INI2016 in Melbourne
Dec 4-8, 2016

Sponsored by NSFC National Natural Science Foundation of China

Anthropogenic aerosol deposition reduces the sensitivity of oceanic productivity to warming

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1 Motivation

EDITORIAL

Oceans and Earth's habitability

On 8 June, the United Nations Educational, Scientific and Cultural Organization (UNESCO) celebrates World Oceans Day, a fitting occasion to remind ourselves of the essential role of the oceans in making Earth a habitable planet. We have had an official day of celebration for the oceans only since December 2008. In contrast, Earth Day has been celebrated every year since 1970. Conceived by U.S. Senator Gaylord Nelson in the aftermath of the 1969 Santa Barbara oil spill, Earth Day became a focus for the growing environmental movement (it became an international event in 1990) and the catalyst that led to the Clean Air, Clean Water, and Endangered Species Acts in the United States. Imagine what might be accomplished if World Oceans Day could similarly inspire actions for improving the state of the oceans worldwide.

Many environmental crises play out in the ocean in slow motion and are not currently addressed by the protections that are in place. For example, oceans absorb about 30% of the heat building up from the release of excess greenhouse gases. The system of Argo profiling floats indicates that the heat content of the upper 2000 meters of the ocean has increased by about 8×10^{22} joules over the past 10 years. The yearly increase in heat in the ocean is roughly equivalent to 100 times the average annual energy consumption of the United States (100 quadrillion BTU ~ 10^{22} joules). We have so much to learn about the microbiota in the upper ocean (see the Zero Oceans special section on p. 975), and the effect that this added heat will have on them is entirely unknown. It is likely to have deleterious impacts on fisheries already stressed from overharvesting. And yet, if it were not for the large amount of heat that the oceans absorb, the amount of global warming we would otherwise experience would be truly intolerable.

It is not just excess heat that the oceans absorb. As CO_2 is released to the atmosphere from the burning of fossil fuels, about a quarter is absorbed by the ocean, lowering its pH. Since the start of the Industrial Revolution, ocean acidity has increased by 30%, with negative repercussions for many organisms, including those that build their shells from calcium carbonate minerals. Such organisms are essential links in marine food webs and the foundation for very profitable fisheries. As the oceans become more saturated with CO_2, their ability to mitigate the buildup of CO_2 in the atmosphere by absorbing it will decrease, and greenhouse warming will accelerate.

The oceans help to moderate climate, keeping tropical latitudes cool and temperate latitudes warm through major circulation systems that transport large amounts of equatorial heat poleward. The ongoing warming could change ocean circulation in complex ways, a problem worth addressing at the UN Framework Convention on Climate Change (COP21) in December. World Oceans Day's focus on the ocean's role in the climate system will expand global awareness just ahead of this summit.

"...World Oceans Day could... inspire actions for improving the state of the oceans worldwide."

When scientists search for extraterrestrial worlds that might be habitable, they look for water and signs of an ocean. I find it ironic that in the most recent budget for the National Aeronautics and Space Administration, the U.S. Congress is willing to explore these distant worlds but slashes funding to monitor Earth, the one planet we know is suitable for life as we know it.

With every other breath you take this 8 June, take a moment to thank the ocean for supplying half of your oxygen and for all the other ways in which it makes Earth a habitable planet. It is time to start valuing the ocean and stop using it as a dump for waste heat, CO_2, sewage, pollutants, and other trash.

– Marcia McNutt

Marcia McNutt
Editor-in-Chief
Science Journals

SCIENCE

Published by AAAS

Ocean is a large sink of the Earth's carbon emission, sustaining the habitability of Earth

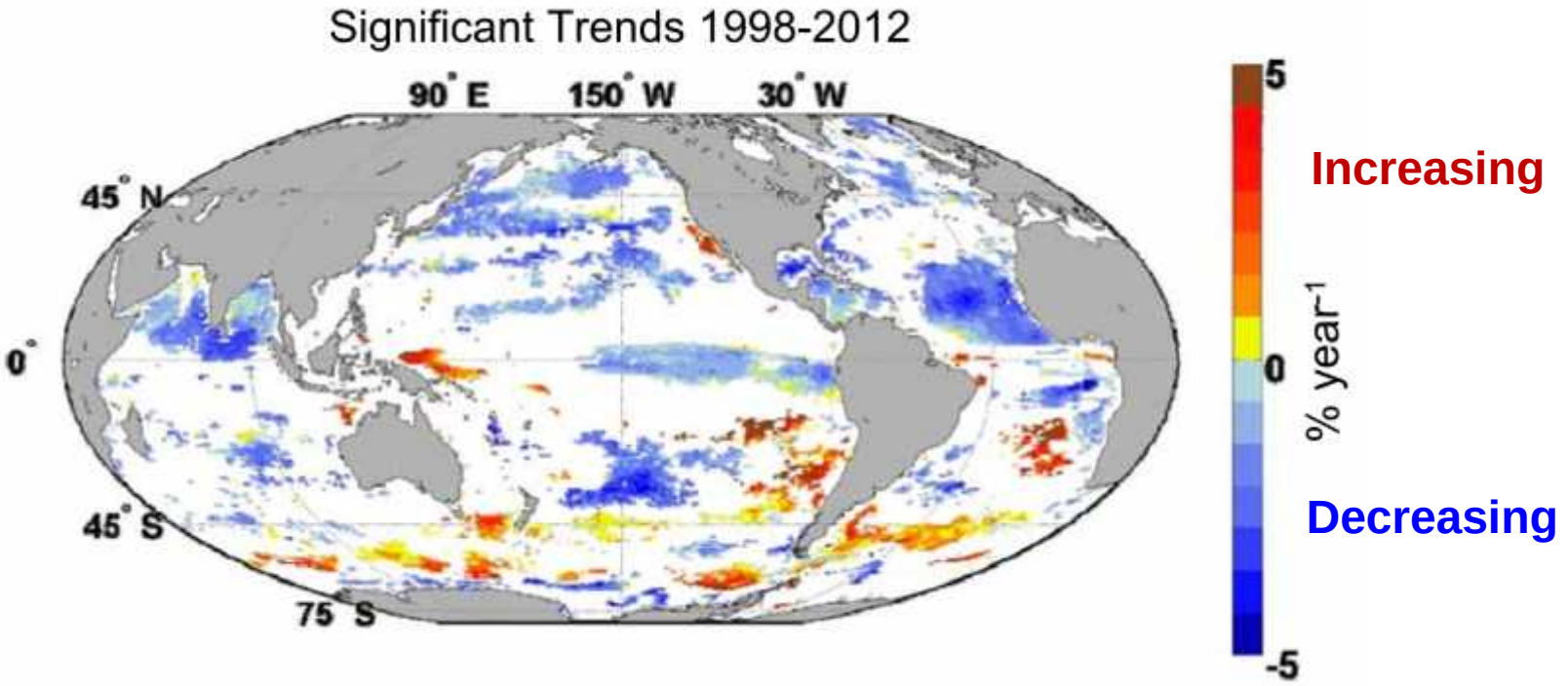
25% **CO_2 is absorbed by the ocean, moderating climate warming**

30% **Ocean acidity increased by 30%, having negative impact on oceanic net primary productivity (NPP)**

McNutt, M. (2015), Science, 348, 841–841

1 Motivation

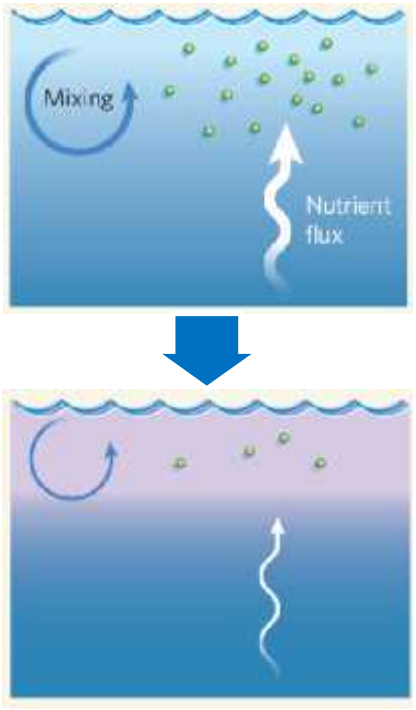
Multiple satellite data indicated that all North Hemisphere and Equatorial Indian basin experienced a significant decline of Chlorophyll-*a* (or NPP)

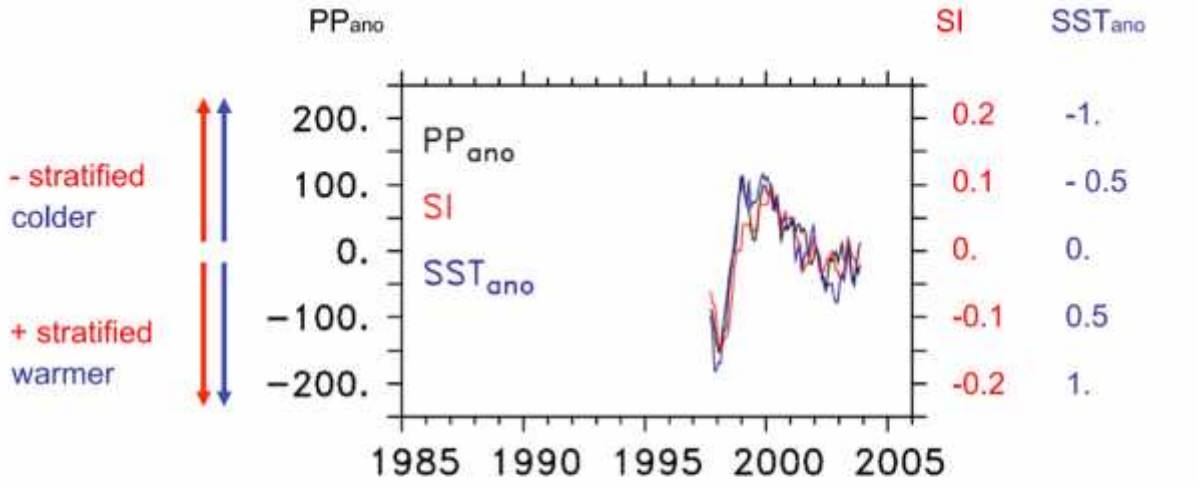


Behrenfeld et al. (2010) in Nature; Gregg and Rousseaux (2014), JGR

1 Motivation

Current: Such climate-driven decline is attributed mainly to the increasing thermal stratification of ocean water columns (reduced mixing, lower N supply, decreased phytoplankton).





PP_{ano} = anomaly of NPP (TgC/month)

SI = stratification index : $\rho_{200} - \rho_{surf}$ (kg m-3)

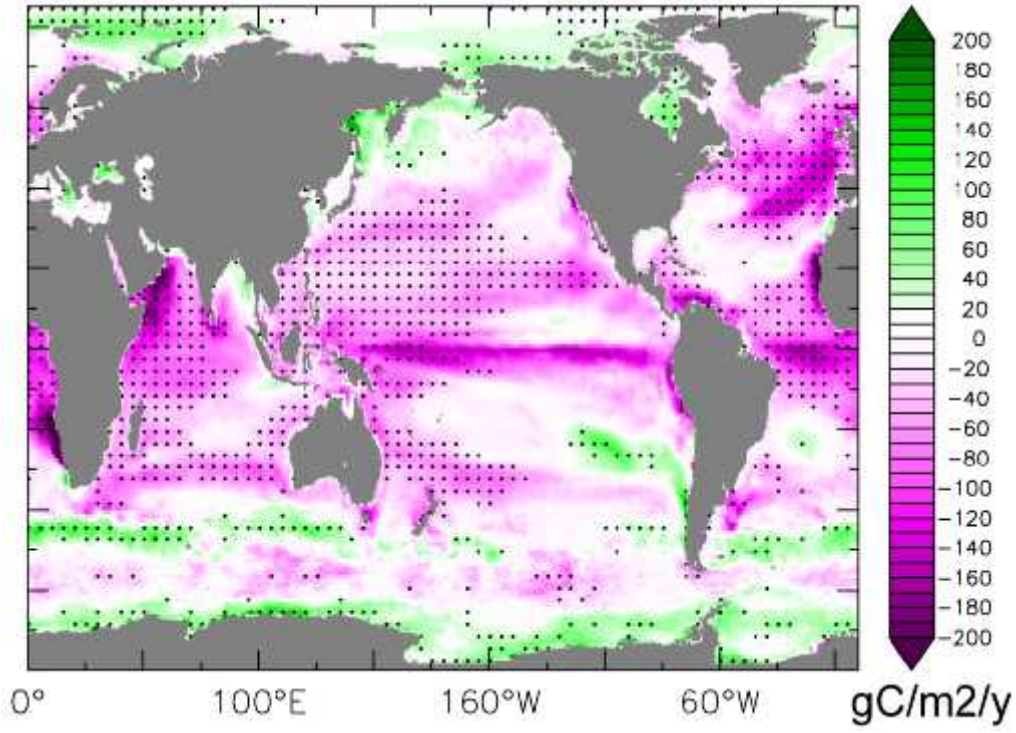
SST_{ano} = anomaly of SST (°C)

ENSO - Observations

From L Bopp in LSCE

1 Motivation

Future: The decline is simulated by ocean biogeochemical model and is expected to continue further, reducing oceanic NPP and hence CO_2 sink (-6% to -25% in 2050).



Bopp et al., 2013 in Biogeosciences

1 Motivation

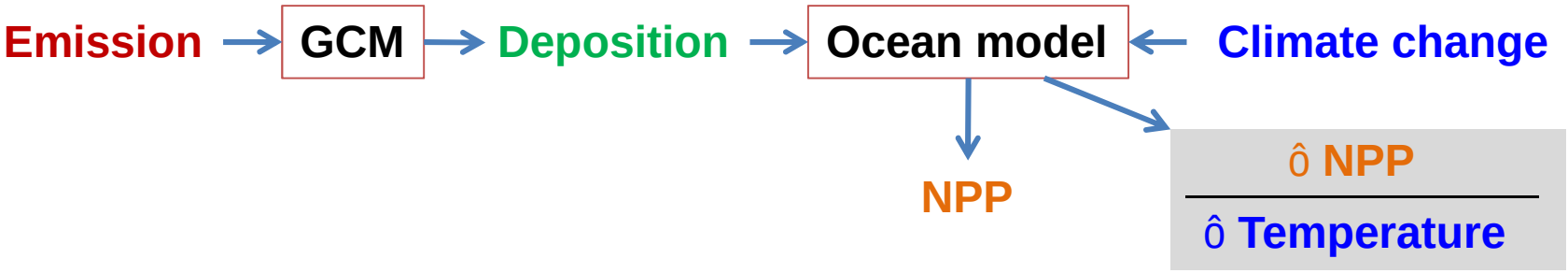
In contrast, anthropogenic aerosols provide nutrients to the surface oceans, which stimulate the phytoplankton and promote the oceanic NPP.

Key question addressed -------

Can aerosol deposition partly offset the decline of NPP caused by warming?

2 Data and methods

To understand the impact of aerosol deposition, we simulated the change of Nr, phosphate (PO_4), and sFe, deposition from 1850 to 2010 in a global atmospheric general circulation model (GCM) and input the results into an ocean biogeochemical model with the varying climate.



2 Data and methods Emission

http://inventory.pku.edu.cn/

Species	Sector	Source	Period
NH_3 + NO_x + N_2O	Agriculture, Combustion	ACCMIP and MACCity PKU-inventory	1850-2010
NO + N_2O + NH_3	Natural soil, ocean	PKU-inventory	Constant
P + Fe	Combustion, wildfire	PKU-inventory	1960-2007
P + Fe	Dust, biogenic aerosol, volcano	Mahowald et al., 2008	Constant

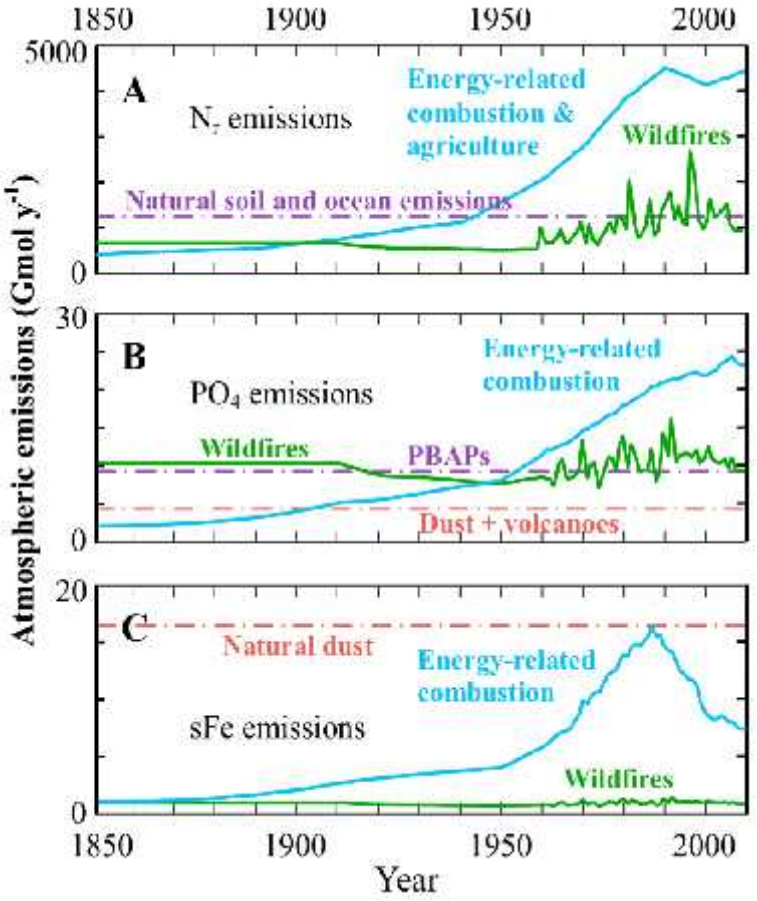
P Bioavailability: 10% of P from dust, 100% of P from volcanoes, and 50% of P from others

Fe Bioavailability: 12 ± 9% for coal fly ash, 63.0 ± 17.0% for vehicle oil, 79.8 ± 8.5% for heavy oil, 30 ± 14% for biomass, 2 ± 4% for dust

2 Data and methods

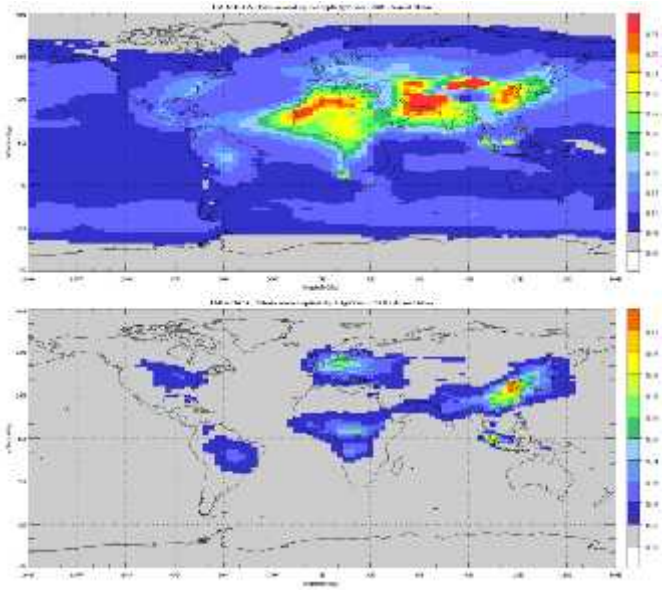
Historical emissions of Nr, PO_4 and sFe (0.5î ò 0.5î grid cell)

- Increased by 1.8, 0.8, 0.4 times since 1850 globally
- **Nr:** increased until 1990s, then kept stable
- **PO_4:** persistently increased due to biofuels and deforestation
- **sFe:** increased until 1990s and then declined, due to dust abatment & use of cleaner fuels



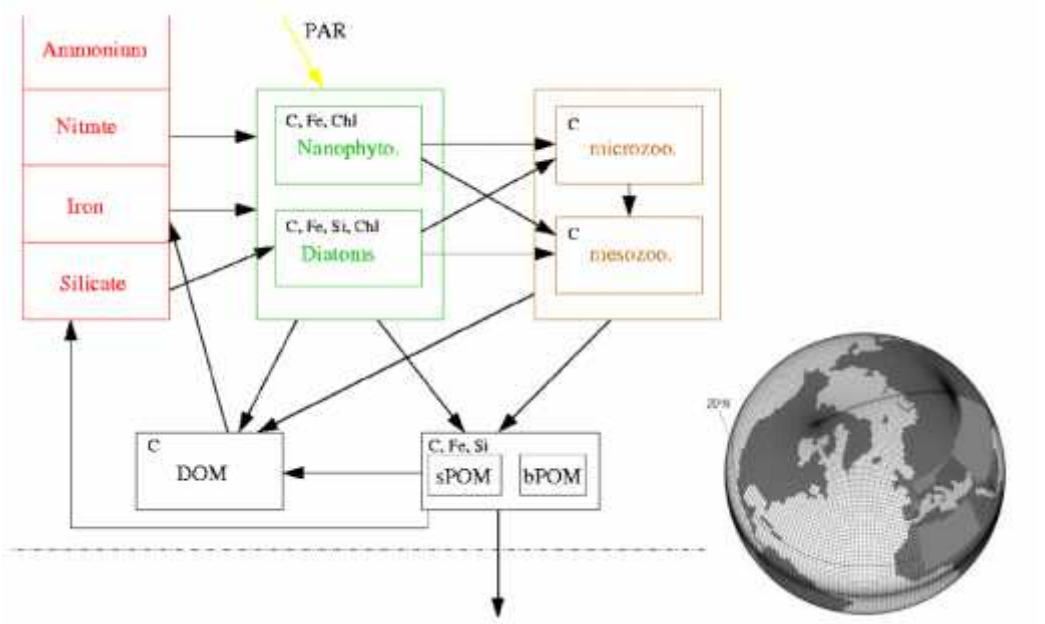
2 Data and methods Models from LSCE

A global chemistry-aerosol-climate model **LMDz-OR-INCA** to simulate aerosol deposition



Hauglustaine et al., 2014 in ACP

An oceanic biogeochemical model **NEMO-PISCES version 2** to simulate Nr, PO4, sFe as well as Chlorophyll and NPP



Aumont et al., 2015, Geosci. Model Dev., 8, 2465–2513

2 Data and methods

Two Experiments:

Without anthropogenic aerosol deposition (CTL):

✓ We used the standard model configuration as done in Bopp et al., 2013.
✓ The deposition of N, P and Fe was fixed at the 1850 levels.

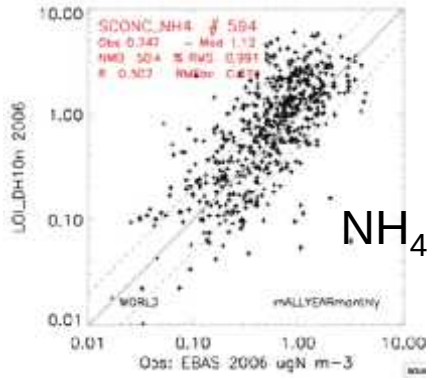
With anthropogenic aerosol deposition (DEP):

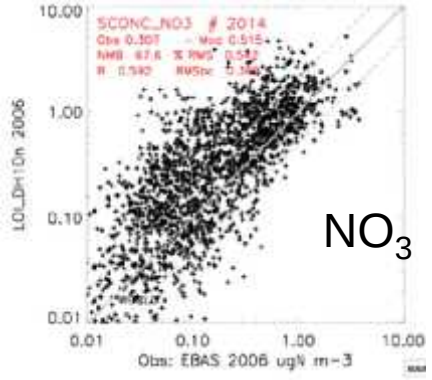
✓ We used the standard model configuration as done in Bopp et al., 2013.
✓ The monthly deposition of N, P and Fe simulated by our 3-D atmospheric transport model (LMDZ-ORCHIDEE-INCA) from 1850 to 2010 was prescribed to NEMO-PISCES.

The difference was considered as the response to aerosol deposition

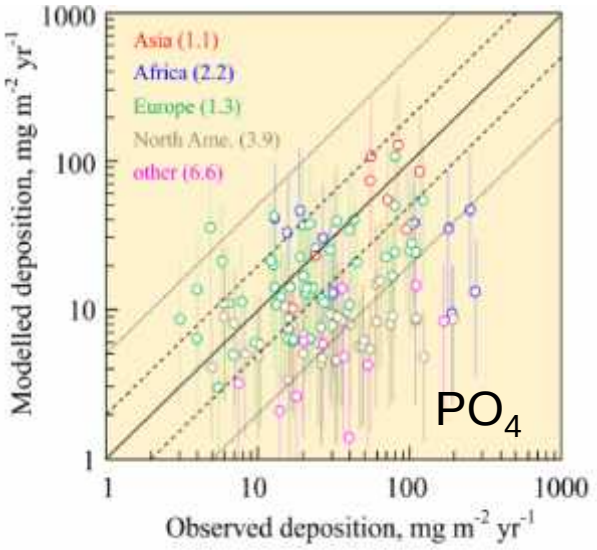
3 Model performance

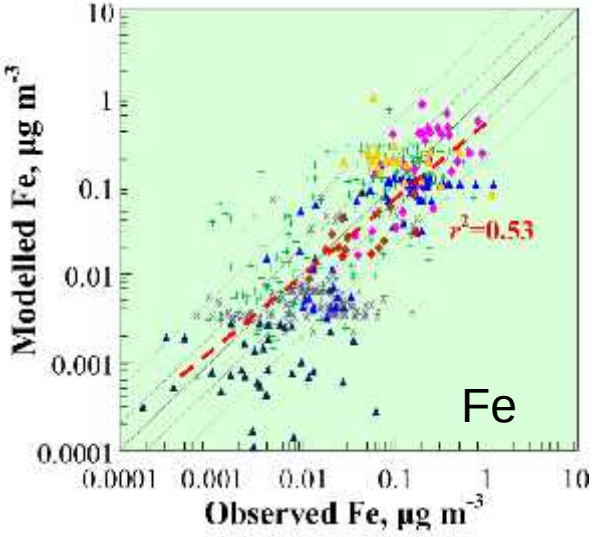
Modeled v.s. observed deposition





Hauglustaine et al., 2014

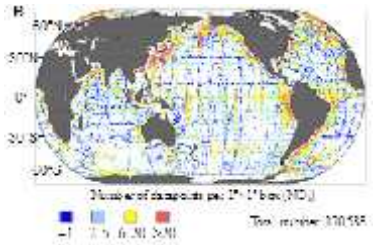




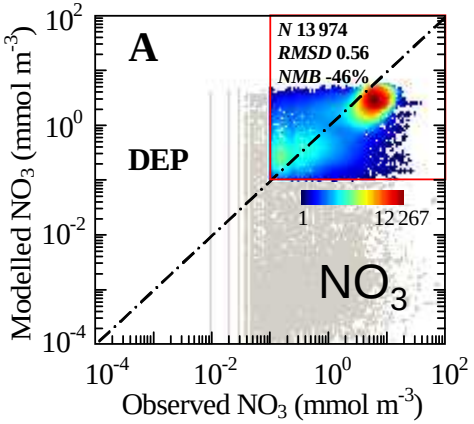
Wang et al., ACP, 2015

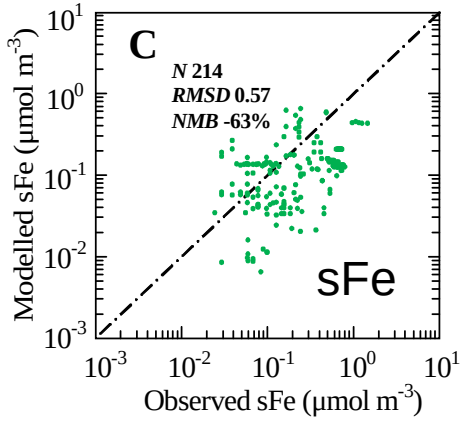
Observed deposition: CASNET, EMEP, EANET

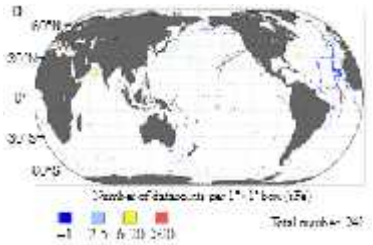
3 Model performance



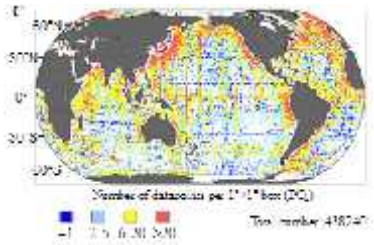
170,588 data



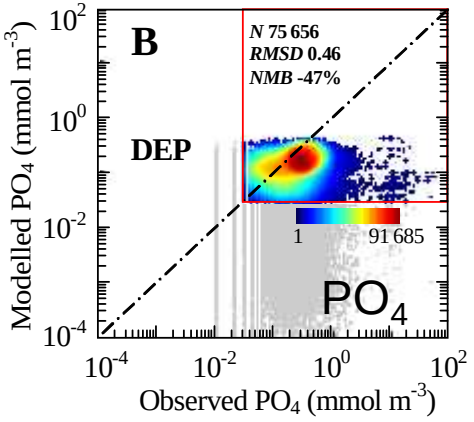


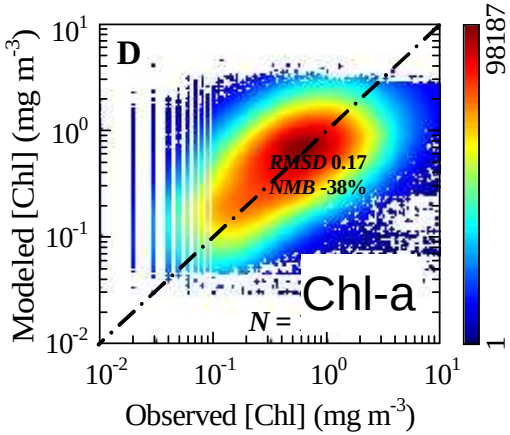


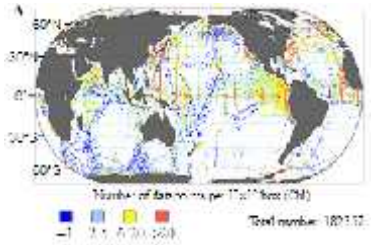
214 data



438,240 data



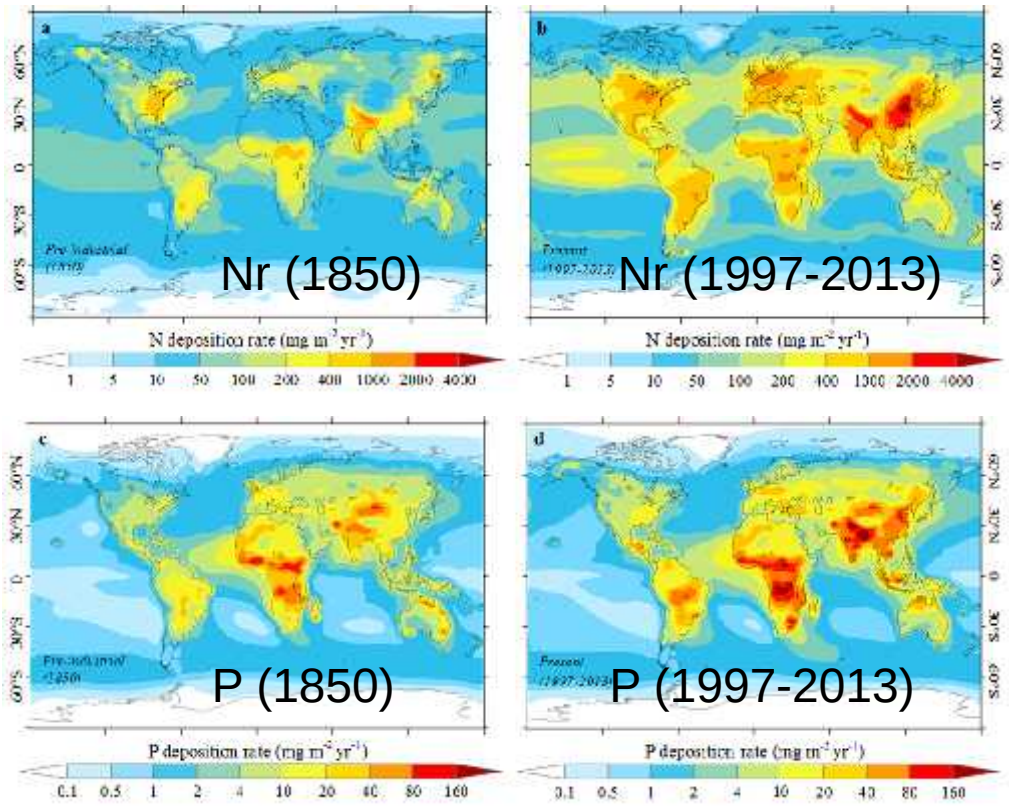




182,552 data

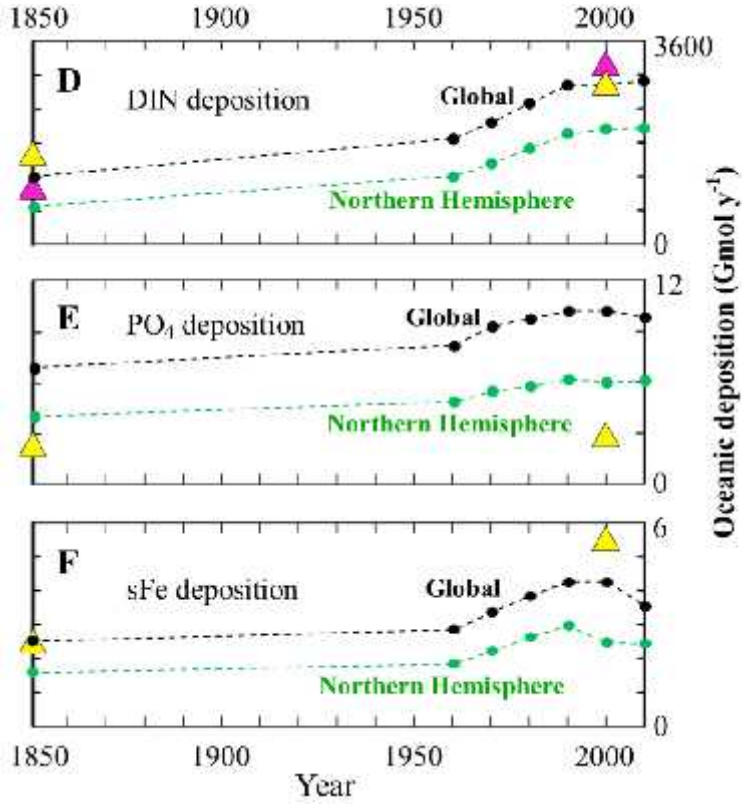
https://www.nodc.noaa.gov/OC5/WOD13/; http://www.bodc.ac.uk/geotraces/

3 Model performance



Pre-industrial, 1850

1997-2013

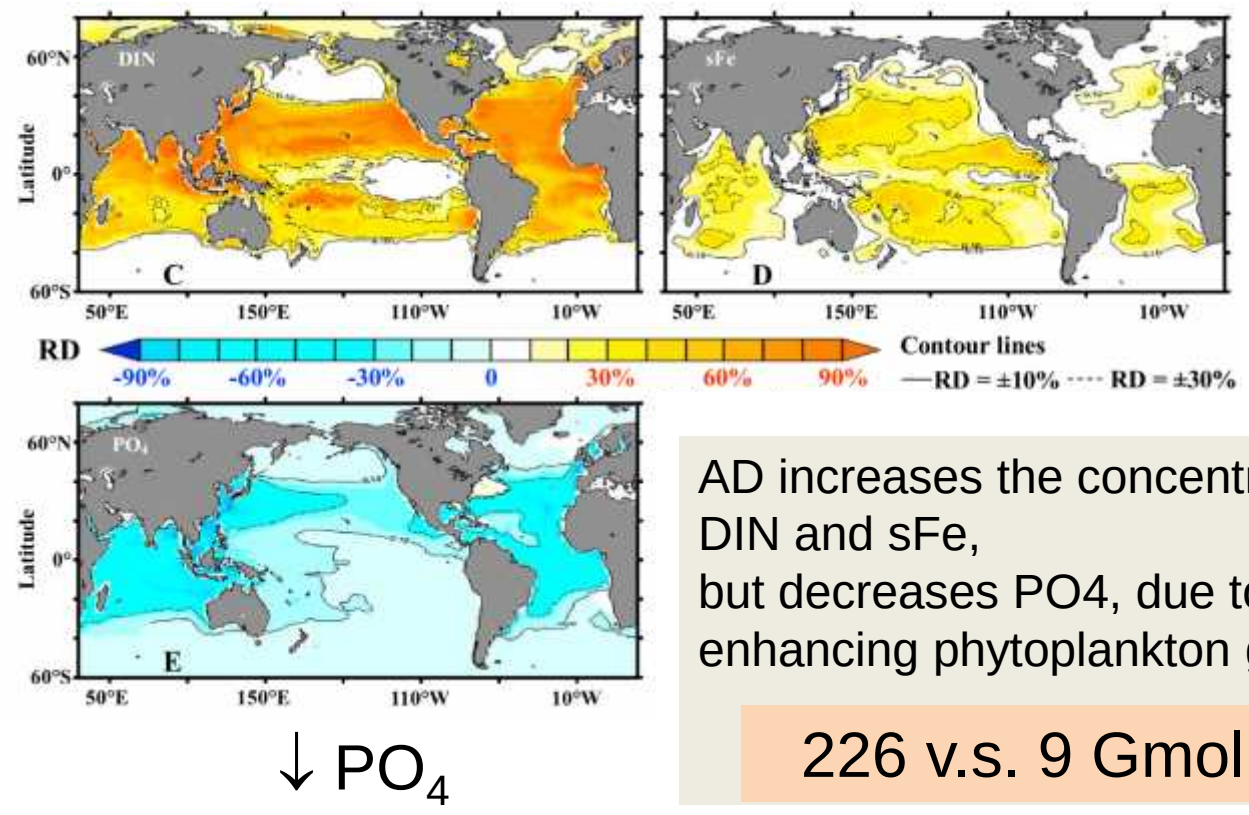


4 Impact to concentration

Difference of 2 experiments

↑ DIN

↑ sFe



↓ PO_4

AD increases the concentrations of DIN and sFe,
but decreases PO4, due to the enhancing phytoplankton growth

226 v.s. 9 Gmol yr^{-1}

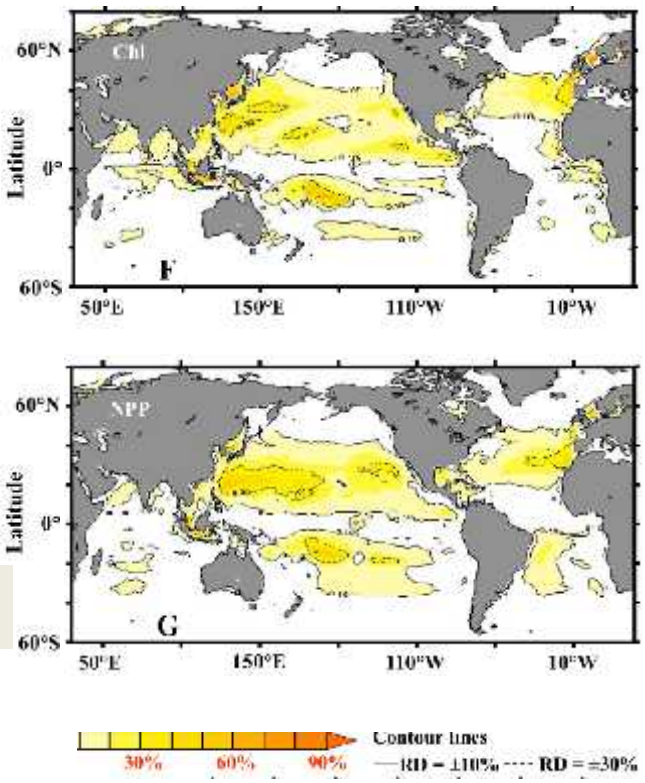
4 Impact to concentration

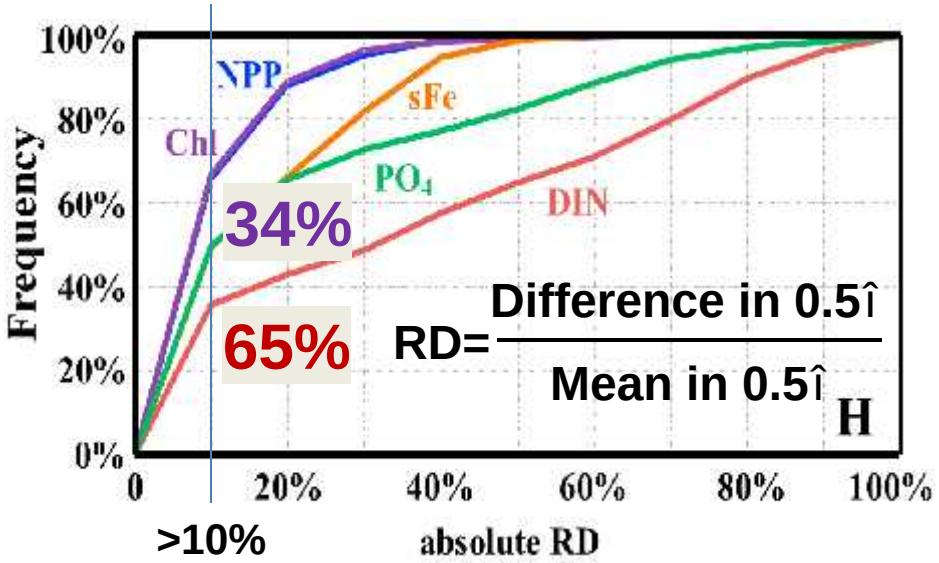
Difference of 2 experiments

↑ Chl-a

↑ NPP

1.3 Pg yr^{-1}





the ocean area with a relative difference larger than 10% for DIN and Chl-a/NPP accounts for 65% and 34%, respectively

5 Impact to NPP sensitivity

Behrenfeld *et al*. [2006] found an inverse relationship. We observed a similar relationship when comparing the period from 1948–1977 to 1978–2007

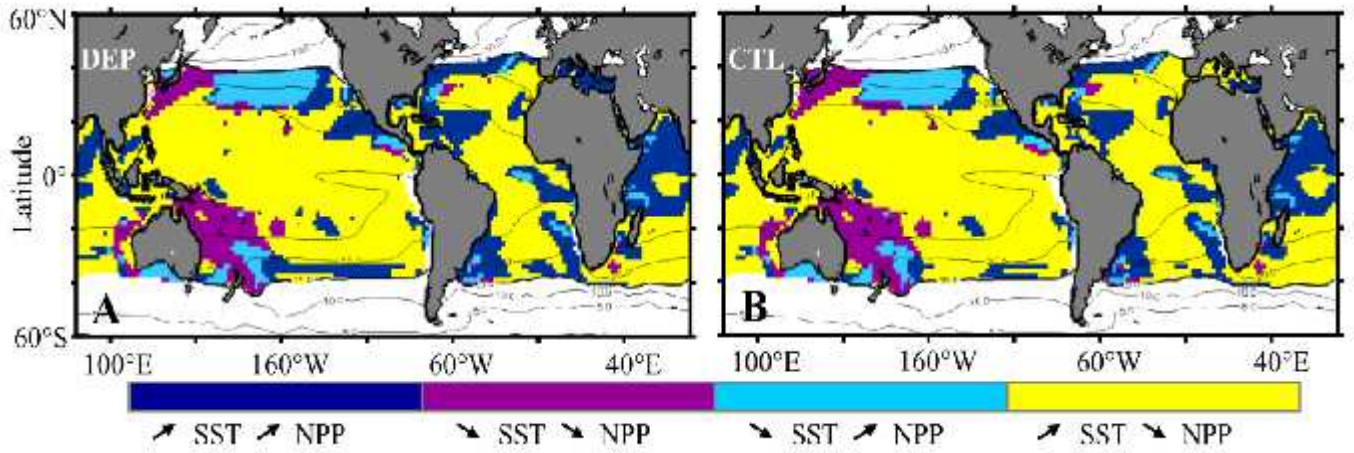


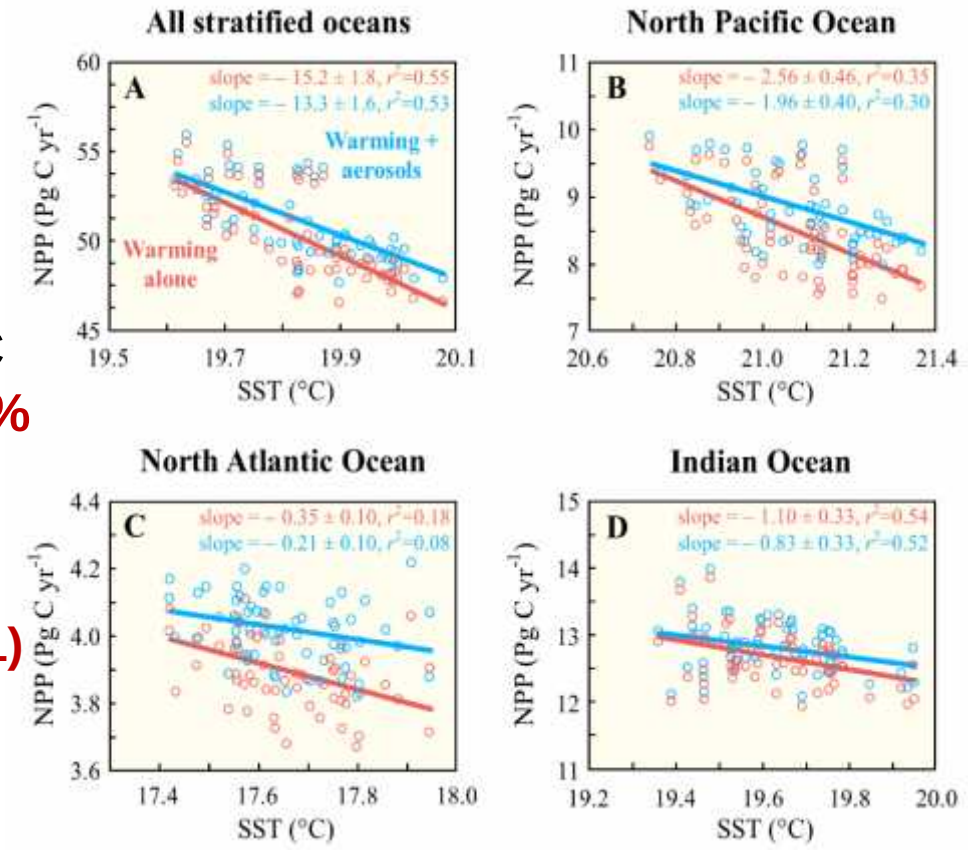
Figure: Changes of the annual mean sea-surface temperature (SST) and oceanic NPP in the permanently stratified oceans from 1948-1977 to 1978-2007 in the simulations (**A**) with, or (**B**) without aerosol deposition

5 Impact to NPP sensitivity

However, aerosol deposition decreases the sensitivity of NPP to SST changes

$$\frac{\delta\,\text{NPP}}{\delta\,\text{Temperature}}$$ **í J15 to J13 Pg C yr^{-1} îC^{-1} or – 12.5%**

- **North Pacific: J23% (2.56->1.96)**
- **North Atlantic: J40% (0.35 to 0.21)**
- **Indian: J25% (1.1 to 0.83)**



SST: Sea-surface temperature

6 Take-home messages

- **Aerosol deposition offsets the oceanic NPP sensitivity to SST, which is much important for calculating terrestrial carbon source/sink (=Emission – atmosphere sink – ocean sink)**

- **Future observation-based techniques to detect the influence of global warming on oceanic NPP have to take into account the role of aerosol deposition esp. of Nr**

- **Fertilizing effects of aerosols (N, PO_4, sFe) should be considered along with the effects of climate change in driving NPP variations**

Wang R., Zhou F., et al., GRL, 2016

Thanks so much for your attention

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