

Mitigating the Atmospheric CO₂ Increase and Ocean Acidification by Adding Limestone Powder to Upwelling Regions

Presentation to

Ocean Carbon and Biogeochemistry
Scoping Workshop on Ocean Acidification Research,
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By

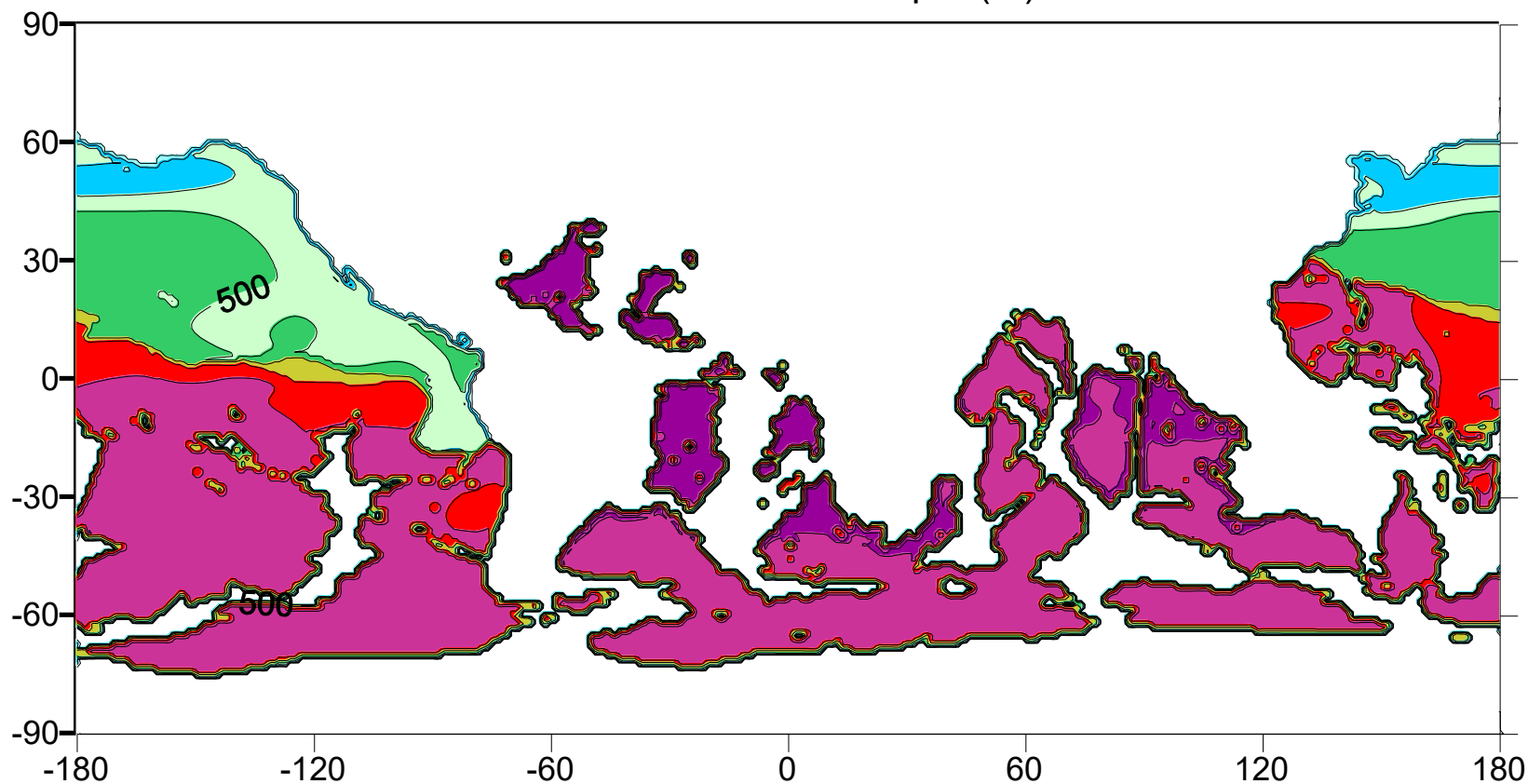
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Basic Idea:

- Add finely ground (40-um radius) limestone powder to regions of the ocean where the boundary between saturated (upper) and unsaturated (lower) water wrt calcite is relatively shallow (250-500 m depth) and the upwelling velocity relatively large (50-100 m/year)
- The limestone powder will dissolve within the first few hundred meters of the saturation boundary, restoring CO_3^{2-} , increasing the pH, and reducing pCO_2
- When this water upwells to the surface, additional CO_2 will be absorbed from the atmosphere, pushing pH back down, thereby offsetting some of the beneficial increase in pH

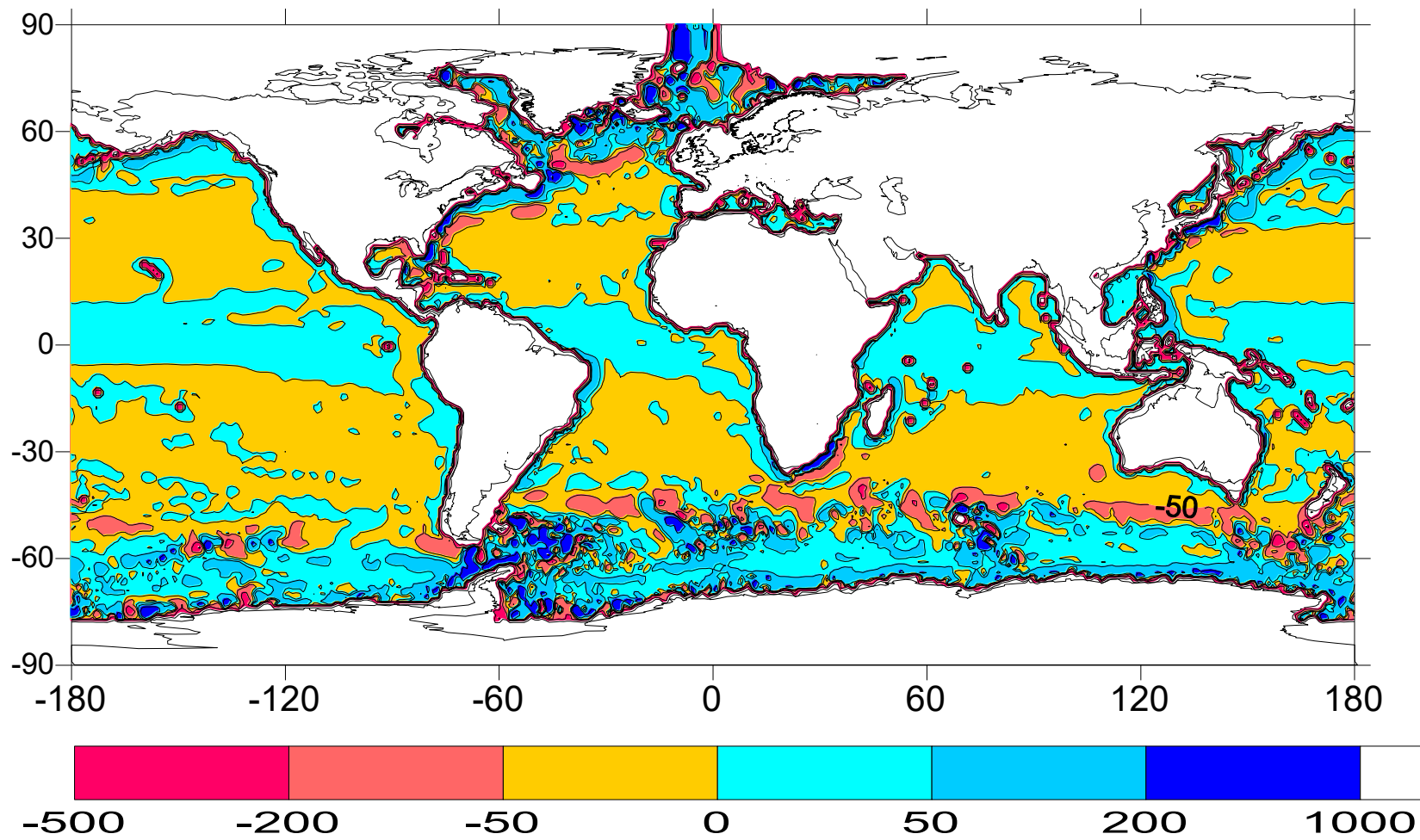
In the analysis to follow, I use the 7-component carbonate chemistry algorithm of Peng et al. (1987), and use global datasets on a $1^\circ \times 1^\circ$ latitude-longitude grid and at 33 depths for total dissolved inorganic carbon (TDIC), total alkalinity (TALK), dissolved phosphate, temperature, salinity, and upwelling velocity

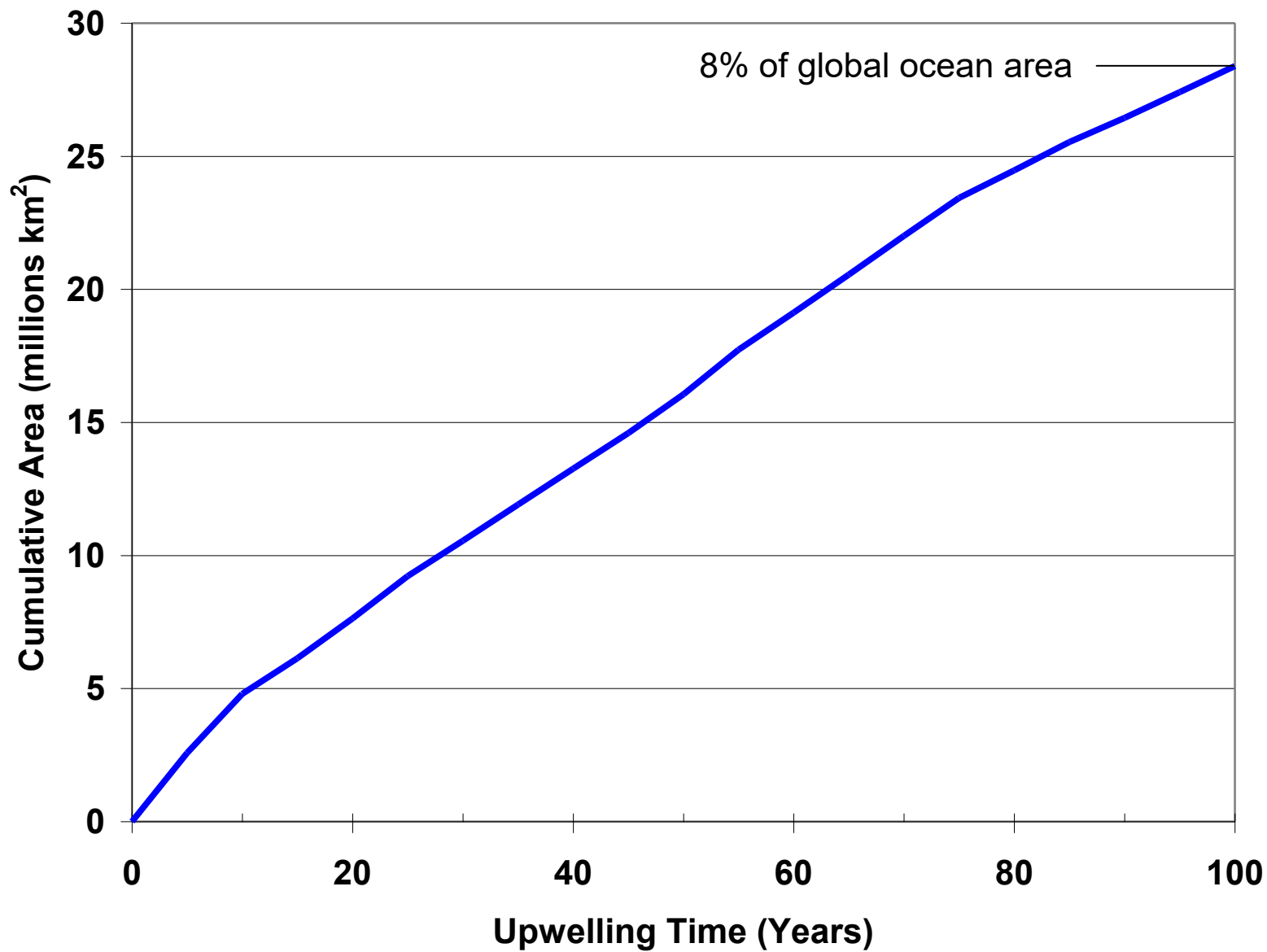
Calcite Saturation Depth (m)



-500 1 100 250 500 1000 2000 3000 4000 6000 7500

Vertically Averaged Upwelling Velocity (m/year)





The analysis to follow consists of 3 phases

- Simulation of the dissolution of falling CaCO_3 particles in a single column, calculation of the impact on mixed layer pCO_2 when the carbonate-enriched water upwells to the surface, and calculation of the amount of atmospheric CO_2 that would need to be absorbed in order to restore the original mixed layer pCO_2
- Analysis of the effect of feedback between atmospheric and mixed layer pCO_2
- Simulations with a global-scale coupled climate-carbon cycle model

Simulations with 5 Representative Columns

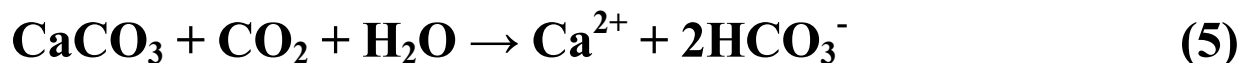
The reaction when CaCO_3 dissolves is



This induces the following reactions:



If reactions 2-4 are fully carried out, the net result is



That is: **one mole** of CO_2 absorbed for every mole of CaCO_3 dissolved, and **no net effect on acidity**.

In reality, less than one mole of CO_2 is absorbed from the atmosphere for every mole of dissolved CaCO_3 entering the mixed layer, and there is a net reduction in acidity.

Why?

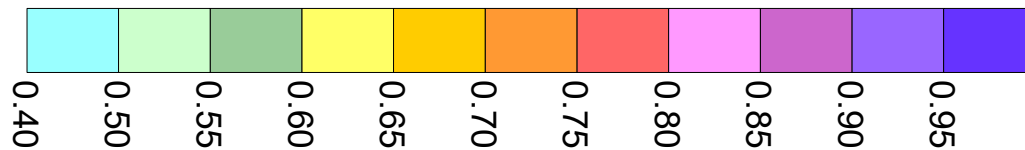
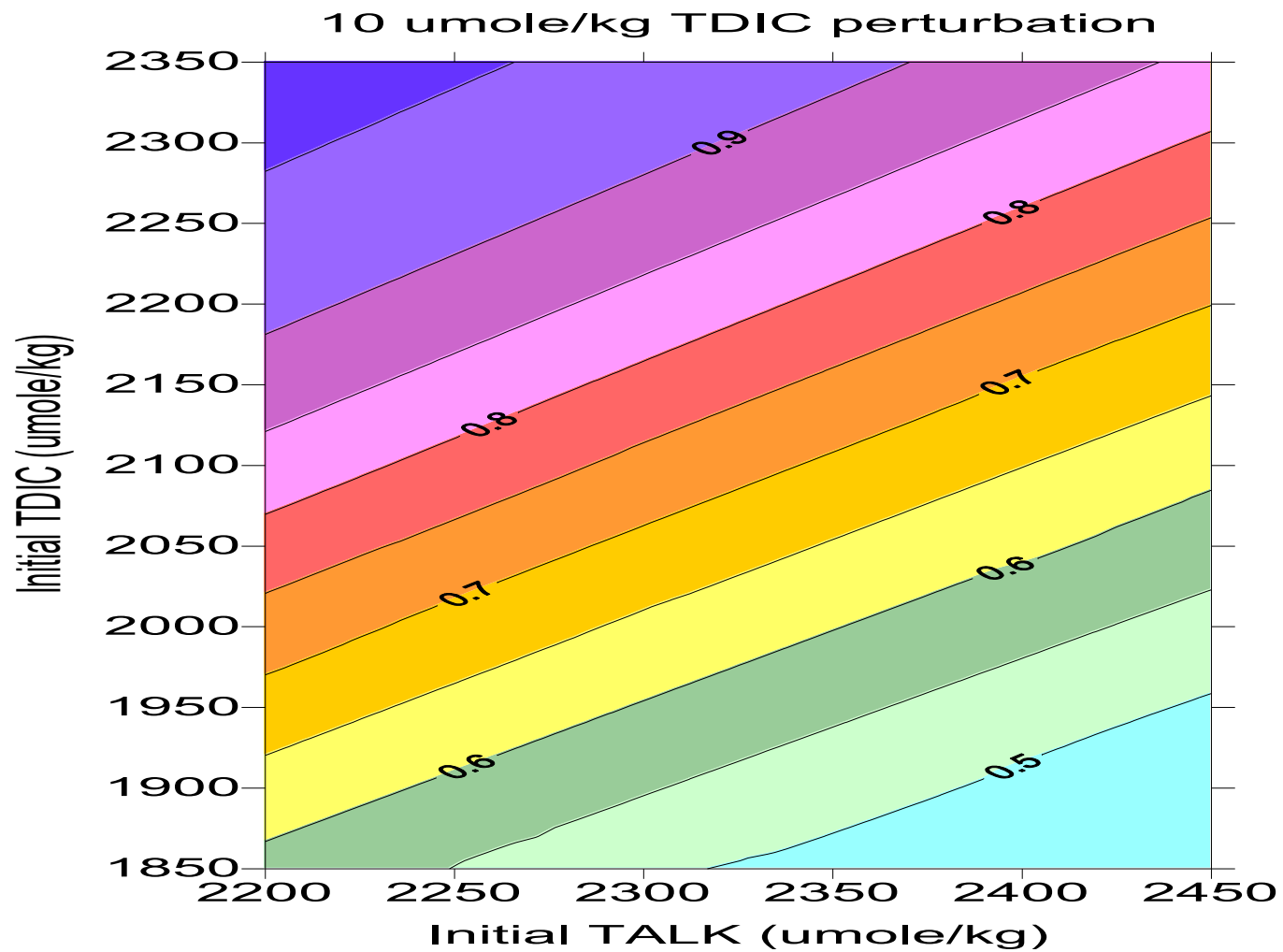
Because only as much CO_2 will enter the mixed layer from the atmosphere as is required to restore the initial pCO_2 difference between the mixed layer and atmosphere.

For fixed atmospheric $p\text{CO}_2$, the following applies after adjustment of mixed layer $p\text{CO}_2$ to the dissolution of CaCO_3 :

$$\Delta TDIC_a \frac{\partial p\text{CO}_2}{\partial TDIC} + \Delta TDIC_p \frac{dp\text{CO}_2}{dTDIC} = 0$$

Thus, the molar ratio M_R is given by

$$M_R = \frac{\Delta TDIC_a}{\Delta TDIC_p} = - \frac{dp\text{CO}_2 / dTDIC}{\partial p\text{CO}_2 / \partial TDIC}$$



Initial Profiles for 5 Representative Columns

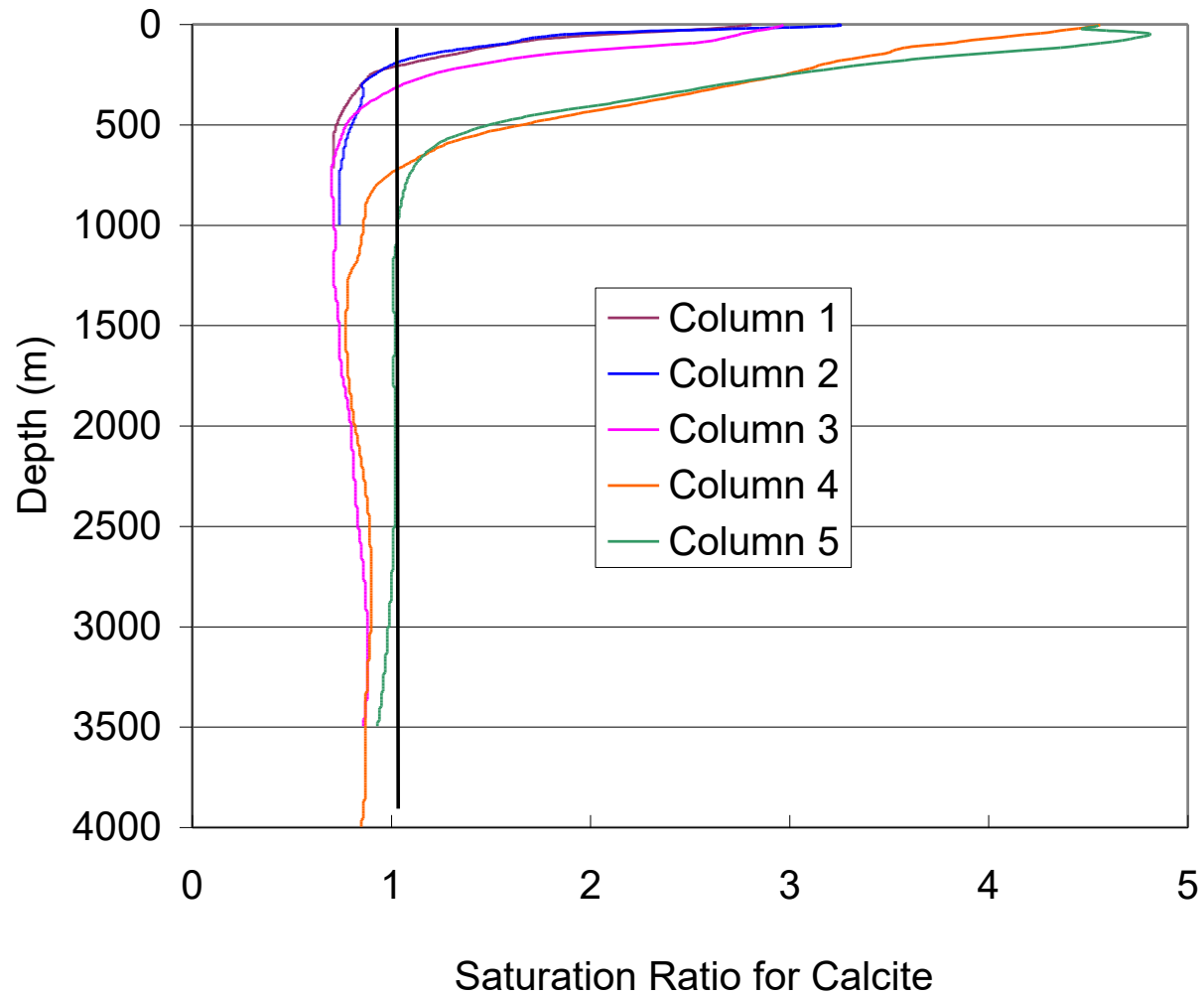
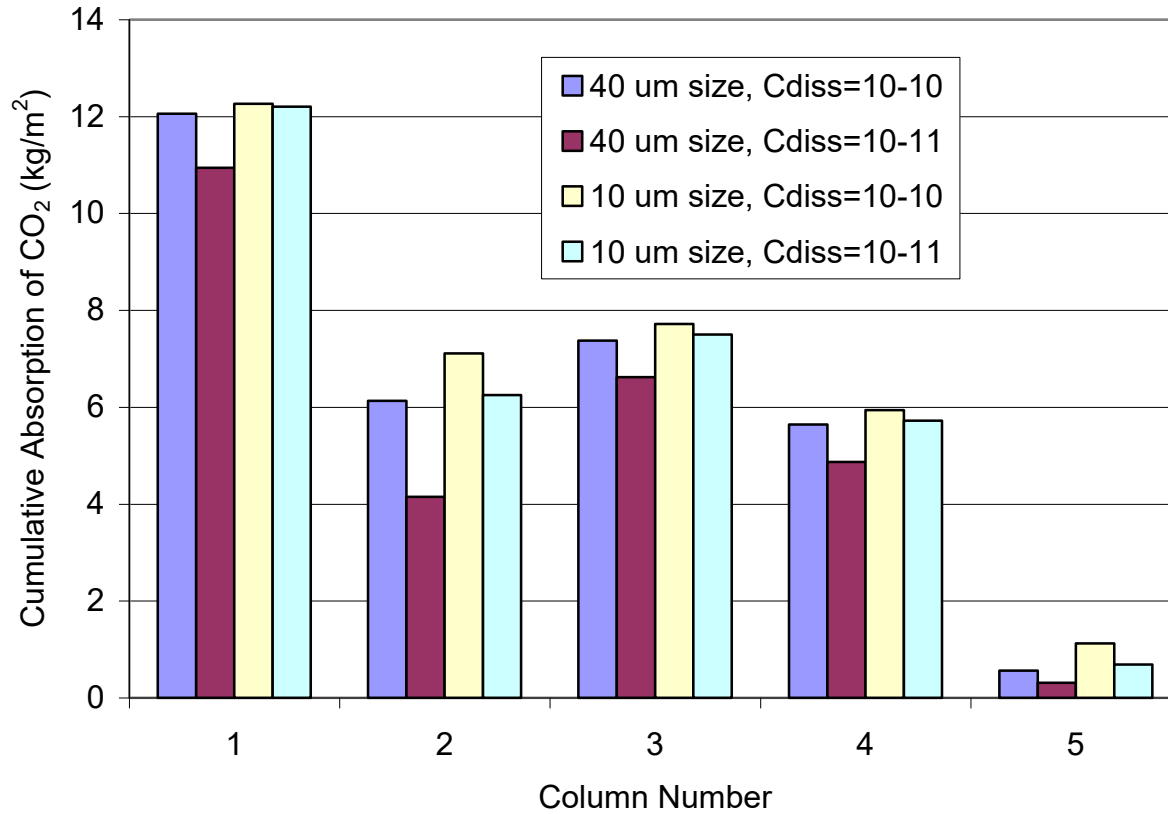


Table 3. Steady state impact on mixed layer properties of applying 200 gm/m²/yr of CaCO₃ (assumed to be calcite) at 40 μm radius with C_{dis} = 10⁻¹⁰ m/s/μmole/kg.

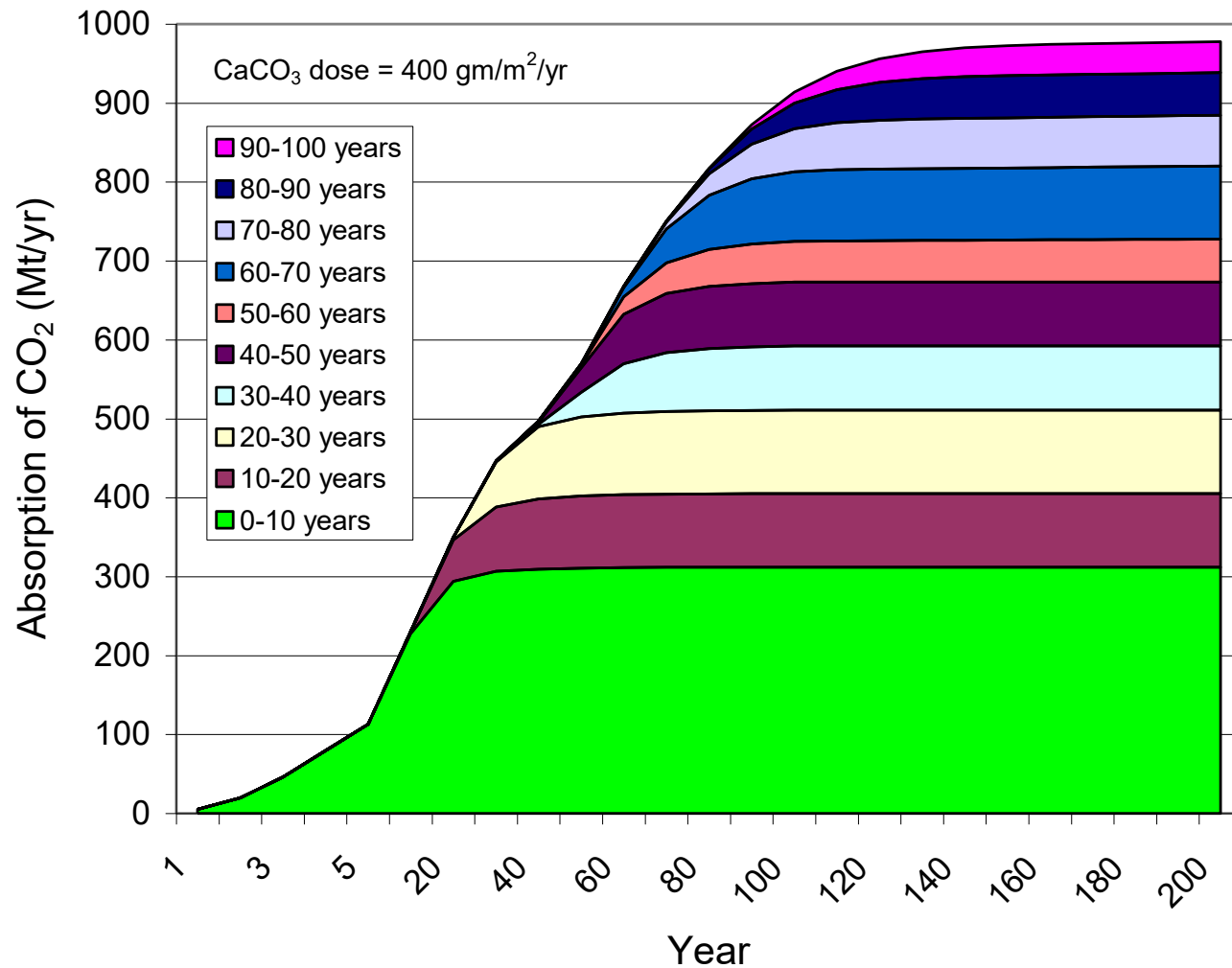
Column	Changes prior to absorption of atmospheric CO ₂ (changes in TALK are twice those of TDIC)		Equilibrium adjustment of TDIC (μmole/kg)	Moles CO ₂ absorbed over moles CaCO ₃ added	Fraction of added CaCO ₃ in the mixed layer (F)	Mass of CO ₂ absorbed over mass of CaCO ₃ added (R)
	TDIC (μmole/kg)	pCO ₂ (μatm)				
1	39.8	-40.5	28.9	0.727	0.943	0.302
2	37.6	-27.5	26.2	0.696	0.501	0.153
3	44.4	-48.7	31.7	0.714	0.587	0.184
4	33.4	-26.7	20.5	0.613	0.522	0.141
5	8.5	-10.3	5.2	0.615	0.052	0.014
	Changes in pH			Changes in Supersaturation		
	Initial	Adjustment	Final	Initial	Adjustment	Final
1	0.073	-0.059	0.014	55%	-36%	19%
2	0.063	-0.050	0.013	63%	-34%	20%
3	0.078	-0.063	0.015	62%	-41%	22%
4	0.044	-0.033	0.011	51%	-28%	23%
5	0.012	-0.009	0.003	13%	-7%	6%

Cumulative Absorption after 200 Years

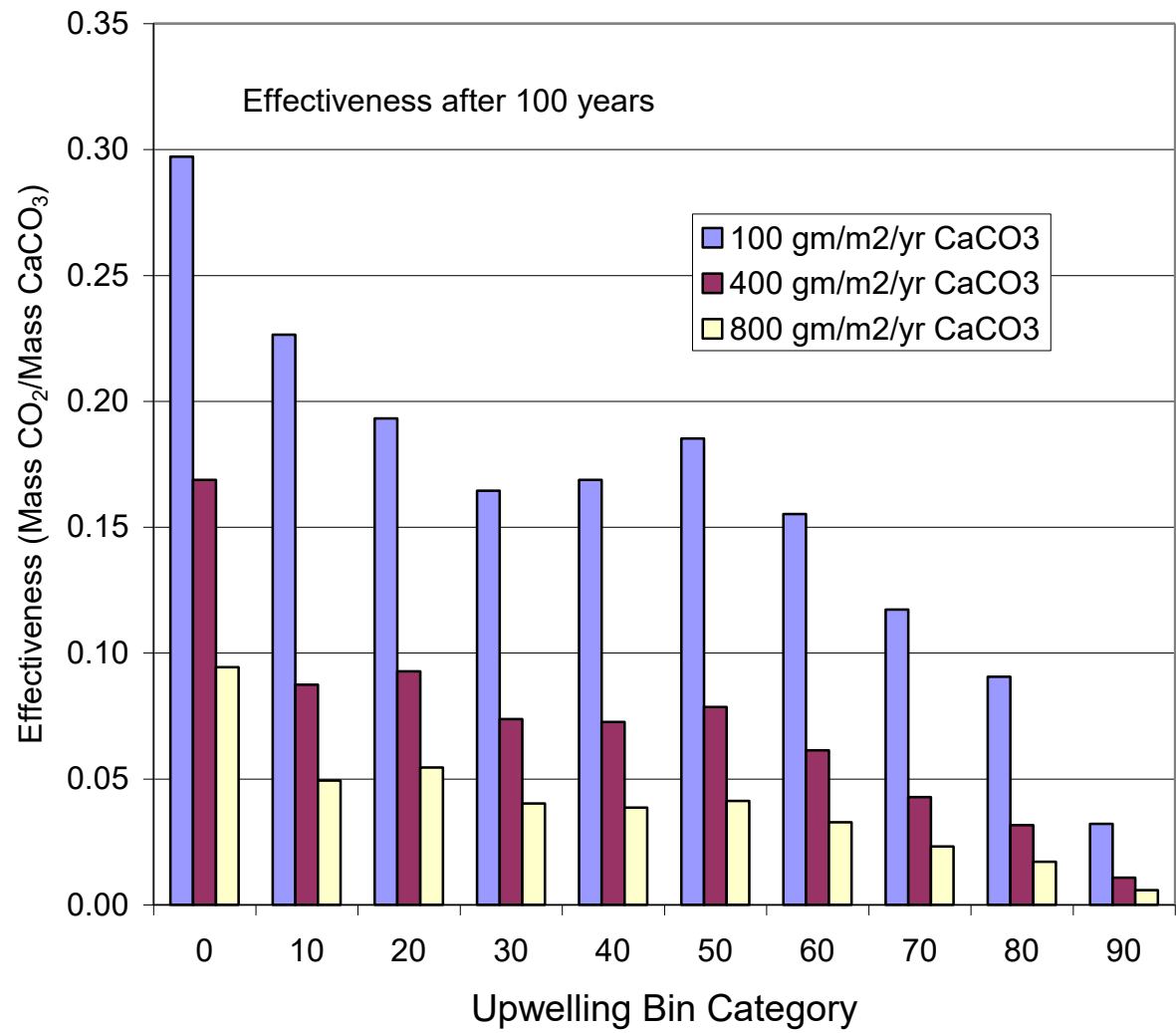


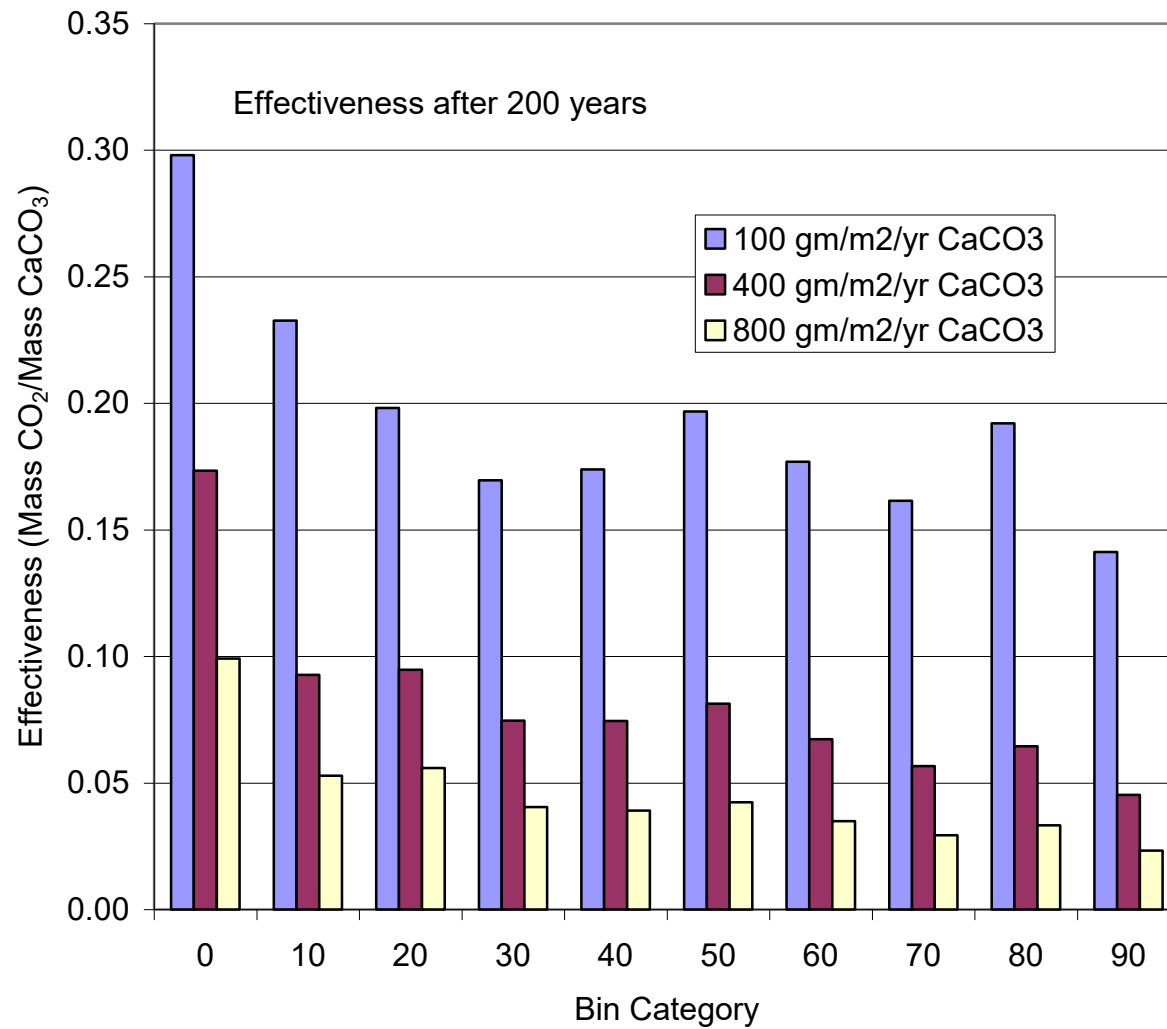
Simulations with all 3713 $1^\circ \times 1^\circ$
columns having an upwelling time
of 100 years or less

Rate of absorption of CO₂ for one uniform rate of application of limestone powder, showing contributions from groups of columns with different upwelling times



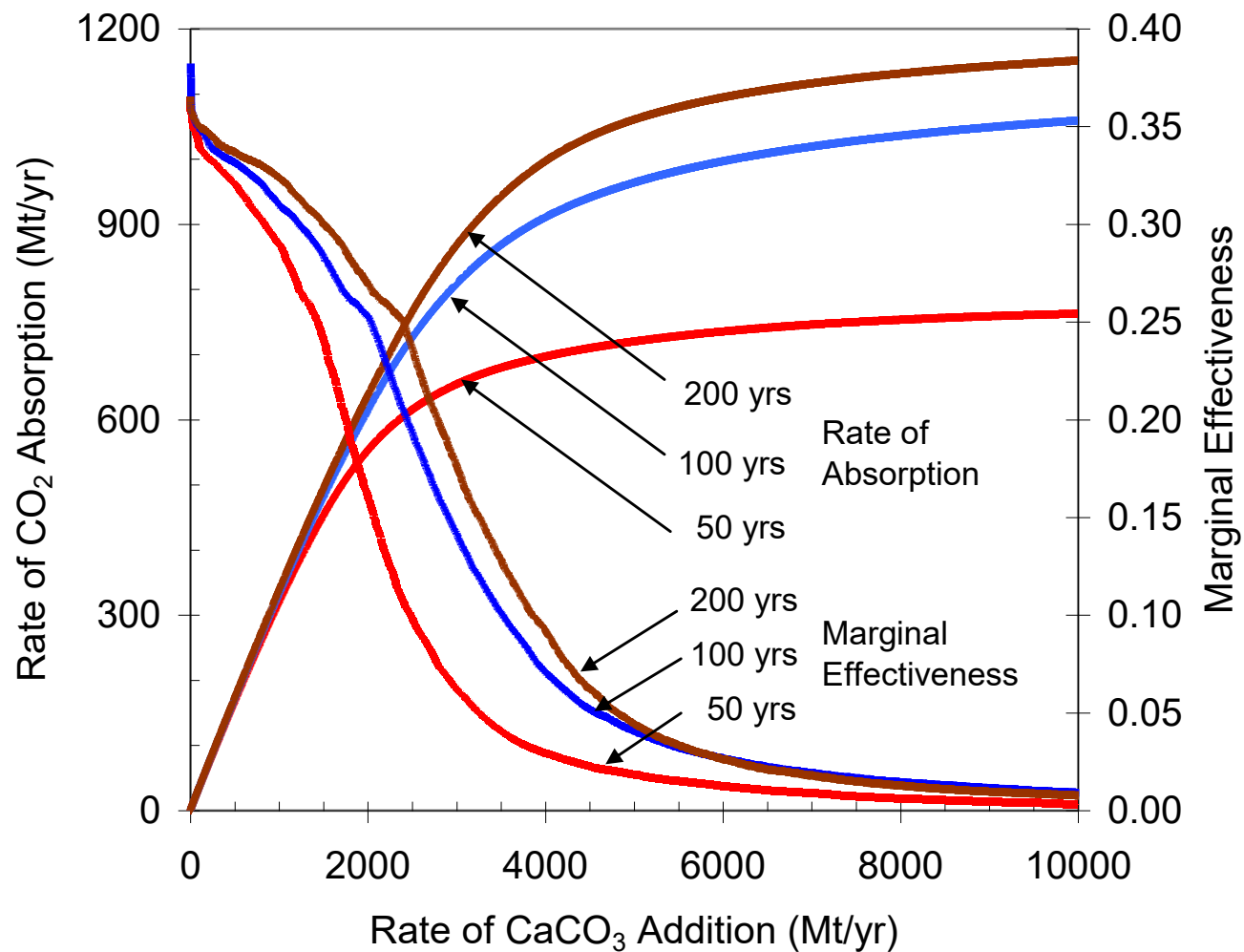
The effectiveness of adding limestone powder in terms of absorbing atmospheric CO₂ decreases with increasing rate of application, varies between columns in different upwelling bins, and varies over time



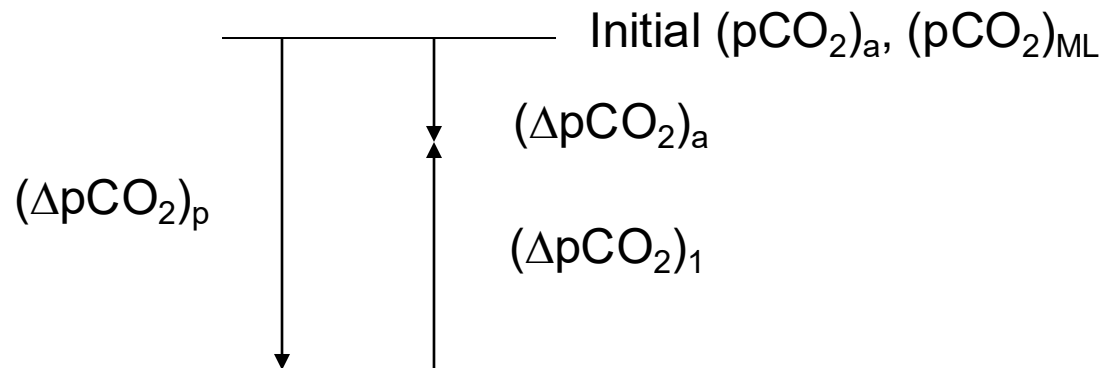
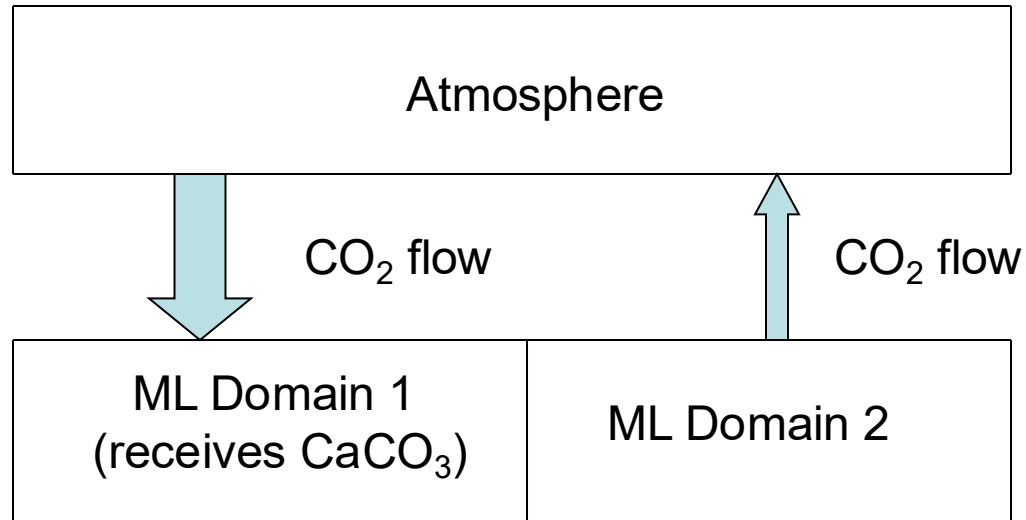


Optimization Strategy:

- Compute the marginal effectiveness of adding limestone powder in each of 3713 columns for successively greater rates of limestone addition
- Sort all of the column/limestone-increment combinations in order of decreasing effectiveness
- Prepare a plot of rate of absorption of CO_2 vs total rate of addition of limestone, as the rate of addition of limestone is increased according to the order established in step (2).



Global-scale Interactions



Balance Equations:

Domain 1 $p\text{CO}_2$

$$\Delta(p\text{CO}_2)_1 - (\Delta p\text{CO}_2)_a + (\Delta p\text{CO}_2)_p = 0$$

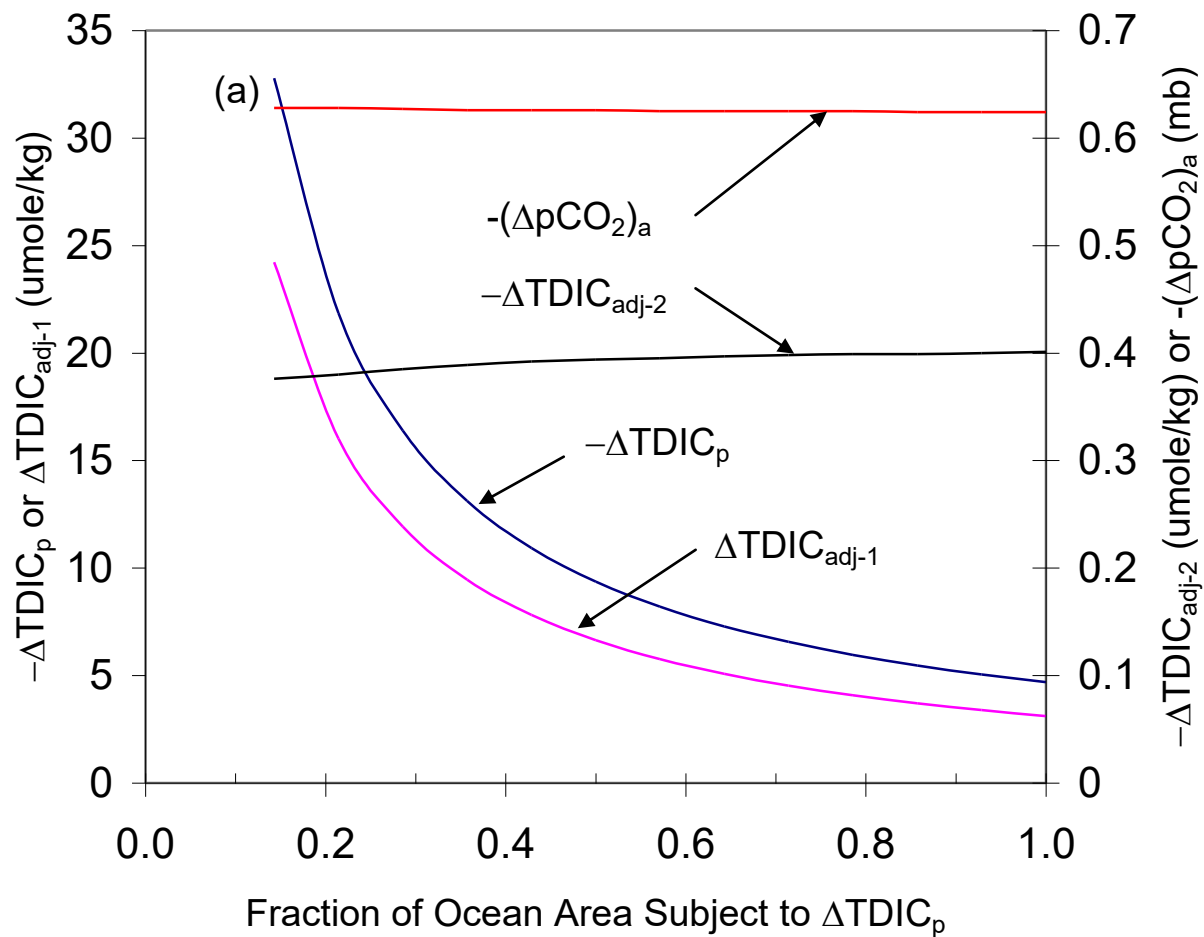
Domain 2 $p\text{CO}_2$

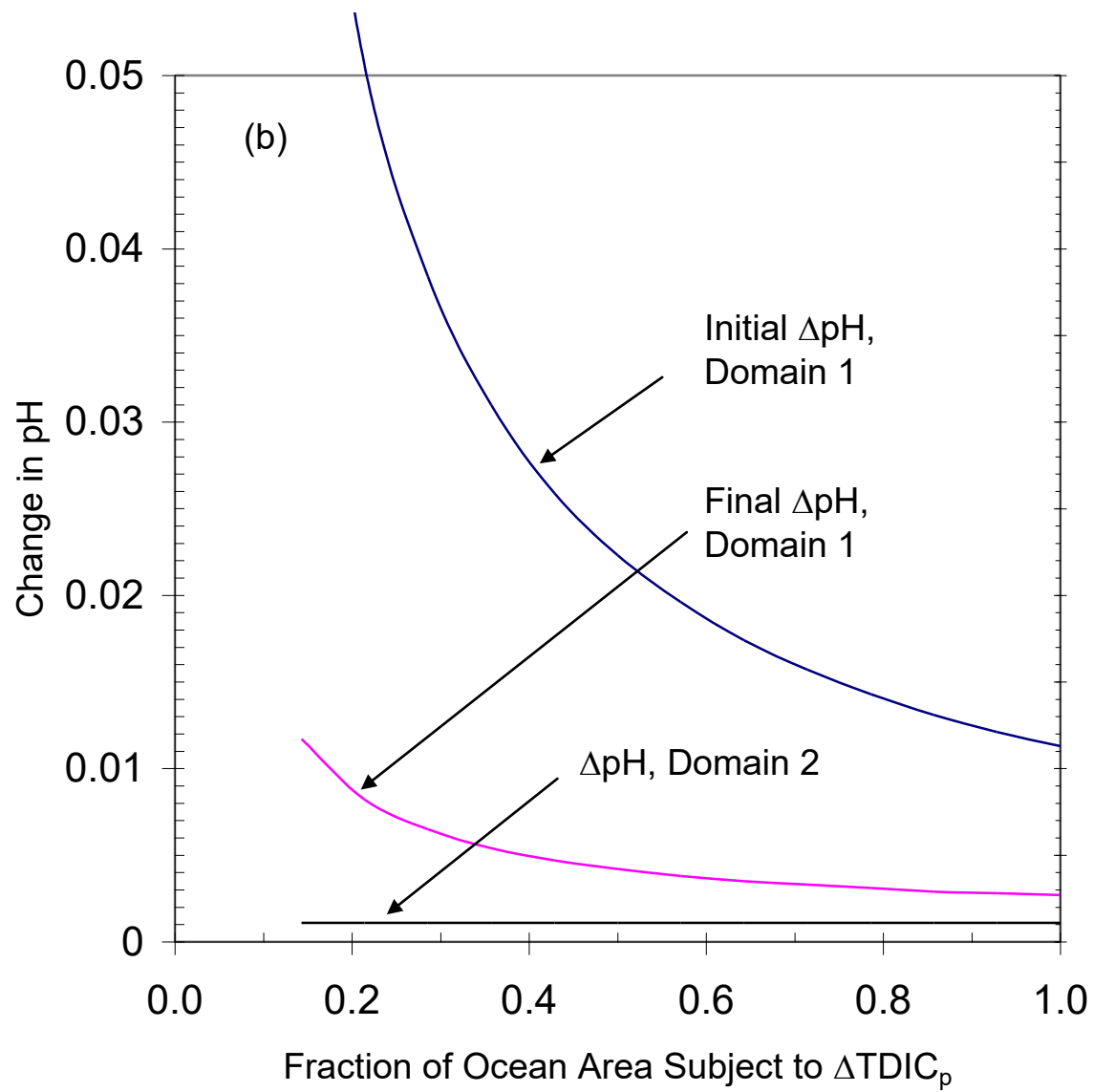
$$\Delta(p\text{CO}_2)_2 - (\Delta p\text{CO}_2)_a = 0$$

Conservation of mass

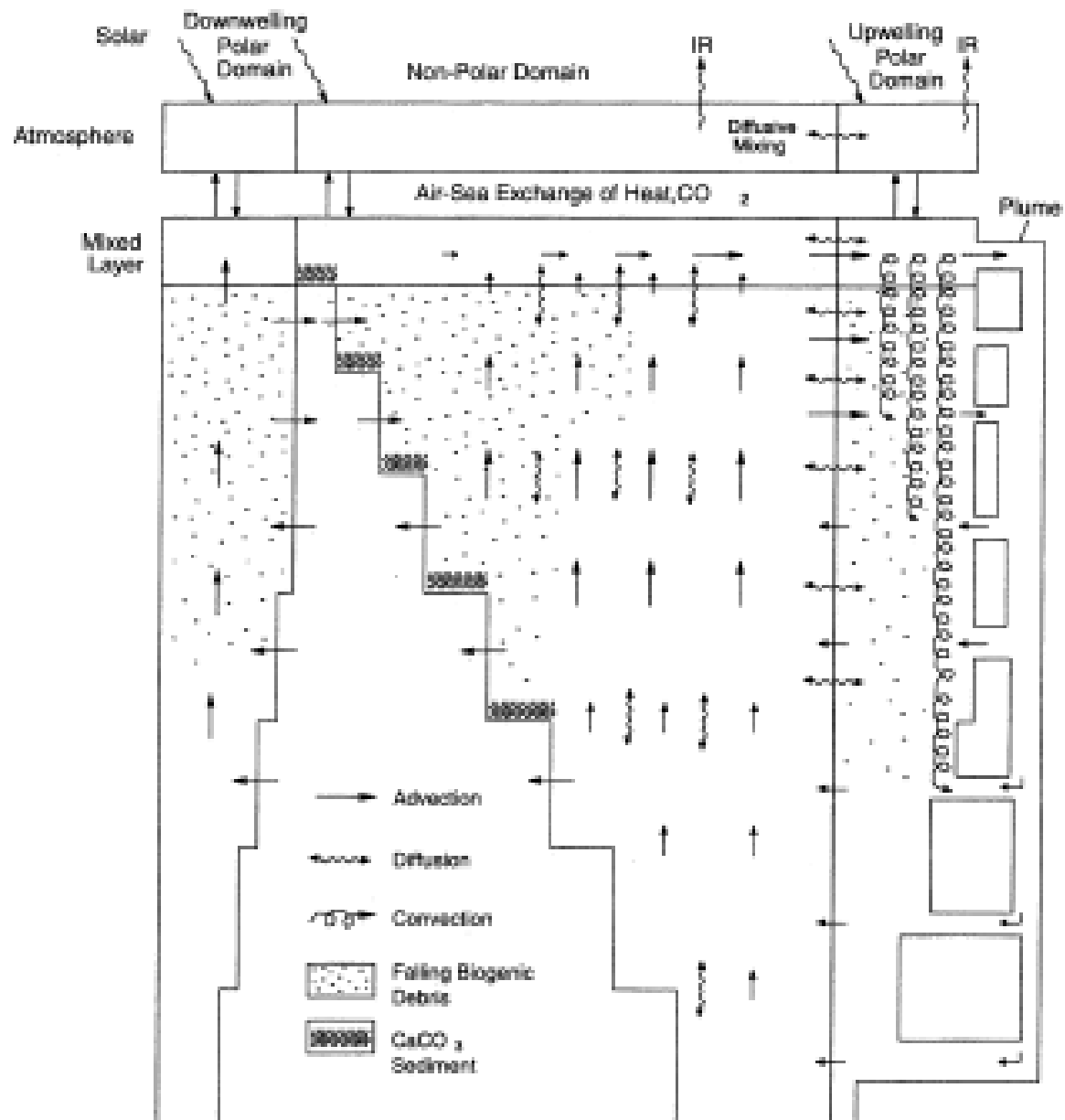
$$\Delta C_1 + \Delta C_2 + \Delta C_a = 0$$

Impact of Dissolving 2 Gt CaCO_3 into the Mixed Layer of
Domain 1



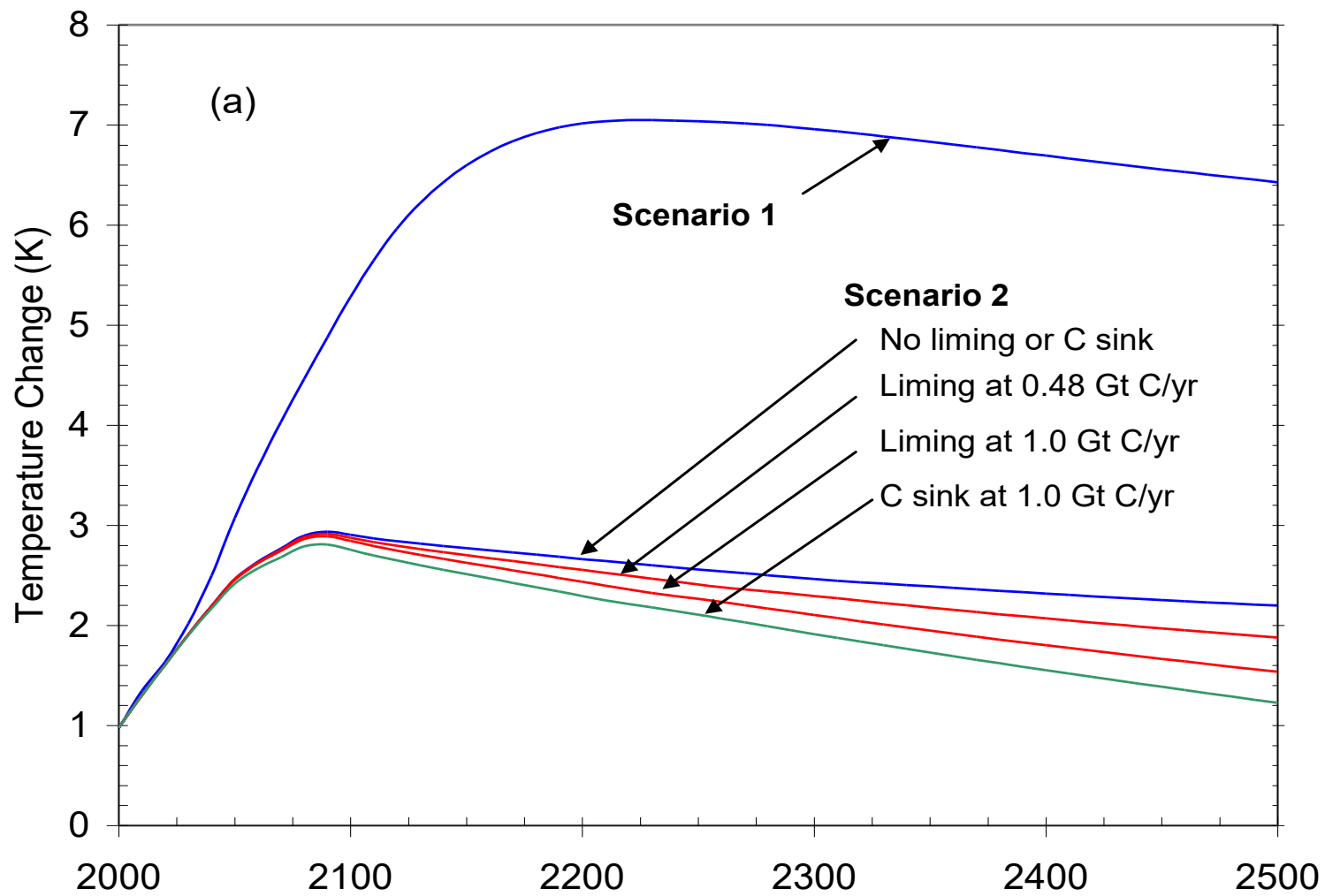


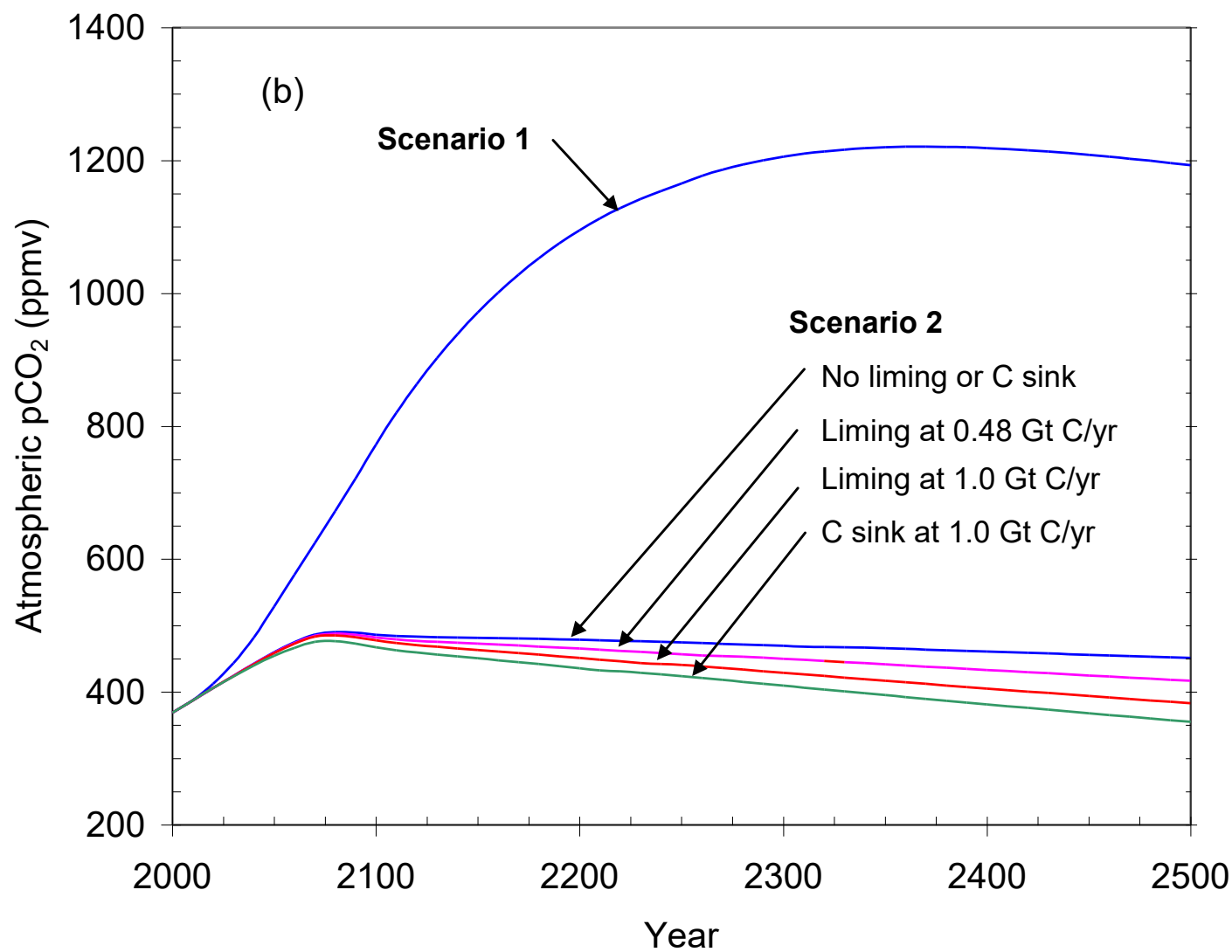
Simulations with a coupled climate-
carbon cycle model

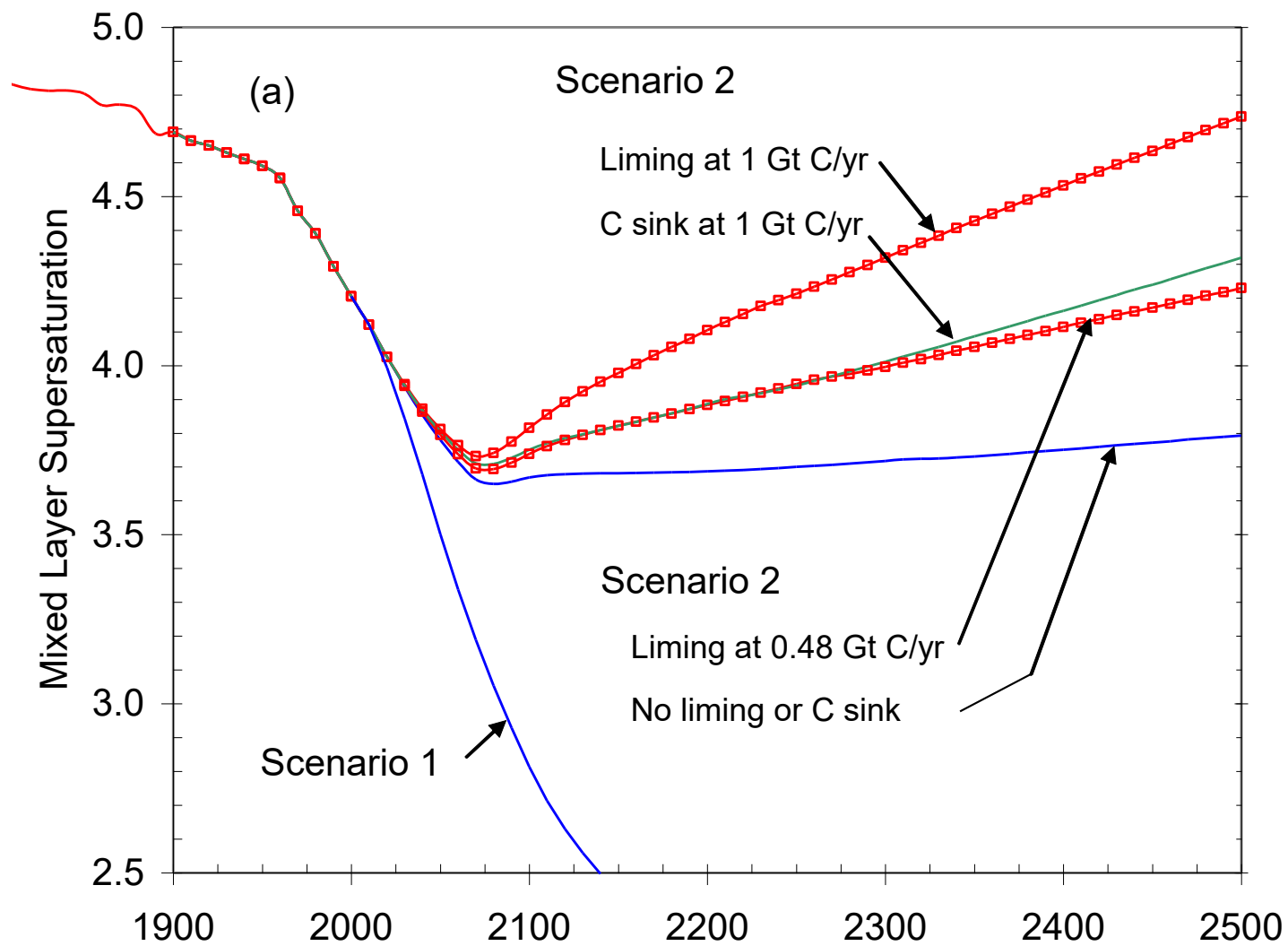


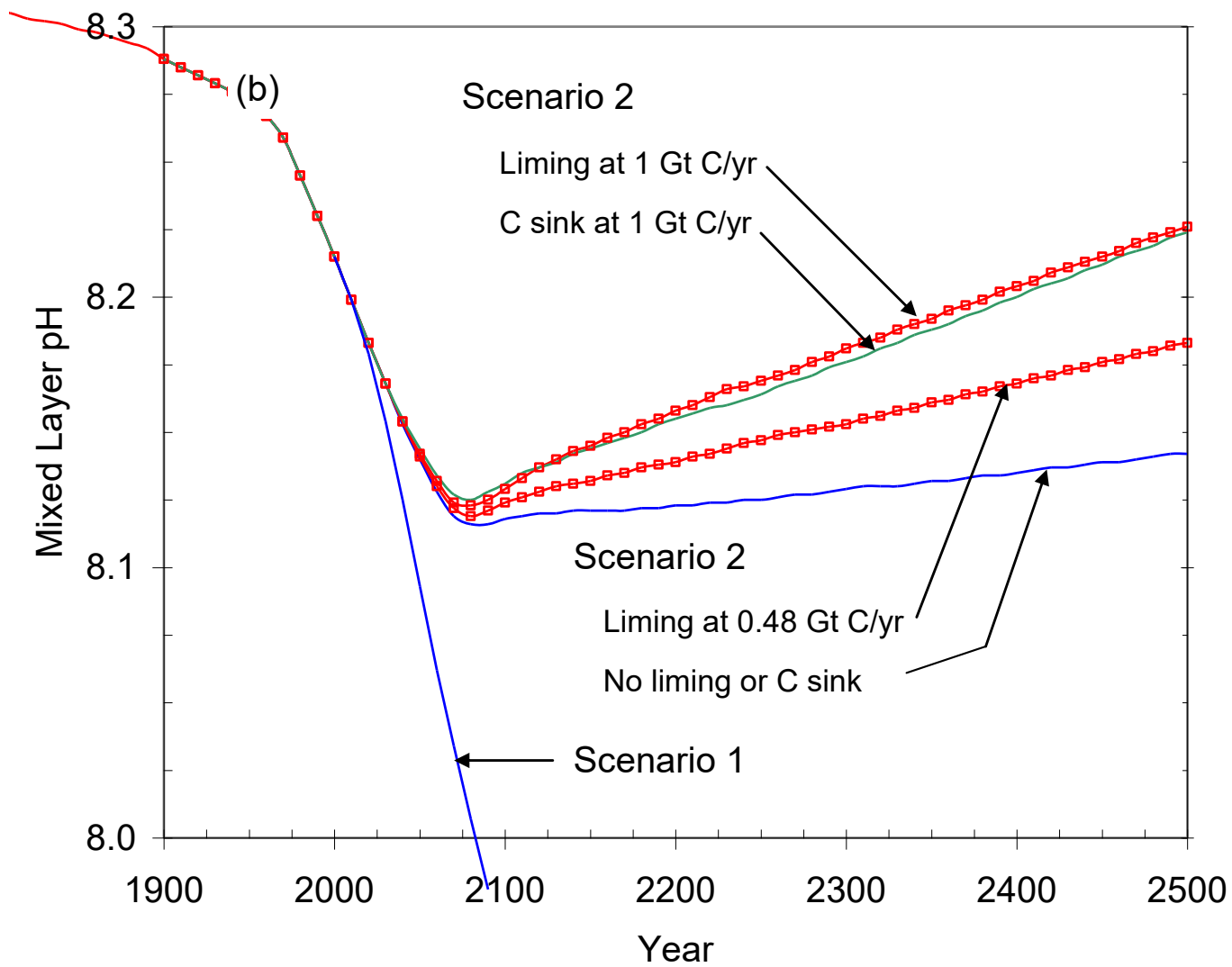
Scenarios and Assumptions

- Scenario 1: Fossil fuel CO₂ emission peaks at 17.5 Gt C/yr in 2100, then declines by 1%/yr
- Scenario 2: Fossil fuel CO₂ emission peaks at 7.5 Gt C/yr in 2010, drops to zero by 2100, and stringent reductions in emissions of other GHGs or precursors occur
- Climate sensitivity of 3 K









Conclusions

- Phasing out CO₂ emissions by 2100 has the single largest impact in reducing the ocean acidification that will otherwise occur
- Extraordinary additional measures (adding 4 Gt limestone/yr to the ocean for > 200 years) provides a modest additional benefit
- Compared to sequestering 0.5 Gt C/yr in soils or in geological strata, adding 0.5 Gt C/yr of dissolved CaCO₃ to the mixed layer (by adding 4 Gt/yr of limestone powder) has
 - - about twice the effect of ML supersaturation,
 - - about the same effect on ML pH, and
 - - about $\frac{3}{4}$ the effect on atm pCO₂ and ΔT