Air emissions from shipping stimulate oceanic phytoplankton growth

Chao Zhang[1,2], Zongbo Shi[2], Huiwang Gao[1]*, and Yan Zhang[3]*

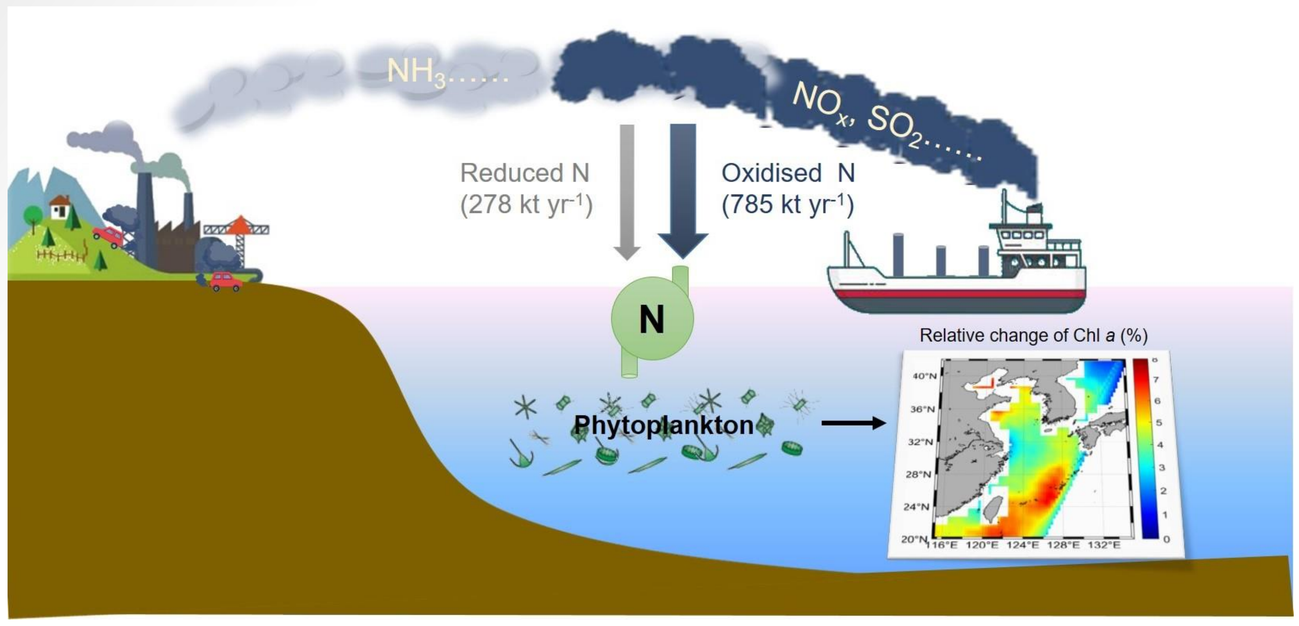
1 Key Laboratory of Marine Environment and Ecology, Ministry of Education of China, Ocean University of China, Qingdao 266100, China;

2 School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham B152TT, UK;

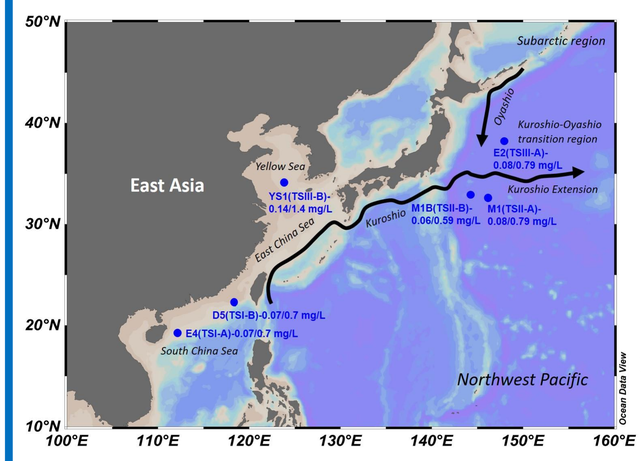
3 Shanghai Key Laboratory of Atmospheric Particle Pollution and Prevention (LAP3), Fudan University, Shanghai 200092, China

zhangchao@ouc.edu.cn

Graphic Abstract

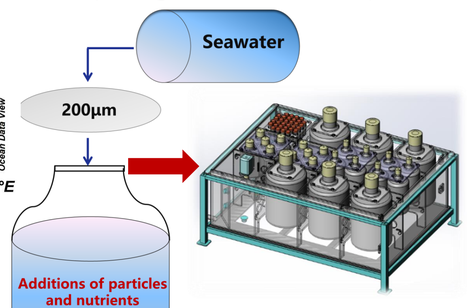


Methods



Locations of the sampling stations and added concentrations of ship emitted particle (SEP) for microcosm experiments

Particle sampling system
(Zhang et al., ES&T, 2018)



Incubation process

Results and Discussion

I. Response of phytoplankton in Chl *a* to SEP additions

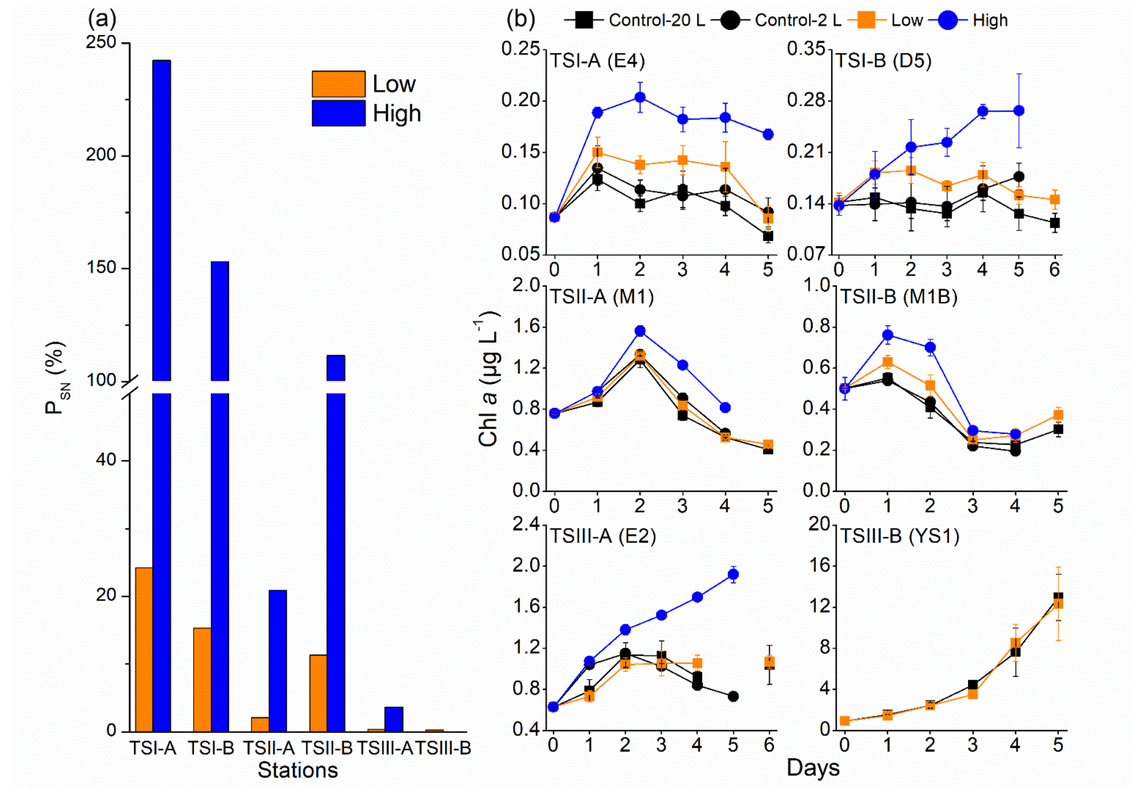


Fig. 1. (a) Proportion of N supplied by SEPs relative to N stocks in the baseline seawater (P_{SN}, [N supplied by SEP additions/N stocks in the baseline seawater]×100) for low and high SEP treatments at the sampling stations. (b) Responses of total Chl *a* to low and high SEP additions during the incubation experiments

Additions of SEP generally stimulated phytoplankton growth.

II. Key nutrient determining phytoplankton growth

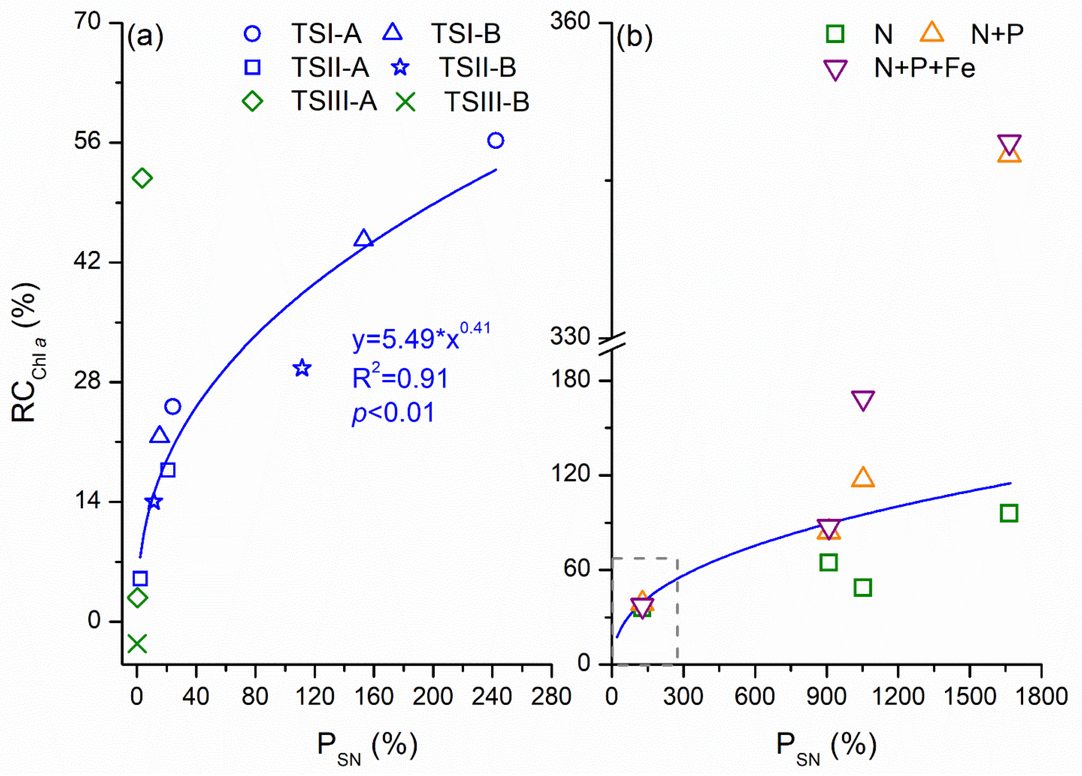


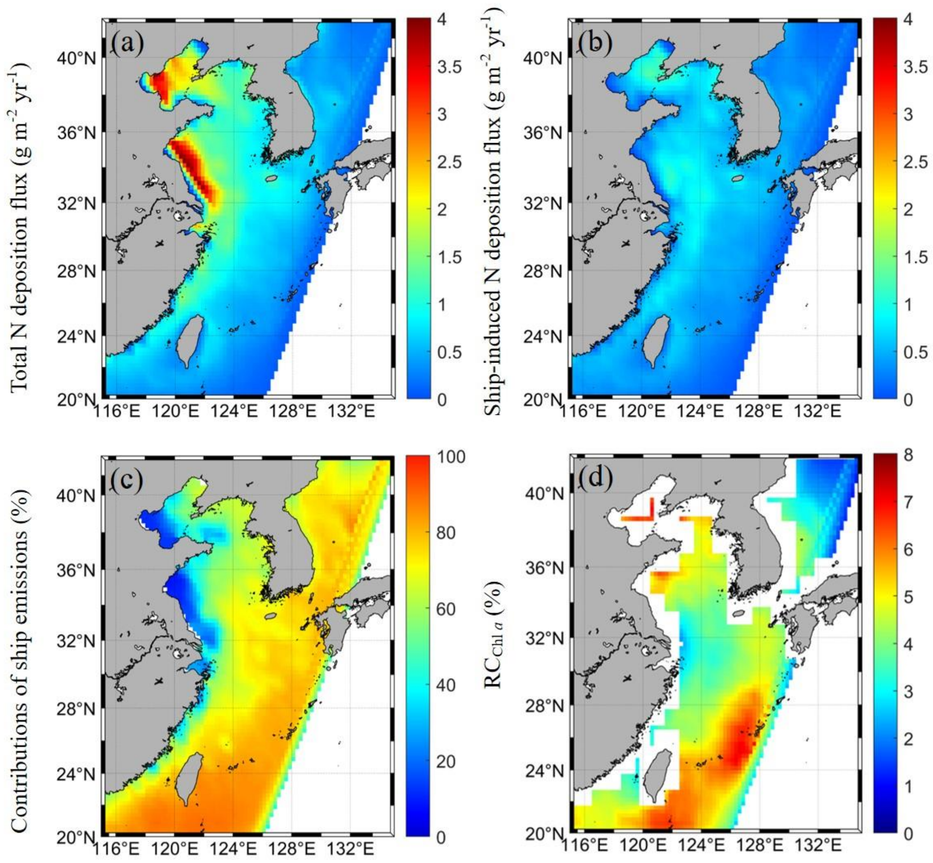
Fig. 2. Relationships between relative change in Chl *a* ($RC_{Chl\ a}$, ([Mean in SEP treatments-Mean in the control]/Mean in the control)×100) and P_{SN} for (a) SEP and (b) nutrient (N, N+P, and N+P+Fe) treatments. In (b), the dashed panel region corresponds to the fitted curve in (a). The P_{SN} (x-axis) in (b) corresponds, in increasing order, to stations TSII-A (M1), TSII-B (M1B), TSI-B (D5), and TSI-A (E4).

Nitrogen supplied by SEP plays an important role in stimulating phytoplankton growth.

III. Seasonal and annual N deposition fluxes induced by ship emissions and all anthropogenic sources (kt N yr^{-1}).

Seasons	All anthropogenic sources			Ship-induced oxidised N deposition (Direct)	Ship-induced reduced N deposition (Indirect)	Contribution (%) of ship-induced oxidised N deposition to total N deposition	Contribution (%) of ship-induced reduced N deposition to total N deposition
	Total N deposition	Oxidised N deposition	Reduced N deposition				
Spring	417.1	237.0	180.1	178.2	63.4	42.7	15.2
Summer	360.7	220.1	140.6	162.8	35.3	45.1	9.8
Autumn	418.3	255.1	163.2	176.8	48.4	42.2	11.6
Winter	644.6	359.5	285.0	267.2	130.9	41.4	20.3
Annual	1840.7	1071.8	768.9	785.0	278.1	42.6	15.1

IV. Impact of ship emissions on the northwest Pacific Ocean (NWPO).



Combination of Model (WRF–CMAQ), incubation experiment, and observational data.

Fig. 3. Annual N (including oxidised N and reduced N) deposition fluxes in the NWPO from (a) all anthropogenic sources, (b) ship emissions, and (c) contributions of ship emissions to the annual N deposition fluxes. (d) Relative change in Chl *a* ($RC_{Chl\ a}$), based on the empirical equation obtained from the incubation experiments as shown in Fig. 2a, in surface seawater owing to ship-induced N deposition.

$RC_{Chl\ a}$ values ranged from 1.0% to 7.1% (4.2% on average) in the study region.

Take home message

- Nitrogen supplied by SEPs stimulated phytoplankton growth in the NWPO;
- Ship-induced nitrogen made a considerable contribution to nitrogen deposition flux;
- Shipping traffic had an important impact on primary production across the NWPO.

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