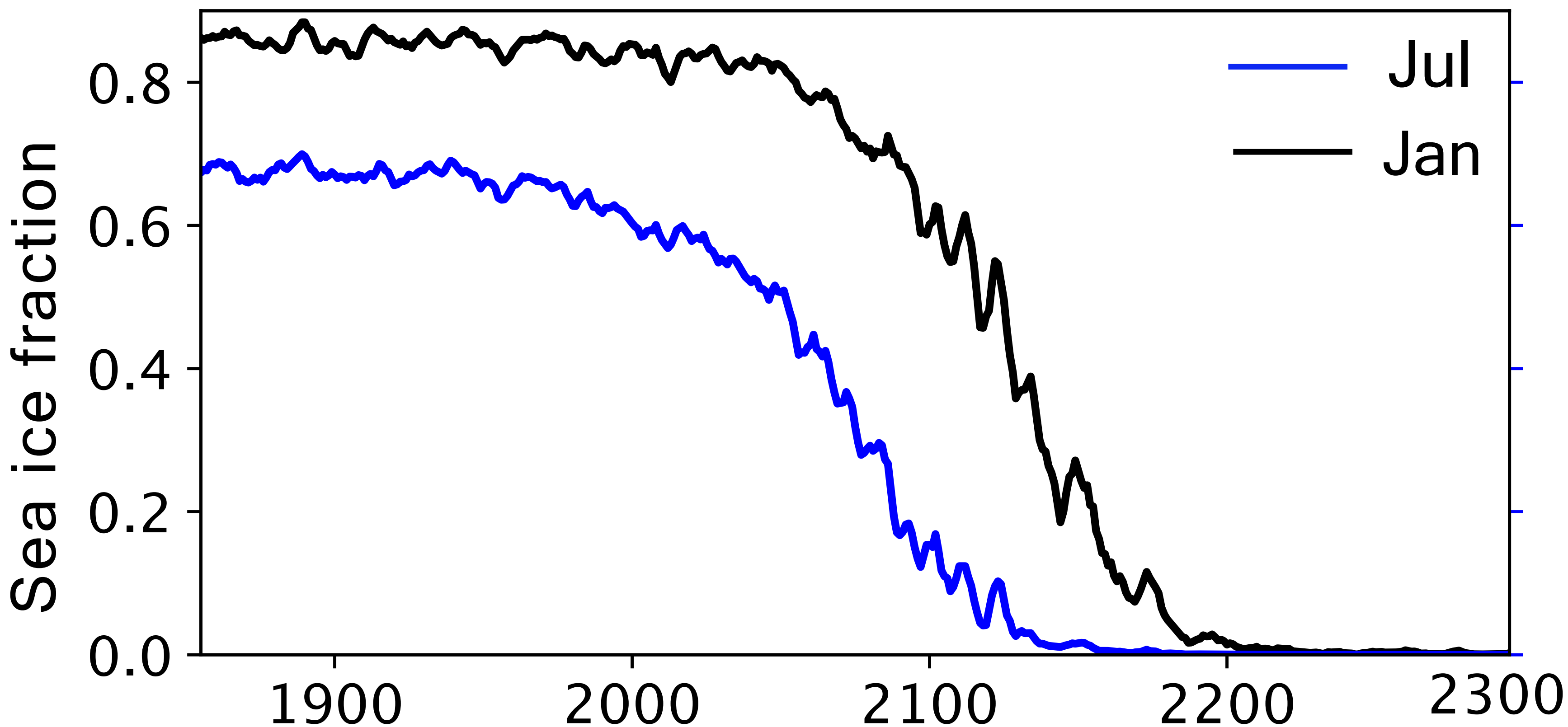


Warming and freshening increases stratification with more contribution from salinity



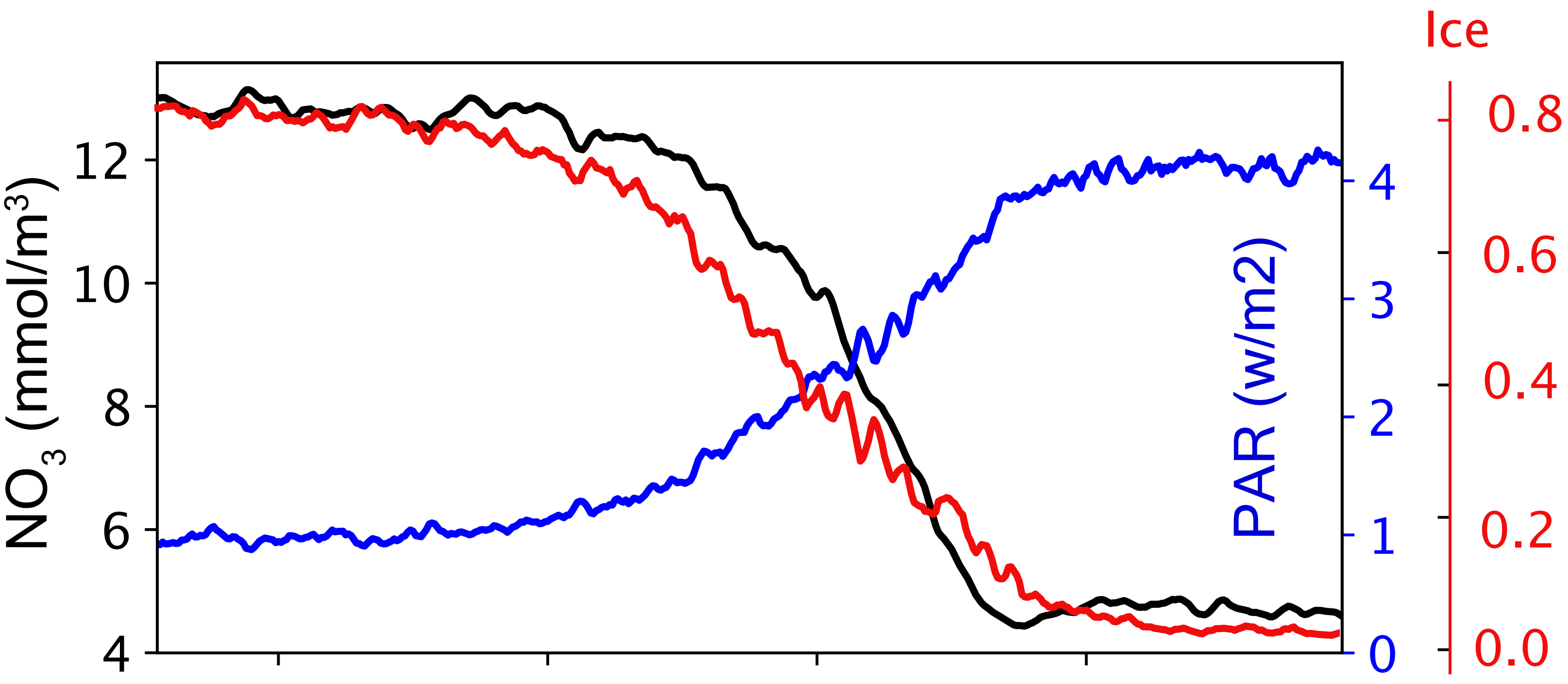


Vertical diffusivity is weakened and exchange with the North Atlantic is speeding up.

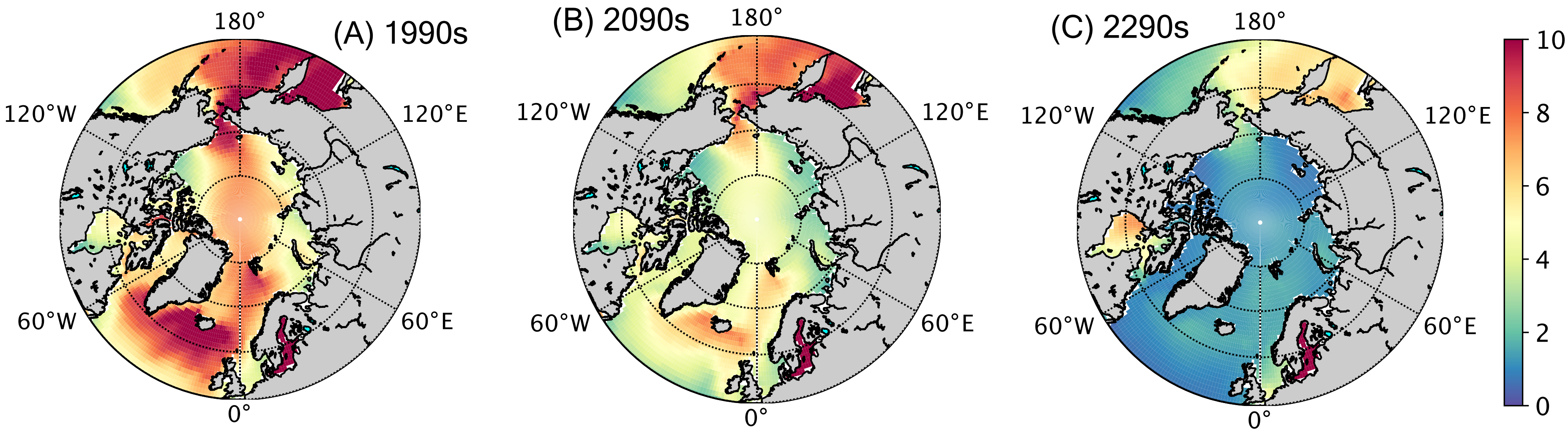


Jul
Jan
Sea ice fraction
0.0
0.2
0.4
0.6
0.8
1900
2000
2100
2200
2300

Increasing stratification depletes surface nutrients

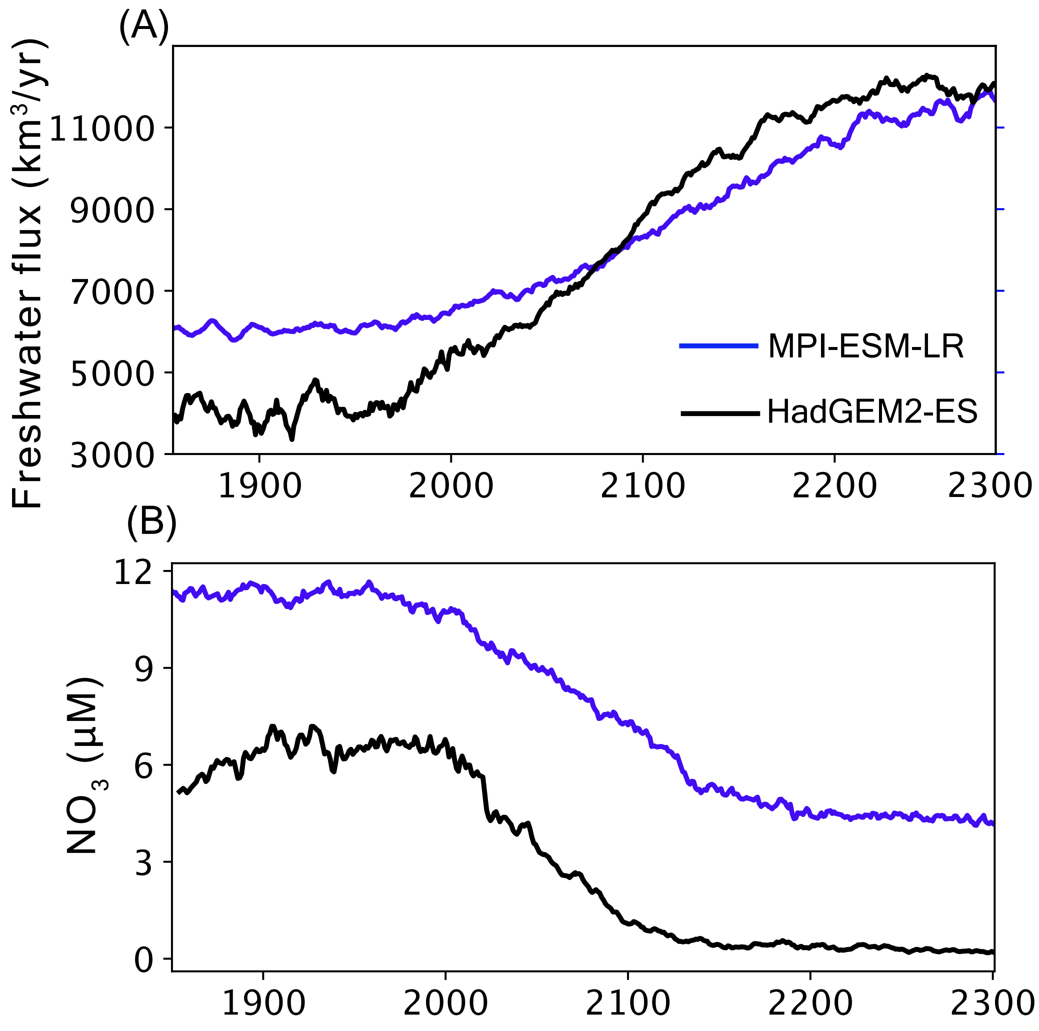


Melting of sea ice increases light availability

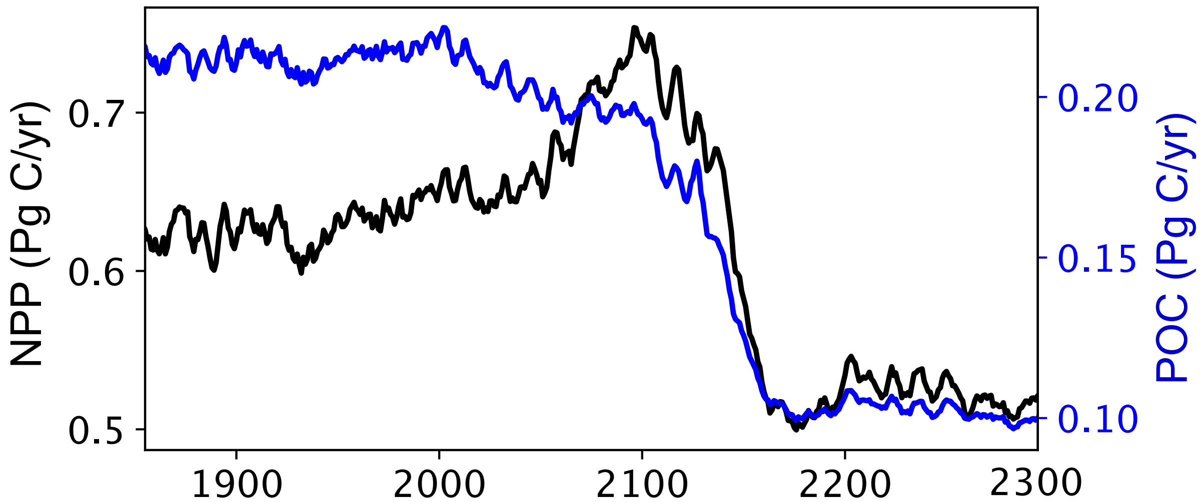


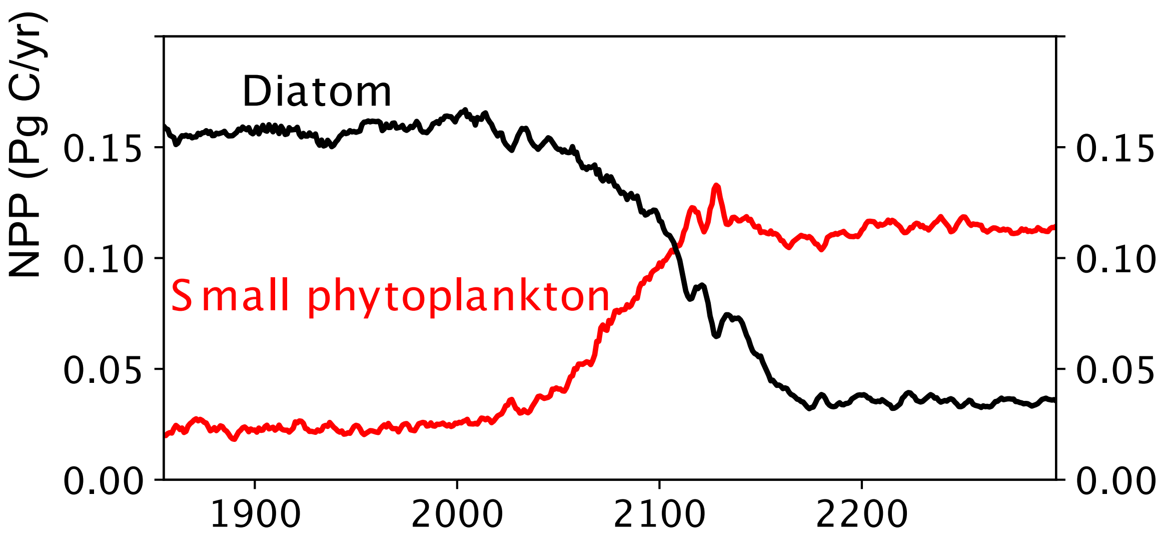
lateral supply of nutrients is weakened climate with warming

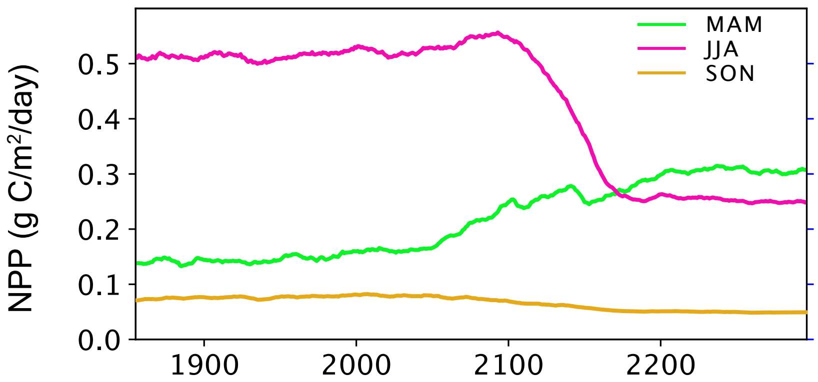
Freshwater lens effect is observed in other CMIP5 models

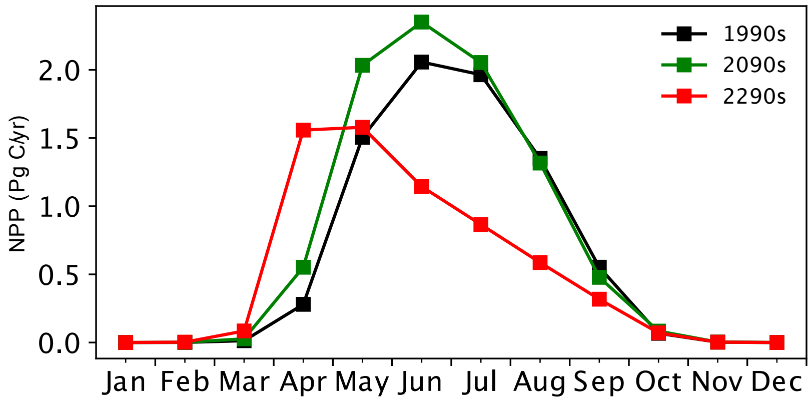


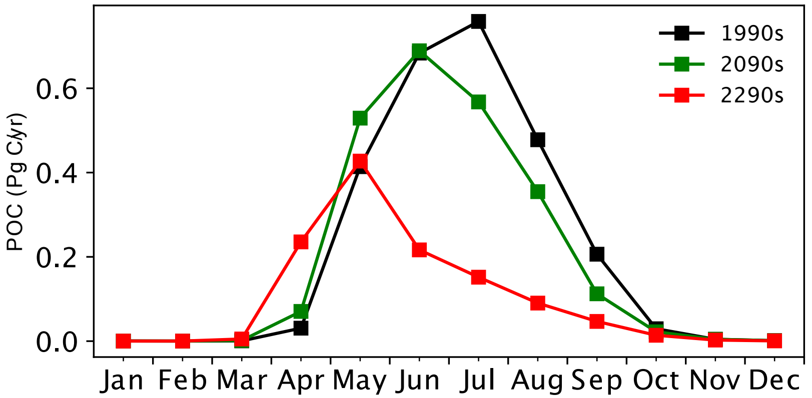
Nutrient limitation reduces productivity, export production and drastically changes phytoplankton community composition



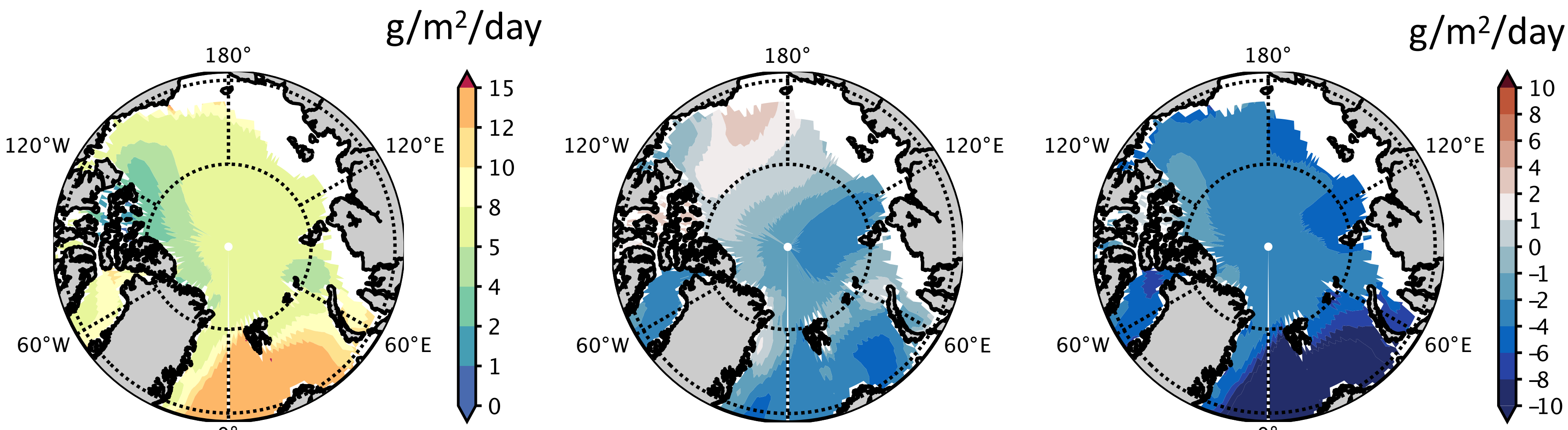



NPP (g C/m²/day)
0.0
0.1
0.2
0.3
0.4
0.5
1900
2000
2100
2200
MAM
JJA
SON


NPP (Pg C/yr)
0.0
0.5
1.0
1.5
2.0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
1990s
2090s
2290s


POC (Pg C/yr)
0.0
0.2
0.4
0.6
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
1990s
2090s
2290s

Export production declines by more than 50%



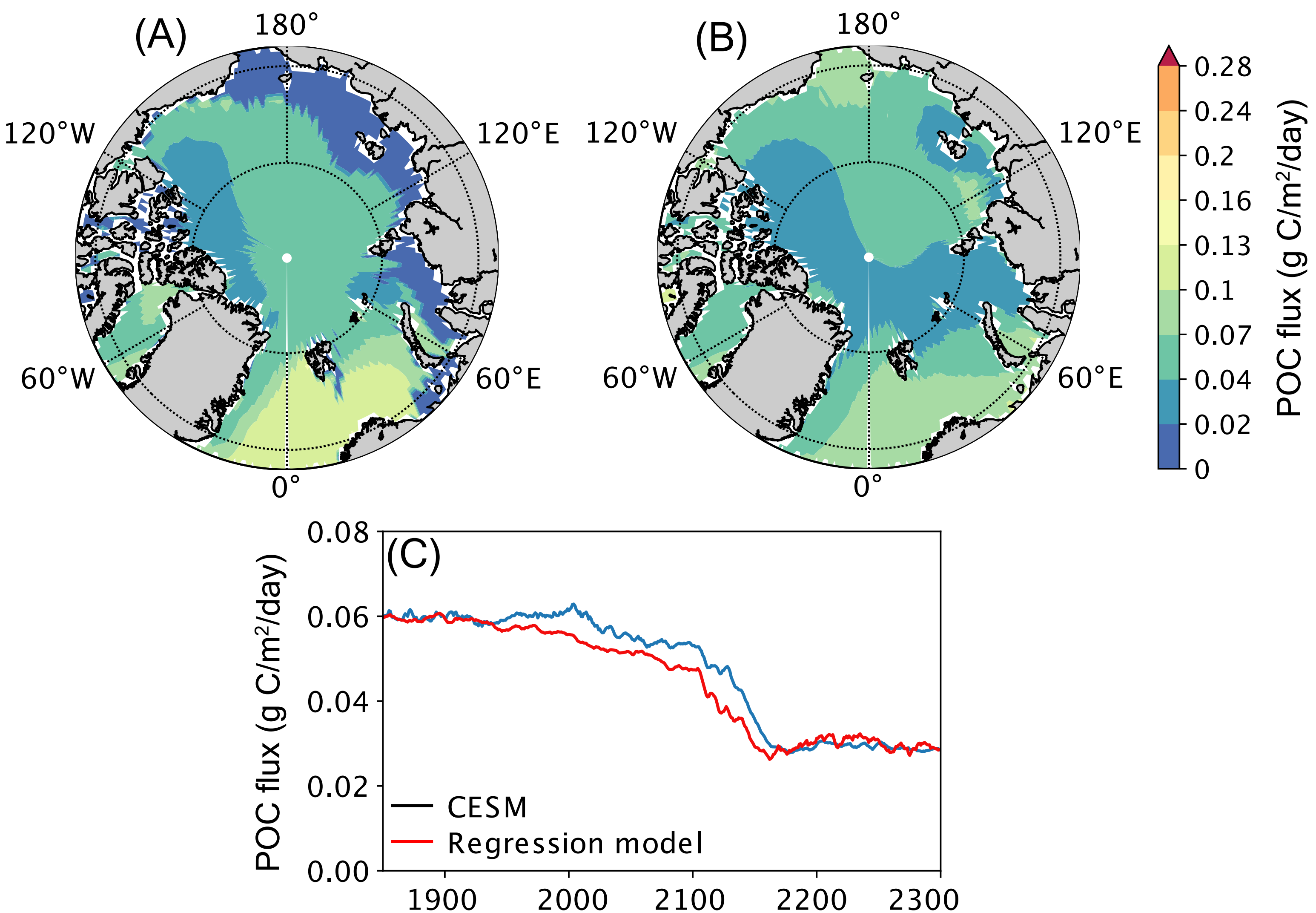
1990s 2090s-1990s 2290s-1990s

Regression model

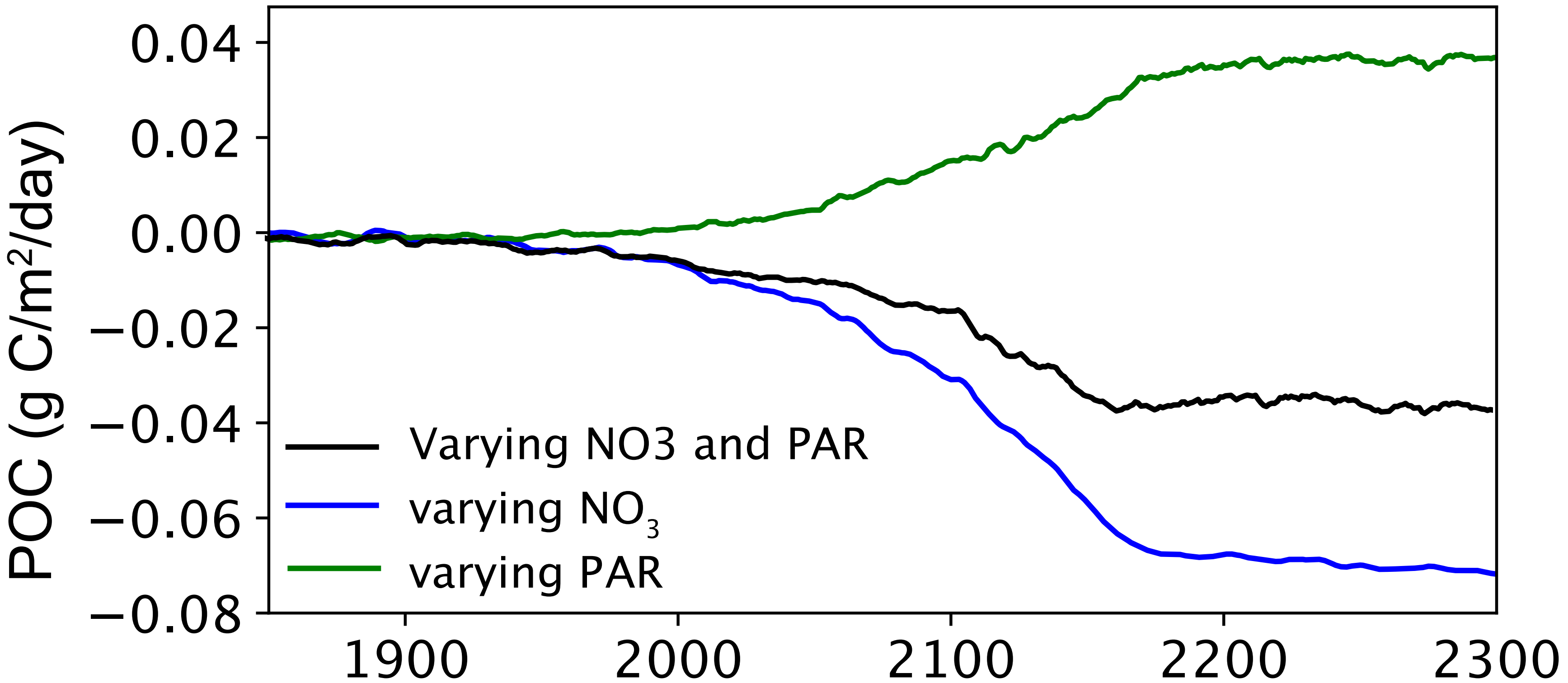
$$POC(x,t) = a + b \times PAR(x,t) + c \times NO_3(x,t)$$

- A multiple linear regression model for export production (POC flux) is set up as a function of model surface PAR and mean NO_3 in 0-100 m.
- We use the year 1990 to build up the regression model, which produces the coefficients of $a =$ -0.05 g C m^{-2} day^{-1}, $b =$ 0.009 g C day^{-1} W^{-1}, $c =$ 0.006 g C m day^{-1} $mmol^{-1}$.

Regression model validation



Contribution of light and NO3 to the change of POC



Summary

- Polar amplification of hydrological cycle creates a lens of freshwater in the Arctic.
- Continuous freshwater runoff increases vertical stratification of the Arctic Ocean and accelerates water exchange with the North Atlantic, significantly reducing nutrients in the euphotic zone.
- POC declines by 53%, suggesting high trophic levels are at risk for loss of food chain.
- A preeminent example of land-ocean coupling drive large biogeochemical changes.
- Greenland ice melting makes this worse!
- An important next step in this context is to strengthen the representation of terrestrial nutrient flows (including mineralization and nitrification), subsequent loading of nutrients in rivers, and ultimately nutrient transport through river, estuarine, and coastal ecosystems to the open ocean.