Ocean Carbon and Biogeochemistry Summer Workshop
Woods Hole Oceanographic Institution

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The CLIVAR/CO_2 Repeat Hydrography Program

by

Richard A. Feely, NOAA/PMEL, Seattle, WA USA

Acknowledgements: Christopher L. Sabine (PMEL), Frank Millero (RSMAS), Andrew Dickson (SIO), Rik Wanninkhof (RSMAS), Toste Tanhua (IFM-geomar), Taro Takahashi (LDEO) , Niki Gruber (ETH Zürich)

Outline of the Talk

1. Review history of carbon storage estimates using ocean interior measurements.
2. Summarize the current state of decadal change estimates (based on observations).
3. Where do we go from here.

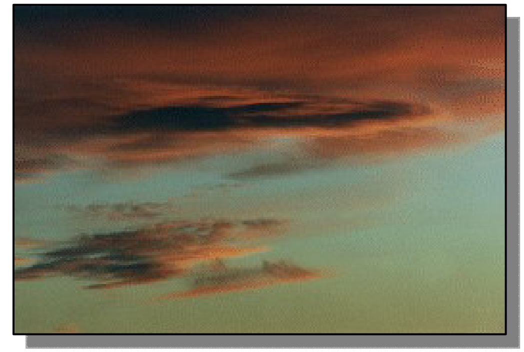
Fate of Anthropogenic CO_2 Emissions (2000-2007)

1.5 Pg C yr^{-1}

+

7.5 Pg C yr^{-1}

4.2 Pg yr^{-1}
Atmosphere
46%



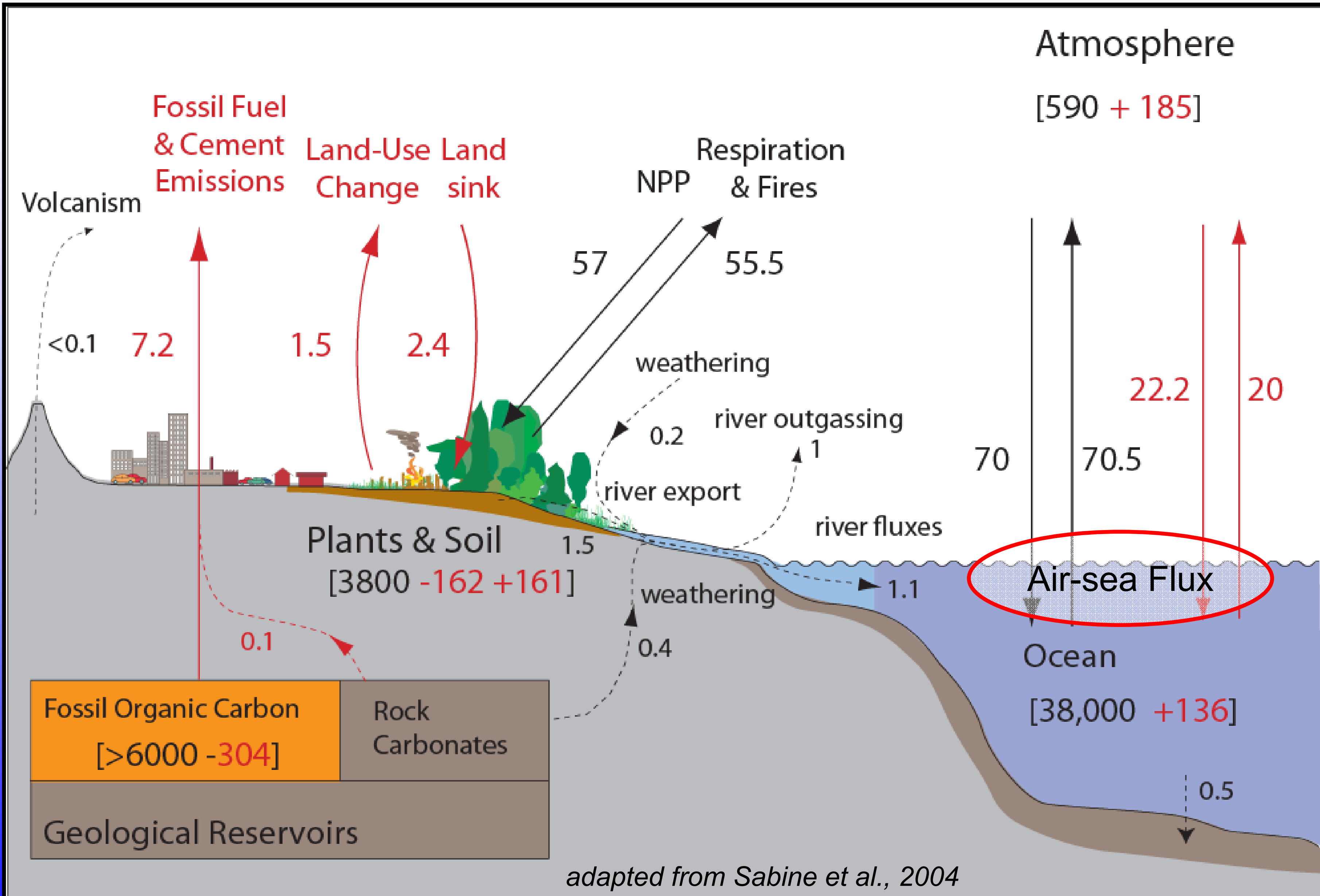
2.6 Pg yr^{-1}
Land
29%

2.3 Pg yr^{-1}
Oceans
26%

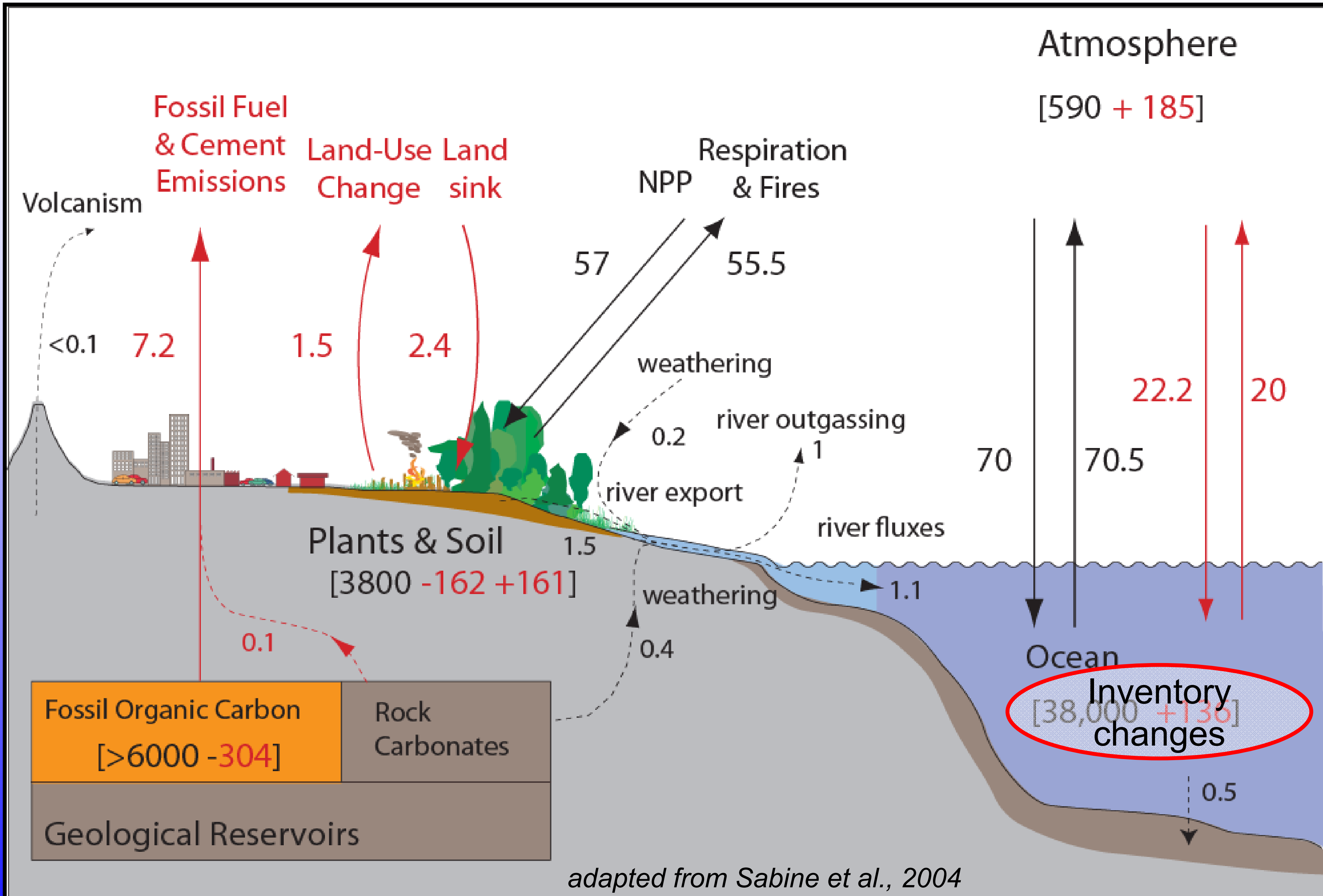
Atmospheric growth rate has increased 54% over the past 37 years; whereas the efficiency of ocean and land sinks have decreased 5% over the last 50 years.

Canadell et al. 2007, PNAS (updated)

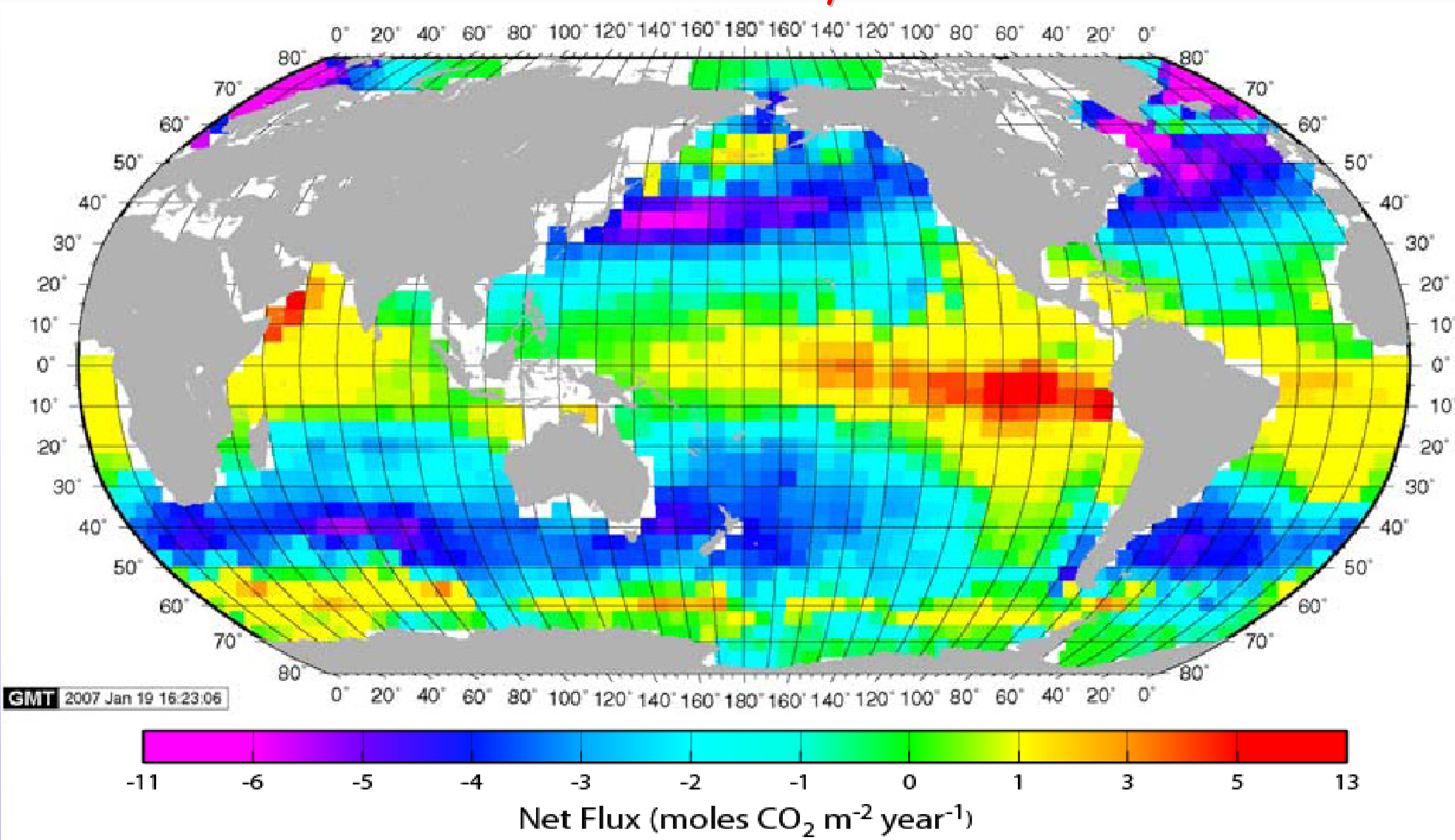
Global Carbon Budget for 2000-2005



Global Carbon Budget for 2000-2005



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

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.

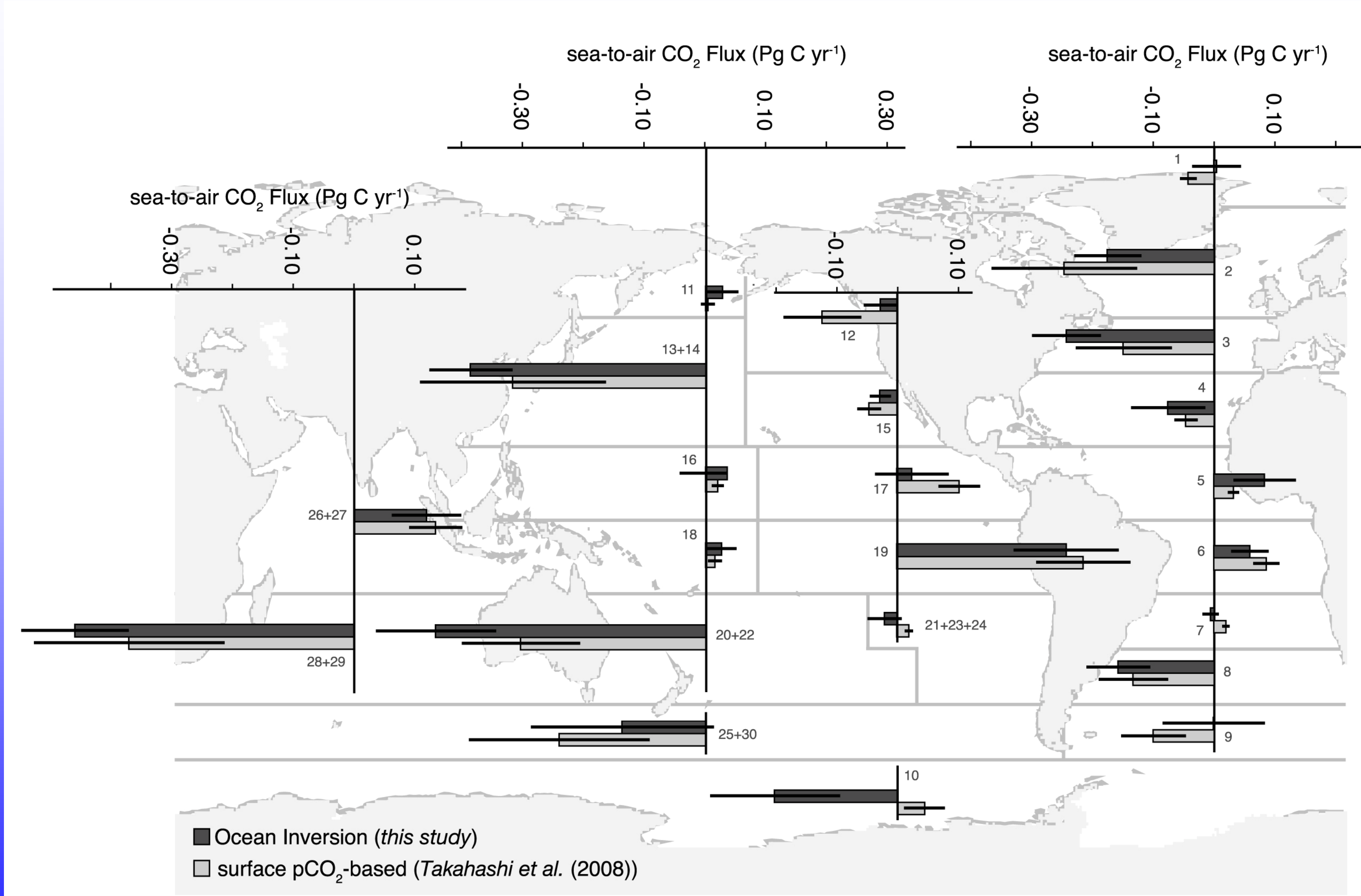
[b] The estimate for a nominal year of 1995 would be less than 0.1 Pg C a^{-1} smaller.

[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.

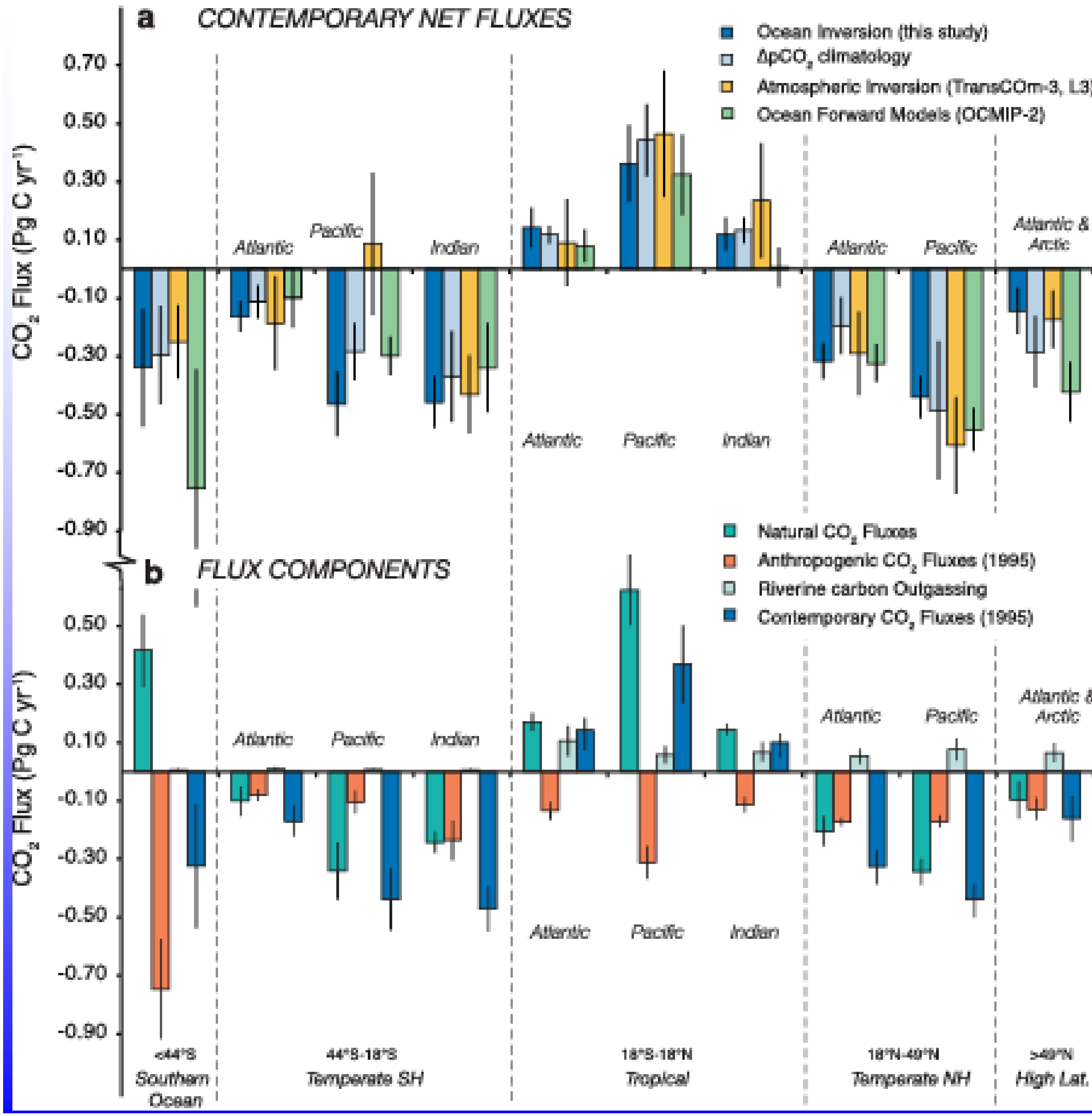
[d] These models were selected on the basis of their ability to simulate correctly, within the uncertainty of the data, the observed oceanic inventories and regional distributions of chlorofluorocarbon and bomb radiocarbon.

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

Comparison of Ocean Inversion Model of air-sea CO_2 net flux with observations based on Takahashi et al (2009)



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

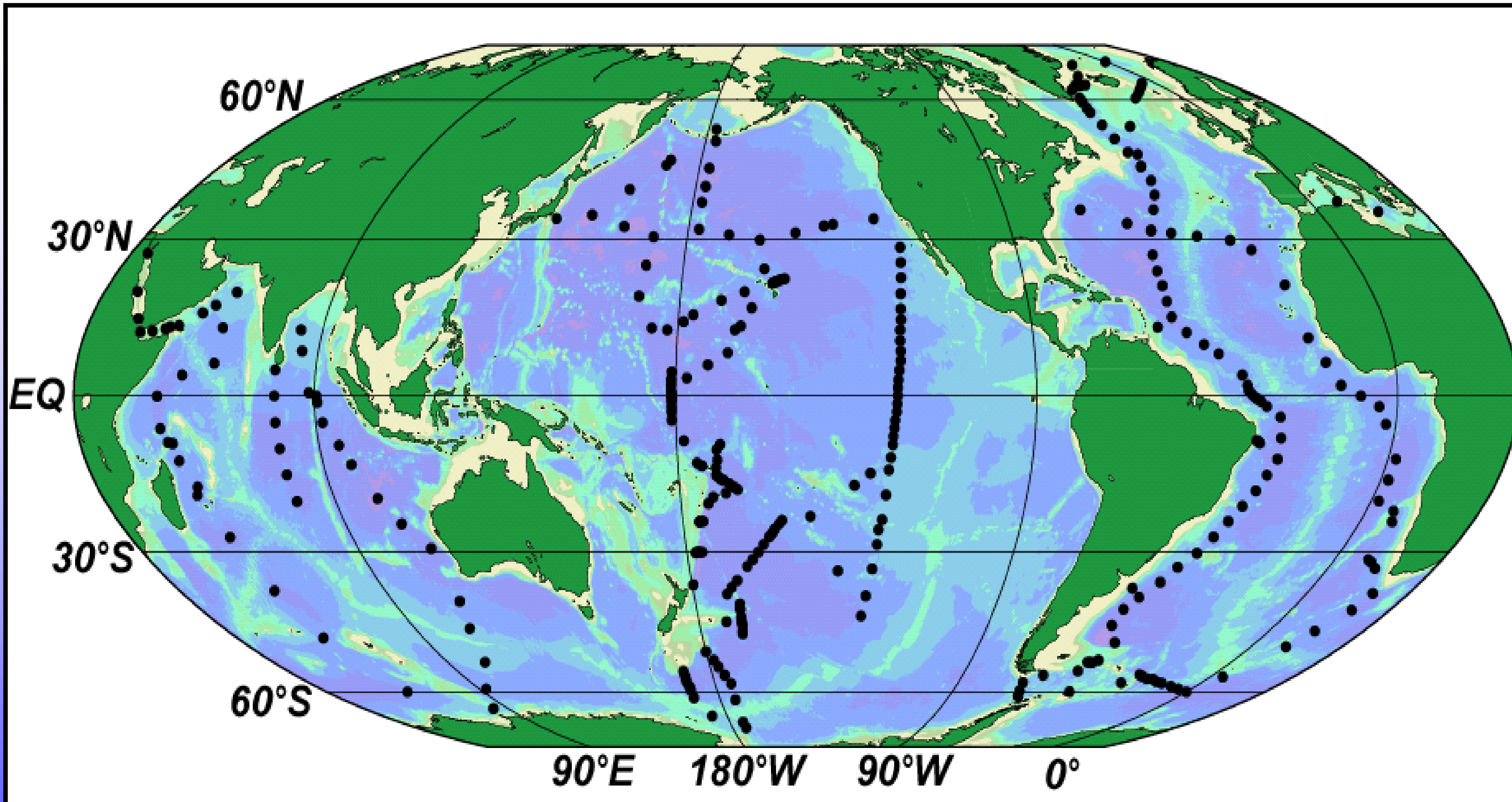


Summary of carbon fluxes from Gruber et al. 2009

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

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 μmol kg^{-1}

Shortly after GEOSECS was completed two papers came out at about the same time suggesting similar approaches for estimating anthropogenic CO_2 from the ocean carbon measurements:

Brewer, P.G., Direct observation of the oceanic CO_2 increase, Geophys. Res. Lett., 5, 997-1000, 1978.

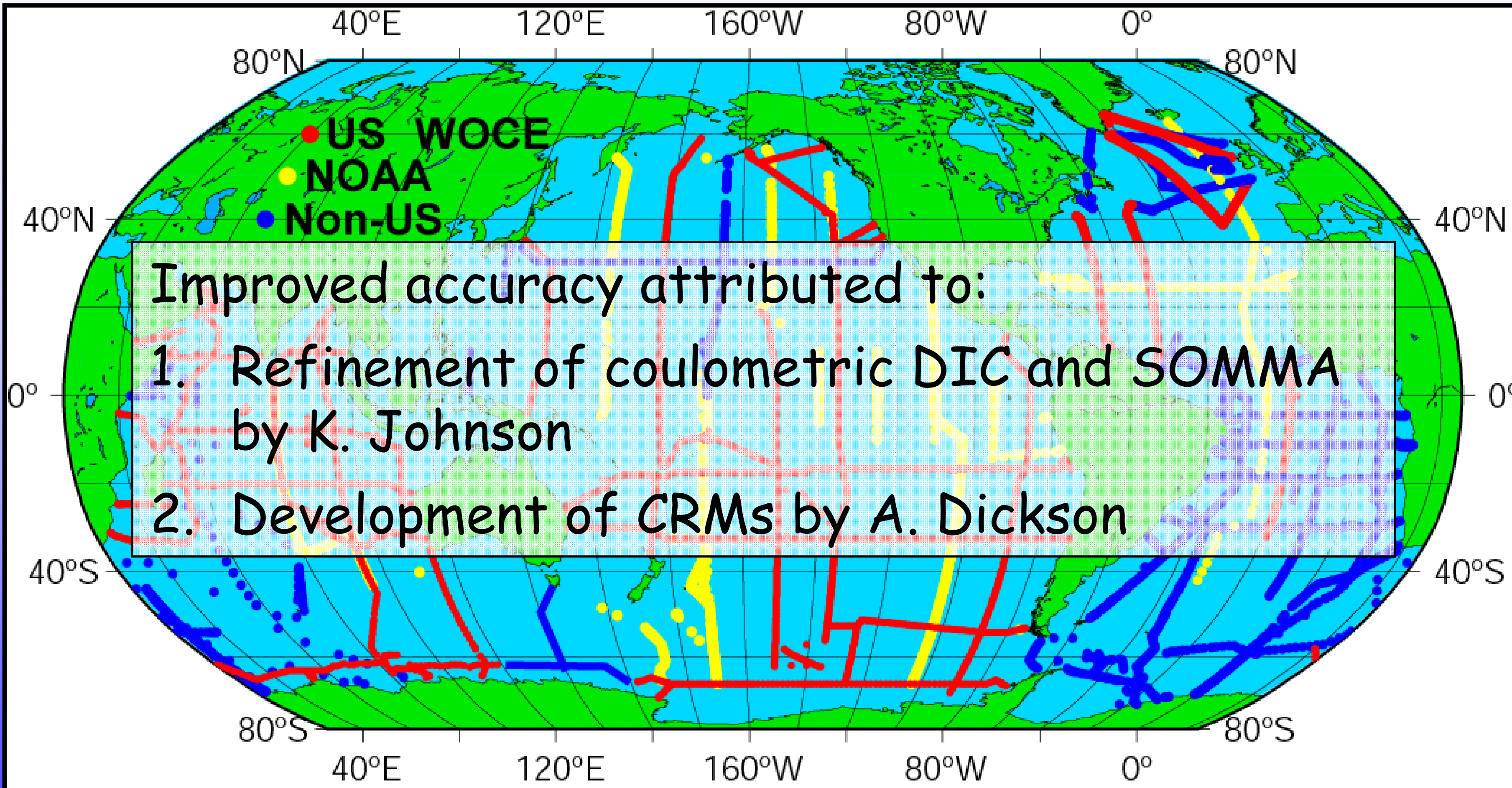
Chen, C.-T. A. and F. J. Millero, Gradual increase of oceanic CO_2, Nature, 277, 205-206, 1979.

$$C_{anth} = C_m - \Delta C_{bio} - C_{pre}$$

"...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.

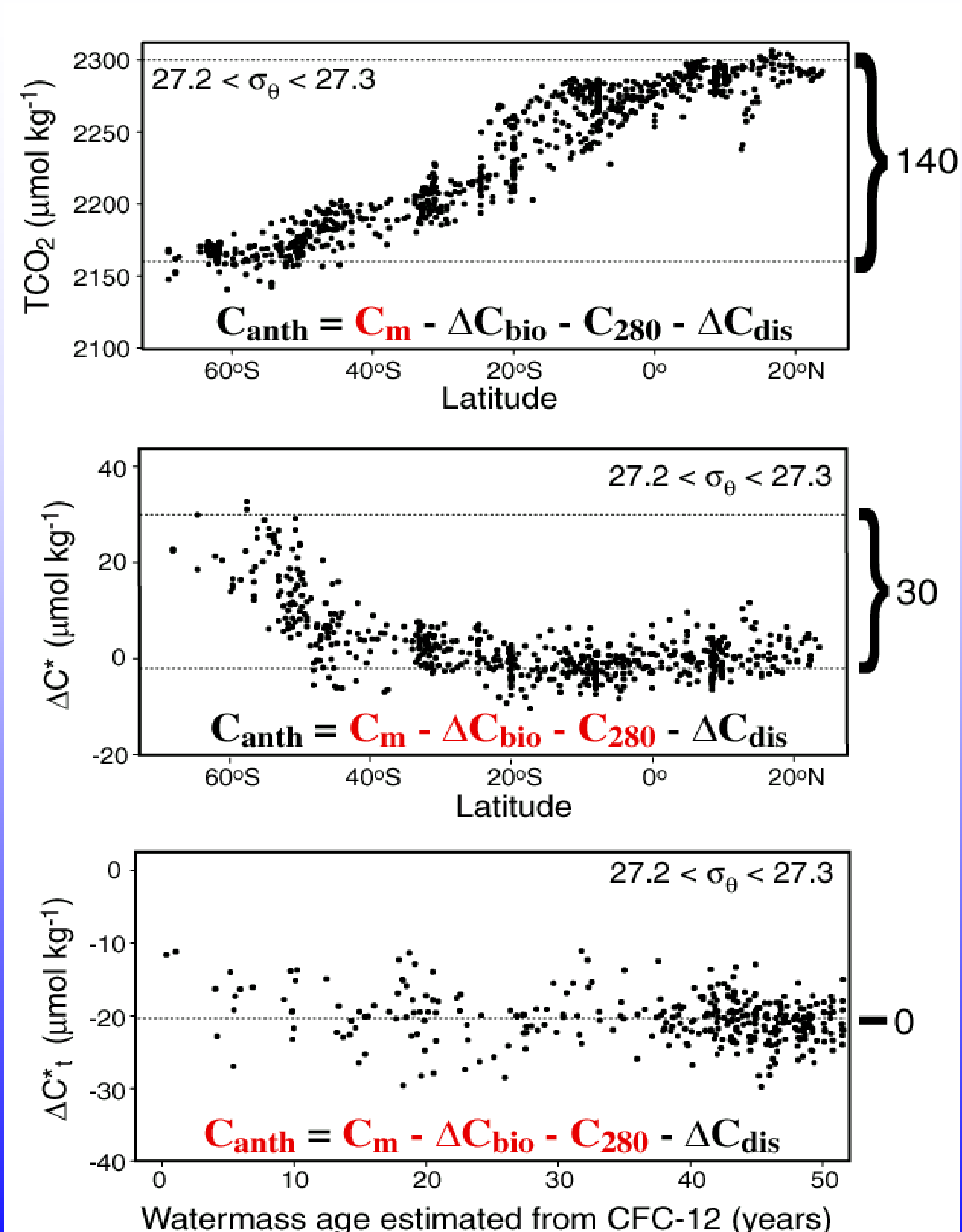


Improved accuracy attributed to:

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



Gruber, N., J. L. Sarmiento and T. F. Stocker, An improved method for detecting anthropogenic CO_2 in the oceans, *Global Biogeochem. Cycles*, 10, 809-837, 1996.

$C_{anth} = C_m - \Delta C_{bio} - C_{280} - \Delta C_{dis}$

Where:

C_{anth} = Anthropogenic C concentration

C_m = Measured total C concentration

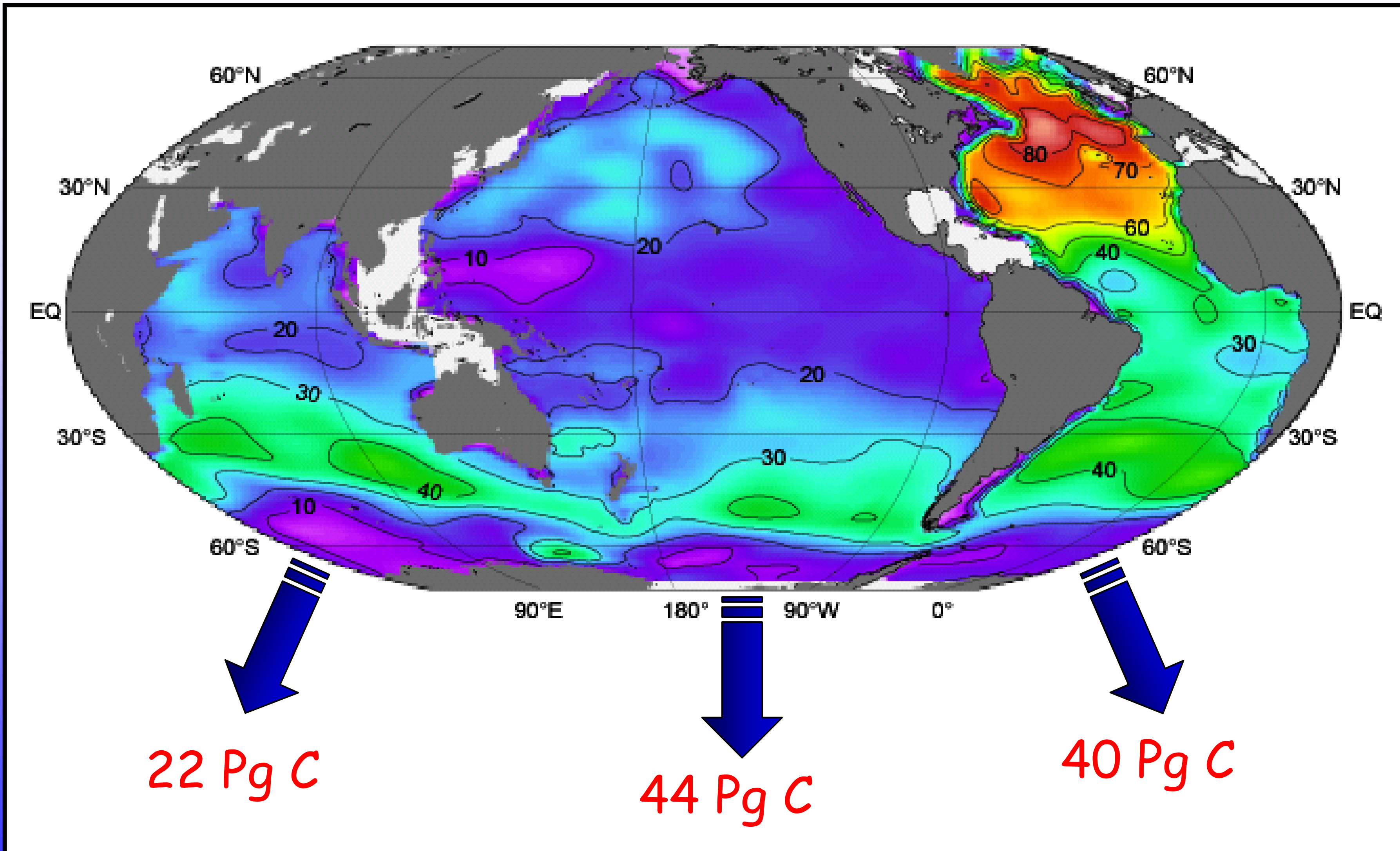
ΔC_{bio} = Change in TCO_2 as a result of biological activity

C_{280}= TCO_2 of waters in equilibrium with a preindustrial atmospheric CO_2 concentration of 280 µatm

ΔC_{dis} = Air-sea difference in CO_2 concentration in µmol kg^{-1} of TCO_2

$\Delta C^* = C_m - \Delta C_{bio} - C_{280} = C_{anth} + \Delta C_{dis}$

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

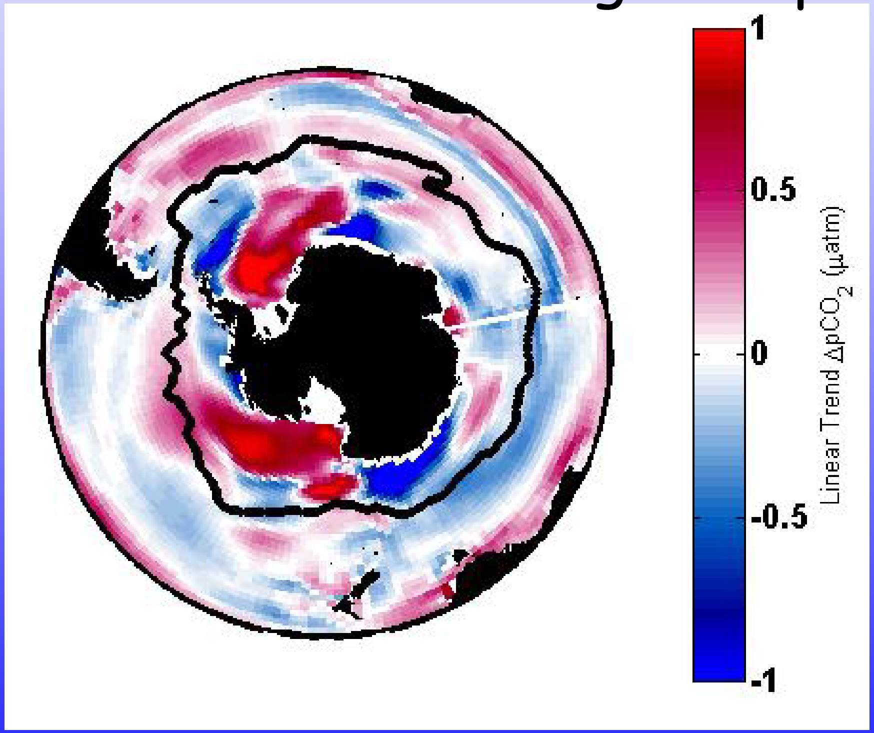


Mapped Inventory =106±17 Pg C; Global Inventory =118±19 Pg C

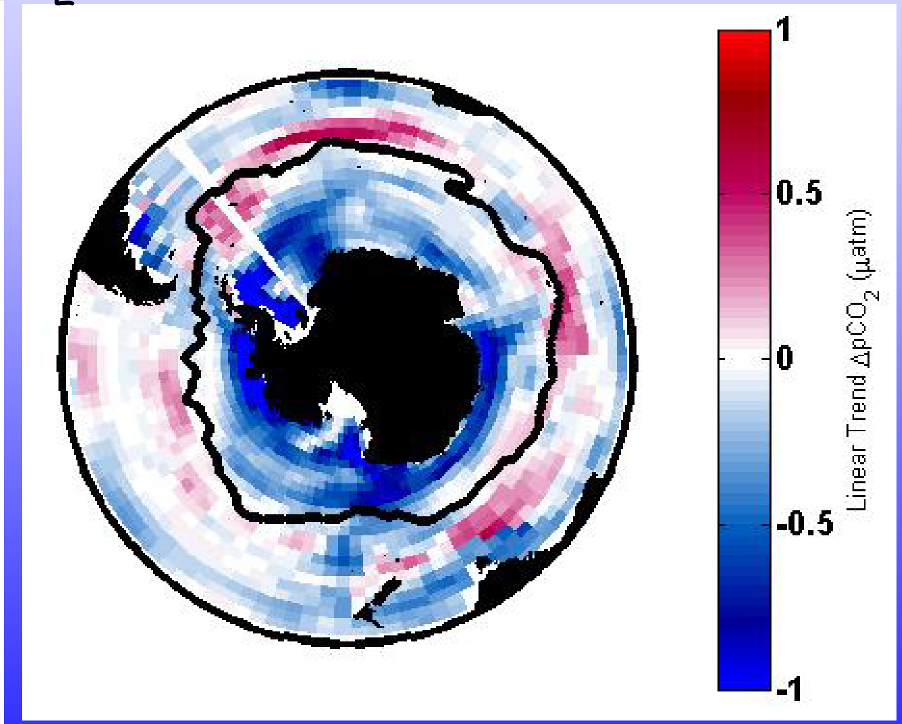
Knowing the total distribution of anthropogenic CO_2 is great, but what we really want to know is how is the ocean storage of carbon changing with time?

For Example…is the Southern Ocean sink for carbon saturating?

Change in ΔpCO_2 1979-2005



Le Quere 2007



Lovenduski 2008

CLIVAR/CO_2 Repeat Hydrography Program

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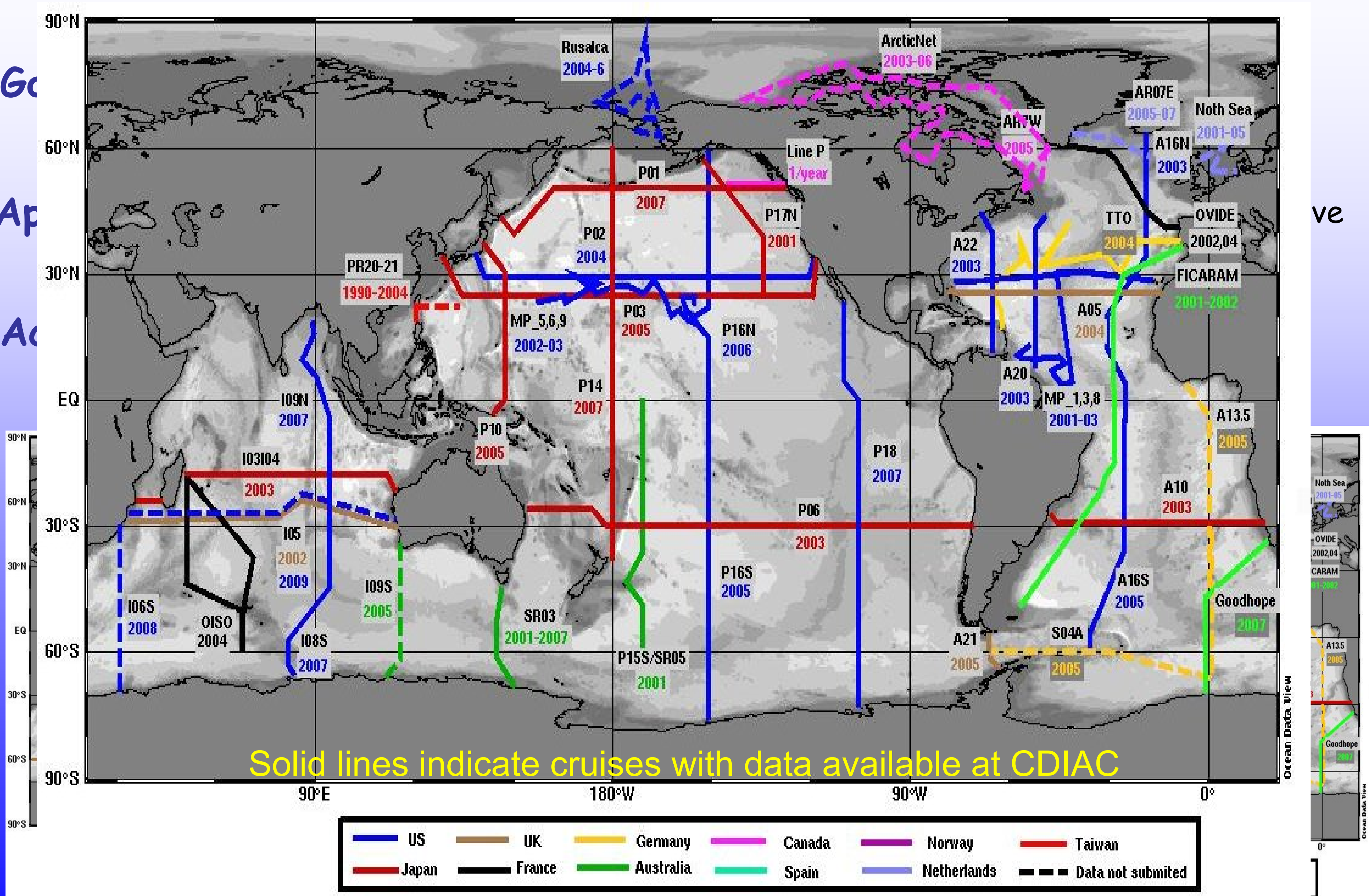
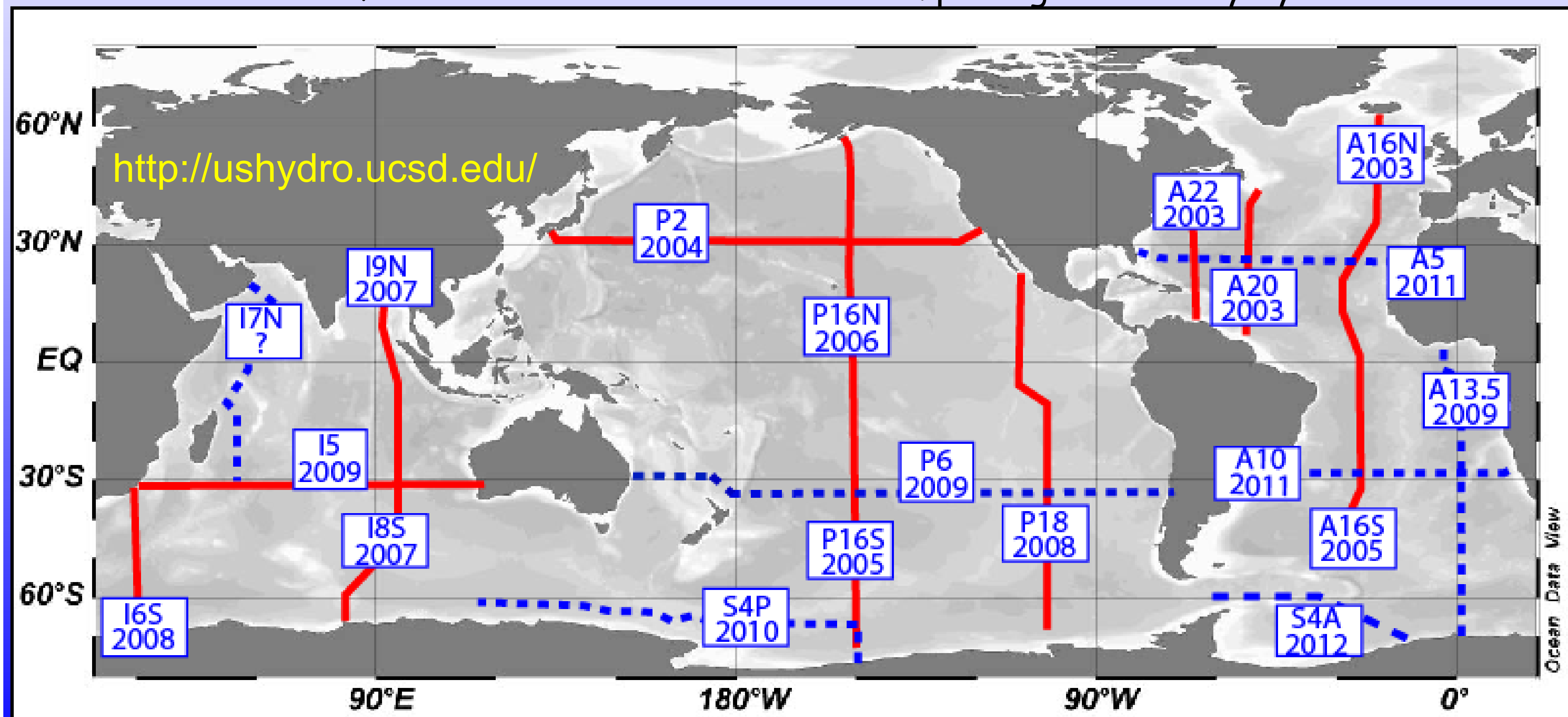


US CLIVAR/CO_2 Repeat Hydrography Program

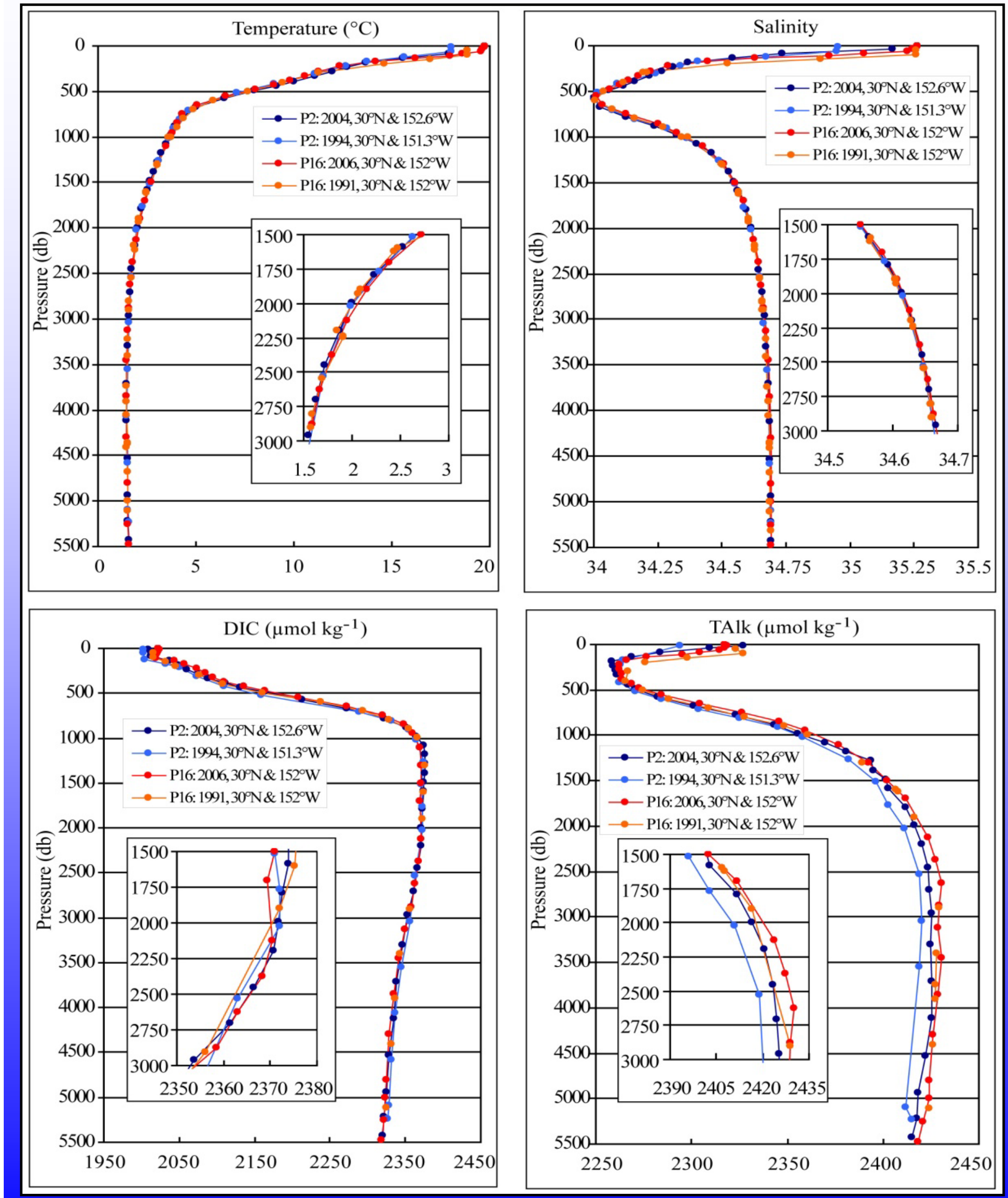
Goal: To quantify decadal changes in the inventory and transport of heat, fresh water, carbon dioxide (CO_2), chlorofluorocarbon tracers and related parameters in the oceans.

Approach: The sequence and timing of the U.S. CLIVAR/CO_2 Repeat Hydrography cruises have been selected so that there is roughly a decade between them and the WOCE/JGOFS global survey.

Achievements: The U.S. CLIVAR/CO_2 Repeat Hydrography Program has completed 12 of 18 lines and is on schedule to complete global survey by 2011.

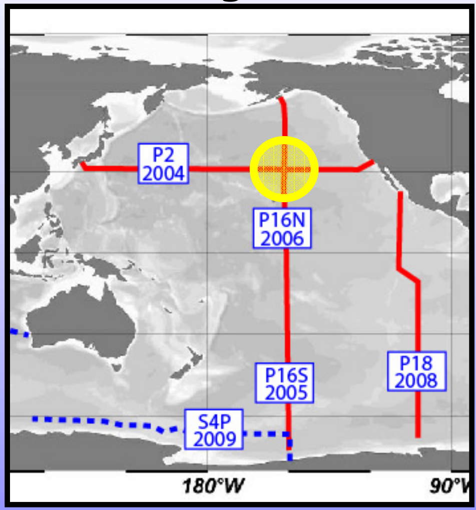


Comparison of profiles from stations near the intersection of P2 and P16N.



Repeat Hydrography Data Are Very High Quality

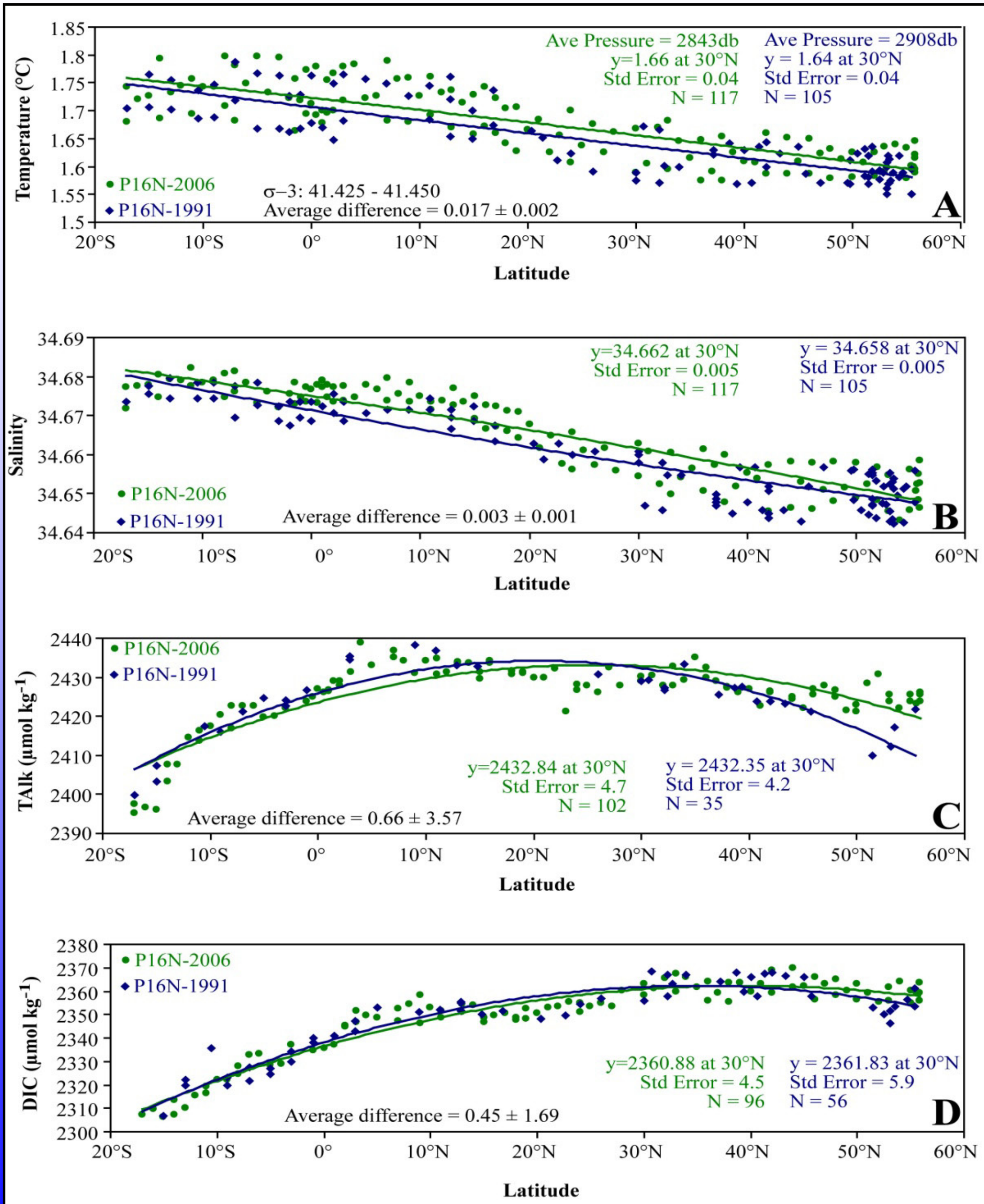
P02 along 30°N
Japan to San Diego, CA
June-August 2004



P16N along 152°W
Tahiti to Kodiak, AK
Feb.-March 2006

Comparison of crossover and overlap stations indicate the DIC data are good to +/- 1 μmol kg^{-1} and alkalinity data are good to +/- 2 μmol kg^{-1}

Comparison of 1991 P16N data with 2006 P16N data along 41.425-41.450 σ_3 isopycnal surface.

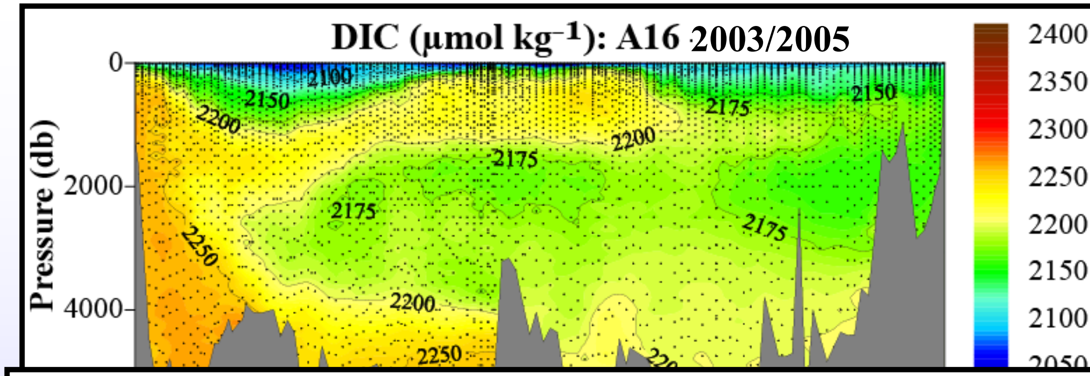


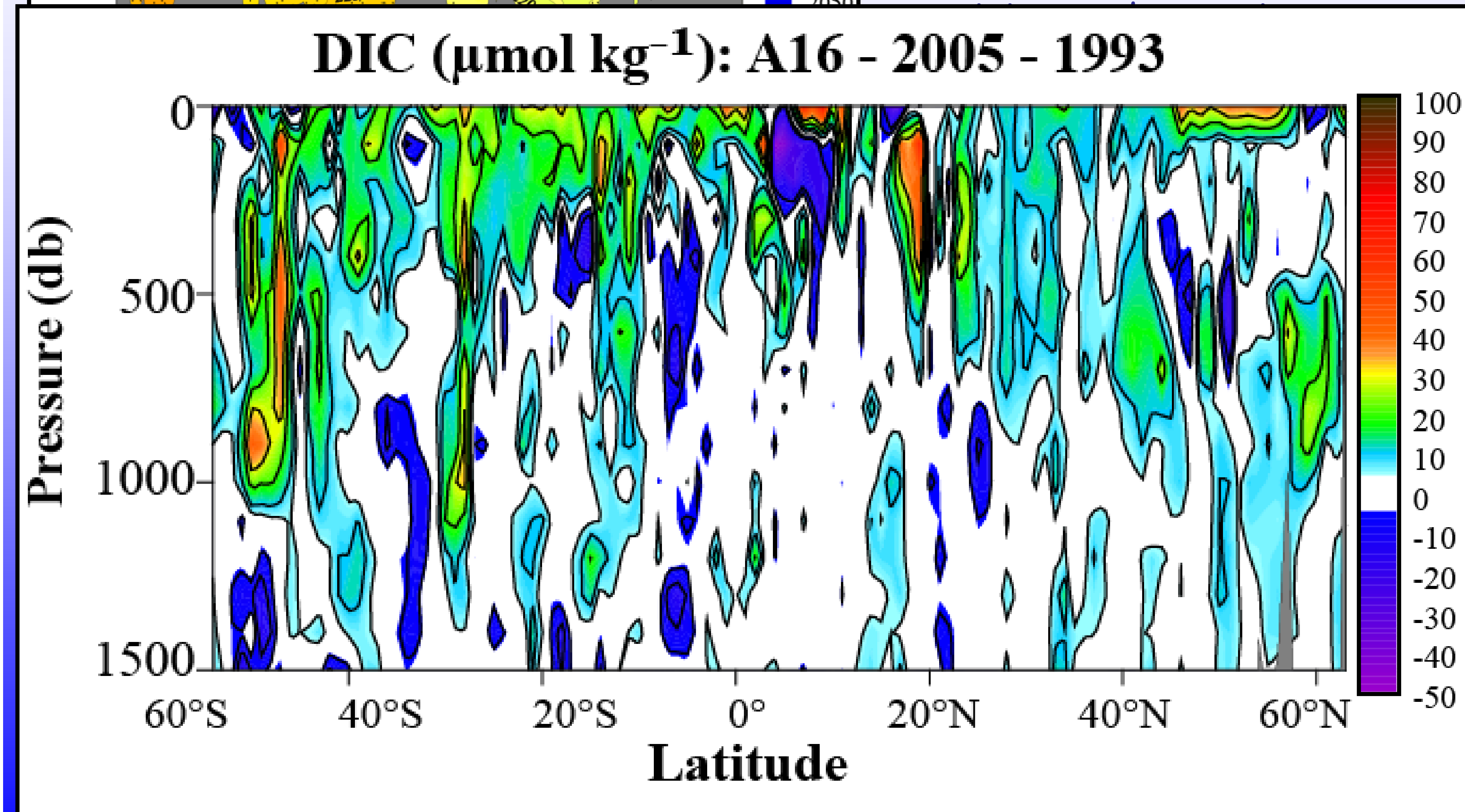
Repeat Hydrography Data Agree Well With Historical Data

These cruises repeat WOCE lines
P02 occupied in 1994 (10 yr diff.)
P16S/P16A in 1991/2 (14 yr diff.)
P16C/P16N in 1991 (15 yr diff.)

Comparison of deep waters on isopycnal surfaces show no significant offsets between Repeat Hydrography and WOCE cruises.

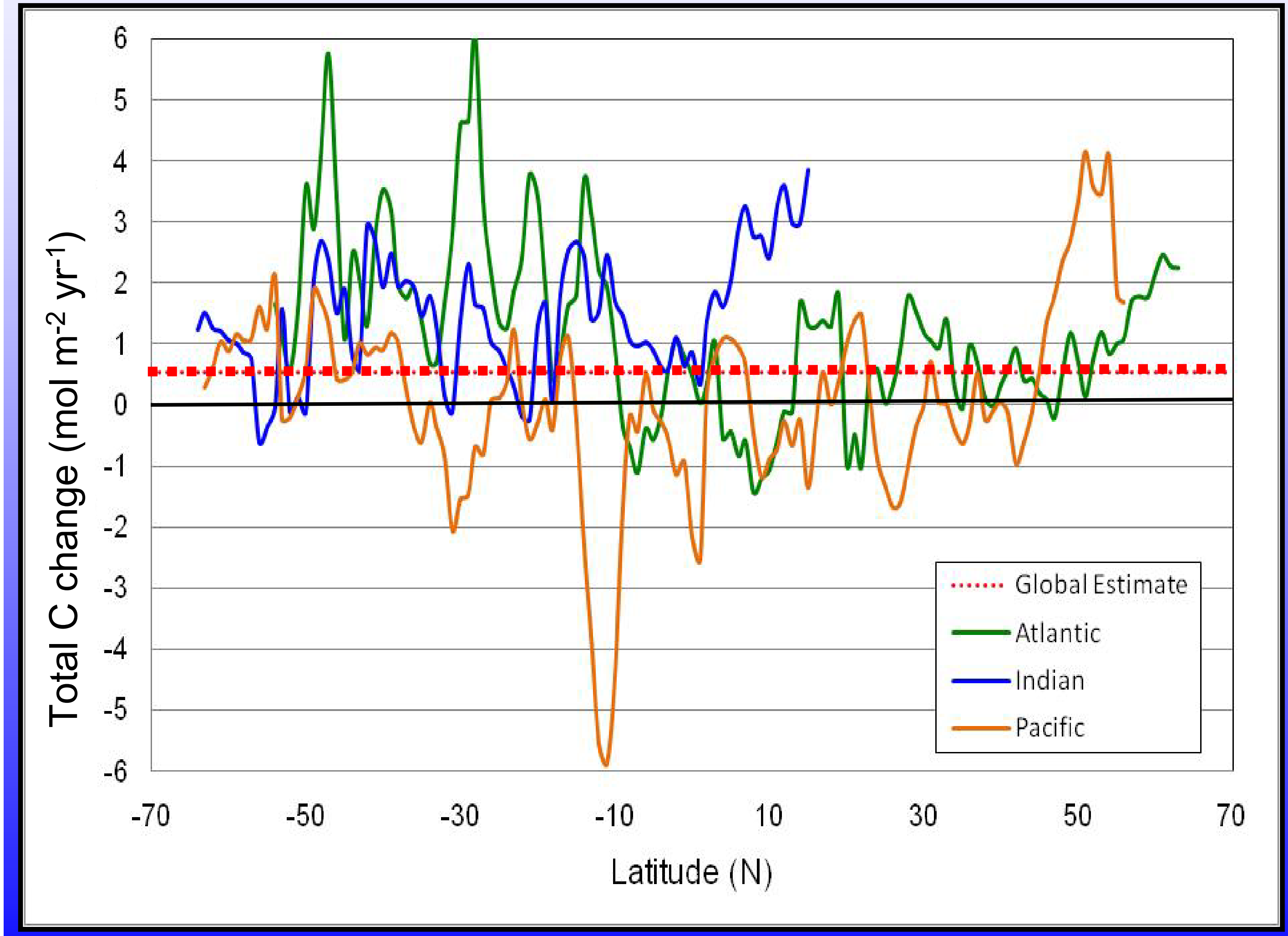
The first order Atlantic DIC distributions look very similar to each other but there are significant differences with both





Measured DIC changes show large variability on small spatial scales

- DIC from each cruise gridded as a function of Latitude and potential density
- The two grids are subtracted
- DIC changes are summed for each station and plotted as a function of Latitude



Average:

Atlantic = 1.2+/-1.4

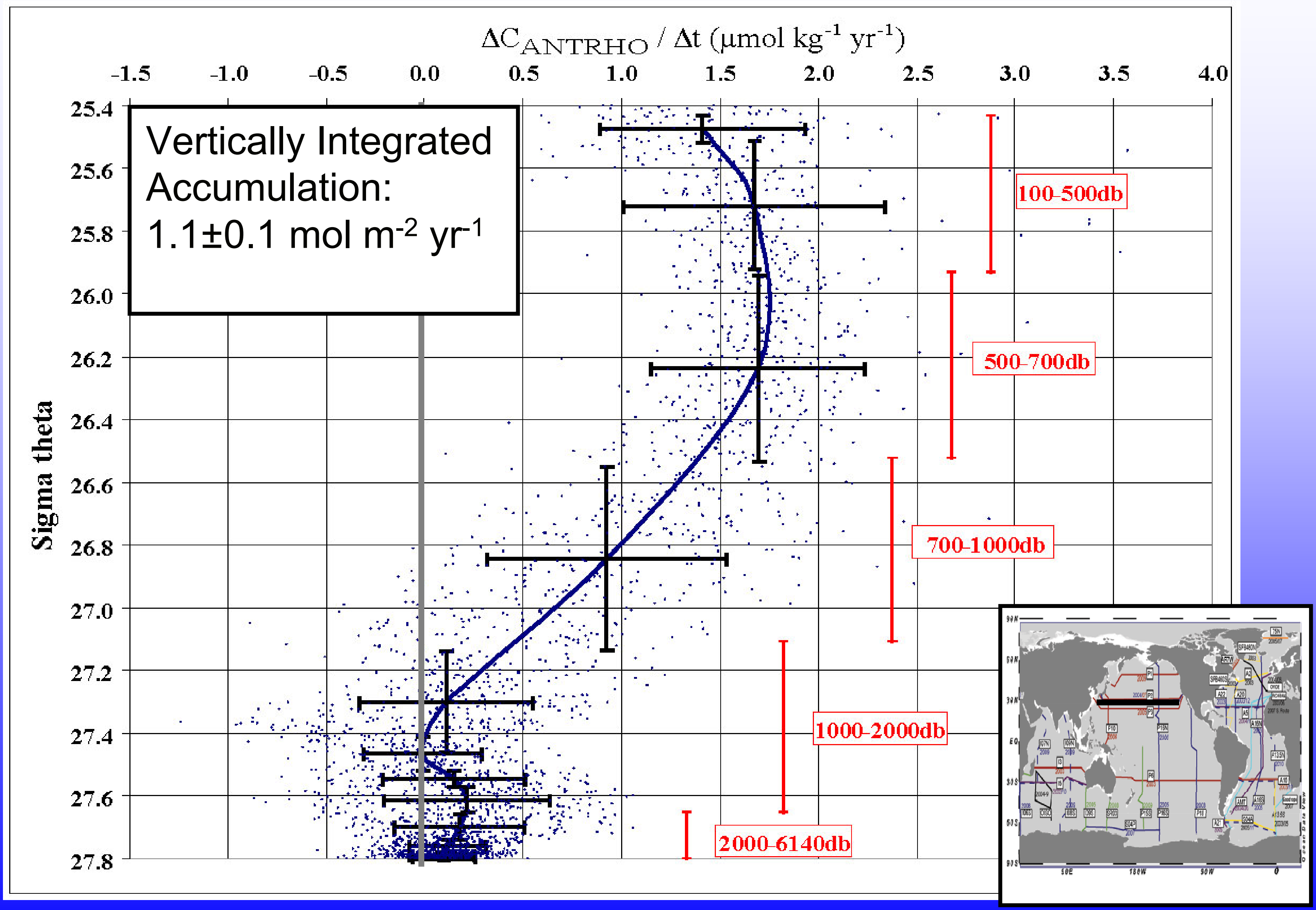
Pacific = 0.1+/-1.6

Indian = 1.5+/-1.0

Average Global Growth Rate of Anthropogenic C is 0.55 mol m^{-2} yr^{-1} Based on uptake of 2.2 Pg C yr^{-1} over a global ocean area of 335.2 x 10^9 km^2

ΔC* column inventory estimates shown previously give a maximum average uptake rate of 0.4 mol m^{-2} $year^{-1}$

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



Use of a Multiple Linear Regression Approach to Isolate the Secular C Changes

Wallace (1995, OOSDP Report #5) first recognized that empirical relationships between carbon and other hydrographic properties could be used to isolate the CO_2 uptake in the ocean.

Approach:

1) Fit carbon data from older cruise with properties that should not be affected by rising atmospheric CO_2,
2) Use empirical fit of older cruise together with hydrographic data from new cruise to predict carbon distributions on the new cruise,
3) The difference between the measured carbon values on the new cruise and the predicted values is a measure of the additional carbon taken up from the atmosphere.

Friis et al. (2005, Deep Sea Res.) refined this approach with the extended MLR where both cruises are fit and take difference in fits.

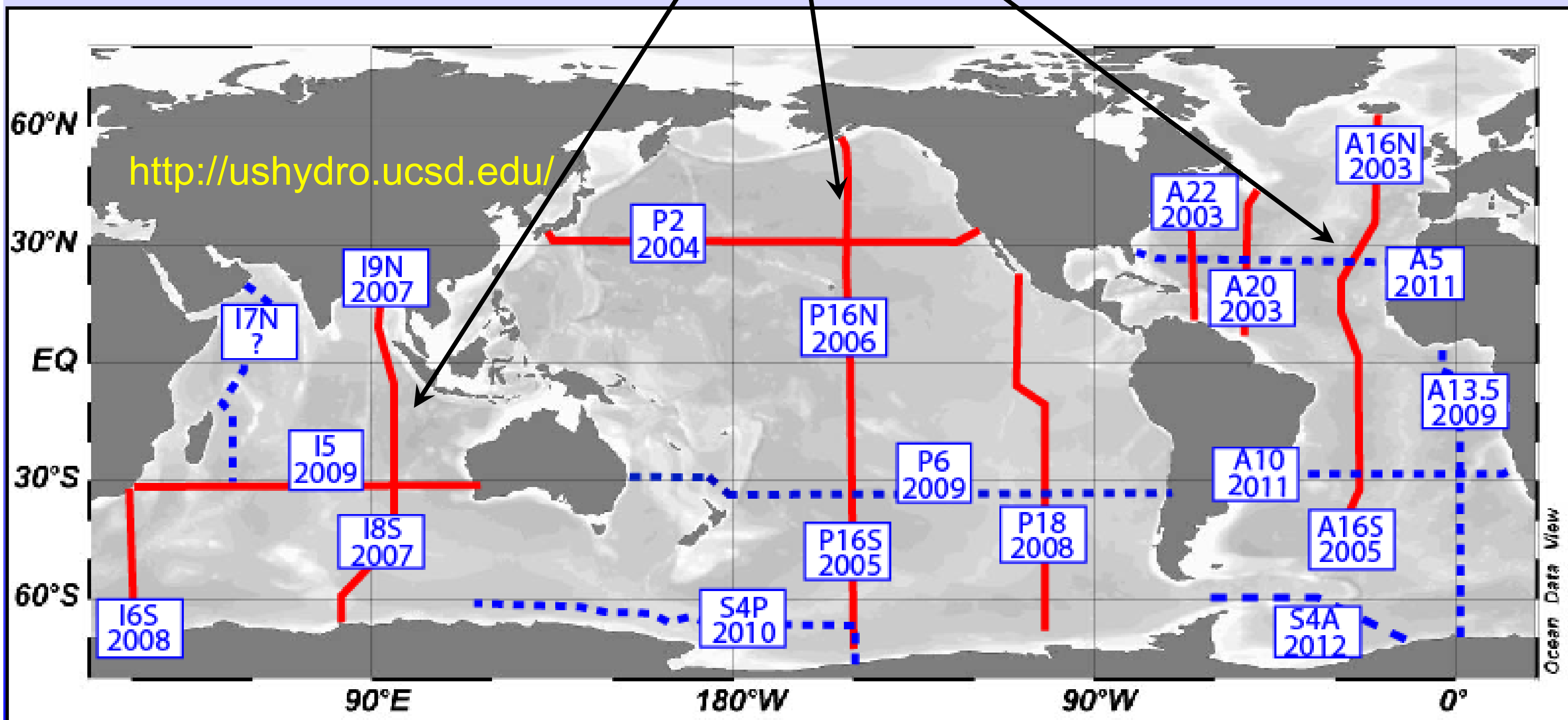
$$DIC_{(1991)} = a^*\sigma_\theta + b^*\theta + c^*S + d^*Si + e^*P + f$$

$$DIC_{(2006)} = A^*\sigma_\theta + B^*\theta + C^*S + D^*Si + E^*P + F$$

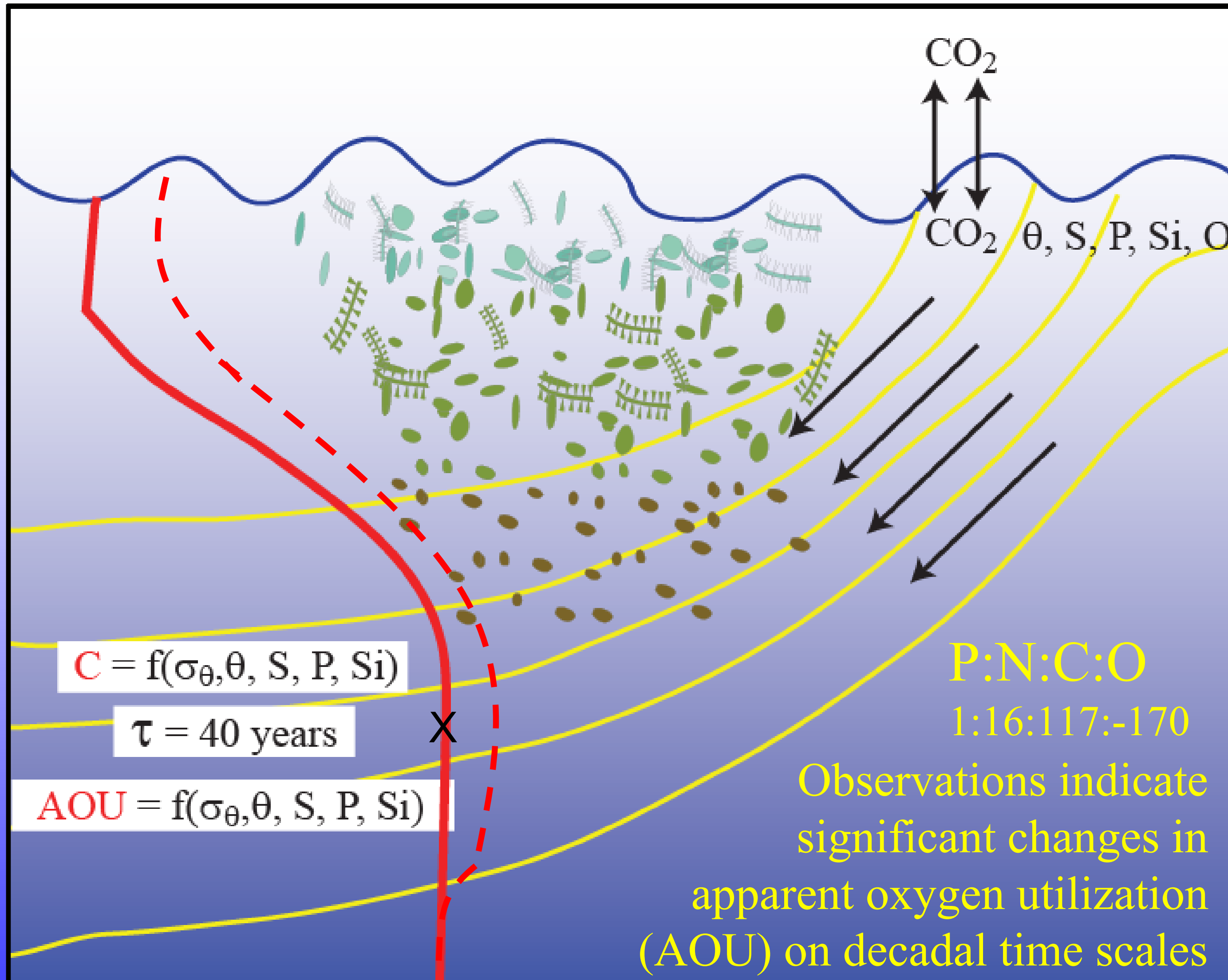
$$\Delta DIC_{(06\text{-}91)} = A\text{-}a^*\sigma_\theta + B\text{-}b^*\theta + C\text{-}c^*S + D\text{-}d^*Si + E\text{-}e^*P + F\text{-}f$$

What are the data telling us?

Compare representative lines from each of the basins to examine some of the issues we are facing

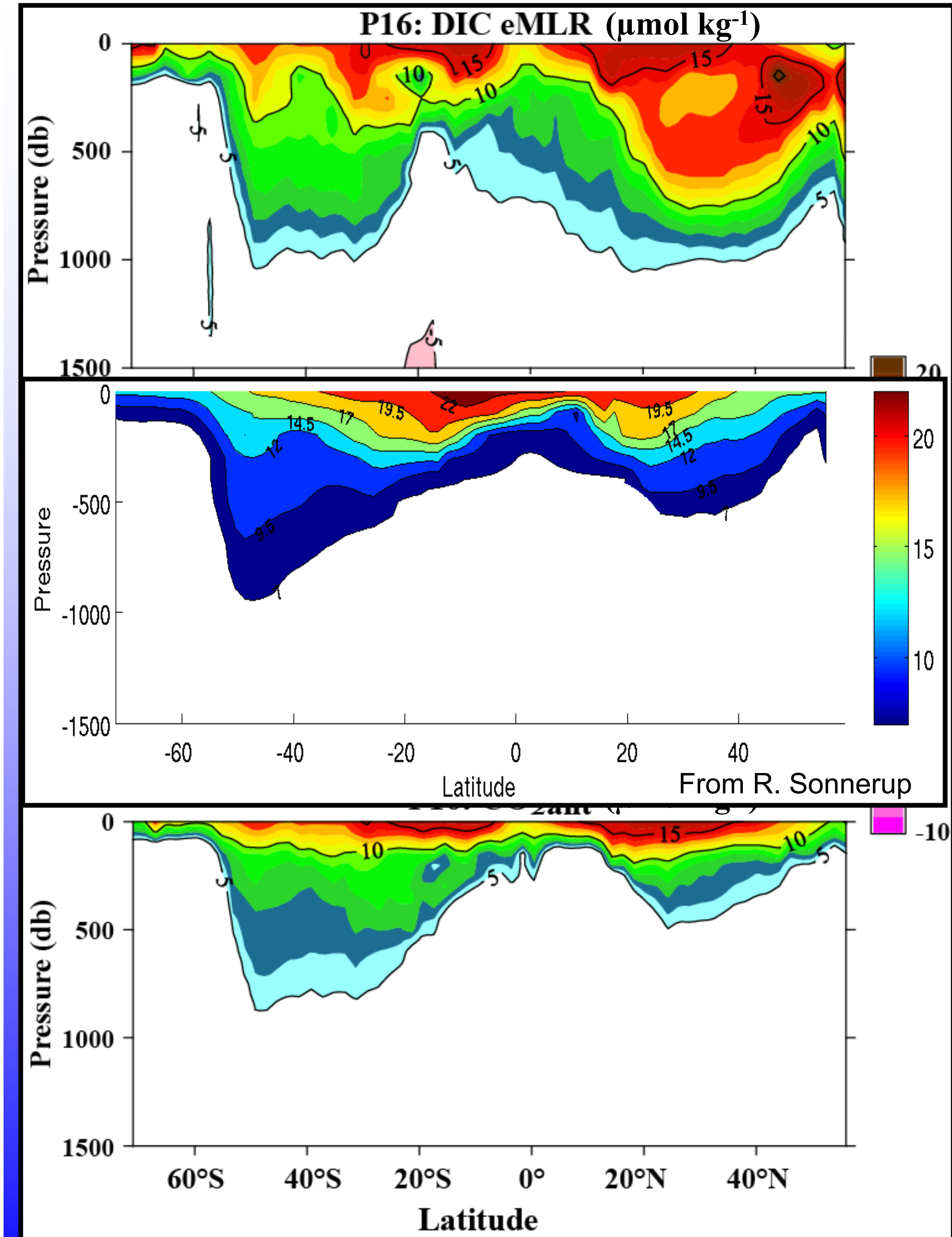


How do changes in circulation affect decadal carbon storage?



By excluding AOU from the DIC fit and fitting AOU independently with an eMLR function we can separate the atmospheric uptake from the changes in remineralization rates

Changes in circulation or changes in export flux can alter the apparent remineralization rate affecting the carbon distributions relative to the other parameters - use AOU to estimate this change



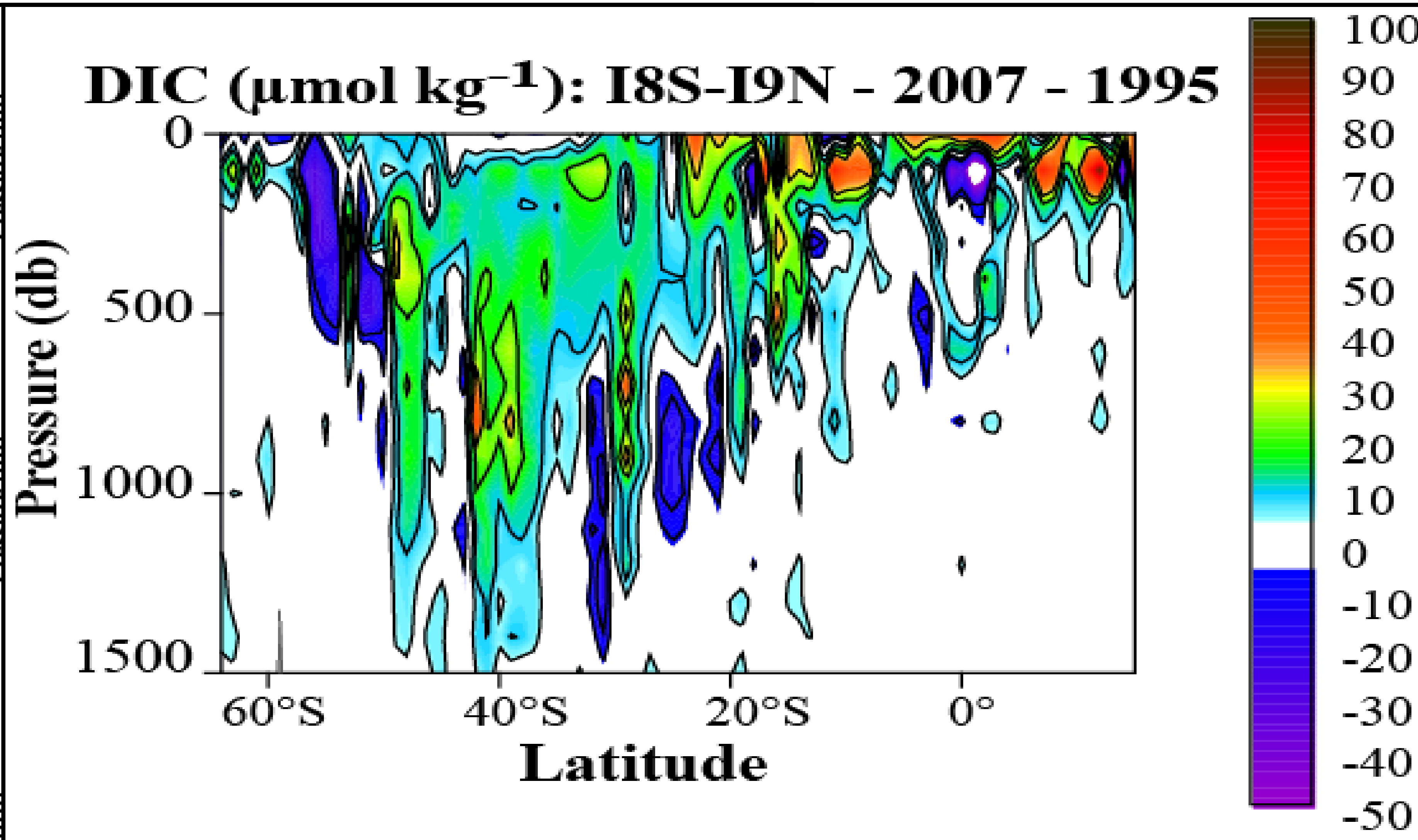
Pacific eMLR Sections Show Much More Coherent Patterns of Change

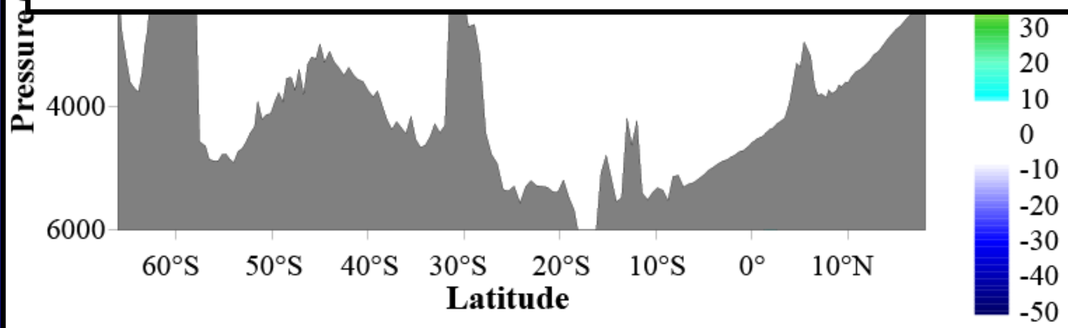
eMLR function without AOU shows a very large DIC change in the North Pacific

The AOU eMLR function isolates the change in apparent remineralization rate

Subtracting the AOU eMLR from the DIC eMLR gives the atmospheric CO_2 uptake

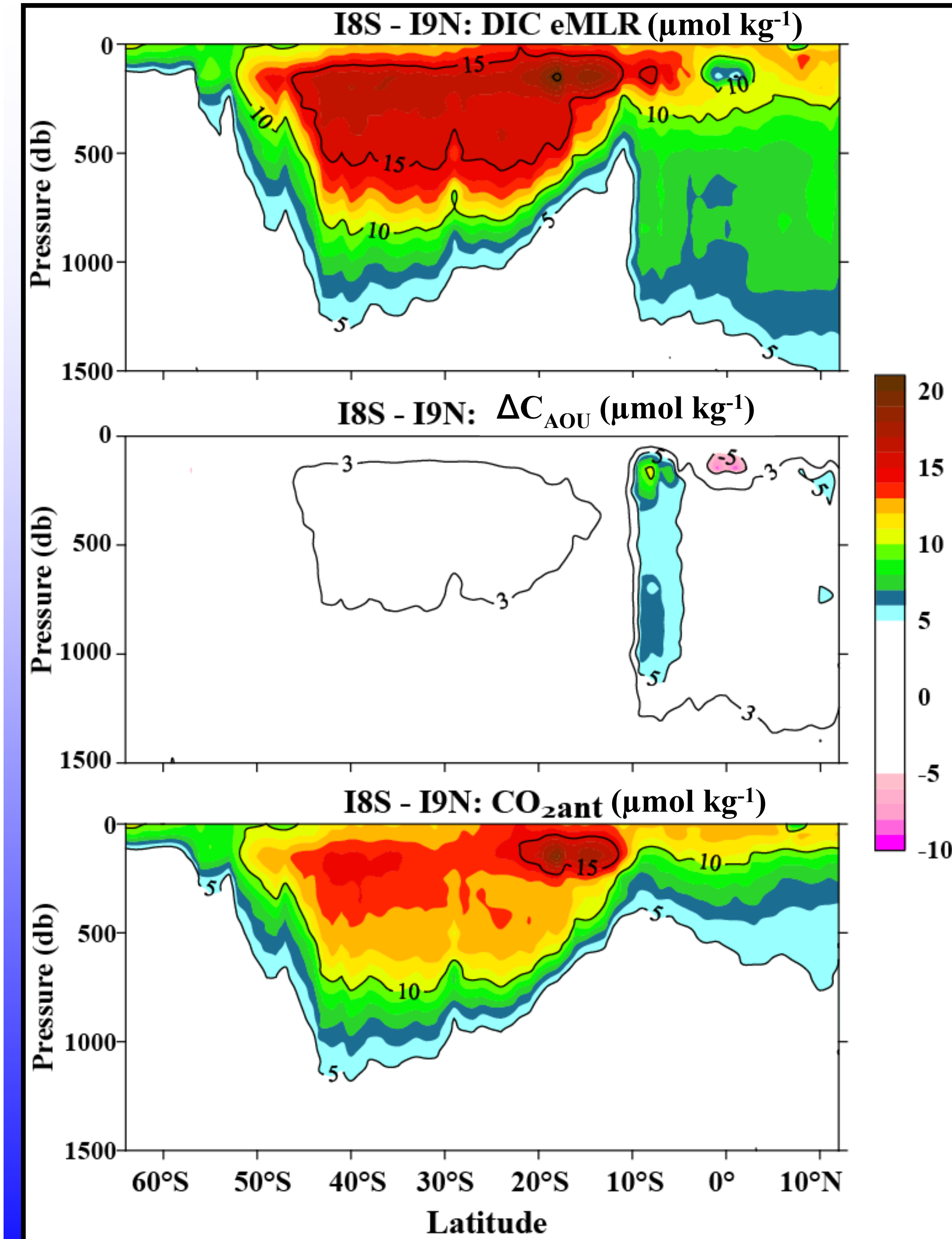
* AOU converted to C units using Redfield Ratio





However, there are some negative values and the magnitude of the change is larger than expected.

Indian eMLR Sections Are Similar To The Pacific



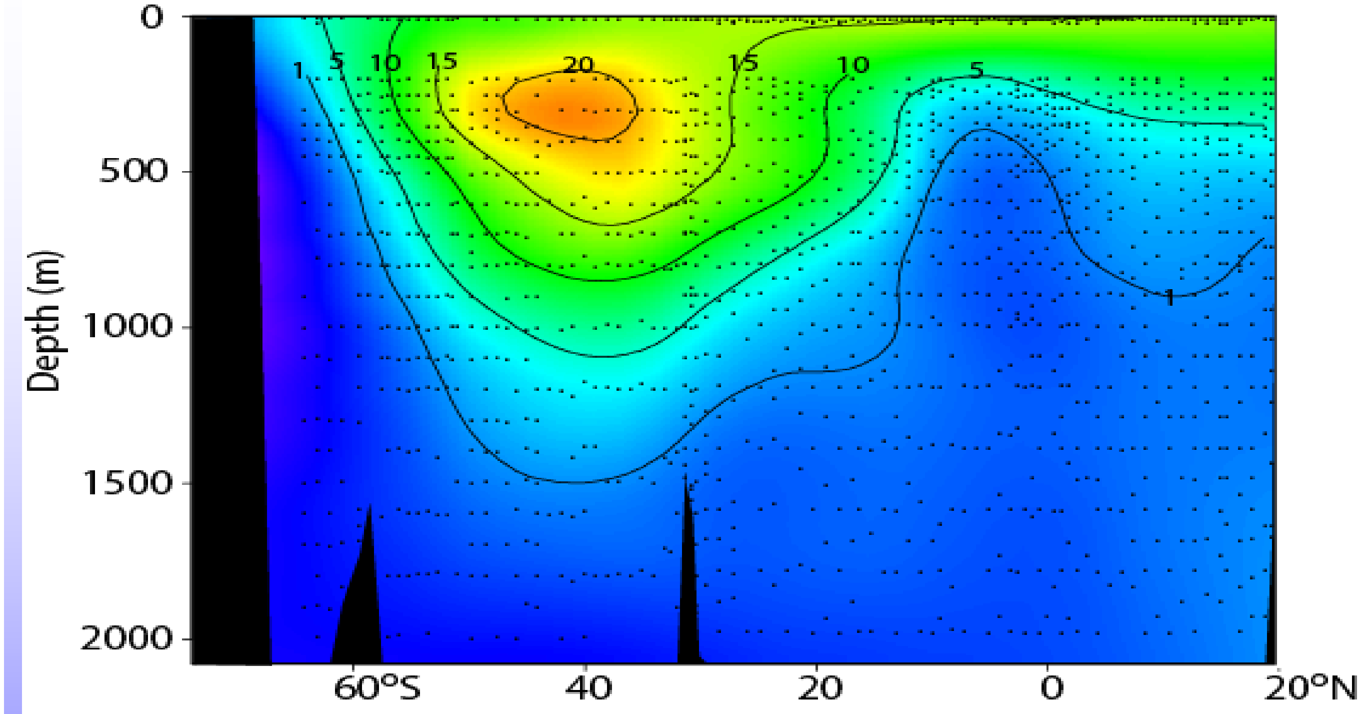
eMLR function without AOU suggests deep carbon changes north of the chemical front (~10S)

The AOU eMLR function also shows modest changes

Subtracting the AOU eMLR from the DIC eMLR gives a pattern of change that is more consistent with previous estimates

Sabine et al., in prep

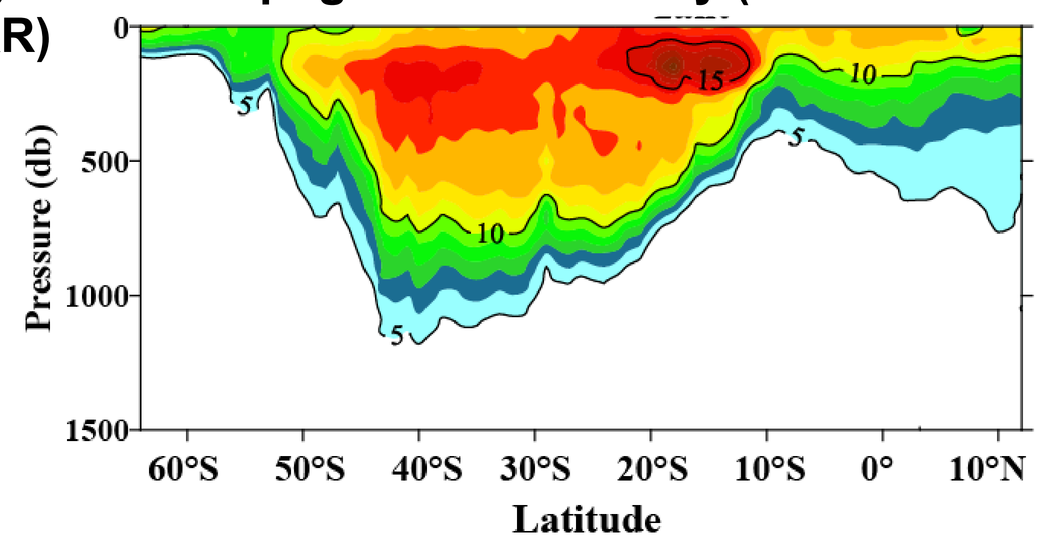
Change in Anthropogenic C Inventory (GEOSECS to WOCE)



Average inventory Change 1995-1977: 0.45±0.3 mol m^{-2} yr^{-1}

From Sabine et al. (1999)

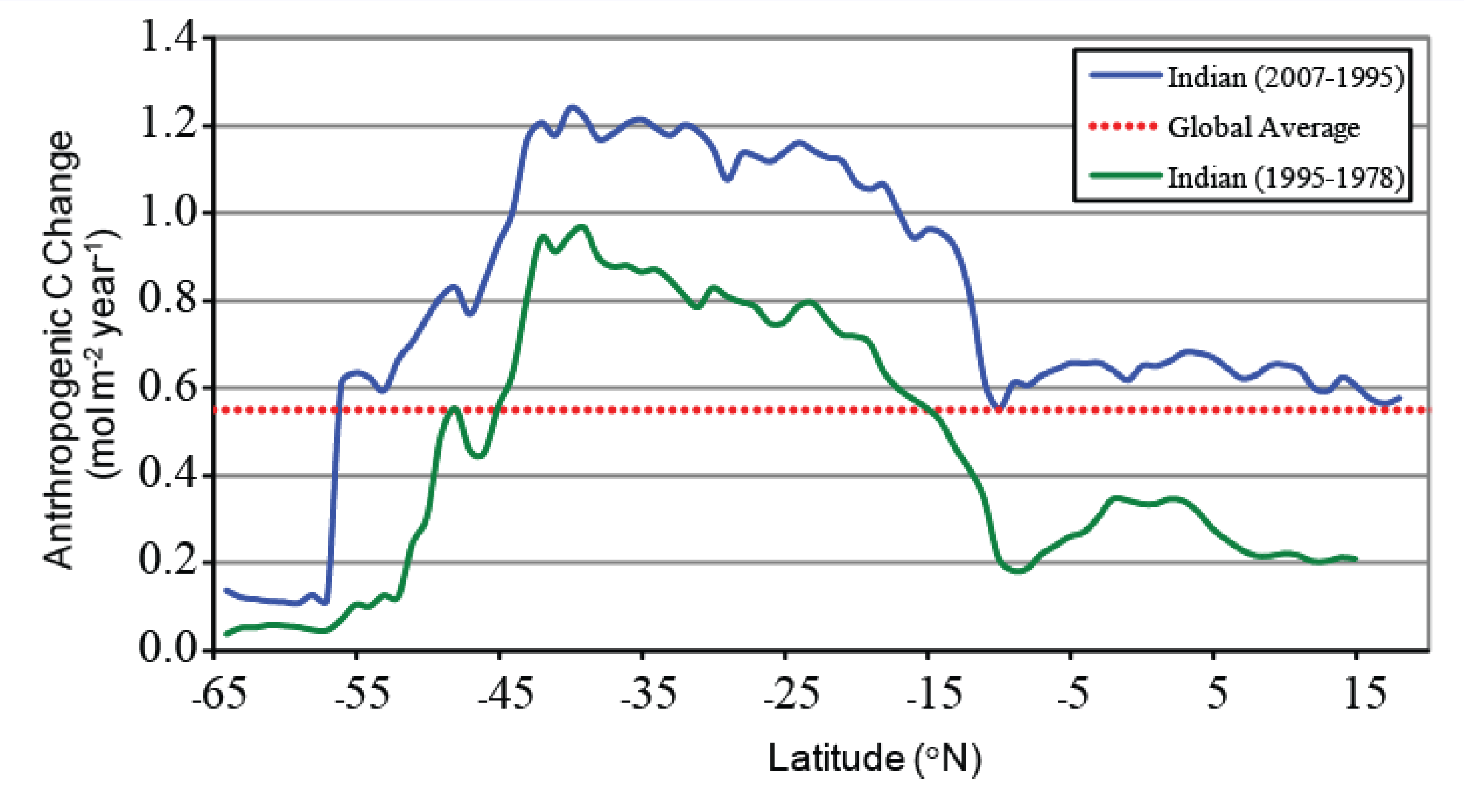
Change in Anthropogenic C Inventory (WOCE to CLIVAR)



Average inventory Change 2007-1995: 0.79±0.3 mol m^{-2} yr^{-1}

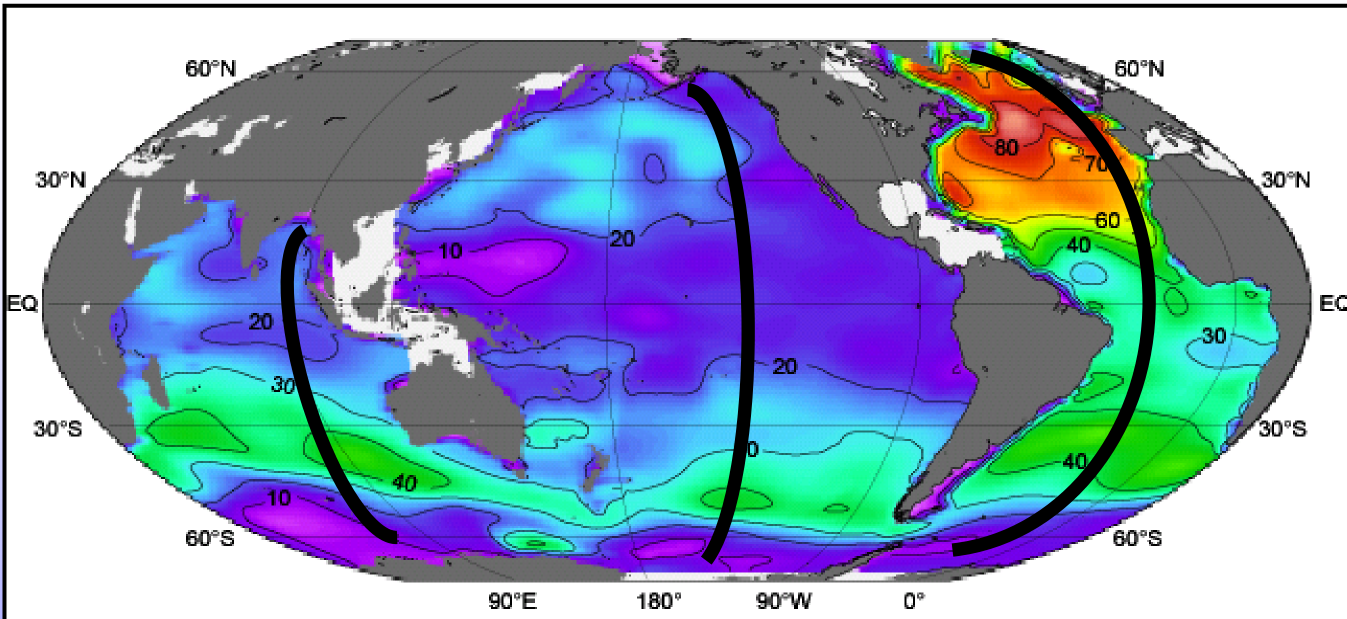
Comparison of the Change in Anthropogenic C Inventory over two decadal periods

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.

CLIVAR/CO_2 Repeat Hydrography Interim Results

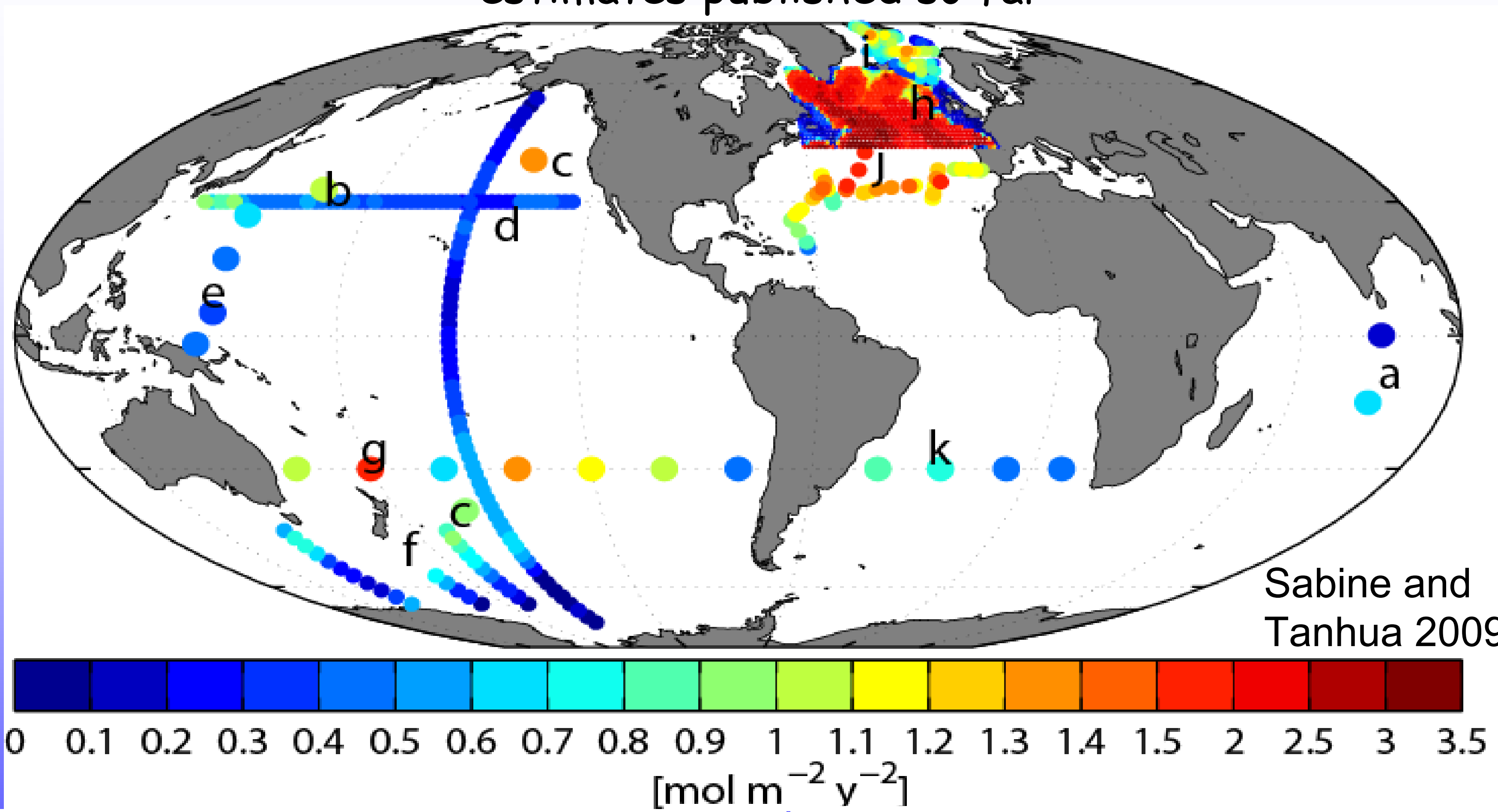


Preliminary analyses suggest that the regional anthro. C inventory changes over the last decade may have a different pattern from the long-term carbon storage distributions.

Preliminary Estimates of Decadal Ocean Anthropogenic Carbon Column Inventory Changes since WOCE (mol C m^{-2} yr^{-1}).

$\frac{\text{mol C}}{\text{m}^2\ \text{yr}}$	Atlantic Ocean (along 25°W)	Indian Ocean (along 90°E)	Pacific Ocean (along 152°W)
Northern Hemisphere	0.63	0.63	0.25
Southern Hemisphere	0.75	0.83	0.41

The situation is not so clear when you consider all of the different estimates published so far



#	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 1994 - 2004	eMLR
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

So, where do we go from here?

Primary goal of the Repeat Hydrography Program is to evaluate the global decadal C inventory changes to answer the question :

Are the patterns of ocean carbon uptake changing with time…if so, how and why?

Assets:

- Many new high quality data sets collected since WOCE
- Recent completion of the CARINA synthesis and QC
- Initialization of a Pacific synthesis effort with ~200 new cruises

Challenges:

- Cruises are not synoptic in time (only a few cruises per year)
- Significant decadal scale variations in circulation
- Inconsistent approaches for evaluating carbon changes
- Different physical and chemical characteristics in each basin

Conclusions

1) The Repeat Hydrography program is providing high quality data that is essential for detecting inventory changes
2) The observations reveal very large changes in carbon concentrations on decadal time scales.
3) Changes in apparent organic remineralization rates can have a significant impact on total carbon changes on decadal time scales and must be accounted for.
4) The full international repeat hydrography data set will be required to properly constrain the global decadal carbon change signal.
5) A coordinated approach to making decadal carbon inventory assessments will lead to more consistent results and a faster understanding of a global carbon storage.

Thank you for your time!

The R/V Thomas G. Thompson arriving in Papeete, Tahiti
for the beginning of P16N February 2006