The Oceanic Sink for Anthropogenic CO_2: Past, Present and Future

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"The Ocean Carbon System: Recent Advances and Future Opportunities"
An Ocean Carbon and Climate Change (OCCC) Workshop

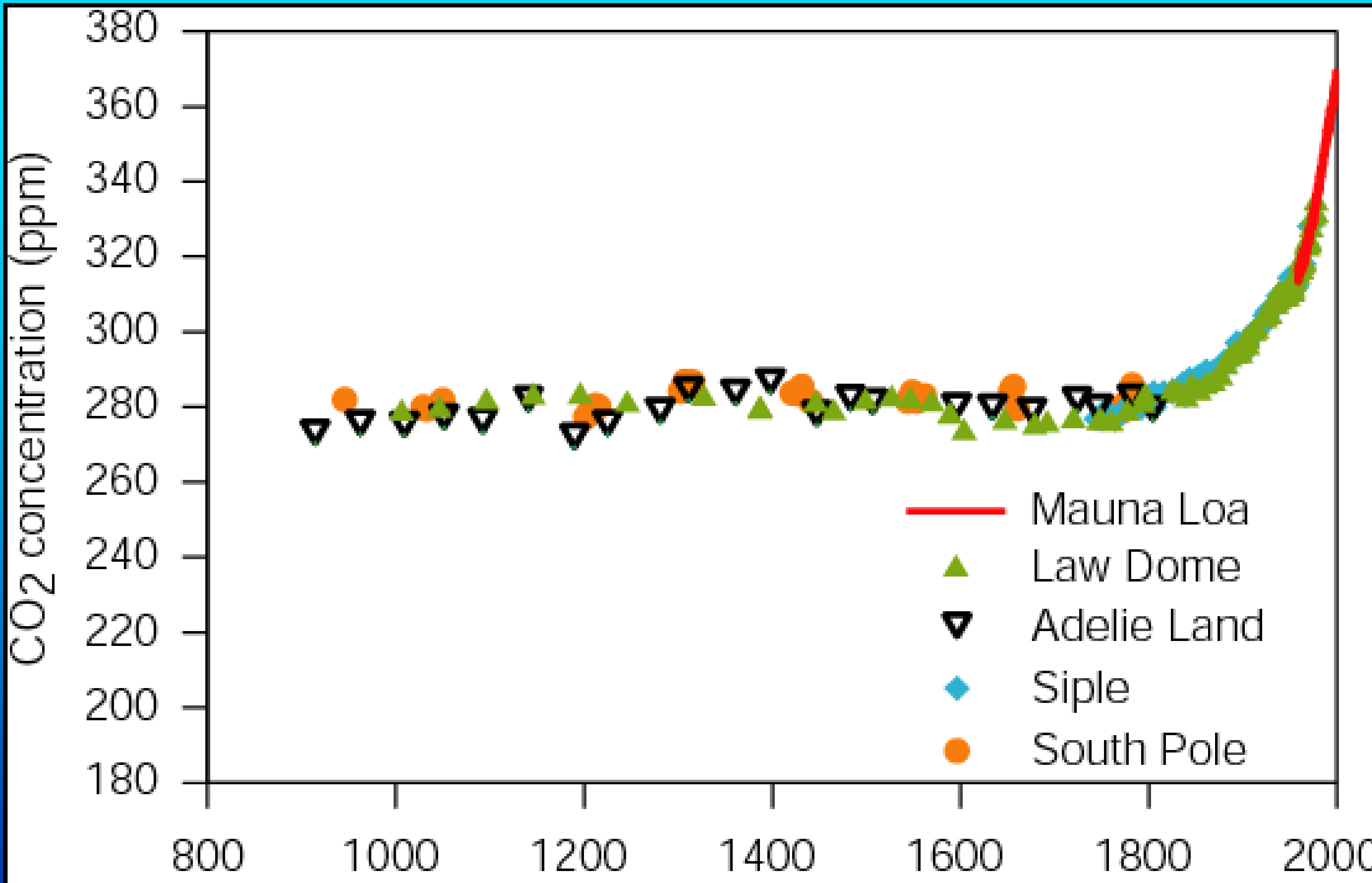
August 1-4, 2005

Woods Hole, MA

Outline

1. Briefly review preindustrial carbon system
2. Look at modern CO_2 fluxes and anthropogenic CO_2 uptake estimates
3. Examine distributions of anthropogenic CO_2 in ocean
4. Consider time scales and significance of carbon feedbacks
5. Present some intriguing preliminary findings from the CLIVAR/CO_2 Repeat Hydrography Program

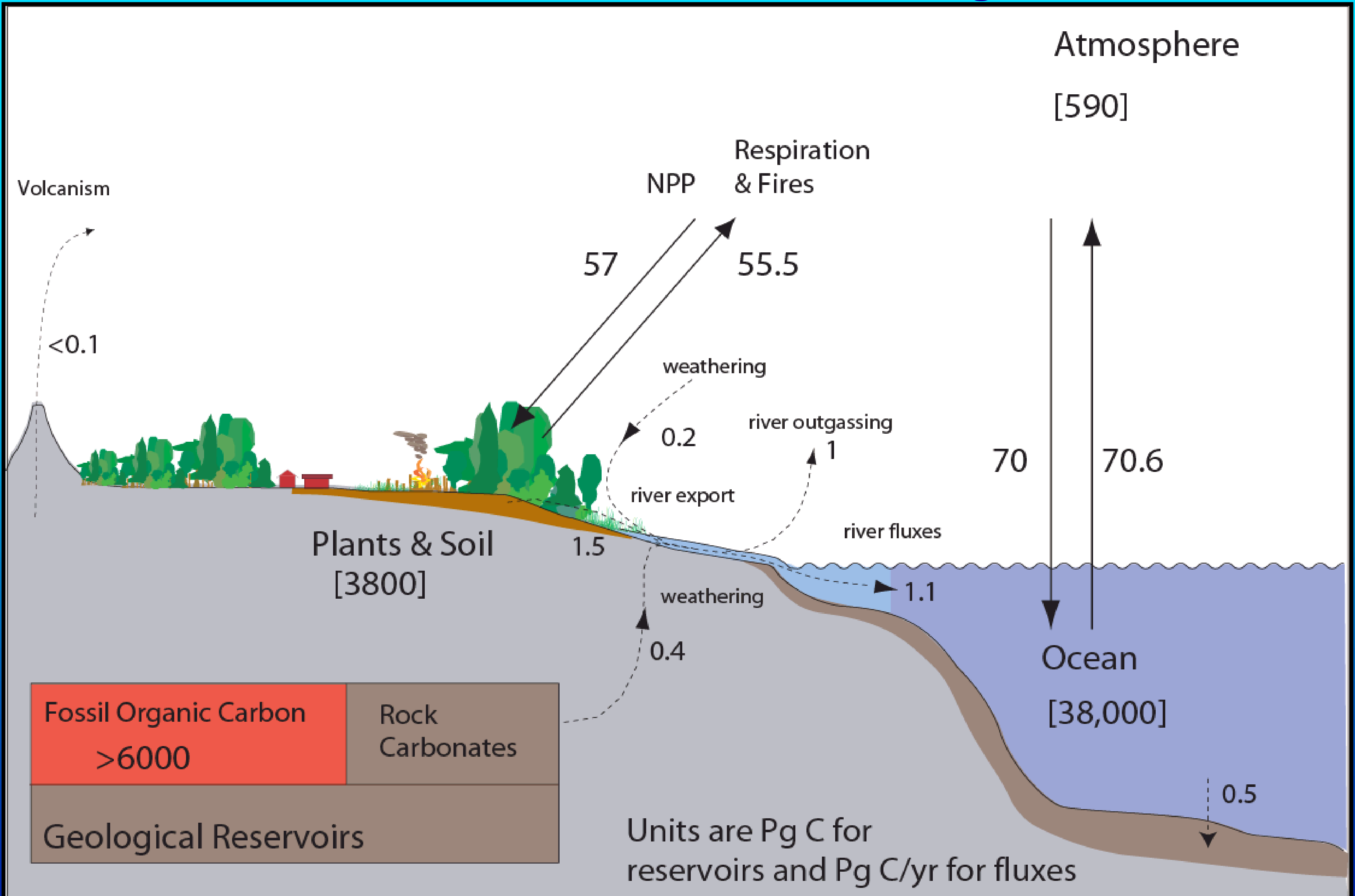
Motivation: Understanding Long Term Carbon Cycle Changes



Prentice et al., 2001

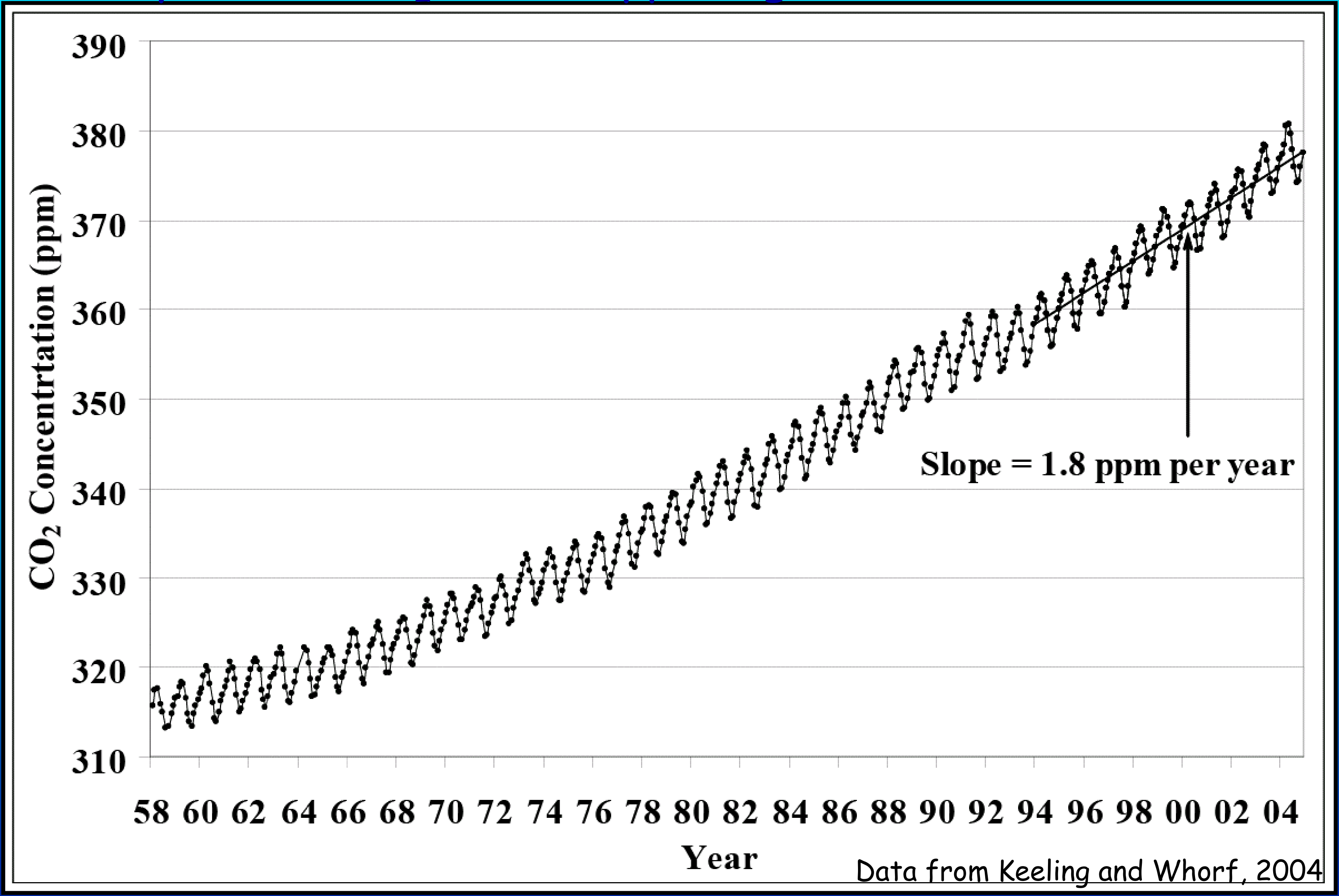
Atmospheric CO_2 was at 280±10 ppm for last 11,000 years

Preindustrial Global Carbon Budget



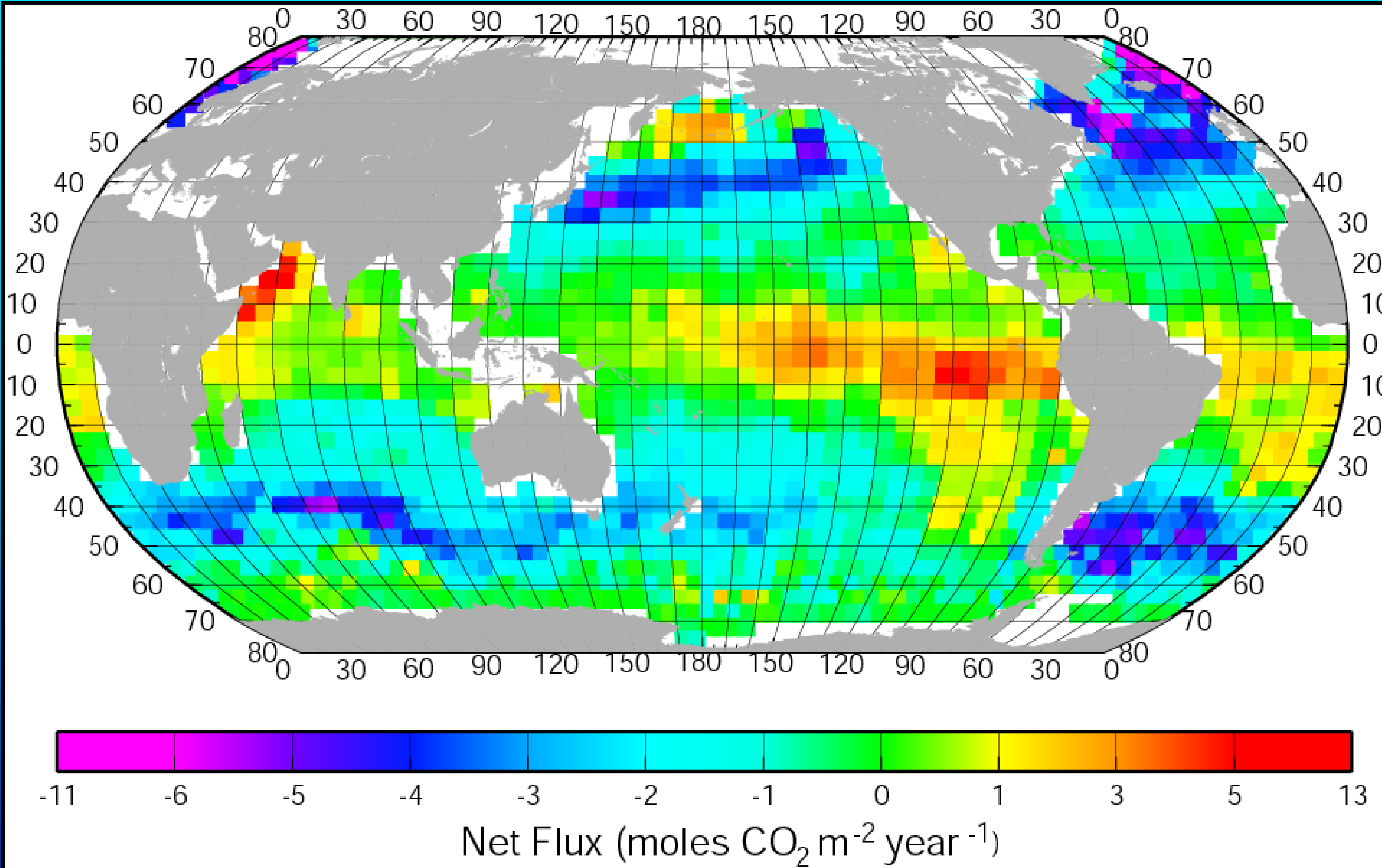
Ocean Must Have Been CO_2 Source to Balance Global Budget

Today's Atm. CO_2 is ~100 ppm higher than Preindustrial



We own Dr. C.D. Keeling a debt of gratitude for pioneering this field…his presence will be missed.

1995 Net CO_2 Flux from Takahashi et al., 2002



Takahashi data set now up to 2 million data points

Net Flux: -1.5 Pg C yr^{-1}

Several Independent Approaches are Converging on an Estimate of the 1990s Anthropogenic CO_2 Uptake

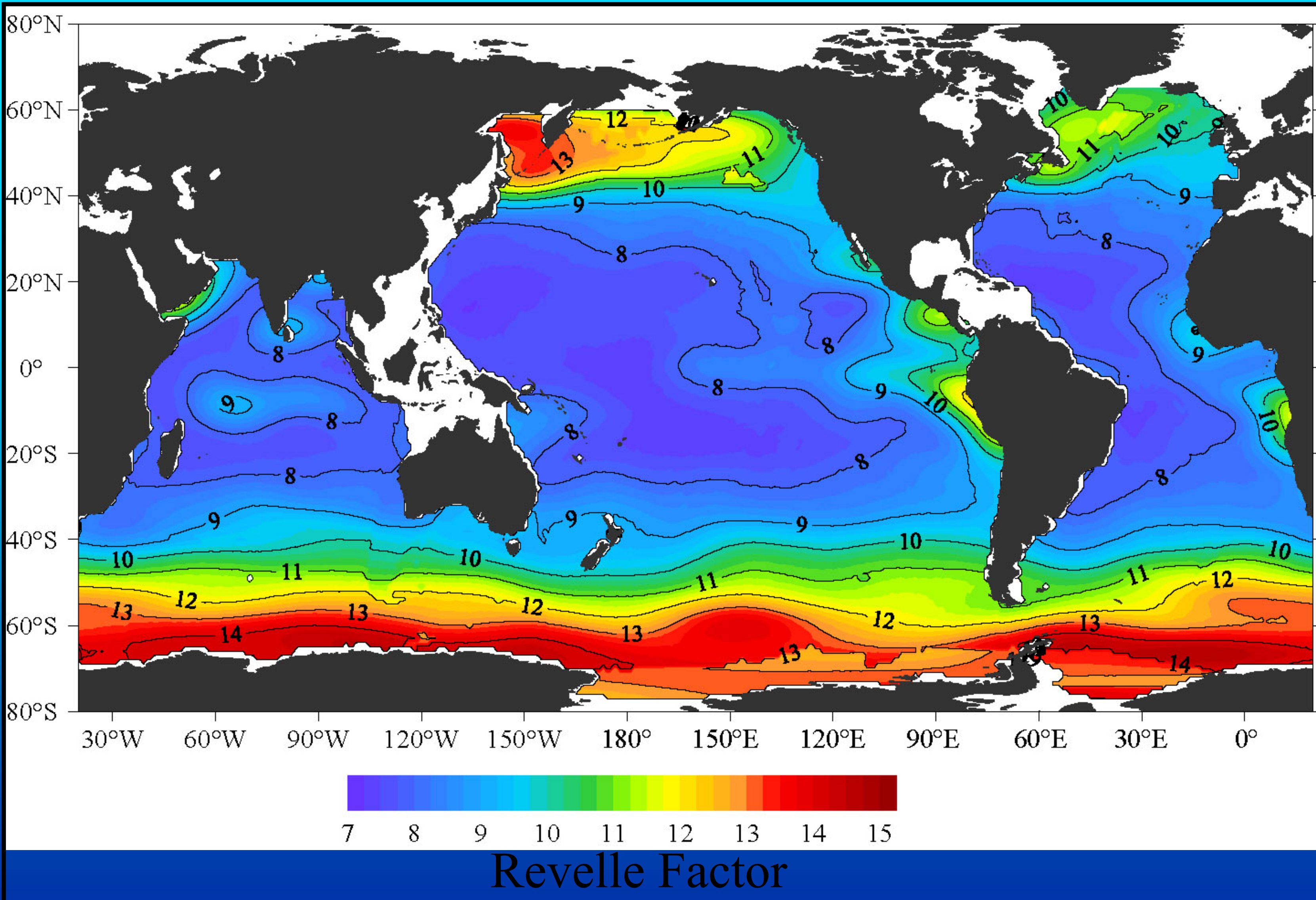
Estimates of Oceanic Anthropogenic CO_2 Uptake in Pg C/yr.

Method	Carbon Uptake (Pg C/yr)	Reference
Measurements of sea-air pCO_2 Difference	2.1 ± 0.5	Takahashi *et al.* (2002)
Inversion of atmospheric CO_2 observations	1.8 ± 1.0	Gurney *et al.* (2002)
Inversions based on ocean transport models and observed DIC	2.0 ± 0.4	Gloor *et al.* (2003)
Model simulations evaluated with CFC's and pre-bomb radiocarbon	2.2 ± 0.4	Matsumoto *et al.* (2004)
OCMIP-2 Model simulations	2.4 ± 0.3	Orr *et al.* (2004)
Based on measured atmospheric O_2 and CO_2 inventories corrected for ocean warming and stratification	2.2 ± 0.5	Keeling & Manning (submitted)
GCM Model of Ocean Carbon	1.93	Wetzel *et al.* (2005)
CFC ages	2.0 ± 0.4	McNeil *et al.* (2003)

Fluxes are normalized to 1990-1999 (except Keeling & Manning which is for 1993-2004) and corrected for pre-industrial degassing flux of ~0.6 Pg C/yr.

These approaches do not tell us about long-term CO_2 storage

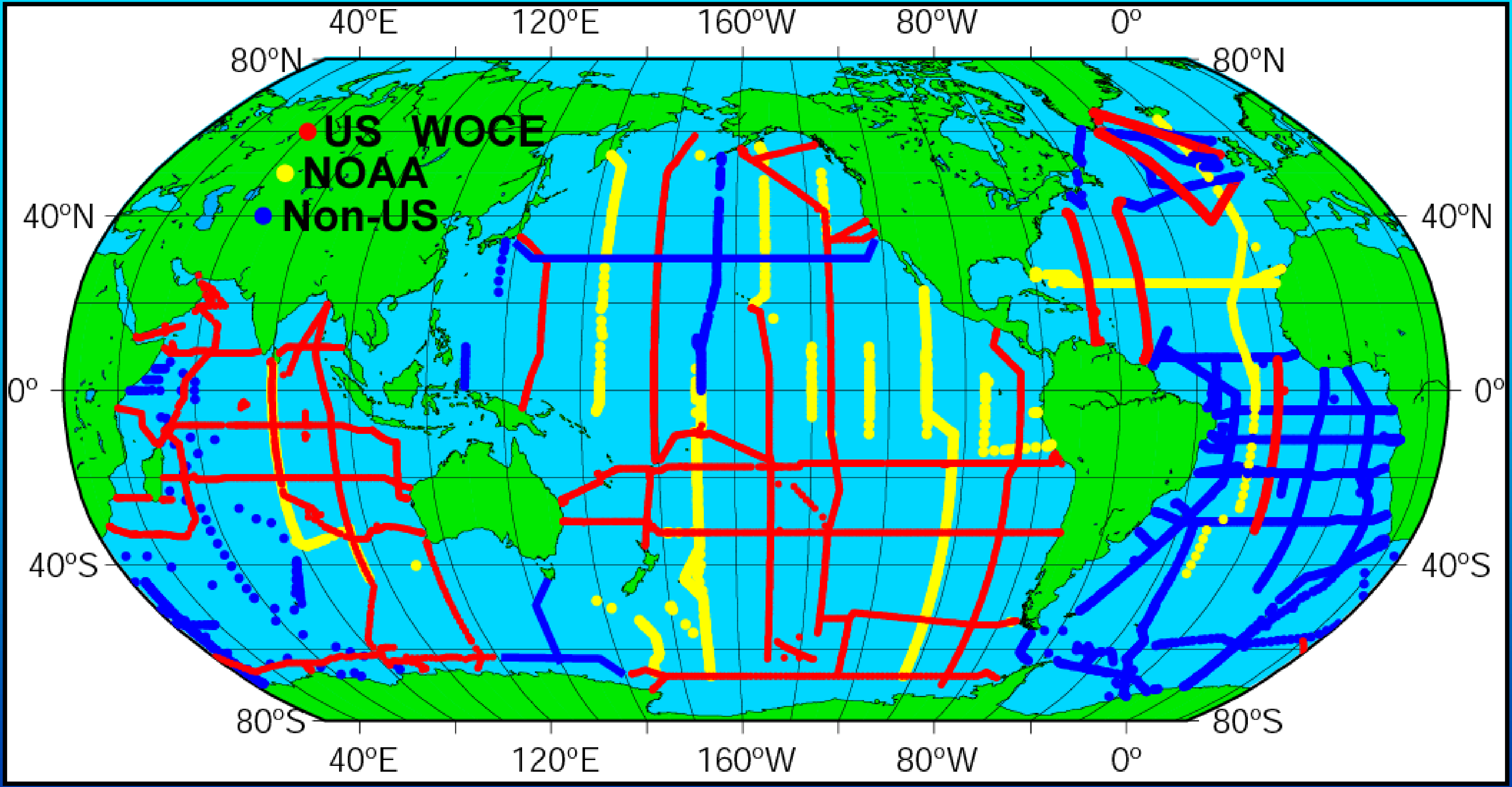
CO_2 is Stored in the Ocean as Dissolved Inorganic Carbon



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

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

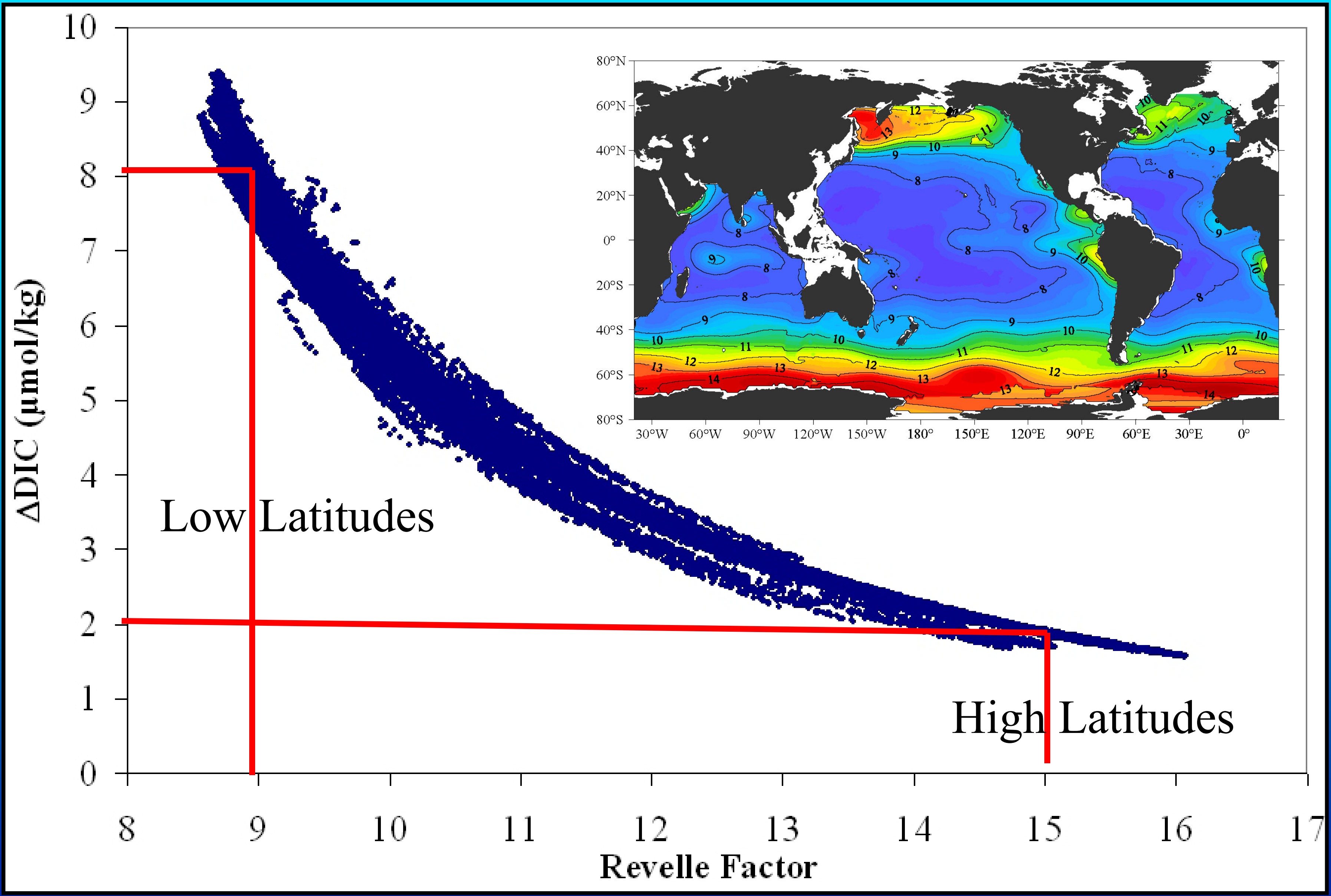
In the early 1990s the World Ocean Circulation Experiment (WOCE), the Joint Global Ocean Flux Study (JGOFS), and the NOAA/OACES program joined forces to conduct a new global survey of CO_2 in the oceans.



>70,000 sample locations; DIC ± 2 μmol kg^{-1}; TA ± 4 μmol kg^{-1}

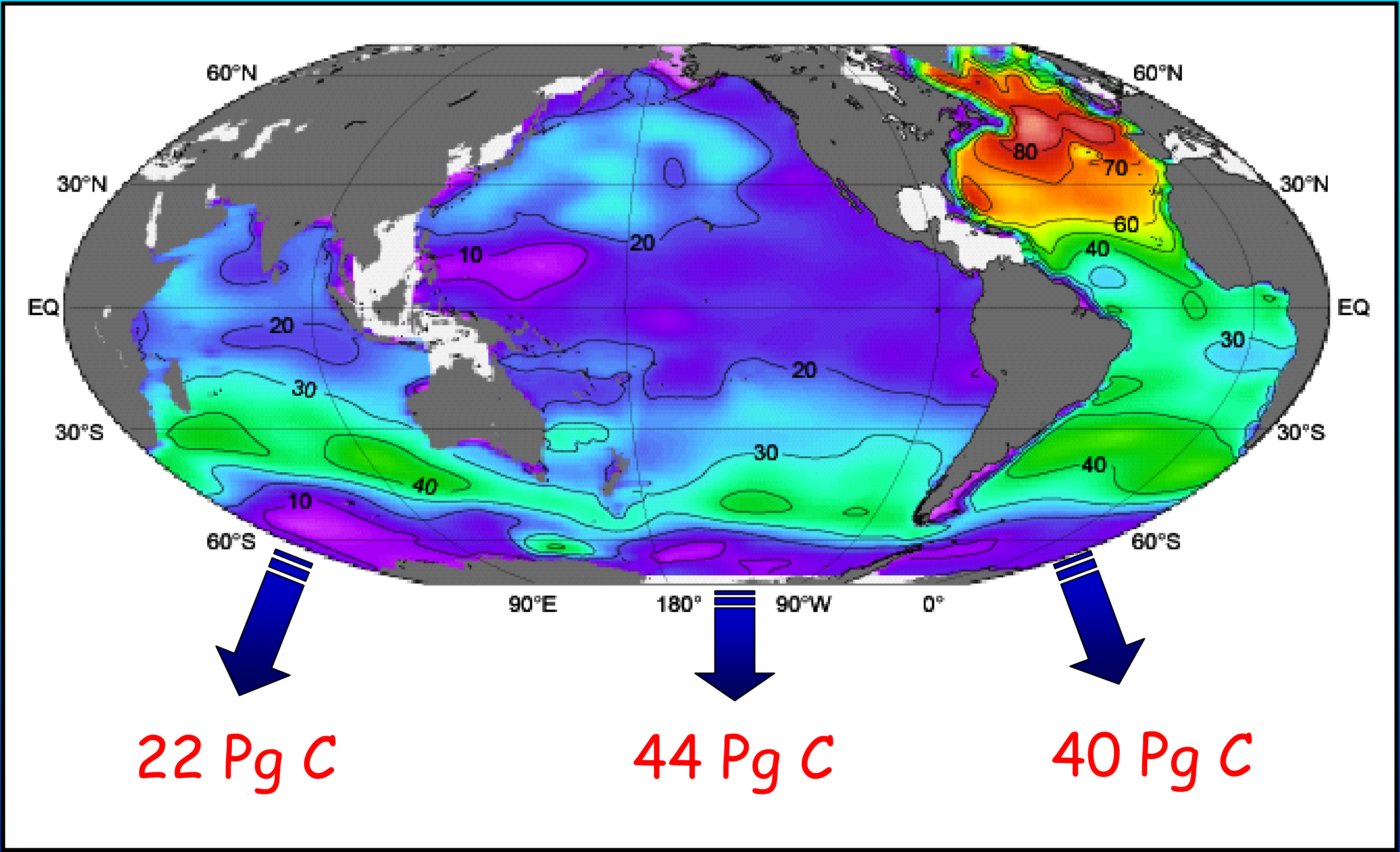
http://cdiac.esd.ornl.gov/oceans/glodap/Glodap_home.htm

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



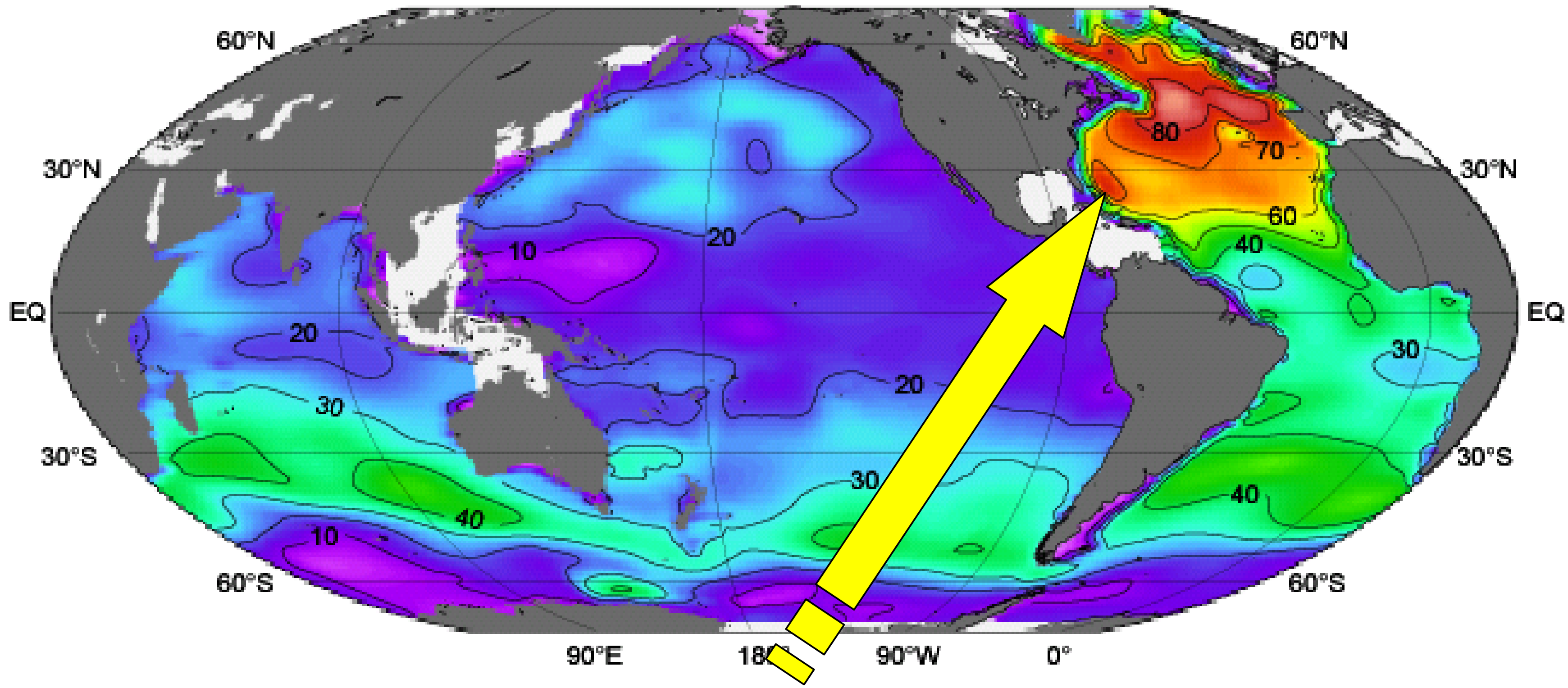
Lower latitudes are more efficient at taking up atmospheric CO_2

Column inventory of anthropogenic CO_2 that has accumulated in the ocean between 1800 and 1994 (mol m^{-2})



Column Inventory of anthropogenic CO_2 does not reflect uptake efficiency

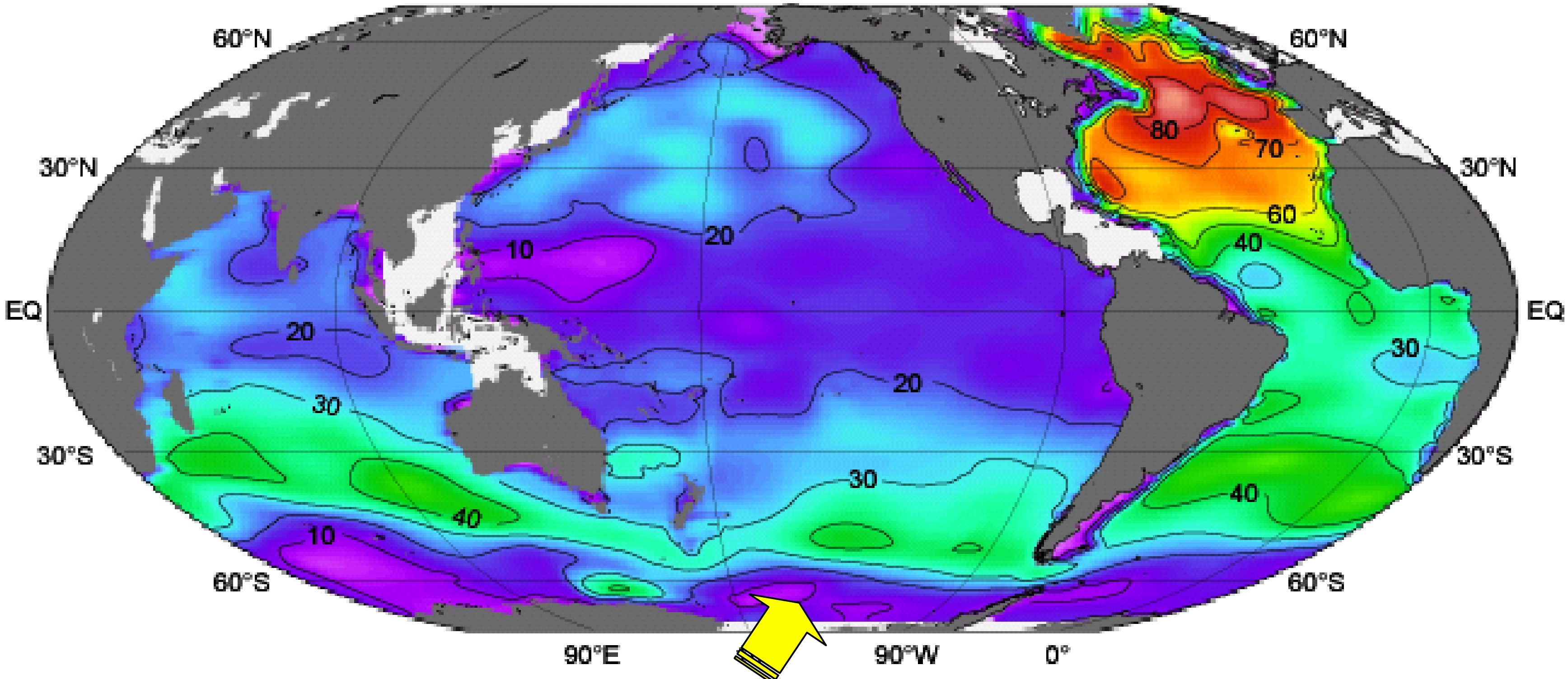
Column inventory of anthropogenic CO_2 that has accumulated in the ocean between 1800 and 1994 (mol m^{-2})



North Atlantic = 25% of inventory with 15% of area

Mapped Inventory 106±17 Pg C

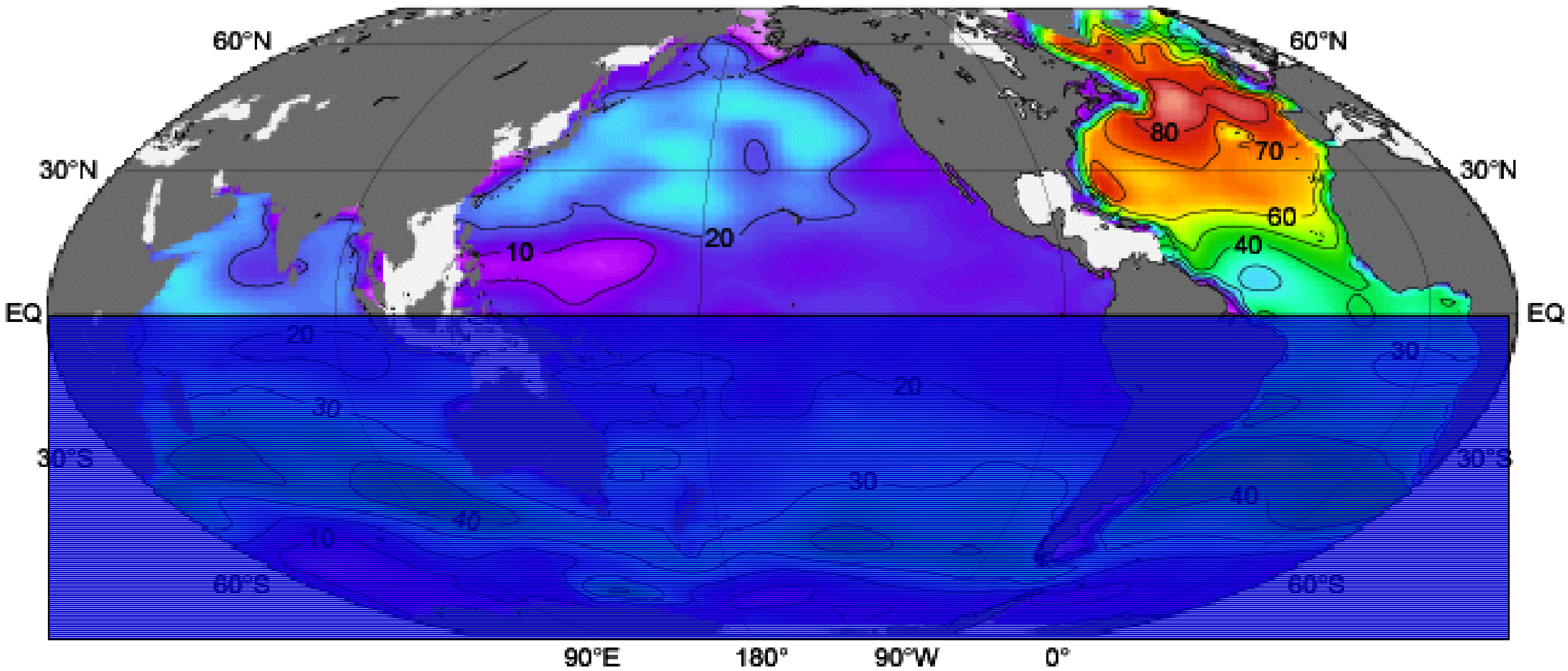
Column inventory of anthropogenic CO_2 that has accumulated in the ocean between 1800 and 1994 (mol m^{-2})



South of 50°S = 9% of inventory with roughly the same area as the North Atlantic

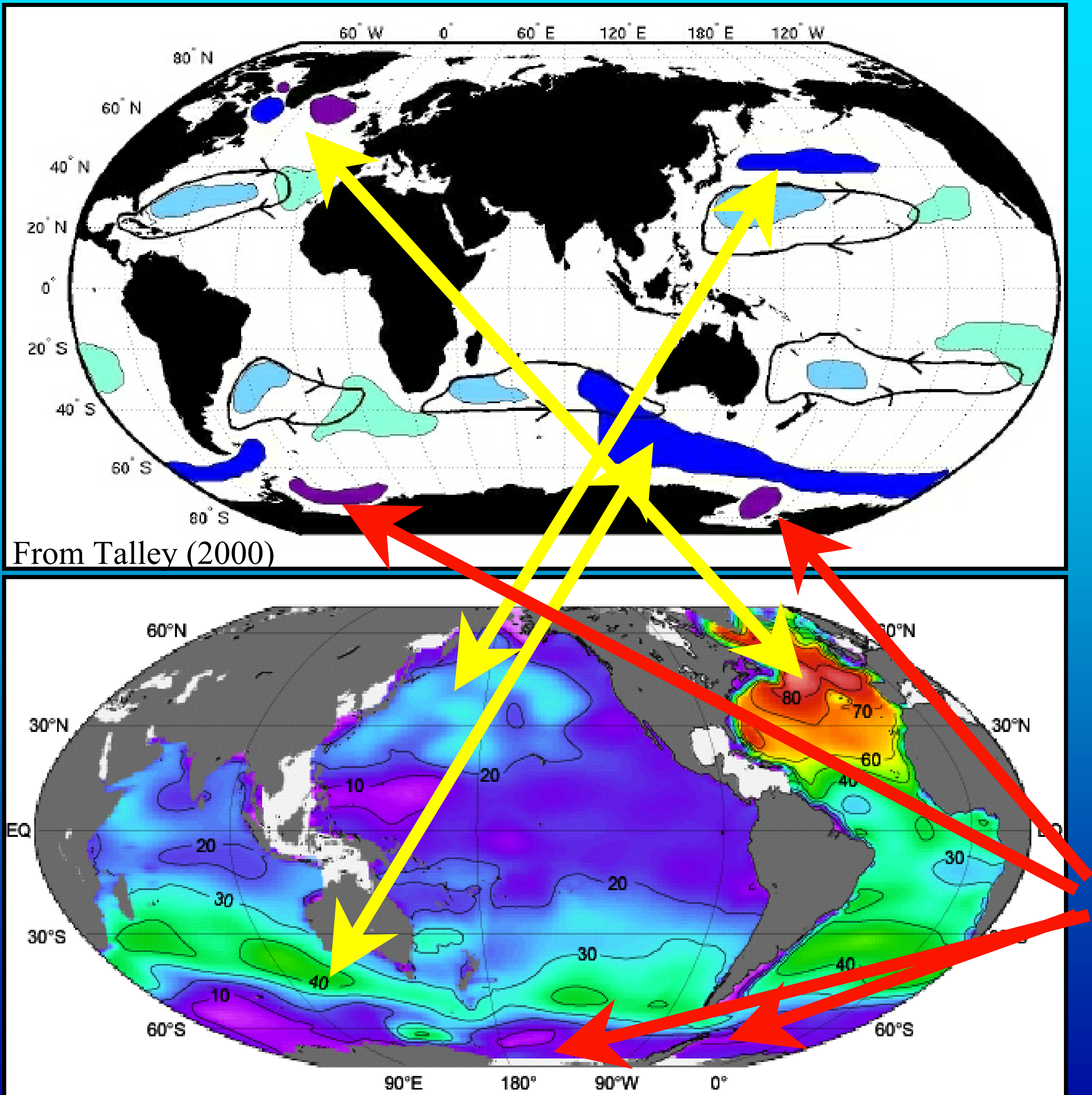
Mapped Inventory 106±17 Pg C

Column inventory of anthropogenic CO_2 that has accumulated in the ocean between 1800 and 1994 (mol m^{-2})



60% of mapped inventory found in Southern Hemisphere in proportion to the ocean area

Mapped Inventory 106±17 Pg C

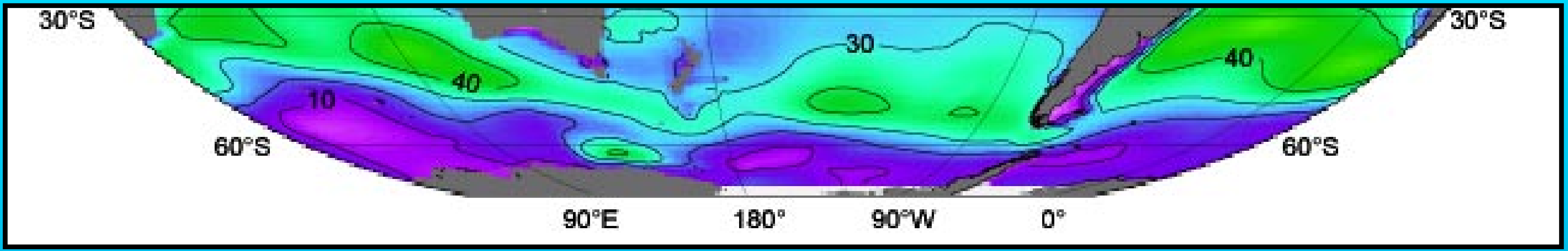


From Talley (2000)

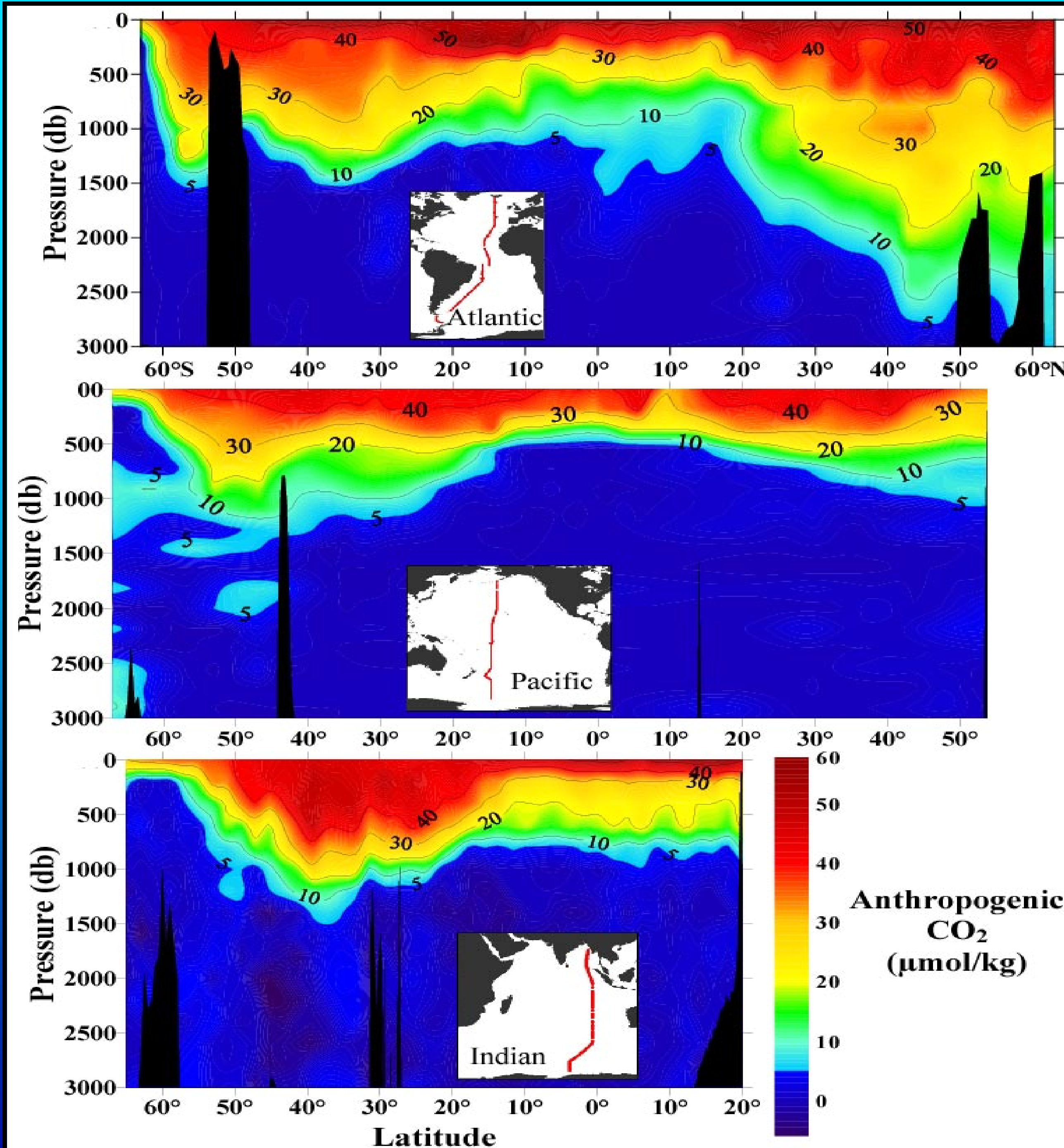
The highest inventories are found in areas where water is sinking into the ocean interior taking with it the anthropogenic CO_2 accumulated at the surface.

Not found in Antarctic bottom waters

Possible Reasons for Low Anthropogenic CO_2 Inventory in the High Latitude Southern Ocean



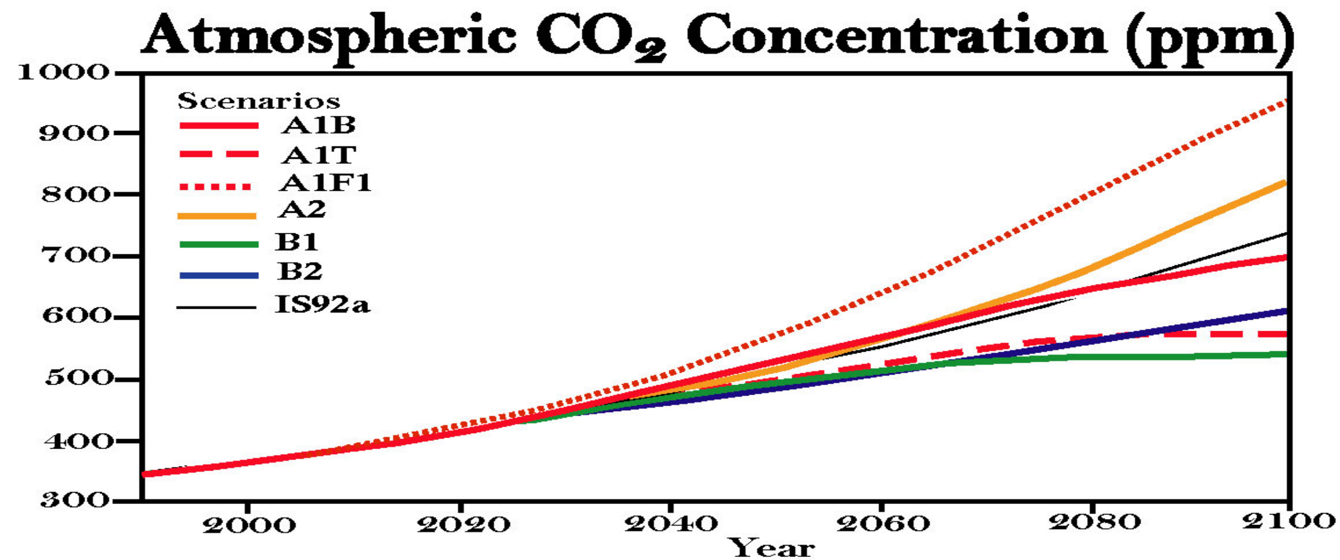
- Inadequate data coverage;
- Low vertical stratification results in substantial mixing invalidating a basic assumption of ΔC^* technique;
- Newly formed bottom waters mix with old anthropogenic CO_2 free waters diluting the signal below the limit of detection;
- Short residence times and ice cover do not allow CO_2 to equilibrate;
- High Revelle Factor makes the Southern Ocean very inefficient at taking up CO_2.



Because the ocean mixes slowly, half of the anthropogenic CO_2 stored in the ocean is found in the upper 10% of the ocean.

50% of anthropogenic CO_2 in the ocean is shallower than 400 m

Average penetration depth 1000 m



	Glacial	Pre-industrial	Present	$2XCO_2$	$3XCO_2$	
$CO_2(g)$						Atmosphere
Gas Exchange	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)	%Δ
$HCO_3^- \rightleftarrows H^+ + CO_3^{2-}$ 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

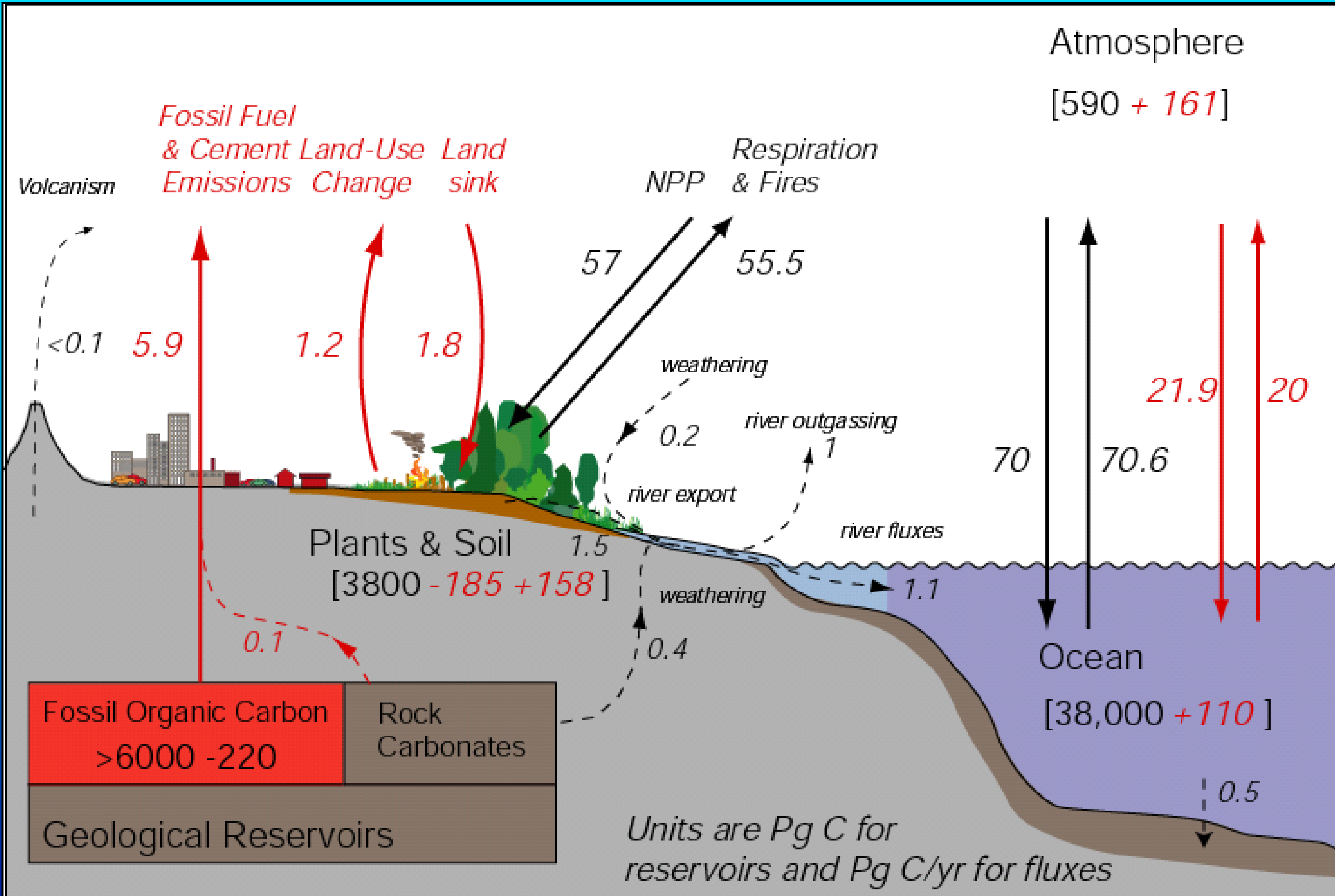
Average Surface Water DIC Increase in 2000 ~ 1.2 μmol $kg^{-1} yr^{-1}$

There have already been substantial changes in surface ocean chemistry & with global warming the physical forcing on the ocean is changing.

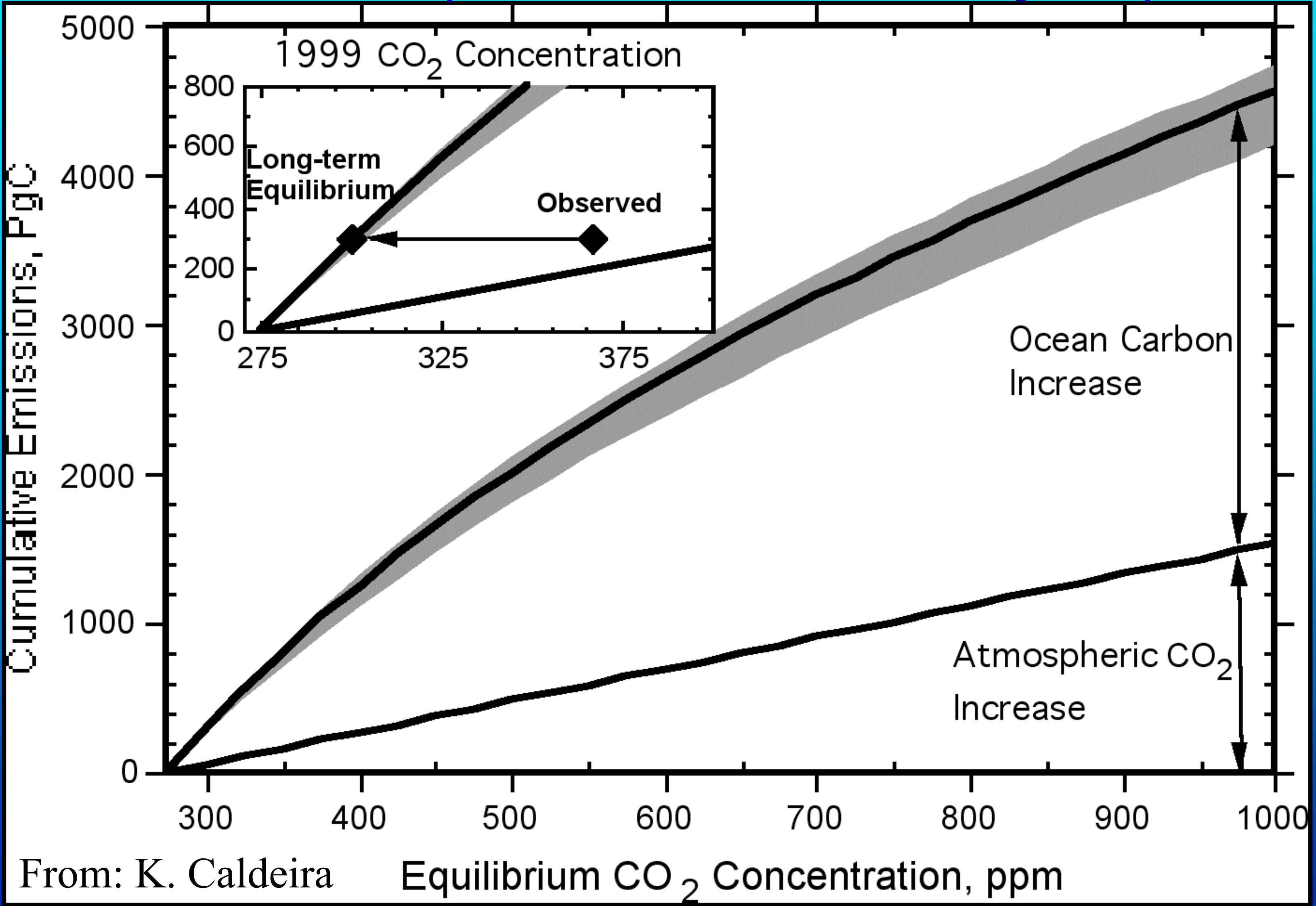
What role will the future ocean play in the global carbon cycle?

Modified from Feely et al., (2001)

The ocean has changed from a net CO_2 source to a net sink



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



From: K. Caldeira

If we consider the dissolution of $CaCO_3$ sediments this number may be as high as 90%

There is a Suggestion That Uptake may Decrease on Decadal to Centennial Time Scales

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	36%
Emissions (f. fuel, cement)	+156 ± 20	+117 ± 5	43%
Ocean Inventory	-90 ± 19	-37 ± 8	29%
Net terrestrial	+50 ± 28	-15 ± 9	
Land-use change	+82 to +162	+24 ± 12	
**Resid. terrestrial sink*	-32 to -112	-39 ± 18	

Ocean uptake dropped from 44% in the first 180 years to 36% in the last 20 years

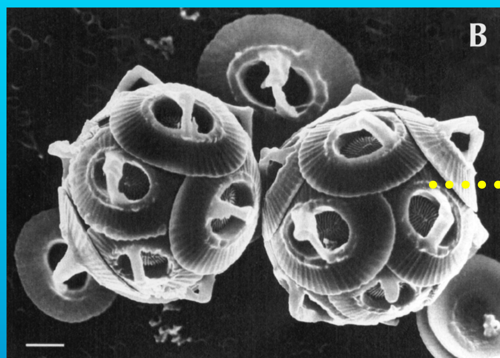
Carbon System Feedbacks: direct effect of rising CO_2 on carbon system

Today's world

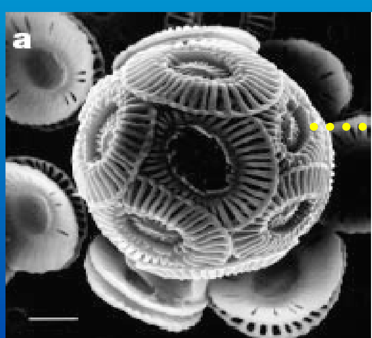
pCO_2: 280-380 ppmV

High-CO_2 world

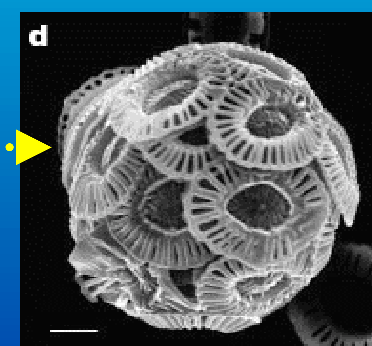
pCO_2: 580-720 ppmV

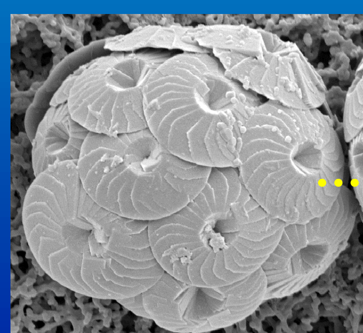


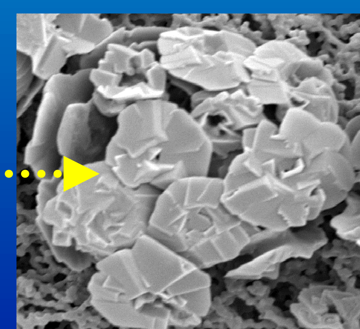
Gephyrocapsa oceanica



Emiliania huxleyi



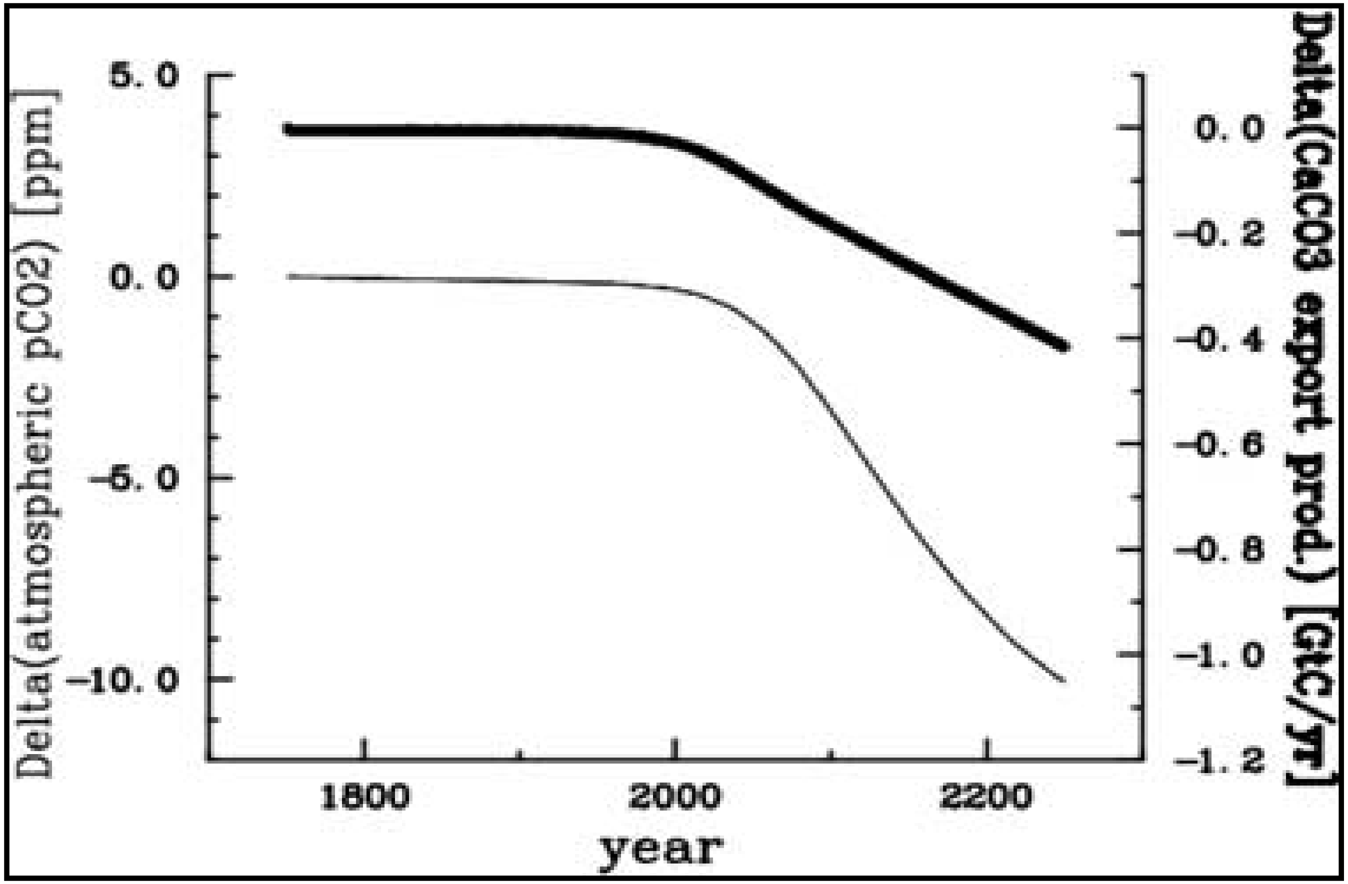




Calcidiscus leptoporus

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

Carbon System Feedbacks:
direct effect of rising CO_2 on carbon system



From C. Heinze

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

Carbon-Climate Feedbacks: effects of climate change on carbon system

Cumulative ocean uptake of CO_2 (PgC) due to different climate-induced feedback effects.

Scenario and years	Climate Baseline	Solubility Effect	Stratification Effect	Biological Effect	Net Effect
[a]1% CO_2/yr for 100 years	554	–52 (–9.4%)	–117 (–21.1%)	+111 (+20.0%)	–58 (–10.5%)
[b]IS92a-like, 1765–2065	401	–56 (–14.0%)	–68 (–17.0%)	+108 (+26.9%)	–16 (–4.0%)
[c]IS92a, 1850–2100	376	–48 (–12.8%)	–41 (–10.9%)	+33 (+8.8%)	–56 (–14.9%)
[d]WRE550, 1765–2100	530	–68 (–12.8%)	–15 (–2.8%)	+33 (+6.2%)	–50 (–9.4%)
[e]WRE1000, 1765–2100	612	–58 (–9.5%)	–27 (–4.4%)	+36 (+5.9%)	–48 (–7.8%)

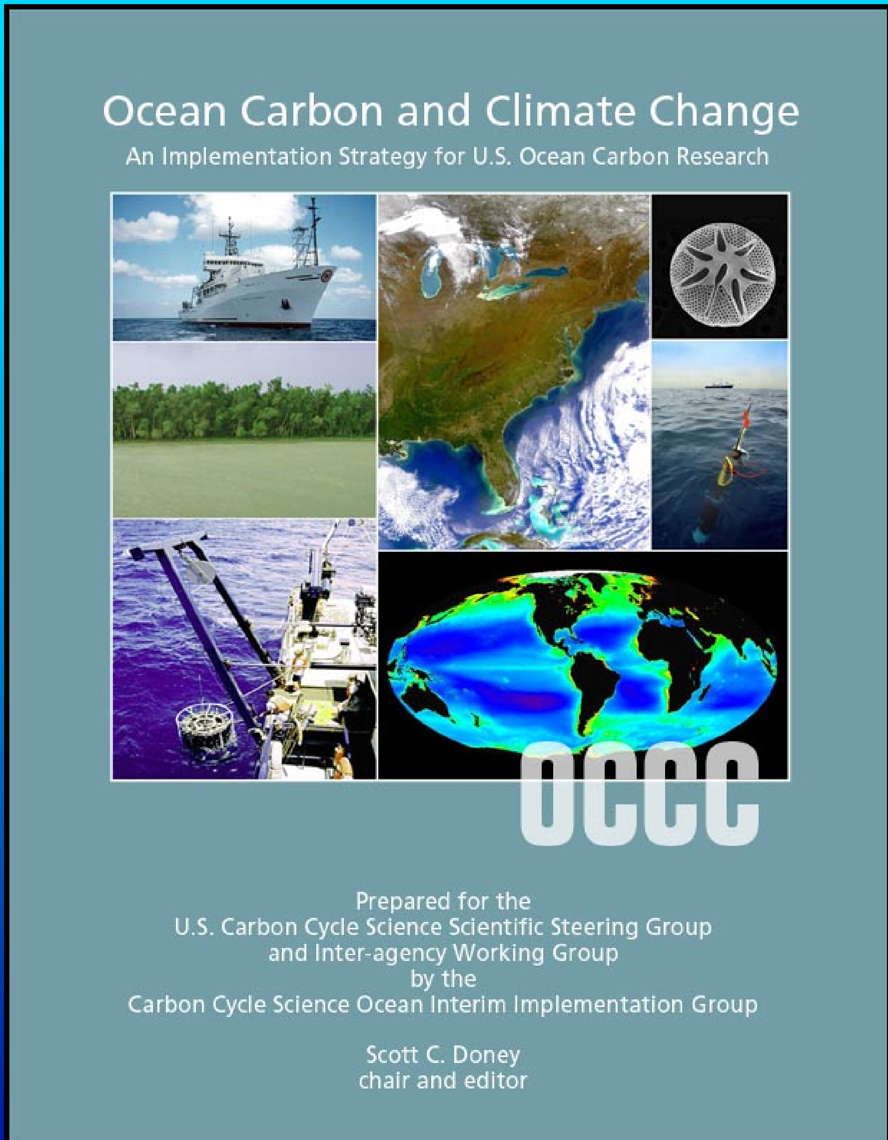
[a]Sarmiento and Le Quéré (1996), [b]Sarmiento et al. (1998), [c]Matear and Hirst (1999), [d]Joos et al. (1999a), [e]Plattner et al. (2001); *Note:* "Climate baseline" refers to a simulation with anthropogenic CO_2 emissions but preindustrial ocean temperatures and circulation. "Effects" refer to uptake changes for various climate feedbacks and are expressed relative to the climate baseline. The "net effect" is the uptake change when all climate feedbacks are present (i.e., full climate change simulation, after Greenblatt and Sarmiento, 2004).

models predict decreased uptake due to climate feedbacks

Must improve our understanding of carbon system feedbacks if we expect to predict future atmospheric CO_2 levels

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

So Where We go From Here?



Implementation Elements

Ocean Carbon Observing System
- Repeat hydrographic survey
- VOS pCO_2 surveys
- Time-series measurements
- N. A. coastal observing network
- Remote sensing

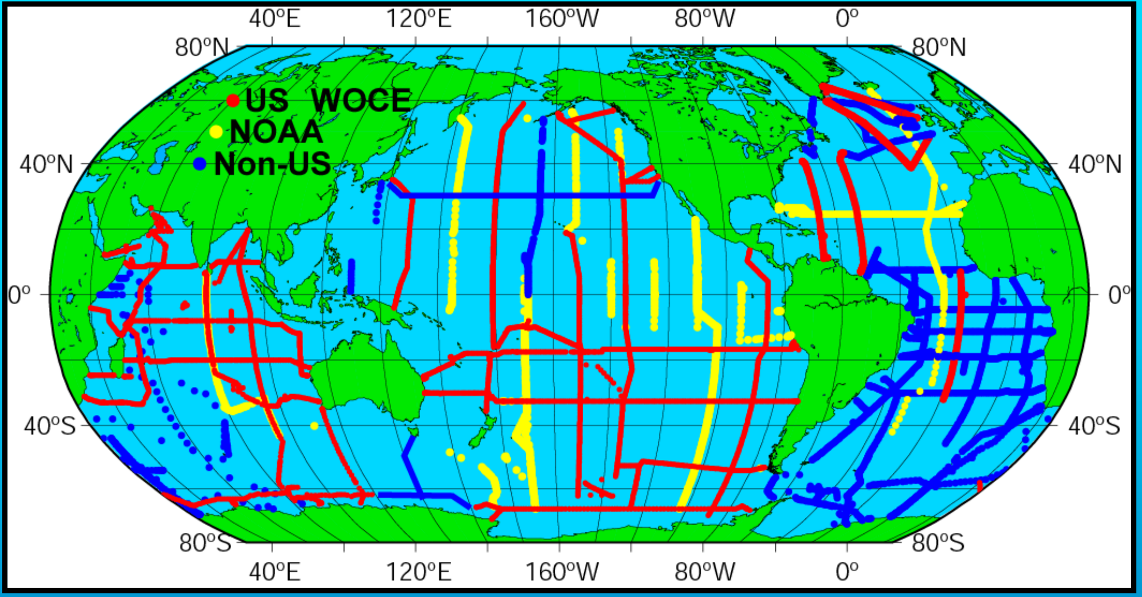
North Atlantic and North Pacific Process Studies
- Upper water column processes
- Mesopelagic processes
- Continental margin biogeochemistry
- Air-sea gas exchange

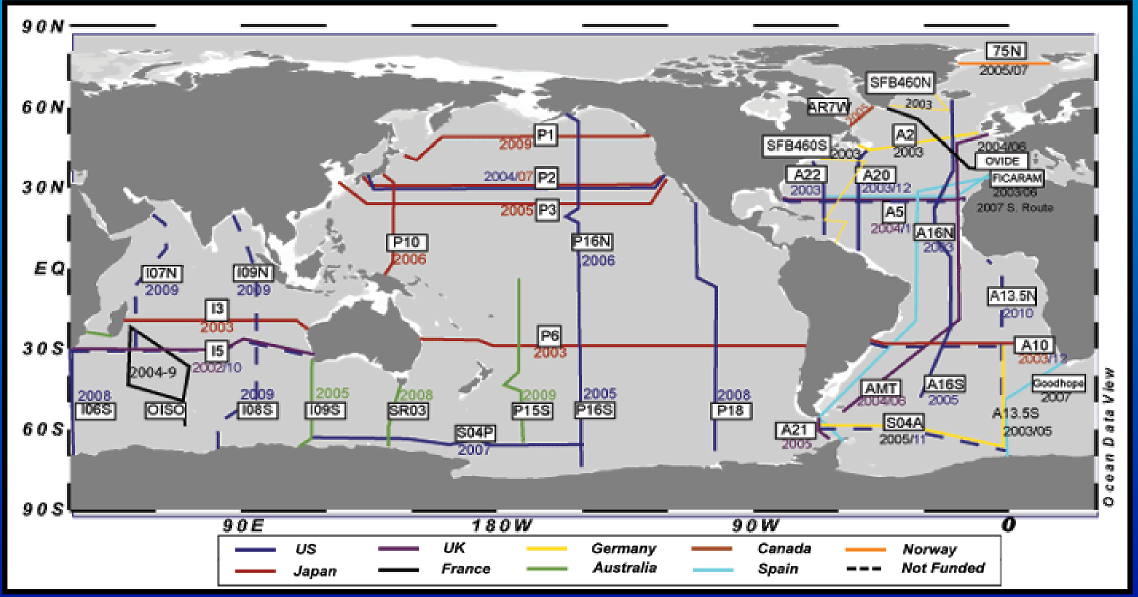
Southern Ocean Pilot Studies

Synthesis and Numerical Modeling

Enabling Activities
- Sensor and platform development
- Data mgmnt. and data availability
- Workshops and educational outreach

CLIVAR/CO_2 Repeat Hydrography



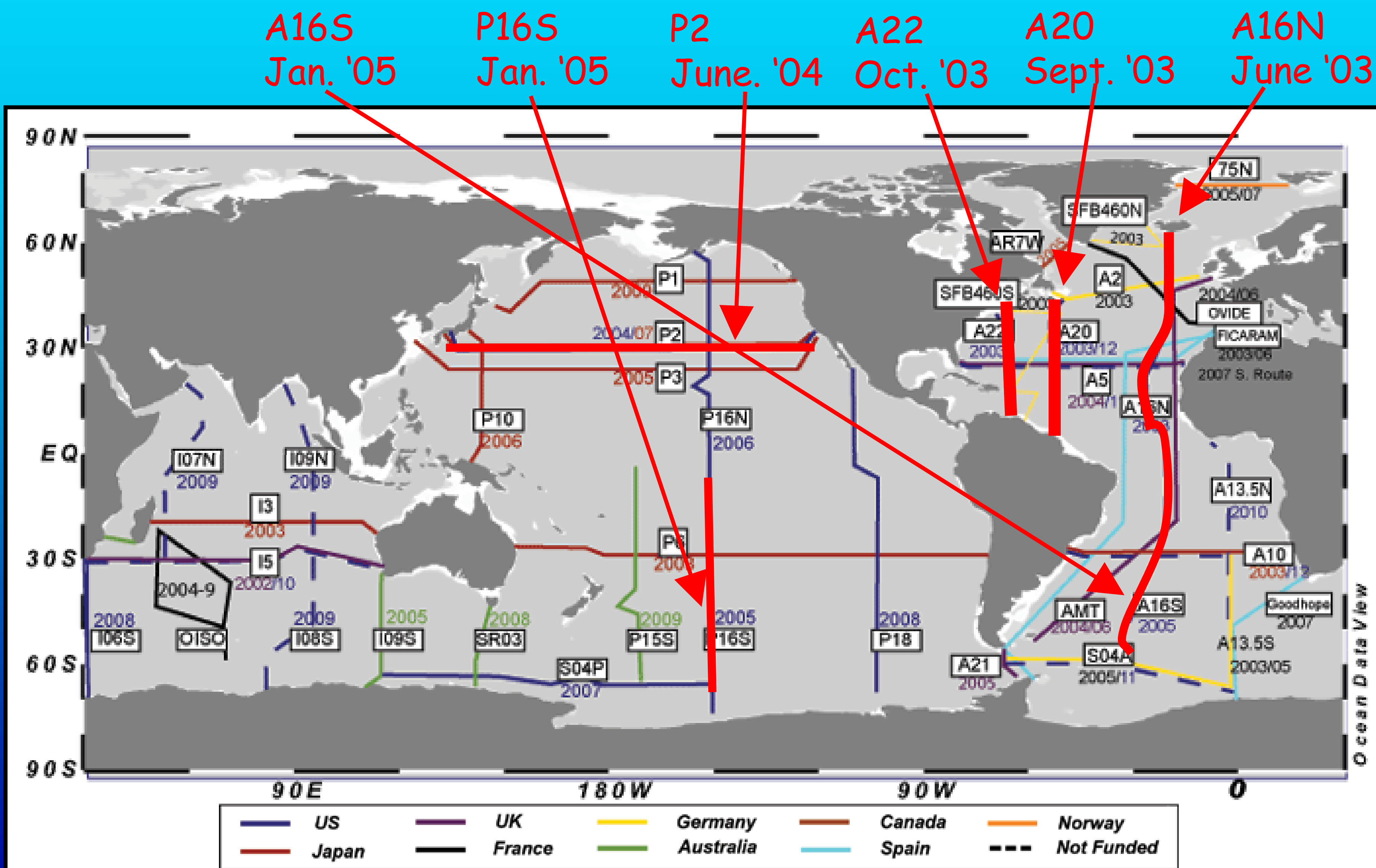


With the WOCE/JGOFS survey as a baseline, we can begin to evaluate changes in ocean carbon over time.

This will allow us to avoid many of the assumptions required for the initial inventory estimate.

CLIVAR/CO_2 Repeat Hydrography

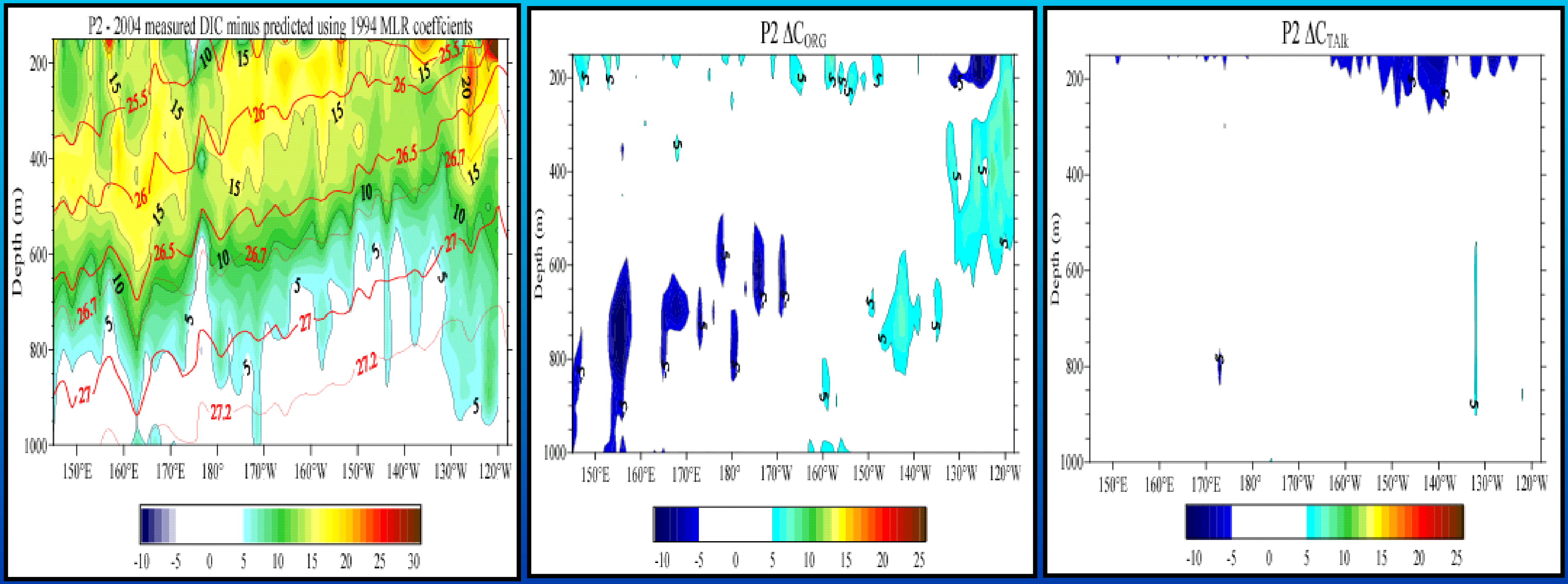
Achievements: The U.S. CLIVAR/CO_2 Repeat Hydrography Program has completed 6 of 19 cruises and is on schedule. For further details see: http://ushydro.ucsd.edu/



Obtaining the decadal anthropogenic CO_2 signal in the ocean
Multiple Linear Regression Approach

1) Fit older cruise DIC as a function of non-carbon tracers
2) Use non-carbon tracers from new cruise to predict DIC
3) Examine difference between measured DIC and predicted

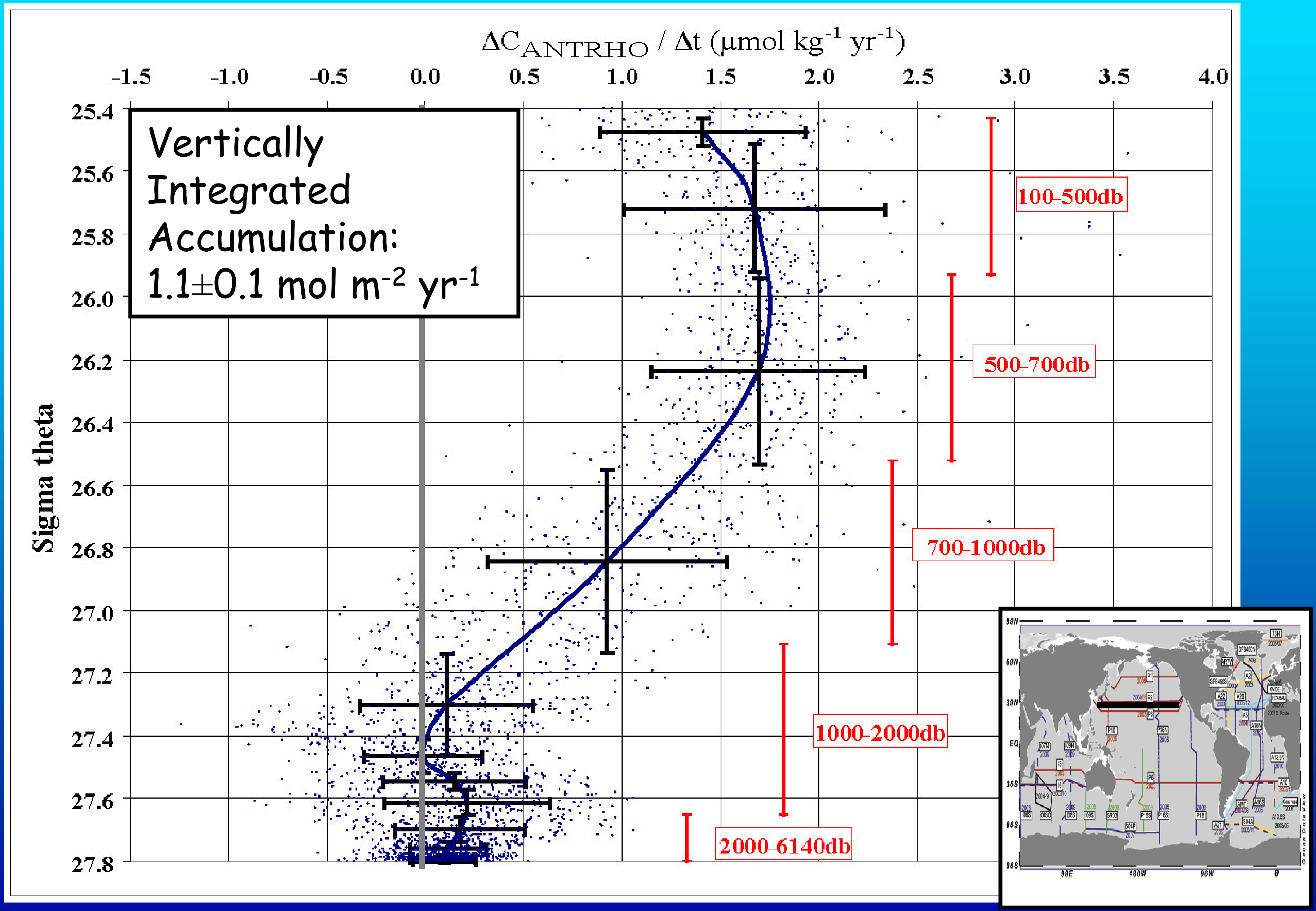
$$DIC = a + bT + cS + dAOU + eNO_3$$



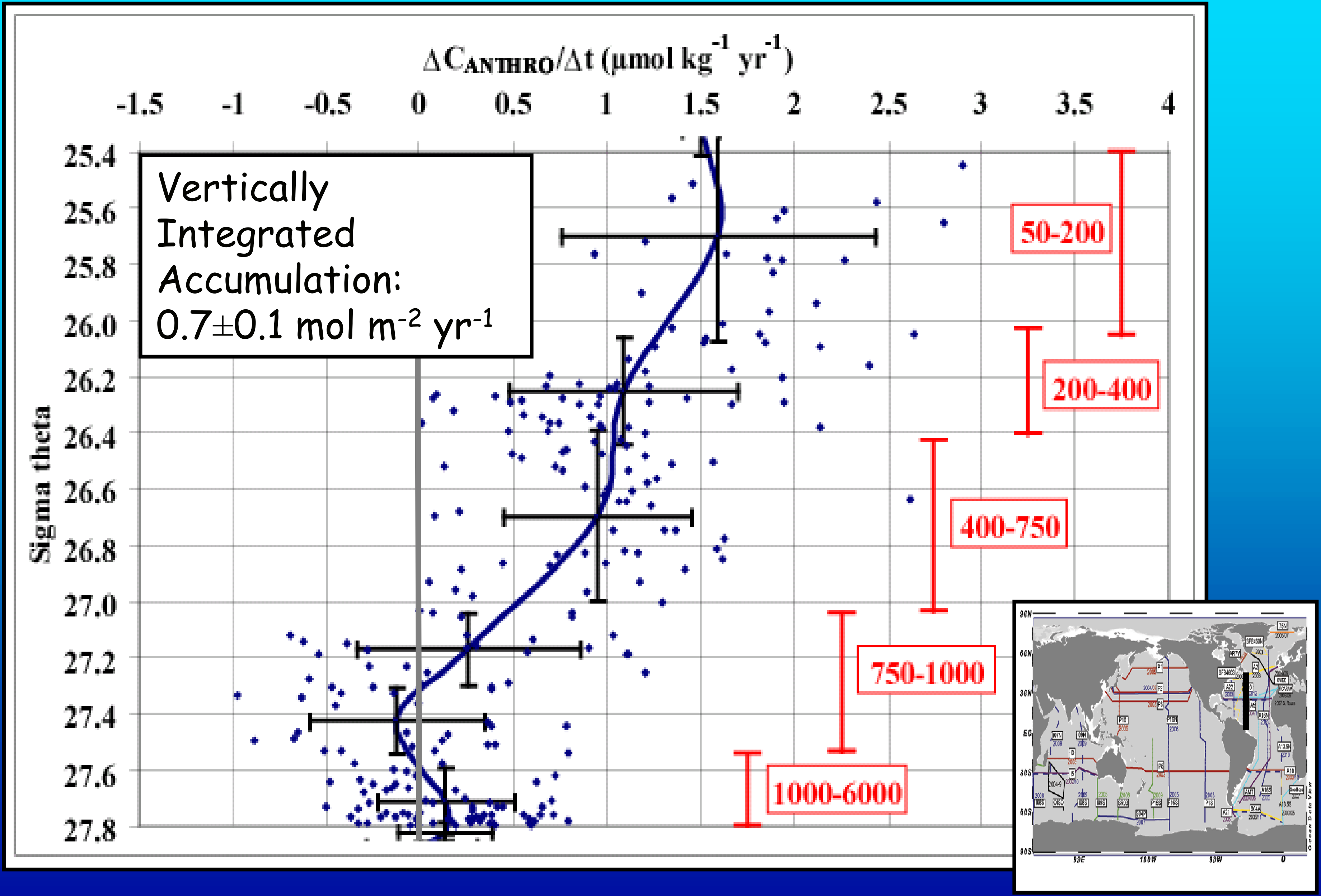
$$\Delta C_{anthro} = \Delta C_{total} - \Delta C_{org} - \Delta C_{alk}$$

$$\Delta C_{anthro} = DIC_m - DIC_{MLR} - (117/170)*(AOU_m - AOU_{MLR}) - 0.5*(ALK_m - ALK_{MLR})$$

CO_2 Accumulation Rate on Isopycnal Surfaces along 30°N Based on P2 2004 - 1994 Comparison



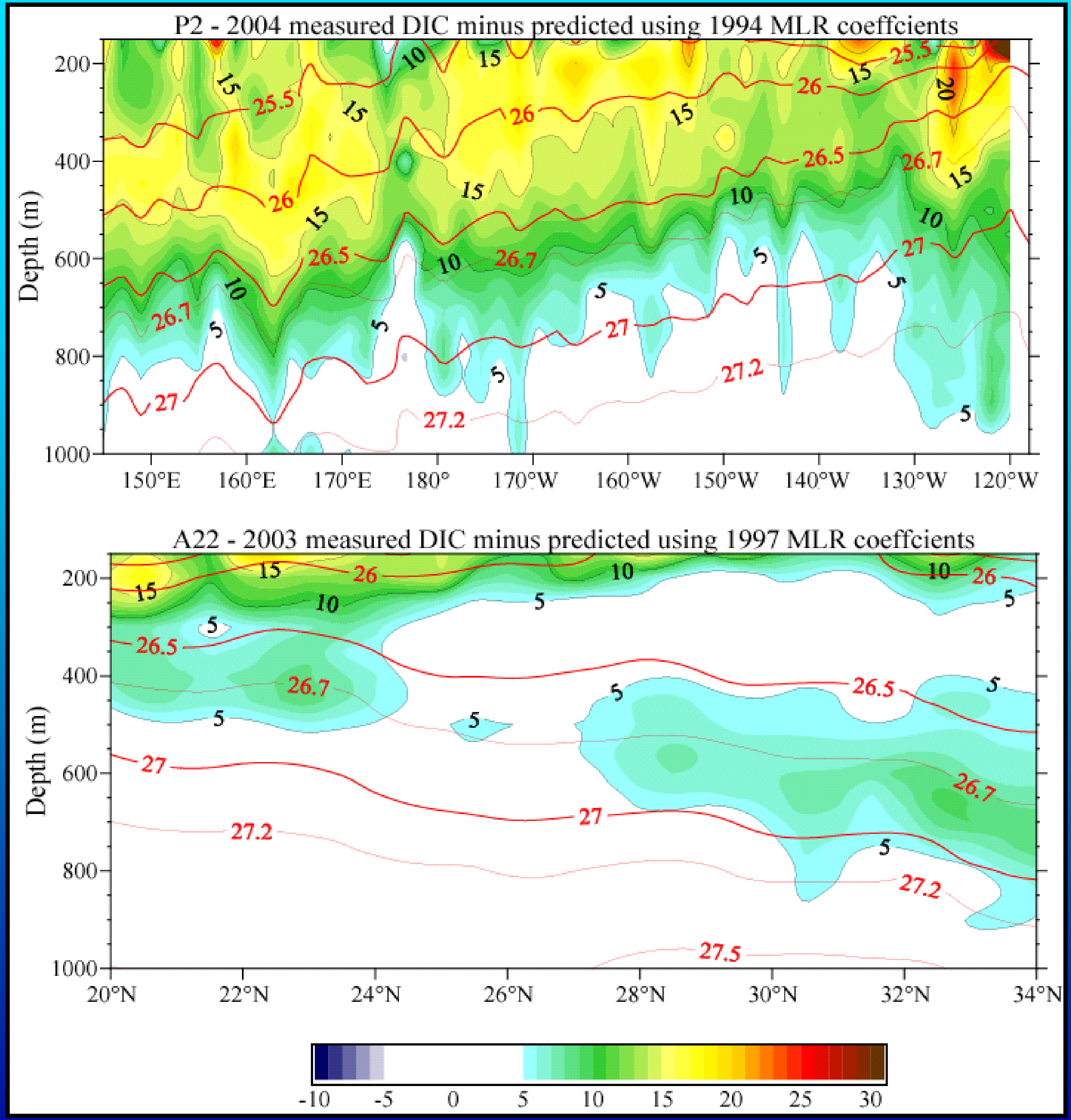
CO_2 Accumulation Rate on Isopycnal Surfaces along 66°W Based on A22 2003 - 1997 Comparison



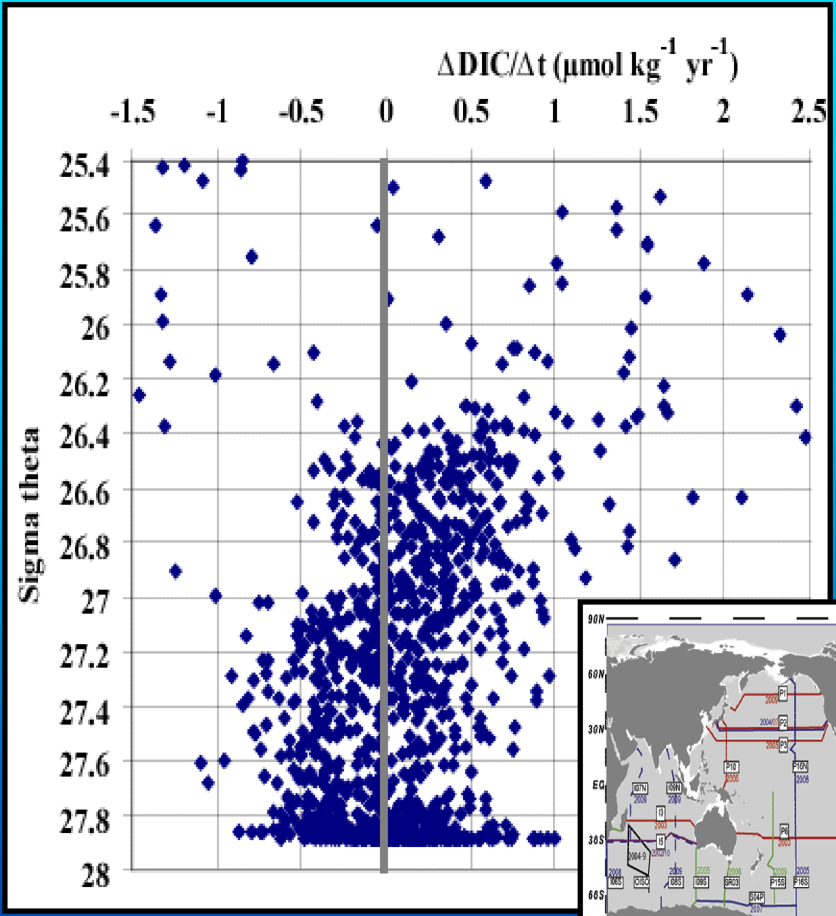
$\Delta C_T = DIC_m - DIC_{MLR}$

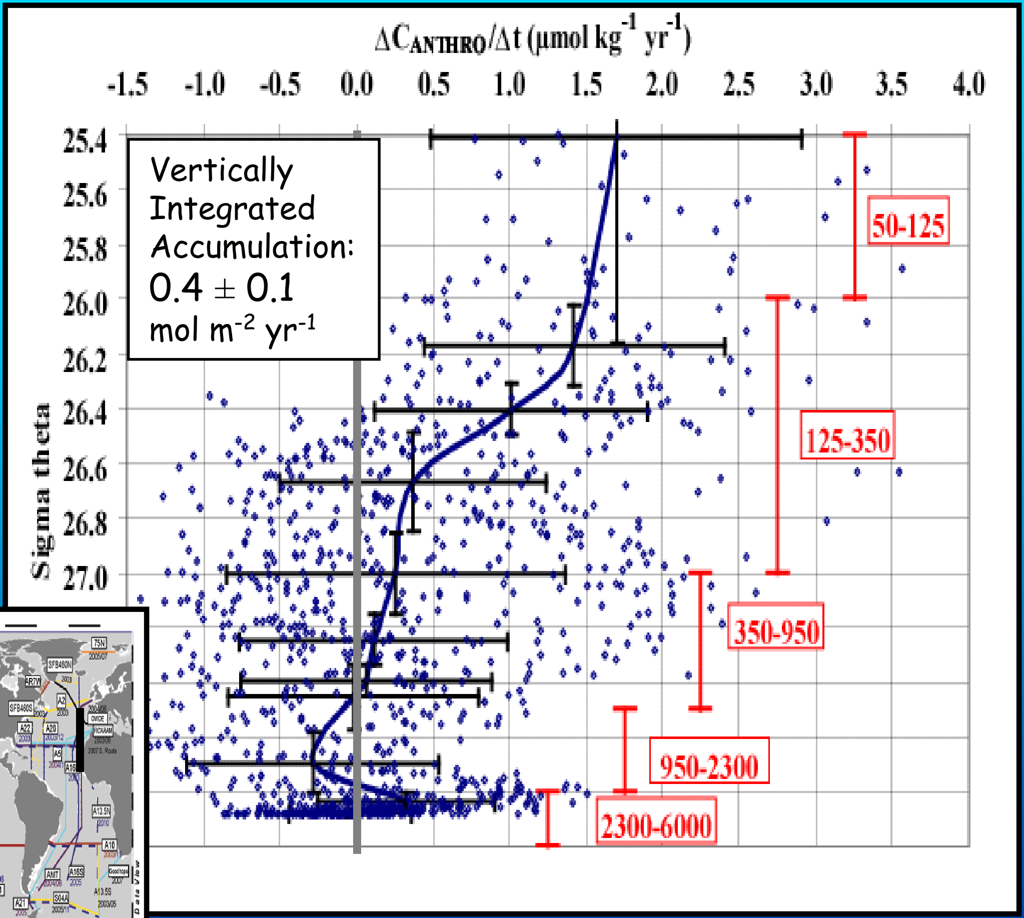
North Pacific
2004-1994

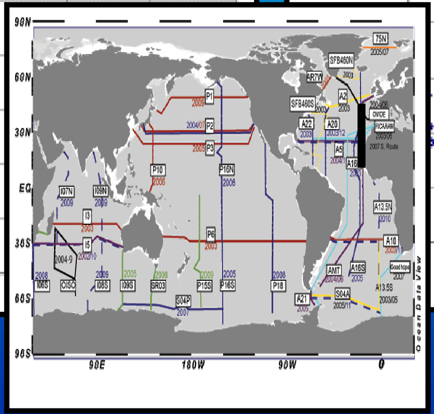
North Atlantic
2003-1997



Intrinsic variability can be of the same order of magnitude as the anthropogenic uptake signal.

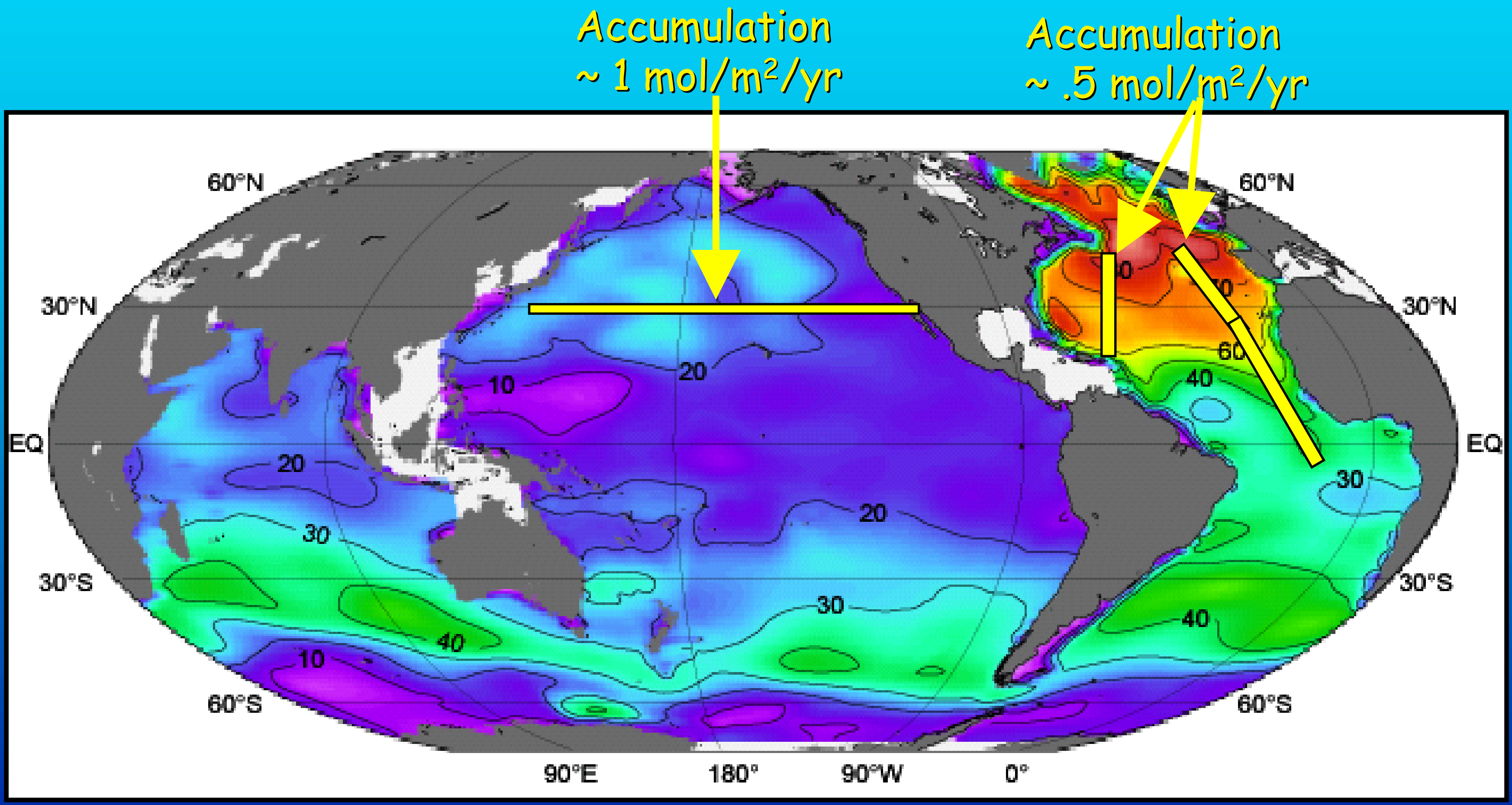






In some cases this may mask anthropogenic accumulation, in others it may enhance the total accumulation.

<u>Preliminary</u> results suggest that North Atlantic accumulation rate over the last decade may have been about half of the North Pacific accumulation rate.



This appears to be a change from the historical operation of these basins.

Conclusions

1. The WOCE/JGOFS data set provides information on global carbon distributions that has not been possible in the past.
2. These data have been used to generate estimates of ocean anthropogenic CO_2 distributions.
3. These results suggest that the global carbon cycle is undergoing dramatic changes over time.
4. 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.
5. Future research needs to focus on understanding carbon system and carbon-climate feedbacks.
6. The CLIVAR/CO_2 (OCCC) repeat section program will monitor decadal scale changes in the ocean carbon cycle.