Mini-conference on Vulnerabilities of the Carbon-Climate-Human System

Vulnerabilities of the calcium-carbonate cycle: positive and negative feedbacks

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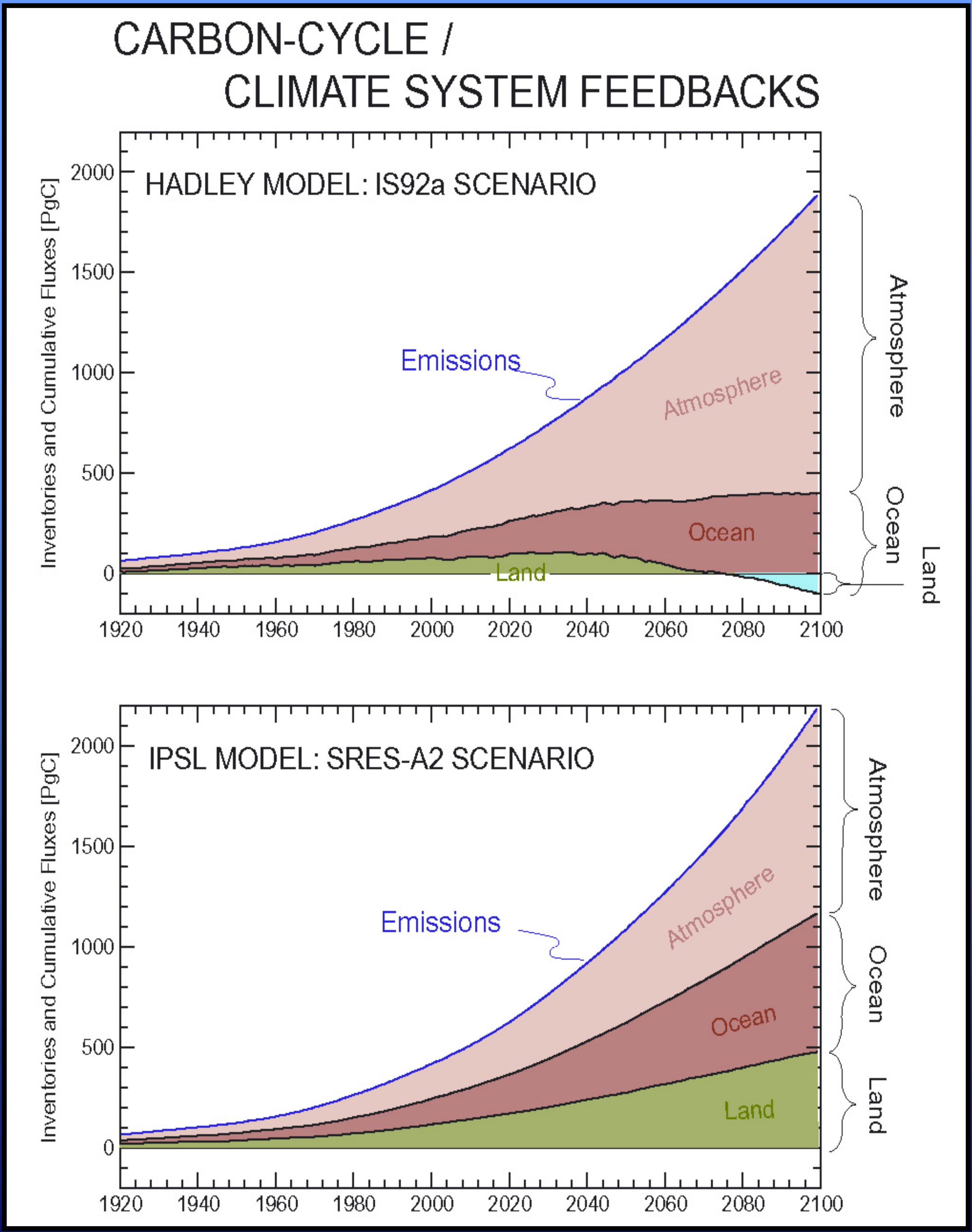
Wednesday, 15 June 2005

UNESCO, Paris, France



Current level of understanding, projected into the future:

- Predictive models differ significantly in future predictions.
- Cannot improve predictions without better understanding of the controlling processes.
- This is no longer just an academic issue
- Disagreements in predictions impact baseline targets for emissions reduction.
- Sequestration cost targets are $10-35/t of C.
- Differences between models imply differences in ecosystem services of trillions of dollars.
- = big incentive for research.

- A. Gnanadesikan, GFDL

The Global Carbon Budget [Pg C]. Positive values represent atmospheric increase (or ocean/land sources), negative numbers represent atmospheric decrease (sinks).

	1800-1979	1980-1999
Atmospheric increase	116 ± 4	65 ± 1
Emissions (f. fuel, cement)	[redacted]	[redacted]
Ocean Inventory		
Net terrestrial	+50 ± 28	-15 ± 9
Land-use change	+82 to +162	+24 ± 12
**Resid. terrestrial sink*	-32 to -112	-39 ± 18

First 180 years the ocean absorbed 57% of FF emissions

Last 20 years the ocean absorbed 31% of FF emissions

Relative to total emissions the ocean absorbed 44% and 36%

There are a number of feedbacks in the global carbon cycle and between the carbon and climate systems that we must understand if we are ever to predict the future role of the ocean as a sink for CO_2

Carbon Cycle Change	Climate Feedback	direction
CO_3^{2-} decrease	Less efficient uptake	positive
Calcification decrease	lower natural CO_2 production	negative
$CaCO_3$ dissolution-sed.	higher CO_3^{2-} increasing uptake	negative
$CaCO_3$ dissolution-water	higher CO_3^{2-}/lower org. transport	Neg./pos.
Increasing SST	Convert ocean HCO_3^- to CO_2	positive
Increased stratification	Reduced mixing and transport	positive
Increased stratification	Lower productivity and uptake	positive
Increased dust input	Increased productivity-N fixers	negative
Ecosystem structure	Lower or higher productivity	Pos./neg.
CH_4 hydrate release	Increased greenhouse forcing	Positive

2005 Headlines on CO_2 & Coral Reefs

Ocean acidification represents "potentially a gigantic problem for the world." -Dr. Carol Turley, Plymouth Marine Laboratory, Feb. 7, 2005.

"Scientists warn growing acidity of oceans will kill reefs" Paul Brown, environment correspondent, The Guardian

"As an ecosystem our grandchildren will not see coral reefs any more" – Professor Jonathan Erez, Hebrew University of Jerusalem – BBC News, Feb. 13, 2005

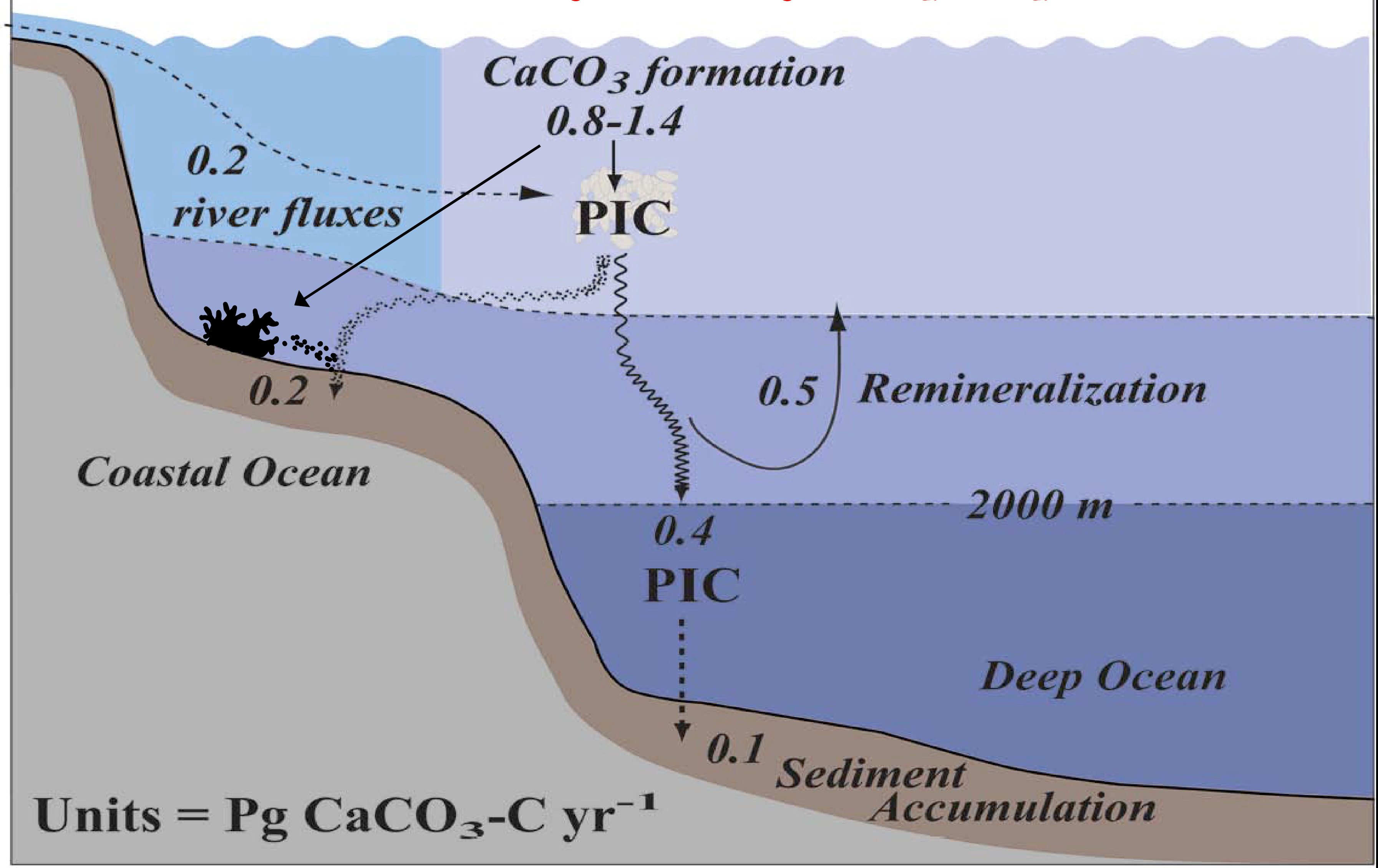
"If CO_2 levels continue to rise, the oceans could be more acidic in 2100 than they have been for 400 million years." Ulf Riebesell - BBC News, Feb. 07, 2005.

"The Other CO_2 Problem: Ocean Acidification," GCC News, Feb. 05, 2005.

"The world scientific community is only just waking up to this." Cape Argus, Feb. 5, 2005

$$Ca^{2+} + CO_3^{2-} = CaCO_3$$

$$Ca^{2+} + 2HCO_3^{-} = CaCO_3 + CO_2 + H_2O$$



CO_2 is an acid gas…as we add CO_2 to the surface waters we are reducing the buffering capacity of the ocean and its ability to continue to take up CO_2 from the atmosphere

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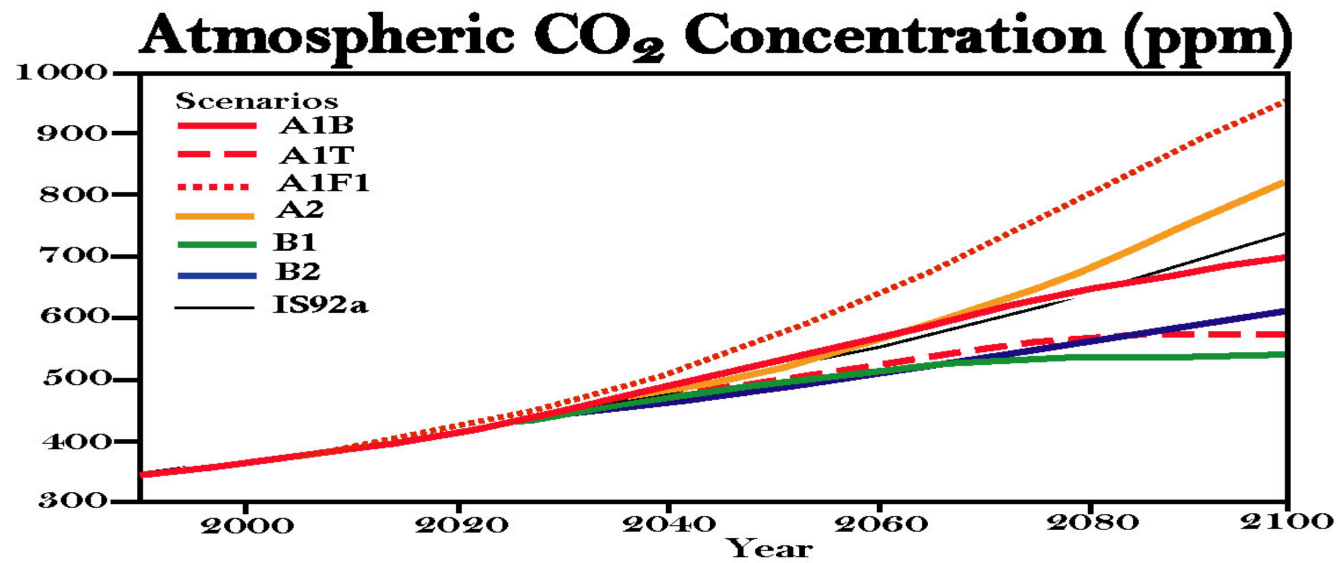


$CO_2(g)$ Gas Exchange	Glacial	Pre-industrial	Present	$2XCO_2$	$3XCO_2$	Atmosphere
	180 (56)	280 (0)	380 (36)	560 (100)	840 (200)	Surface ocean
$CO_2(aq) + H_2O \rightleftarrows H_2CO_3$ Carbonic acid	7 (29)	9 (0)	13 (44)	18 (100)	25 (178)	
$H_2CO_3 \rightleftarrows H^+ + HCO_3^-$ Bicarbonate	1666 (4)	1739 (0)	1827 (5)	1925 (11)	2004 (15)	
$HCO_3^- \rightleftarrows H^+ + CO_3^{2-}$ Carbonate	279 (20)	222 (0)	186 (-16)	146 (-34)	115 (-48)	
$H^+ x10^{-9}$ Hydrogen Ion Concentration	4.79 (45)	6.92 (0)	8.91 (29)	12.3 (78)	17.4 (151)	
Ω Ca Omega Calcite	6.63 (20)	5.32 (0)	4.46 (-16)	3.52 (-34)	2.77 (-48)	
Ω Ar Omega Aragonite	4.26 (19)	3.44 (0)	2.9 (-16)	2.29 (-33)	1.81 (-47)	
	1952 (1)	1970 (0)	2026 (2.8)	2090 (6.1)	2144 (8.8)	DIC
	8.32	8.16	8.05	7.91	7.76	pH

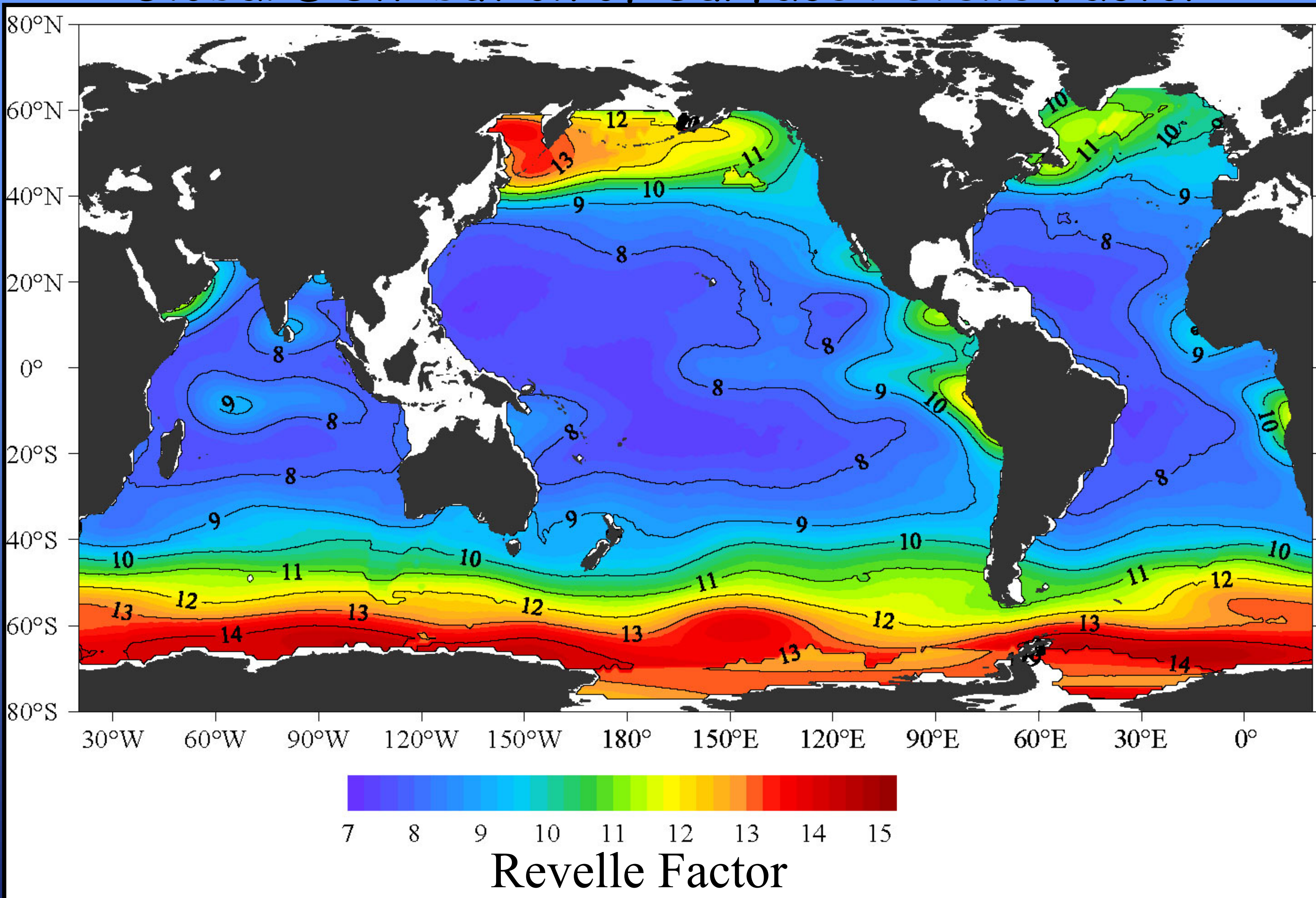
Average Surface Water DIC Increase in 2000 ~ 1.2 μmol kg^{-1} yr^{-1}

Under IPCC "Business as Usual" the pH of surface seawater drops by 0.4 pH units by 2100. $CO_3^{=}$ in surface water drops by 48% from pre-industrial values.

% Change from Pre-industrial Values

Modified from Feely et al., (2001)

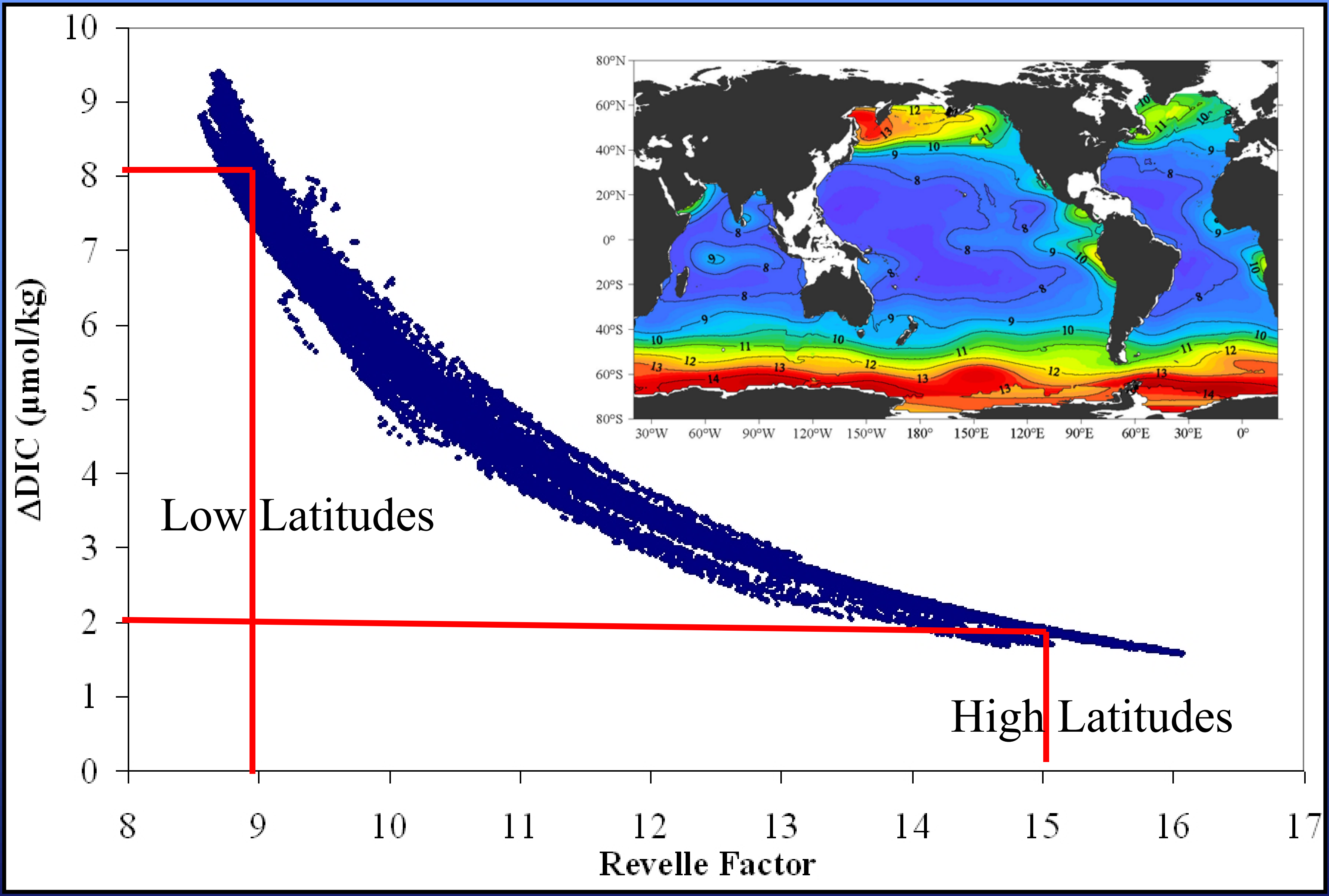
Global Distribution of Surface Revelle Factor



R. Revelle, H.,E. Suess,
Tellus 9, 18 (1957)

$$\frac{(\Delta fCO_2/\Delta TCO_2)}{(fCO_2/\ TCO_2)}$$

ΔDIC for a 10 ppm change in pCO_2 as a function of Revelle Factor



Modern Revelle Factors have already increased by 1 since preindustrial

$CaCO_3$ prod. currently releases ~1 PgC yr^{-1} to the atmosphere, as CO_3^{2-} concentrations drop calcification is expected to decrease

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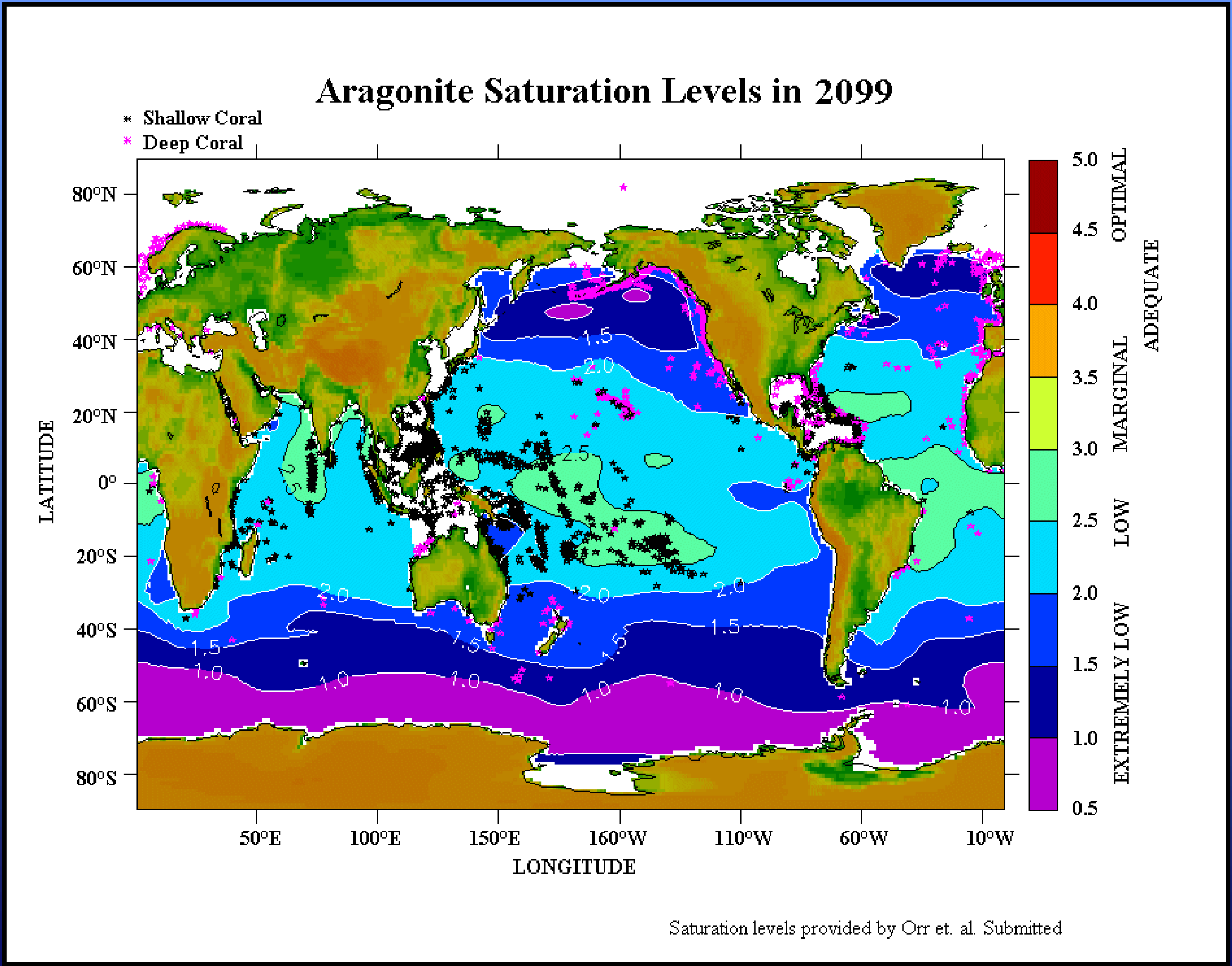
Ecosystem structure	Lower or higher productivity	Pos./neg.
CH_4 hydrate release	Increased greenhouse forcing	Positive

Warm water corals have primarily formed in aragonite saturation levels > 4, can survive at levels > 3.5, and generally stop growing < 3



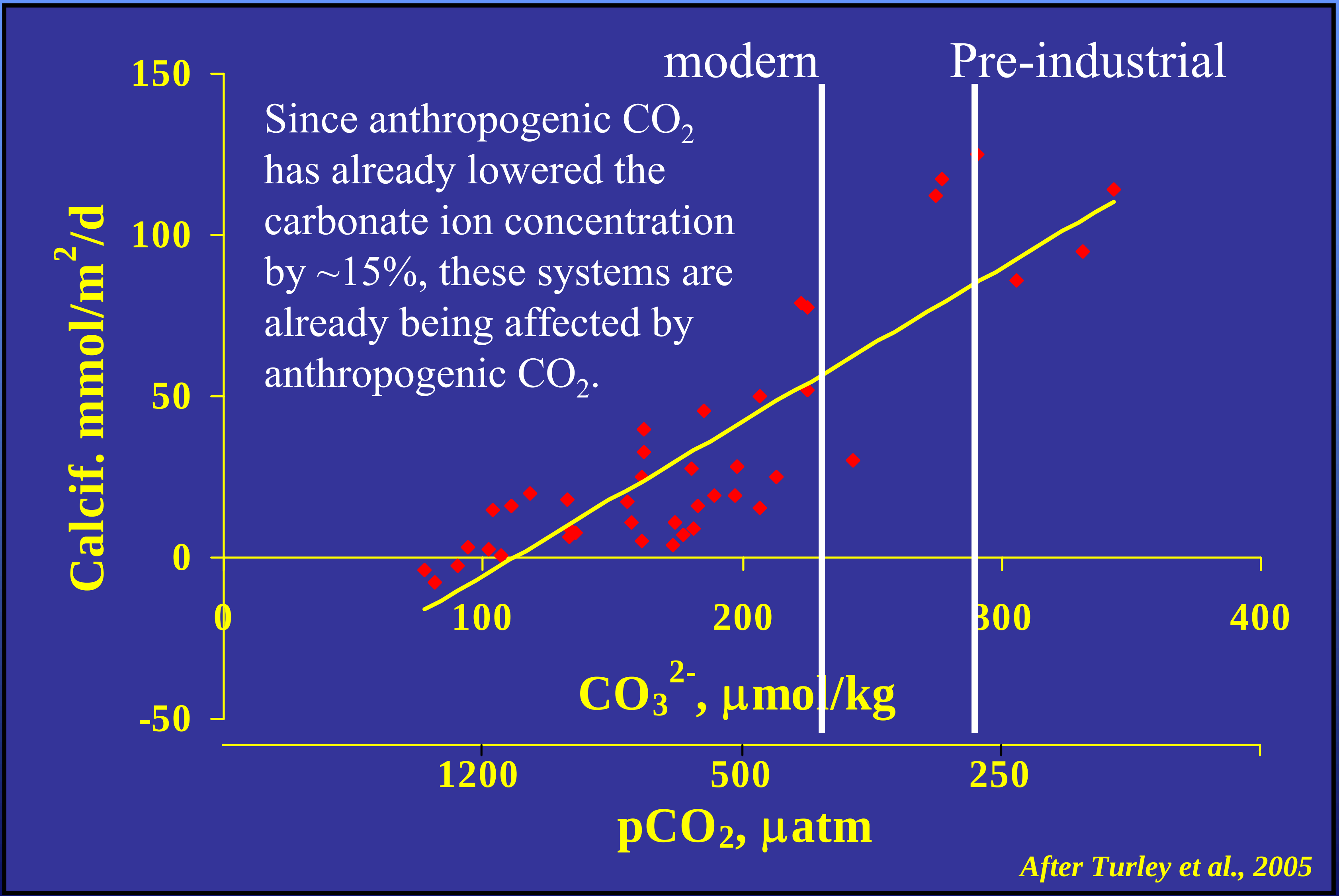
Effects of doubled CO_2 on coral calcification

Organism/ System	Manipulation	% Change in Calc'n	Reference
Corallina	1	-44	Gao 1993
Porolithon	2	-25	Agegian 1985
Amphiroa	3	-36	Borowitzka 1981
Turbinaria	2	-15	
Stylophora	2	-15	
Goniastrea	2	-16	Marubini et al. 2003
Acropora	2	-18	
Porites	2	-18	
	1	-19	Marubini et al. 2001
Acropora	2	-37	Schneider & Erez 2000
Porites	2	-27	Marubini & Atkinson 1999
Porites/ Montipora	2	-51	Langdon et al. (2003)
Montipora	3	-22	Langdon et al. (2003)
Gr. Bahama Banks*	4	-82	Broecker & Takahashi 1964 Broecker et al. 2001
B2 mesocosm*	1,3,4	-54	Langdon et al. 2000
Monaco mesocosm	1	-21	Leclercq et al. 2000

* dominated by coralline algae

Slide from: J. Kleypas

There appears to be a linear decrease in the calcification rate of coral reef systems with decreasing carbonate ion concentrations.



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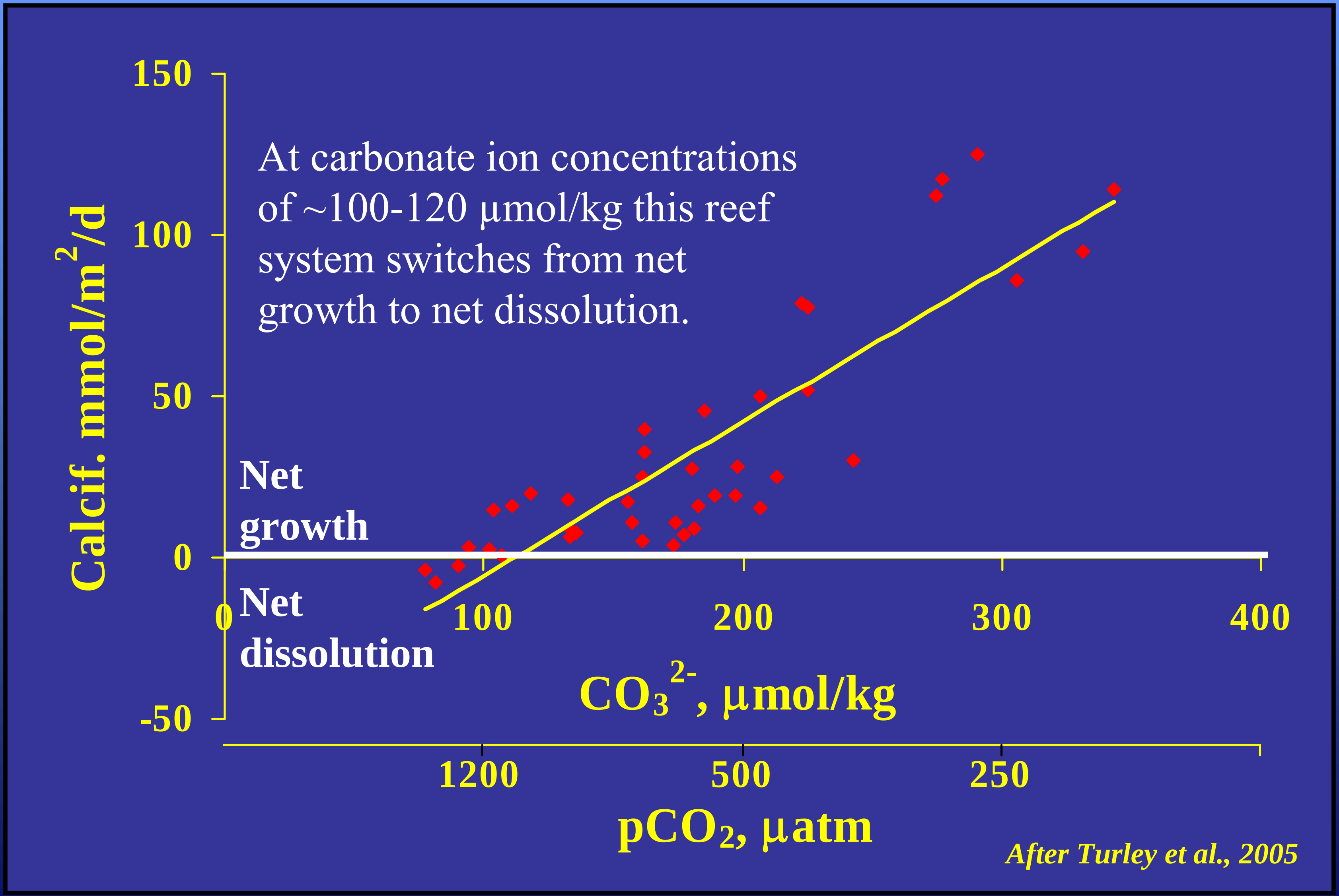
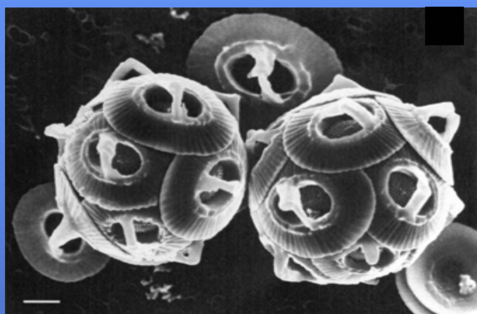


Major planktonic calcifiers

	group	mineral form	generation time	# of extant species
	Coccolithophores **autotroph**	**calcite**	**day(s)**	**~250**
	Foraminifera **heterotroph** (many with auto-trophic symbionts)	**calcite**	**weeks**	**~4000**
	Pteropods **heterotroph**	**aragonite**	**months**	**~30**

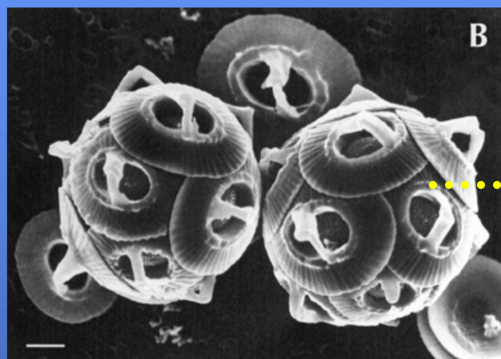
Response to elevated CO_2 (decreased pH, Ω or $[CO_3^{2-}]$)

Today's world

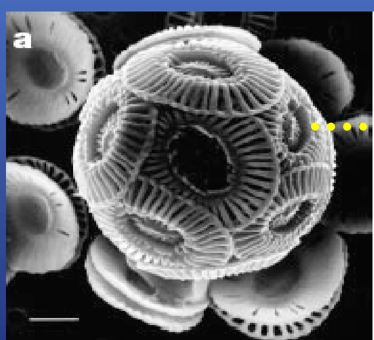
pCO$_2$: 280-380 ppmV

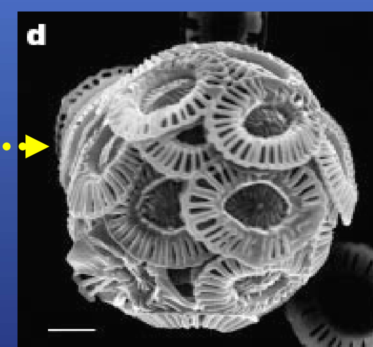
High-CO_2 world

pCO$_2$: 580-720 ppmV

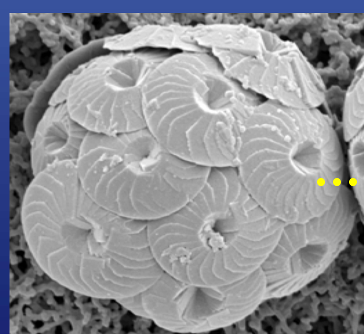


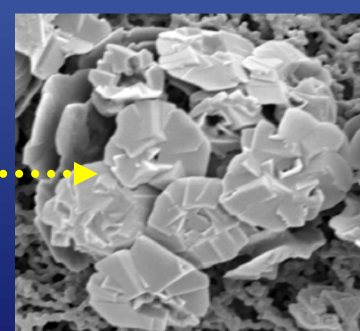
Gephyrocapsa oceanica





Emiliania huxleyi





Calcidiscus leptoporus

Riebesell et al. (2000), Nature; Langer et al. subm.

CO_2 out-gassing as a consequence of $CaCO_3$ production

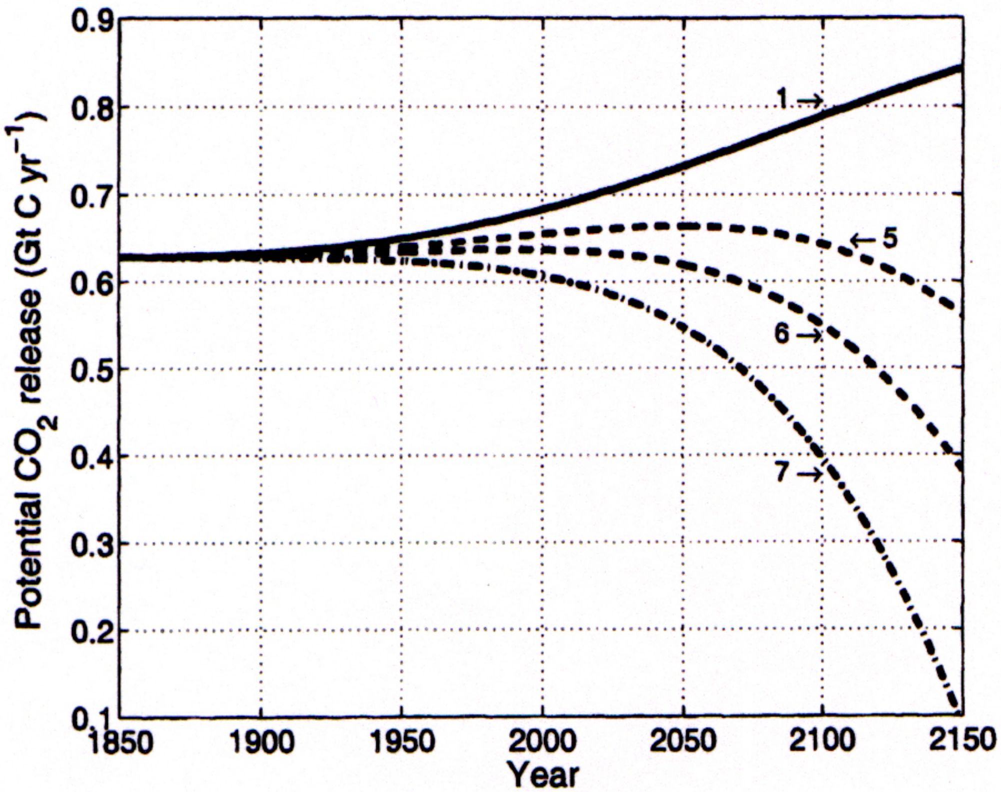
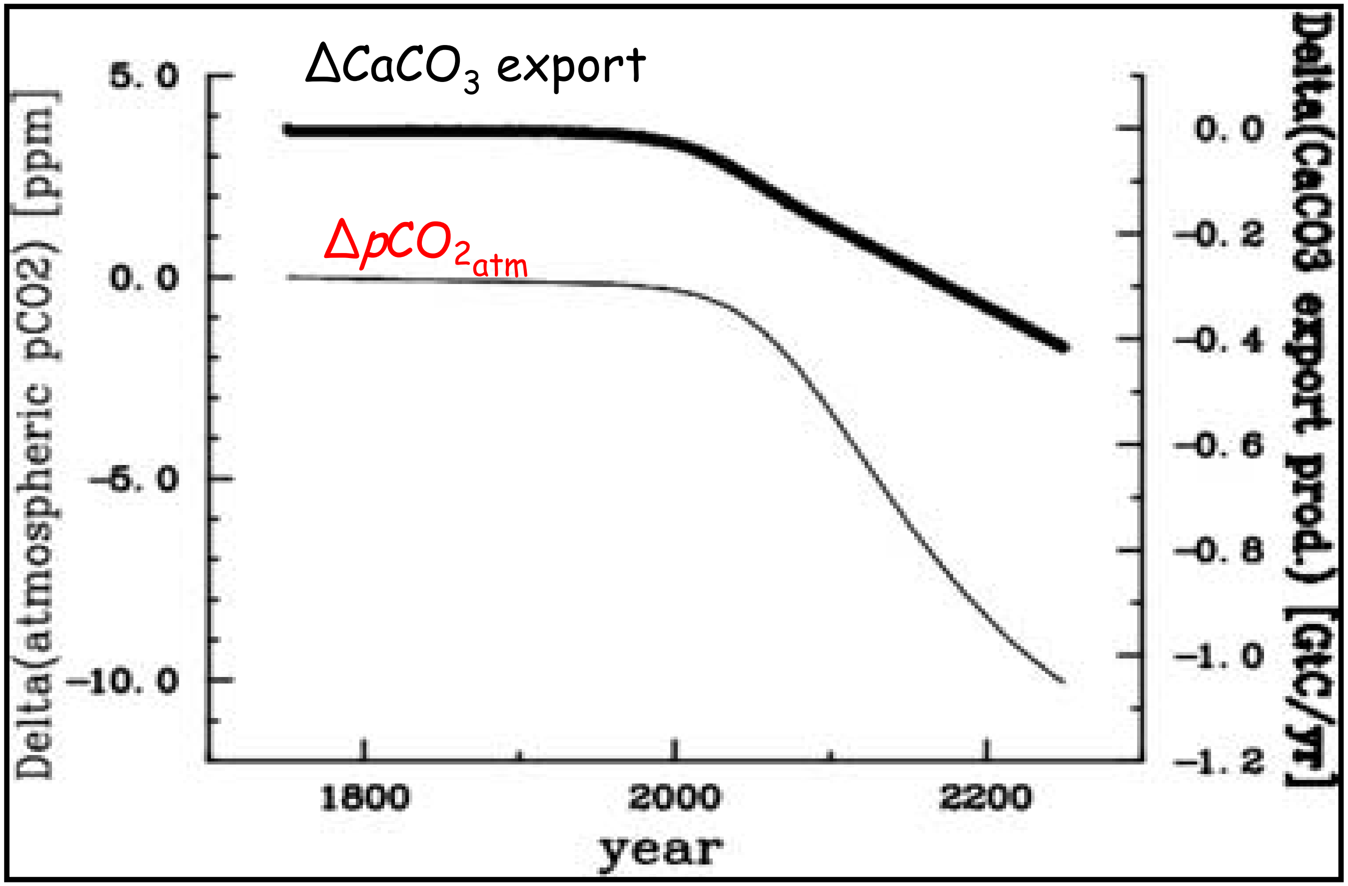


Figure 4. Potential CO_2 release in Gt C yr^{-1} from 1850 to 2150 when annual $CaCO_3$ production remains constant at 1 Gt C yr^{-1} (scenario 1, solid line), PIC/POC ratio decreases as in *E. huxleyi* at a 16/8 L/D cycle (scenario 5, dashed line), or at a 24/0 L/D cycle (scenario 6, dashed line), and PIC/POC ratio decreases as in *G. oceanica* (scenario 7, dashed- dotted line).

Zondervan et al. (2001)

Changes in calcification out-gassing in the future result in an uncertainty of at least 1 Pg C yr^{-1}

40% reduction in $CaCO_3$ export corresponds to 10 ppm reduction in atmospheric CO_2



Heinze 2004, GRL 31

(assuming $CaCO_3$ export = 1Pg C yr^{-1})

In addition to reduced $CaCO_3$ production, exported $CaCO_3$ particles are dissolving at shallower depths

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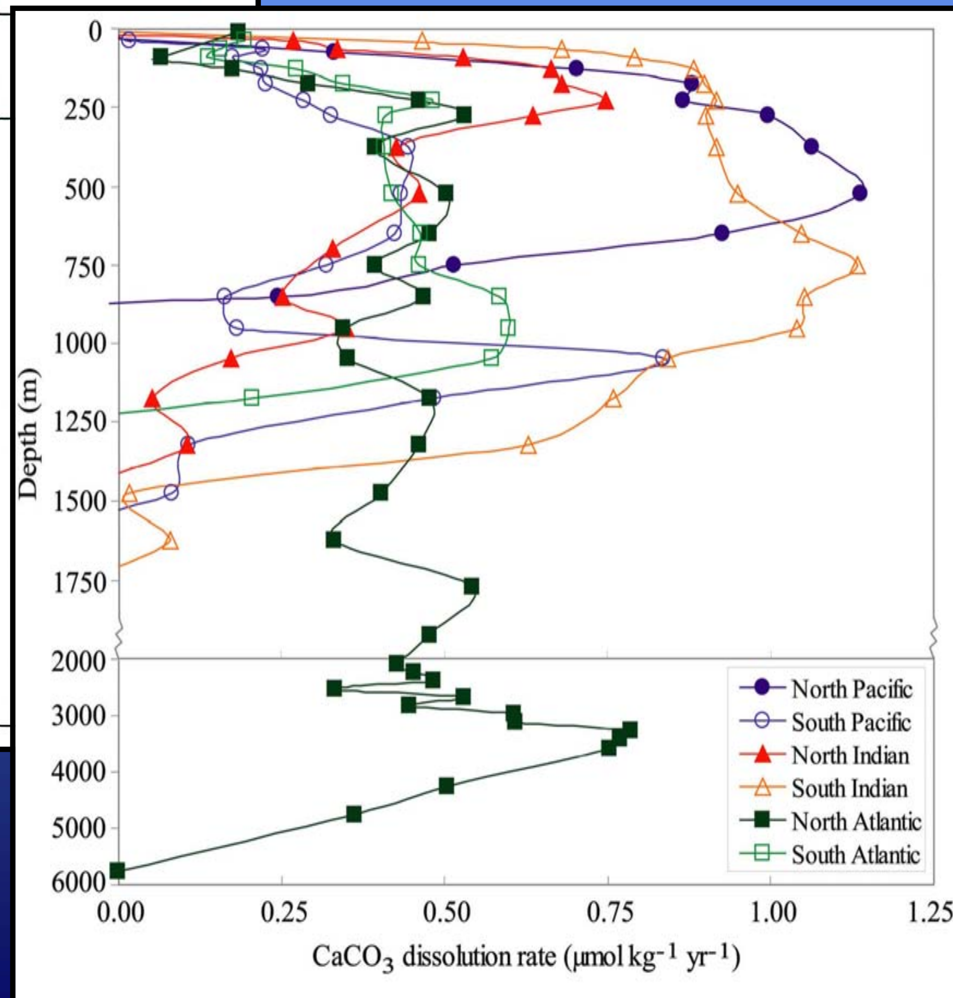
Ecosystem structure	Lower or higher productivity	Pos./neg.
CH_4 hydrate release	Increased greenhouse forcing	Positive

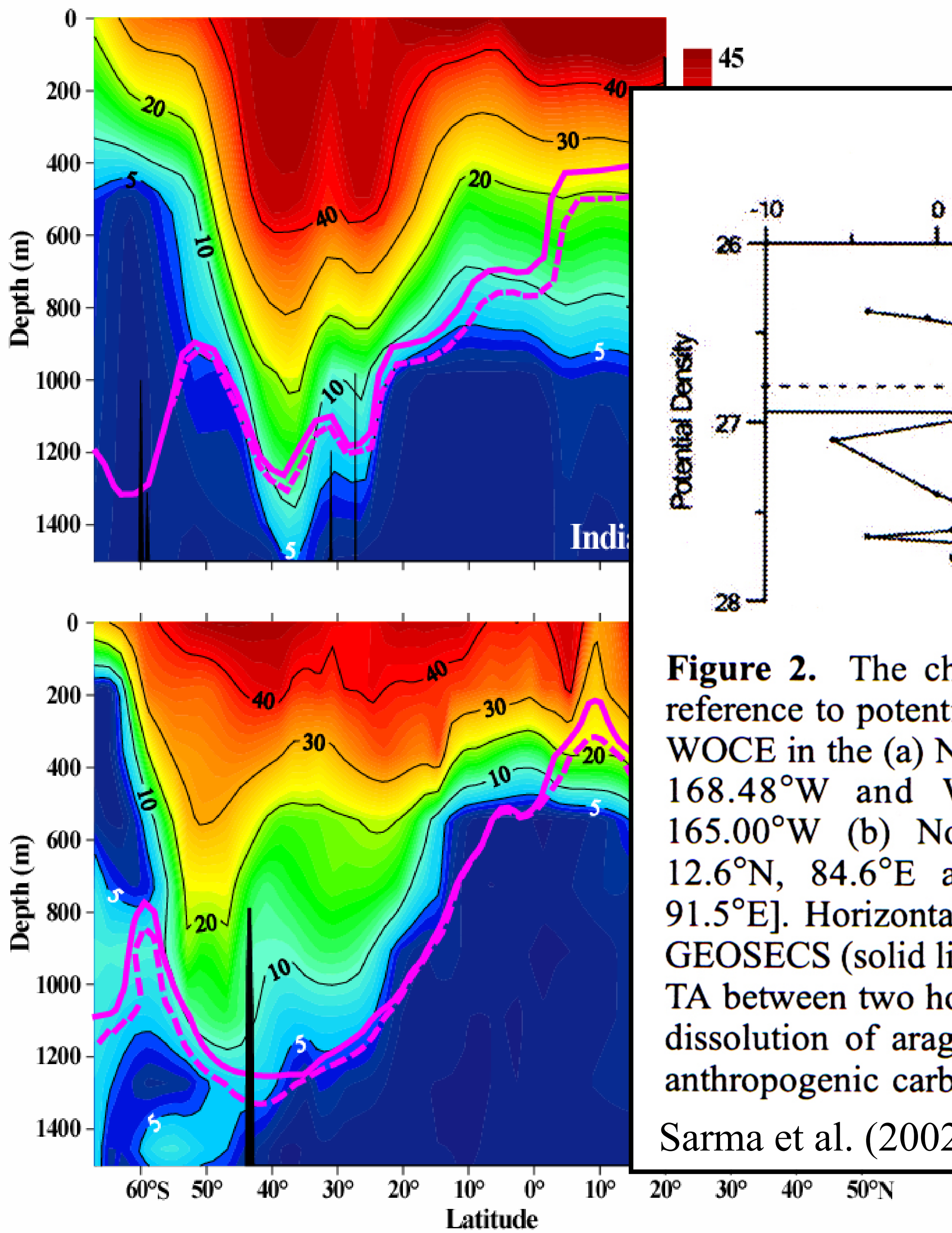
The available sediment trap and water chemistry data indicate that as much as 60% of $CaCO_3$ production dissolves in shallow waters

Table 1. Sediment trap particulate $CaCO_3$ dissolution fluxes in the Pacific Ocean. The difference between the mean carbonate flux in the upper trap and the lower trap defines the dissolution flux. In all but one of the deepwater cases, the $CaCO_3$ flux collected in the midwater trap is higher than the carbonate flux collected in the deepwater trap. The dissolution rates are derived from the differences in $CaCO_3$ sediment trap fluxes between the upper and lower sediment traps divided by the depth range between the traps.

Location	Trap depth range (m)	Dissolution rate (μmol kg^{-1} year^{-1})
	Shallow sediment traps	
Northwestern Pacific	100–1000	0.12
Equatorial Pacific	105–320	0.67
Northwestern Pacific	500–1000	0.02
Northeastern Pacific	200–1000	0.10
	Deep sediment traps	
Northwestern Pacific	2000–4000	0.003–0.006
Equatorial Pacific	2300–3600	0.005–0.014
2°59.8′N 135°1.0′E	1592–3902	0.012
4°7.5′N 136°16.6′E	1769–4574	0.013
0°0.2′N 175°09.7′E	1357–4363	0.005
0°01′N 175°02′E	2200–4300	—
13°00′N 175°01′E	1500–5100	0.006
00°04′N 139°45′W	2284–3618	0.005–0.014
11°58′S 135°02′W	1292–3594	0.003
50°0′N 145°0′W	1000–3800	0.024



Modern Aragonite Saturation Horizon



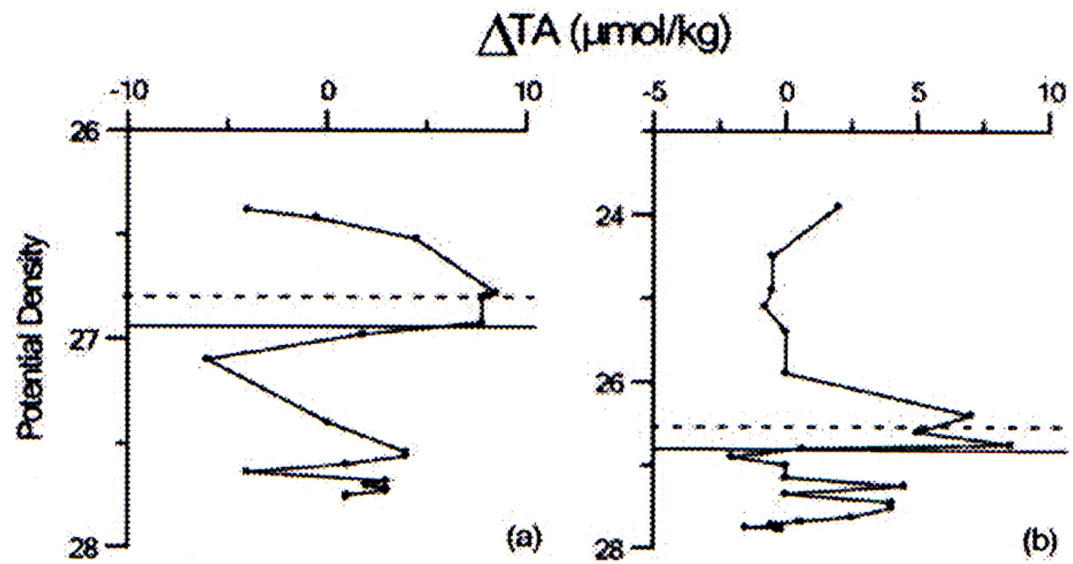
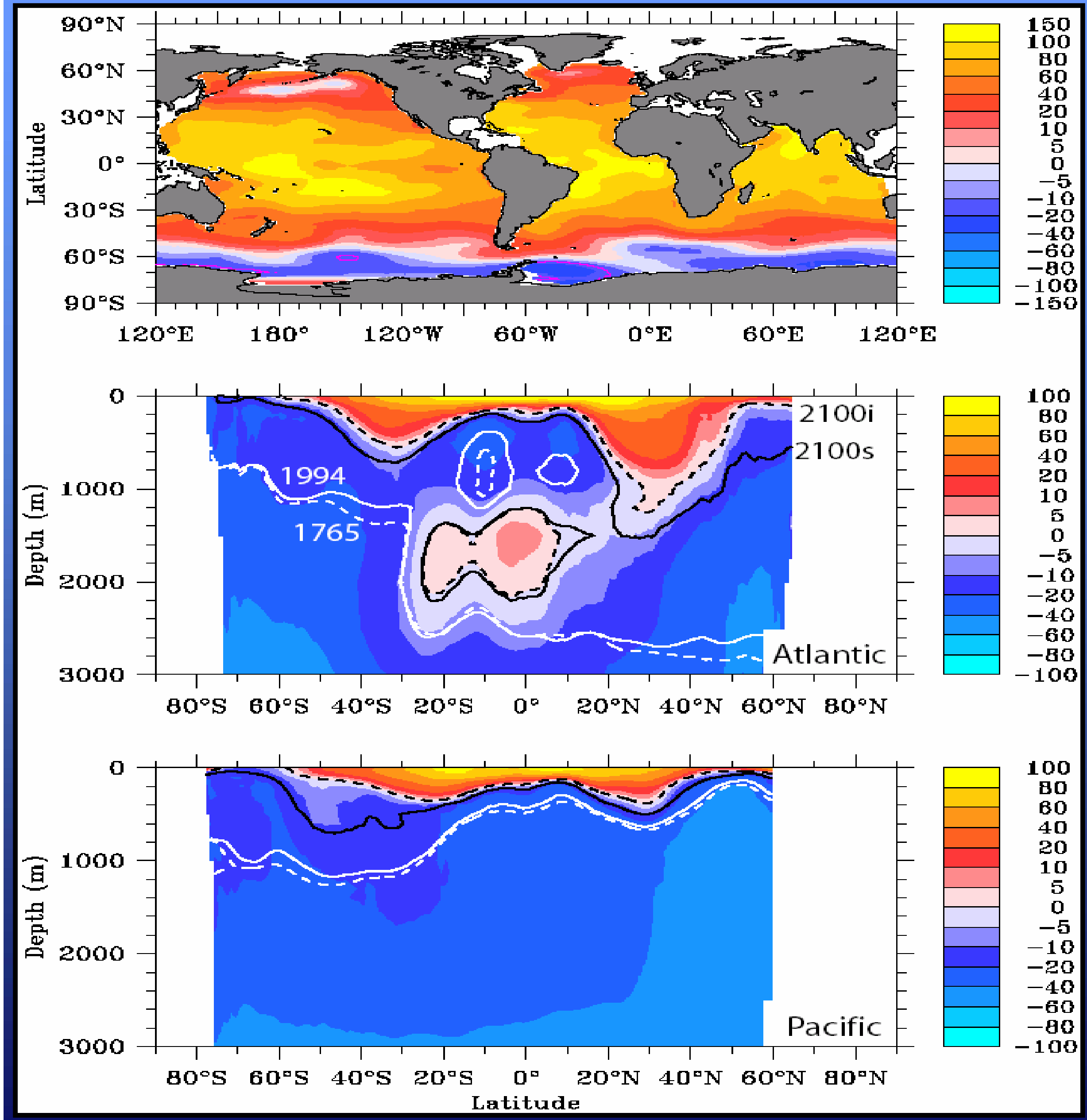


Figure 2. The change in total alkalinity (μmol/kg) with reference to potential density (σ_0), between GEOSECS and WOCE in the (a) North Pacific [GEOSECS #213, 30.97°N, 168.48°W and WOCE leg P15NA, #50, 31.00°N, 165.00°W (b) North Indian Ocean [GEOSECS #446, 12.6°N, 84.6°E and WOCE leg I09, #241, 13.86°N, 91.5°E]. Horizontal lines show aragonite saturation during GEOSECS (solid line) and WOCE (dashed line). Increase in TA between two horizontal lines represents the influence of dissolution of aragonite skeletal material due to increased anthropogenic carbon inputs during past two decades.

Sarma et al. (2002)

Feely et al. (2004)

By 2100 large changes in saturation state

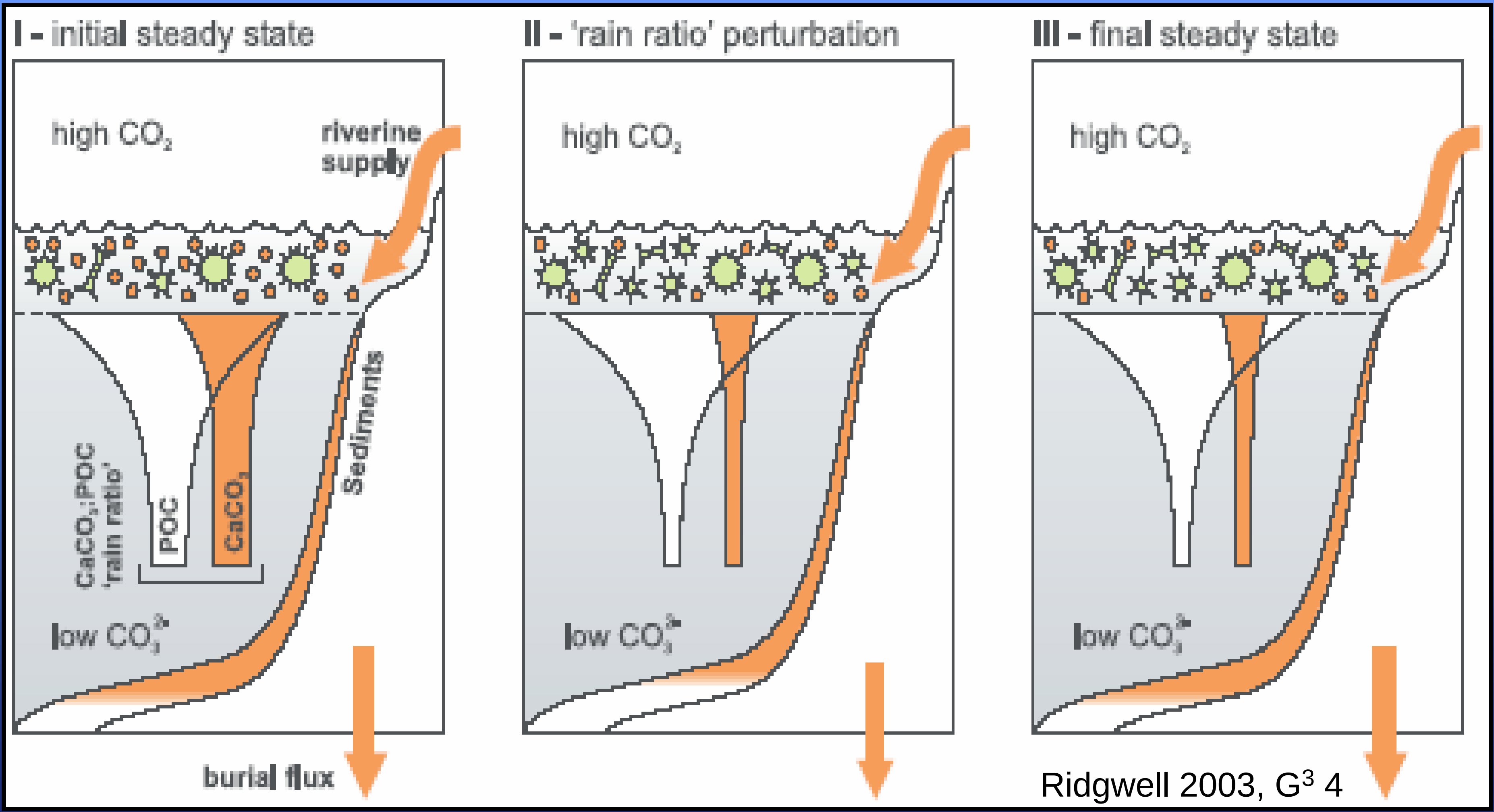


Orr et al., (submitted)

$\Delta[CO_3^{2-}]_A$ in µmol kg^{-1}

- Surface undersaturation ($\Delta[CO_3^{2-}]_A < 0$)
  - Southern Ocean
  - Subarctic Pacific
- Shoaling of the aragonite saturation horizon ($\Delta[CO_3^{2-}]_A = 0$)
  - Southern Ocean (by ~1000 m)
  - North Atlantic (by ~3000 m)

Effect of reduced $CaCO_3$ production and export may be counteracted by decreasing POC export ("ballasting effect")



The long term burial of organic C in the ocean is only ~0.15 PgC yr^{-1}, but annual mixed layer export is ~ 7 Pg C yr^{-1}

There is ~65 Million Pg C stored as $CaCO_3$ in ocean sediments

$$CaCO_3 + CO_2 + H_2O = Ca^{2+} + 2HCO_3^-$$

Dissolution of these sediments provides a huge potential for CO_2 uptake

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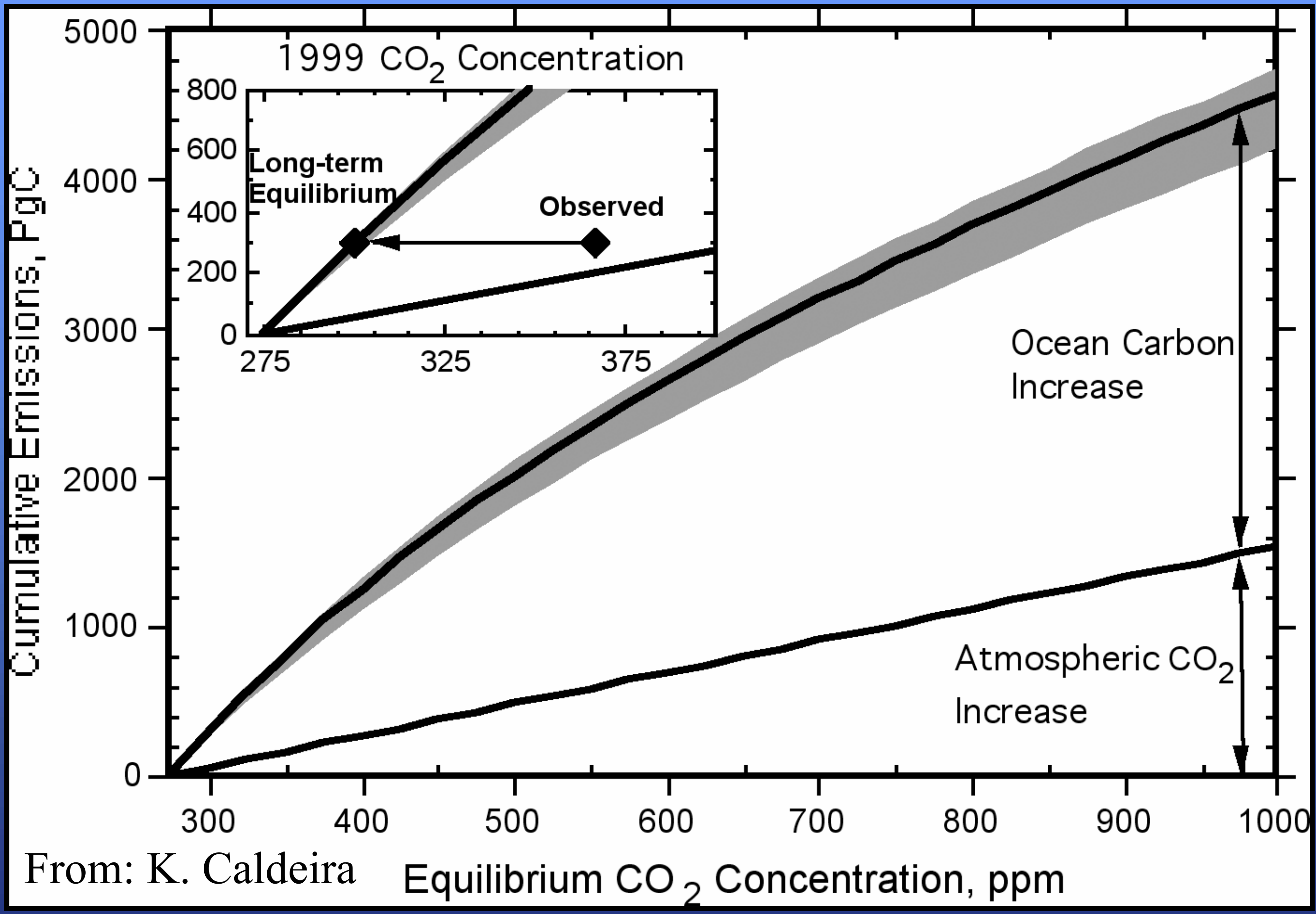
CH_4 hydrate release	Increased greenhouse forcing	Positive

Models predict that on millennial time-scales 65-70% of the emissions would end up in the ocean (no $CaCO_3$ compensation)



Dissolution of $CaCO_3$ sediments increases this number to 80-85%

The depth of carbonate dissolution affects the timing and magnitude of the atmospheric CO_2 signal

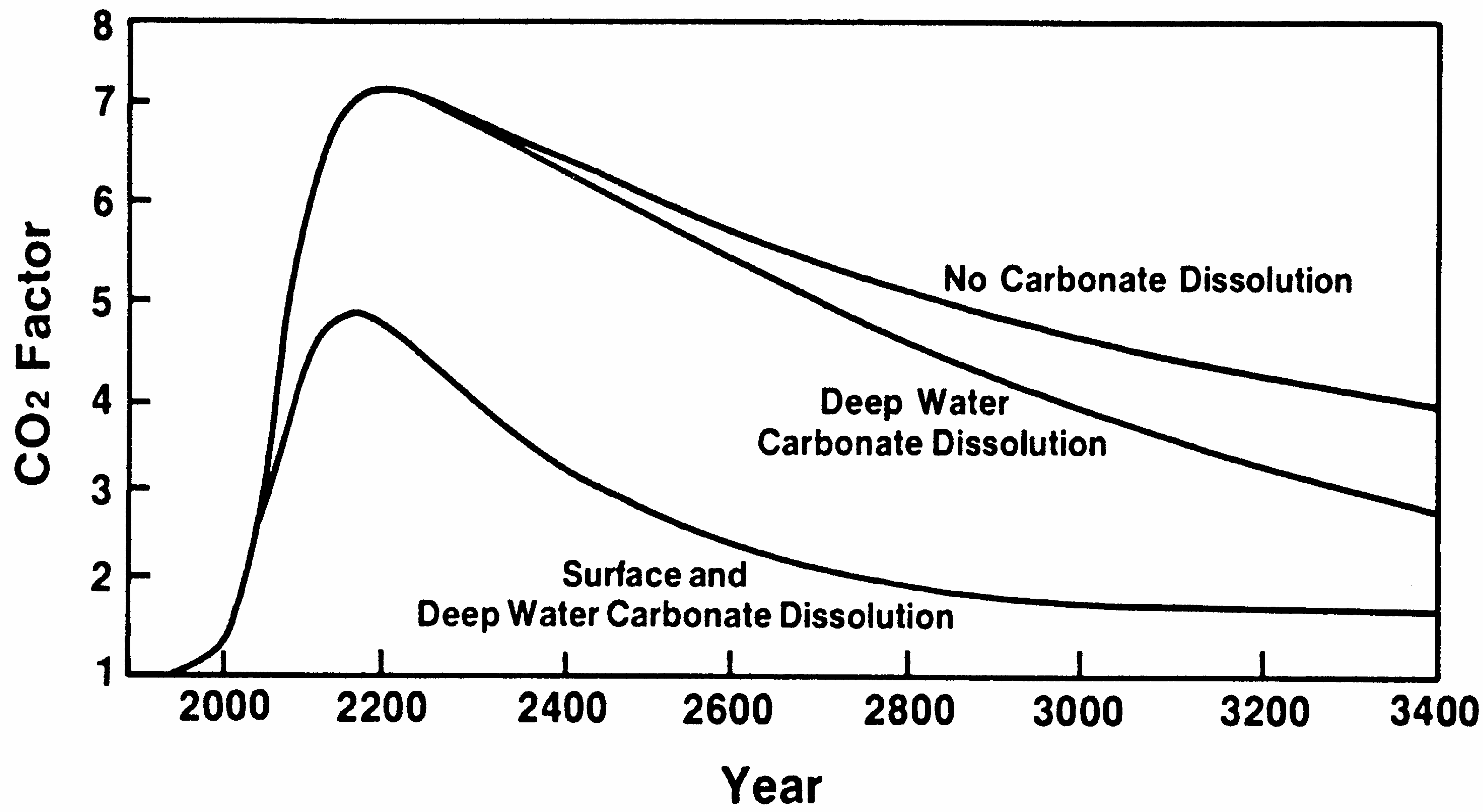
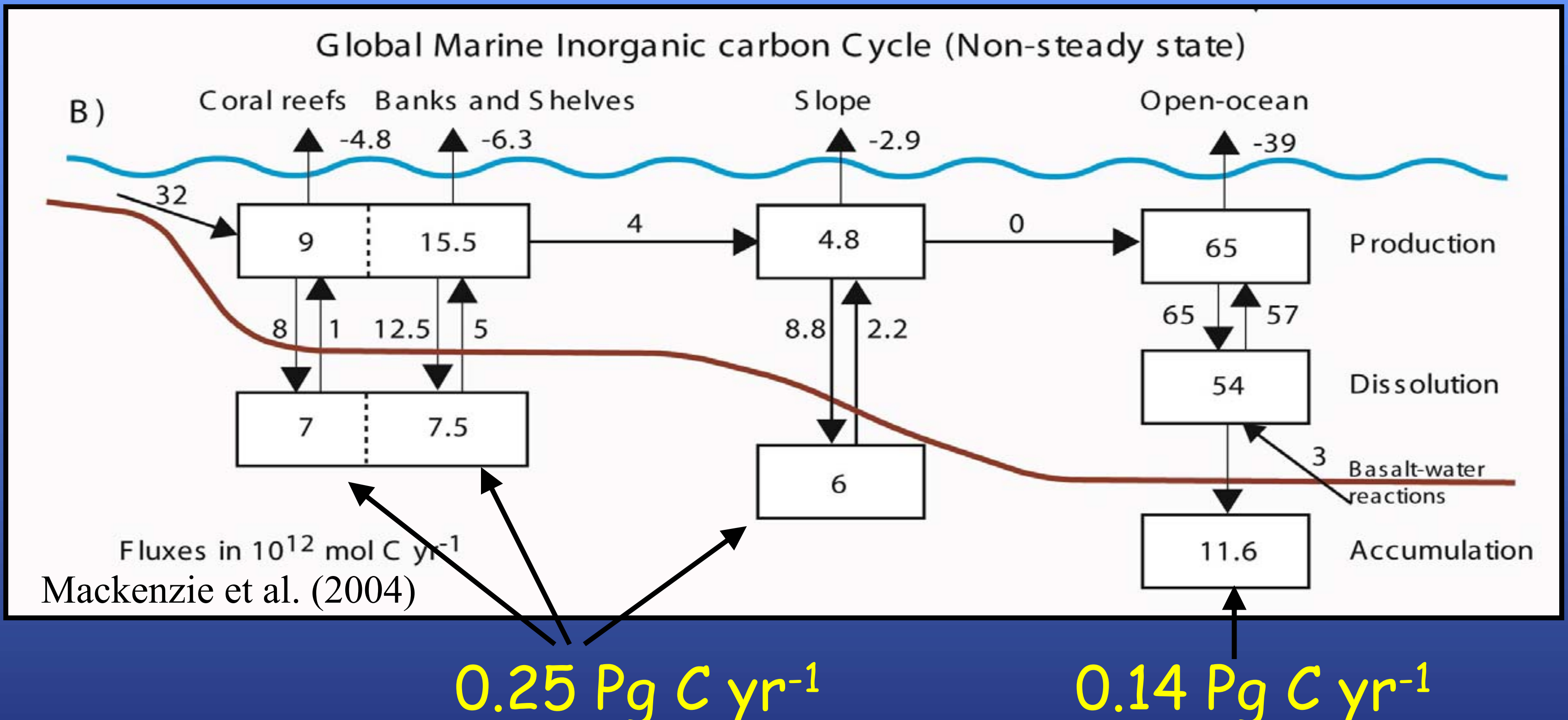
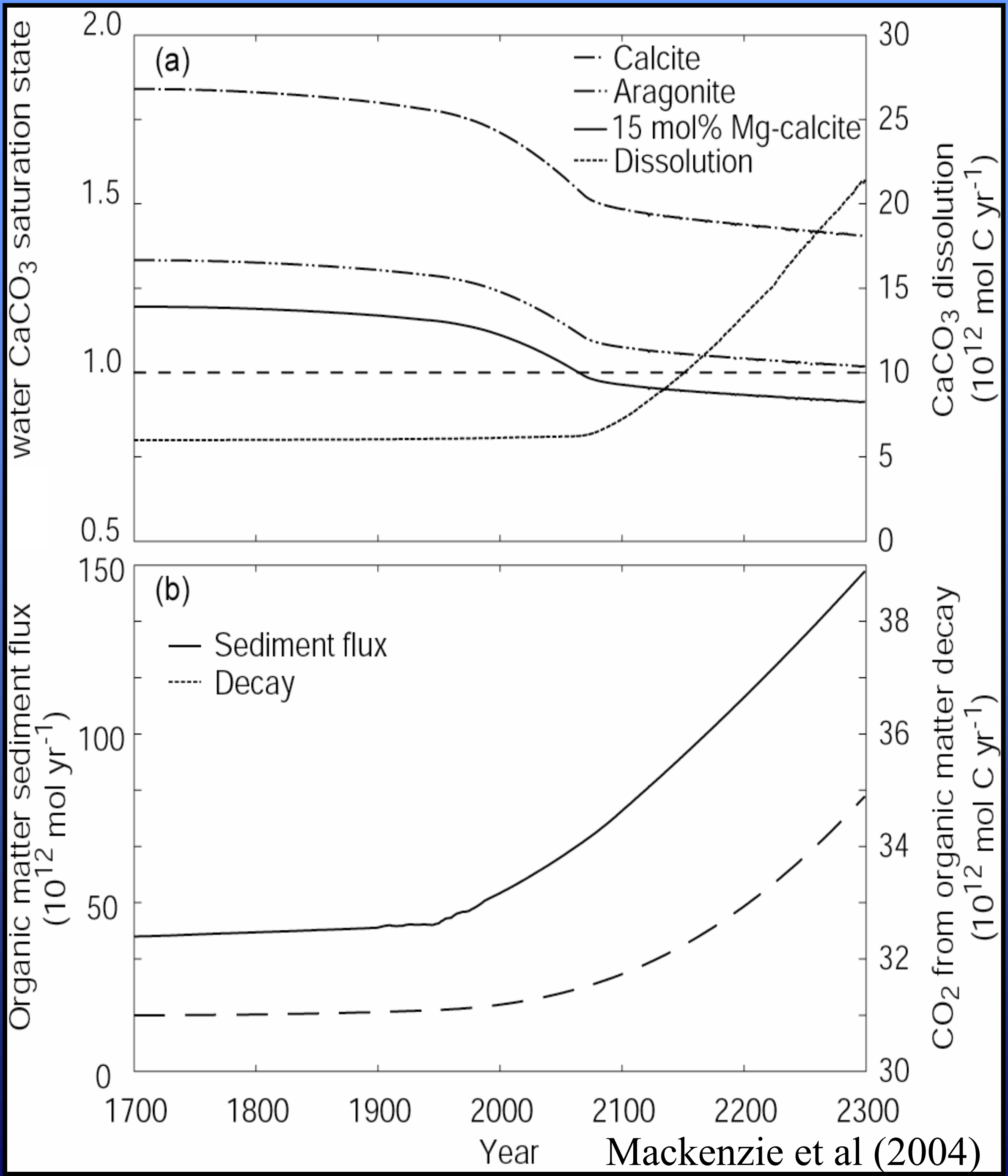


Figure 9.18. Graph illustrating that once CO_2 enters the atmosphere because of human activities, the return to original conditions takes a long time, regardless of whether or not $CaCO_3$ minerals are dissolved. (After Bacastrow and Keeling, 1979.)

The majority of $CaCO_3$ sediments are found on shelves and slopes



64% of Modern $CaCO_3$ accumulation is occurring on shelves and slopes



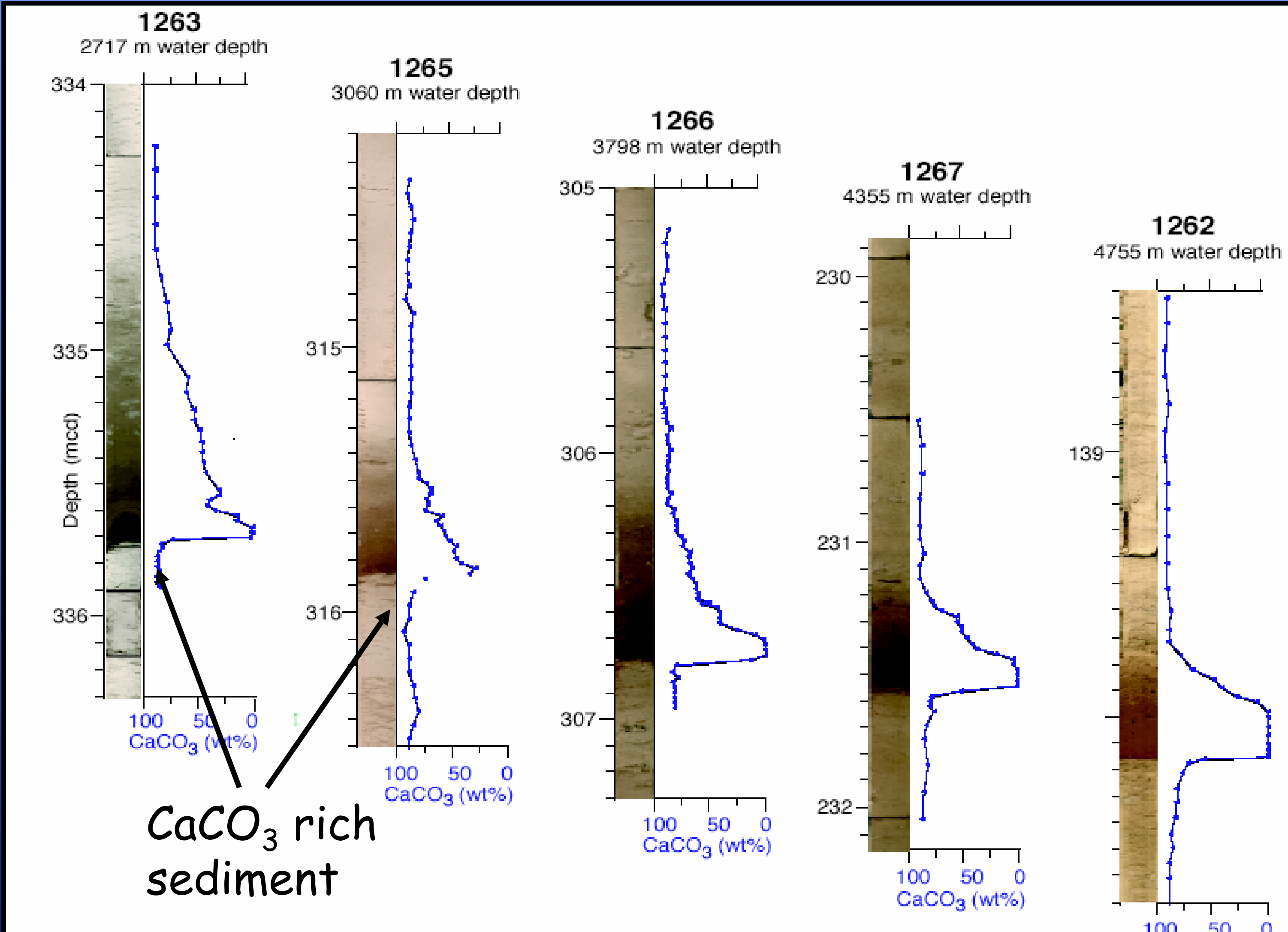
Mackenzie et al (2004)

Pore water $CaCO_3$ dissolution flux increases in shallow sediments because of lower saturation states and increased organic matter oxidation

Organic matter oxidation in sediments increases as ocean temperatures increase

Big dissolution event at Paleocene-Eocene Thermal Maximum

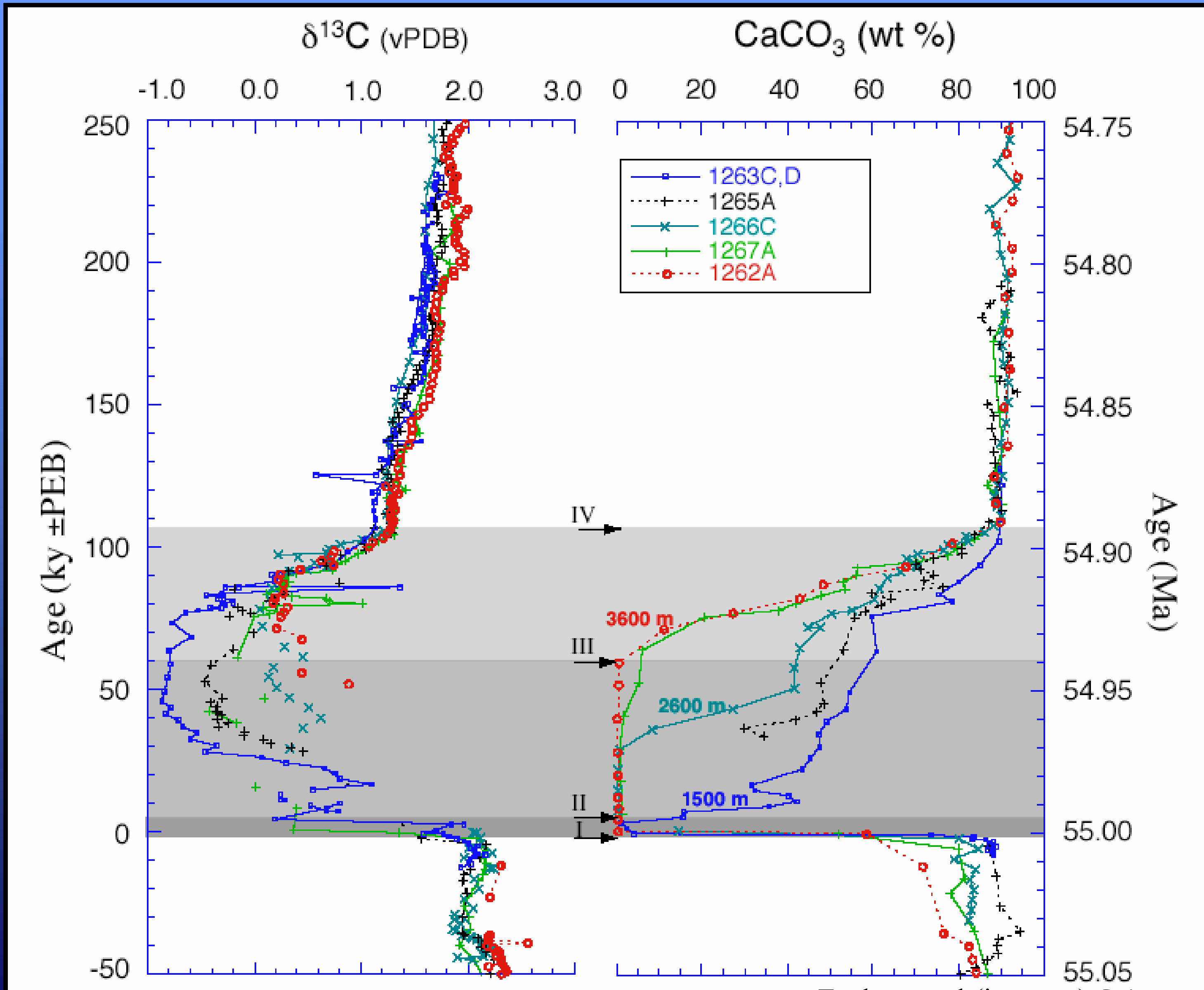
55Ma sea surface temperatures rose by ~8°C over a few thousand years



Zachos et al (in press) *Science*

30-40% of deep sea benthic foraminifera went extinct

A commensurate change in ^{13}C suggests that there was a huge "burp" of methane into the atmosphere.



Zachos et al (in press) *Science*

CONCLUSIONS

1) Many of the ocean carbon cycle and climate feedbacks are tied to the $CaCO_3$ cycle.
2) The $CaCO_3$ cycle is still poorly understood and needs to be studied with a particular emphasis on the magnitudes and timing.
3) We know from thermodynamics that ocean uptake efficiency will decrease, but the real bottle neck is in moving the CO_2 into the ocean interior, which is controlled by circulation.
4) There is general consensus that elevated CO_2 will reduce calcification and lead to shallower dissolution producing a negative feedback, but the related decrease in organic matter export may counteract some or all of this effect.
5) There is a potentially very large negative feedback associated with dissolving carbonate sediments. This has been thought to be a millennial time scale issue, but there is growing evidence that this dissolution may occur quickly.

Take home message:

We should not limit our vulnerability studies only to positive feedbacks, but we also need to understand potential negative feedbacks.