Large-Scale* Time Series of Changes in the Ocean Carbon Cycle

Repeat Hydrography

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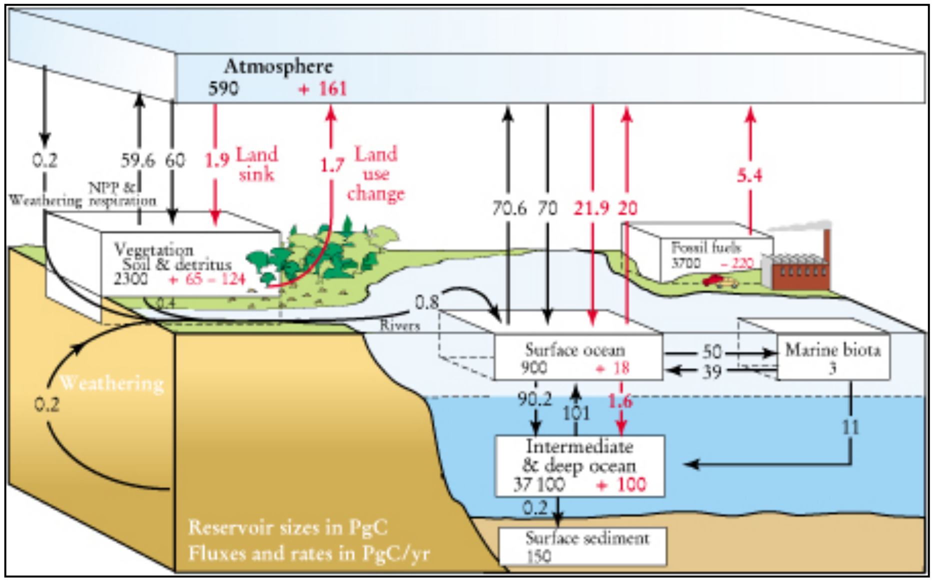
Outline

- Motivation
- Campaigns, Data and Accuracy
- Snapshots of change
  - -Natural variability
  - -Climate impacts
  - -Anthropogenic CO_2 invasion
- Models: Looking into past and future
- Closing thoughts

*: Large Scale = > multi-annual time scale
> regional

Motivation

1. Quantify anthropogenic CO_2 inventory in the ocean and how it is changing over time



Sarmiento, J. L., and Gruber, N., 2002,

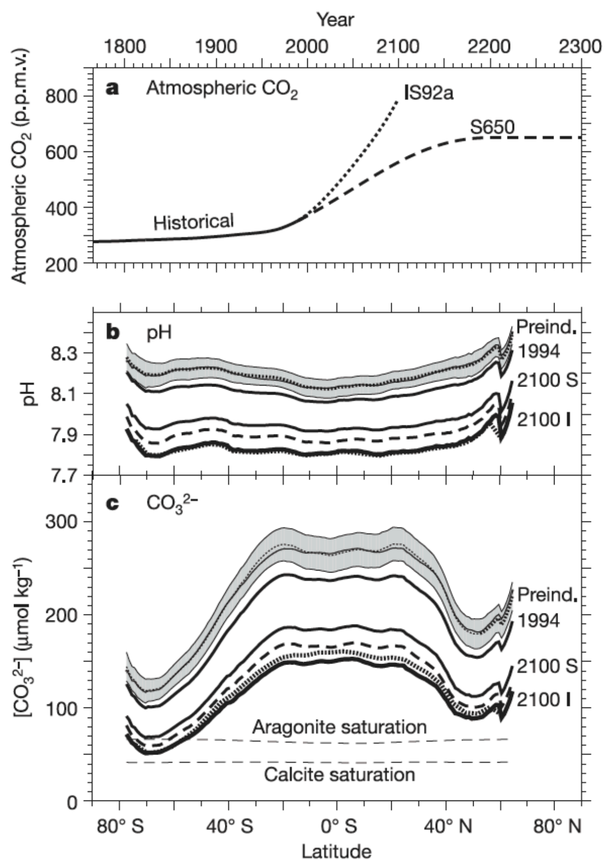
- Currently about 25 % of the anthropogenic carbon is taken up by the ocean
- The ocean always has and always will take up a significant proportion of the excess atmospheric carbon but exact amount is not well known.
- Ocean uptake is modeled is a simple fashion: Uptake = ø Excess
- Uncertainty in ocean carbon cycle is manifested by our inability to definitively attribute cause of atm. CO_2 change during ice age

Motivation

2. Quantify changes in the upper ocean and how it impacts ocean ecology

Ocean acidification: $CO_2 + H_2O = H^+ + HCO_3^-$

$H^+ + CO_3^{2-} = HCO_3^-$



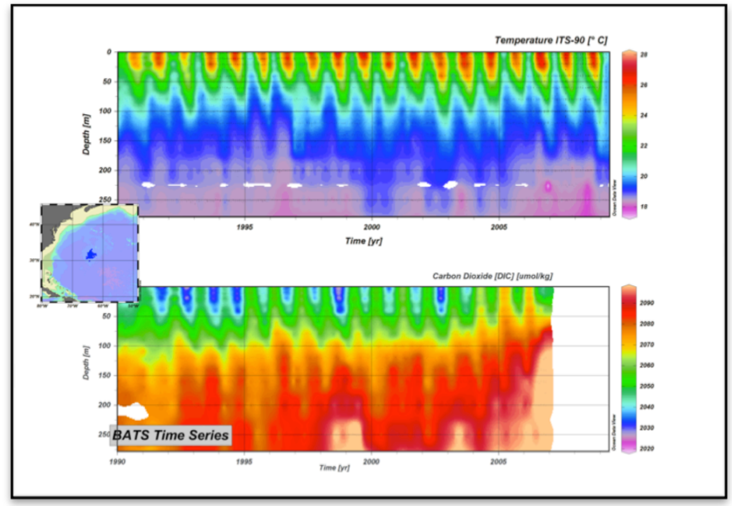
Orr et al.,2005

Motivation

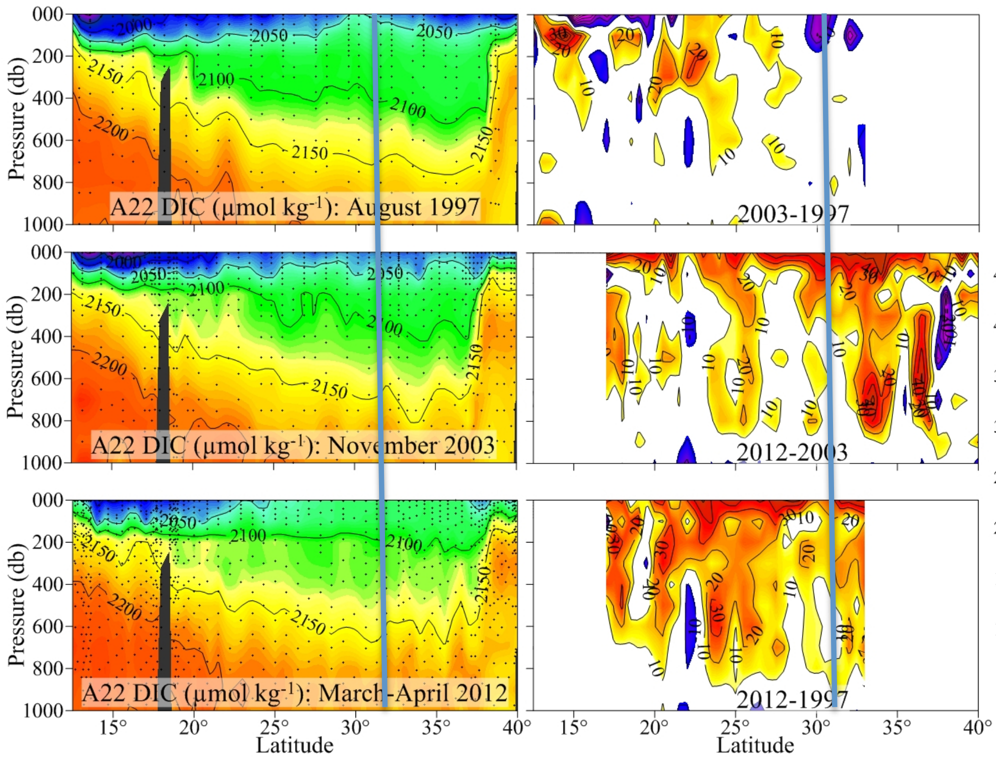
3. Links to [fixed location] time series

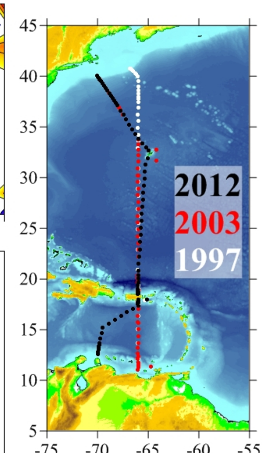
- Validation and calibration of time series
- Spatial extrapolation of time series observations
- Sharing of best practices

BATS



A20 – 1997, 2003, 2012





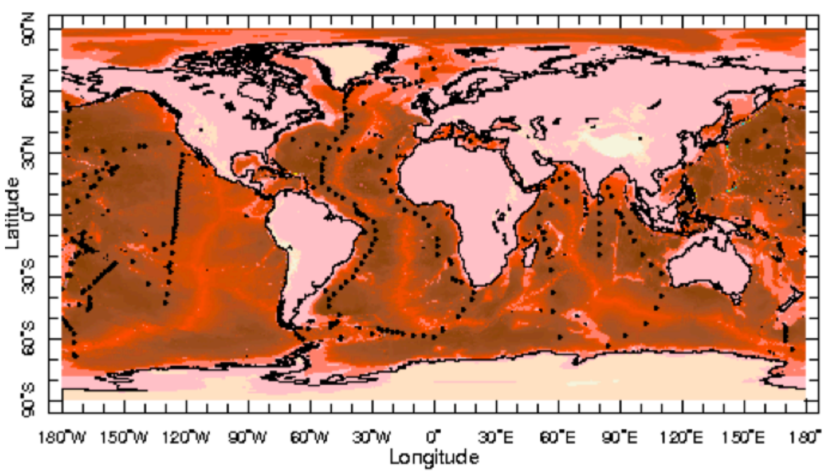
Courtesy G. Greeley, PMEL

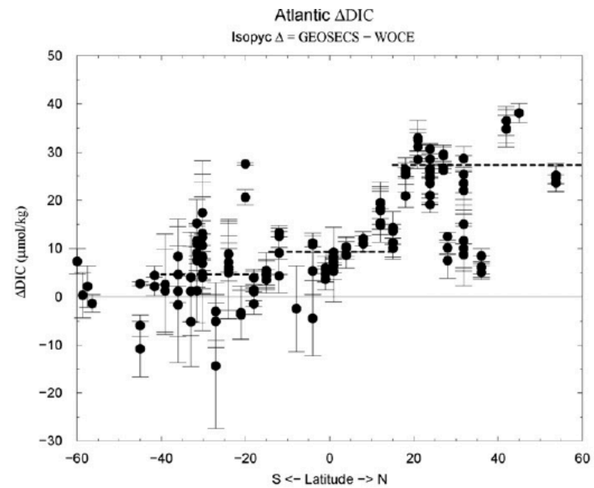
Global Decadal Re-occupations: GEOSECS

GEOSECS: Geochemical Ocean Section Study

“a global survey of the three-dimensional distribution of chemical, isotopic and radiochemical tracers in the ocean”

Atlantic	July 1972 to May 1973
Pacific	August 1973 to June 1974
Indian Ocean	December 1977 to March 1978





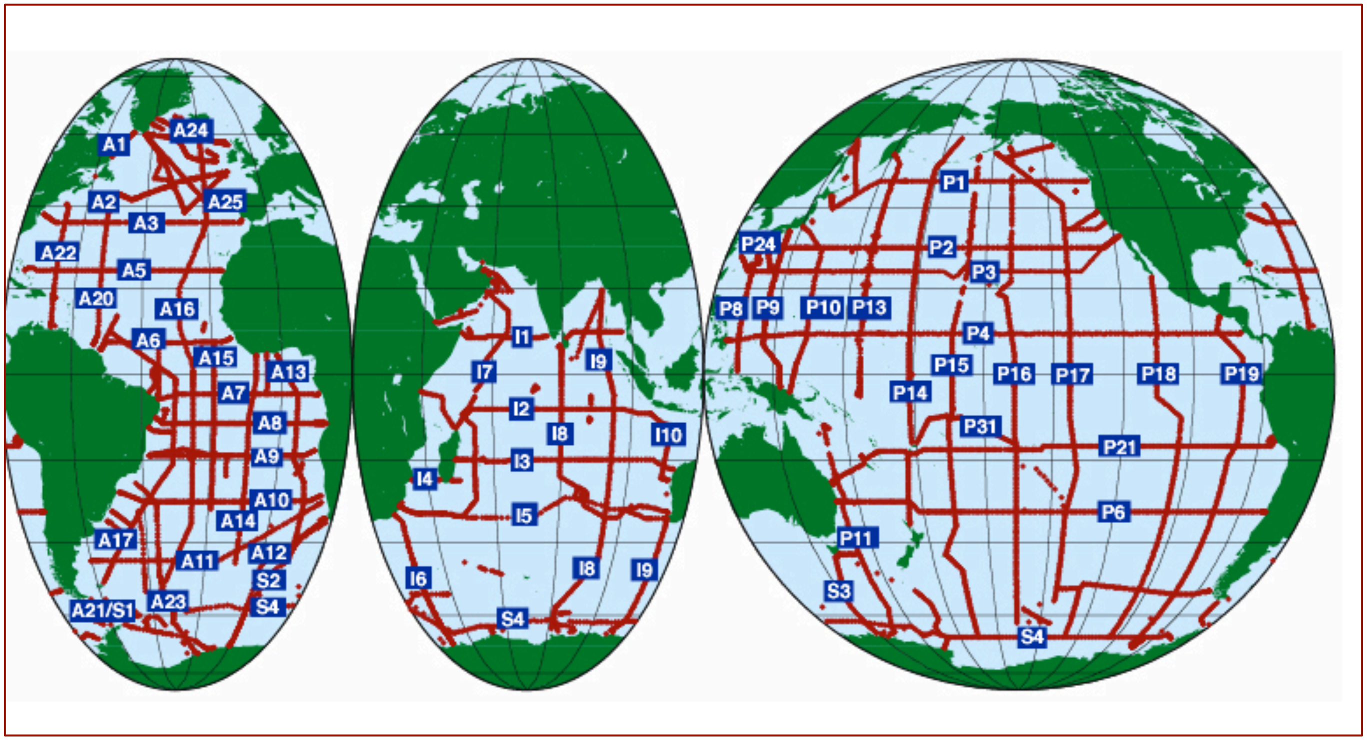
Peng and Wanninkhof, 2010

Rivers of the sea: the story of GEOSECS
http://archive.org/details/cus_00009?start=2873.5

Inorganic Carbon Data:
Offsets up to 20-30 µmol/kg (≈ 1 %)
(surface water change 0.05 % yr^{-1})
Cruise to cruise and regional differences in offsets

Global Decadal Re-occupations: WOCE/WHP
1990-1999

"The main aim of the WOCE observations was to acquire a high quality data set, which in some sense represented the state of the oceans"



http://woceatlas.tamu.edu/Sites/html/atlas/SOA_WOCE.html

Bringing the quality of biogeochemical data up to physical standards

- Reference materials
- Best Practices

WOCE/JGOFS Global Carbon Synthesis Project

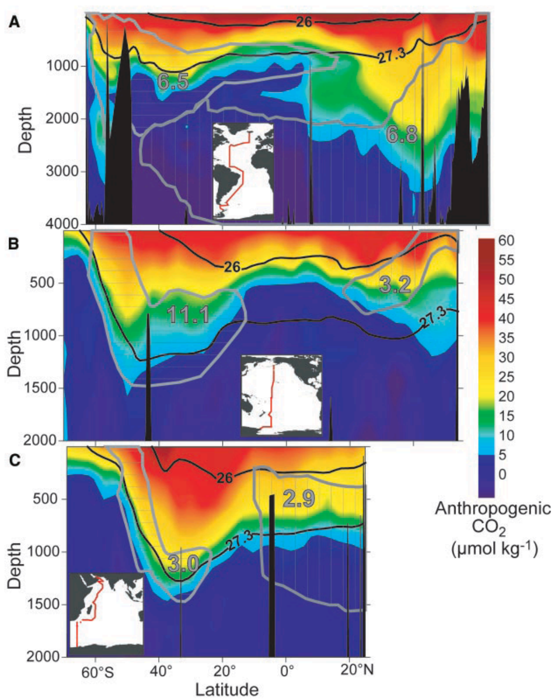
The first observation-based inventory of anthropogenic CO_2

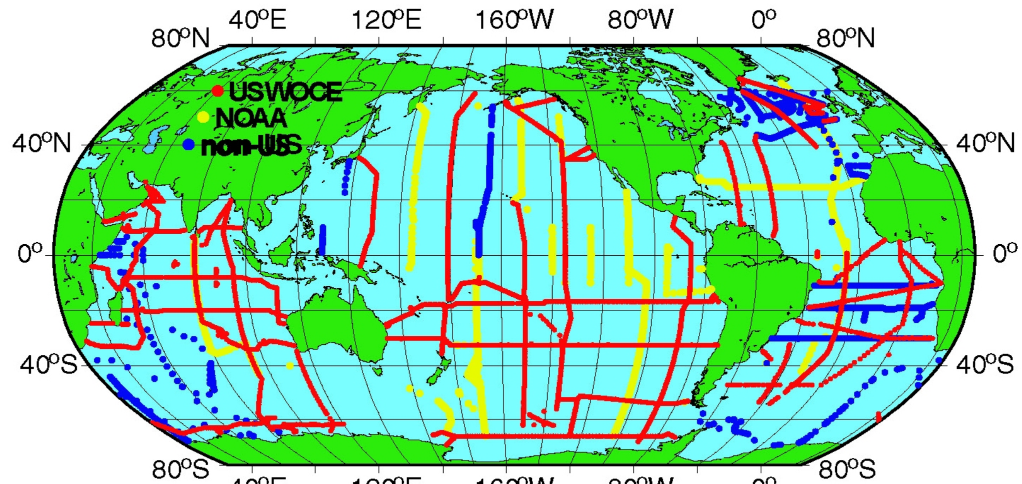
Use of certified reference materials

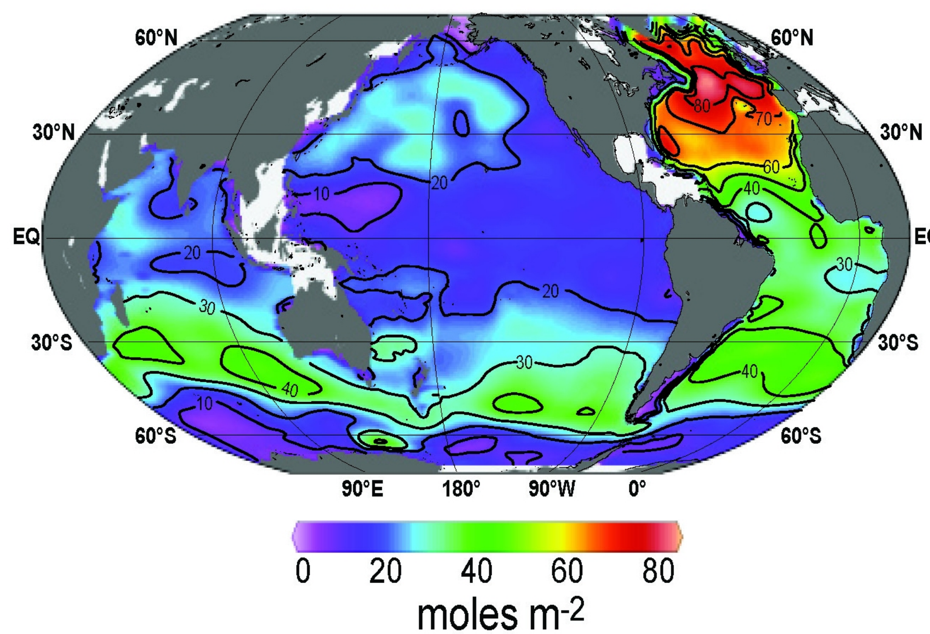
>70,000 sample locations; DIC ± 2 µmol kg^{-1}; TA ± 4 µmol kg^{-1}

Uptake = 118 ± 19 Pg C

Sabine et al (2004)

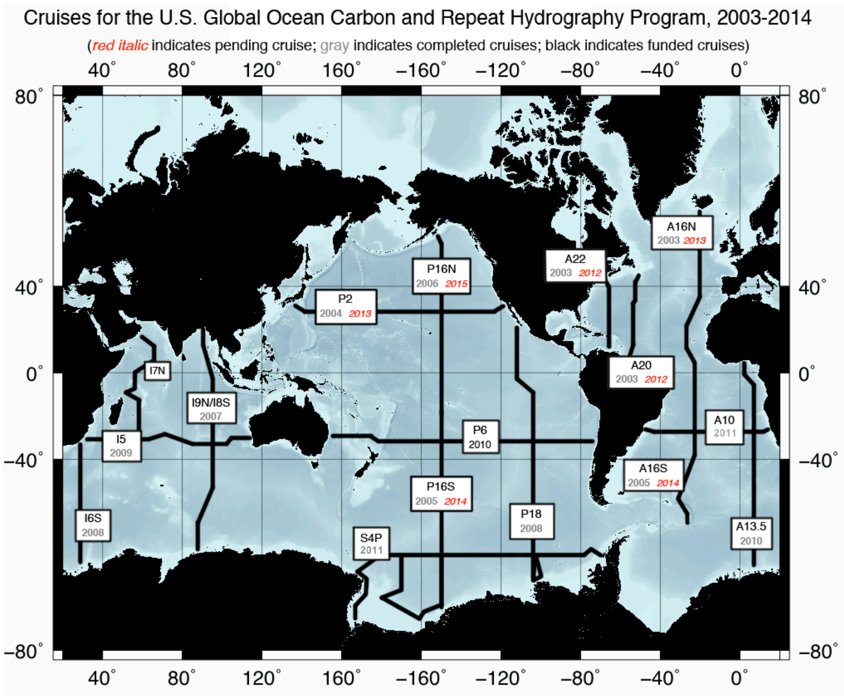






Global Decadal Re-occupations: CLIVAR/CO2 Repeat Hydrography

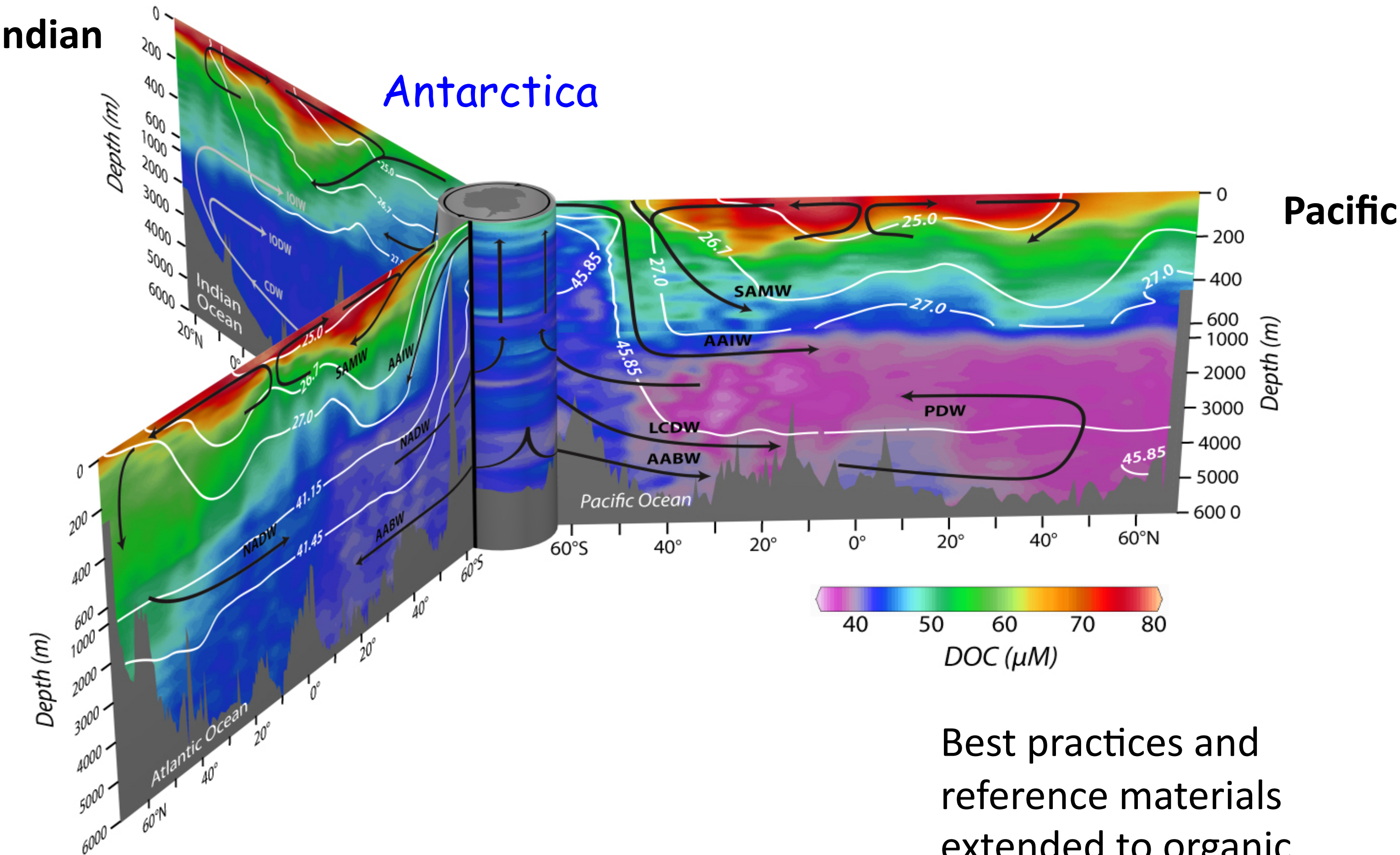
New paradigm: the changing ocean



- Study the stability of internal pathways and **changing** patterns in ocean properties.
- Baseline to assess changes in the ocean's biogeochemical cycle in response to natural and/or anthropogenic activity.
- Long-term measurements can be used to follow global warming-induced **changes** in the ocean's transport of heat and freshwater, which could affect the circulation by decreasing or shutting down the thermohaline overturning.

Baseline of "the other ocean carbon cycle"

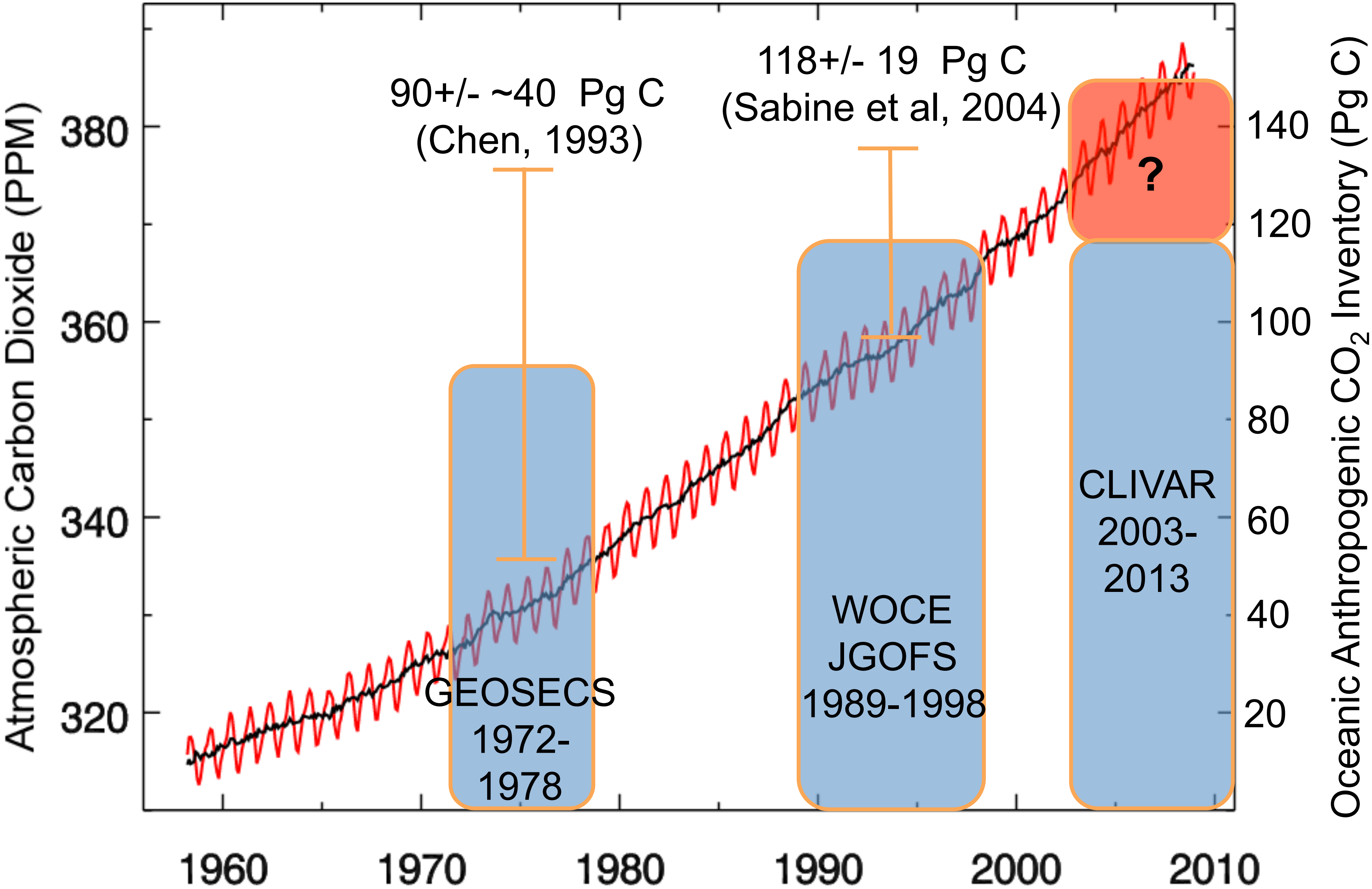
Observed Distribution of Dissolved Organic Carbon in Major Ocean Basins



Best practices and reference materials extended to organic carbon

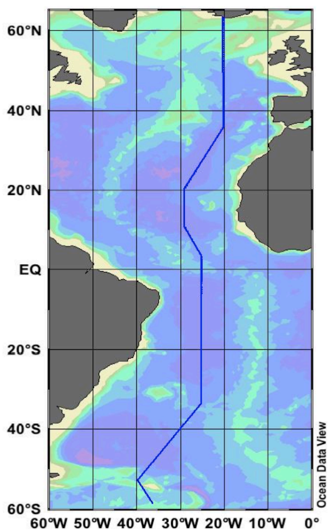
Hansell et al. 2009

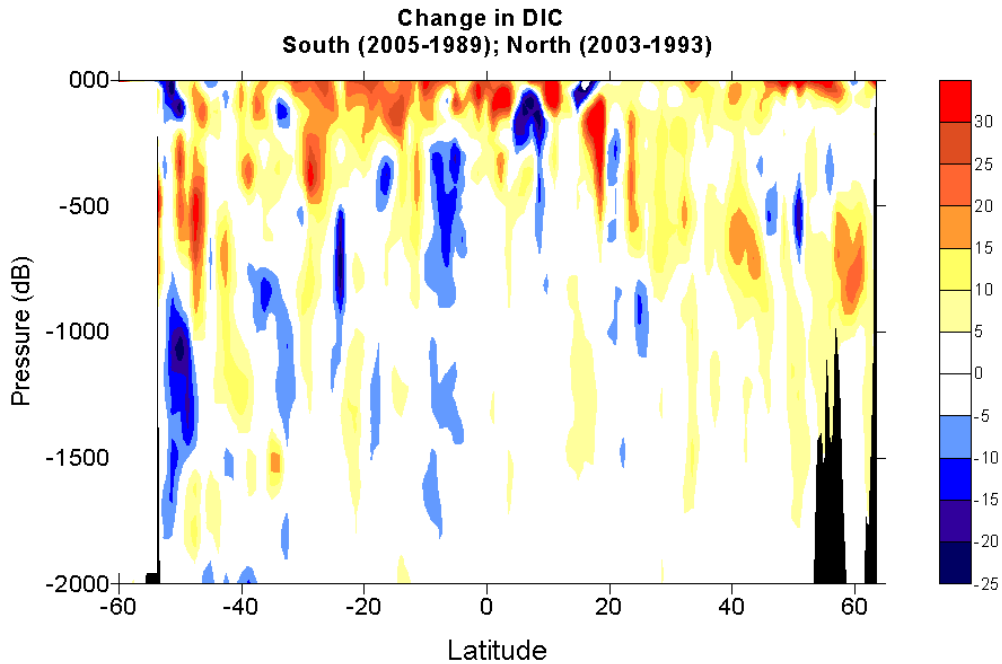
Reducing Uncertainties in Ocean Carbon Inventories



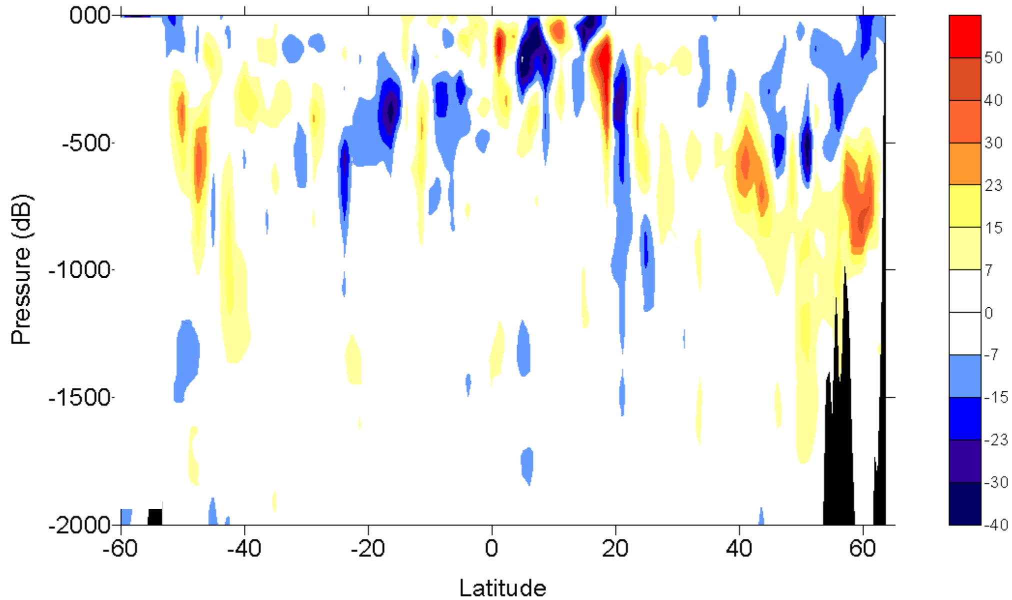
Observed Decadal Changes

A16



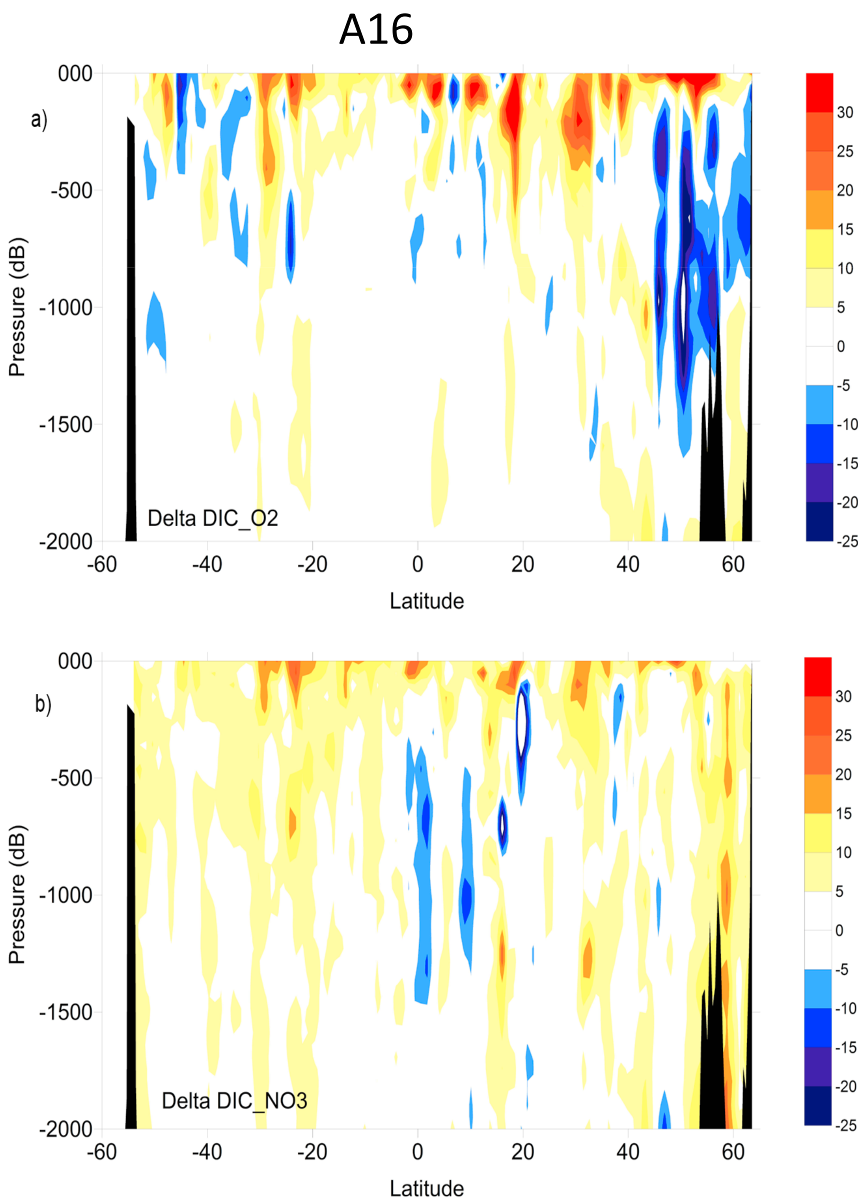


ΔDIC



ΔAOU

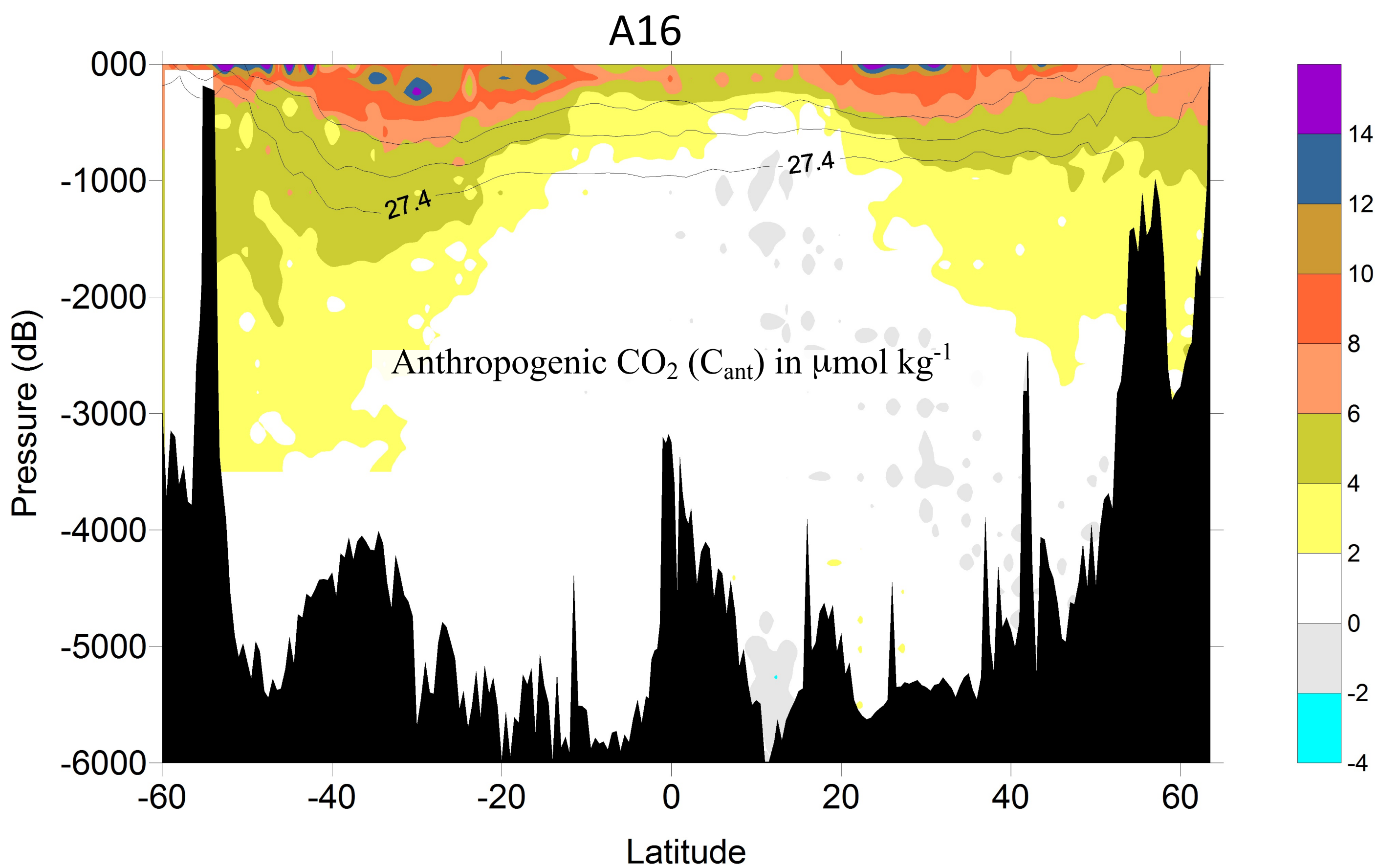
Attributing and deconvolving the changes



Estimated DICanthro distributions for the A16 transect computed from the temporal difference in DIC, ΔDIC, for the A16 transect corrected for differences in remineralization using (a) O_2 (ΔDIC_{O2} in μmol kg^{-1}) and (b) NO_3^- (ΔDIC_{NO3} in μmol kg^{-1}). For the Northern Hemisphere (60°Nto 2°S) the cruises took place in 1993 and 2003; for the Southern Hemisphere (2°S to 54°S) the cruise occupied the line in 1989 and 2005, but values are normalized to 1 decade by dividing the values in the south by 10/16. The top 2000 dB are shown.

Wanninkhof et al. 2010

Decadal Changes in Anthropogenic CO_2

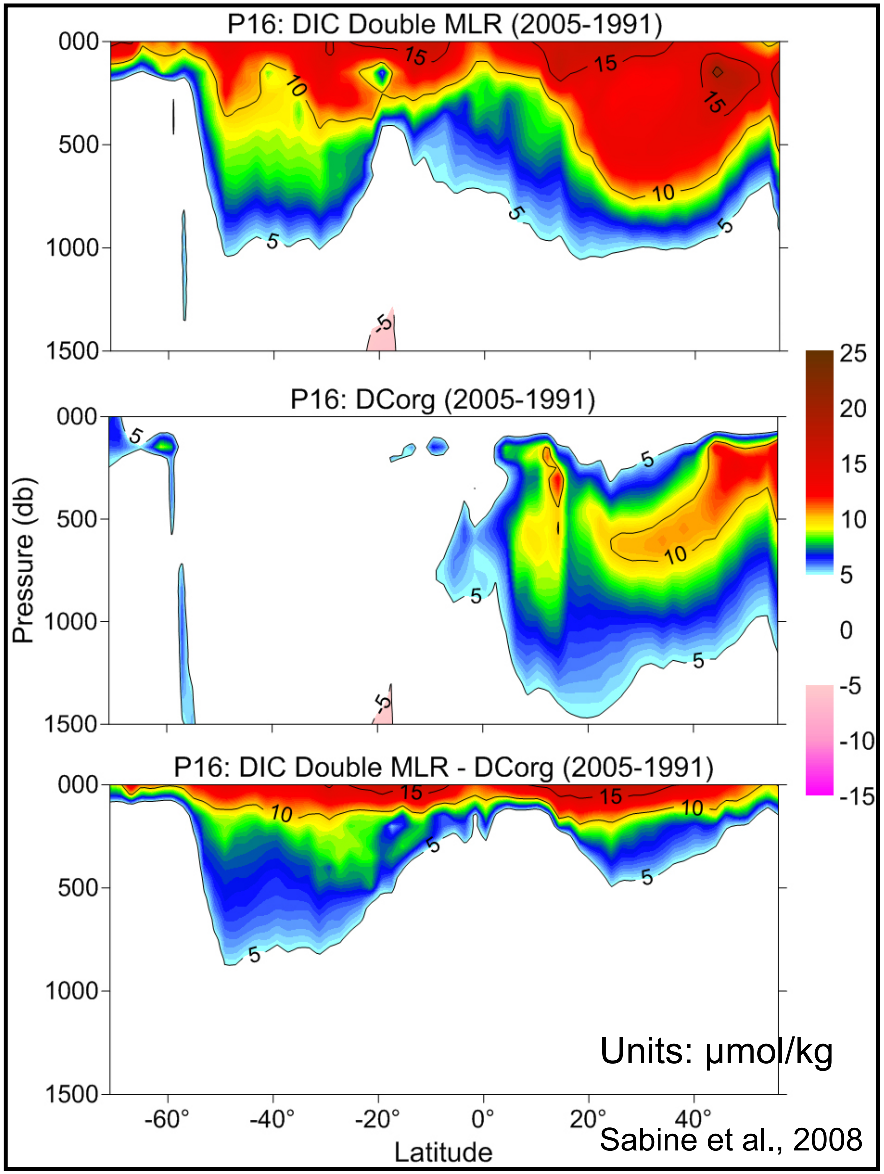


The change in anthropogenic carbon, DC_{ant}, for the time interval between cruises along the A16 transect estimated by the extended multilinear regression (eMLR) method with separate multilinear regressions (MLRs) determined for each of 23 distinct density ranges. The eMLR based change in anthropogenic carbon, $\Delta DIC_{eMLRdens}$, is computed utilizing S, T, AOU, NO_3^-, and SiO_2 from 2003/2005 as input parameters. The solid lines indicate potential density horizons, sigma-0 = 27.0, 27.2, and 27.4 kg m^{-3}.

From Sabine et al. 2009	**Atlantic (25°W)**	**Pacific (152°W)**	**Indian (90°E)**
In: mol C m^{-2} yr^{-1}	1993-2005	1991-2006	1995-2007
Northern Hemisphere	0.63	0.25	0.63
Southern Hemisphere	0.75	0.41	0.183

Wanninkhof et al., 2010

Decadal Changes in Anthropogenic CO_2



P16 (152°W) eMLR Section

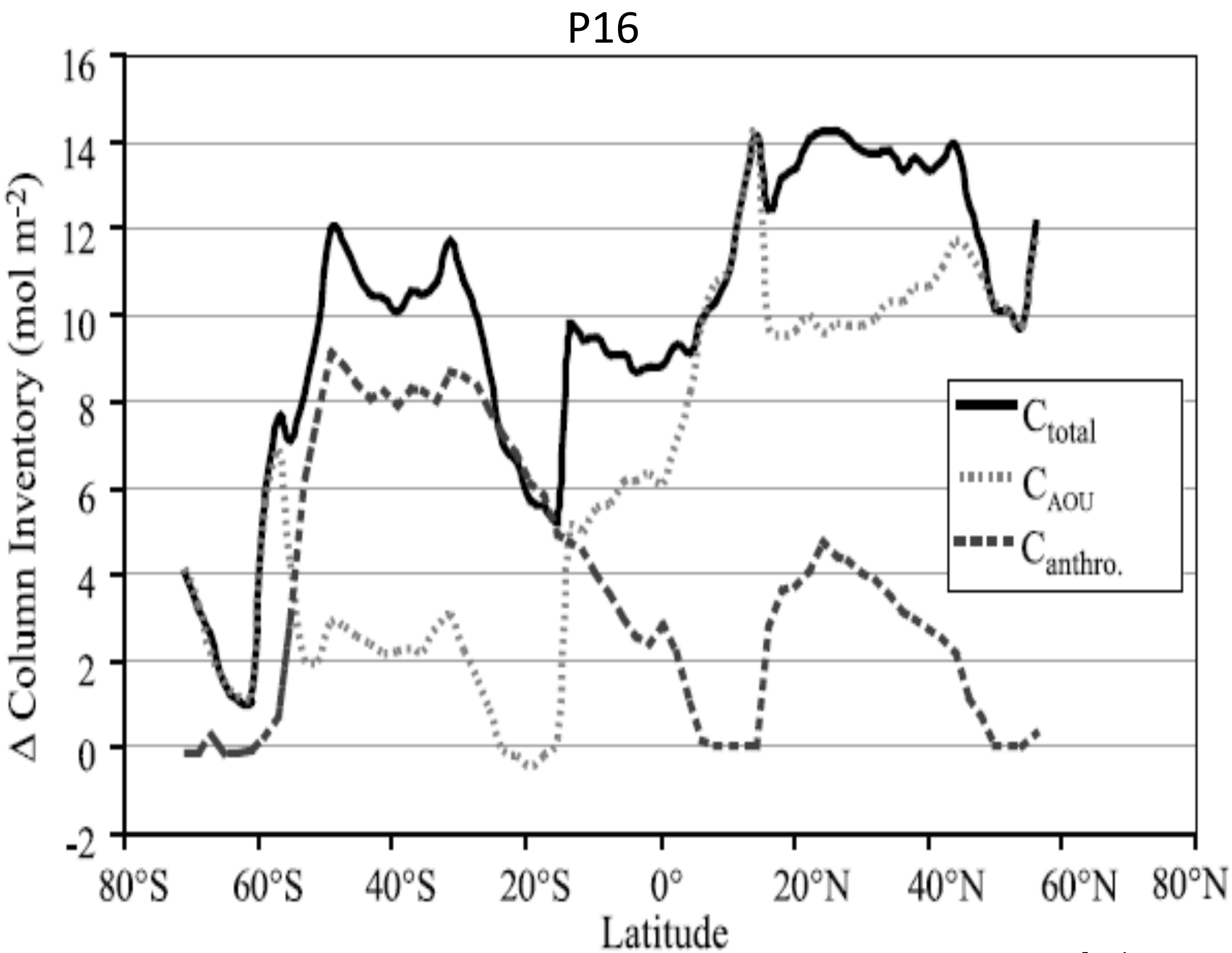
eMLR function without AOU shows a very large DIC change in the North Pacific)

The AOU eMLR function is used to isolate the change in apparent remineralization rate

Subtracting the AOU eMLR from the DIC eMLR gives the atmospheric CO2 uptake

* AOU converted to C units using Redfield Ratio

Decadal Changes in Anthropogenic CO_2

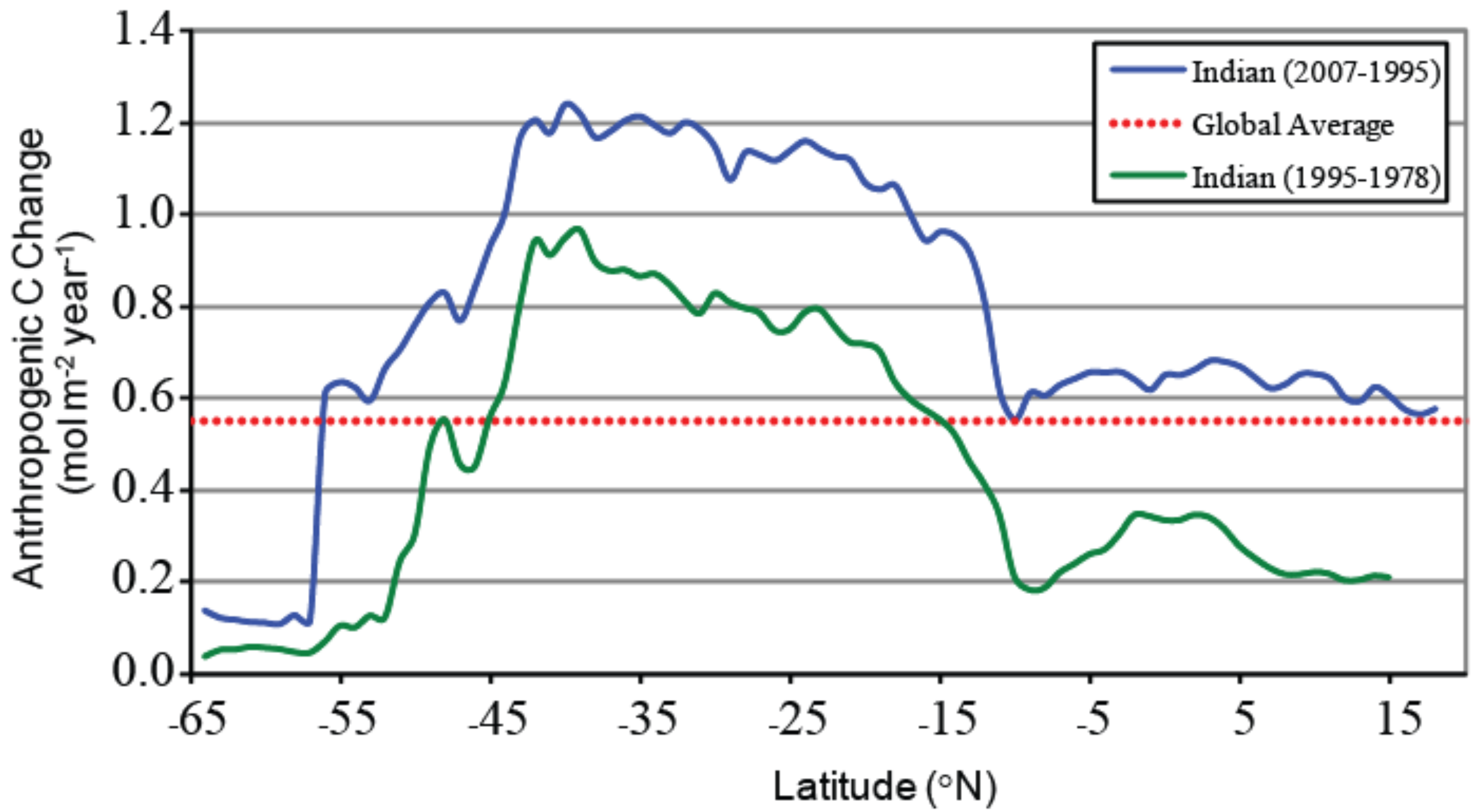


Column inventories of the change in anthropogenic CO_2 (solid black line), circulation carbon changes estimated from AOU (light gray dotted line), and the total DIC change (dark gray dashed line) along the P16 section.

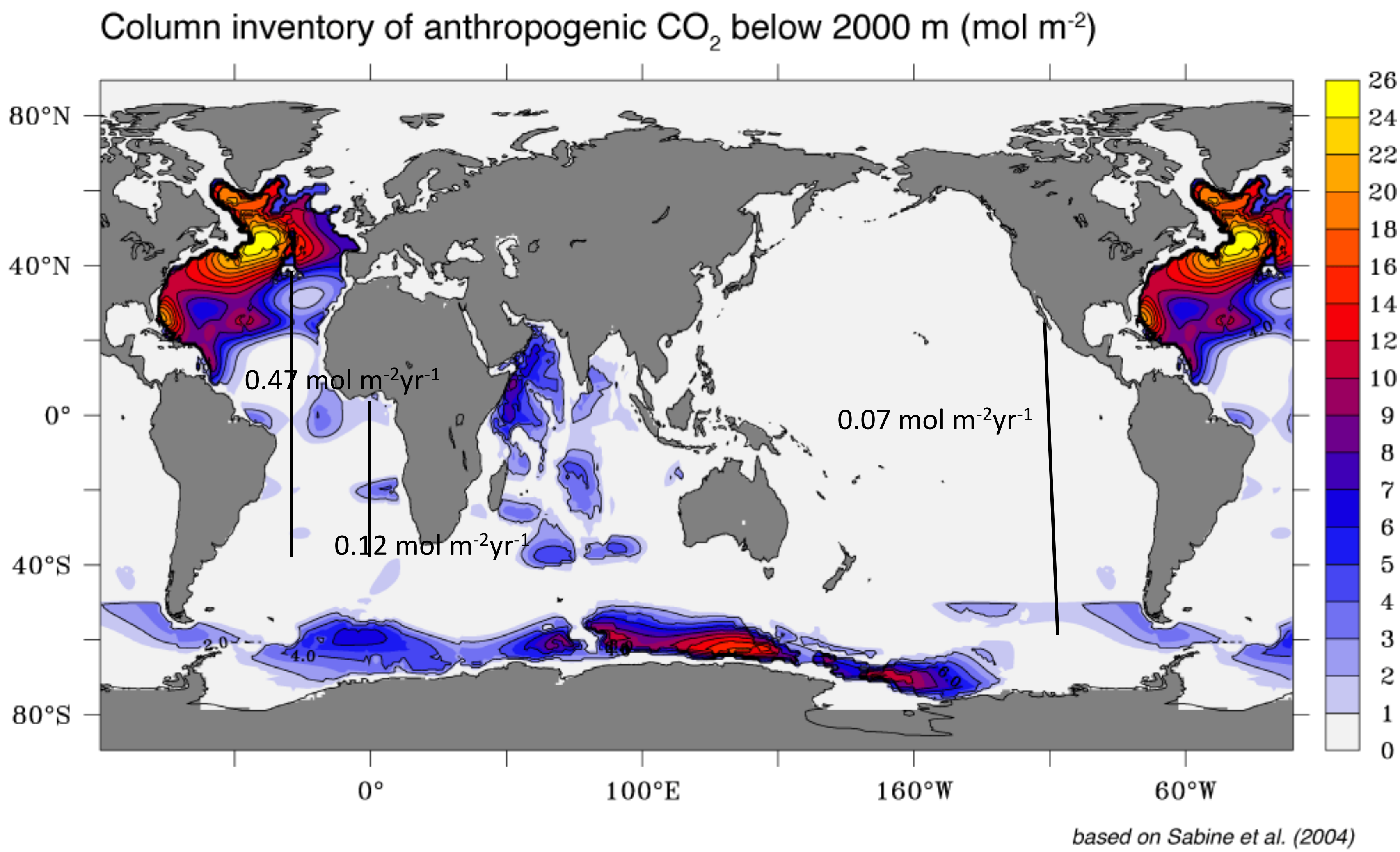
[Sabine et al., 2008]
Decadal changes in Pacific Carbon.

Decadal Changes in Anthropogenic CO_2

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



Anthropogenic Column Inventory below 2000 m



Courtesy of N. Gruber, ETH Zurich

Wanninkhof et al., 2013. DSR-1

US CLIVAR and CO_2 Program - Websites

Open and rapid data exchange

Program Information

U.S. CO_2/Repeat Hydrography Program: **ushydro.ucsd.edu**

U.S. CLIVAR Program: **www.usclivar.org**

The International Ocean Carbon Coordination Project (IOCCP): **www.ioccp.org**

Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP): **www.go-ship.org**

Global Climate Observing System (GCOS): **www.wmo.int/pages/prog/gcos/**

Participating NOAA Laboratories

NOAA Climate Program Office: **www.climate.noaa.gov**

Pacific Marine Environmental Laboratory (NOAA/PMEL), CO_2 Program:

www.noaa.pmel.gov/co2/

Atlantic Oceanographic & Meteorological Laboratory (NOAA/AOML), CO_2 Program:

www.noaa.aoml.gov/ocd/gcc/

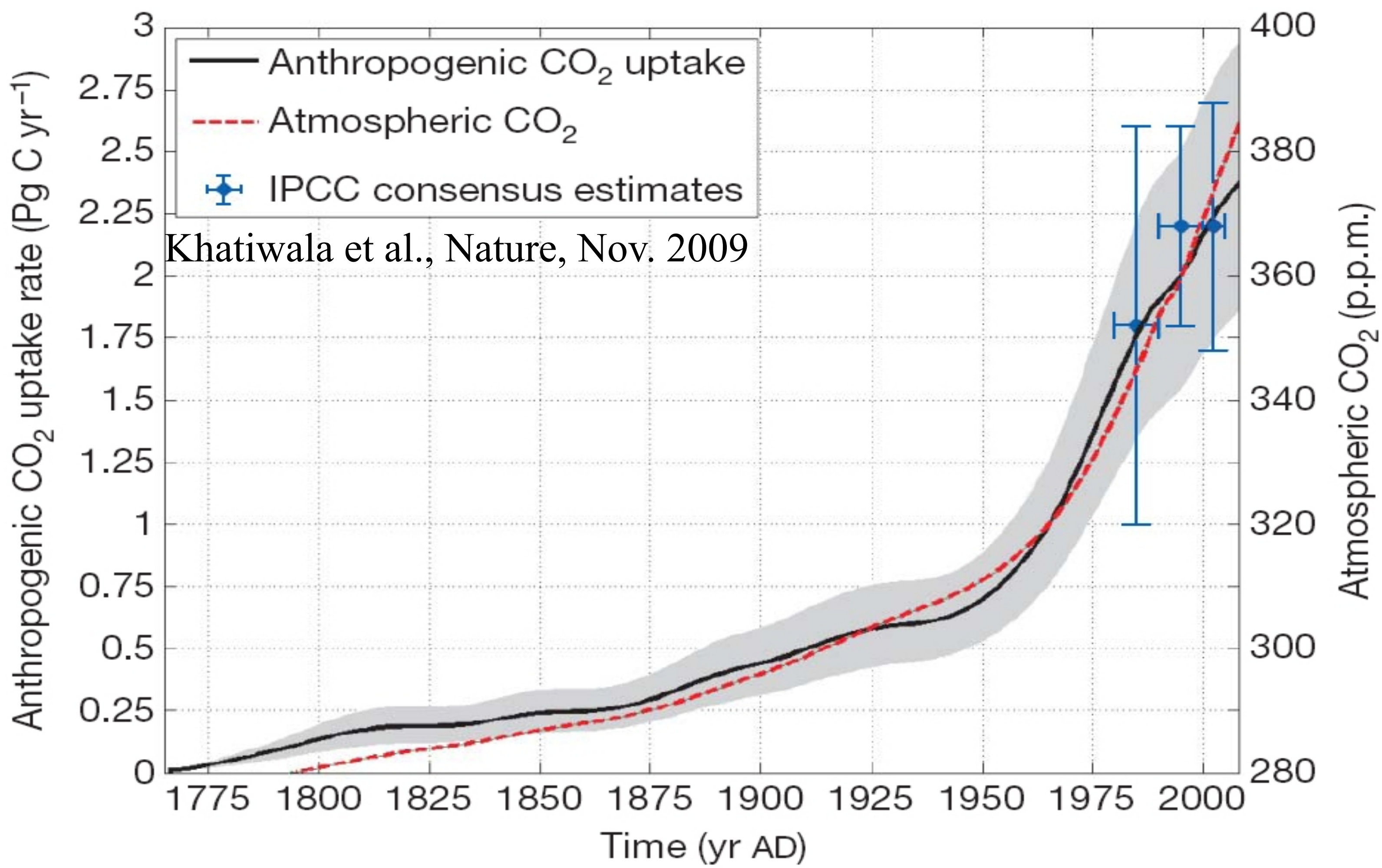
Data Dissemination

CLIVAR and Carbon Hydrographic Data Office (CCHDO): **cchdo.ucsd.edu**

Carbon Dioxide Information Analysis Center (CDIAC), Repeat Hyrography data:

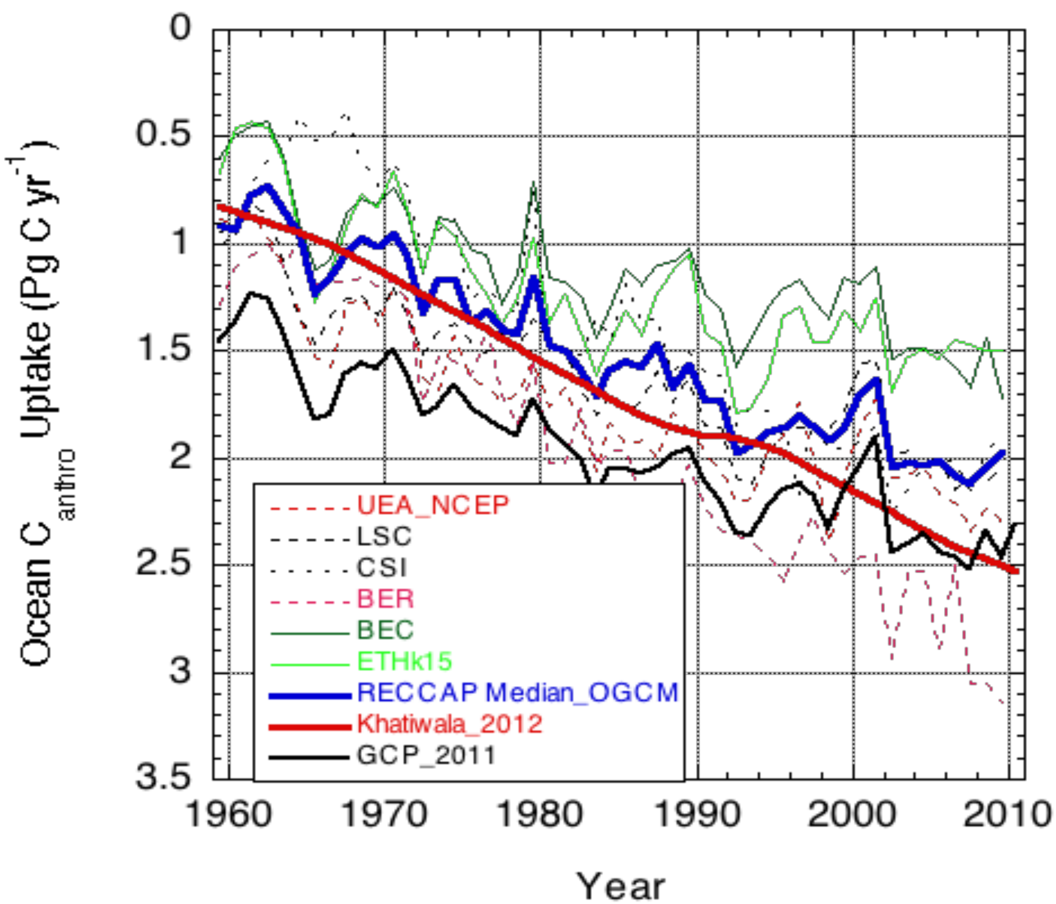
cdiac.ornl.gov/oceans/RepeatSections/

Tracer based estimates of anthropogenic CO_2 uptake



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

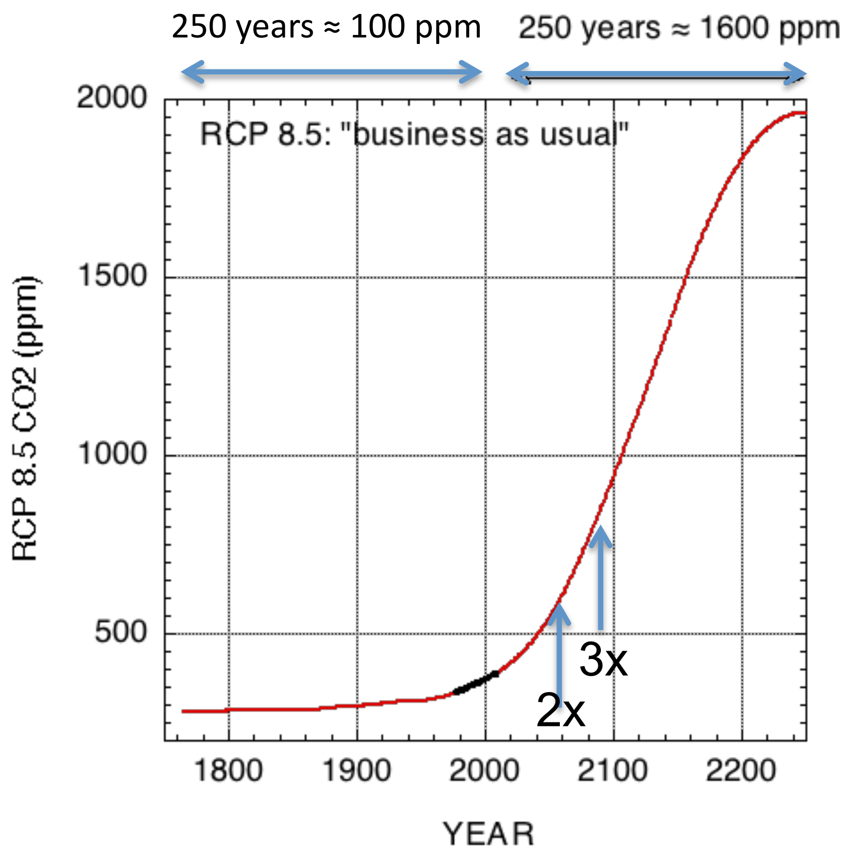
Ocean Carbon uptake in models



Models including ocean biogeochemistry show smaller increases in uptake than those relying on interior changes

The Global Carbon Problem

The Future



- The future projections will depend to some extent on ocean uptake scenarios
- Meaningful mitigation strategies have to address emissions and have to be verified. [carbon accounting]

Closing thoughts

- Synthesis needs to be integral part of the ocean interior observing strategy
- This should be a key activity in GOSHIPS
- Synthesis and data assembly should be an easier job with adherence to standard operating and reporting protocols (including metadata)

- To determine decadal changes in C_{anthro} we must recognize the impacts of natural and climate change
- Use common sense and critical thought when applying approaches
- A key question is: Is the ocean uptake of CO_2 changing

- Carbon accounting will become increasingly important

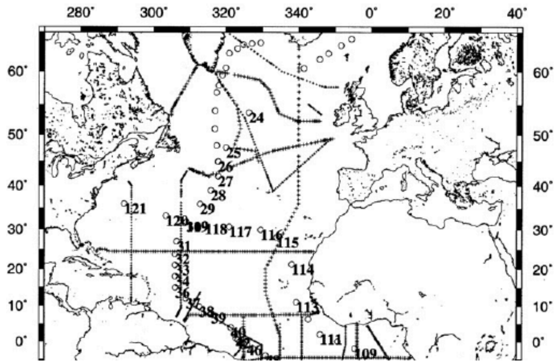


Table 4
Results of integration for anthropogenic CO_2 based on MLR and eMLR methods.

	Western basin		Eastern basin	
	Sp. inventory[a] (mol m^{-2})	CO_2 uptake rate (mol m^{-2} yr^{-1})	Sp. inventory (mol m^{-2})	CO_2 uptake rate (mol m^{-2} yr^{-1})
MLR:				
Zone (1)	14.8	0.70	20.4	0.97
Zone (2)	11.2	0.53	12.1	0.57
Zone (3)	17.5	0.83	5.9	0.28
eMLR:				
Zone (1)	11.1			
Zone (2)	7.6			
Zone (3)	7.4			

Approximate uncertainty:
Zone (1) is defined as lati
Zone (2) is defined as lati
Zone (3) is defined as lati

Table 6
Results of decadal CO_2 increase in the Atlantic Ocean estimated by isopycnal method.

	Western basin		Eastern basin	
	Inventory (mol m^{-2})	CO_2 uptake rate (mol m^{-2} yr^{-1})	Inventory (mol m^{-2})	CO_2 uptake rate (mol m^{-2} yr^{-1})
Zone (1)	11.3	0.54	15.2	0.60
Zone (2)	5.5	0.26	11.3	0.54
Zone (3)	11.2	0.53	6.2	0.29