Mixing Processes and Ventilation in the CESM x3 Ocean Model: Influences on Biogeochemistry

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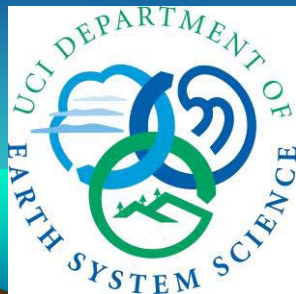
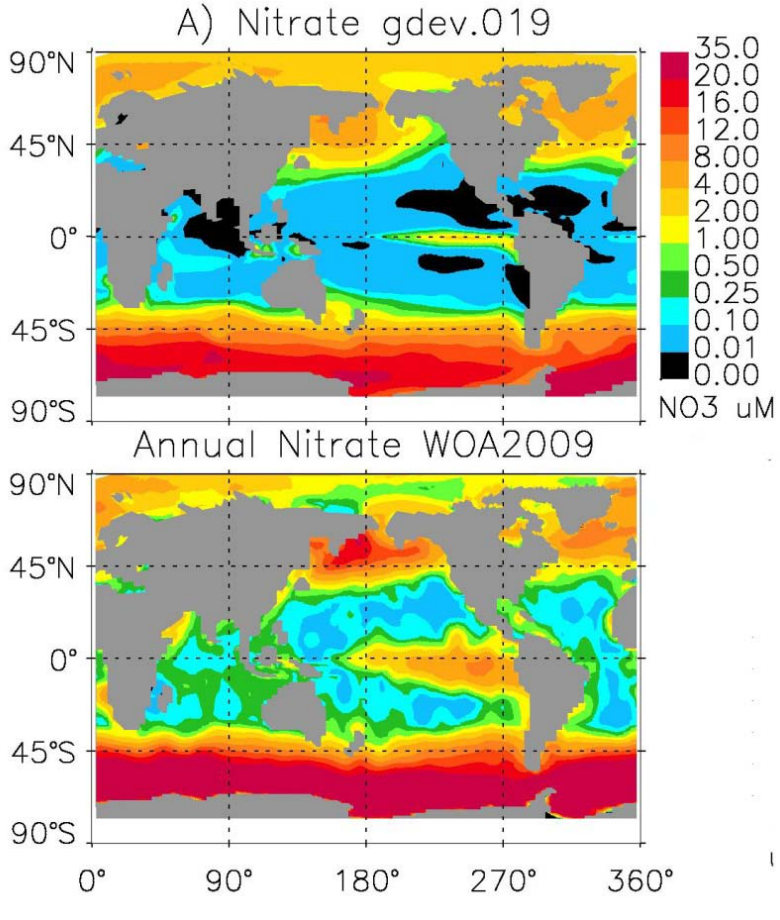


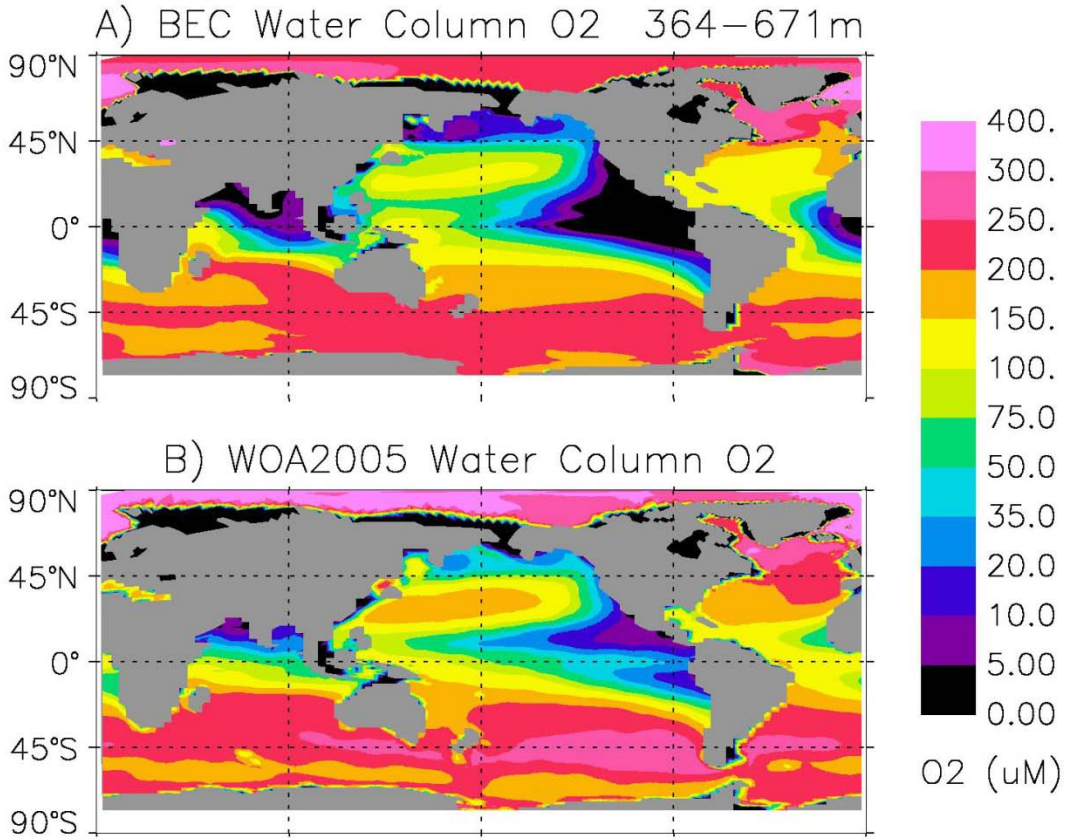
BGC Biases in the Standard CESM-BEC due to BGC and Physics

1) Low nutrient bias at high latitudes.

2) Oxygen Minimum Zones (OMZs) too large.

OMZs occur at mid-depths (~150-650m) where there is weak ventilation and a substantial flux of sinking organic matter, leading to depletion of $[O_2]$ to < 20 µM.





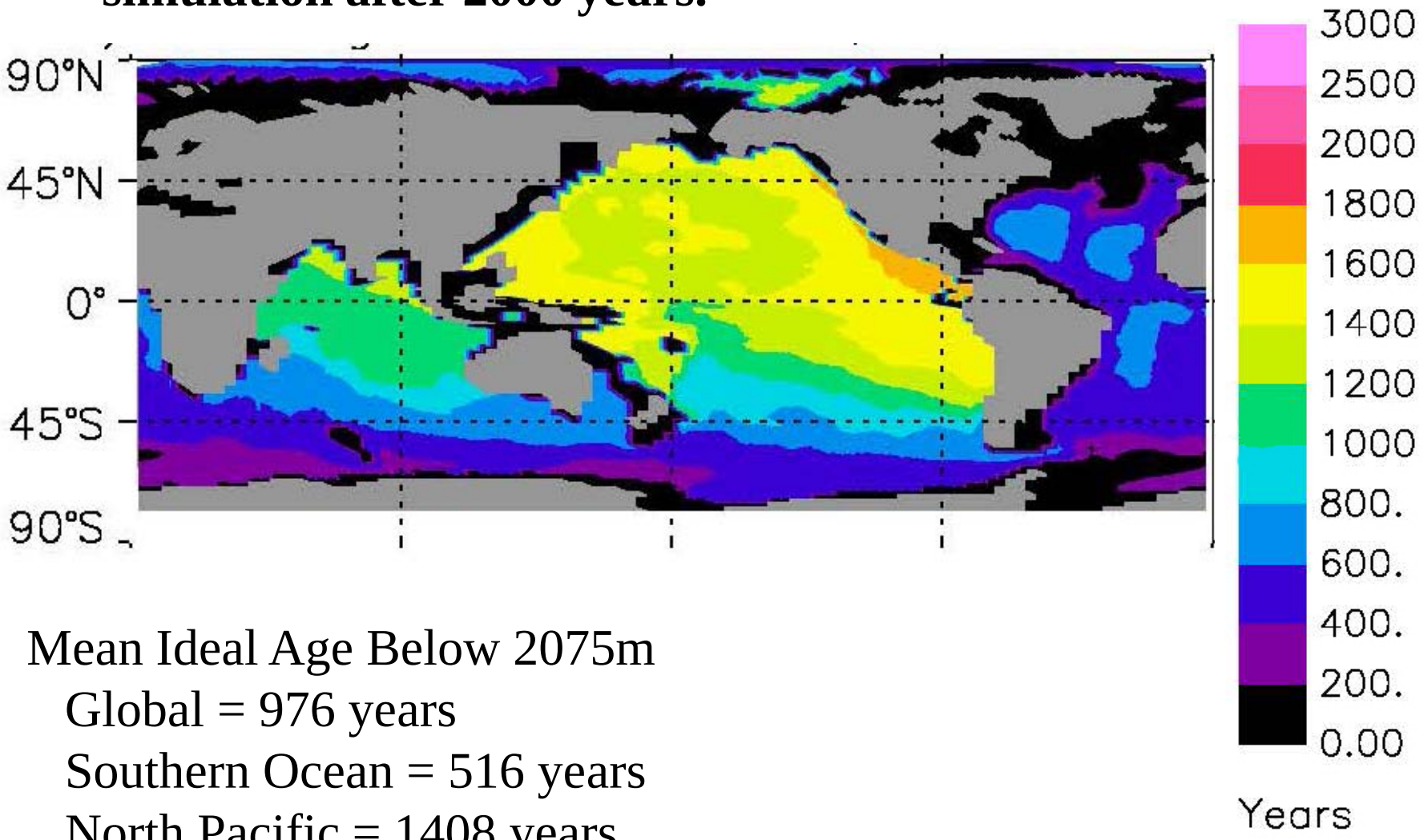
All simulations gx3v7 resolution, active ocean and sea ice,
with strong surface salinity restoring,
and normal year forcing.
Issues discussed are also present at x1 resolution.

Standard Simulation STD:

1) **standard release physics (cesm1.0.1)**
2) **turned off scaling of denitrification**
3) **increased remineralization lengthscale (+20m)**

All other simulations include modified BGC code, which includes additional processes and optimization of prescribed remineralization curves as a function of depth.

Deep Ocean (>2075m) Ideal Age Distribution from STD model simulation after 2000 years.



Mean Ideal Age Below 2075m

Global = 976 years

Southern Ocean = 516 years

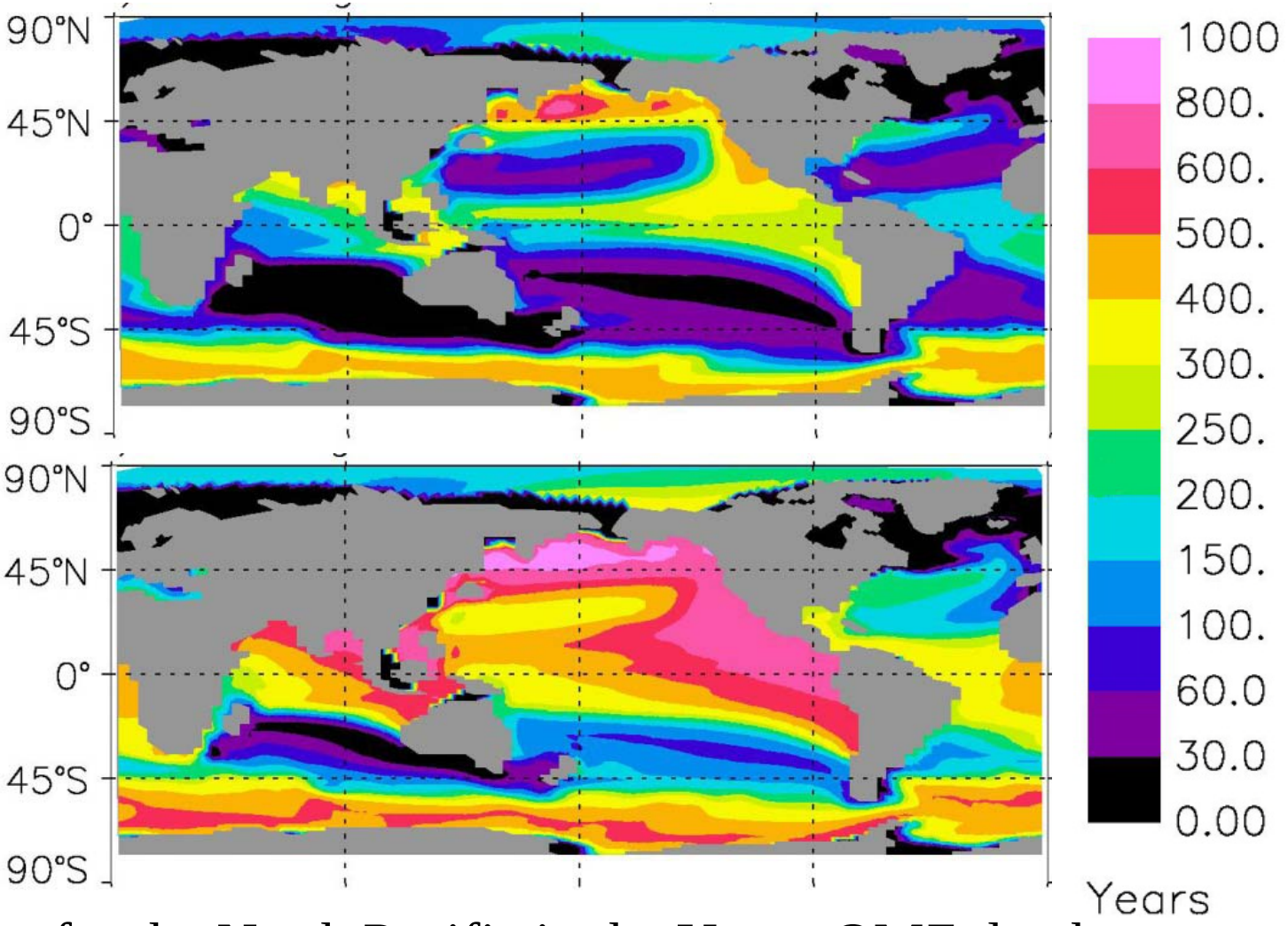
North Pacific = 1408 years

North Pacific age continuing to increase as simulation progresses.

Ideal Age Distribution from STD model simulation at 2000 years.

Upper OMZ
(167-364m)

Lower OMZ
(364-671m)



CFC apparent ages for the North Pacific in the Upper OMZ depth range are < 40 years, with highest values off Baja (Warner et al., 1996; Fine et al., 2001).CESM is not forming North Pacific IntermediateWater(NPIW)

BGC biases linked to physical processes:

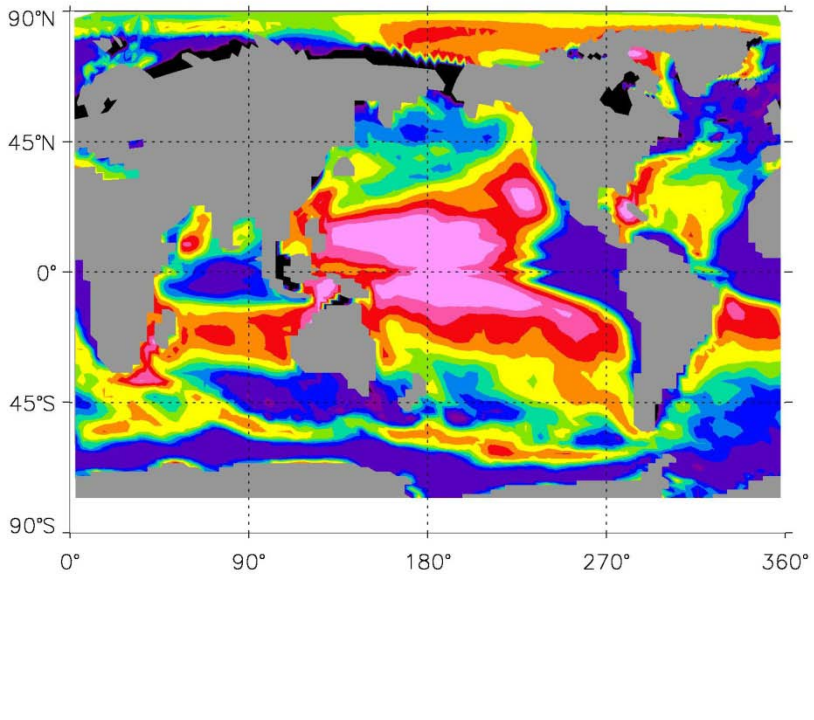
1) Weak vertical exchange at high latitudes.
2) Weak ventilation of oxygen minimum zones.

Modified Physics Simulation (MODPhys):

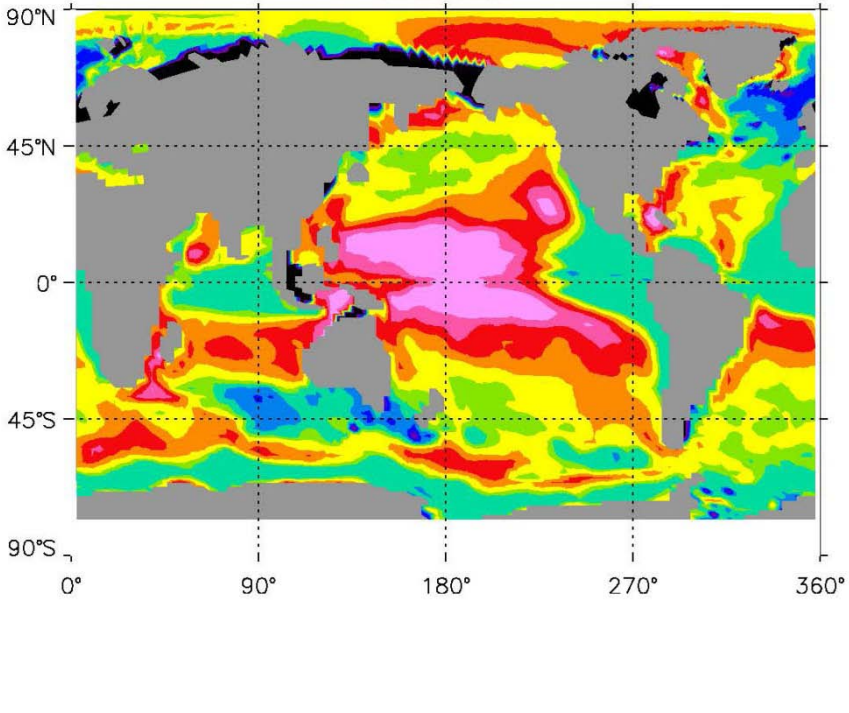
1) Imposed a minimum isopycnal mixing rate of 0.8e7 cm^2/s, typically between 0.3-3.0e7 cm^2/s.
2) Increased diapycnal mixing at high latitudes
   increase from 0.17 to 0.35 cm^2/s 45-55N
   increase from 0.17 to 0.5 cm^2/s ~45-55S
   additional increase in NW Pac and Lab Sea.
3) Increased critical Richardson number in KPP (0.3 -> 0.5), acts to deepen mixed layers.

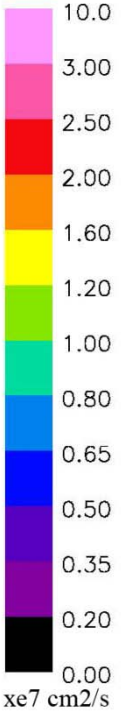
Isopycnal mixing rates at 150m depth

Standard CESM



Modified CESM



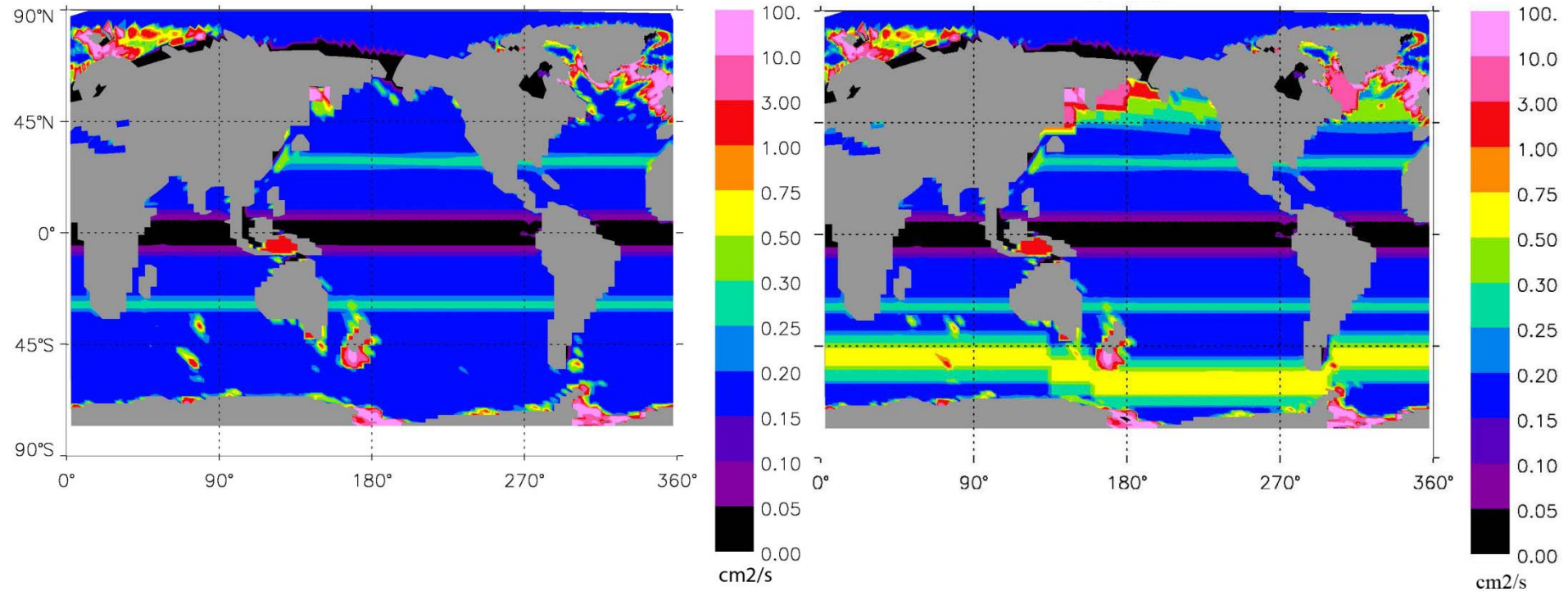


Minimum isopycnal mixing increased by a factor of ~2 to 0.8e7 cm^2/s. Mixing rates not changed above this threshold.

Diapycnal mixing rates at 150m depth

Standard CESM

Modified KV

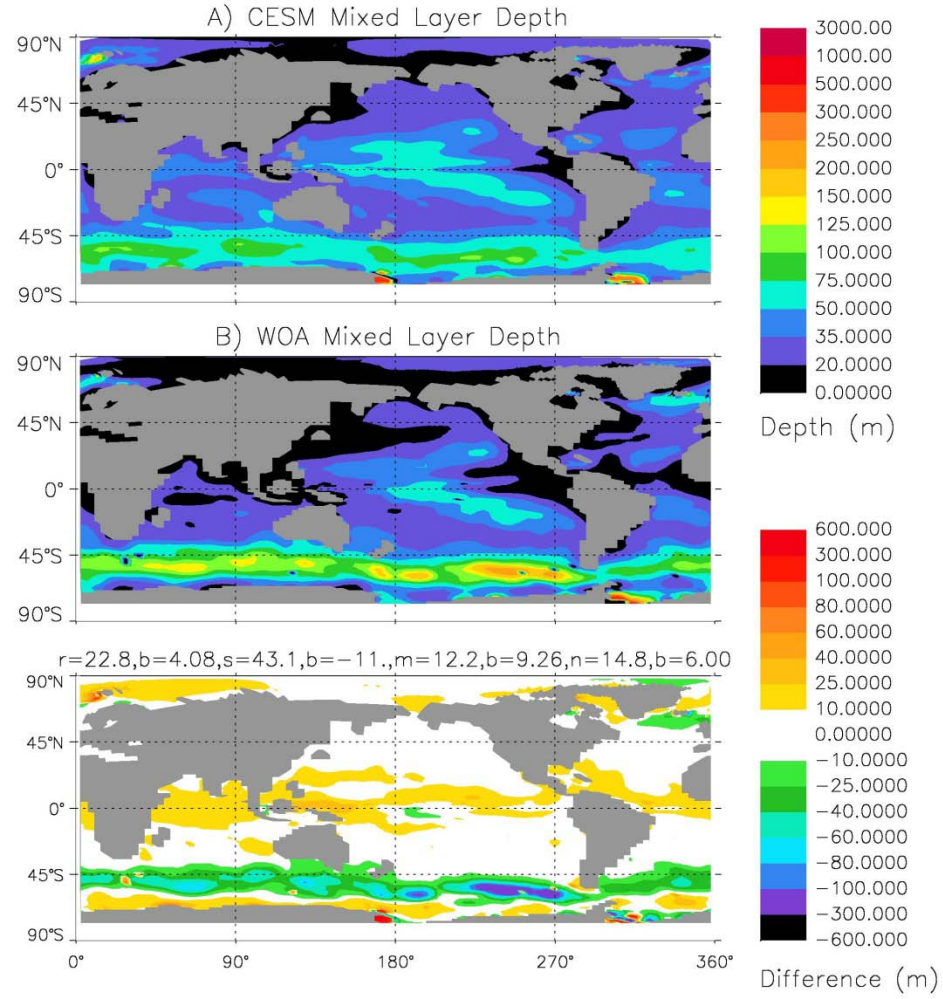


Should there be stronger vertical mixing at high latitudes?

1) Missing NIW mixing
2) Missing Langmuir mixing
3) Shallow mixed layer bias in KPP

Annual Mean Mixed Layer Depth (0.125 density diff)

Standard CESM

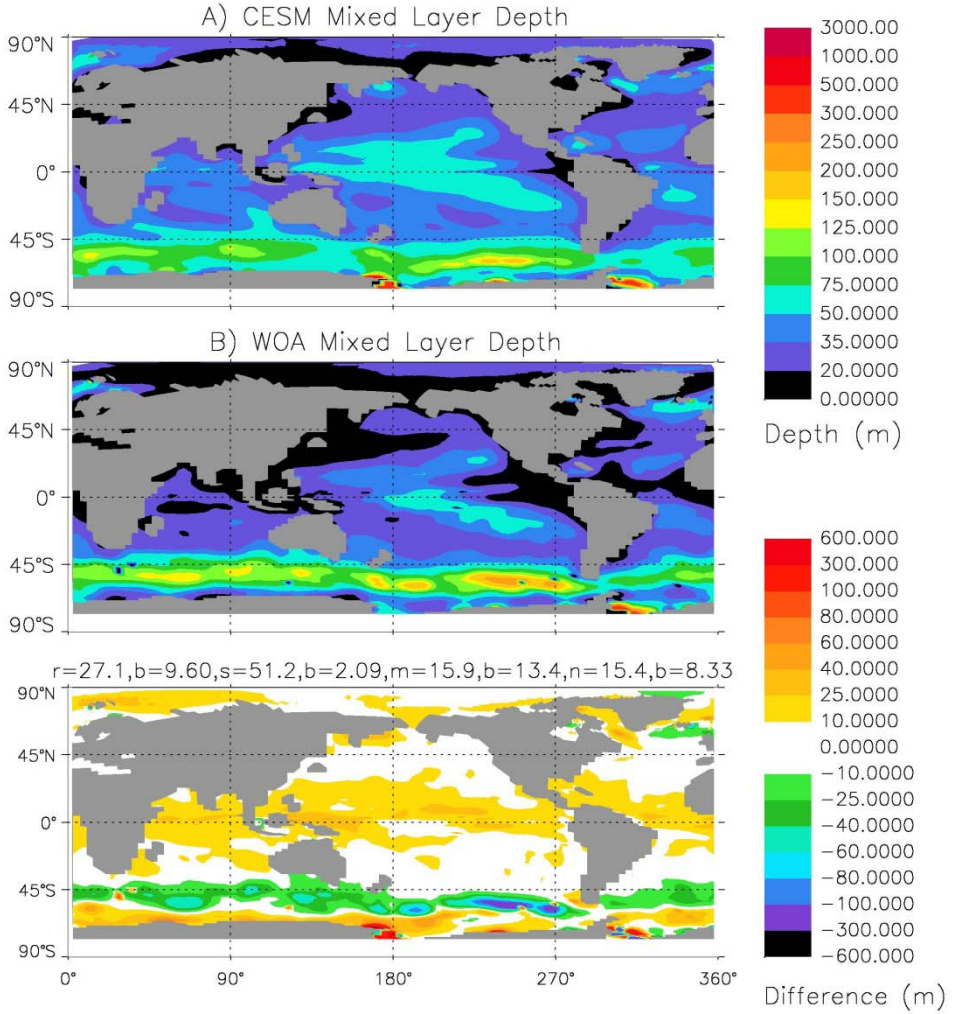


Global bias = +4m, rmse= 23

Southern Ocean bias = -11m, rmse= 43

Mid-latitude bias = +9m, rmse= 12

Modified Ricr (0.3>0.5)



Global bias = +10m, rmse=27

Southern Ocean bias = +2m, rmse= 51

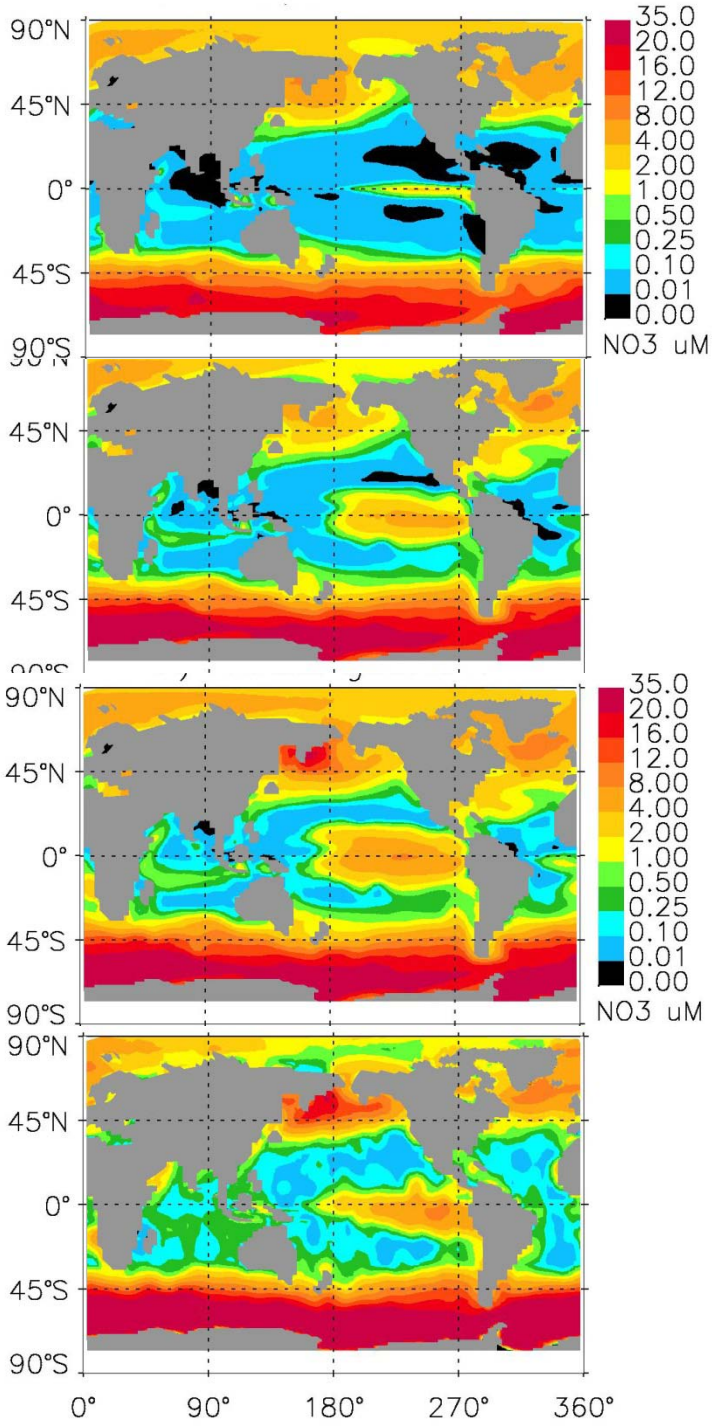
Mid-latitude bias = +16m, rmse=13

STD CESM

MOD BGC

MOD BGC & Physics

Observed Nitrate WOA



Lower OMZ (364-671m)

STD CESM

OMZ volume

282% Observed

MOD BGC, STD Physics

OMZ volume

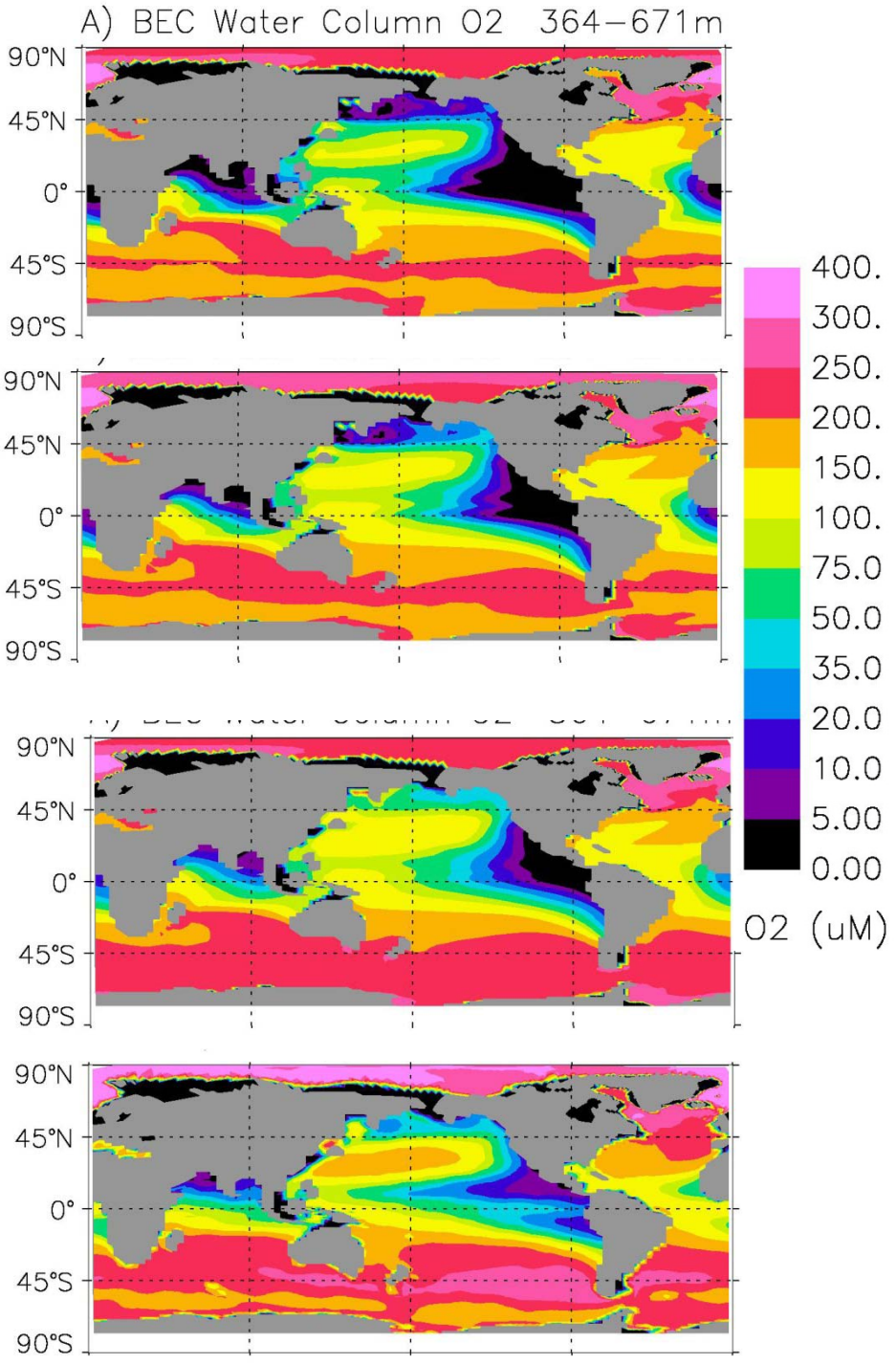
192% Observed

MOD BGC & Physics

OMZ volume

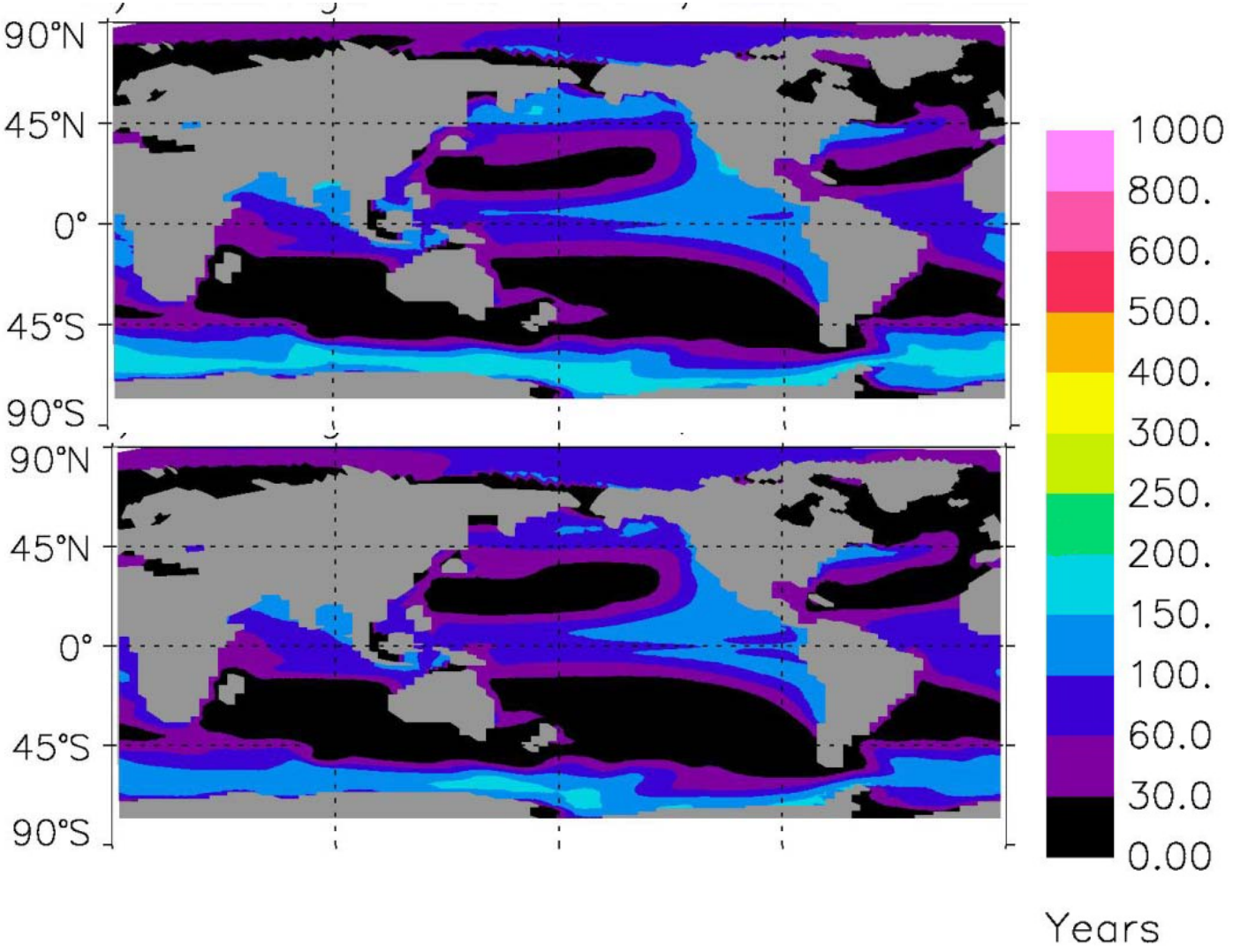
130% Observed

WOA Observed O_2



IAGE (at 250 yrs)
(167-371m)
STD CESM
Mean = 63 yrs
Npac = 76 yrs

MOD Physics
Mean = 56 yrs
Npac = 67 yrs



Simulation: (year 250)	STDCESM	BGCMOD	BGCPHYSMOD
Temperature r, rmse (105m)	0.96, 2.7		0.96, 2.7
Temperature r, rmse (300m)	0.92, 2.0		0.92, 2.0
Salinity r, rmse (105m)	0.89, 8.0		0.89, 8.0
Salinity r, rmse (300m)	0.92, 7.0		0.92, 7.0
Drake Passage Transort (Sv)	179		188
Mixed Layer Depth bias, rmse	+4, 23		+10, 27
Southern Ocean ML bias, rmse	-11, 43		+2, 51
Surface Nitrate r, rmse	0.78, 1.1	0.84, 0.58	0.82, 0.50
Surface Phosphate r, rmse	0.76, 0.33	0.85, 0.36	0.85, 0.32
Oxygen (170-364m) bias, rmse	-17, 47	-10, 43	-7, 43
OMZ (170-364m) (% Vol)	198%	149%	130%
Oxygen (364-671m) bias, rmse	-23, 49	-12, 42	-7, 41
OMZ (364-671m) (% Vol)	287%	192%	131%
Denitrification (TgN/yr)	374	157	102
Nitrogen Fixation (TgN/yr)	253	134	113
Export Production (PgC/yr)	6.3	6.0	6.6

Conclusions

1) Ventilation of the mid-depth North Pacific is very weak, due to weak NPIW formation and isopycnal mixing.
2) This contributes to oxygen minimum zones that are much too large in CESM.
3) BGC mods and increased isopycnal mixing improve the OMZs considerably.
4) Nutrient flux to surface waters is weak in the subarctic North Pacific and throughout the Southern Ocean.
5) NIW mixing will help, but doesn't get the deep winter mixing in both regions, particularly the Southern Ocean.