What we can learn from modeling regarding the downstream impacts of iron fertilization and permanence of ocean carbon sequestration

Jorge L. Sarmiento
Princeton University

with contributions from Rick Slater, Anand Gnanadesikan, John Dunne, Irina Marinov, and DOE funding

LARGE SCALE NUTRIENT DEPLETION

Impact of large scale-long term (millenial) *nutrient depletion* (NOT iron fertilization) on atmospheric CO_2

Region of nutrient depletion	CO_2 drawdown (ppm)	
	Model 1 A_i low, K_v low	Model 2 A_i high, K_v high
Southern Ocean (90°S to 30°S)	63.5	78.8
Tropics (18°S to 18°N)	4.4	3.2
North Atlantic (30°S-80°N)	15.0	11.8
North Pacific (30°N to 67°N)	3.7	3.9

Marinov et al. (in preparation); similar to Sarmiento & Orr (1991)

Effect of terminating fertilization

Sarmiento & Orr
(1991)

Valuable science: atmospheric pCO_2 is determined by the transformation of DIC from the preformed to the remineralized pool

400

300

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

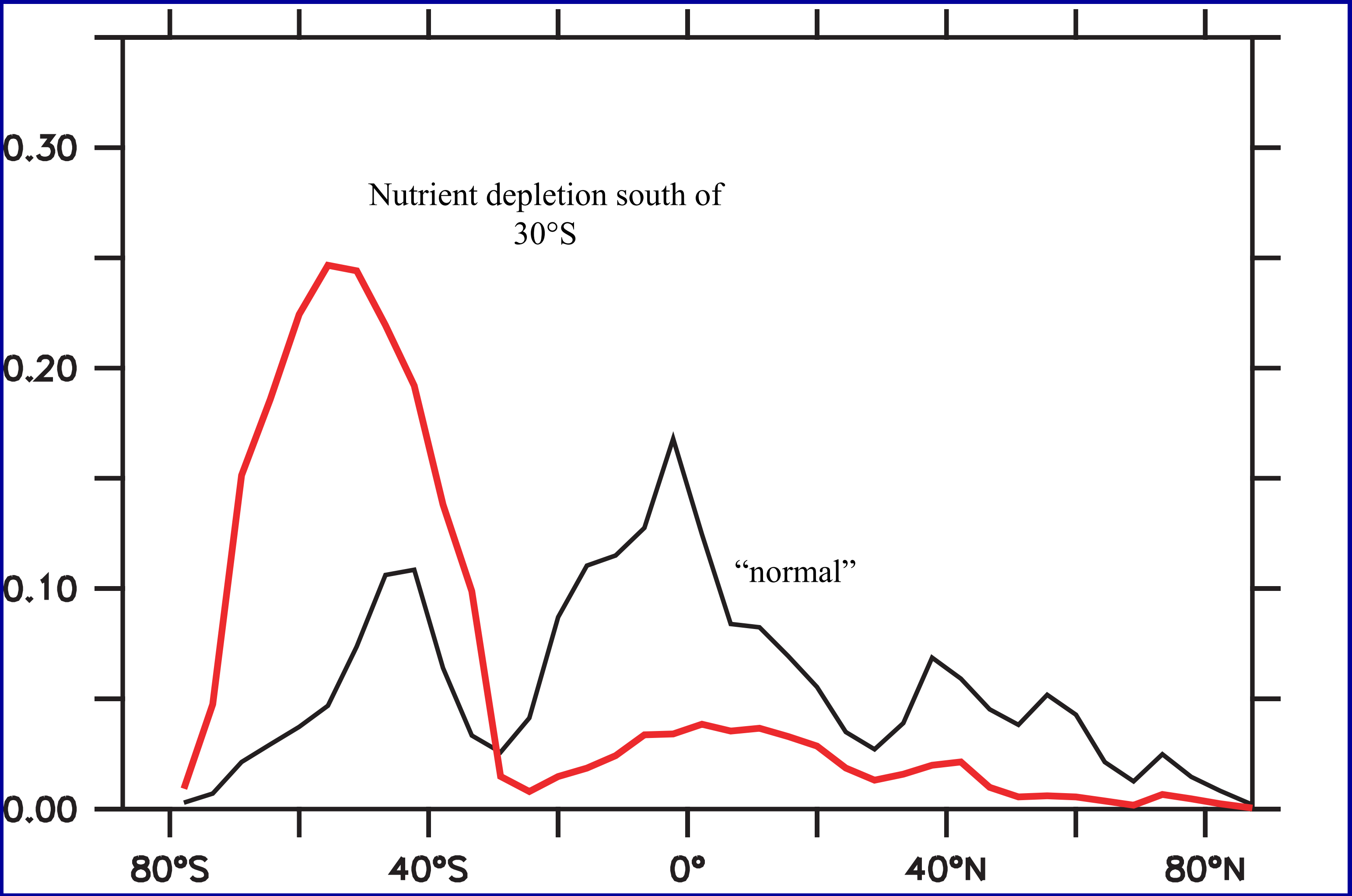
200

1000 2000 3000 4000

The figure shows "potential" atmospheric pCO_2 (in models with rapid gas exchange) as a function of the remineralized DIC pool (Pg C) for a wide range of model simulations

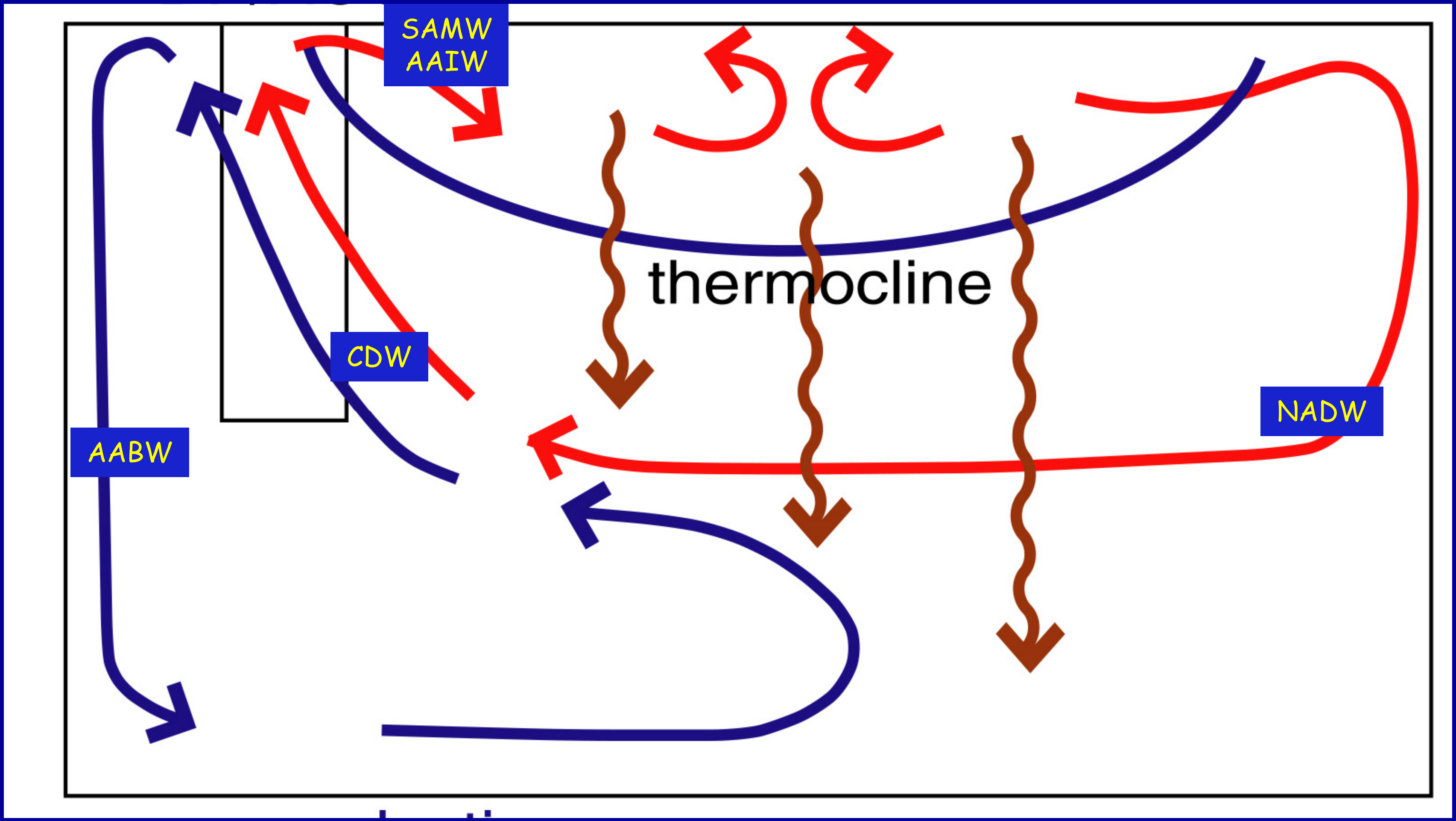
Marinov et al. (in preparation)

Southern Ocean nutrient depletion reduces low lat biological productivity by ~75% (Pg C/deg/yr)



Marinov et al. (2006)

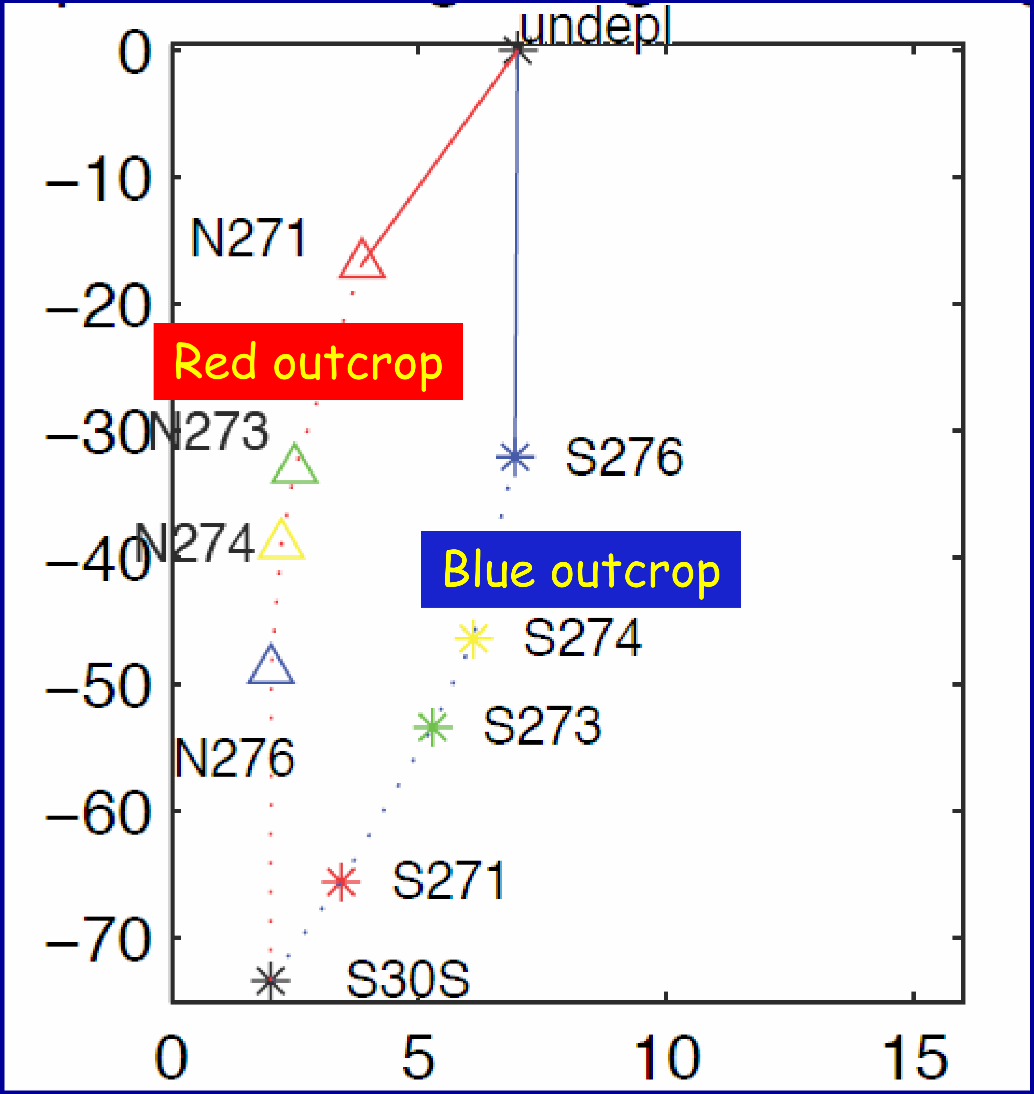
The biogeochemical divide: CO_2 effects confined primarily to “blue” outcrop (AABW), productivity effects to “red” (AAIW & SAMW)



Marinov et al. (2006)

Influence of nutrient depletion in different regions of the Southern Ocean

Reduction in atmospheric CO_2



Production north of 35°S (Pg C yr^{-1})

Marinov et al. (2006)

Conclusions from large scale nutrient depletion simulations

1. Nutrient depletion in the Southern Ocean draws down CO_2 by ~70 ppm. The North Pacific and Tropics can only draw down CO_2 by ~4 ppm

2. Termination of fertilization leads to reversal of uptake.

3. The Southern Ocean biogeochemical divide
   a) Nutrient depletion in the Subantarctic reduces low latitude biological productivity.
   b) Nutrient depletion in the Antarctic polar zone takes up atmospheric CO_2. (However, later we shall see that models show that iron fertilization is very inefficient at depleting nutrients in the polar region -- Ross Sea)

4. CO_2 drawdown is proportional to the conversion of DIC from the preformed to the remineralized pool

PATCH
NUTRIENT
DEPLETION

Gnanadesikan et al. (2003) model of patch scale nutrient depletion

- Assumption: Iron addition results in nutrient depletion.

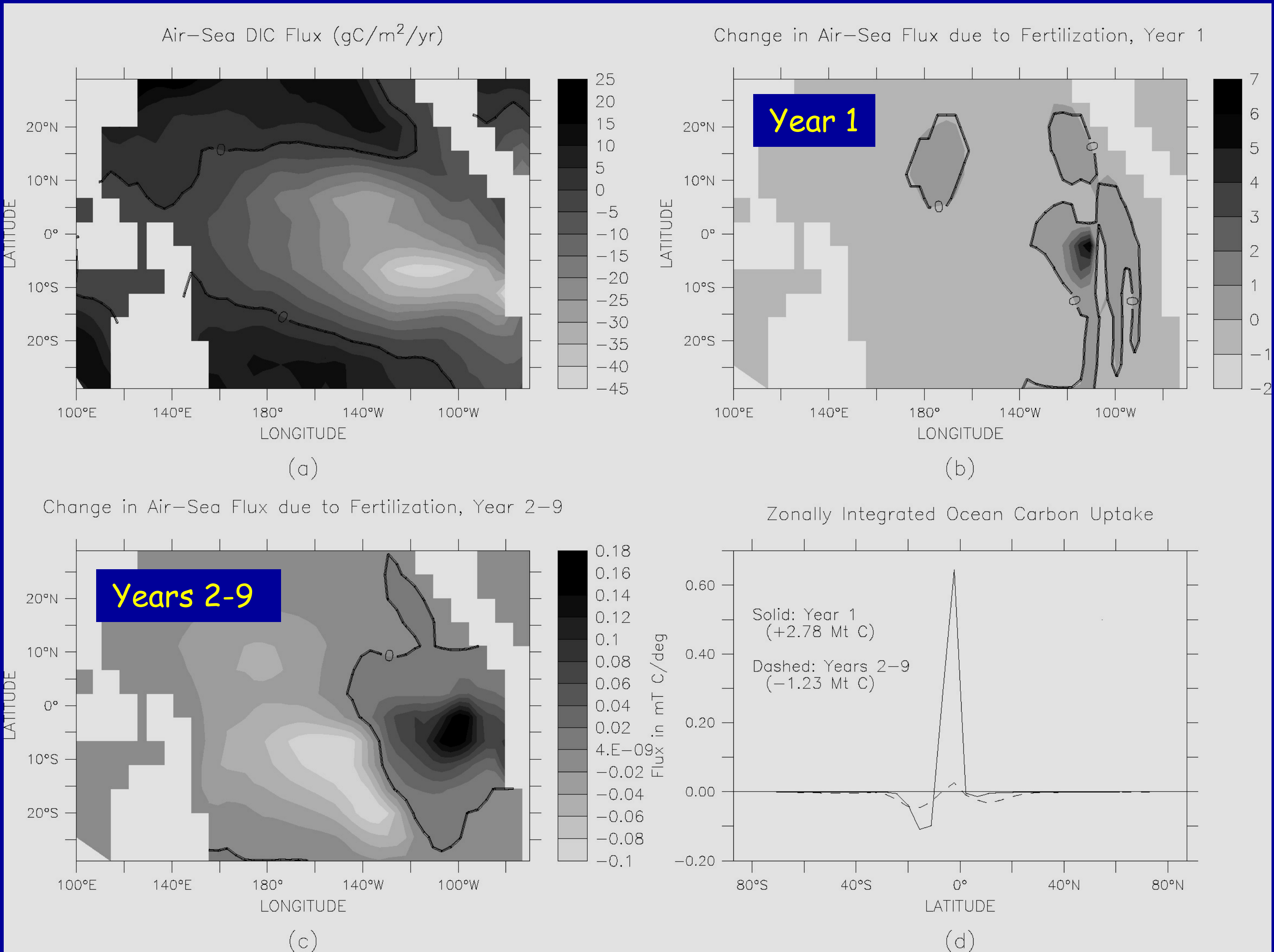
- Simulations:
  - Location : Eastern Equatorial Pacific at 2.2°S, 110°W
  - Area: One model grid cell (4°x4° = 200,000 km^2)
  - Length of time: one month (September)

- Cases considered:

  CASE 1 - Nutrient depletion (equivalent to"Iron added & lost") with
    (a) shallow regeneration of organic matter &
    (b) bottom regeneration of organic matter.

  CASE 2 - Nutrient addition (equivalent to "Iron & macronutrients added & retained") with
    (a) shallow regeneration of organic matter &
    (b) bottom regeneration of organic matter.

Most important result: perturbation to air-sea flux of CO_2 lasts a long time and is undetectably small (macronutrient depletion, flux to bottom case)



Additional results: efficiency of nutrient depletion is low, unless iron & macronutrients are added & retained

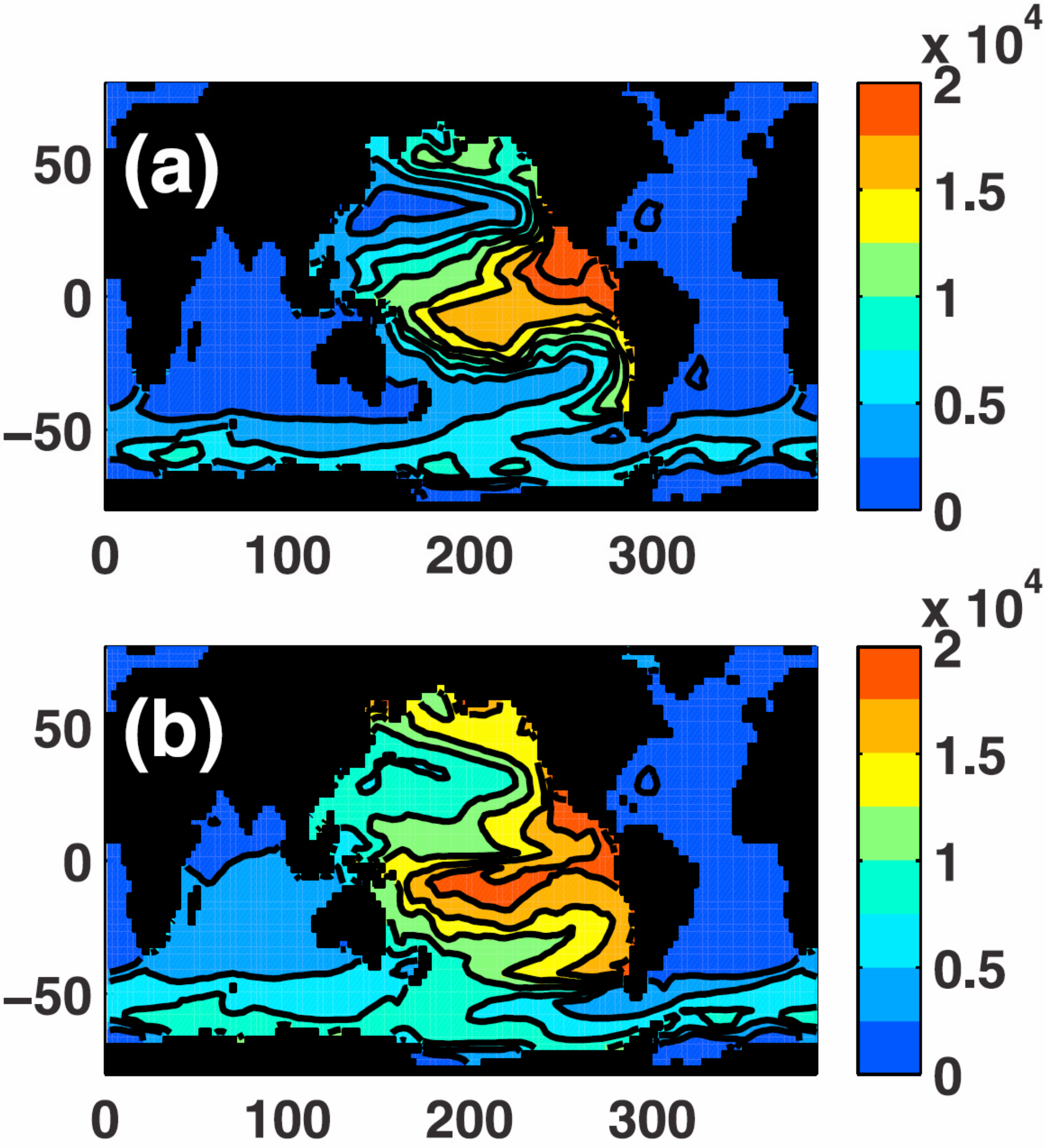
1. After 100 years, efficiency of 1 month nutrient depletion is 2 to 12%; 40 to 42% if macronutrients are added for 1 month and then retained. (Note: this efficiency is defined as cumulative CO_2 uptake over initial 1 month export flux of C at site of fertilization. Later efficiencies are defined differently.)

2. Takes up ~0.001 Pg C (iron added & lost) to 0.1 Pg C (iron & macronutrients added & retained) per episode.

3. Effect of additional patches scales up approximately linearly if they are separated in time, approximately 0.5x if they are separated in space.

4. Macronutrient addition results rely on the assumption that added iron remains in the water column and labile, which is unlikely to be true.

DUTKIEWICZ ET AL. (2006) PATCH IRON FERTILIZATION



Dutkiewicz see highest CO_2 uptake in tropical Pacific, and low uptake in Southern ocean.

Dutkiewicz et al. (2006) atmospheric CO_2 uptake after
(a) 10 years and
(b) 100 years of iron input in MIT adjoint model
(ton C/ton Fe)

Additional iron input = 0.02 mmol m^{-2} yr^{-1}

Cost function:

$$J_{F_{CO2}} = \int_t^{t+\Delta t} \int F_{CO2}(x,y) \ dA \ dt.$$

Motivated IFMIP (Iron Fertilization Model Intercomparison Exercize)

I. Sarmiento & Orr (1991) showed the Southern Ocean gives the greatest atmospheric CO_2 uptake to nutrient depletion, whereas Dutkiewicz et al. (2006) got a bigger response in the Equatorial Pacific than the Southern Ocean. Why?

II. Atmospheric drawdown efficiency in Equatorial Pacific, appeared to be larger than Gnanadesikan et al. (2003), but it was for a different scenario and defined differently.

IFMIP PATCH IRON FERTILIZATION

DOE Iron Fertilization Model Intercomparison Project (IFMIP)

PARTICIPANT LIST

MIT	LANL (Los Alamos Natn'l Lab)	PRINCETON/ GFDL	UCLA	STANFORD
S. Dutkiewicz M. Follows	M. Maltrud	R. Slater J. Dunne J. Sarmiento A. Gnanadesikan	X. Jin, N. Gruber H. Frenzel	A. Tagliabue K. Arrigo

Model Biogeochemistry (new models have ecosystems and Fe cycle)

	MIT	LANL	PRINCETON/GFDL	UCLA	STANFORD
Tracers	No ecosystem, P & Fe limitation, DIC, Alk, DOP	4 functional groups (small, diat, cocc, diaz) w/ N, P, Si, Fe limitation, Z, DOM & POM	5 functional groups (explicit: small, large, diaz, implicit: diat & cocc) w/ N, P, Si, Fe limitation, DOM & POM, grazing modeled implicitly	Same as LANL	Diatoms & *P. antarctica*, w/ P, N, Fe, DIC, Z, DOM, POM
Primary Production (PP)	V_{max}*f(I,P,Fe) -multiplicative Monod functions	Geider et al. (1998) cell quota model dependent on nuts, T & I	Based on Geider et al. (1997). Fe:N ratio modulates Chl:N ratio	"	V_{max}*f(I,N,Fe) - multiplicative Monod functions (?)
Iron	K_{fe} = 0.12 nmol	K_{fe}=0.06 & 0.16 nmol for small phyto & diatoms	K_{fe} = 0.1 & 0.3 nmol for small & large diatoms, 0.1 or diazotrophs; Scavenging onto org C & $CaCO_3$, remin as with particles & in seds.	"	K_{fe} = 0.10 nmol for diatoms, 0.01 nmol for *P. antarctica*
C:Fe	250,000	170,000 to 600,000 for diatoms; 20,000 to 70,000 for diazotrophs	56 to 300,000 for large, 16 to 50,000 for small, 4 to 30,000 for diazotrophs AVERAGE export C:Fe = 148,500	"	450,000 for diatoms, 100,000 for *P. antarctica*
Fe sources	Mahowald et al. (2003), 2% of Fe soluble	Mahowald et al. (2003), 3.5% of Fe soluble	Ginoux et al. (2001), 2% of Fe soluble	Tegen & Fung (1995), 2% of Fe soluble. Sed source of 2 mmol Fe m^{-2} d^{-1}	
Sea ice	Fe falls through	Fe falls through	Fe falls through		

Model Physics

	MIT	LANL	PRINCETON/ GFDL	UCLA	STANFORD
Model resolution	2.8°x2.8° 15 levels (50 m)	3°x3° (2/3° near Equator) 25 levels (12 m)	3°x3° (2/3° near Equator) 28 levels (10 m)	0.5°x0.5° (Pacific only)	Ross Sea area: 25 km 23 σ levels (POM)
Forcing	Monthly winds (Trenberth) & fluxes (Shi) + relaxation to SST & SSS	6 hr winds & fluxes (?) (Large & Yeager - NCEP based), SSS restoring in open ocean	ECMWF and NCAR CLIVAR ocean reanalysis expt. (CORE)	NCEP reanalysis w/ weak T & S damping, including interannual variability	NCEP reanalysis including interannual variability
Mixing	GM	GM, KPP vertical w/ 1000 cm^2 s^{-1} for convection	GM, KPP vertical	Eddy permitting, KPP vertical	Mellor-Yamada vertical
Sea ice & runoff	Sea-ice mask, but no active sea ice. Runoff.	No sea ice or runoff. Restoring of SST and SSS under diagnosed sea ice.	GFDL dynamic sea ice model (SIS)	No sea ice. Covers Pacific only.	Specified

Iron fertilization protocol
(based on Dutkiewicz et al., 2006)

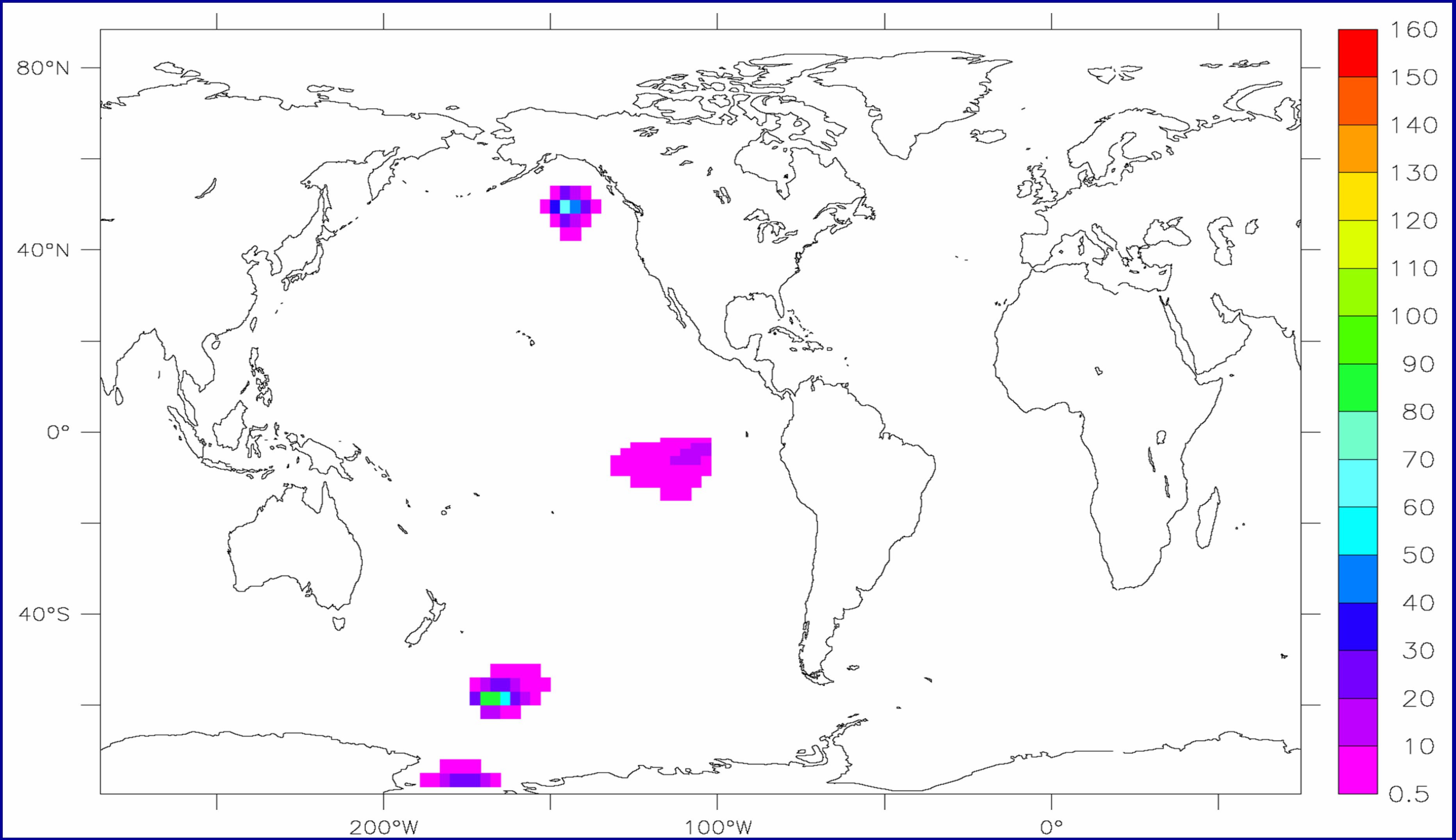
- Flux of 0.02 mmol m^{-2} y^{-1} bio-available iron added continuously for 10 years (Princeton/GFDL carried on to 100 years as well)

- Patch locations & target patch size:

		MIT patch size (10^3 km^2)
PAPA	50° N, 145° W	64
EqPac	3.5° S, 104° W	97
S. Ocean	60° S, 170° W	48
Ross	76° S, 176° E	21

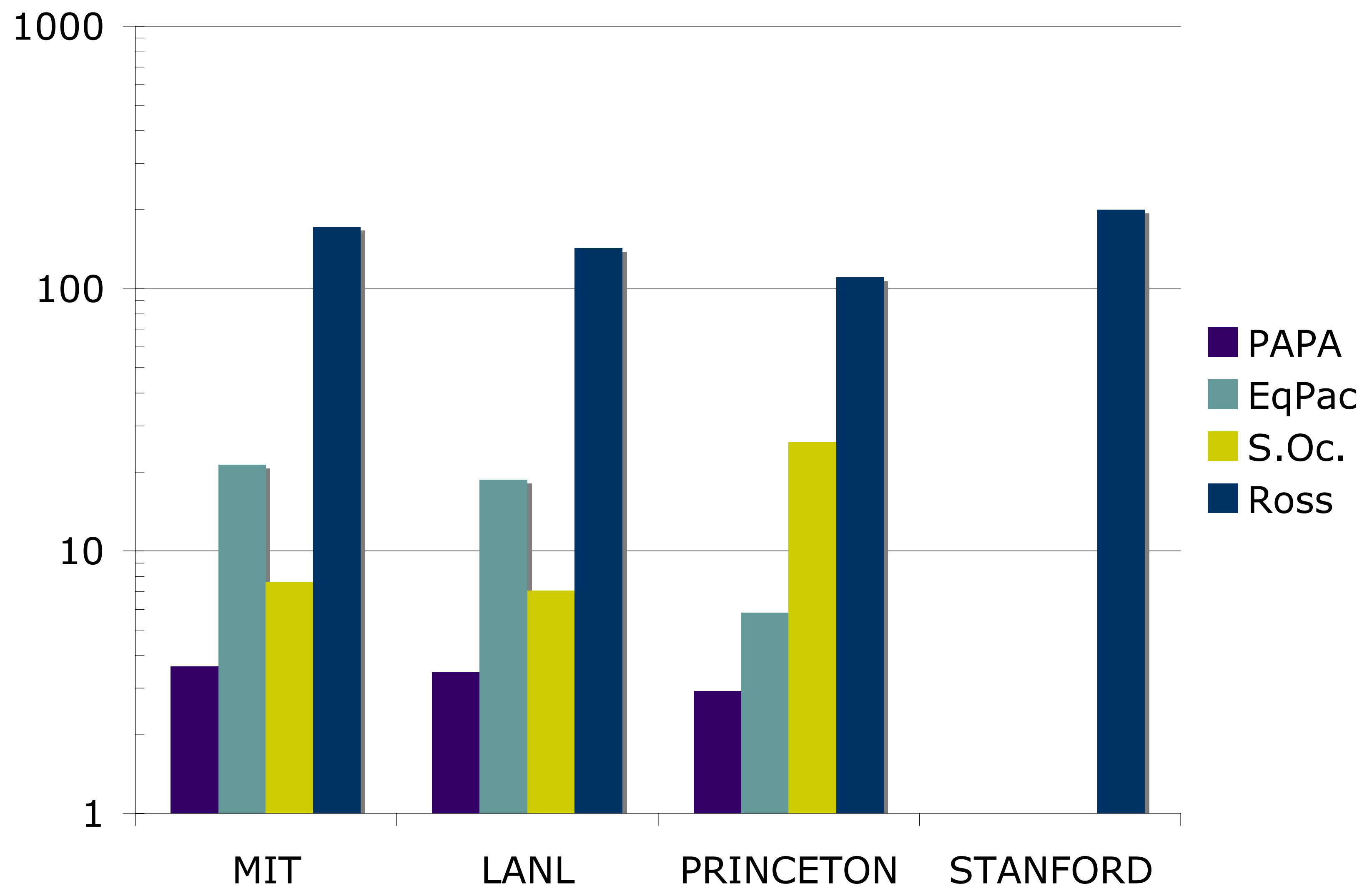
- Atmospheric pCO_2 fixed at 278 ppm

Ten year CO_2 uptake from atmosphere (gC m^{-2})

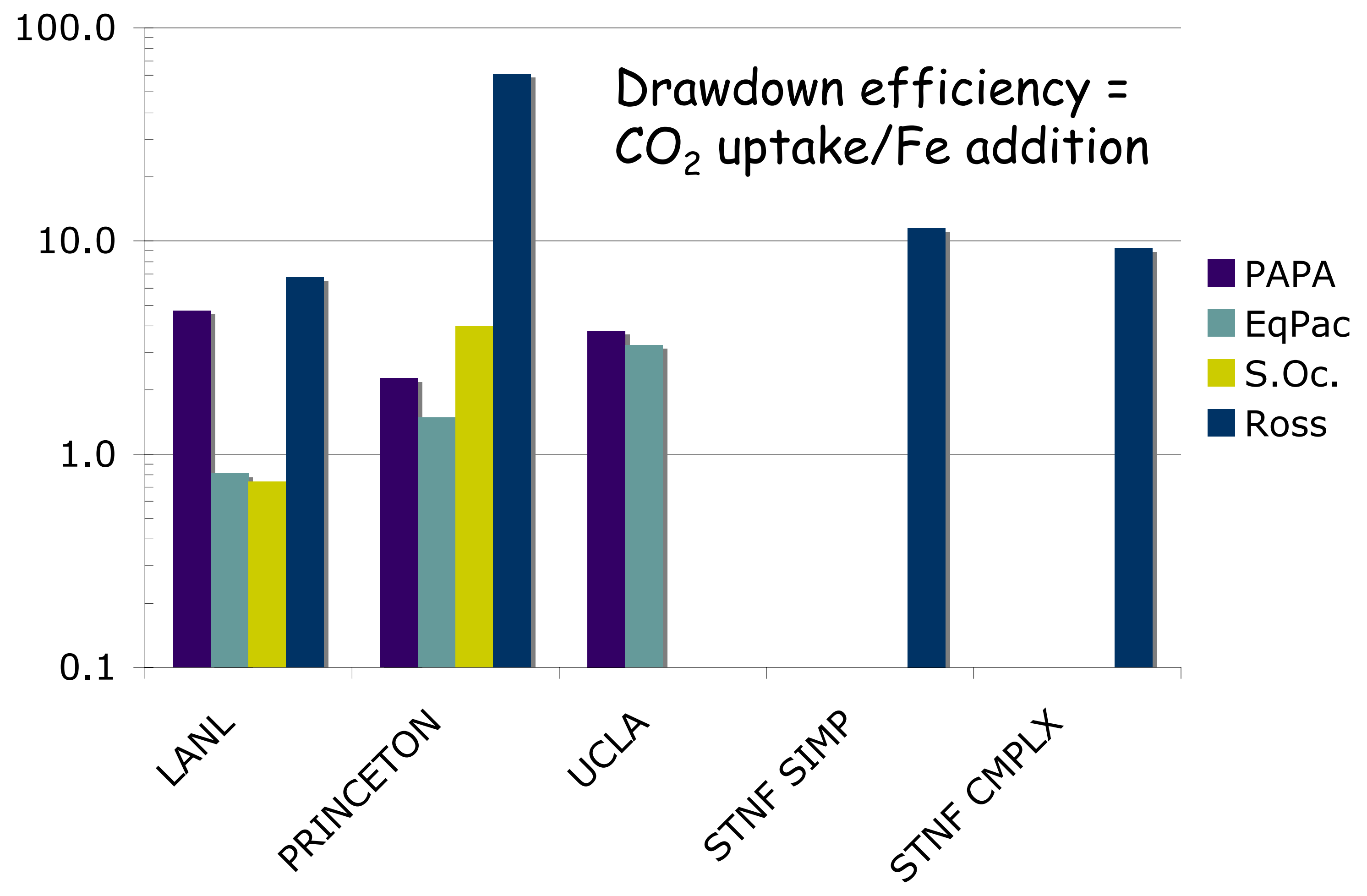


Princeton model

Iron addition/aeolian flux ratio

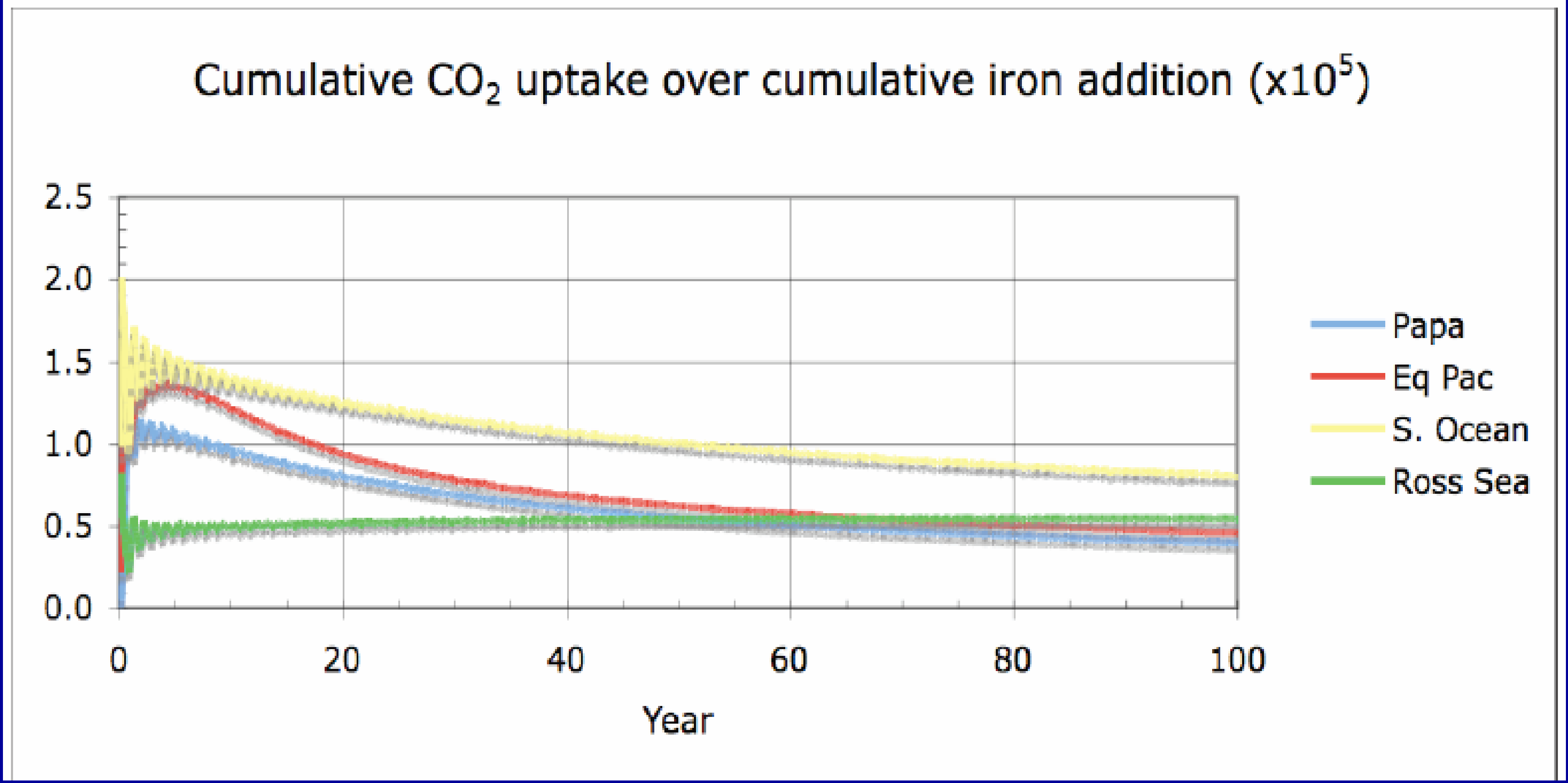


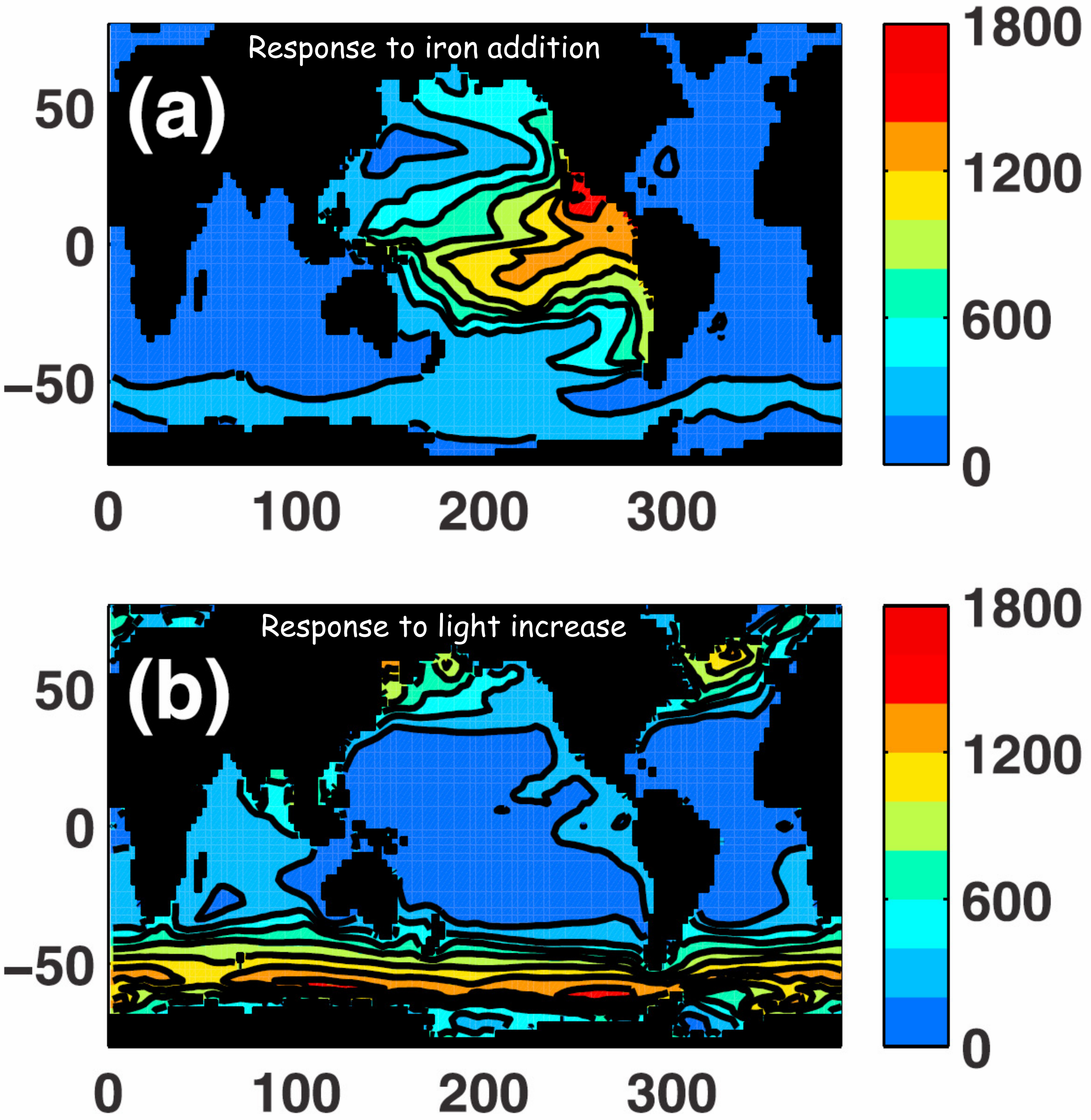
Ratio of drawdown efficiency to MIT



All models are ~10x more efficient than MIT in Ross Sea; Princeton/GFDL is ~4x more efficient in S. Oc.

Southern Ocean fertilization is far more effective than other regions (Princeton/GFDL model)





Reason: The Dutkiewicz et al. model is light rather than iron limited in the high latitudes.

Figures show response of net community production to 10 year (a) iron and (b) light increase in MIT adjoint model (gC m^{-2})

Increased iron input = 0.02 mmol m^{-2} yr^{-1}, light increase = 30 W m^{-2}

Cost function:

$$J_B = \int_t^{t+\Delta t} \int B(x,y,z) \;\; dV \;\; dt$$

Atmospheric uptake efficiency in Gnanadesikan et al. Eq Pac fertilization is much lower than in new models

Iron source	Atmosphere	Atmos uptake	
		Efficiency	
1 mo/1 time	variable	0.25 (macronut. depletion)	Gnanadesikan et al. (2003)
1 mo/1 time	variable	0.37 (macronut. addition)	"
3 mo/1 time	fixed	0.89 (~0.71)	Xin & Gruber (in preparation)

Table shows cumulative CO_2 uptake over cumulative C export over 10 years

Gnanadesikan et al. (2003) efficiency is much lower than Jin & Gruber (in prep) when defined the same way. (Note correction to 71% to account for back flux to atmosphere; see later).

Lower Gnanadesikan et al. efficiency is due to greater depth of CO_2 removal

- Atmospheric uptake efficiency

Low efficiencies result from:

- large area fertilization
- high light sensitivity studies

- Fraction of additional POC export across 100 m that occurs at base of top model layer (10 m)

Jin & Gruber (in prep.)

Atmospheric uptake efficiency also depends on the backflux of CO_2 due to reduced atmospheric CO_2

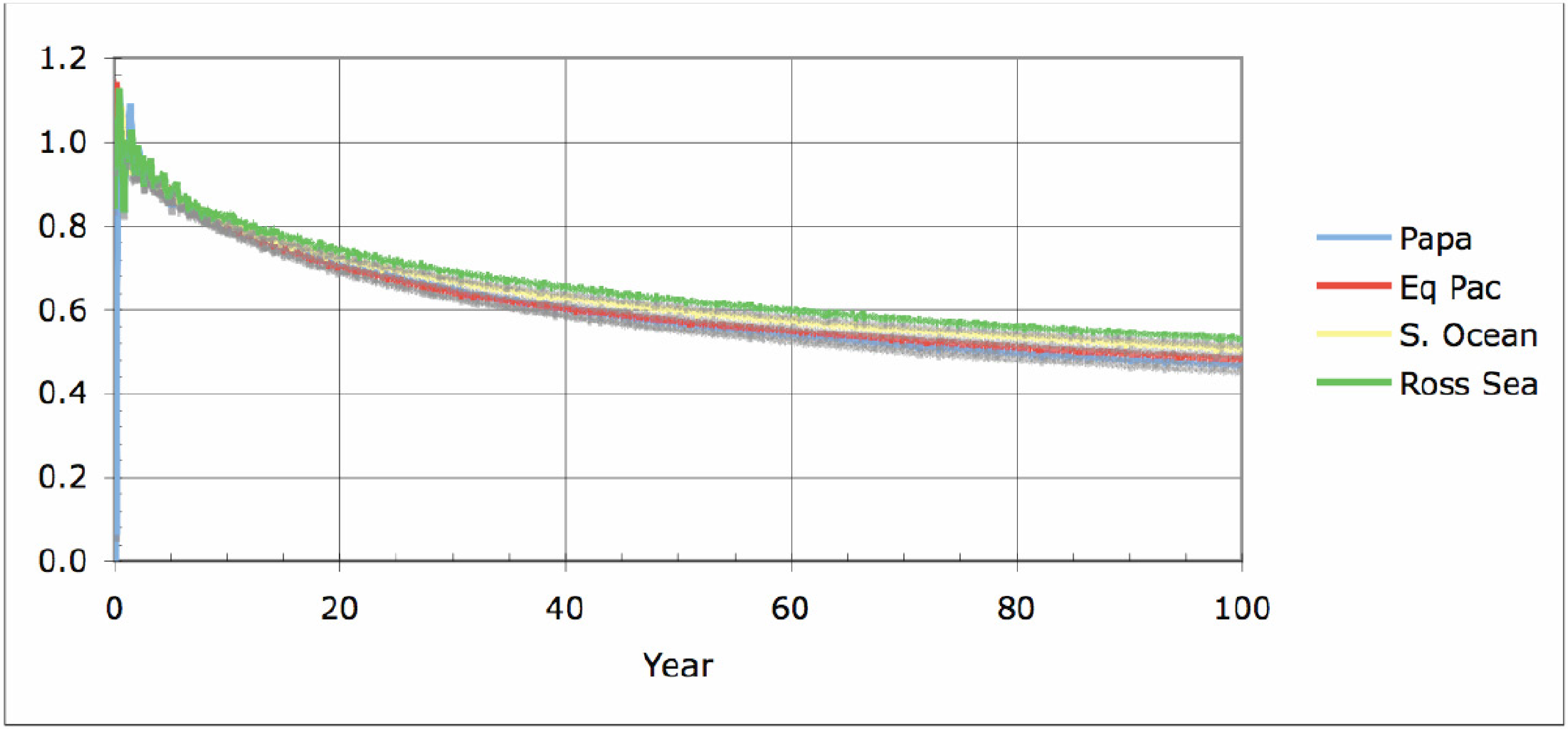


Figure shows the ratio of CO_2 uptake of model with variable atmospheric CO_2 to a model with fixed atmospheric CO_2

Conclusions based on Princeton/GFDL IFMIP model

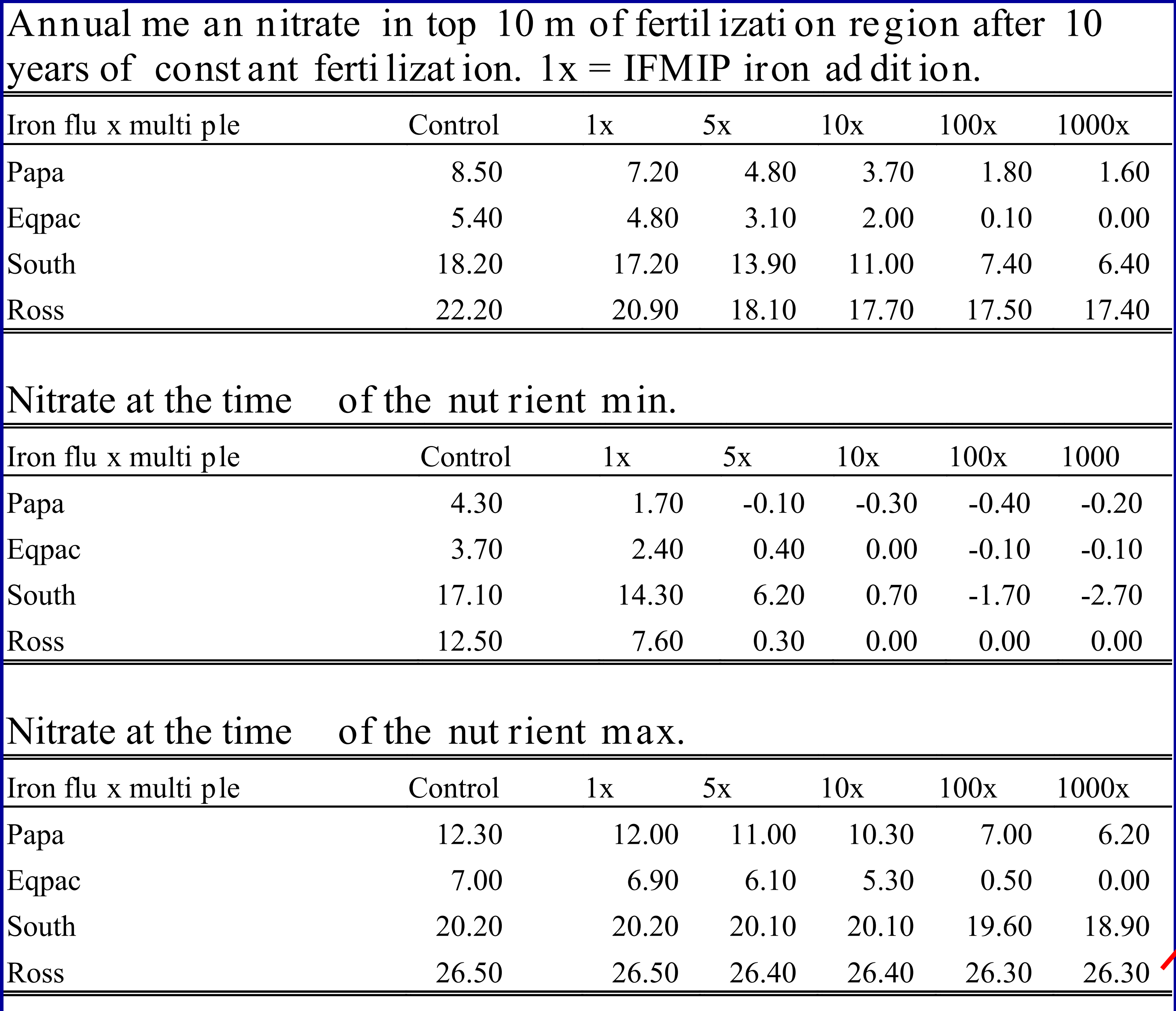
- Southern Ocean is more sensitive to iron addition than Equatorial Pacific. Dutkiewicz et al. (2006) model response to iron in high latitudes is suppressed because of light limitation.

- Eq Pac iron fertilization efficiency in Gnanadesikan et al. (2003) is ~3x lower than Jin & Gruber (in prep.) due to greater depth of DIC depletion in nutrient depletion & addition scenarios.

- Large scale back leakage of CO_2 in models with a variable atmosphere reduces cumulative atmospheric uptake efficiency by ~20% over 10 years and ~50% over 100 years (this depends somewhat on the frequency of the iron fertilization).

ADDITIONAL ANALYSIS OF PRINCETON/GFDL IFMIP

Can iron fertilization deplete surface nitrate?



Annual mean nitrate in top 10 m of fertilization region after 10 years of constant fertilization. 1x = IFMIP iron addition.

Iron flux multiple	Control	1x	5x	10x	100x	1000x
Papa	8.50	7.20	4.80	3.70	1.80	1.60
Eqpac	5.40	4.80	3.10	2.00	0.10	0.00
South	18.20	17.20	13.90	11.00	7.40	6.40
Ross	22.20	20.90	18.10	17.70	17.50	17.40

Nitrate at the time of the nutrient min.

Iron flux multiple	Control	1x	5x	10x	100x	1000
Papa	4.30	1.70	-0.10	-0.30	-0.40	-0.20
Eqpac	3.70	2.40	0.40	0.00	-0.10	-0.10
South	17.10	14.30	6.20	0.70	-1.70	-2.70
Ross	12.50	7.60	0.30	0.00	0.00	0.00

Nitrate at the time of the nutrient max.

Iron flux multiple	Control	1x	5x	10x	100x	1000x
Papa	12.30	12.00	11.00	10.30	7.00	6.20
Eqpac	7.00	6.90	6.10	5.30	0.50	0.00
South	20.20	20.20	20.10	20.10	19.60	18.90
Ross	26.50	26.50	26.40	26.40	26.30	26.30

Note Ross Sea always recovers in winter

How does fertilization affect nitrate?

(Figure shows global horizontal mean of nitrate perturbation.
Note: diazotroph C:N:P = 366:50:1)

Nitrate budget in 100 year continuous fertilization simulations

	N change over 100 years (Tmol/100 yr)			
Field	PAPA	EqPac	South	Ross
N_2 fixation	0.194	0.837	0.125	0.002
Sed denitrification	0.000	-0.003	-0.003	0.016
Water Col Denitrification	-0.337	4.827	-0.269	-0.014
ΔNO_3	0.520	-3.960	0.267	-0.039

Denitrification causes 4 Tmol NO_3 loss in Eq Pac!

N standing crop (Tmol)	Year 100
NO_3	33,212
NH_4	28
Small Phyto	4
Large Phyto	1
Diazotrophs	0
Large DON	34
Small DON	248
Total N	33,527

Iron cycle in model

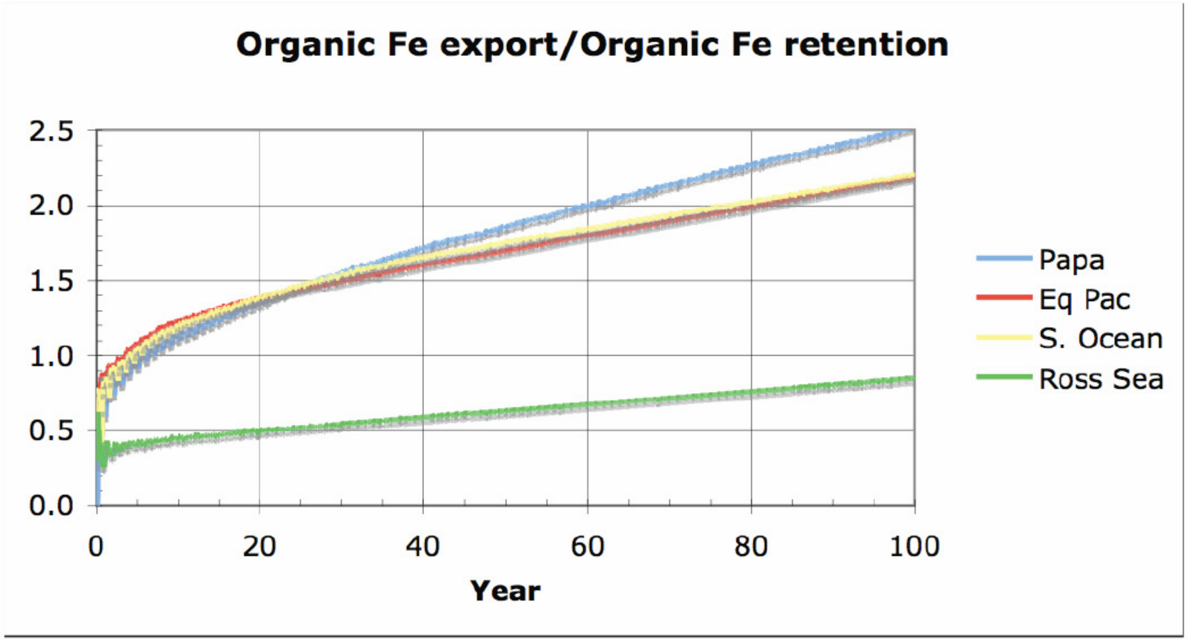


Figure 4a

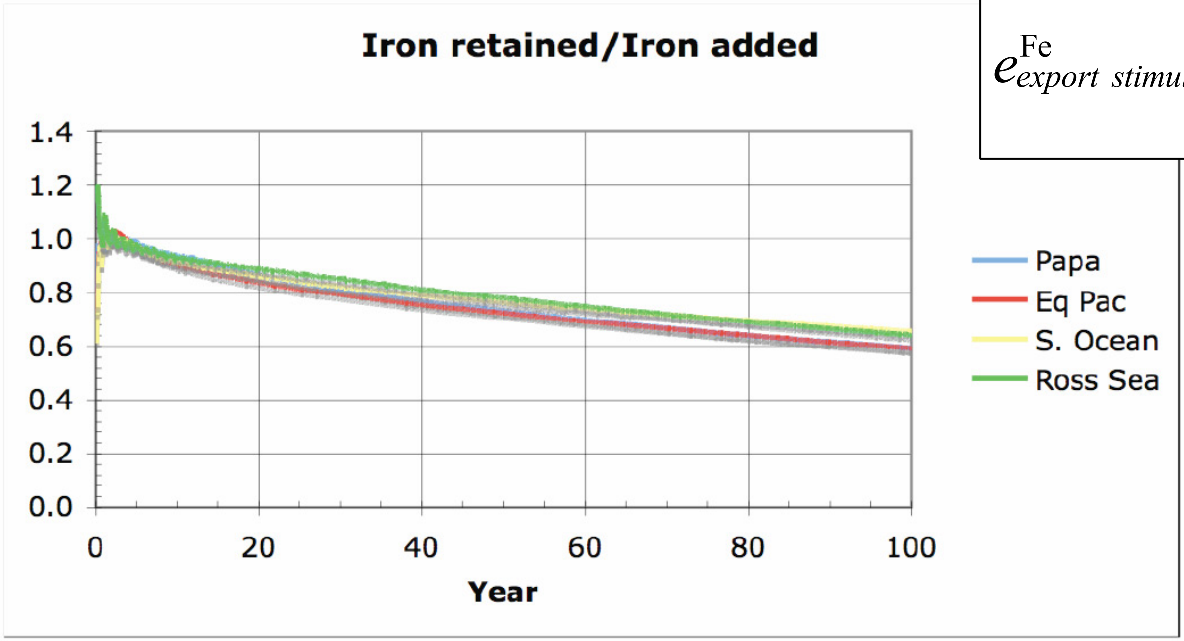
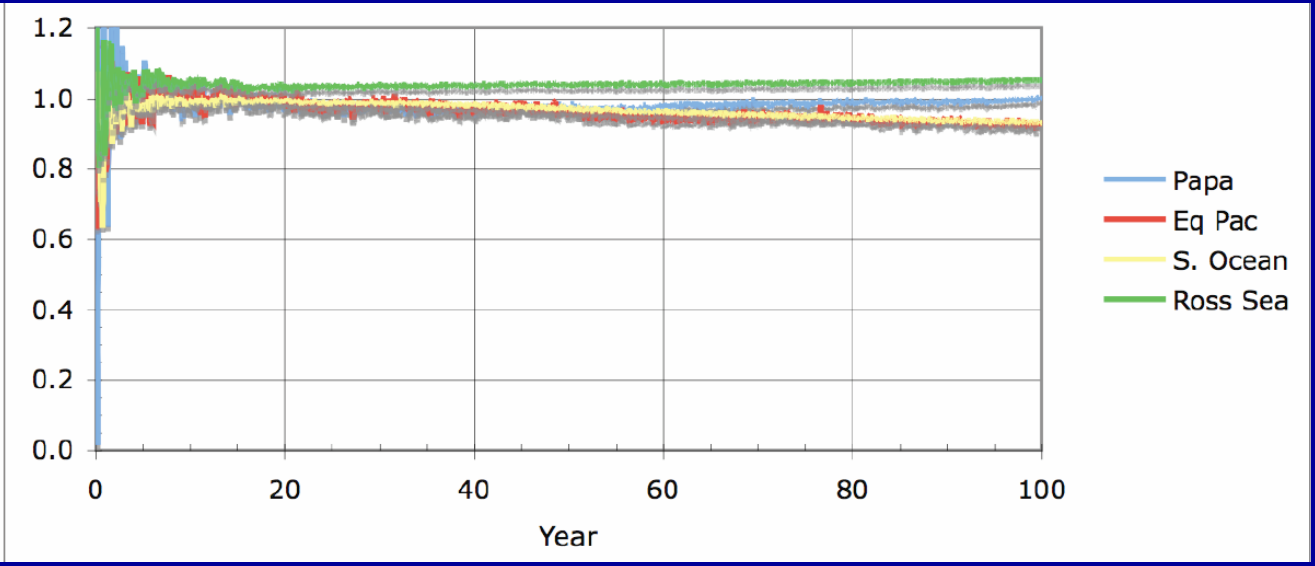


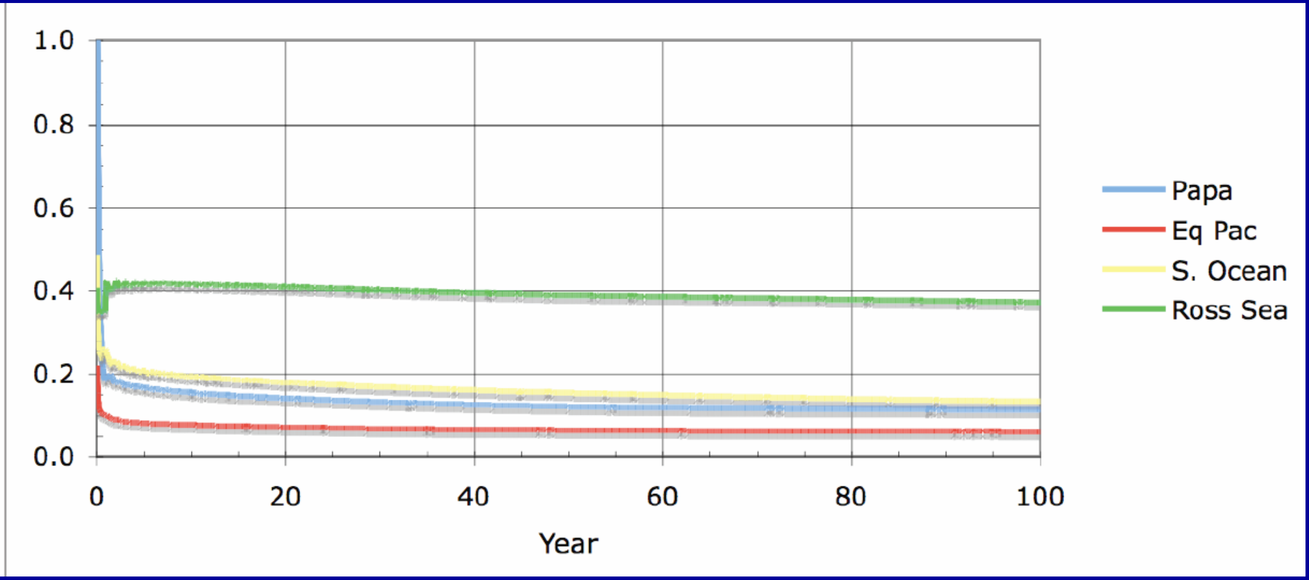
Figure 4b

$$e^{\mathrm{Fe}}_{export\ stimulation} = \frac{\Delta\Phi^{\mathrm{Org\ Fe}}_{export}}{\Delta\Phi^{\mathrm{Fe}}_{retention}} \cdot \frac{\Delta\Phi^{\mathrm{Fe}}_{retention}}{\Delta\Phi^{\mathrm{Fe}}_{fertilization}}$$

Contribution of iron retention: ratio of model with no iron regeneration to model with "normal" iron cycle



The atmospheric uptake efficiency is insensitive to iron retention



The biological export response to a given iron addition plummets to as little as 6% of the model with iron retention

CONCLUSIONS

Conclusions

- Quantification and verification of CO_2 uptake from the atmosphere for patch fertilization
  - Direct verification is not possible because the relevant processes are global in scale and too small to measure
  - Indirect verification by models requires understanding both the physical and biological efficiency and there are many uncertainties (cf. Gnanadesikan et al., 2003)
- Consequences (studied in models)
  - Increased N_2O production and degassing, which counteracts some or all of the reduction in radiative forcing by fertilization (Watson presentation)
  - Decreased oxygen, which leads to net loss of nitrate by denitrification when fertilization occurs in the eastern Equatorial Pacific
  - Loss of macronutrients from the upper ocean reduce biological productivity in other regions when fertilization ends (not shown)

Key unknowns in models

- As regards the physical efficiency (air-sea CO_2 uptake divided by CO_2 export)
  - Depth of enhanced DIC removal by phytoplankton

- As regards the biological efficiency (CO_2 export divided by Fe addition)
  - Long term fate of added Fe!!
  - Magnitude and C:Fe ratio of enhanced uptake, export, and remineralization
  - Depth of remineralization

Relevance of model results to the use of iron fertilization in carbon trading

- Fertilization in North Pacific and Tropics has miniscule impact on CO_2 growth. In the Southern Ocean, subAA fertilization impacts low latitude productivity, AA fertilization is inefficient.

- The "Faustian bargain" - Fe does not stay in the ocean, and CO_2 does not stay sequestered
  - Direct, observable verification of CO_2 uptake should be a requirement. It is not possible for iron fertilization.
  - Indirect verification by models has too many uncertainties and they will not be easy to overcome

- Potential for negative consequences is high