# Impacts of Atmospheric Nutrient Deposition on Marine Productivity and Biogeochemistry


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# Atmospheric Deposition of Key Nutrients

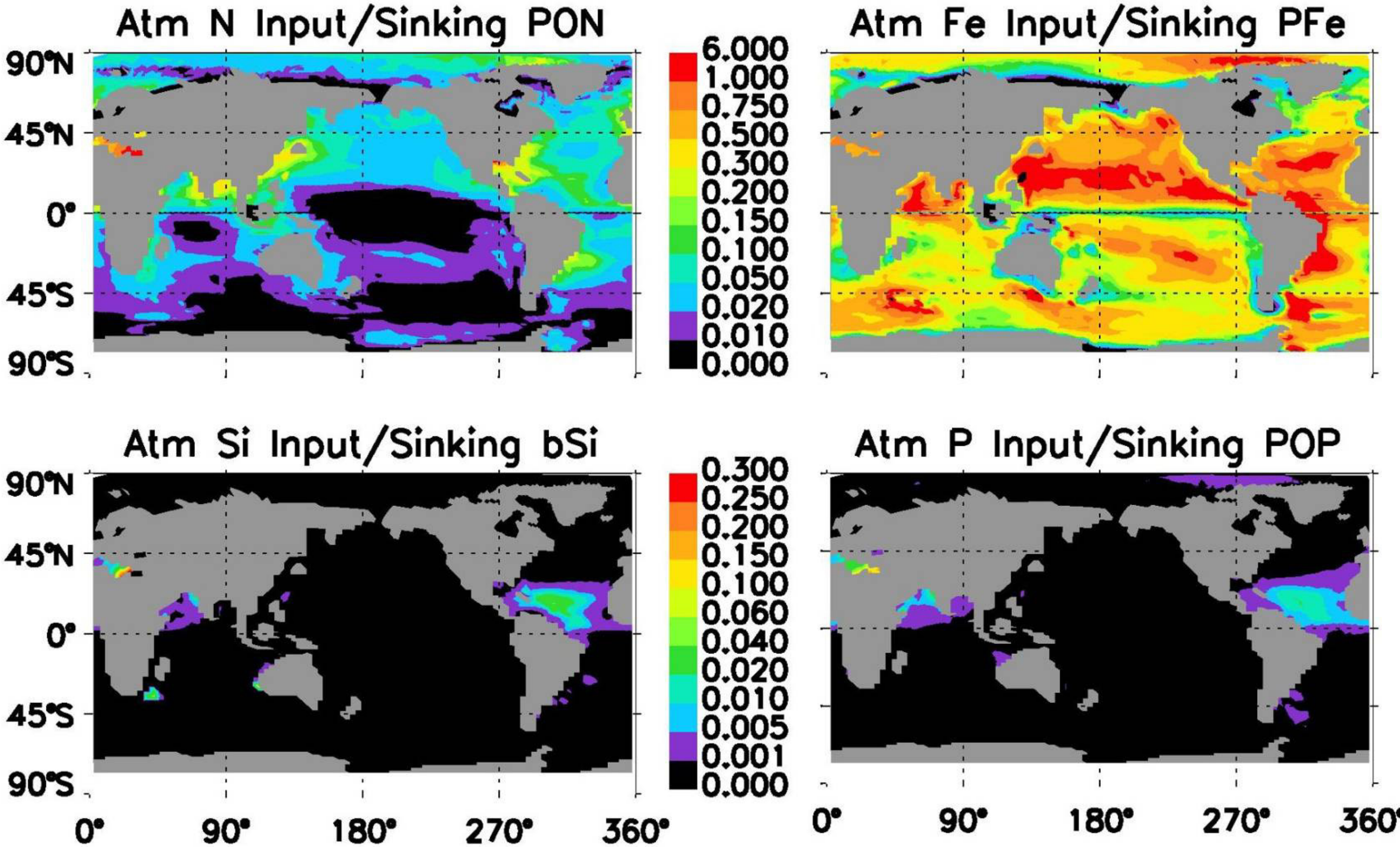
Key nutrients (iron, nitrogen, phosphorus, silicon) all have sources to the oceans from atmospheric deposition.

The impacts on marine productivity and biogeochemistry are a function of the quantity of inputs relative to the ambient seawater concentrations.

If the nutrient deposited is not the growth-limiting nutrient locally, it may be transported great distances before being utilized.

Other nutrients may have impacts as well. For example, Mahaffey et al. (2014) argue that atmospheric zinc inputs enhance APA production and DOP utilization in the North Atlantic.

Nutrient deposition may alter productivity and biogeochemical cycling by shifting the biotic community structure.




**N = 5 %**

**Fe = 55 %**

**Si = 0.2 %**

**P = 0.1 %**

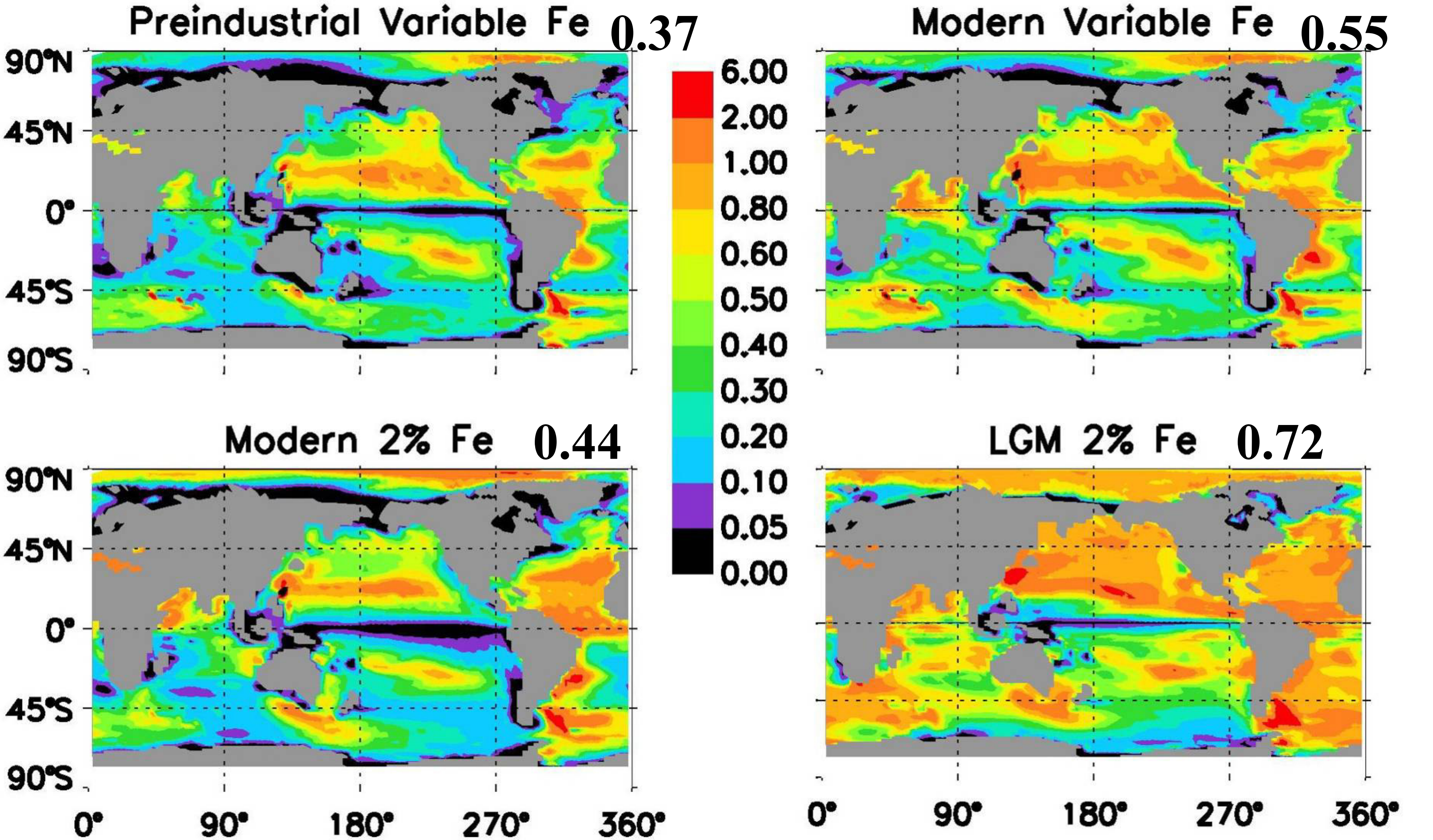
# What are the relative impacts on marine biogeochemistry of the nutrient inputs from the atmosphere?

Atmospheric inputs of Si and P are small relative to internal ocean cycling.

Atmospheric N has significant impacts regionally.

Atmospheric Fe deposition has strong impacts globally.

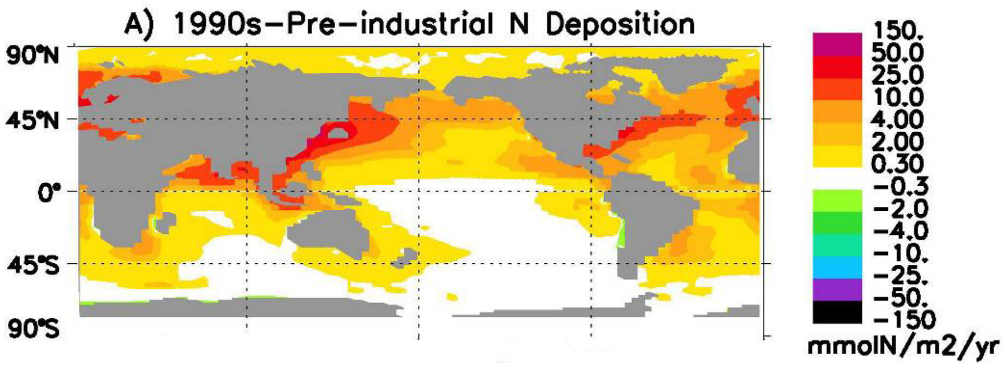
Nutrients supplied in excess are transported, mainly laterally by circulation.




The ratio of dFe inputs divided by sinking PFe (biological + scavenged) under different atmospheric deposition scenarios.

Small atmospheric contribution in upwelling zones. Big differences between variable and constant solubility. Top panels show end members from transient simulation.

(Krishnamurthy et al., 2010)



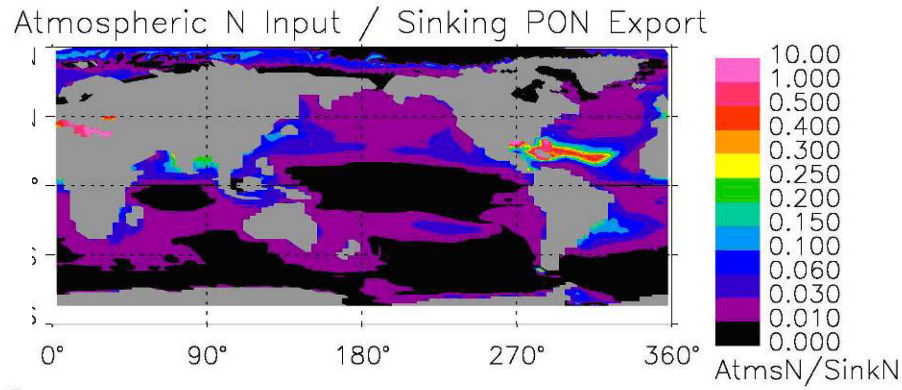

The largest increases since preindustrial era downwind of industrialized countries.

In these regions, atmospheric N deposition can support > 20% of export production, approaching 50% in the fossil fuel intensive A1FI future scenario.

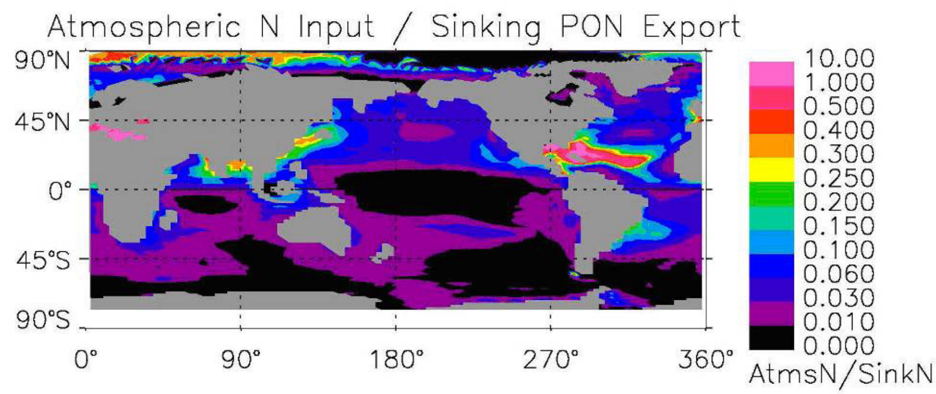
River nitrogen inputs are also expected to increase substantially off SE Asia.

(Krishnamurthy et al., 2007)

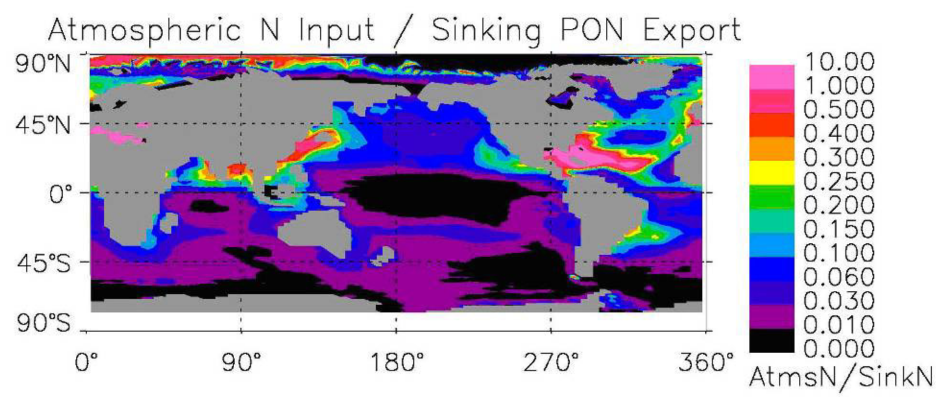
Pre-industrial

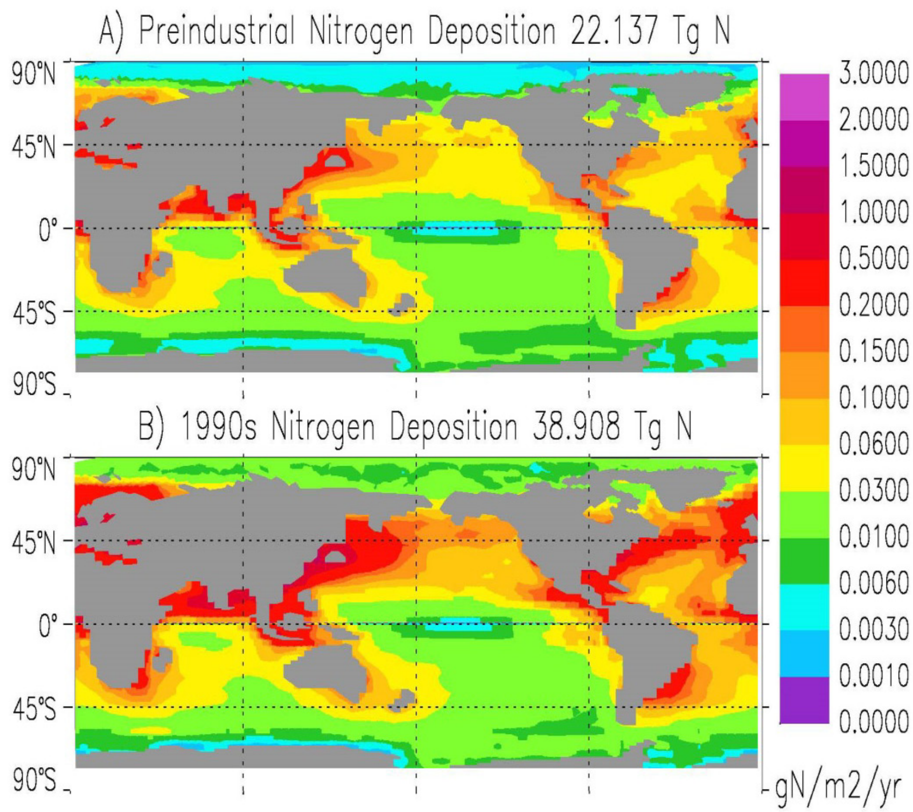


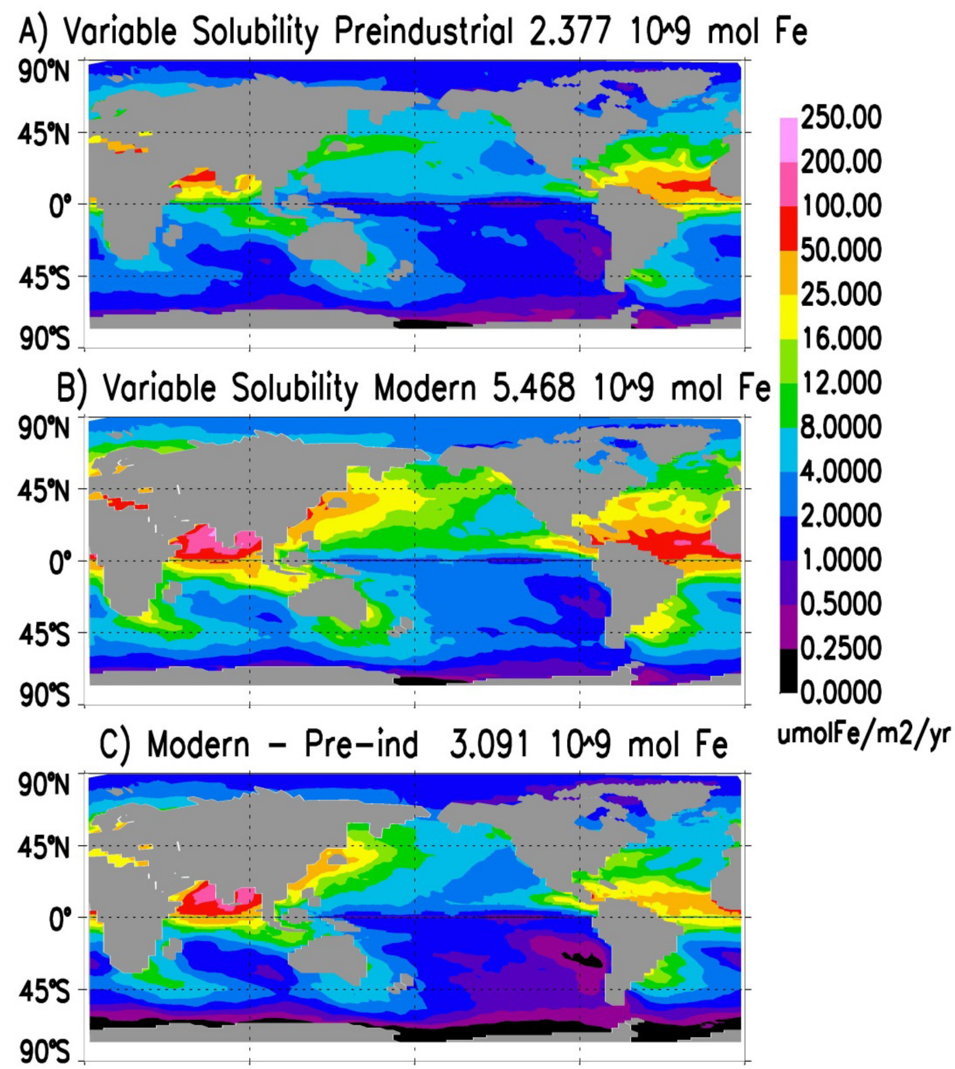

1990s




IPCC-A1FI

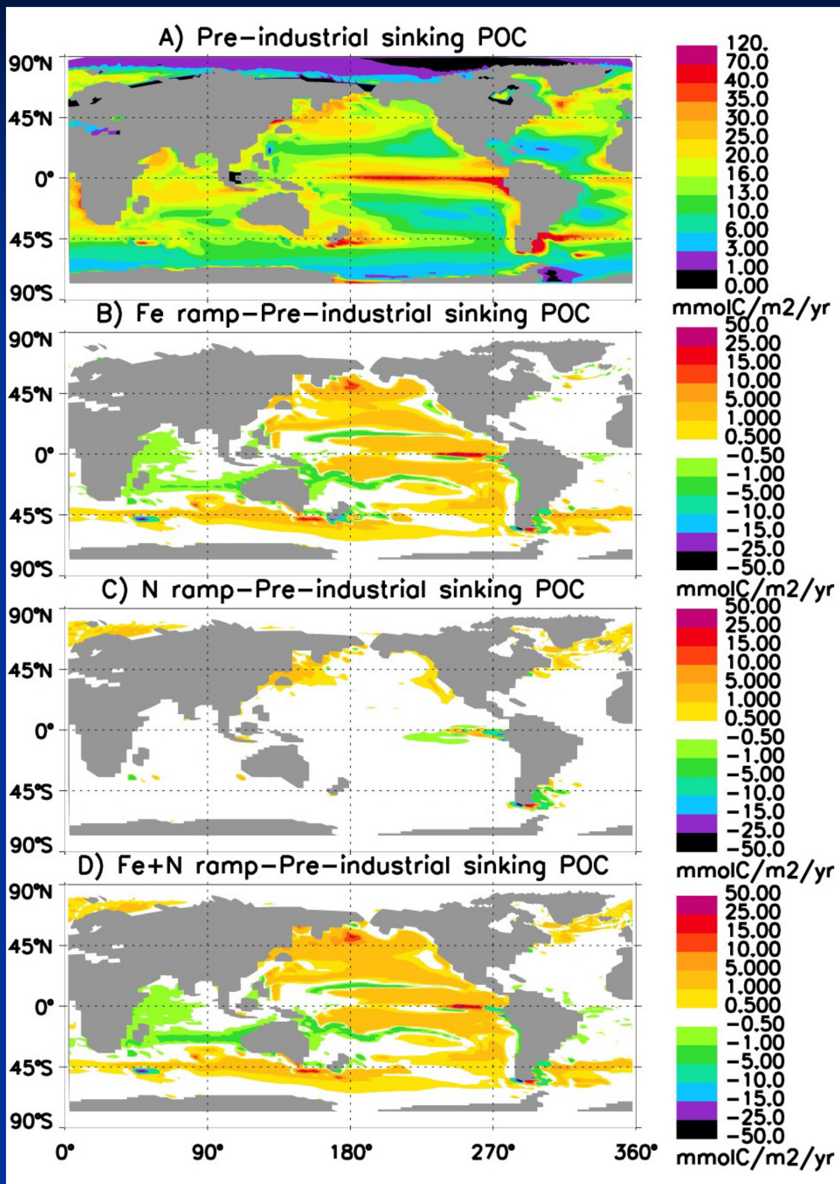




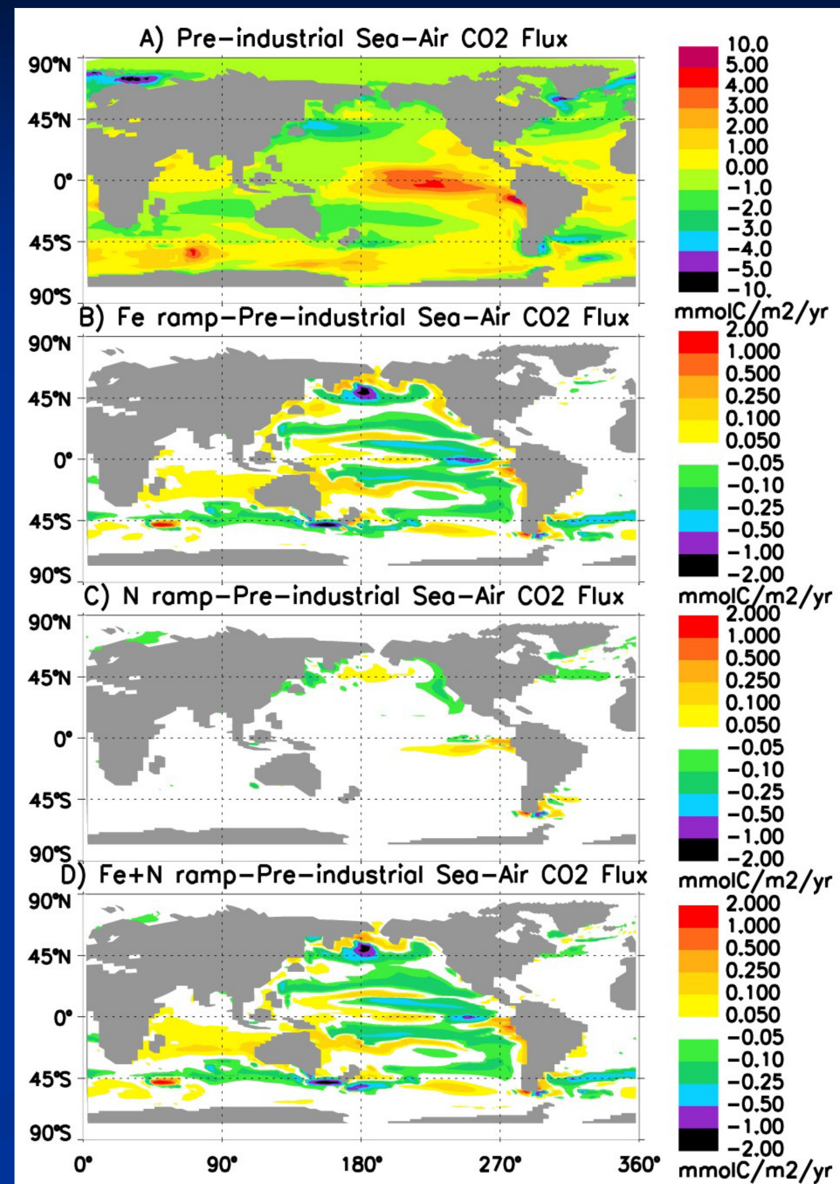




Krishnamurthy et al. (2009) simulated impacts of increasing N and Fe deposition on marine biogeochemistry, assuming a linear increase (over 150 years) since preindustrial. Much of the additional iron deposited is lost to scavenging.

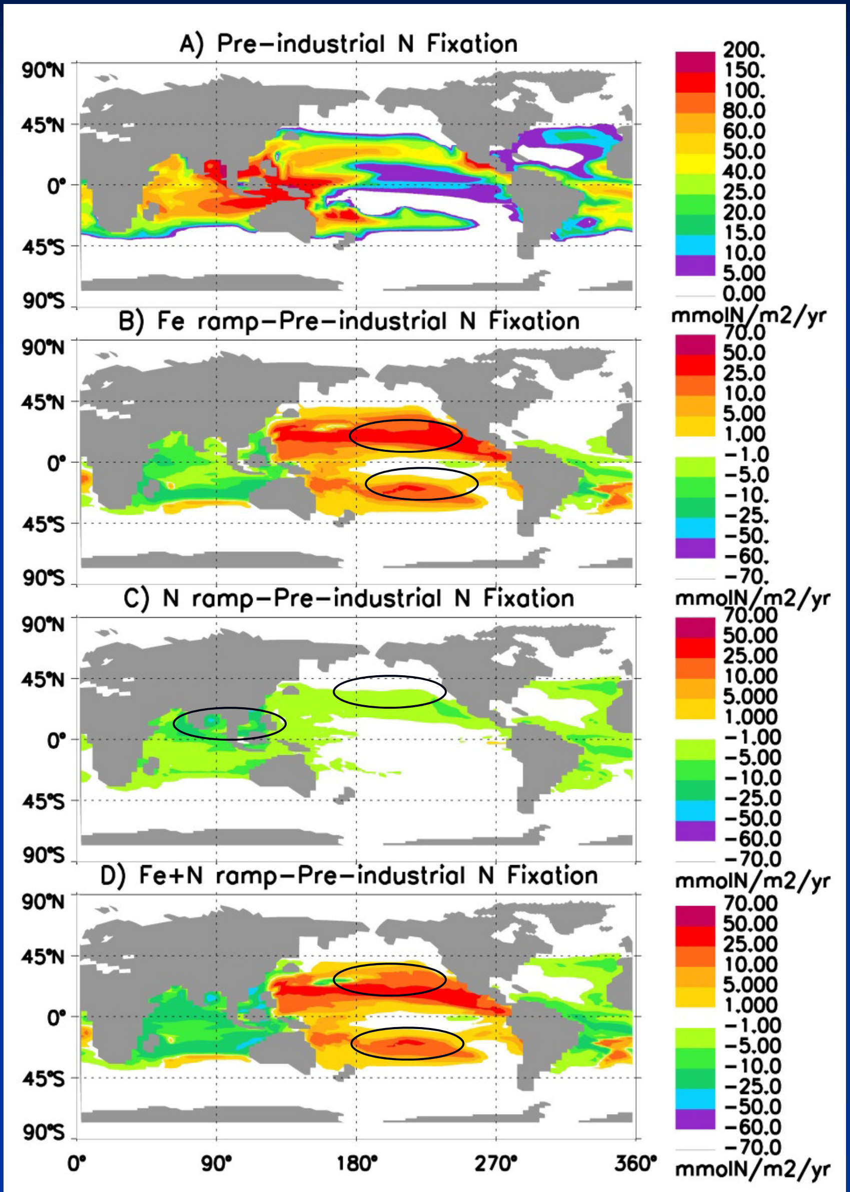
**Sinking POC export at 103m from year 150 of transient simulations**




**Sea-air $CO_2$ flux from year 150 of transient simulations**



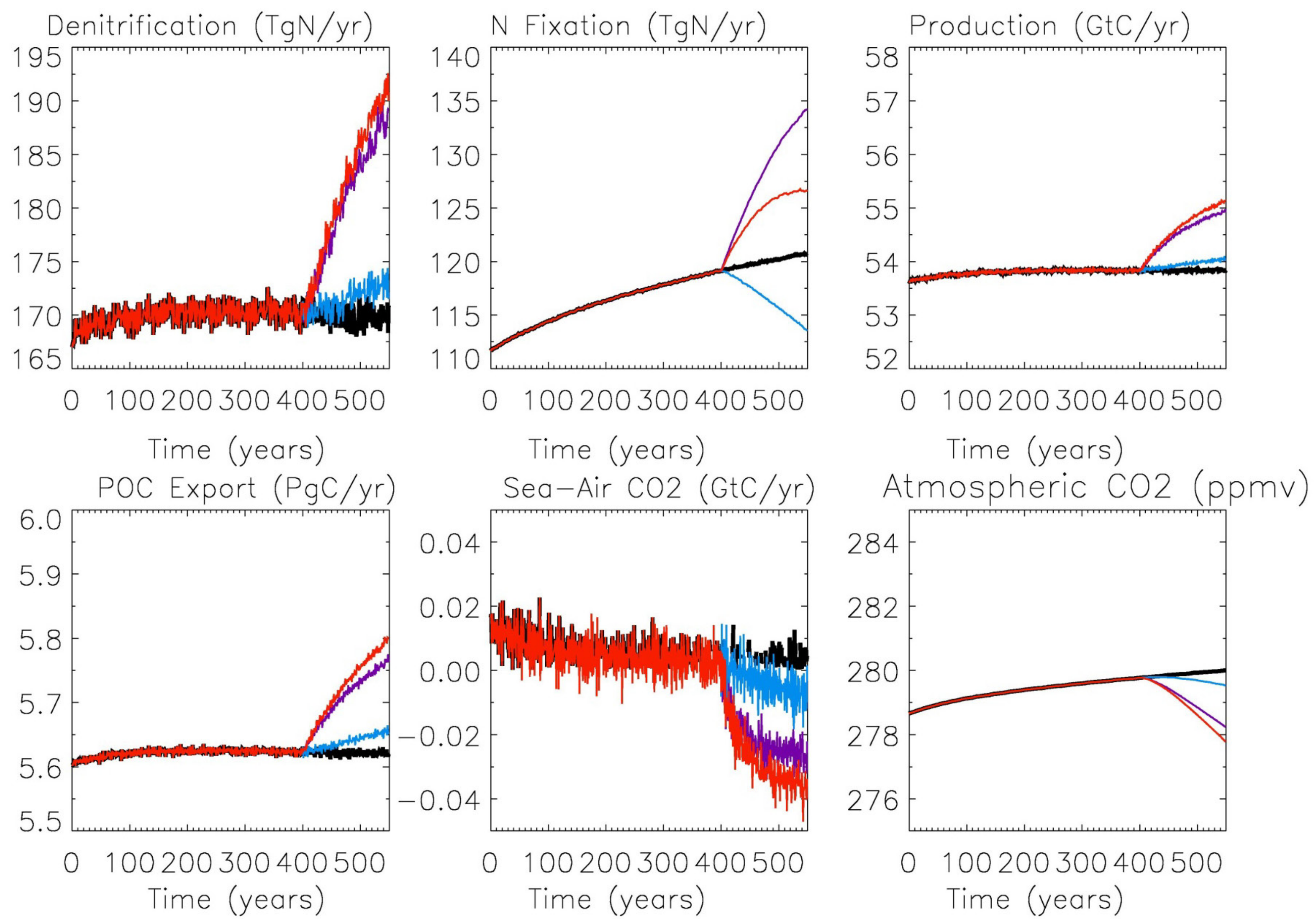
## N fixation from final year (year 150) of transient simulations




**Increasing atmospheric iron deposition increases nitrogen fixation.**

**Increasing atmospheric nitrogen deposition, decreases nitrogen fixation, offsetting ~ 25% of the increasing N inputs.**

**Modest impacts on productivity from increasing Fe and N deposition, but more substantial impacts on N fixation and denitrification.**




**pre-industrial, case 1 (Fe), case 2 (N), case 3 (Fe+N)**

## Why were the perturbations of production and air-sea $CO_2$ flux so modest?

Some of the added N and Fe was not utililized by the biology.

Much of the additional iron was lost to particle scavenging, particularly in regions with elevated ambient iron concentrations.

Particle scavenging rates increase sharply as iron exceeds the assumed ligand concentrations.

For nitrogen, the deposition to the open ocean is a small fraction of the new nitrogen coming from below and from N fixation.

Increasing nitrogen deposition to N-limited regions leads to drawdown of ambient Fe and P as production and export are stimulated. This reduces the growth rates of the diazotrophs, making them less competitive and reducing total N-fixation. The N-fixation reduction was equivalent ~25% of the increased atmospheric deposition.

It is really hard to change global productivity and air-sea CO2 flux, due to compensating downstream effects.

# Atmospheric Nutrient Deposition in Earth System Models

All of the coupled climate-carbon cycle models in the most recent IPCC studies (CMIP5) included iron as a growth-limiting nutrient.

However, atmospheric iron inputs to the oceans were held constant throughout the simulations, a climatological dust/iron deposition file.

No dynamic linking of climate, dust production and transport, and iron inputs to the oceans.

Progress limited by large uncertainties in iron inputs (total flux and solubility), role of ligands, and in the losses to particle scavenging.

Current models assume a wide range of iron input fluxes and then modify the scavenging losses to optimize simulated iron distributions.

Better observational constraints needed on iron inputs and on removal rates due to scavenging and biological uptake.

GEOTRACES and SOLAS efforts can help constrain these fluxes.

# Atmospheric Nutrient Deposition in Earth System Models

External sources of iron to the oceans from 10 global-scale ocean models.

| | **GmolFe/yr** |
|---|---|
| **Atmospheric Deposition:** | **1.4 – 87** |
| **Sedimentary Sources:** | **0.6 - 194** |
| **Hydrothermal Vents:** | **11 - 18** |
| **Riverine Sources:** | **0.06 – 2.5** |
| **Total Iron Inputs:** | **1.4 - 195** |

**Mean ocean iron concentration: 0.31 - 0.81 nM**

**Residence time for dissolved Fe: 3.7 – 626 years, 8 models < 20 years**

**Sources not yet included: volcanic eruptions, icebergs, ET dust particles…?**

**(Tabliabue et al., in prep.)**

# As stratification increases, surface nutrient concentrations decline

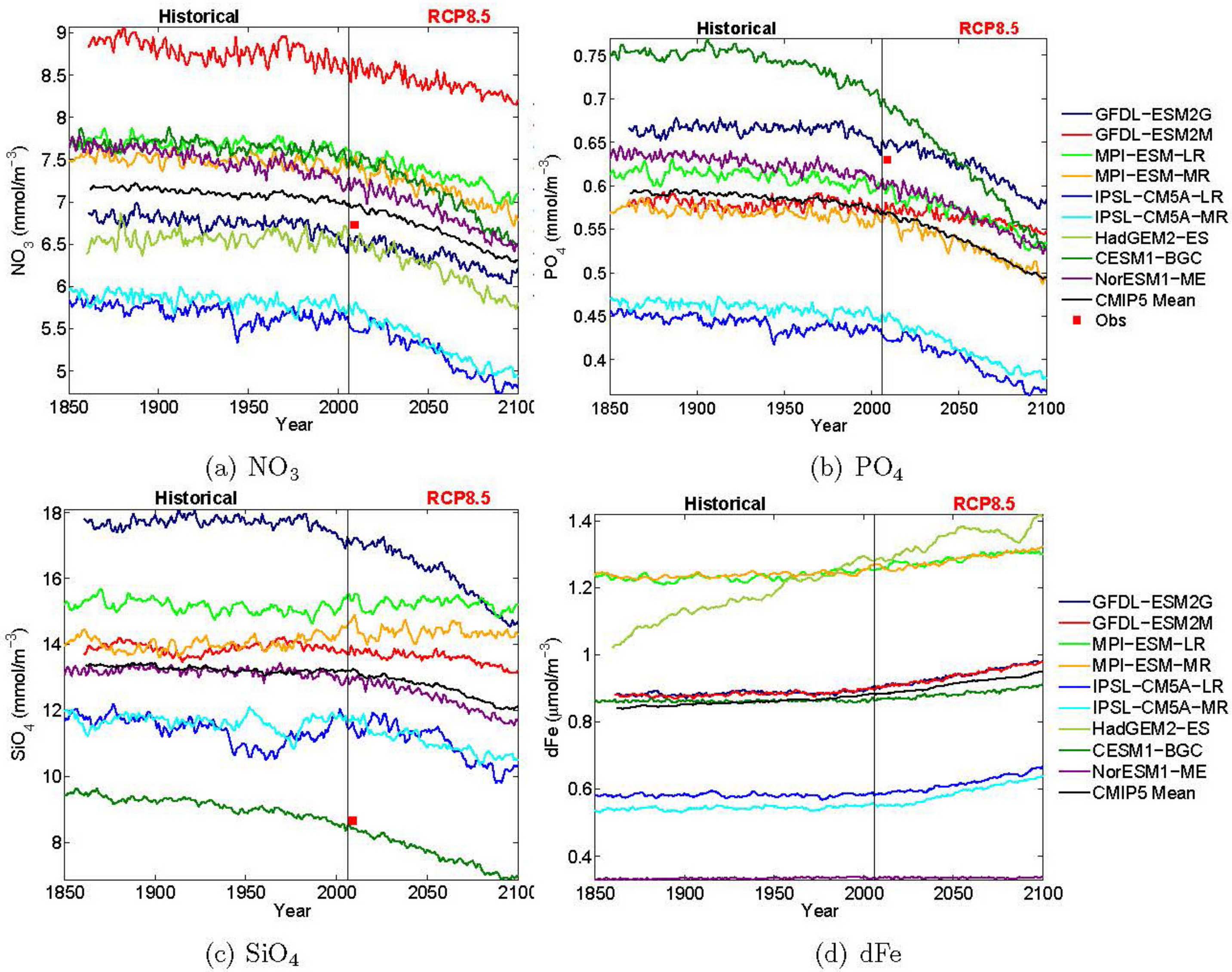



Fig. 5: Time series of mean nitrate ($NO_3$), phosphate ($PO_4$), silicate ($SiO_4$) and dissolved iron (dFe) concentrations (0-100 m) are shown for 1850-2100. Red square indicates WOA2009 global mean values.

**(Fu et al., submitted)**

# Net primary production decreases with climate warming

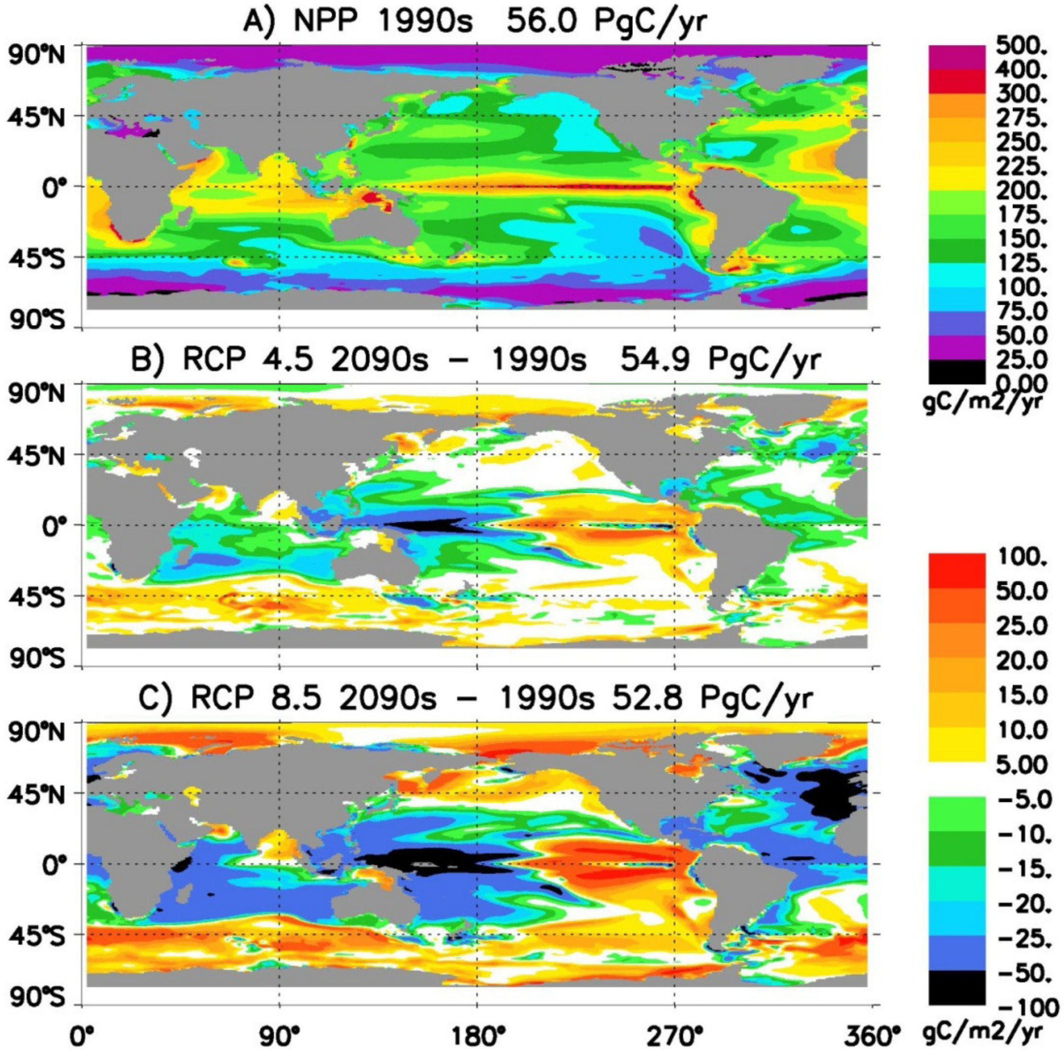



**Figure 16. Annual mean net primary production for the 1990s is compared with the 2090s under the RCP 4.5 and RCP 8.5 scenarios.**

But note that NPP increases in the HNLC regions

**Net Primary Production 1990s**

**Decreases 2% under RCP 4.5**

**Decreases 6% under RCP 8.5**

(Moore et al., 2013)

# Export production decreases with climate warming

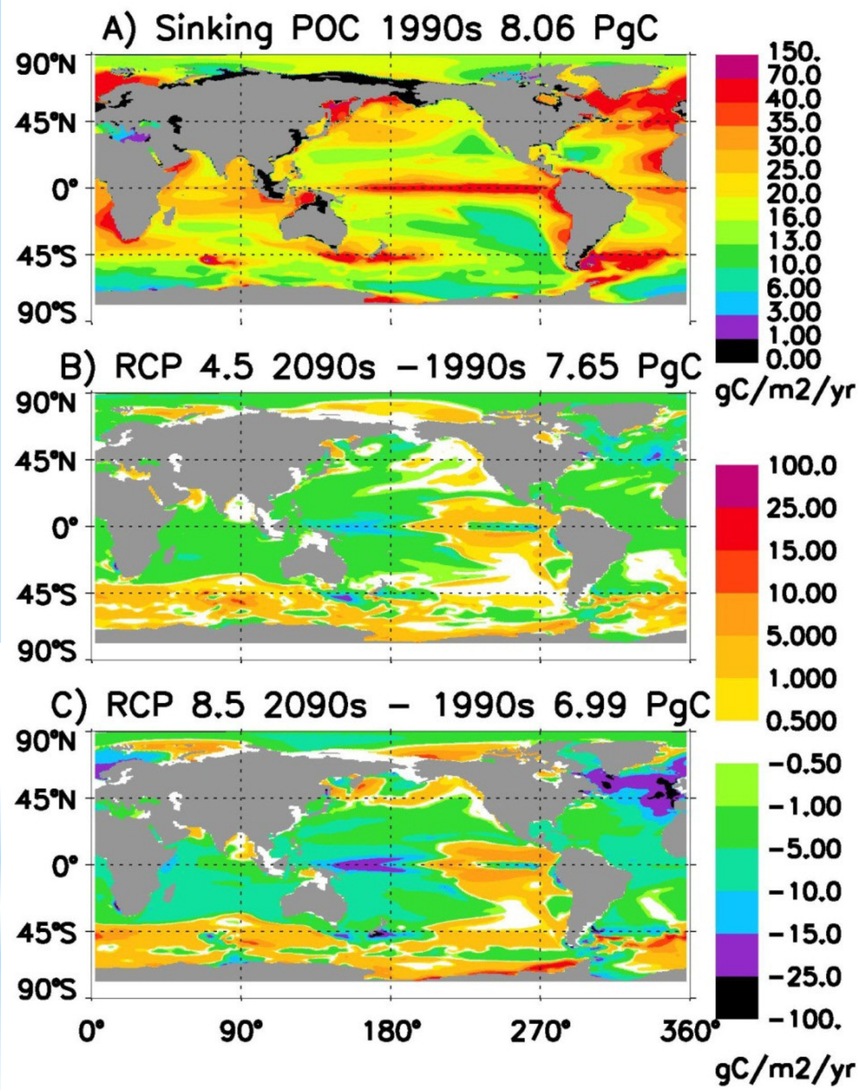



Figure 17. The annual mean sinking particulate organic carbon flux at 100 m depth for the 1990s is compared with the 2090s under the RCP 4.5 and RCP 8.5 scenarios.

**Export production in the 1990s**

**Decreases by 5% under RCP 4.5**

**Decreases by 13% under RCP 8.5**

**Increased HNLC export offsets ~25 % of the decreases elsewhere.**

(Moore et al., 2013)

# External Nutrient Sources in the NCAR CESM

Atmospheric Deposition: N, Fe, Si, and P, additional Fe from combustion sources. Iron solubility varies spatially and temporally, and is higher for combustion aerosols (Luo et al., 2008, Mahowald group).

**Note: CESM is on the high end of soluble iron deposition.**

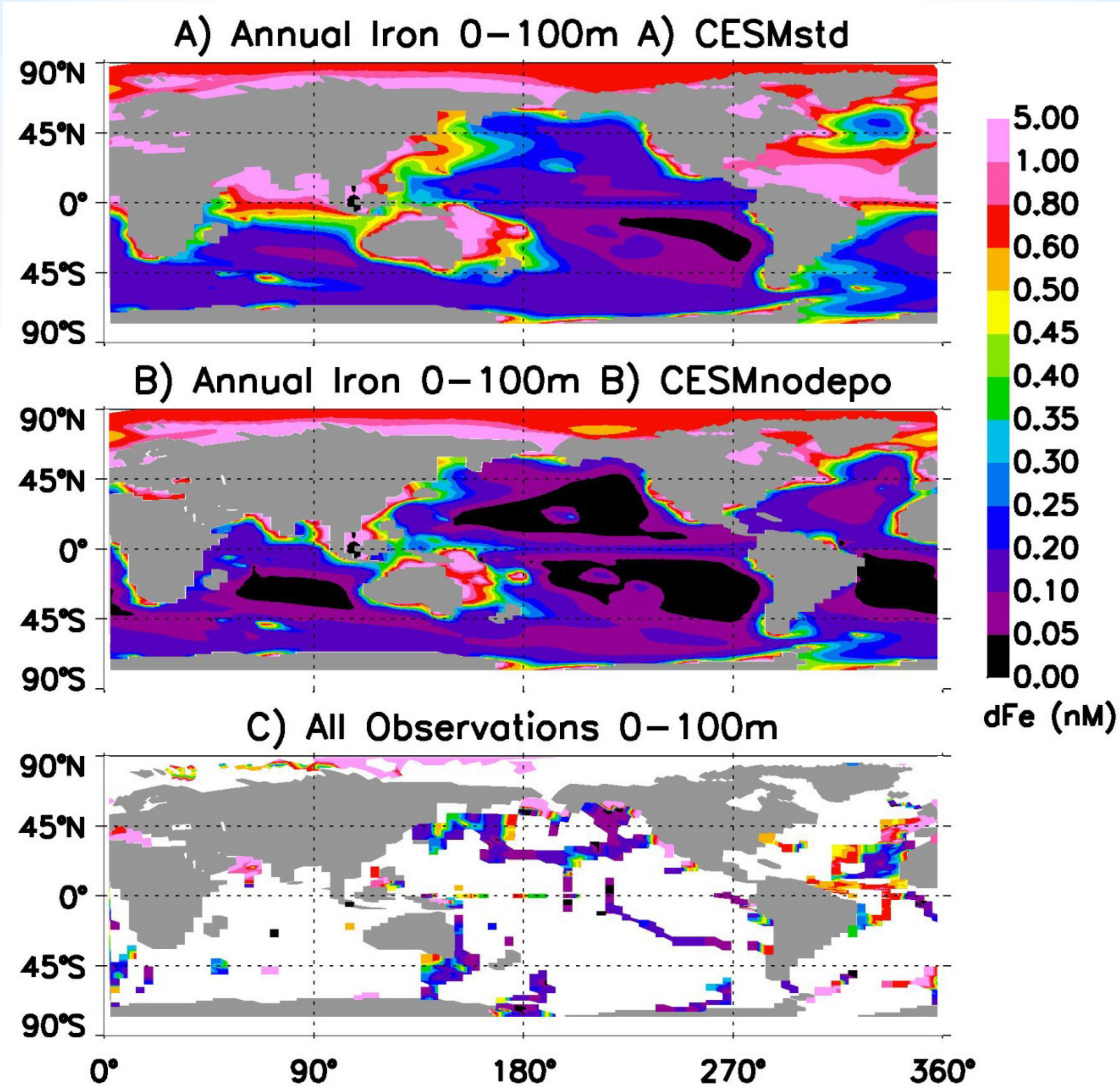
Riverine Inputs: C, N, P, Si, and Fe from input file based output from the Global NEWS linked models (Mayorga et al., 2010; Seitzinger et al., 2010). (Fe not simulated by NEWS, we assume a constant river water concentration of 10nM)

Sediments: Fe source based on high resolution etopoV2 bathymetry using Elrod et al. (2004) relation between sinking POC and Fe efflux.

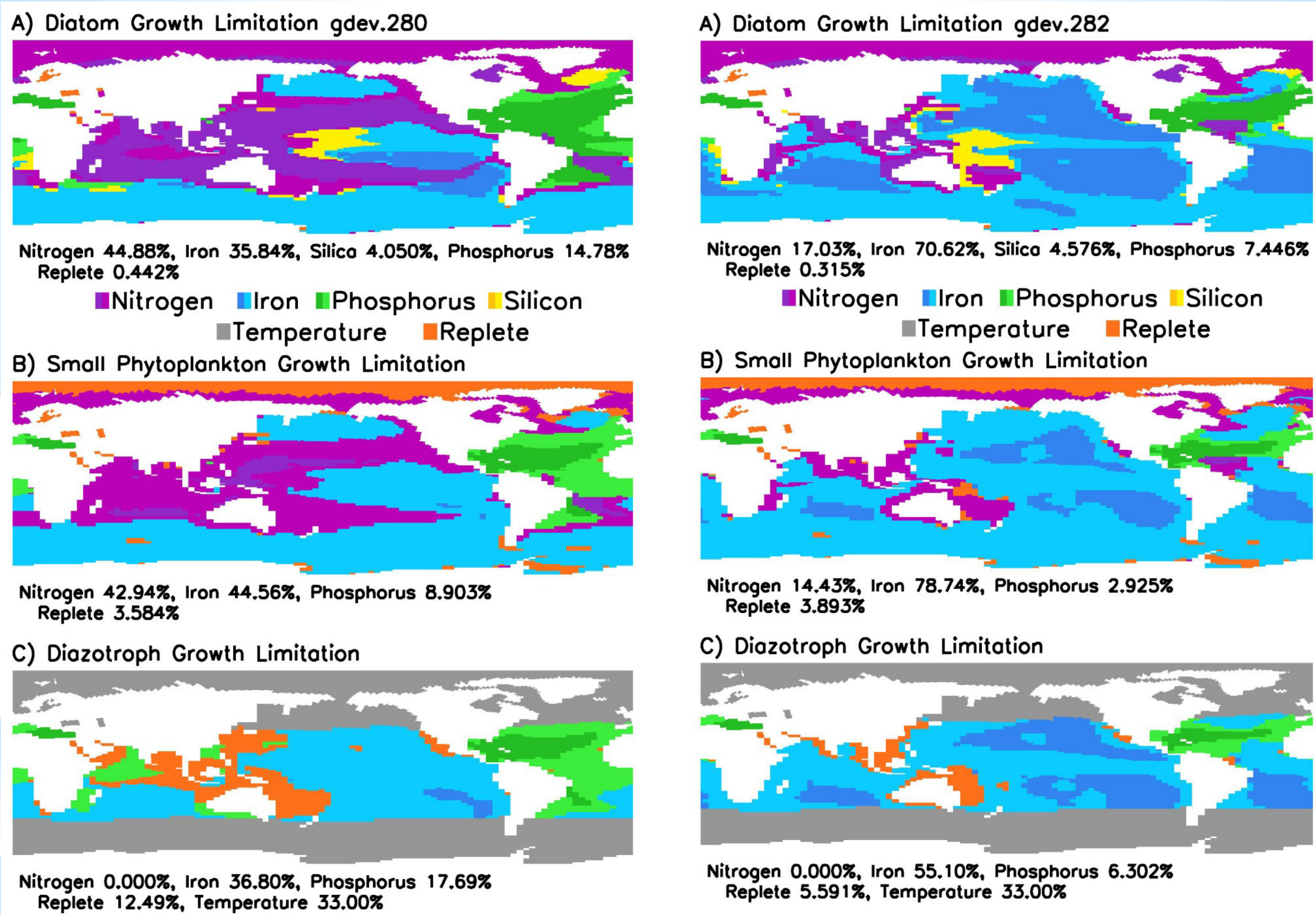
Hydrothermal Vents: Constant source along ridges and known vent sites.

**Experiment with all atmospheric nutrient deposition turned off, compare standard model with no deposition case after 124 years.**

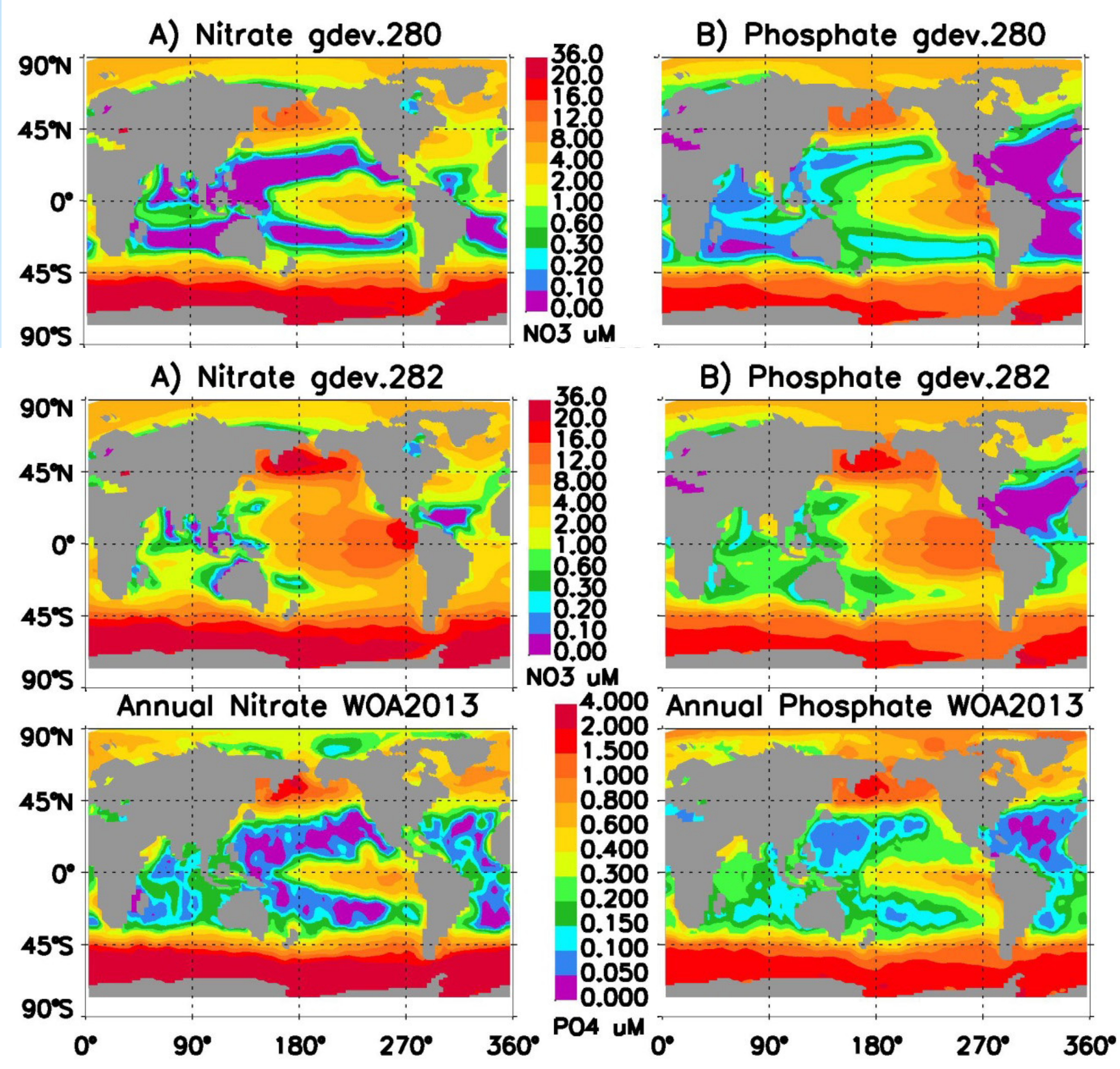
# Atmospheric Deposition Effects on Surface Iron



# Atmospheric Deposition Effects on Nutrient Limitation



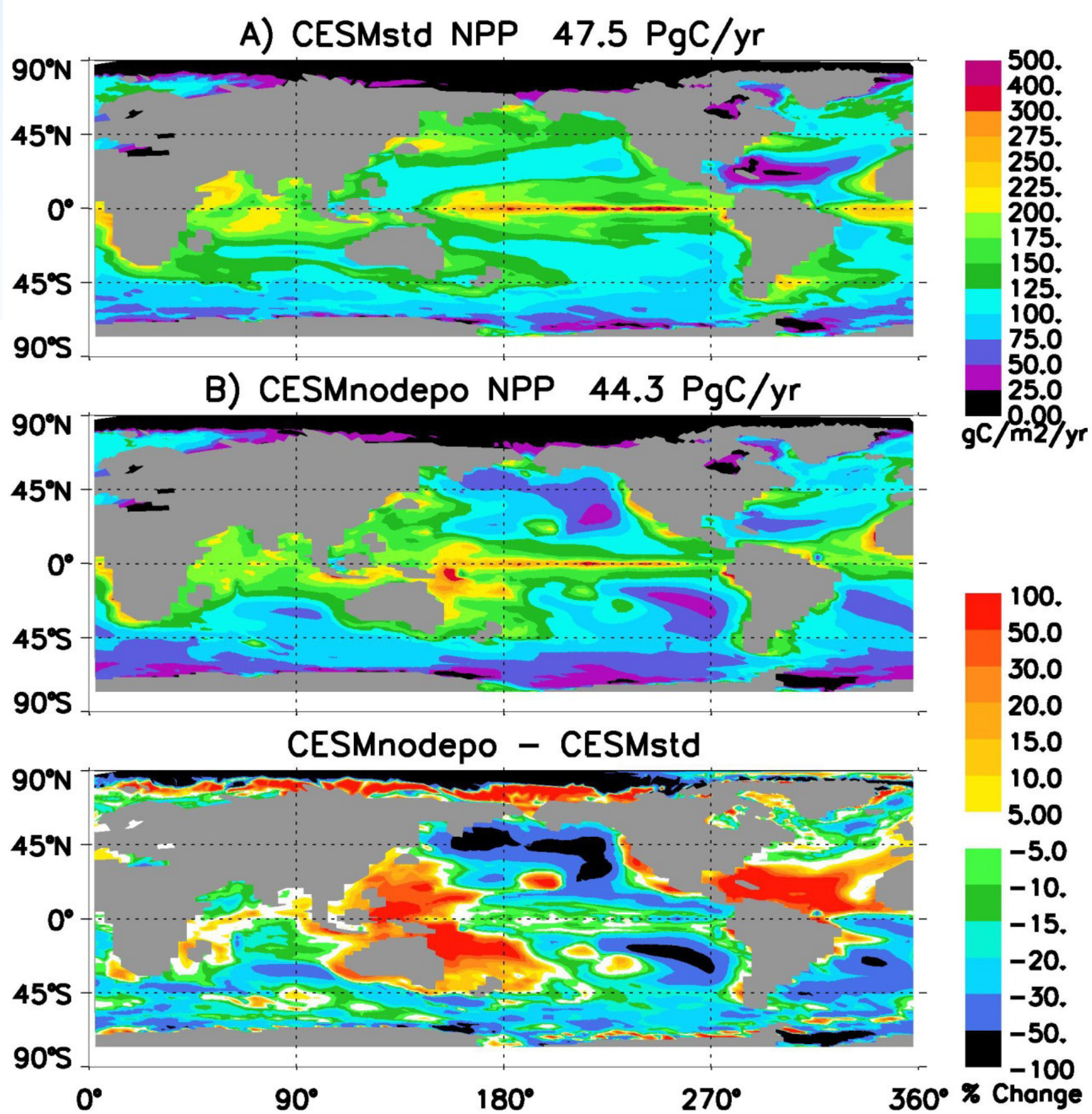
# Atmospheric Deposition Effects on Surface Nutrients



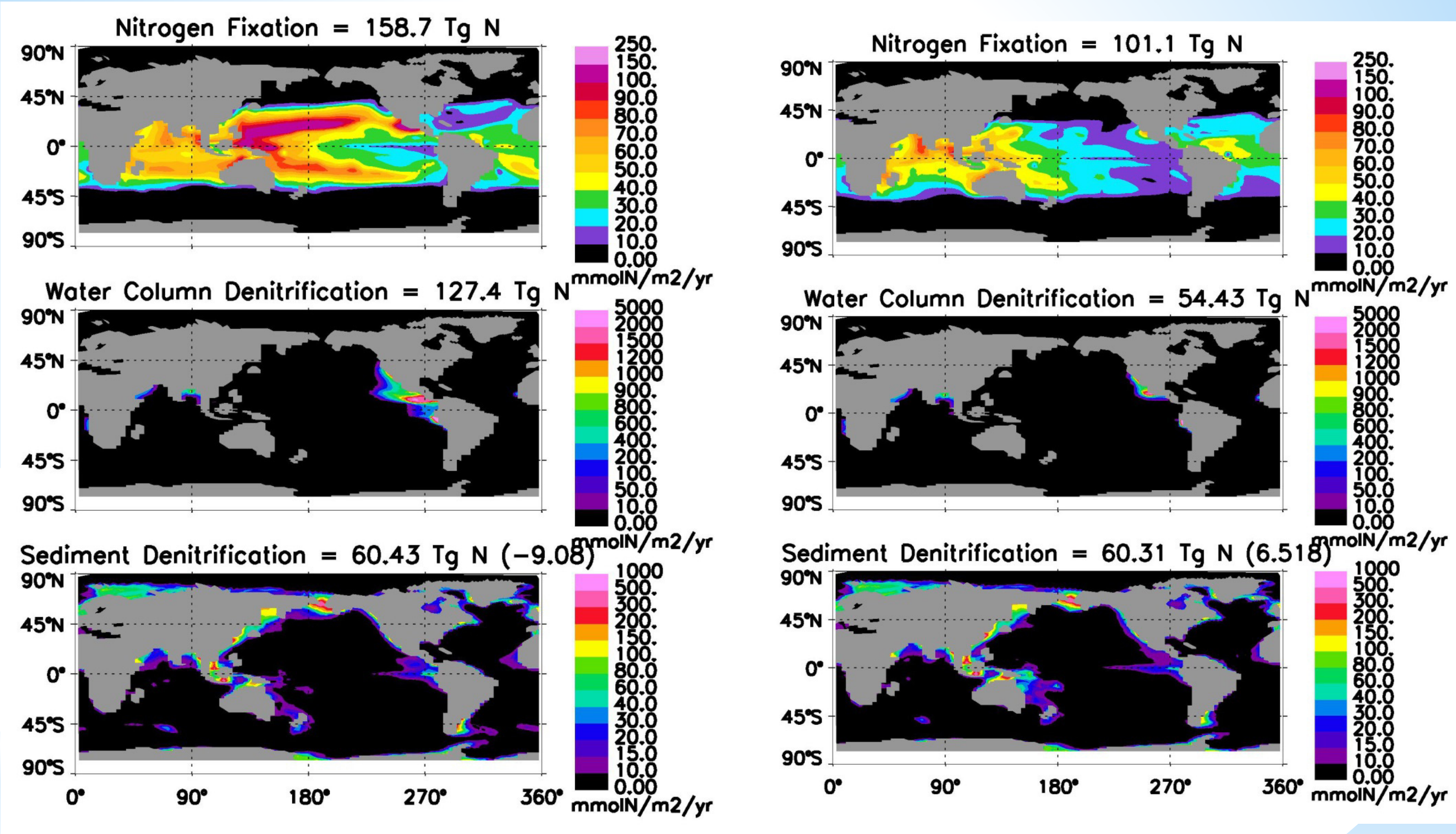

**CESM standard**

**CESM no deposition**

# Atmospheric Deposition Effects on NPP



# Atmospheric Deposition Effects on Nitrogen Cycle



## Summary and Discussion Topics

1) Atmospheric nutrient deposition strongly impacts marine productivity and biogeochemistry (Fe >> N >> Si and P)
2) Nitrogen cycle fluxes appear more sensitive to perturbations than carbon cycle fluxes.
3) Nutrient deposition can have effects far from deposition sites due to lateral transport (particularly where the nutrient is not limiting growth at deposition site).
4) How does atmospheric nutrient deposition help structure communities?
5) Current coupled climate or Earth System Models (ESMs) have not fully incorporated the nutrient deposition feedbacks in climate change studies.
6) Uncertainties in iron source magnitudes, scavenging losses, and the role of ligands are hampering efforts to simulate nutrient deposition feedbacks with climate (future warming scenarios, last glacial maximum).