Marine Ecosystem Dynamics and Biogeochemistry in the CESM1-BGC:

1990s vs. Observations

1990s vs. 2090s RCP 8.5

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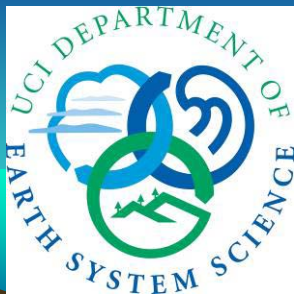
Funded by the National Science Foundation



Biogeochemical Elemental Cycling (BEC) Model

Small Phytoplankton
C, Chl, Fe, CaCO3

Diatoms
C, Chl, Fe, Si

Diazotrophs
C, Chl, Fe

Zooplankton
C

Sinking Particulates
C, Fe, Si, $CaCO_3$, Dust

Dissolved Organic Matter
C, N, P, Fe

C/N/P ratios are fixed, diazotroph N/P higher.
Coarse resolution NCAR CESM POP2 ocean model
~1 degree resolution with 60 vertical levels

Nitrate

Ammonium

Phosphate

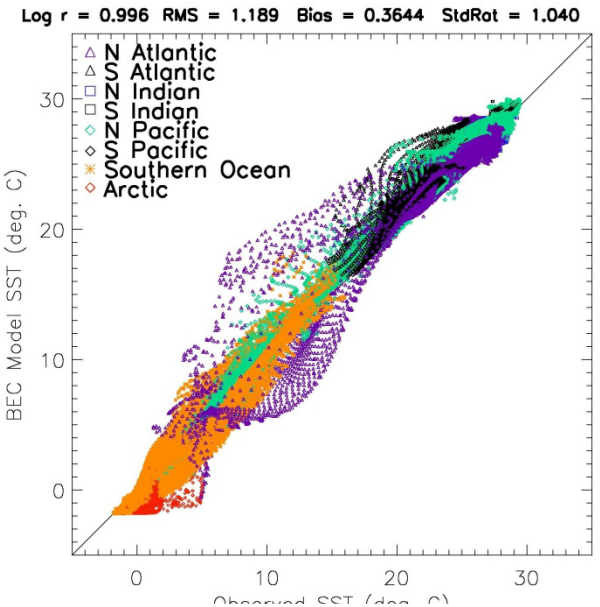
Iron

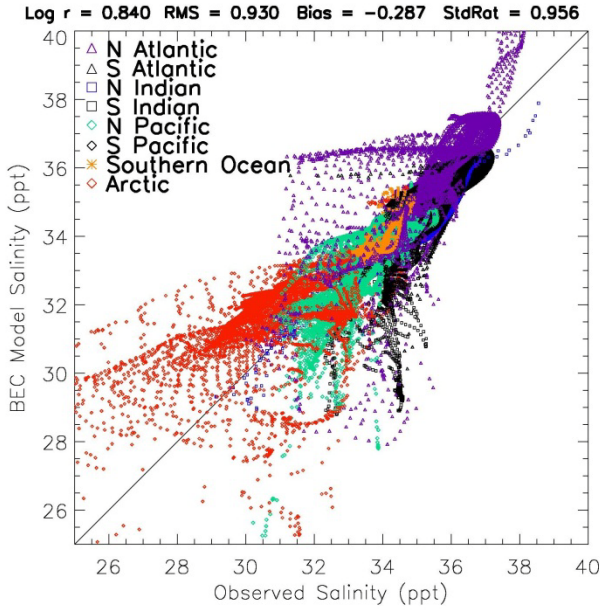
Silicate

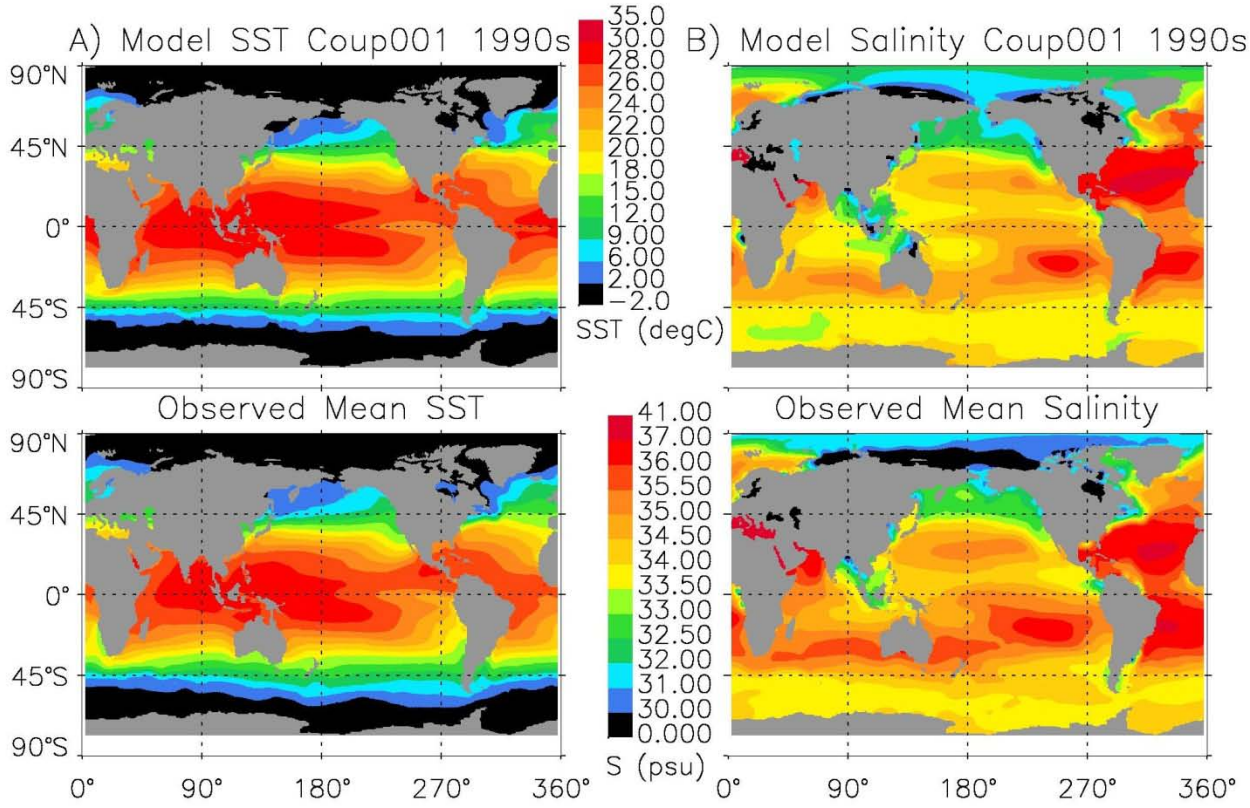
Oxygen

DIC

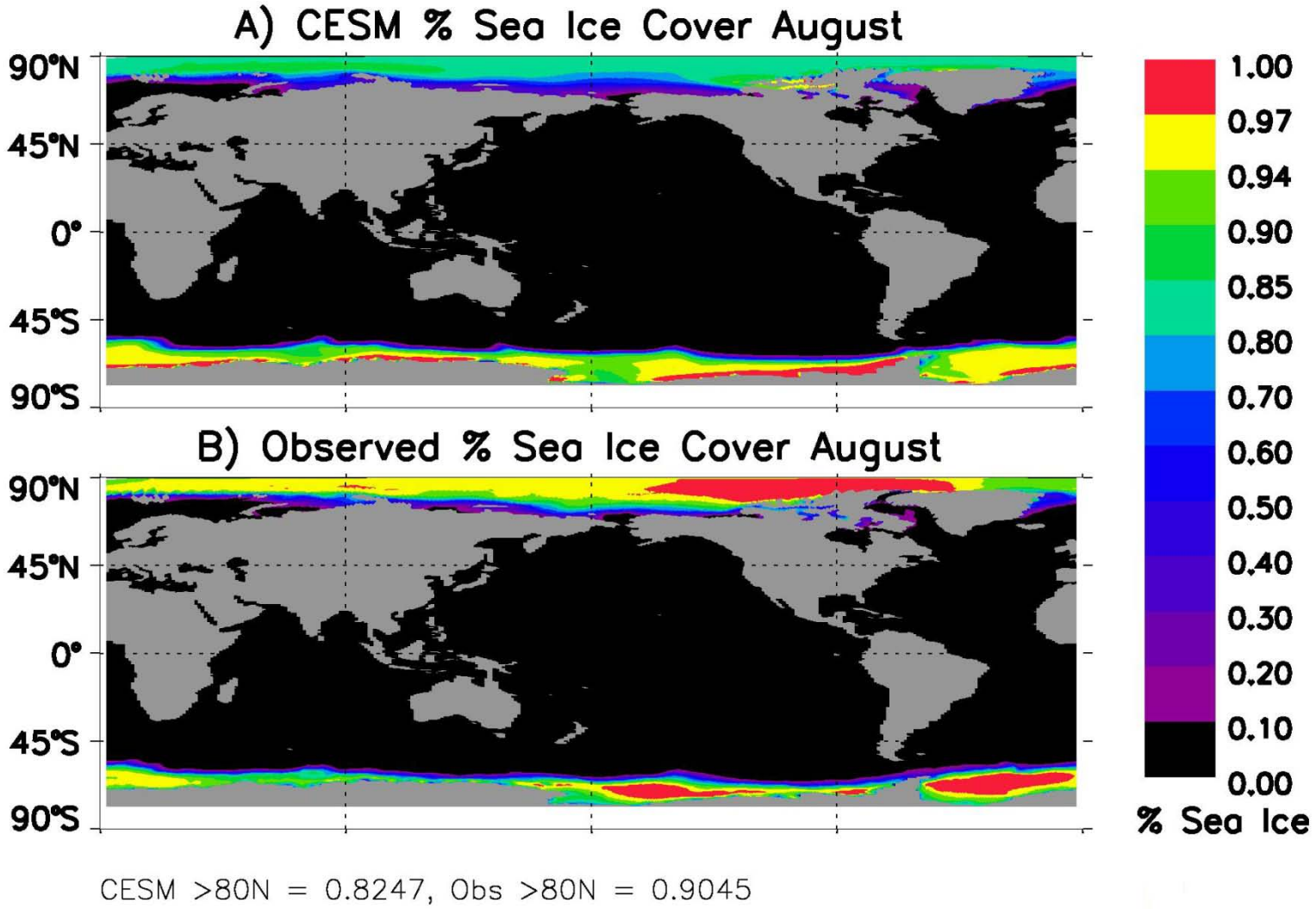
Alkalinity



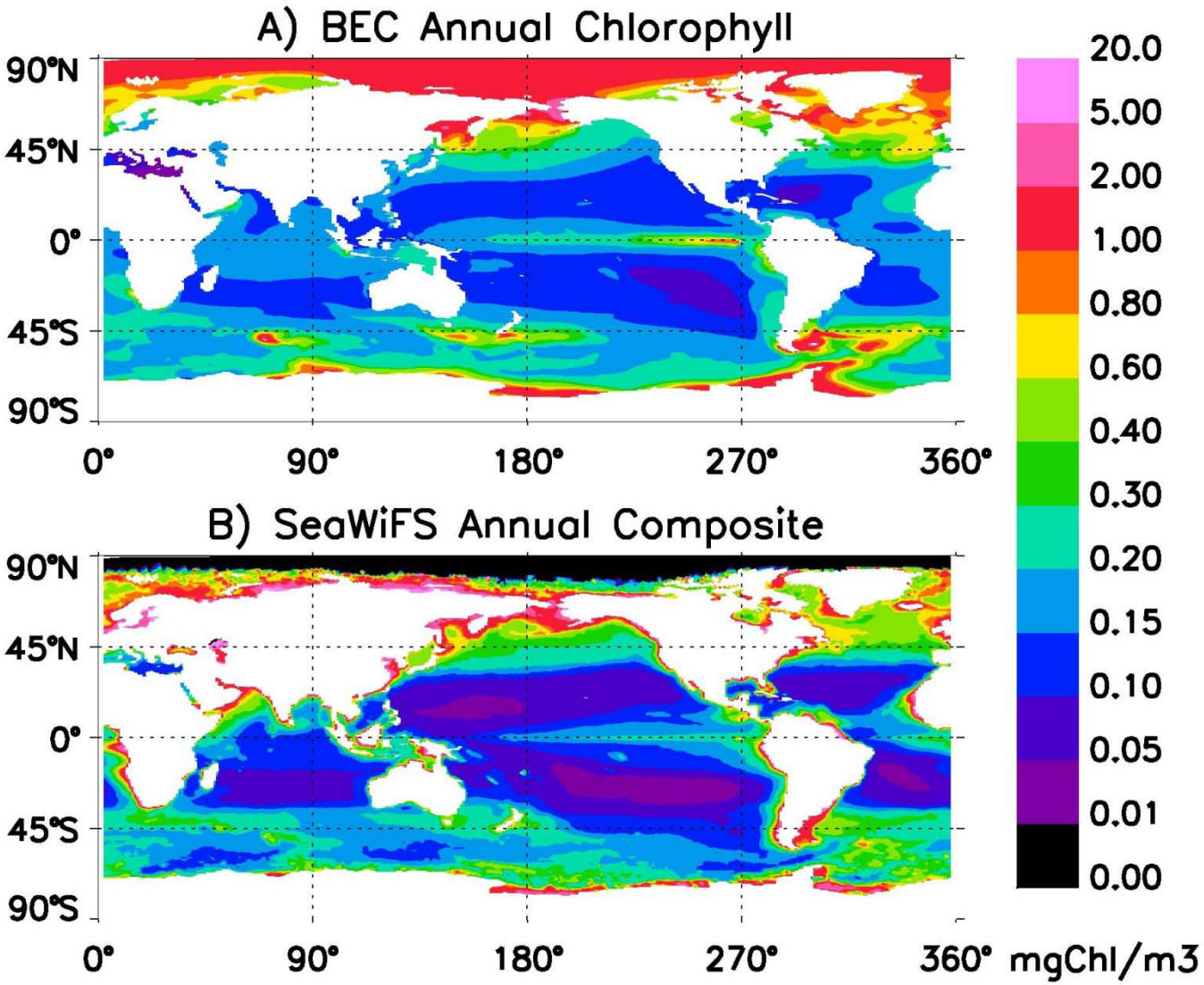




Sea surface temperature close to observations, salinity not as close, biases in several regions.

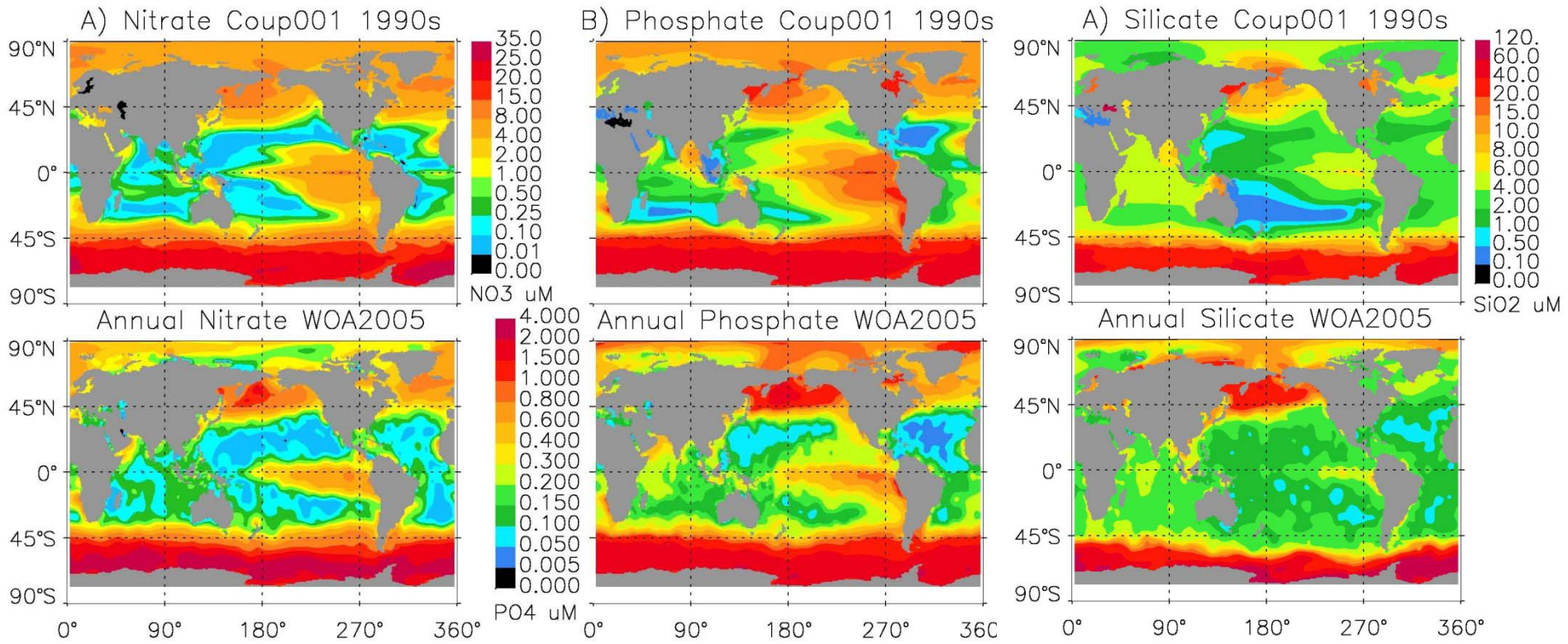


Less summertime sea ice cover than is observed. Allows too much light into the ocean fueling phytoplankton blooms throughout the Arctic.



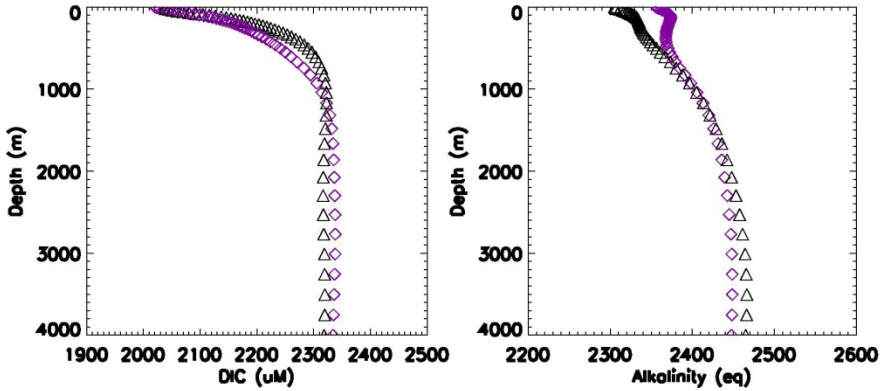
Reasonable simulation of surface chlorophyll concentrations.

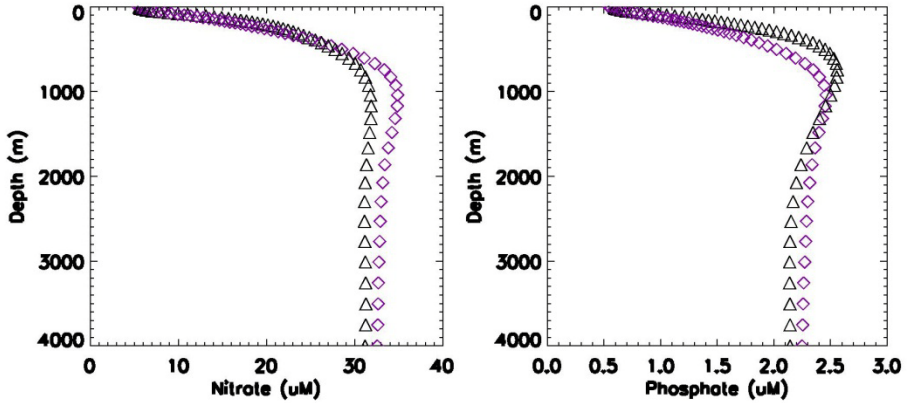
Positive biases in the Arctic and in the subtropical gyres.

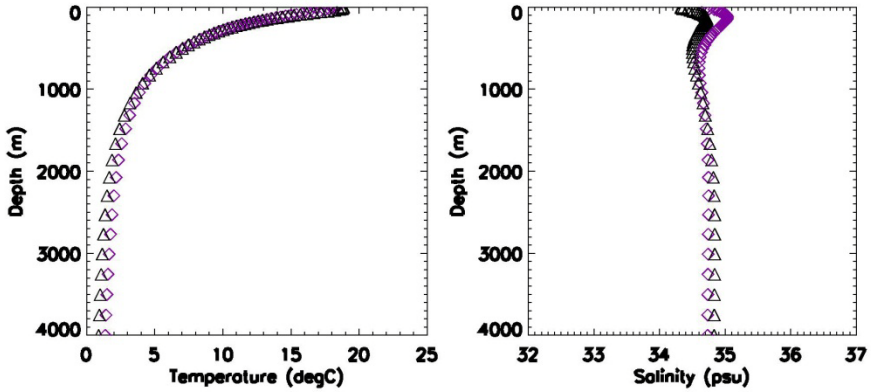


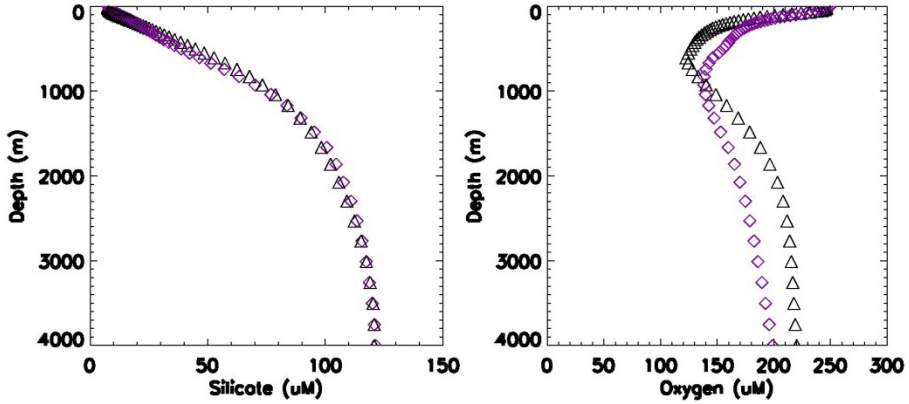
Surface macronutrient concentrations are reasonably simulated (r ~0.8-0.9).

Negative biases in the subarctic North Pacific and the Southern Ocean.









NO3 N = 55 points
DIC Log r = 0.975
DIC Mean bias = 18.3123
DIC rms = 0.005
DIC Stdev. Mod = 0.064
DIC Stdev. Obs = 0.064
DIC Ratio StdDev Mod/Obs = 0.994

TEMP N = 55 points
TEMP Log r = 0.998
TEMP Mean bias = −0.0600
TEMP rms = 0.072
TEMP Stdev. Mod = 0.430
TEMP Stdev. Obs = 0.370
TEMP Ratio StdDev Mod/Obs = 1.161

PO4 N = 55 points
ALK Log r = 0.979
ALK Mean bias = −20.678
ALK rms = 0.005
ALK Stdev. Mod = 0.062
ALK Stdev. Obs = 0.062
ALK Ratio StdDev Mod/Obs = 1.006

O2 N = 55 points
SALT Log r = 0.181
SALT Mean bias = −0.1782
SALT rms = 0.003

SALT Stdev. Mod = 0.028
SALT Stdev. Obs = 0.028
SALT Ratio StdDev Mod/Obs = 0.998

NO3 N = 55 points
NO3 Log r = 0.990
NO3 Mean bias = −0.0561
NO3 rms = 0.038
NO3 Stdev. Mod = 0.239
NO3 Stdev. Obs = 0.257
NO3 Ratio StdDev Mod/Obs = 0.932

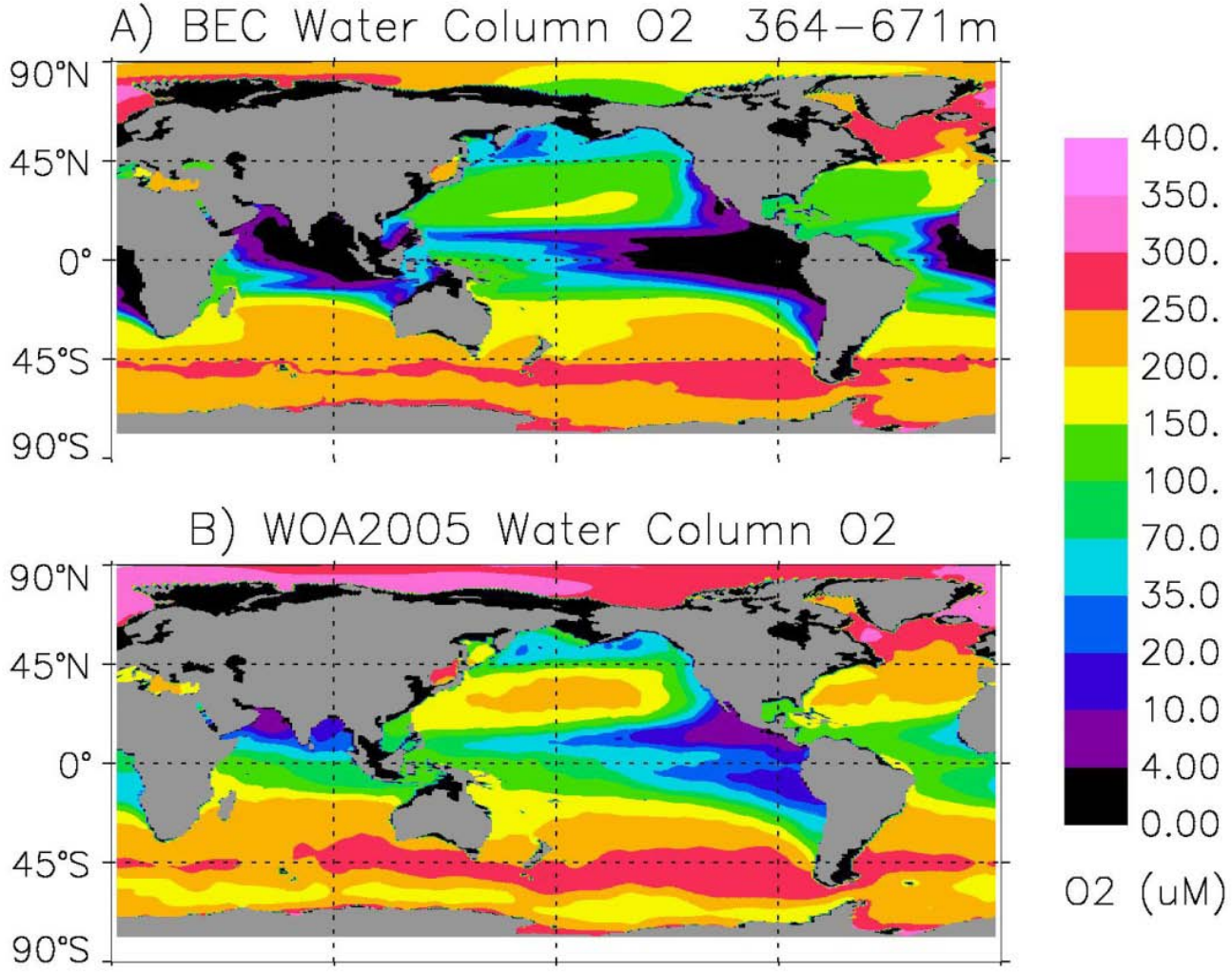
SiO4 N = 55 points
SiO4 Log r = 0.997
SiO4 Mean bias = 0.86583
SiO4 rms = 0.034
SiO4 Stdev. Mod = 0.417
SiO4 Stdev. Obs = 0.403
SiO4 Ratio StdDev Mod/Obs = 1.035

PO4 N = 55 points
PO4 Log r = 0.969
PO4 Mean bias = 0.17210
PO4 rms = 0.071
PO4 Stdev. Mod = 0.199
PO4 Stdev. Obs = 0.210
PO4 Ratio StdDev Mod/Obs = 0.948

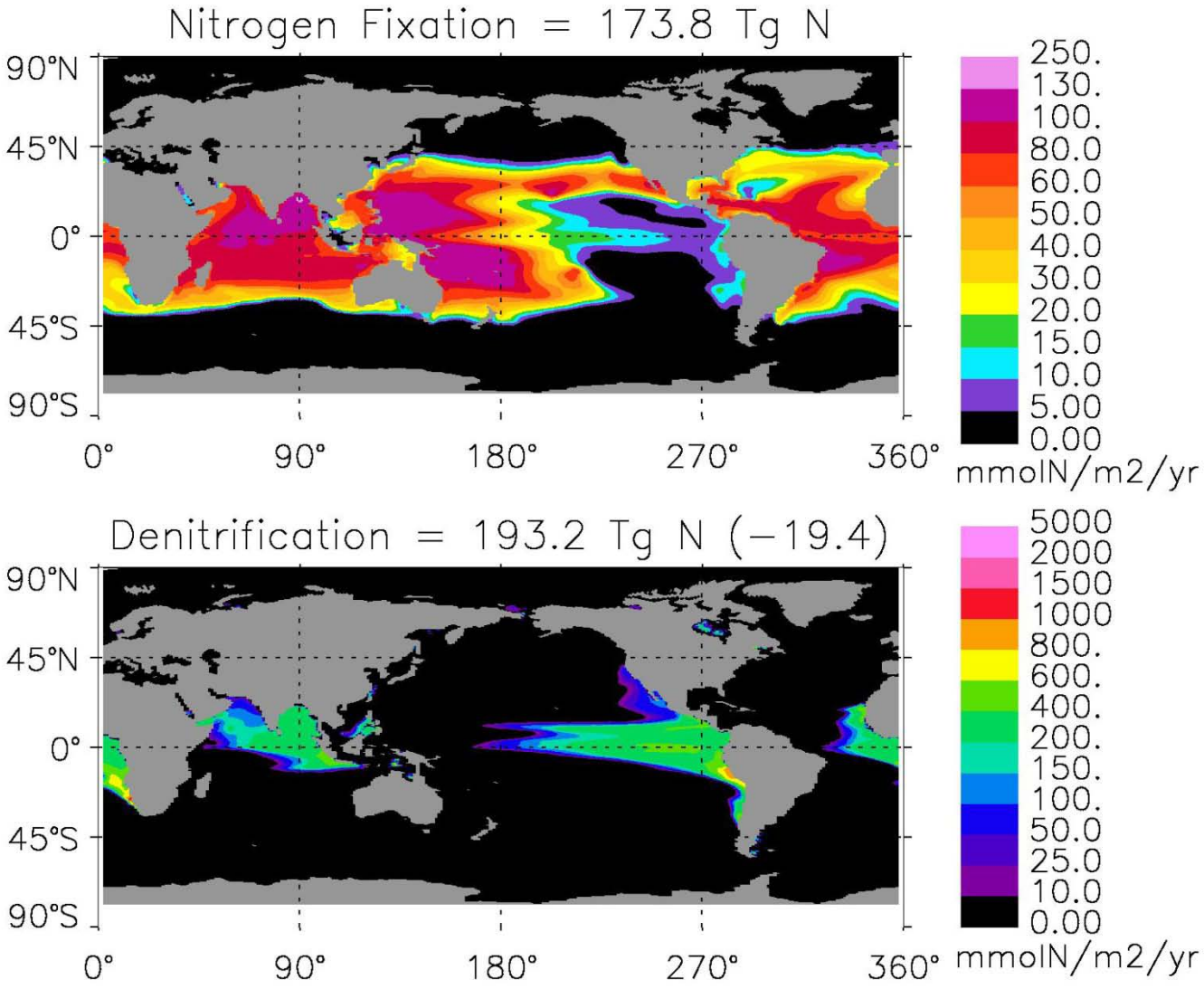
O2 N = 55 points
O2 Log r = 0.823
O2 Mean bias = −5.1834
O2 rms = 0.058

O2 Stdev. Mod = 0.107
O2 Stdev. Obs = 0.085
O2 Ratio StdDev Mod/Obs = 1.246

Too much sinking organic matter remineralizes at mid-depths, not enough makes it to the deep ocean. The opposite problem is apparent for sinking $CaCO_3$, which controls the alkalinity.



Significant biases in the mid-depth oxygen concentrations and in the location and size of the Oxygen Minimum Zones (OMZs, where O2 < 20 µM).

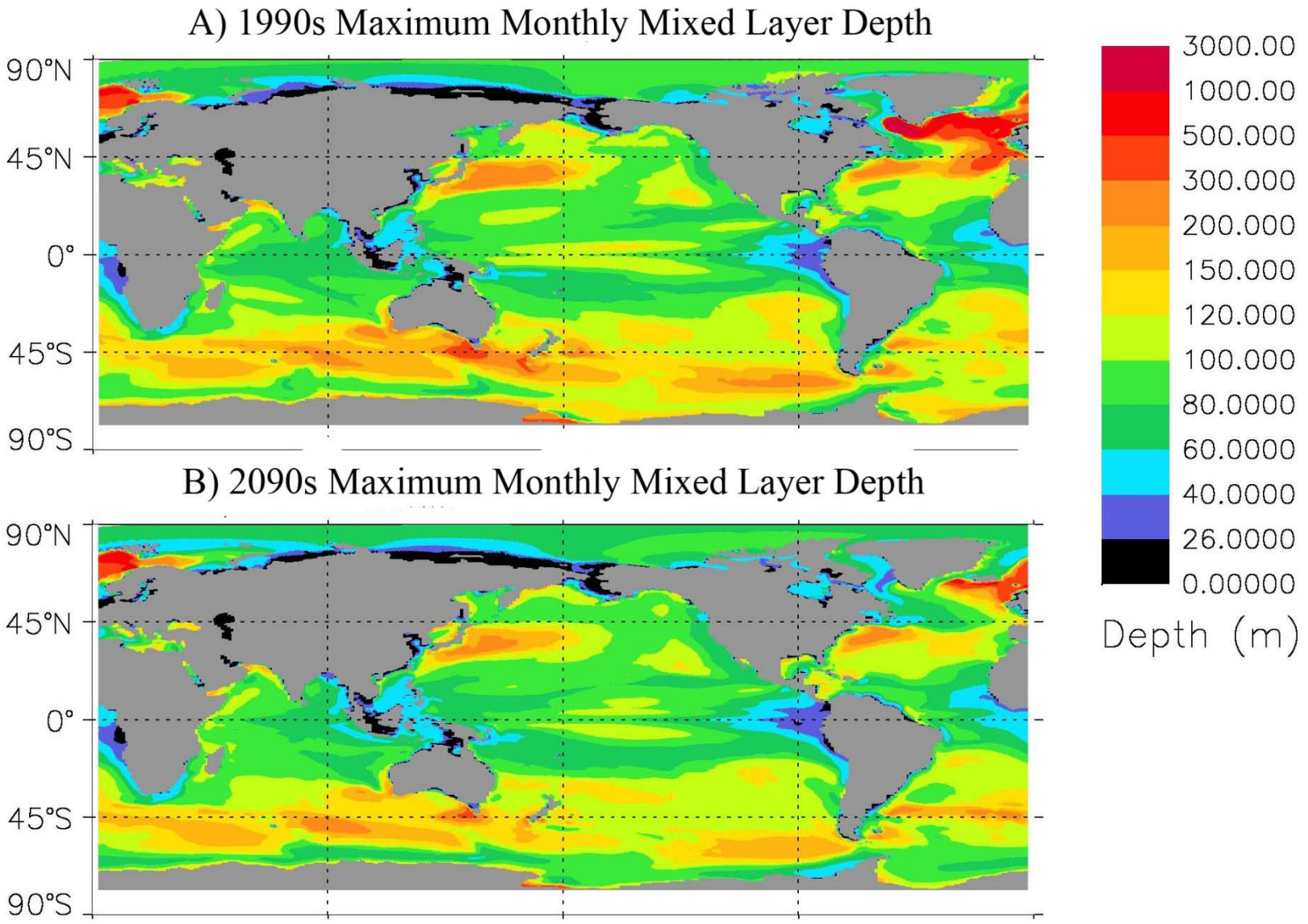


Due to the oxygen biases, denitrification is too high and too spatially extensive, even with the downscaling factor.

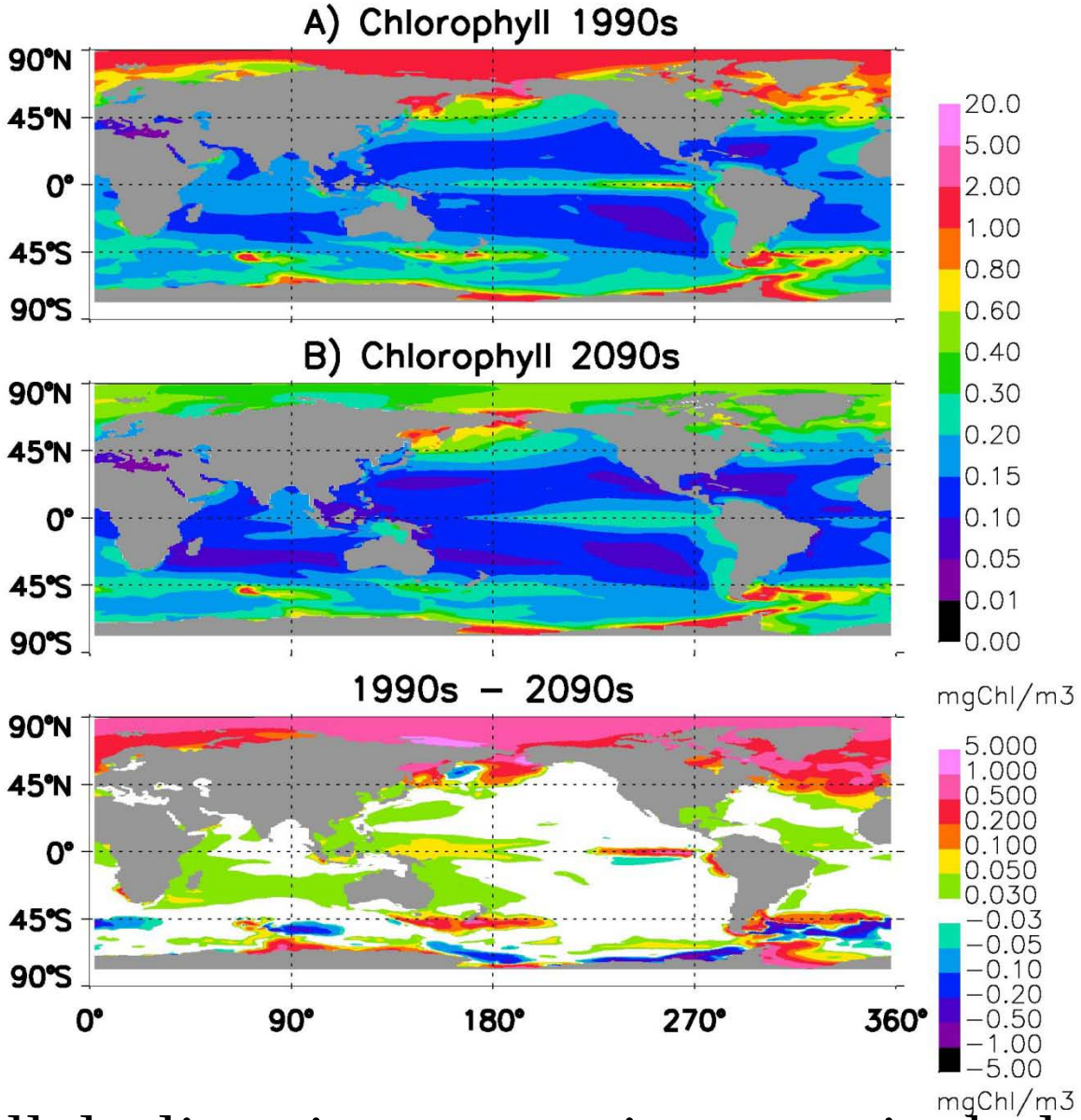
Table 1. Key biogeochemical fluxes from the preindustrial control simulation, the 1990s and the 2090s under the RCP 4.5 and 8.5 scenarios are shown.

Flux	Preindustrial	1990s	RCP4.5 2090s	RCP8.5 2090s
Primary Production[a]	55.6	56.1	54.9	52.9
Sinking POC 100m[a]	8.10	8.07	7.66	7.00
Sinking $CaCO_3$ 100m[a]	0.762	0.752	0.723	0.726
Rain Ratio ($CaCO_3$/POC) 100m	0.094	0.093	0.094	0.10
Nitrogen Fixation[b]	174	173	159	141
Nitrogen Deposition[b]	6.70	30.0	21.3	30.9
Denitrification[b]	192	193	187	185
N Cycle Imbalance[c]	-11.3	10	-6.7	-13.1
Air-Sea CO_2 Flux[a]	-0.0693	2.19	1.89	4.94
Diatom % Primary Production	38	37	35	29

a – PgC/yr; b – TgN/yr; c – N deposition + fixation – denitrification;

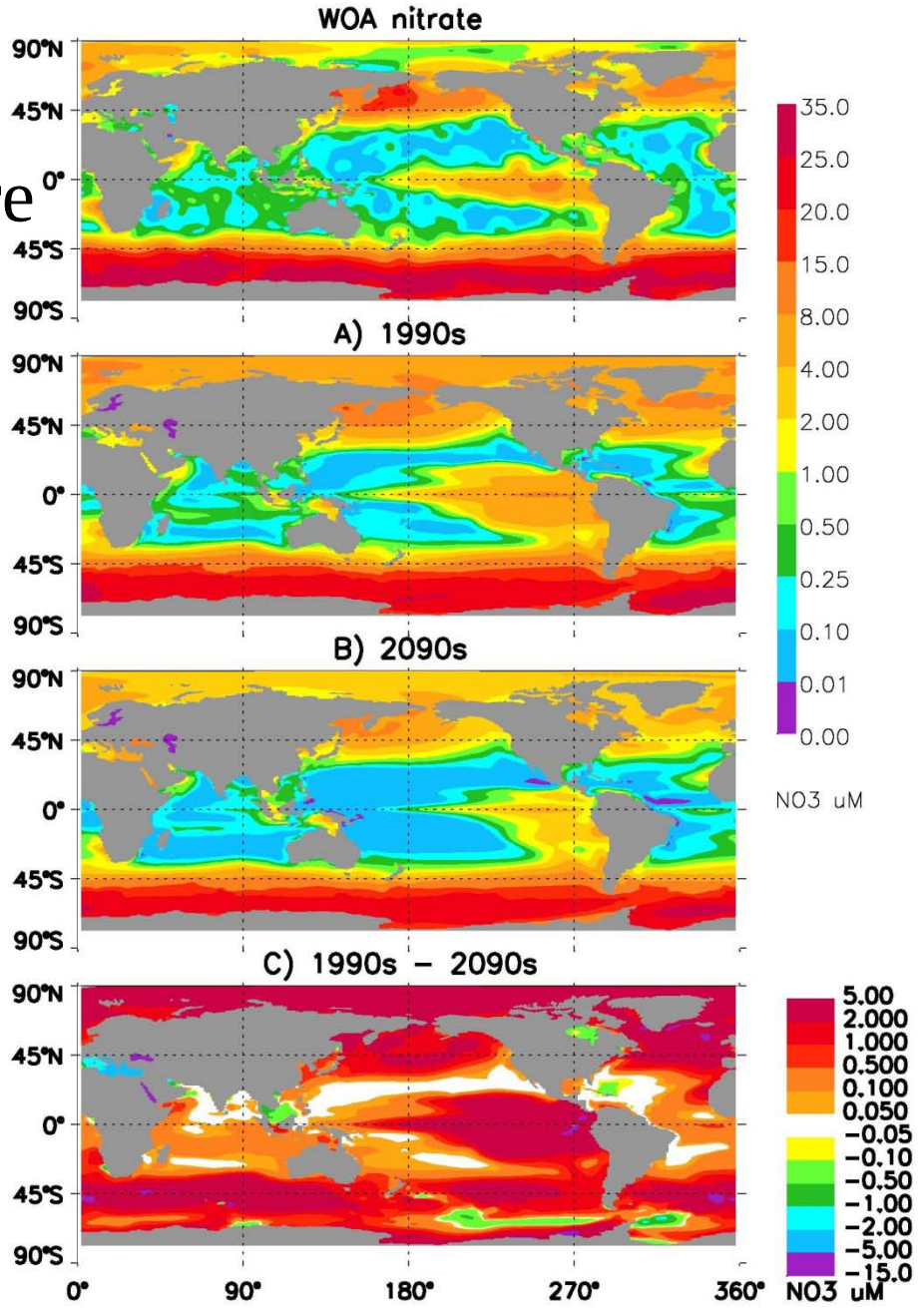


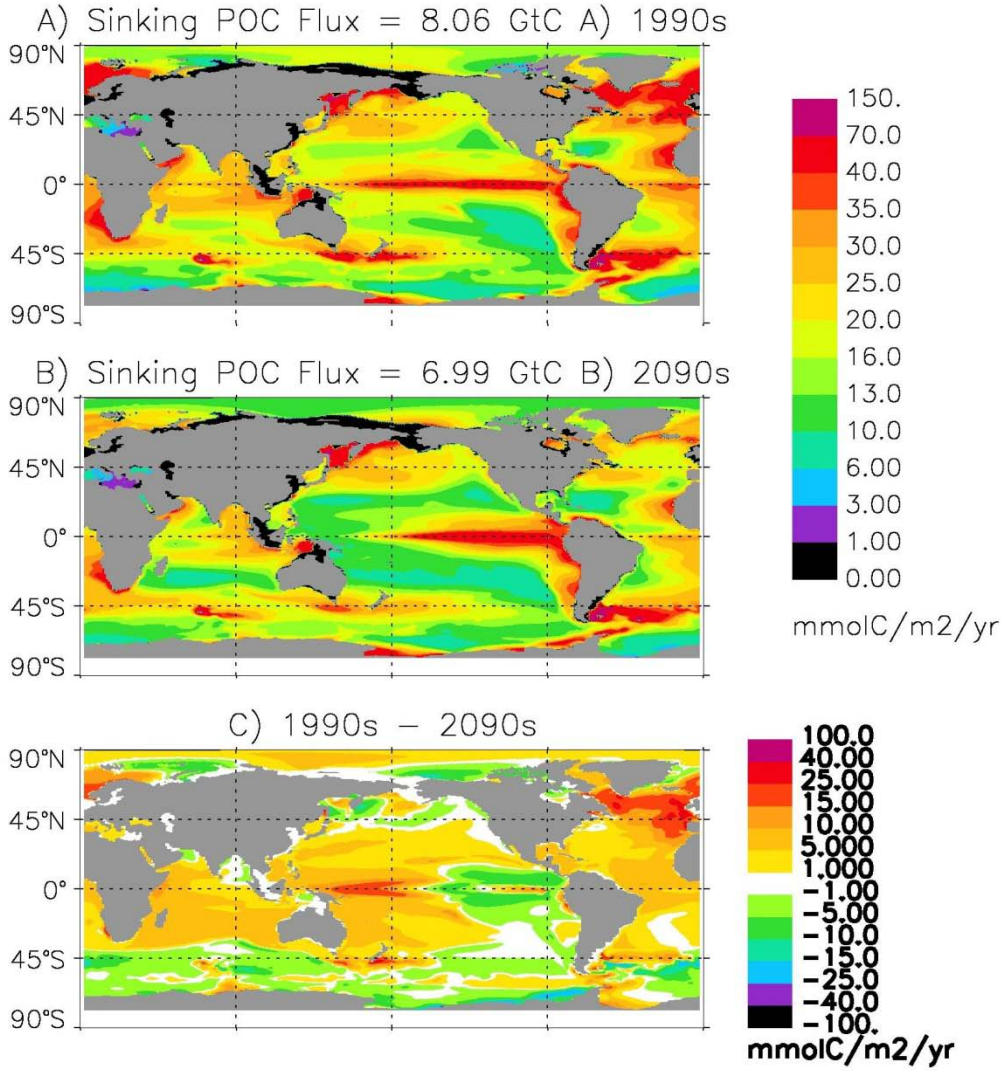
Mixed layers get shallow as the upper ocean warms and stratification increases. North Atlantic deep convection is greatly reduced.



Chlorophyll declines in most regions, particularly in the Arctic and the high latitude North Atlantic, some increases in the Southern Ocean.

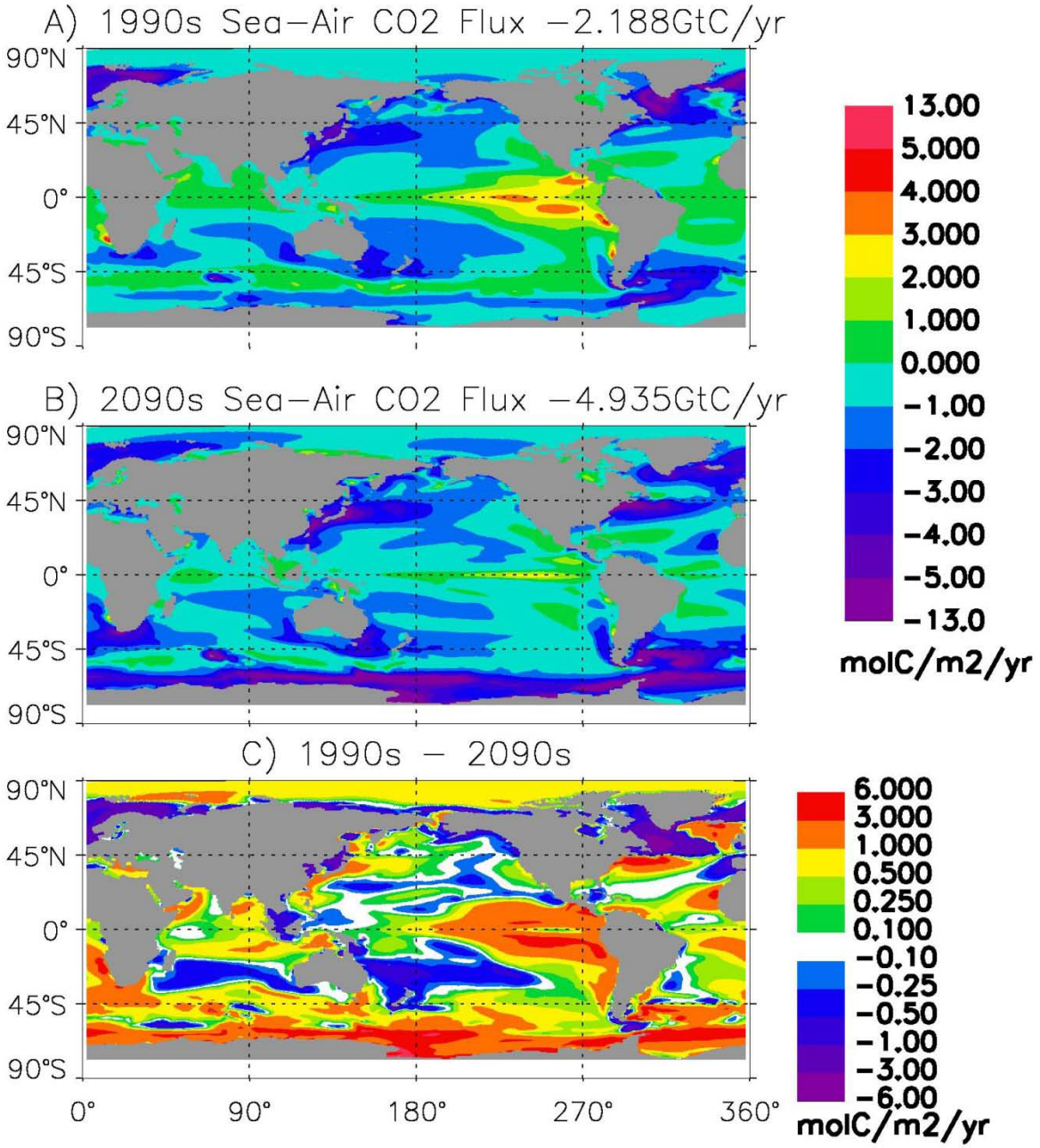
Surface nitrate concentrations are lower nearly everywhere.



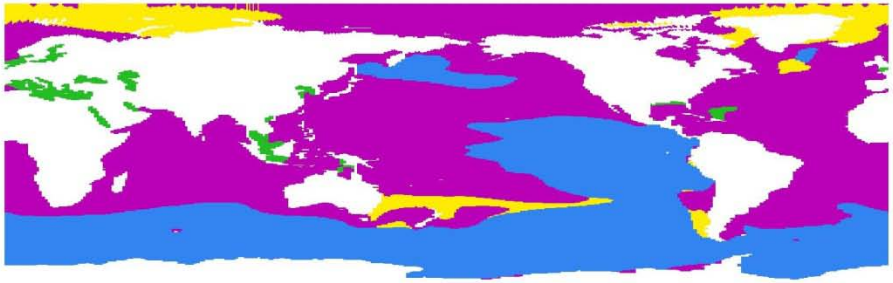


Large decreases in export production in the high latitude North Atlantic and over most low latitude areas.

Increased export in the equatorial Pacific and over much of the Southern Ocean.


A) 1990s Sea–Air CO2 Flux −2.188GtC/yr
B) 2090s Sea–Air CO2 Flux −4.935GtC/yr
C) 1990s − 2090s
90°N
45°N
0°
45°S
90°S
0°
90°
180°
270°
360°
13.00
5.000
4.000
3.000
2.000
1.000
0.000
−1.00
−2.00
−3.00
−4.00
−5.00
−13.0
molC/m2/yr
6.000
3.000
1.000
0.500
0.250
0.100
−0.10
−0.25
−0.50
−1.00
−3.00
−6.00
molC/m2/yr

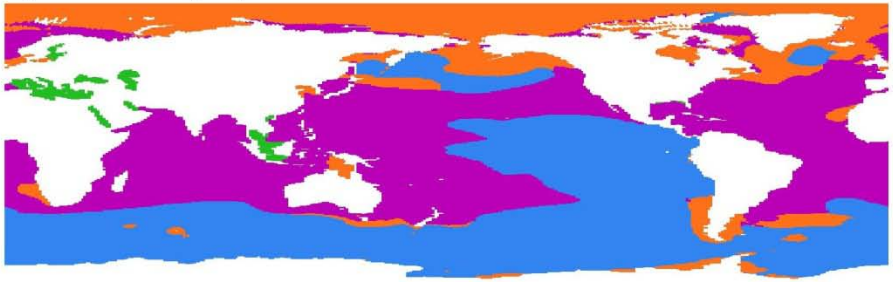
A) Diatom Growth Limitation Coup001 1990s



Nitrogen 57.70%, Iron 37.90%, Silica 2.255%, Phosphorus 2.137%
Replete 0.000%

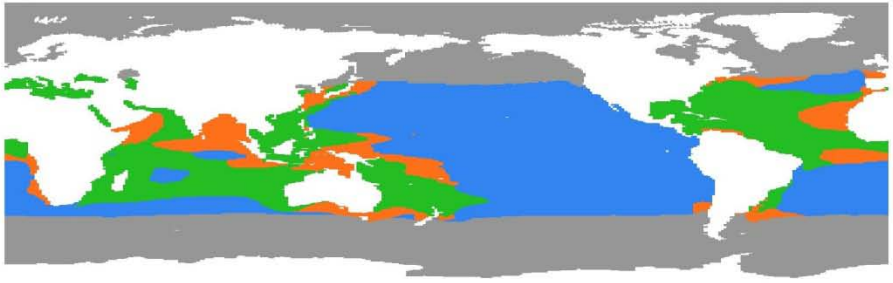
Nitrogen Iron Phosphorus Silicon
Light Temperature Light/Grazing

B) Small Phytoplankton Growth Limitation



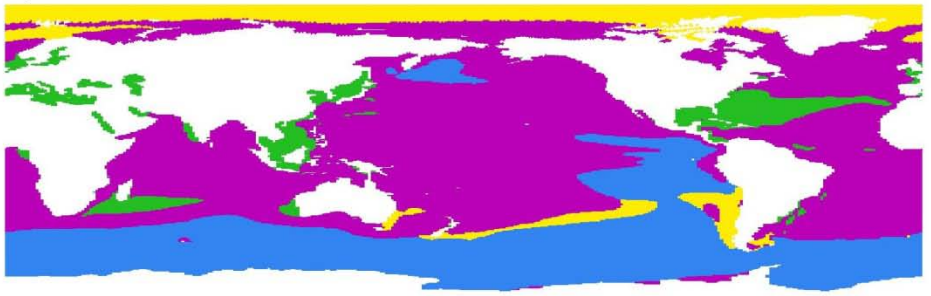
Nitrogen 50.40%, Iron 38.31%, Phosphorus 1.645%
Replete 9.632%

C) Diazotroph Growth Limitation



Nitrogen 0.000%, Iron 38.18%, Phosphorus 21.74%
Replete 9.144%, Temperature 30.92%

A) Diatom Growth Limitation RCP 8.5 2090s



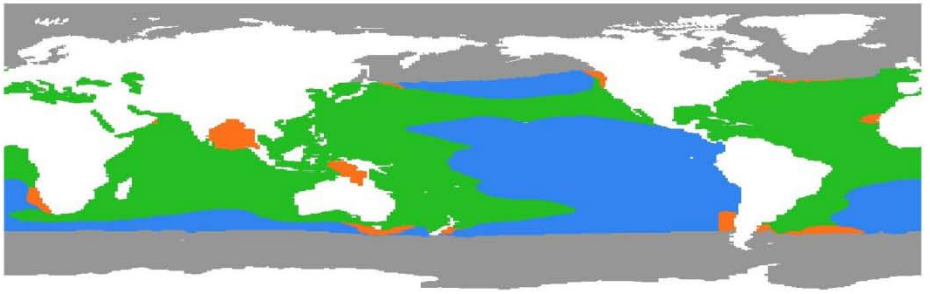
Nitrogen 62.61%, Iron 26.89%, Silica 2.582%, Phosphorus 7.898%
Replete 0.000%

Nitrogen Iron Phosphorus Silicon
Light Temperature Light/Grazing

B) Small Phytoplankton Growth Limitation

Nitrogen 60.43%, Iron 29.37%, Phosphorus 5.956%
Replete 4.235%

C) Diazotroph Growth Limitation



Nitrogen 0.000%, Iron 28.26%, Phosphorus 43.67%
Replete 2.537%, Temperature 25.52%

Conclusions

1) The CESM-BGC reproduces the global-scale, observed patterns of sea surface temperature, sea surface salinity, chlorophyll and nutrient concentrations.
2) Significant biases exist in the simulated oxygen concentrations at mid-depths.
3) The biological pump is significantly weakened by the 2090s in the RCP 8.5 climate simulation, acting as a positive feedback to the climate warming.
4) The reduced export production is due to stronger stratification as surface waters warm and a big decrease in deep convective mixing in the high-latitude North Atlantic.