Quantifying Sources & Sinks of Atmospheric CO_2

Uptake and Storage of Anthropogenic Carbon

by

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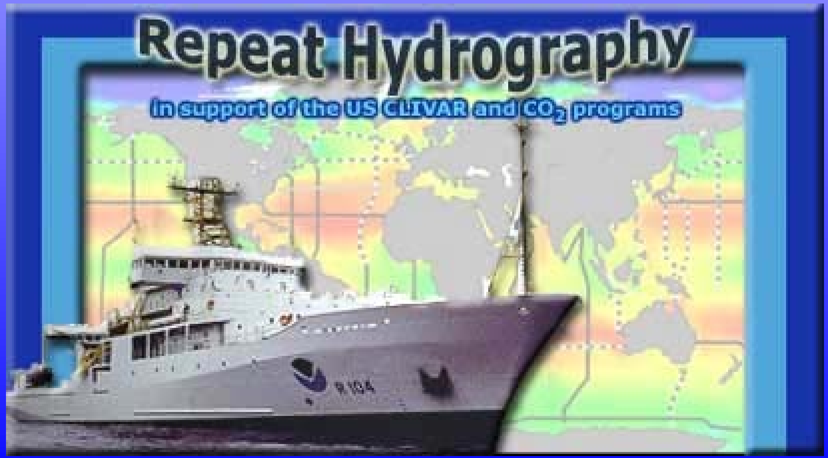
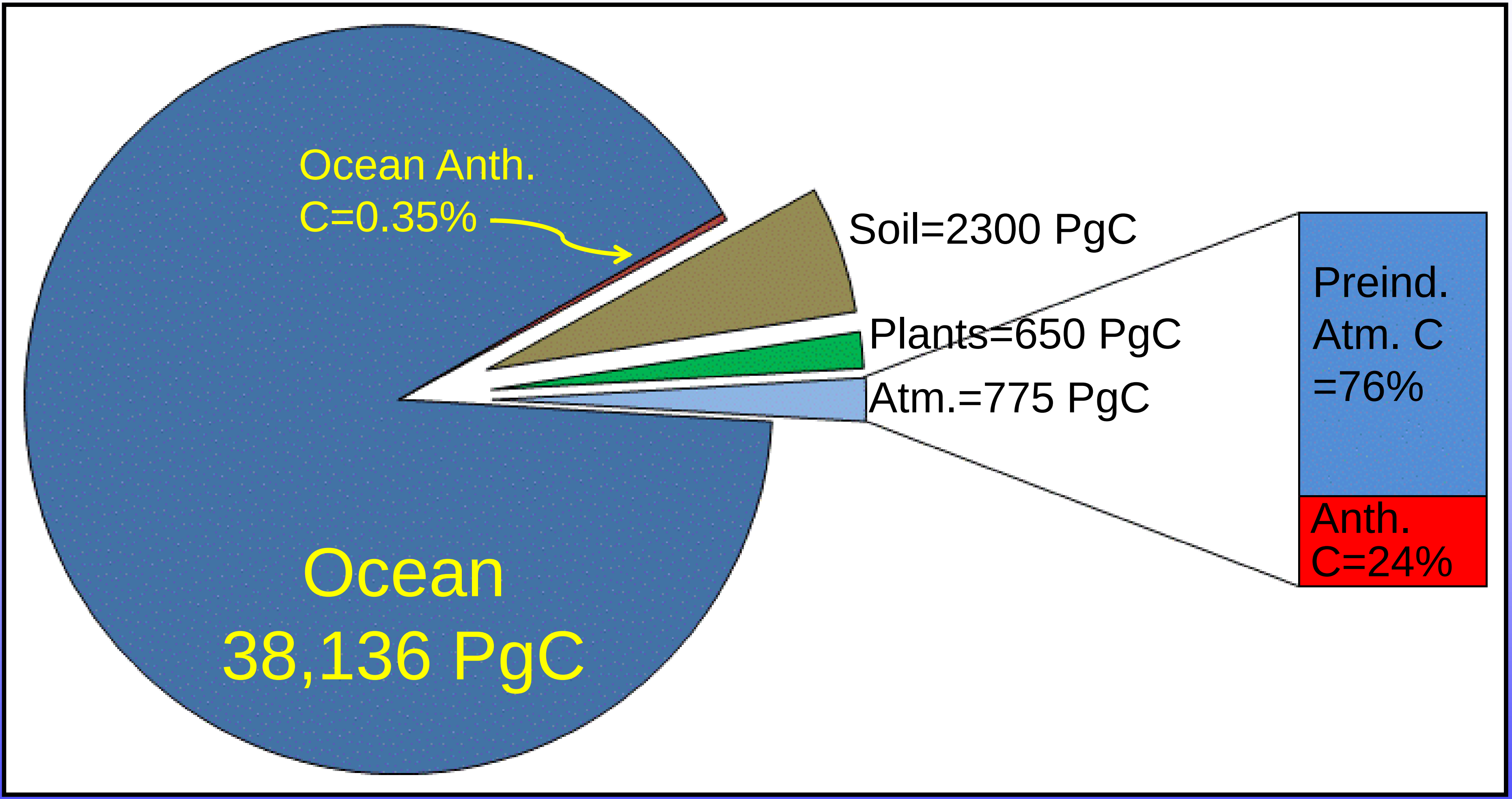


OUTLINE

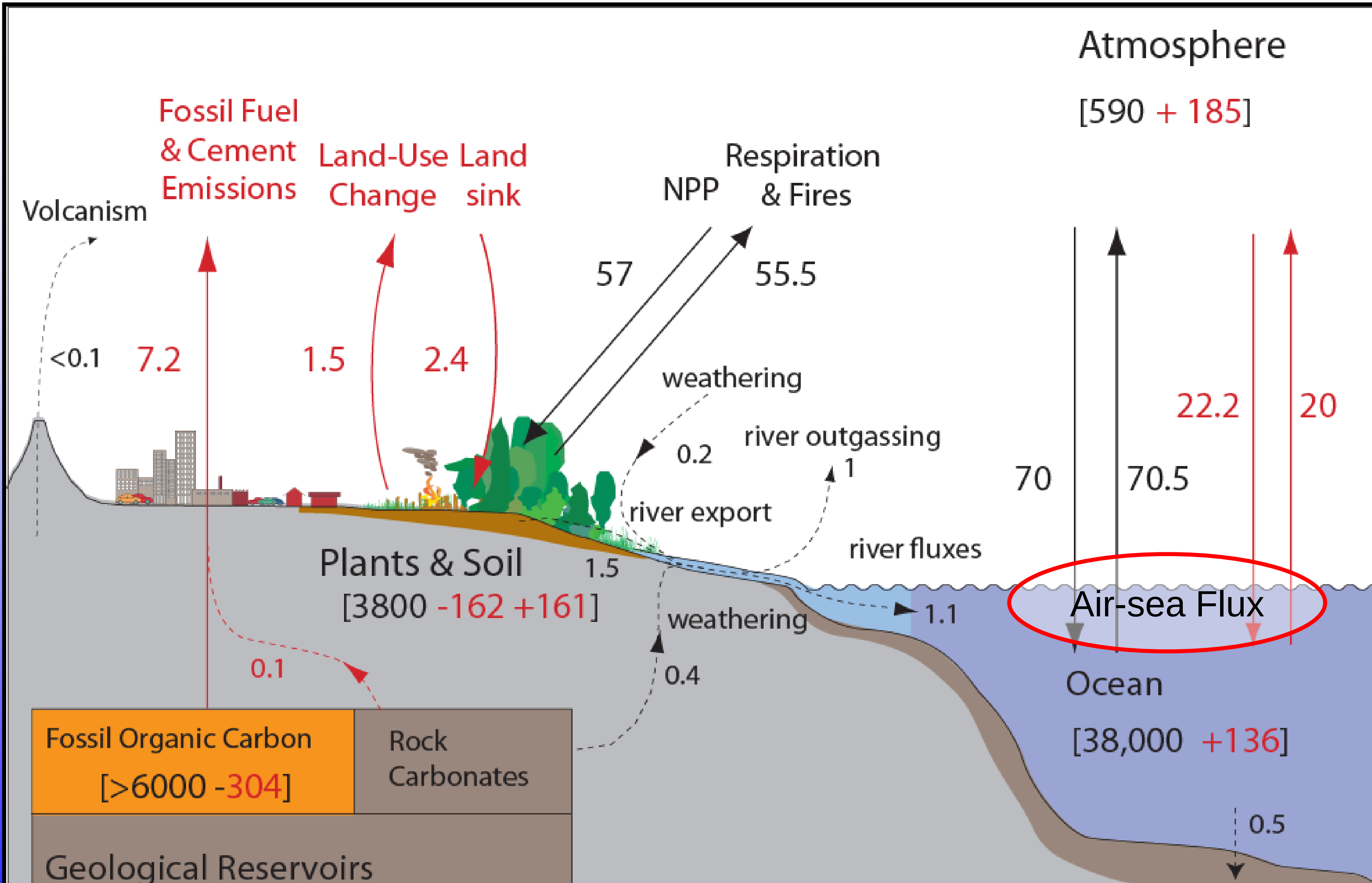
1. Briefly review how observations contribute to Carbon uptake estimates
2. Describe how we determine ocean carbon inventories
3. Consider issues for understanding future ocean carbon uptake and storage
4. Suggest an approach for where we go from here

Carbon Inventories of Reservoirs that Naturally Exchange Carbon on Time Scales of Decades to Centuries



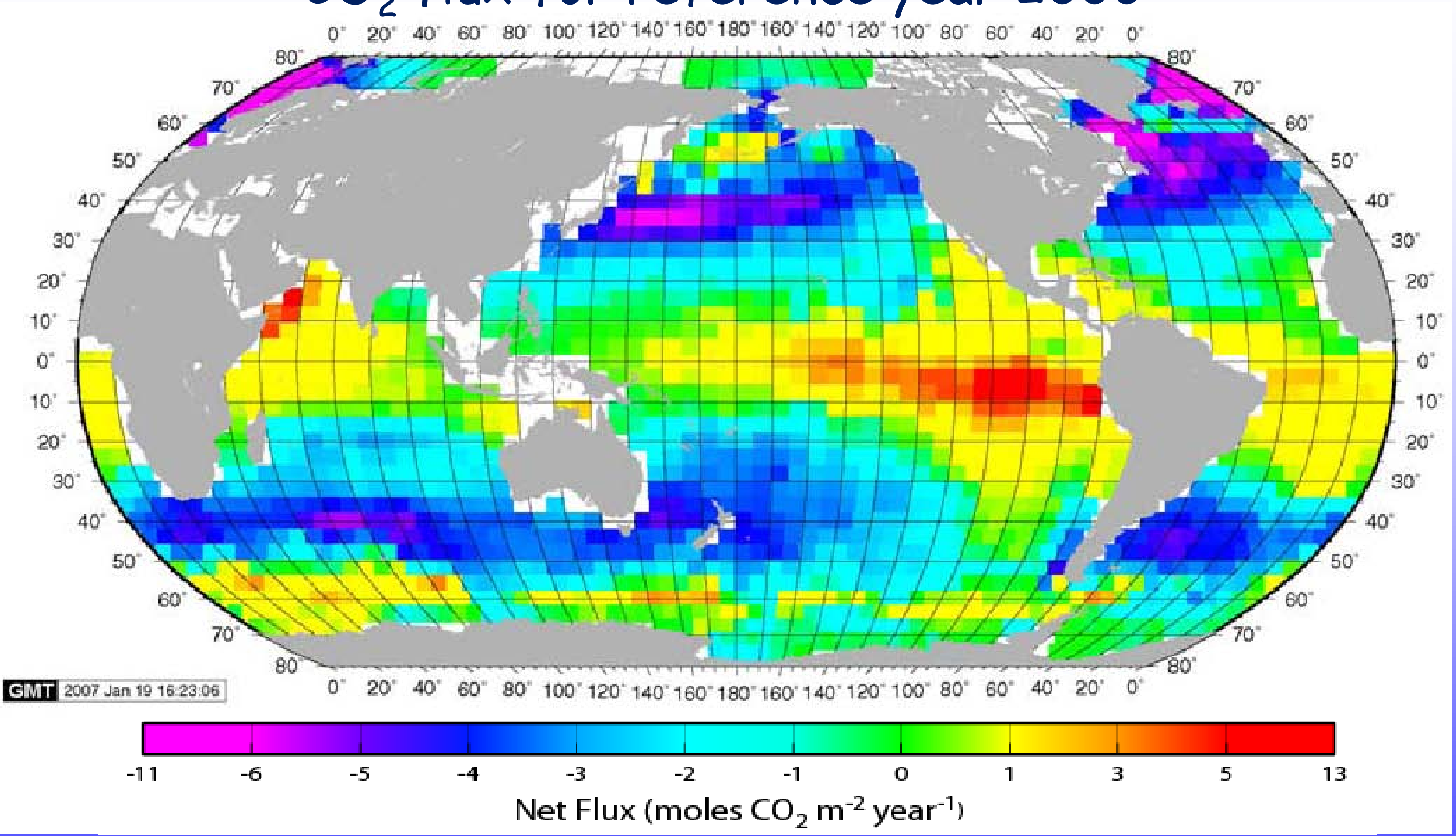
- Oceans contain ~90% of carbon in this 4 component system
- anthropogenic component is difficult to detect

Global Carbon Budget for 2000-2005



adapted from Sabine et al., 2004

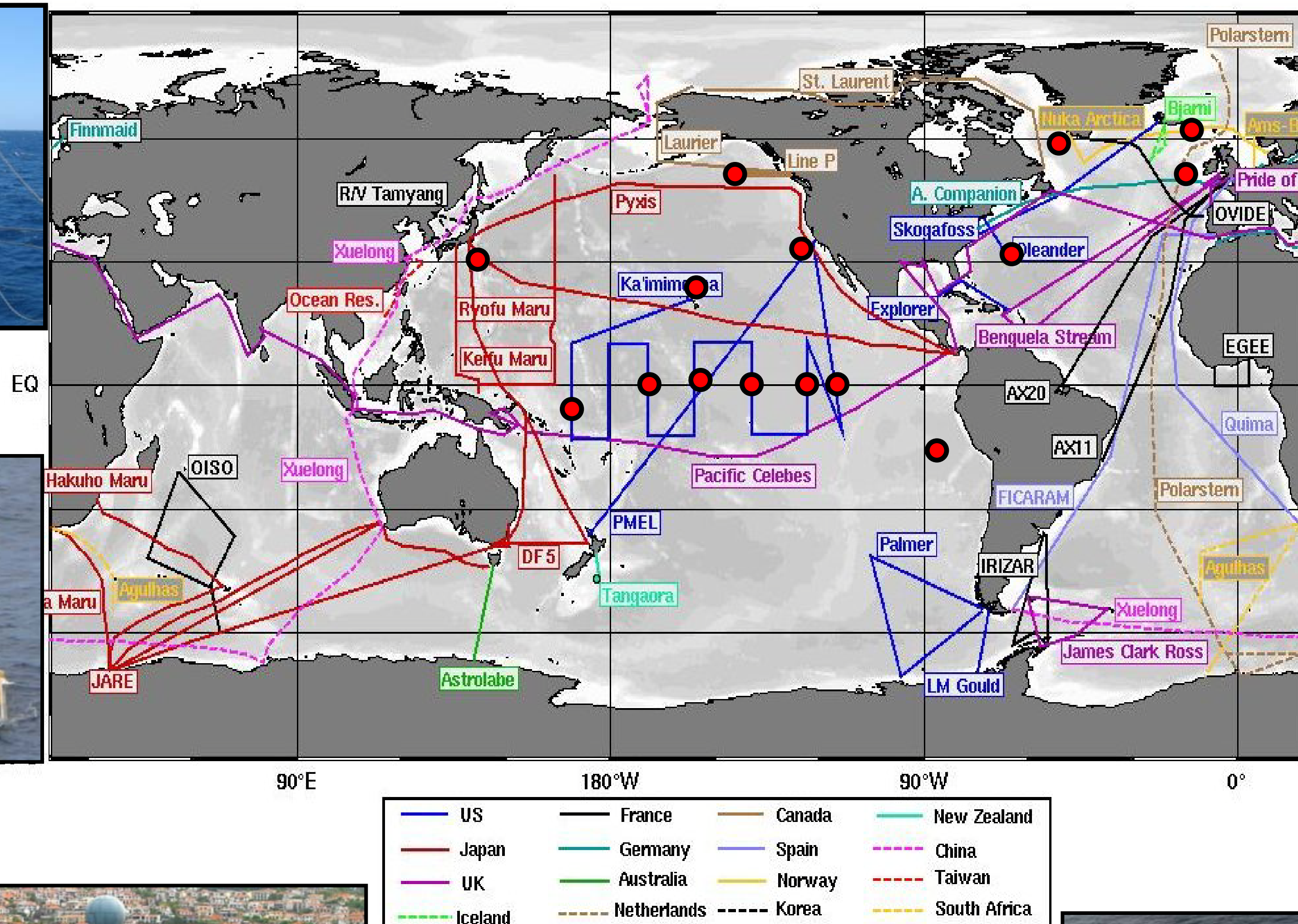
Takahashi climatological annual mean air-sea CO_2 flux for reference year 2000

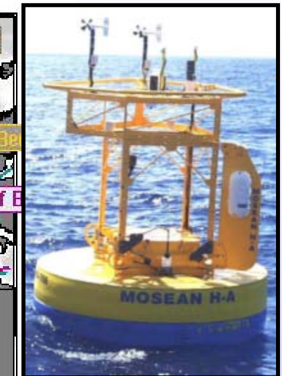


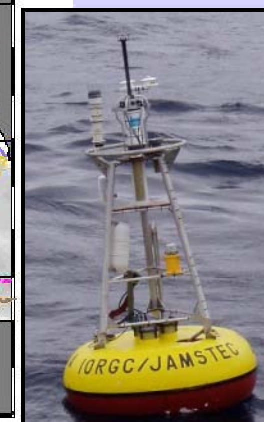
Based on ~3 million measurements since 1970 and NCEP/DOE/AMIP II reanalysis.
Global flux is 1.4 ±0.7 Pg C/yr

Takahashi et al., Deep Sea Res. II, 2009

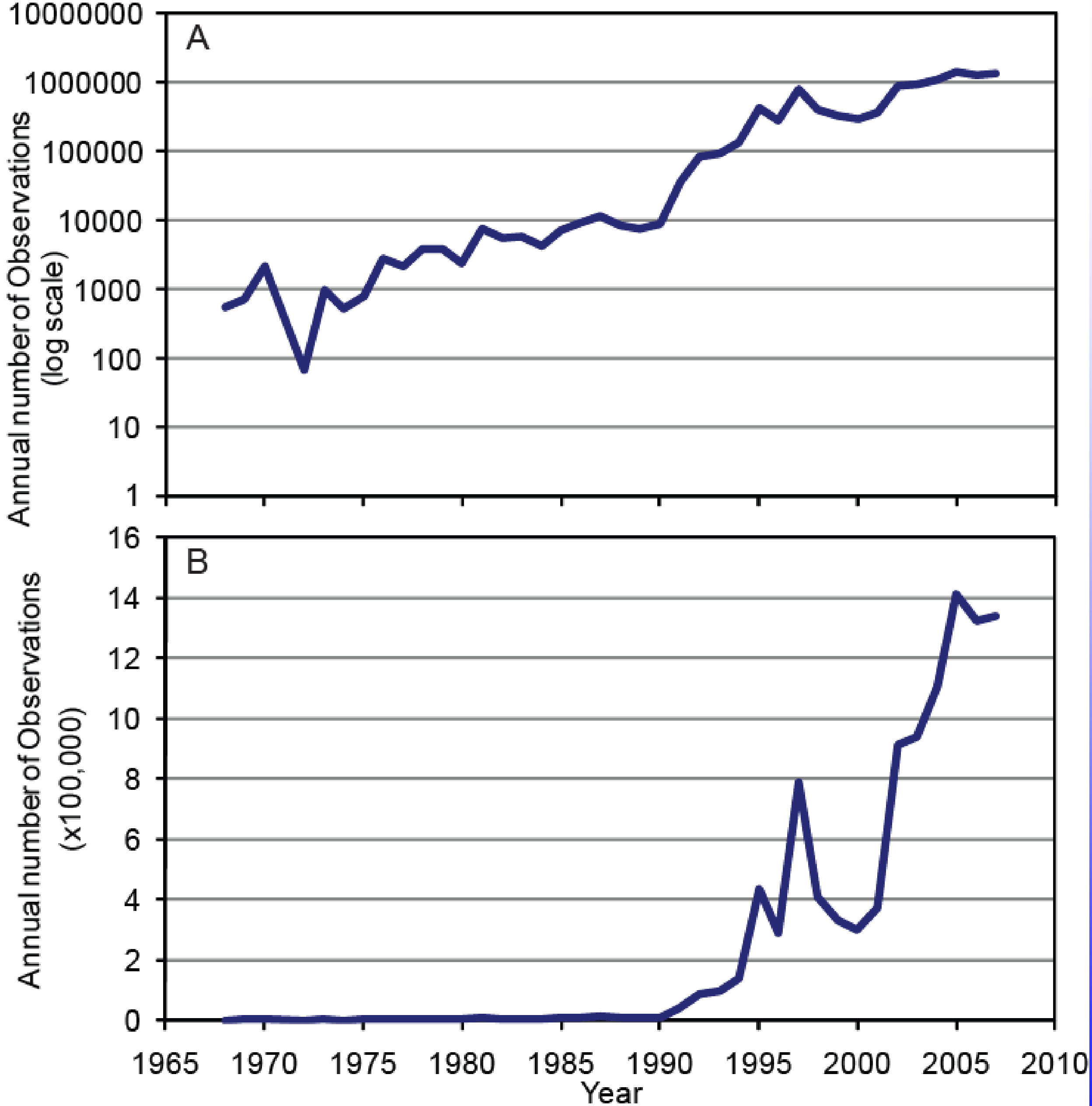
Surface CO_2 observation network







Global Surface CO_2 observations by year



Based on SOCAT version 1 Jan. 2010

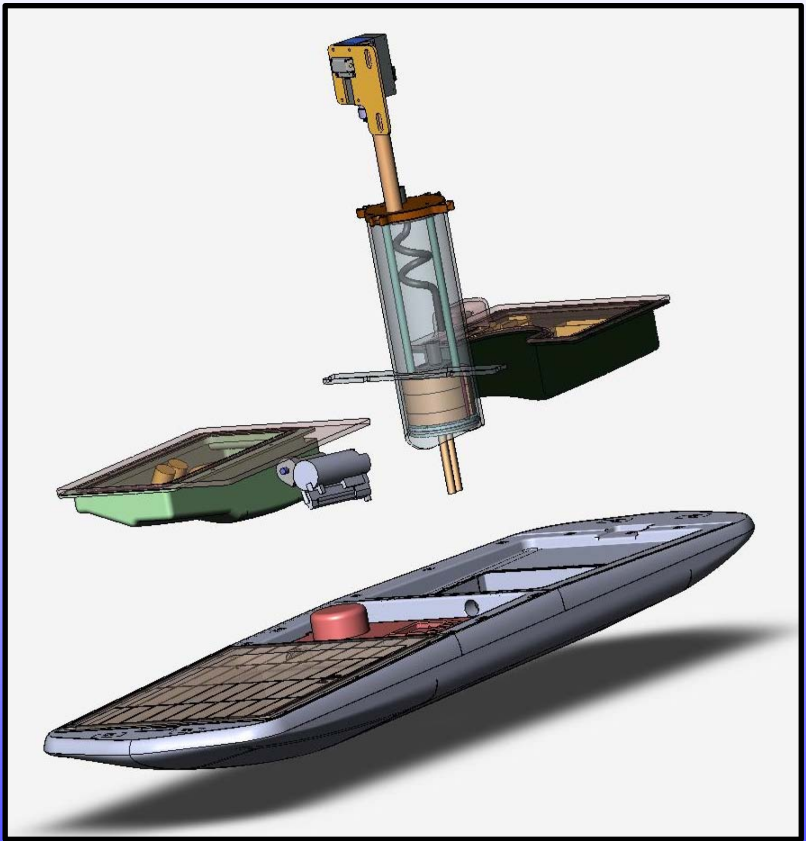
From Sabine et al., 2010

The number of annual measurements has been increasing exponentially since for the last 50 years

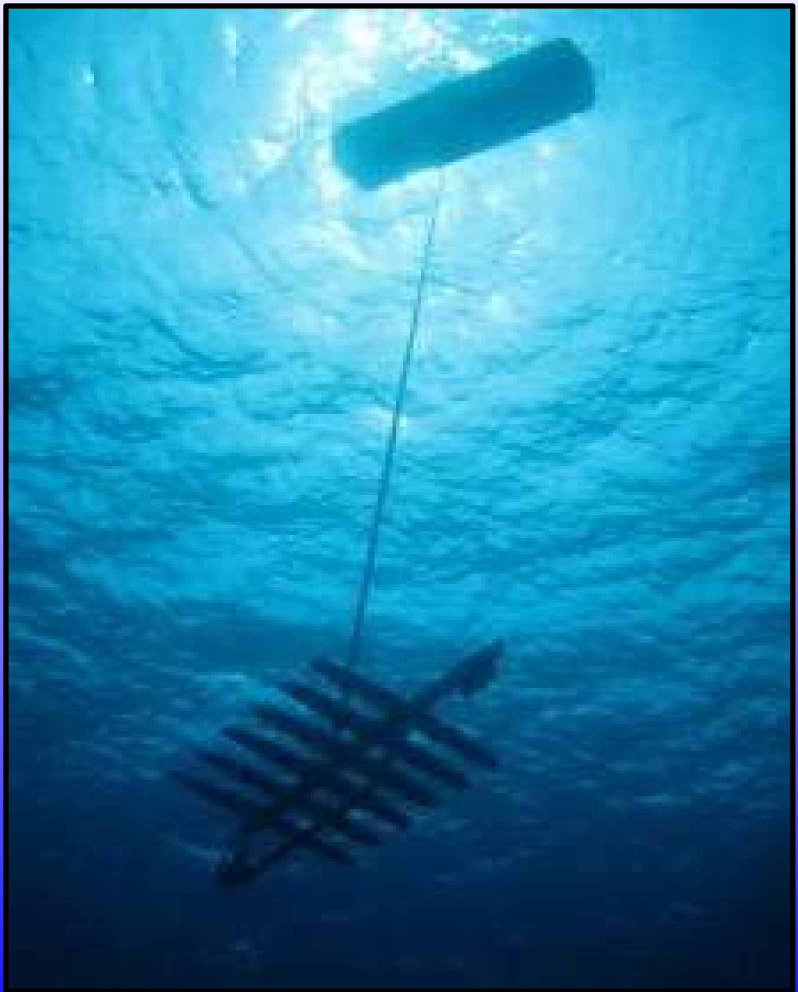
A focus on studying ocean carbon in the 1990s led to the instrumenting of many more research ships

The dramatic increases in the 2000s can be attributed to the instrumenting of commercial ships

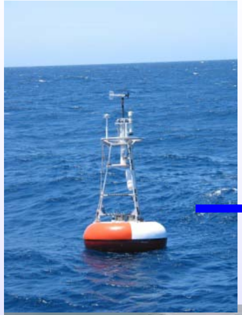
New Technologies can Help Expand the Surface CO_2 Observation Network



One Example: Integrated MapCO$_2$/Wave Glider system under development



Producing Seasonal CO_2 Flux Maps

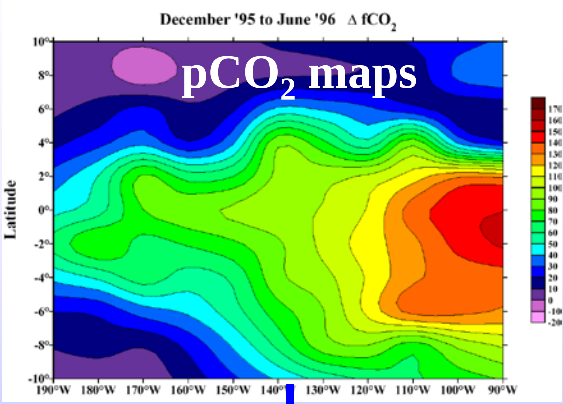


In situ sampling
pCO_2, SST, SSS

Algorithm development
pCO_2= f(SST, *color*)

Co-located satellite data

Apply algorithm to regional SST& *color* fields to obtain seasonal pCO_2maps



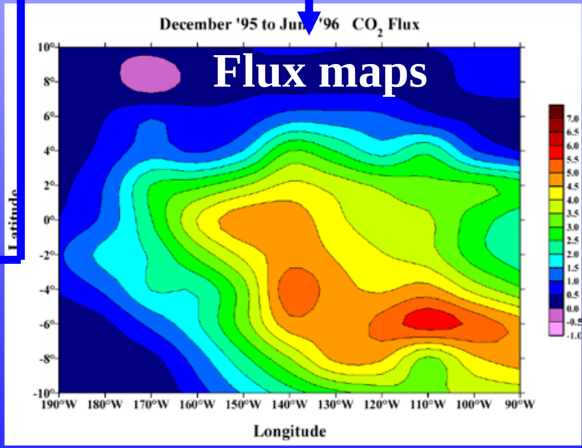
Flux = k s ΔpCO_2

Remote sensing
SST, color & wind
Soon SSS

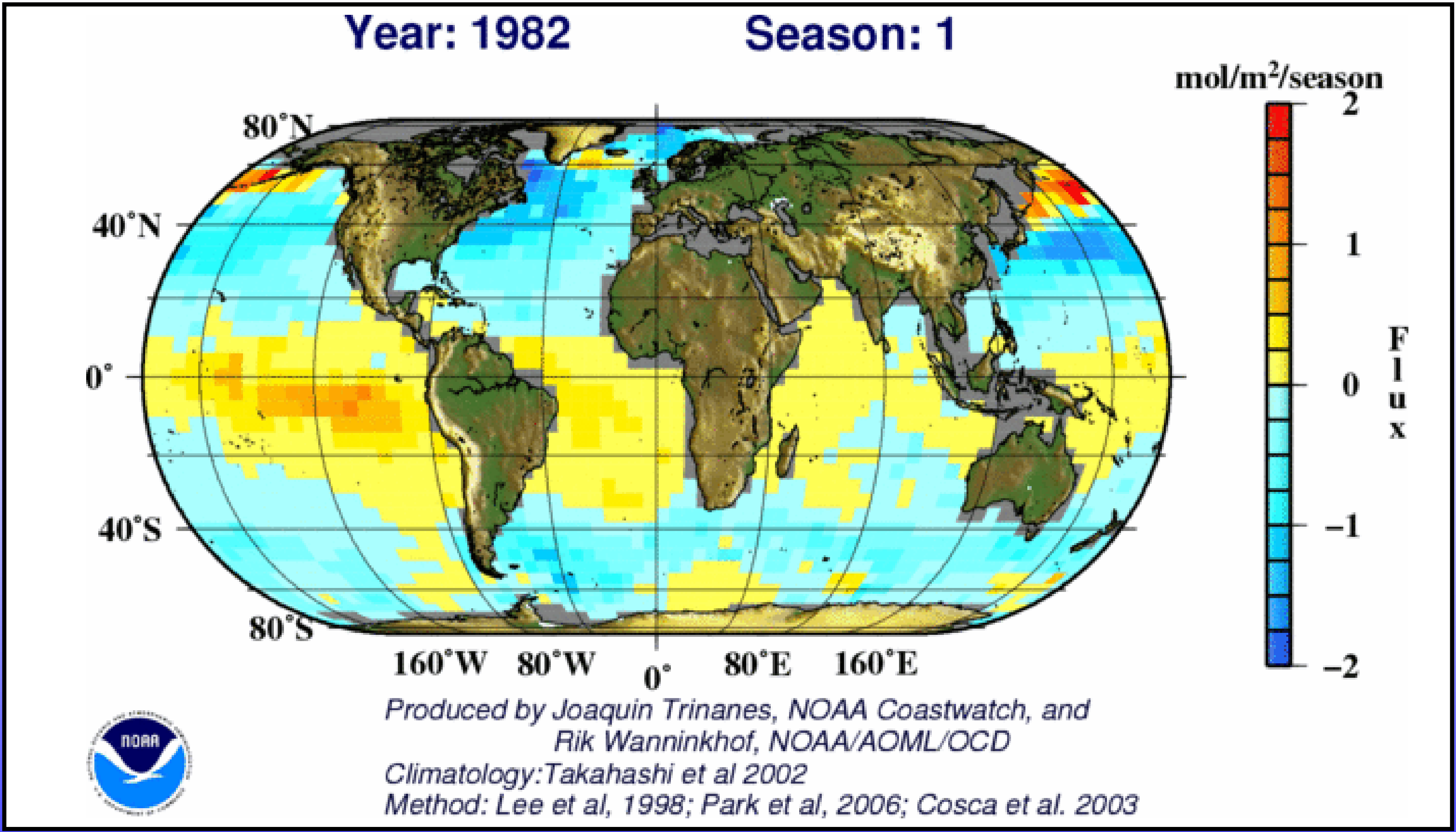
Regional satellite SST & *color* data

Wind data

Algorithm development
Gas transfer, k = f (U_{10},SST)



Global Flux Map suggests an interannual variability of 0.23 Pg C



Surface observations have large variability over a wide range of time and space scales making it very difficult to properly isolate the anthropogenic increases. Uptake of 2 Pg C yr^{-1} only requires a ΔpCO_2 of 8ppm.

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

Table 1. Summary of Recent Estimates of the Oceanic Uptake Rate of Anthropogenic CO_2 for the Period of the 1990s and Early 2000s

Method	Estimate ($Pg\ C\ a^{-1}$)	Time Period	Authors
Estimates Based on Oceanic Observations			
Ocean Inversion (10 models)	−2.2 ± 0.3	Nominal 1995	this study and Mikaloff - Fletcher et al. [2006]
Ocean Inversion (3 models)	−1.8 ± 0.4	Nominal 1990	Gloor et al. [2003]
Air-sea pCO_2 difference (adjusted)[a]	−1.9 ± 0.7	Nominal 2000[b]	Takahashi et al. [2008]
Air-sea pCO_2 difference (adjusted)[a,c]	−2.0 ± 60%	Nominal 1995	Takahashi et al. [2002]
Estimates Based on Atmospheric Observations			
Atmospheric O_2/N_2 ratio	−1.9 ± 0.6	1990–1999	Manning and Keeling [2006]
Atmospheric O_2/N_2 ratio	−2.2 ± 0.6	1993–2003	Manning and Keeling [2006]
Atmospheric O_2/N_2 ratio	−1.7 ± 0.5	1993–2002	Bender et al. [2005]
Atmospheric CO_2 inversions (adjusted)[a]	−1.8 ± 1.0	1992–1996	Gurney et al. [2004]
Estimates Based on Oceanic and Atmospheric Observations			
Air-sea ^{13}C disequilibrium	−1.5 ± 0.9	1985–1995	Gruber and Keeling [2001]
Deconvolution of atm. $\delta^{13}C$ and CO_2	−2.0 ± 0.8	1985–1995	Joos et al. [1999a]
Joint atmosphere-ocean inversion	−2.1 ± 0.2	1992–1996	Jacobson et al. [2007b]
Estimates Based on Ocean Biogeochemistry Models			
OCMIP-2 (13 models)	−2.4 ± 0.5	1990–1999	Watson and Orr [2003]
OCMIP-2 (4 "best" models)[d]	−2.2 ± 0.2	1990–1999	Matsumoto et al. [2004]

[a] Adjusted by 0.45 $Pg\ C\ a^{-1}$ to account for the outgassing of natural CO_2 that is driven by the carbon input by rivers.

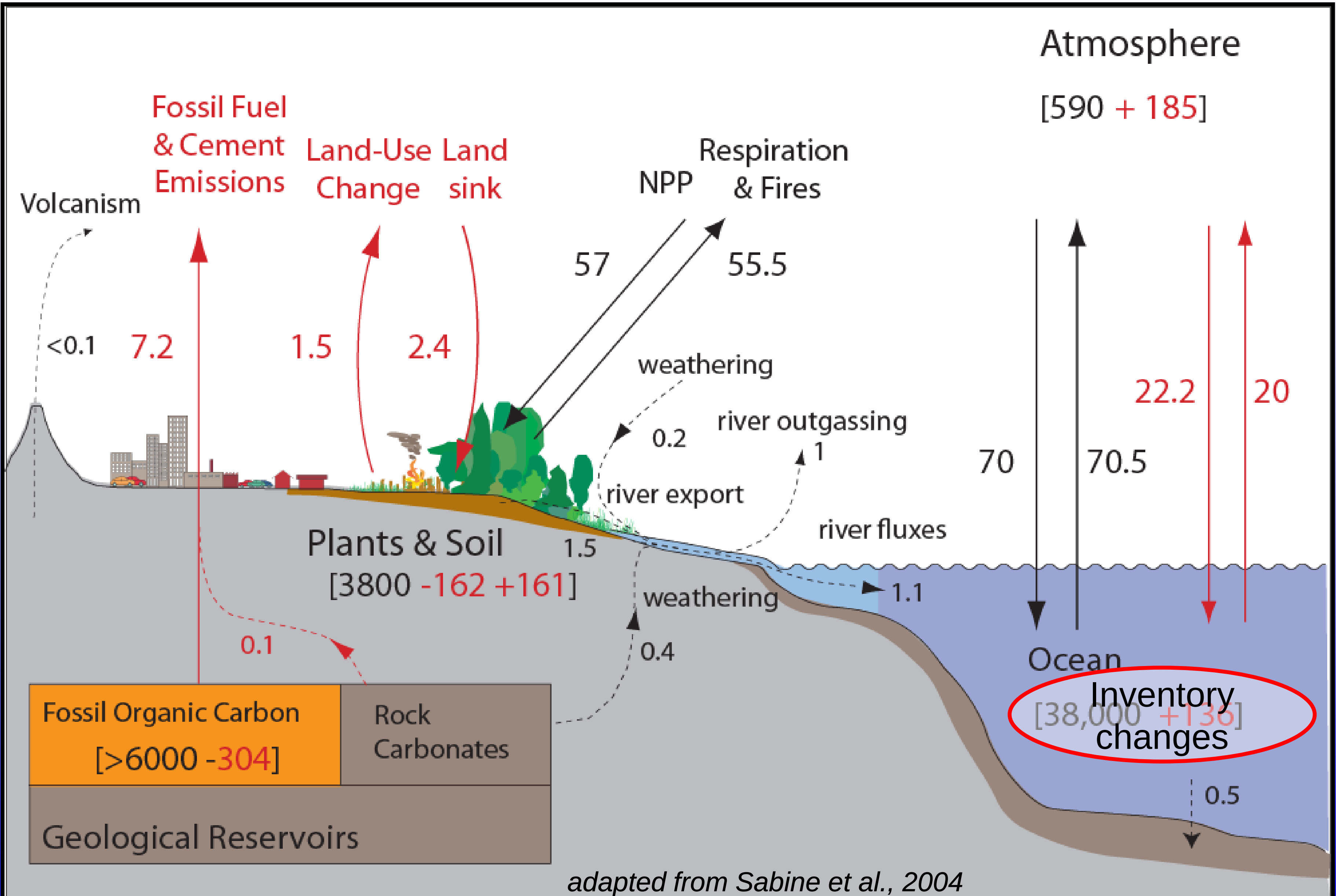
[b] The estimate for a nominal year of 1995 would be less than 0.1 $Pg\ C\ a^{-1}$ smaller.

[c] Corrected for wrong windspeeds used in published version; see http://www.ldeo.columbia.edu/res/pi/CO2/carbondioxide/pages/air_sea_flux_rev1.html.

[d] These models were selected on the basis of their ability to simulate correctly, within the uncertainty of the data, the observed oceanic inventories and regional distributions of chlorofluorocarbon and bomb radiocarbon.

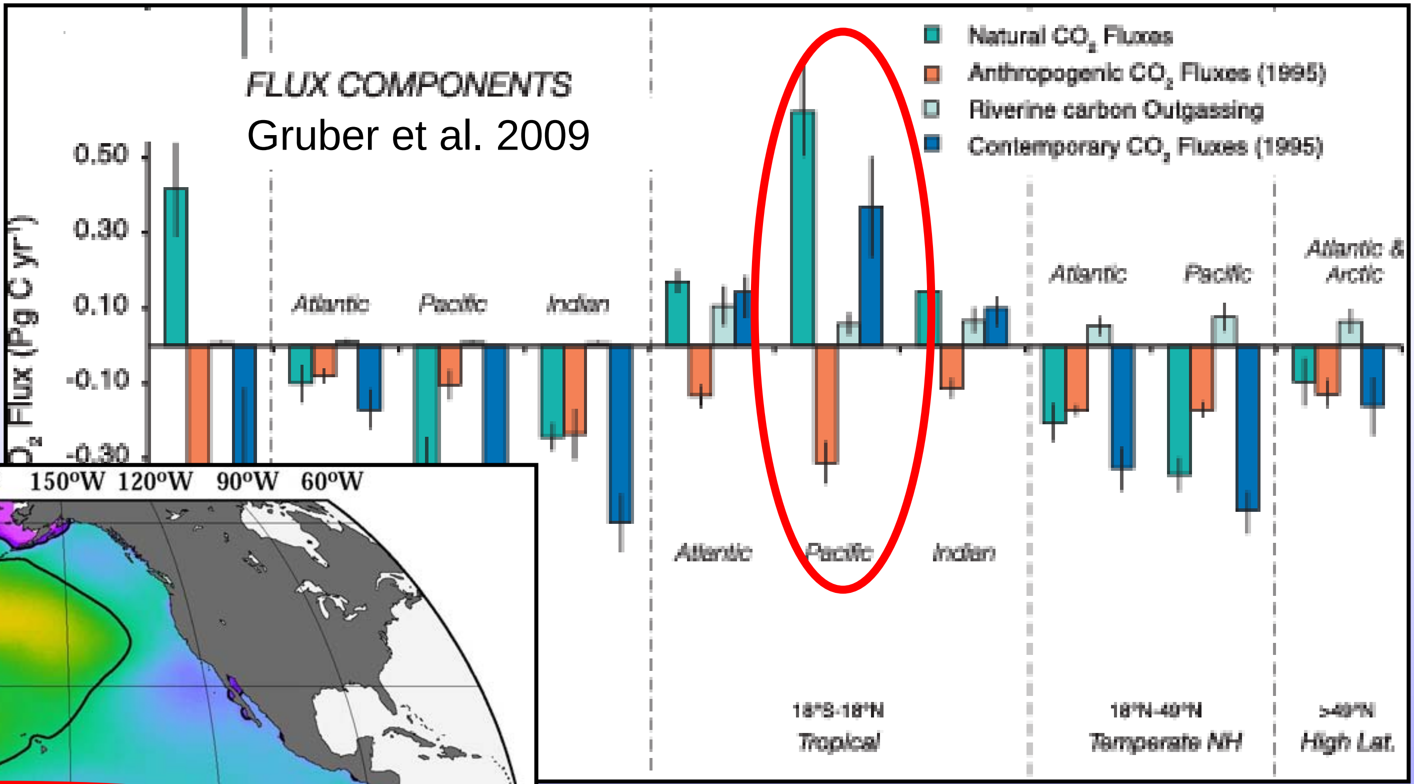
From Gruber et al., Glob. Biogeochem. Cy., V 23, doi:10.1029/2008GB003349, 2009

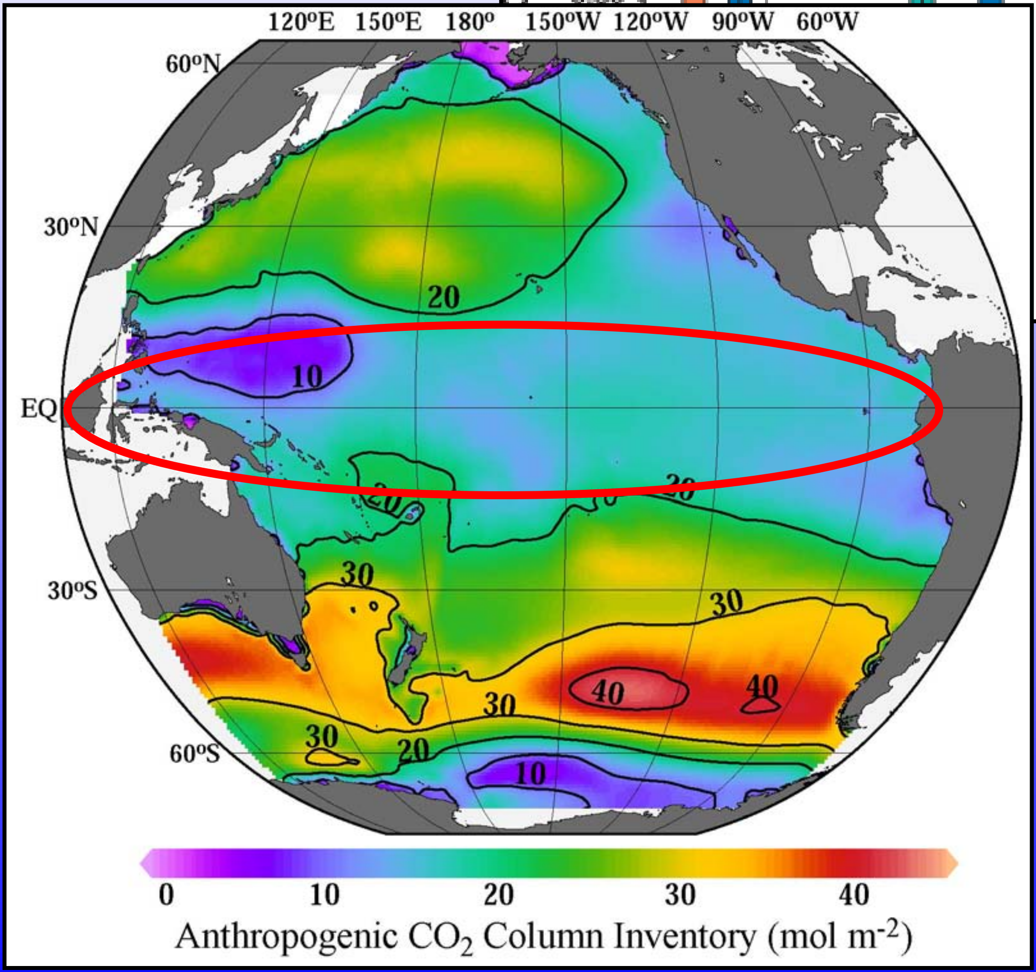
Global Carbon Budget for 2000-2005



adapted from Sabine et al., 2004

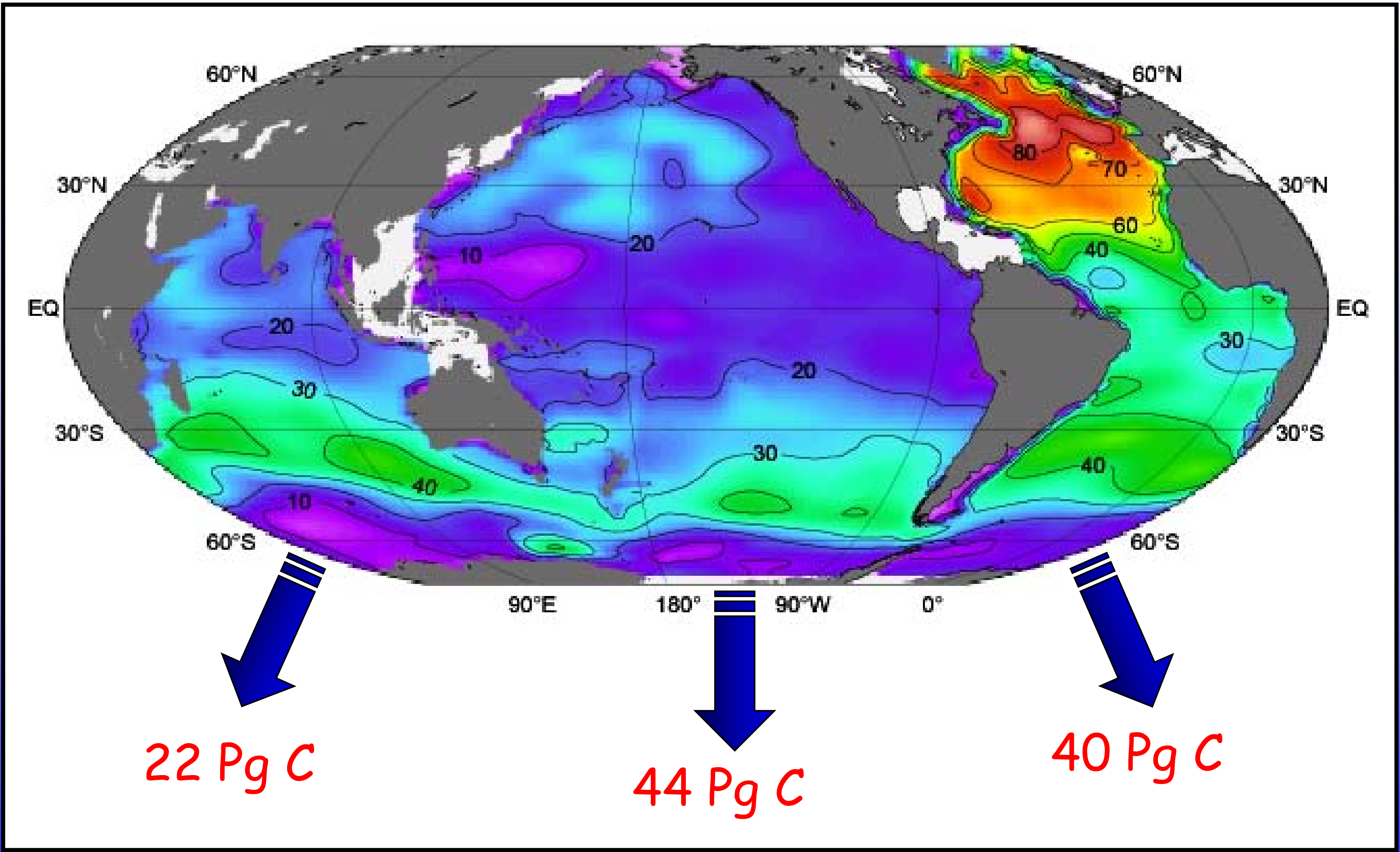
An example of the differences between uptake and storage can be found in the Tropical Pacific





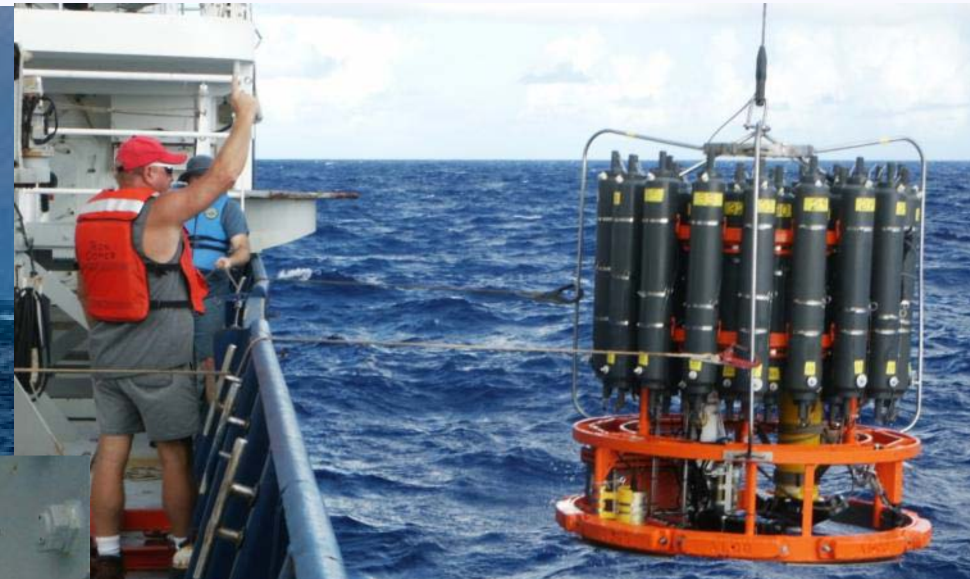
Tropical Pacific shows up as a significant sink for CO_2 despite the fact that net fluxes are out of the ocean and inventory estimates show a minimum near the equator

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

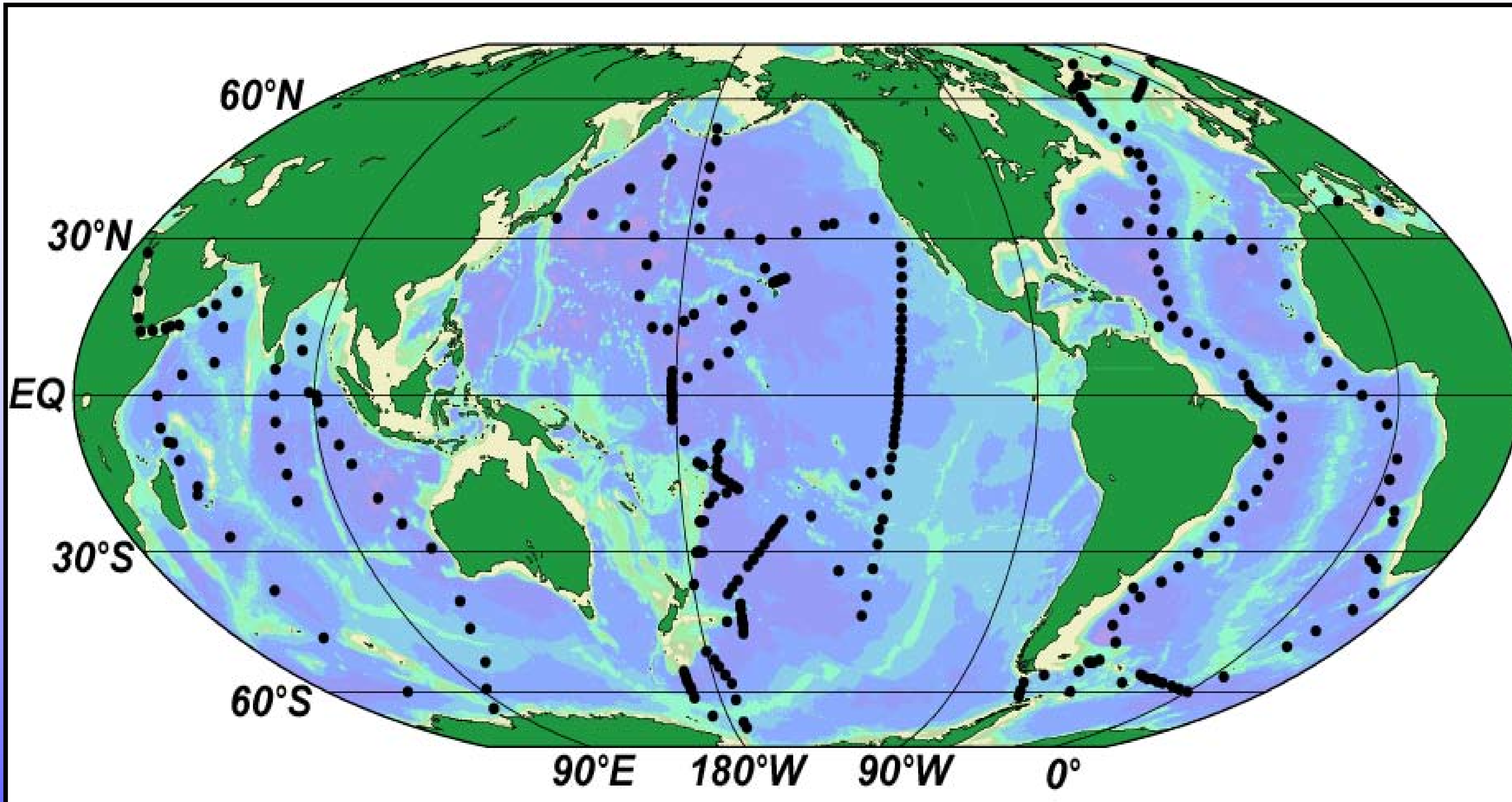


Mapped Inventory =106±17 Pg C; Global Inventory =118±19 Pg C

Shipboard Sampling for Ocean Carbon



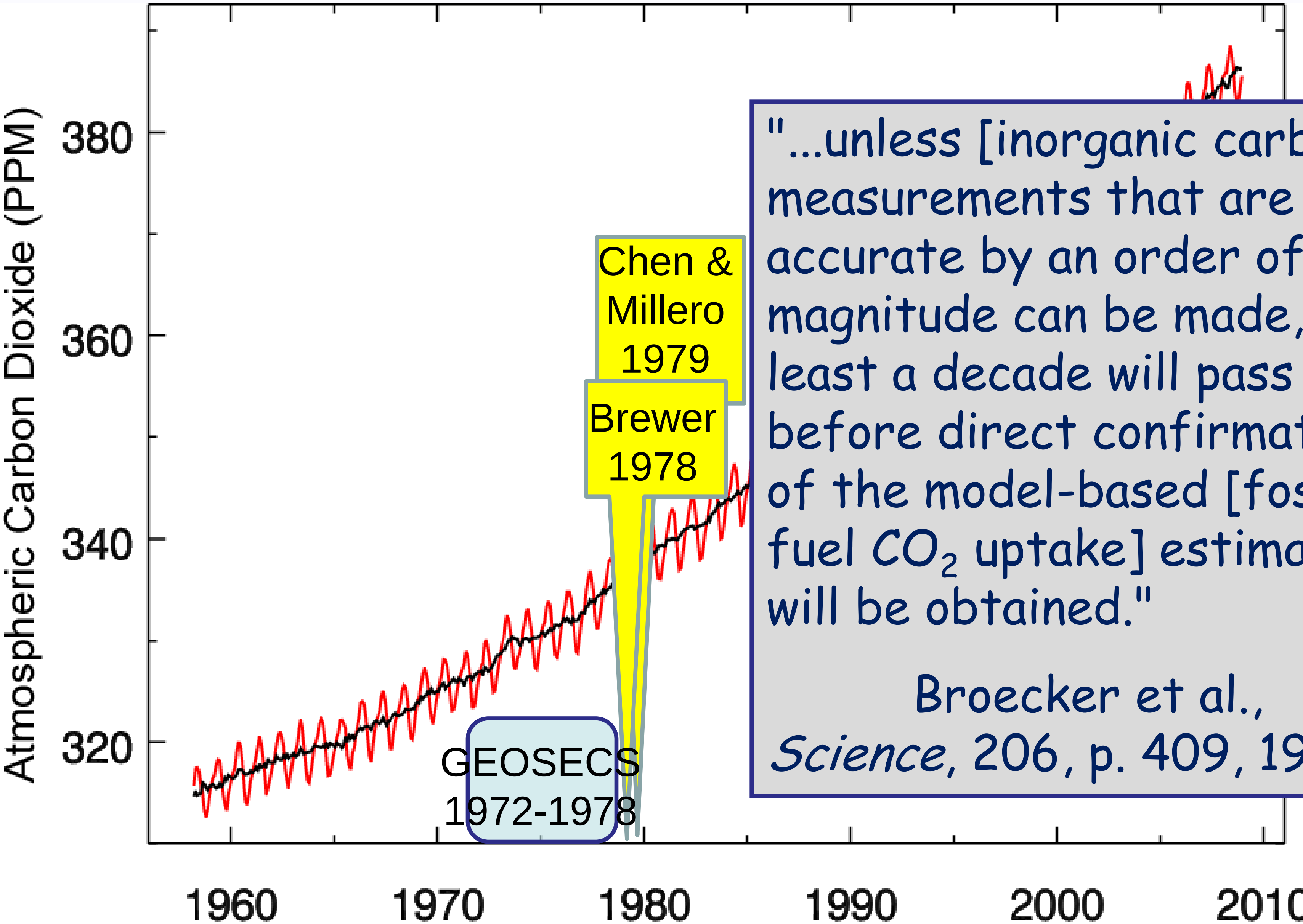
GEOSECS Station Locations



Much of our understanding of the modern ocean carbon cycle was based on the GEOSECS program of the 1970s.

6,037 carbon samples with a DIC uncertainty ~ 20 $\mu mol\ kg^{-1}$

GEOSECS: the first global, documented, high precision ocean carbon measurements

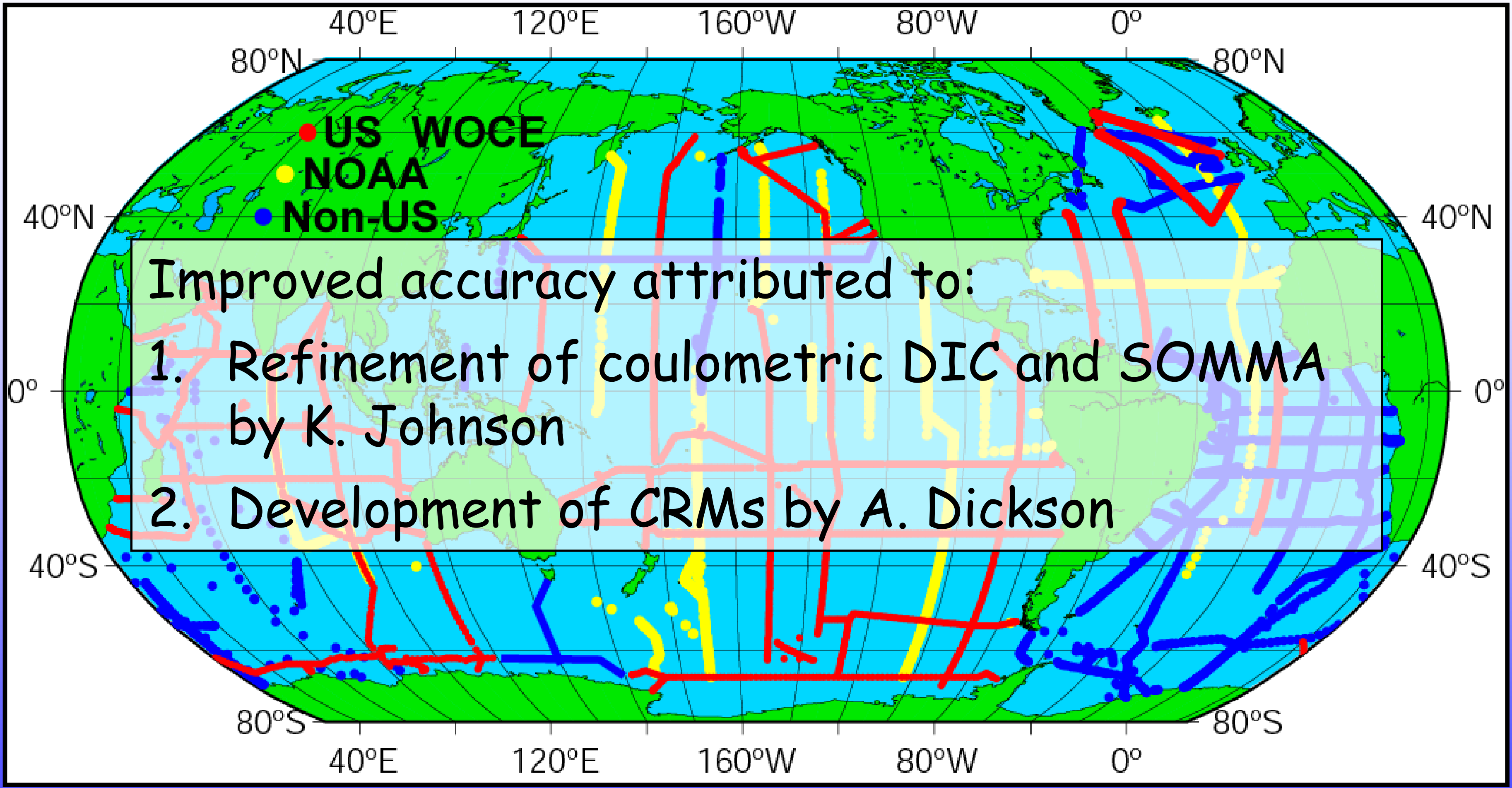


Atmospheric data from SIO and ESRL courtesy of P. Tans

"...unless [inorganic carbon] measurements that are more accurate by an order of magnitude can be made, at least a decade will pass before direct confirmation of the model-based [fossil fuel CO_2 uptake] estimates will be obtained."

Broecker et al., *Science*, 206, p. 409, 1979

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 global survey of CO_2 in the oceans.



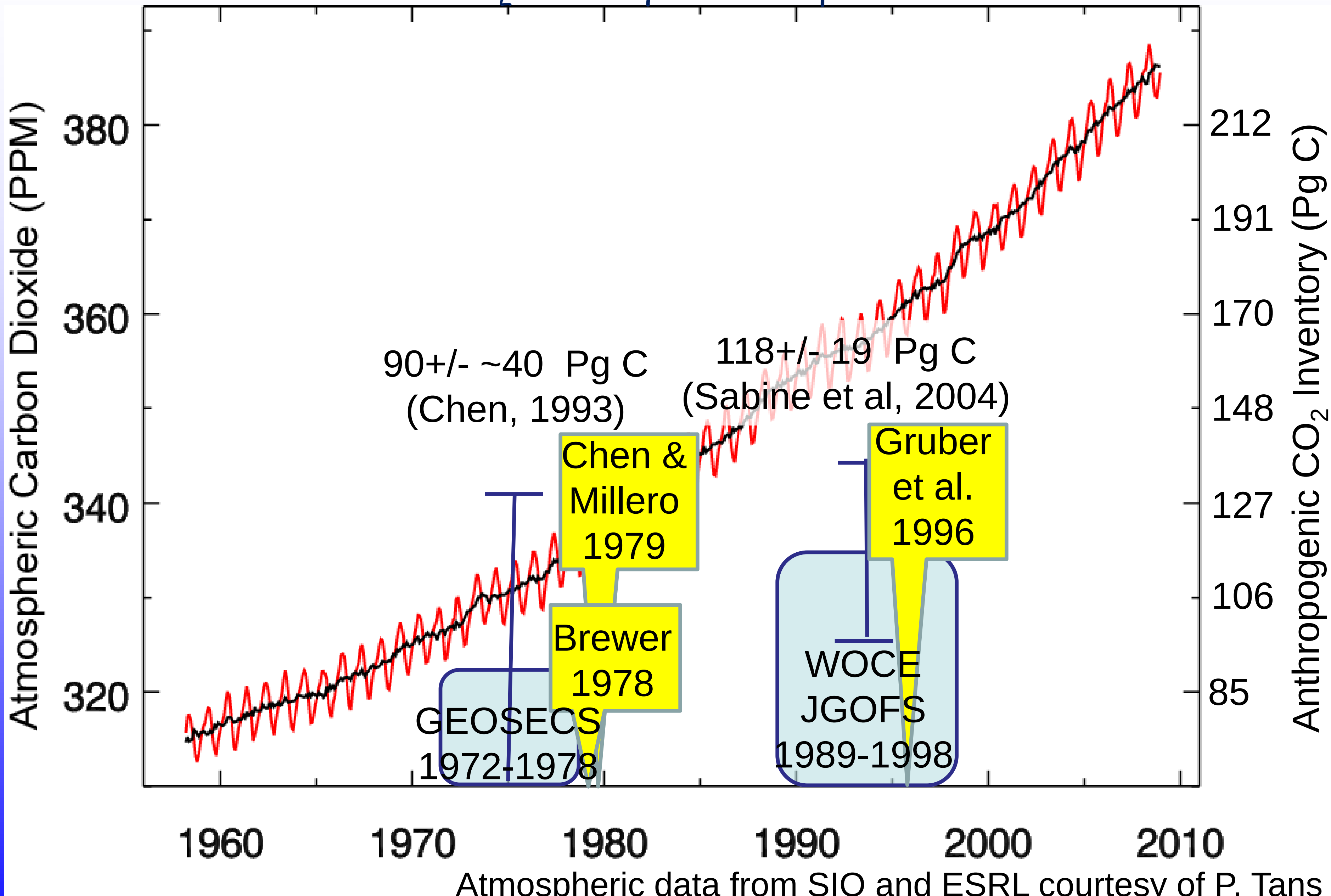
Improved accuracy attributed to:

1. Refinement of coulometric DIC and SOMMA by K. Johnson
2. Development of CRMs by A. Dickson

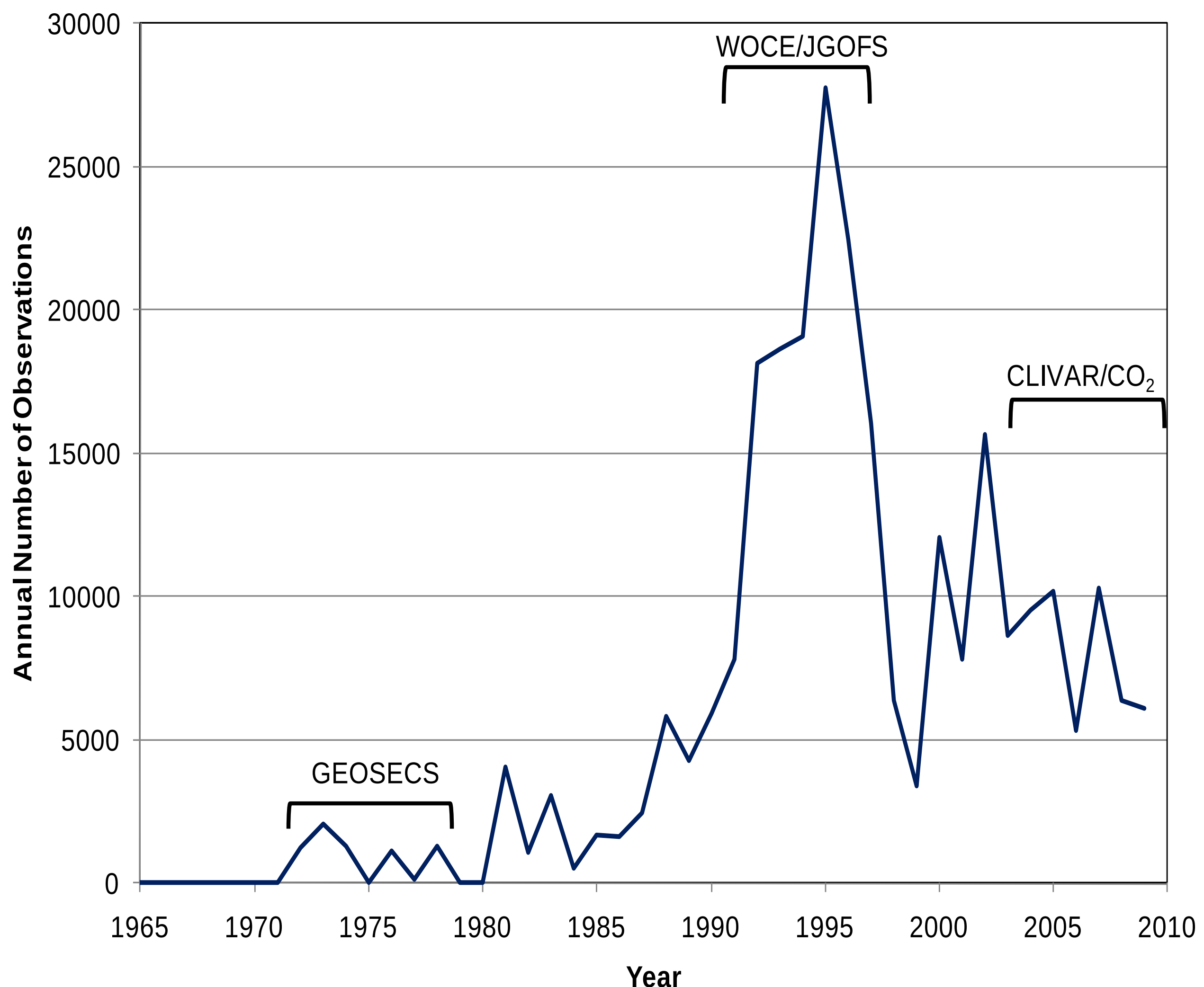
>70,000 sample locations; DIC ± 2 μmol kg^{-1}; TA ± 4 μmol kg^{-1}

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

It was almost 20 years later before an improved anthropogenic CO_2 technique developed



Global Interior Ocean Carbon Observations by Year

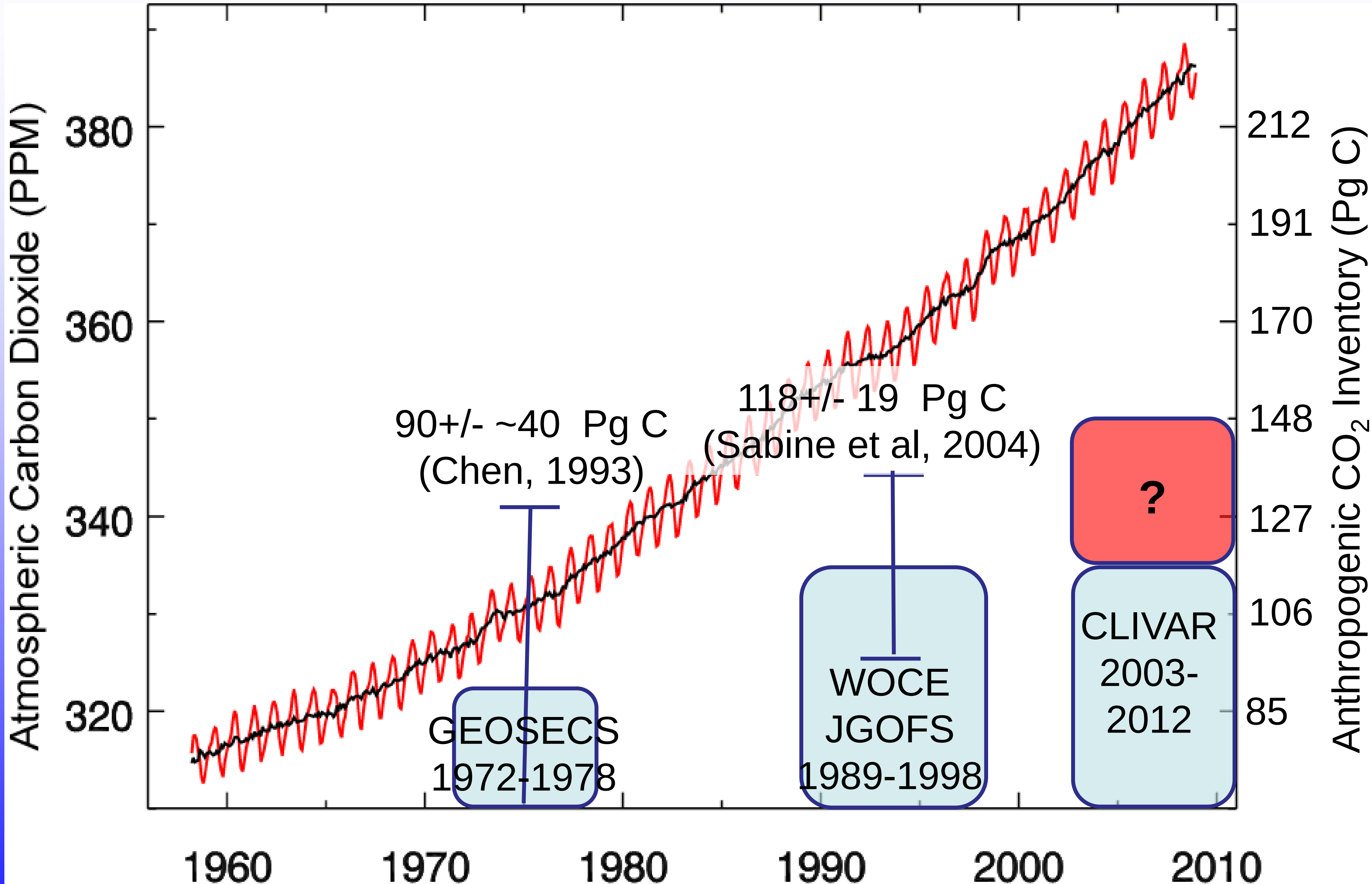


From Sabine et al., 2010

The WOCE/JGOFS period resulted in an unprecedented number of annual observations.

The CLIVAR/CO_2 program is making observations at 1/3 to 1/2 of the WOCE/JGOFS rate.

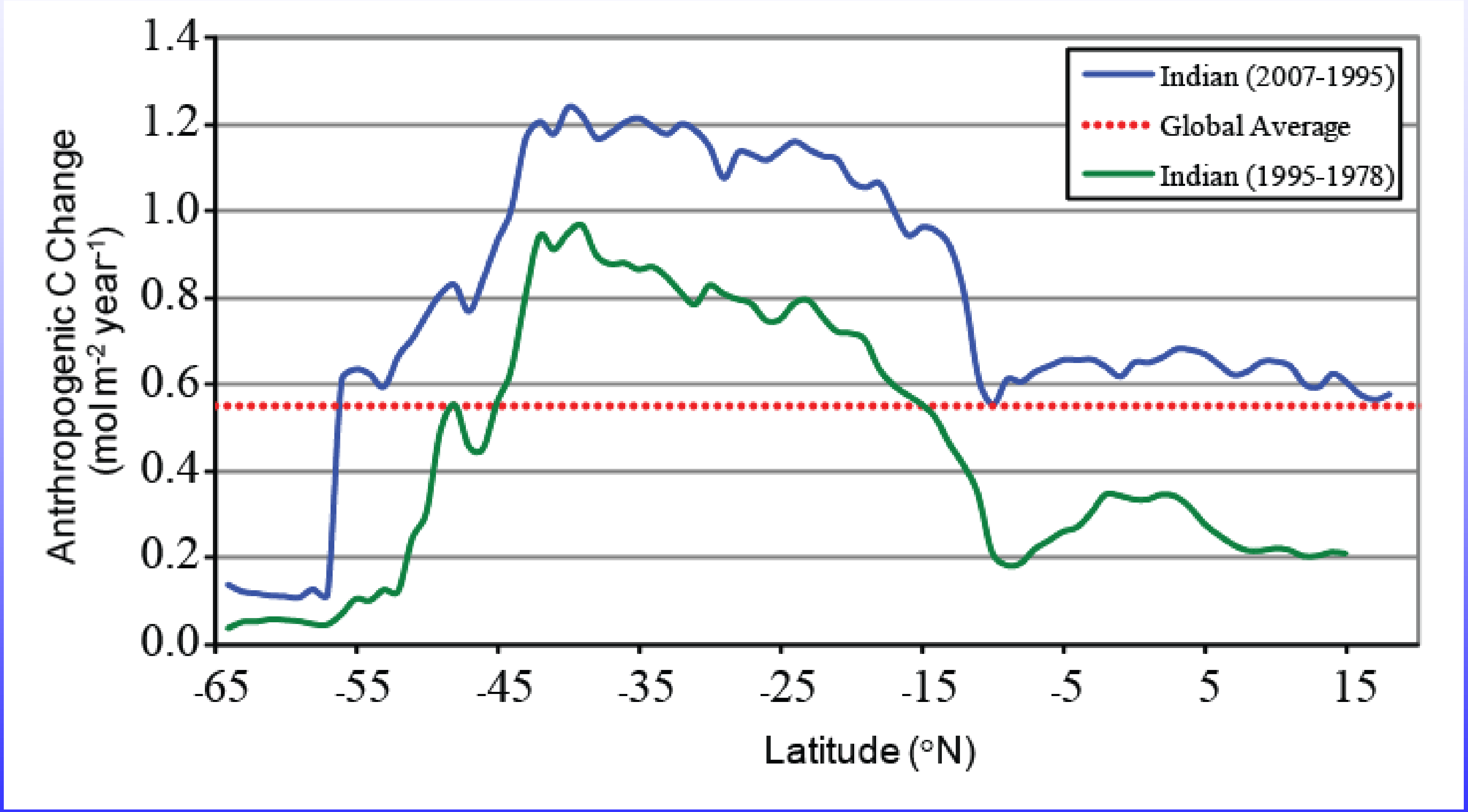
Moving beyond total carbon inventories…



Atmospheric data from SIO and ESRL courtesy of P. Tans

Comparison of the Change in Anthropogenic C Inventory over two decadal periods

Anthropogenic carbon inventory increases were higher at all latitudes over the last decade than the average increases between GEOSECS and WOCE



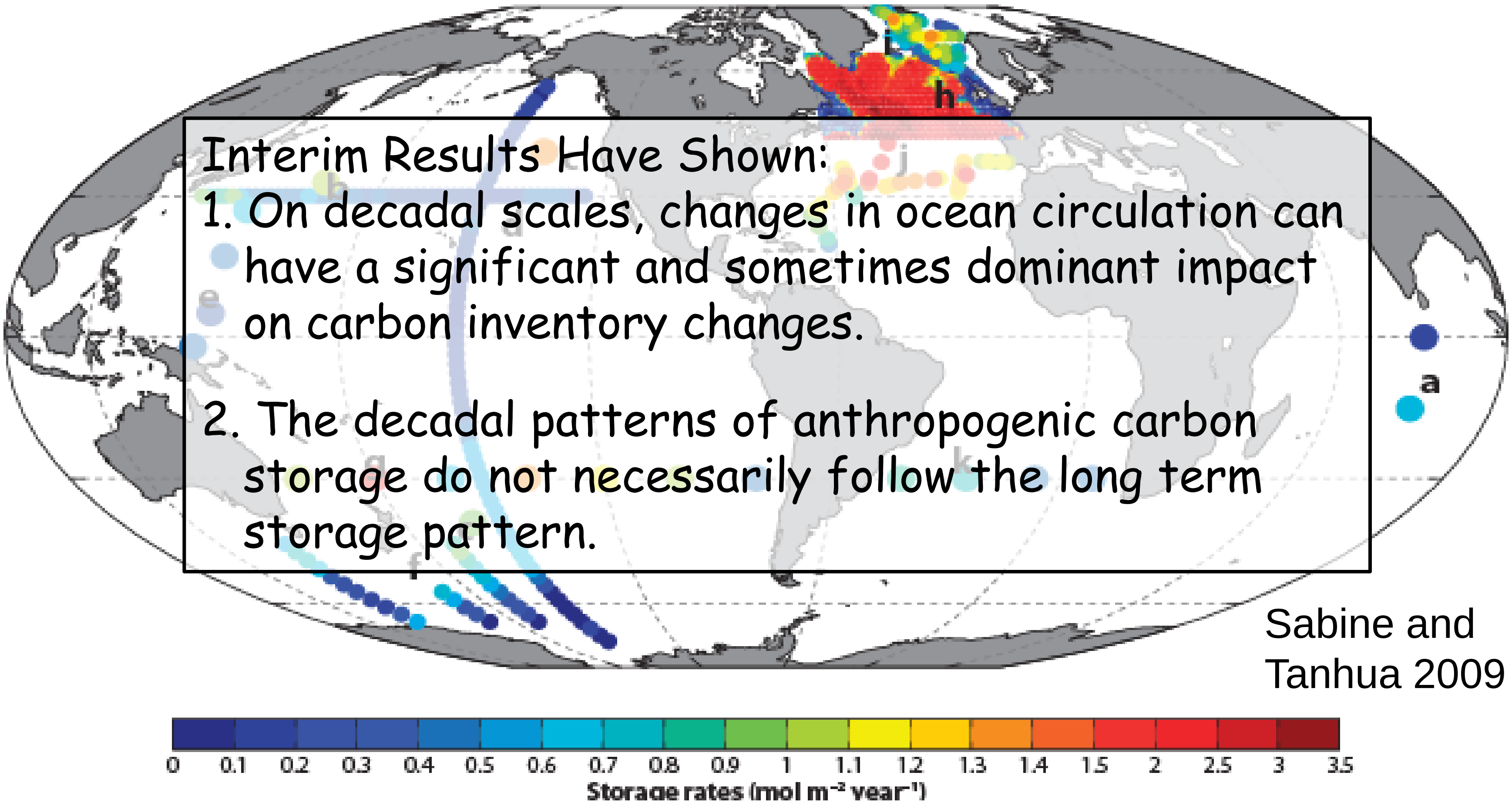
The GEOSECS-WOCE changes were re-evaluated using the exact same techniques used for the WOCE-CLIVAR changes for these calculations.

Individual assessments of decadal carbon changes all show increases the patterns of change are complicated

Interim Results Have Shown:

1. On decadal scales, changes in ocean circulation can have a significant and sometimes dominant impact on carbon inventory changes.

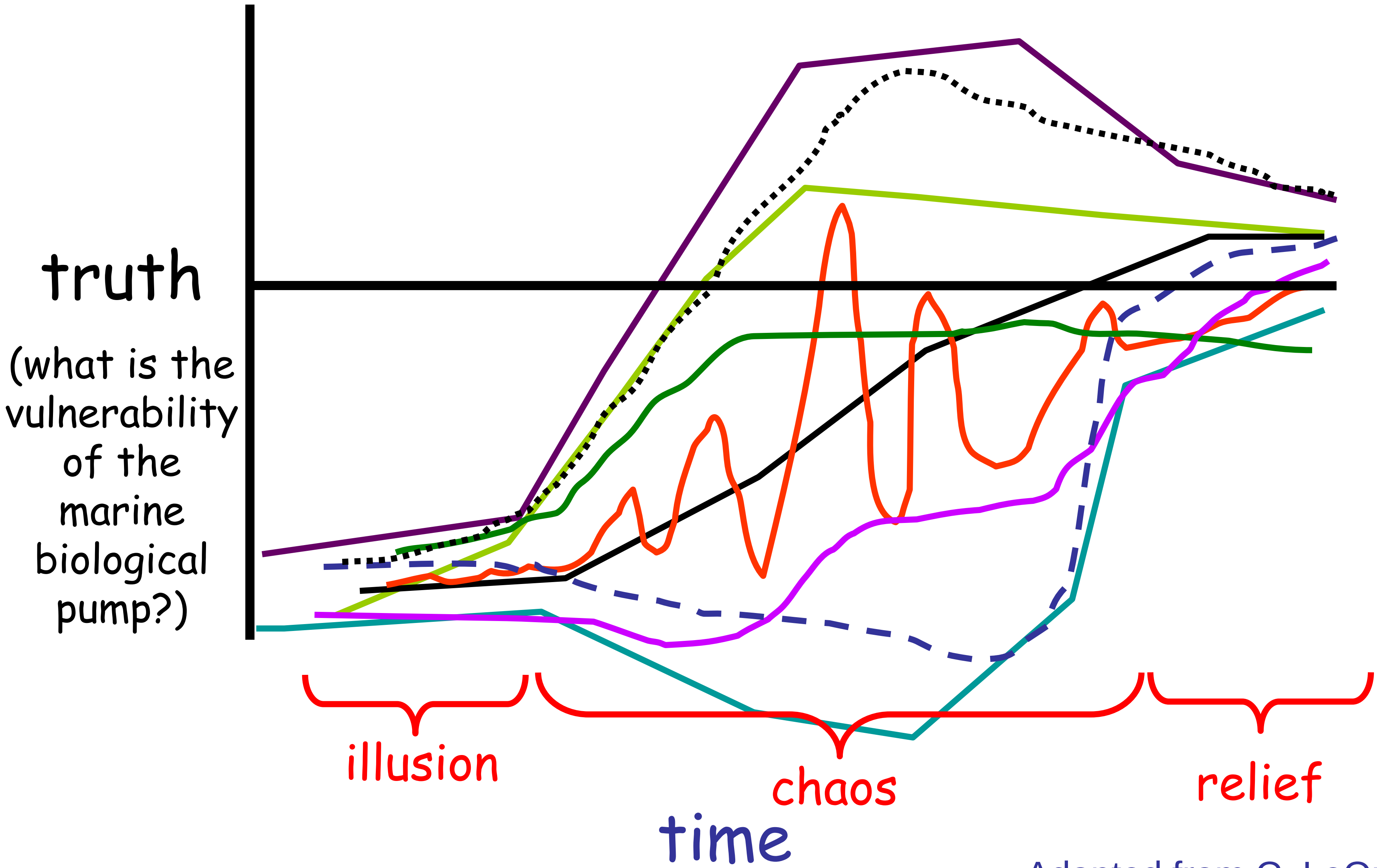
2. The decadal patterns of anthropogenic carbon storage do not necessarily follow the long term storage pattern.



Sabine and Tanhua 2009

#	Data from:	Time period	Method
a	(Peng et al 1998)	1978-1995	Isopycnal, O_2 adjusted
b	(Tsunogai et al 1993)	1974-1991	Column integrated change in preformed carbonte
c	(Peng et al 2003)	1973-1991	MLR
d	(Sabine et al 2008)	1991/2 – 2005/6	eMLR
		1994 - 2004	
e	(Murata et al 2009)	1993-2005	Isopycnal, O_2 adjusted
f	(Matear & McNeil 2003)	1968-1991/1996	MLR
g	(Murata et al 2007)	1992-2003	Isopycnal, O_2 adjusted
h	(Friis et al 2005)	1981-1997/99	eMLR
i	(Olsen et al 2006)	1981-2002/03	eMLR
j	(Tanhua et al 2007)	1981-2004	eMLR
k	(Murata et al 2008)	1992/93-2003	Isopycnal, O_2 adjusted

I believe we are in a situation similar to the model evolution proposed by Corinne LeQuere a few years back



Adapted from C. LeQuere

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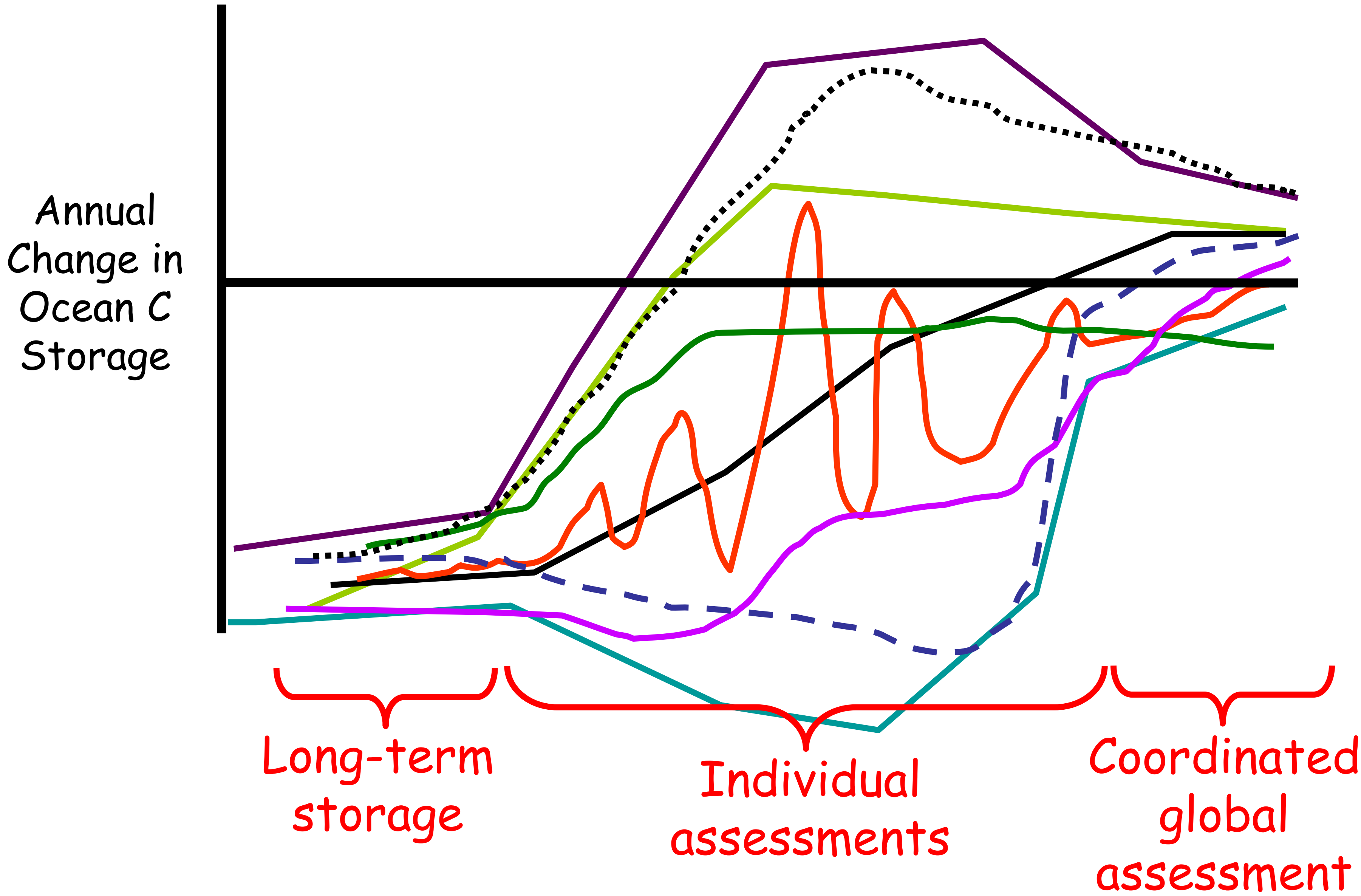
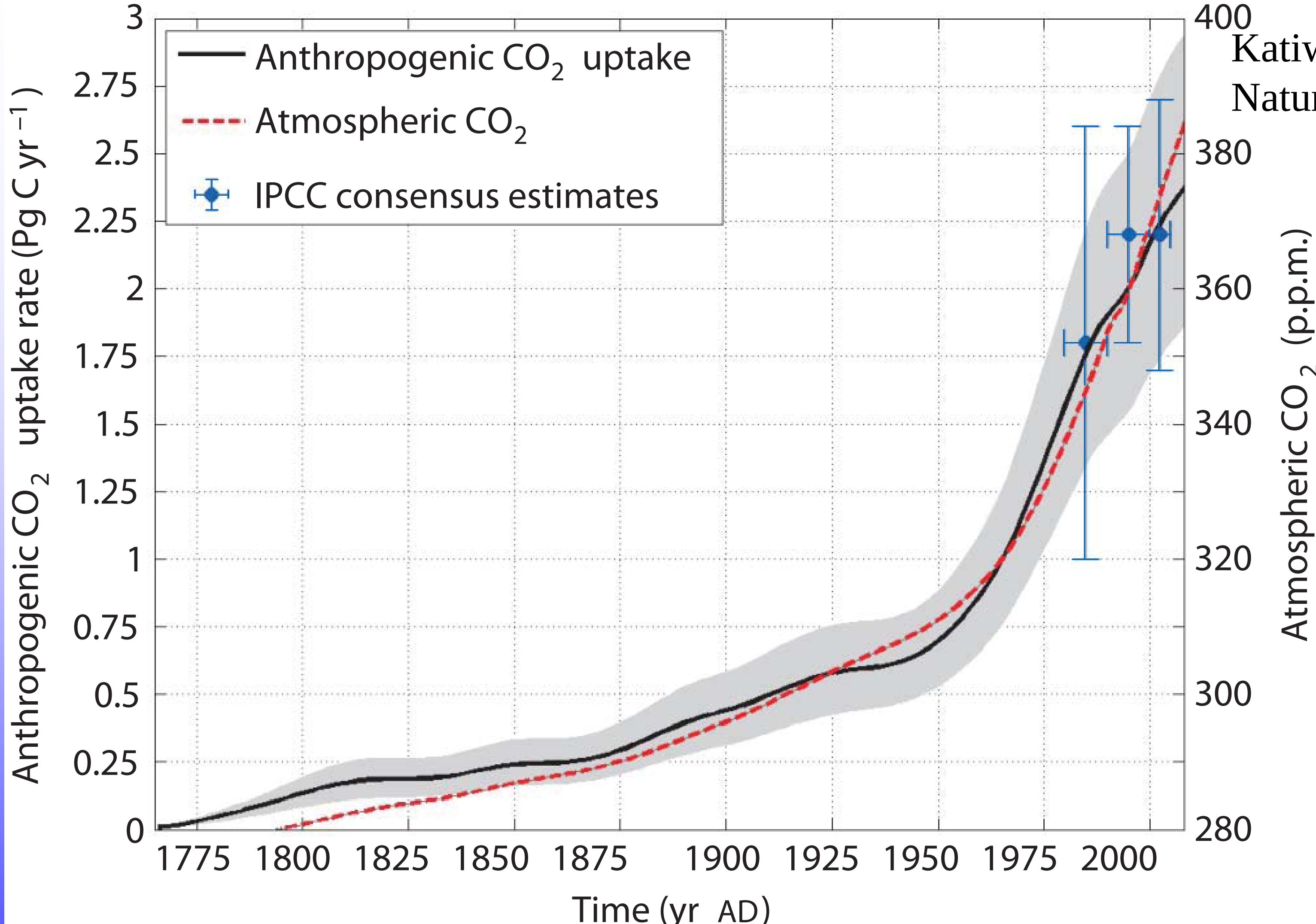
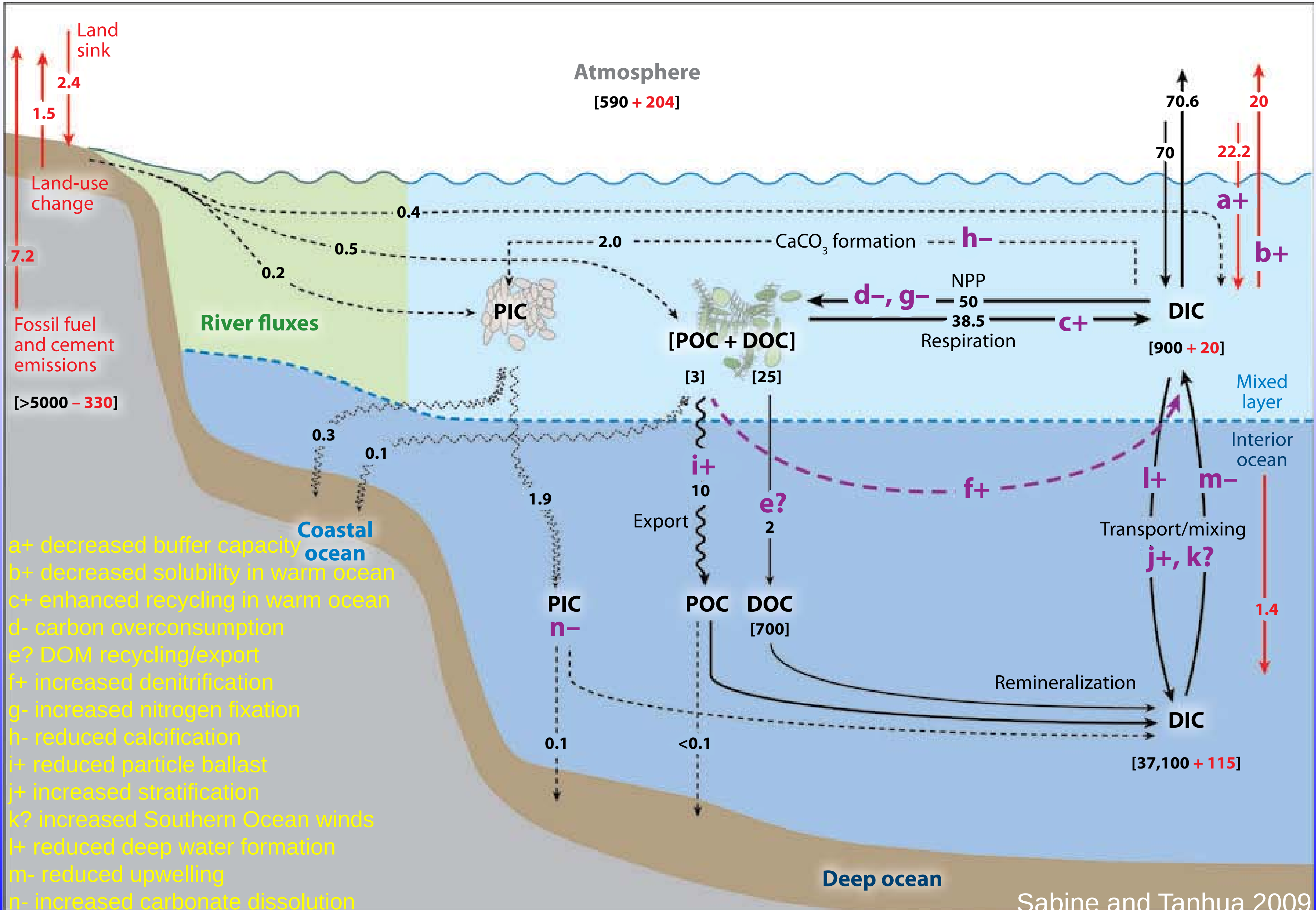




Katiwala et al., Nature, Nov. 2009

Figure 2 Anthropogenic carbon uptake rate from 1765 to 2008 (black solid line). The shaded area represents the error envelope (see Fig. 1 legend). Also shown are the decadal average uptake rates adopted by the IPCC fourth-assessment report (AR4)[4] (blue circles; vertical error bars are6 1 s.d. and horizontal error bars span the averaging period of years) and the atmospheric CO_2 mixing ratio[29] used for the inversion (red dashed line).

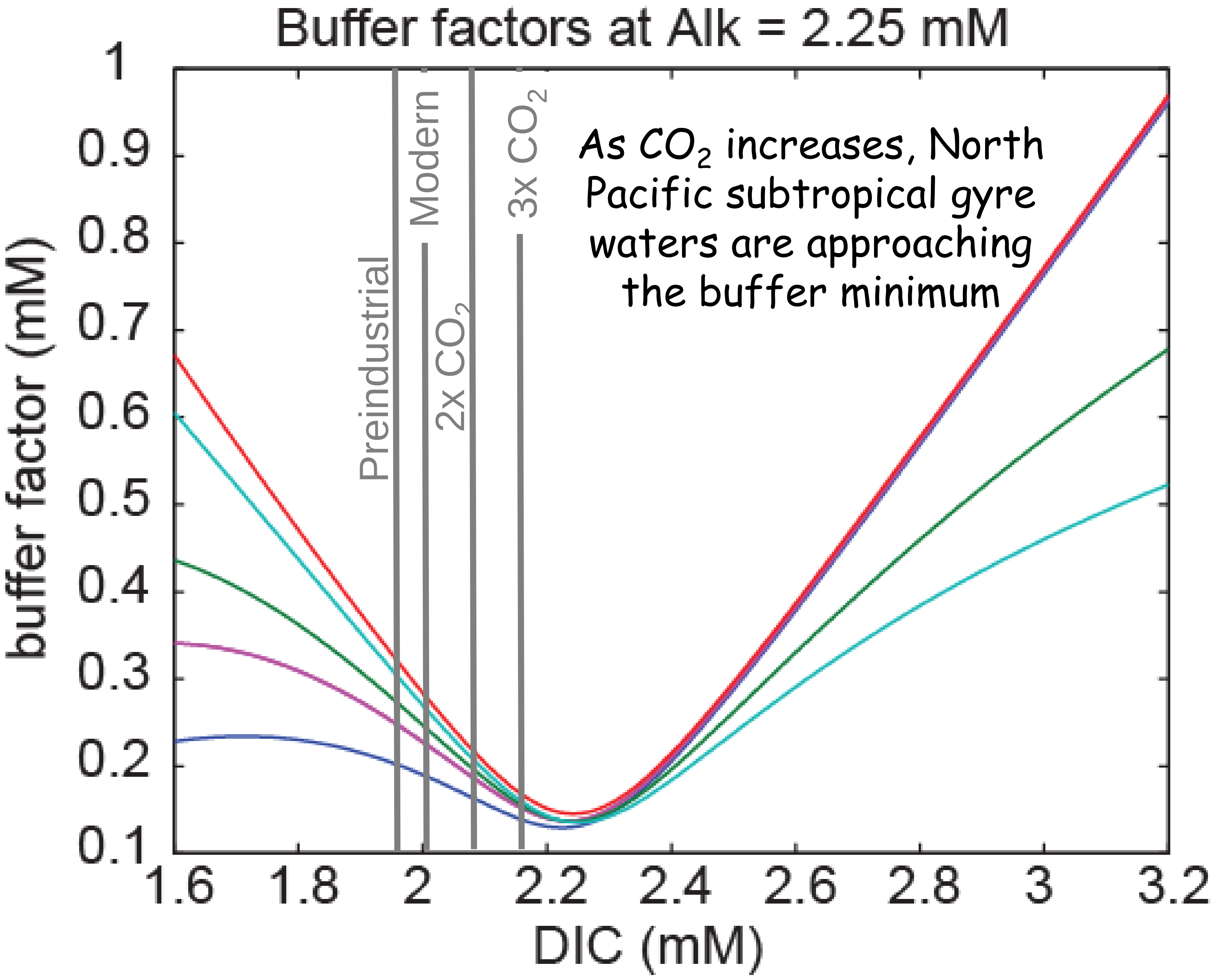
Feedbacks



a+ decreased buffer capacity
b+ decreased solubility in warm ocean
c+ enhanced recycling in warm ocean
d- carbon overconsumption
e? DOM recycling/export
f+ increased denitrification
g- increased nitrogen fixation
h- reduced calcification
i+ reduced particle ballast
j+ increased stratification
k? increased Southern Ocean winds
l+ reduced deep water formation
m- reduced upwelling
n- increased carbonate dissolution

Sabine and Tanhua 2009

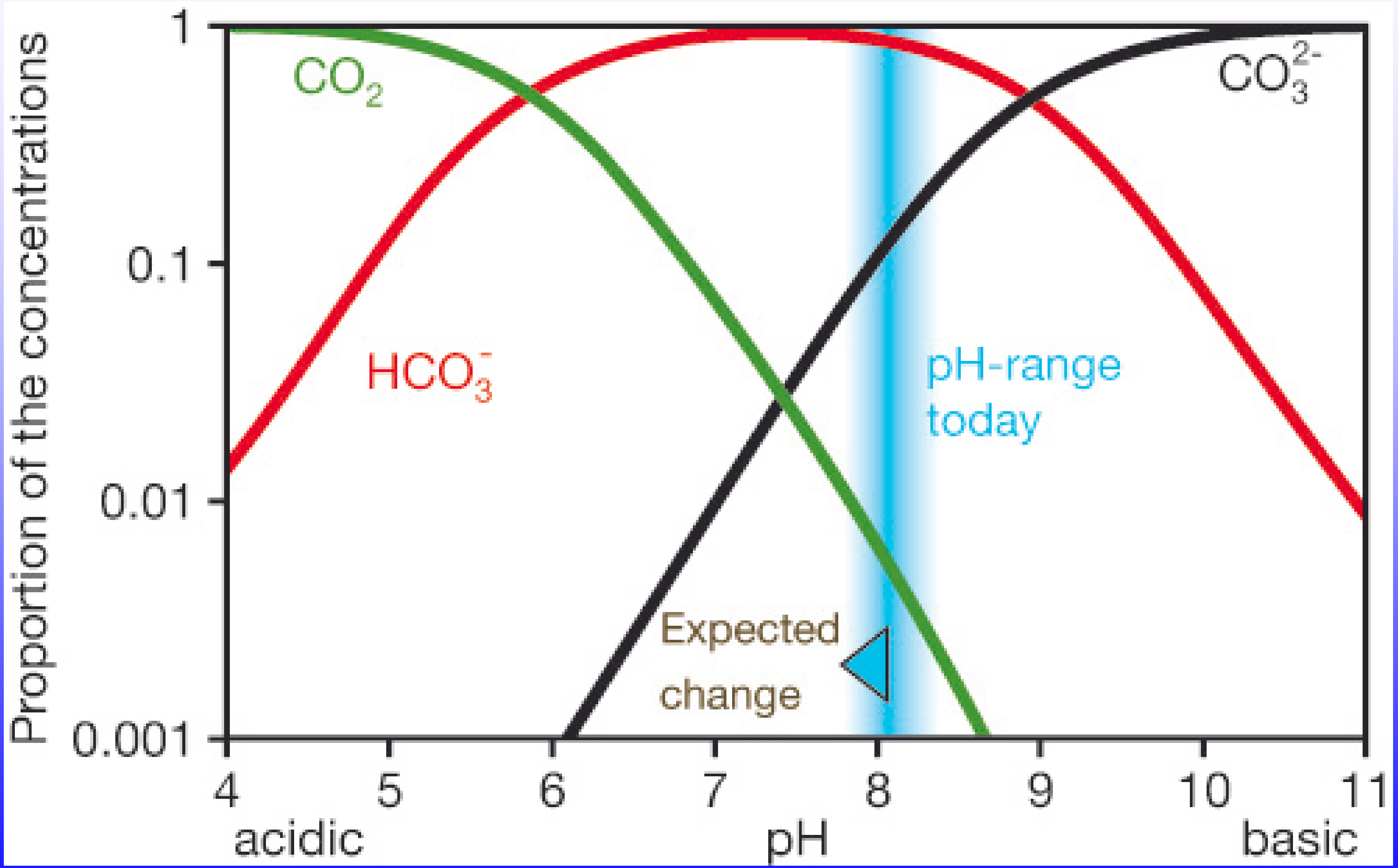
All Buffer Factors show a minimum where DIC=Alk



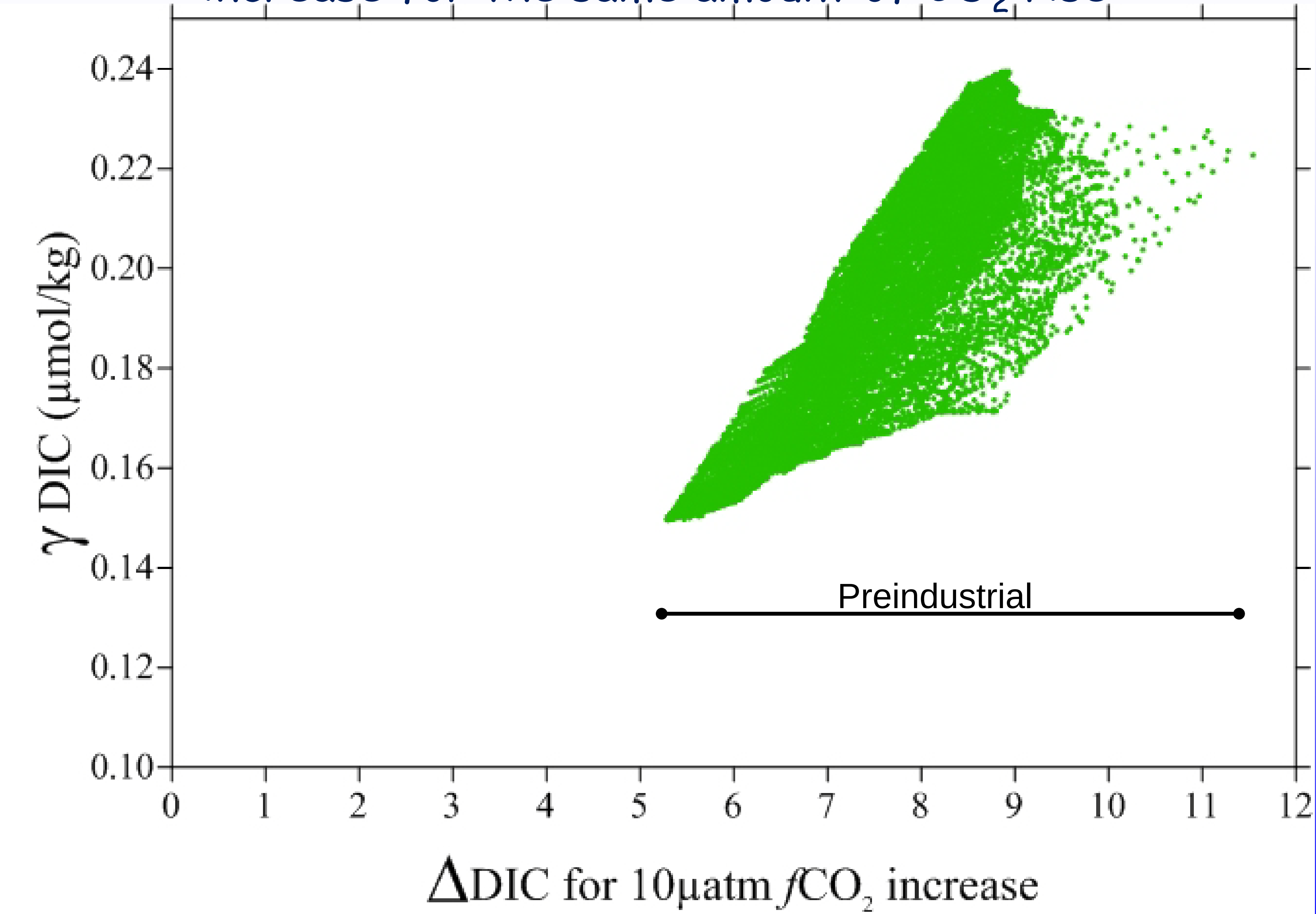
Egleston et al. (GBC, 2010)

$$CO_{2(aq)} + H_2O + CO_3^{2-} \longleftrightarrow 2HCO_3^-$$

$$CO_{2(aq)} + H_2O \longleftrightarrow HCO_3^- + H^+$$



Higher buffer factor means larger DIC increase for the same amount of CO_2 rise



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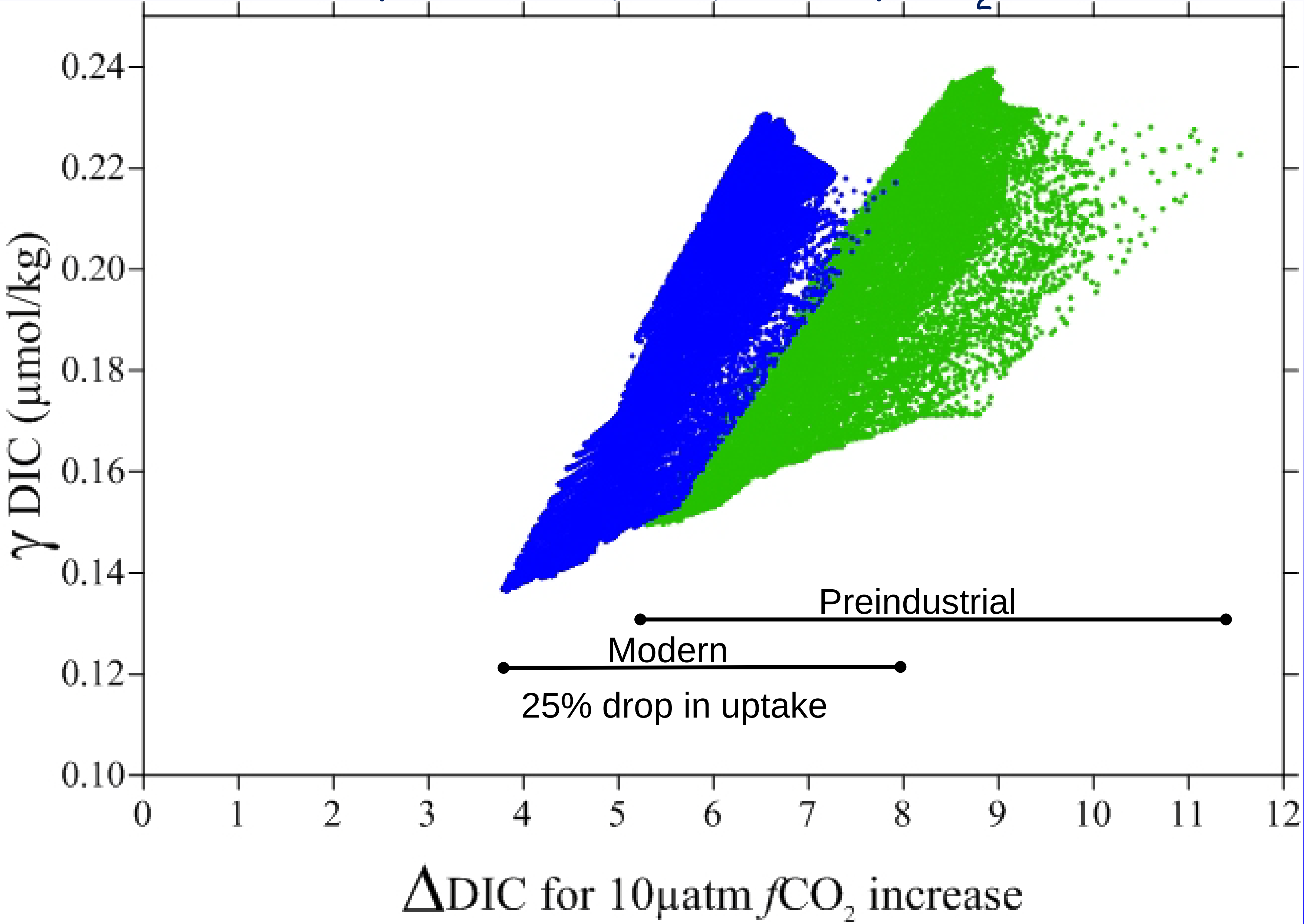

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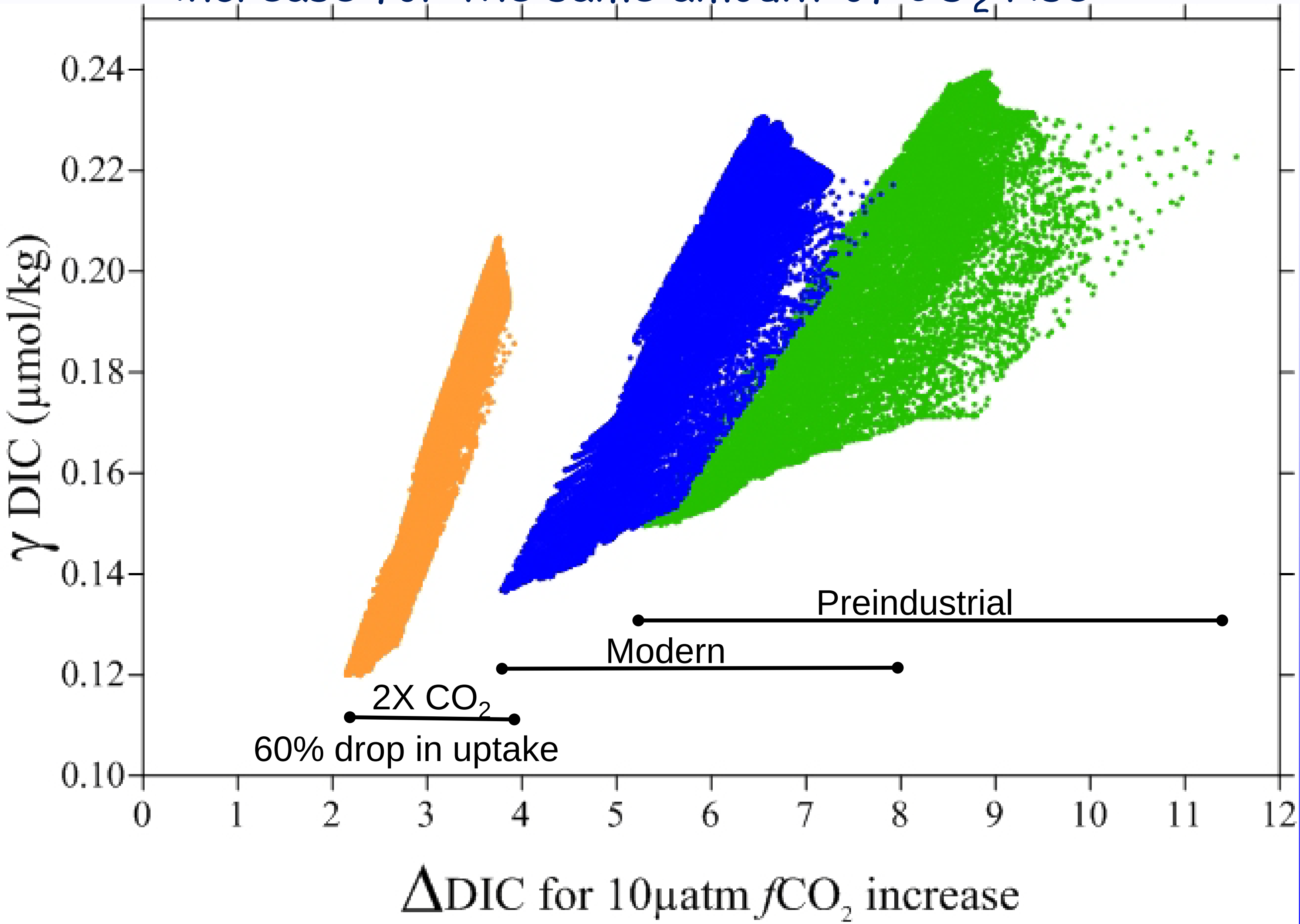

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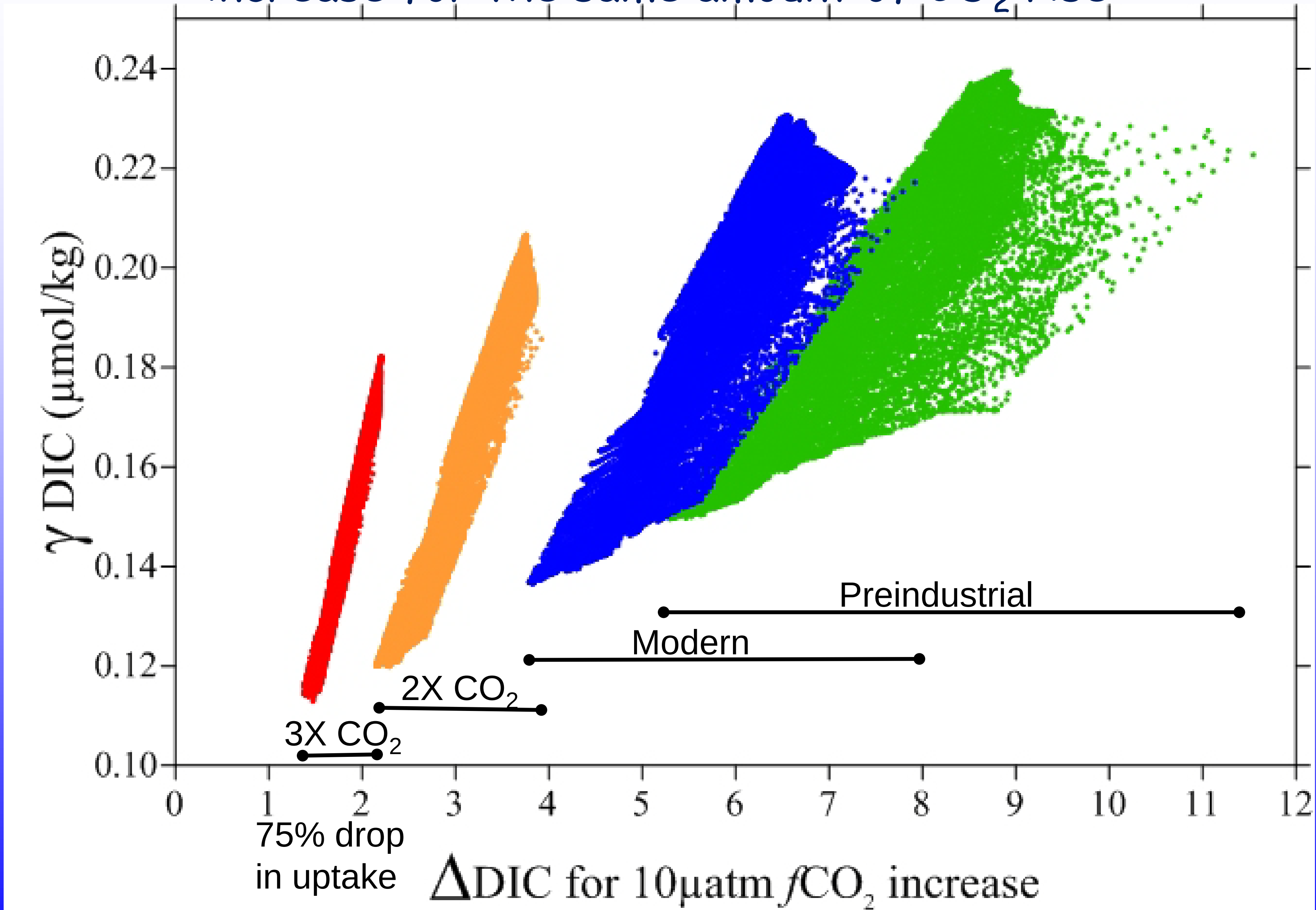

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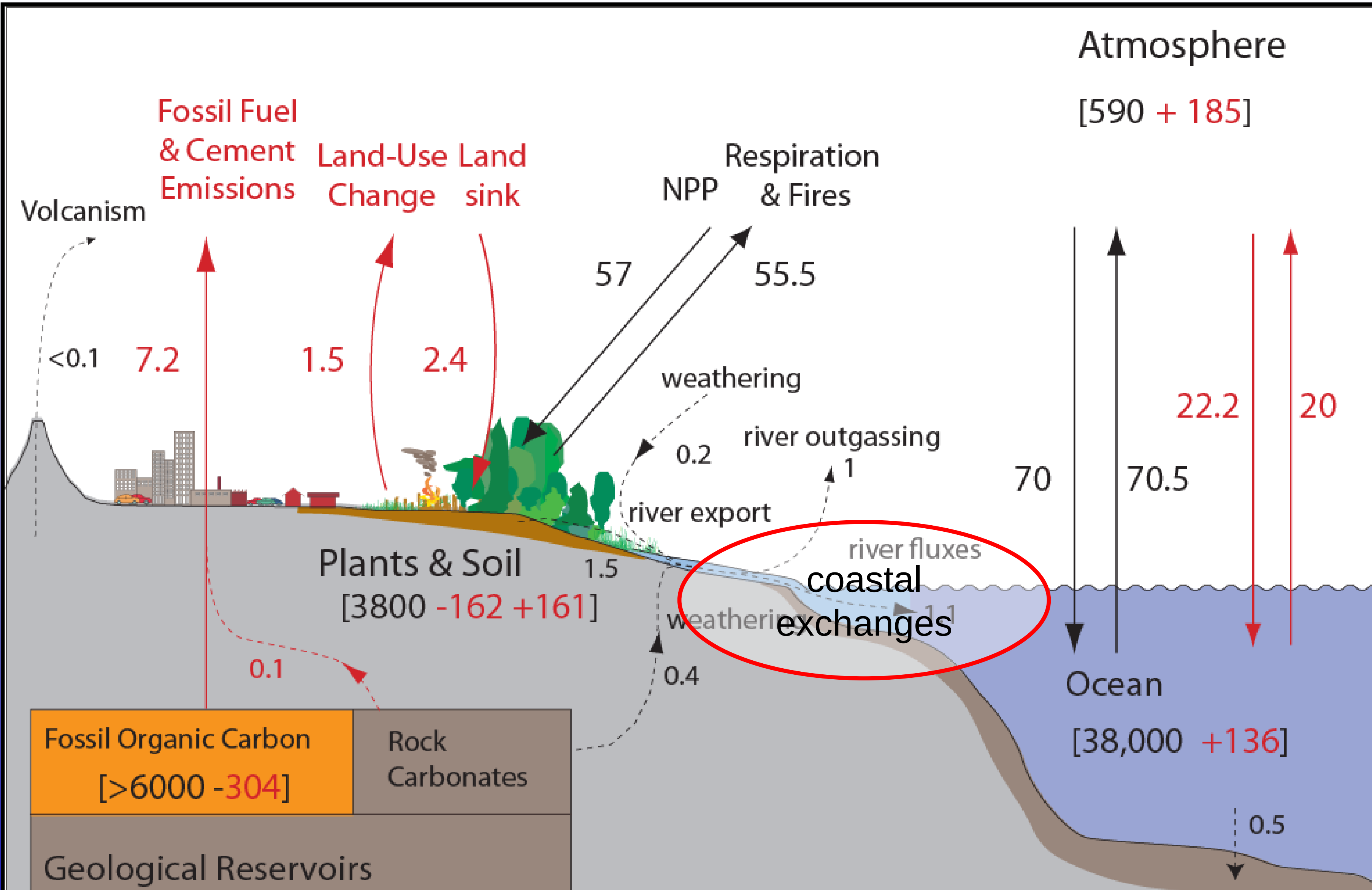

adapted from Sabine et al., 2004

Summary and Challenges

-Surface ocean observations and modeling are increasing and improving our ability to constrain the air-sea fluxes (uptake)

*This is still being done in an ad hoc manner and we will not be able to reach needed accuracy without better coordination and embracing new technologies

- Ocean interior measurements and modeling (inventories) compliment the uptake estimates and provide information on feedbacks

* These observations are personnel and infrastructure intensive thus they are not well supported with their current funding through research

- Coastal exchanges are not well understood

* Currently there is no coordinated effort to improve our understanding

- The above observing systems may also be able to address verification of ocean carbon capture and storage approaches

* However, the current programs are not optimized for this.