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Decadal Changes in the Atlantic, Pacific and Indian Ocean Inorganic Carbon Inventories

by

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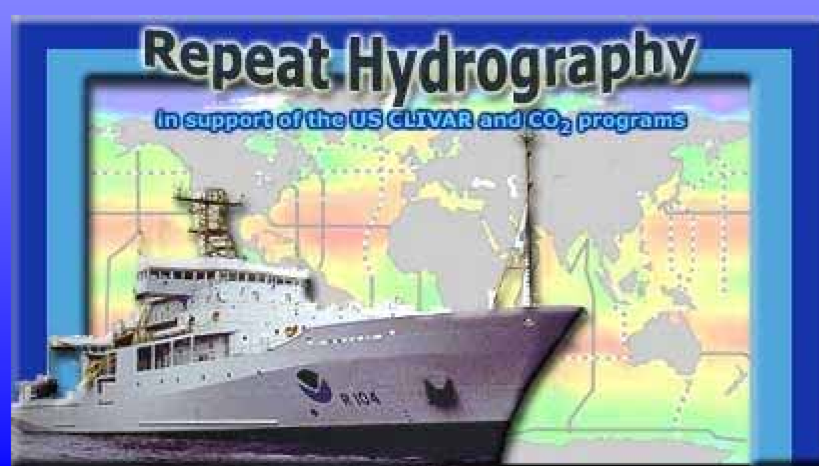
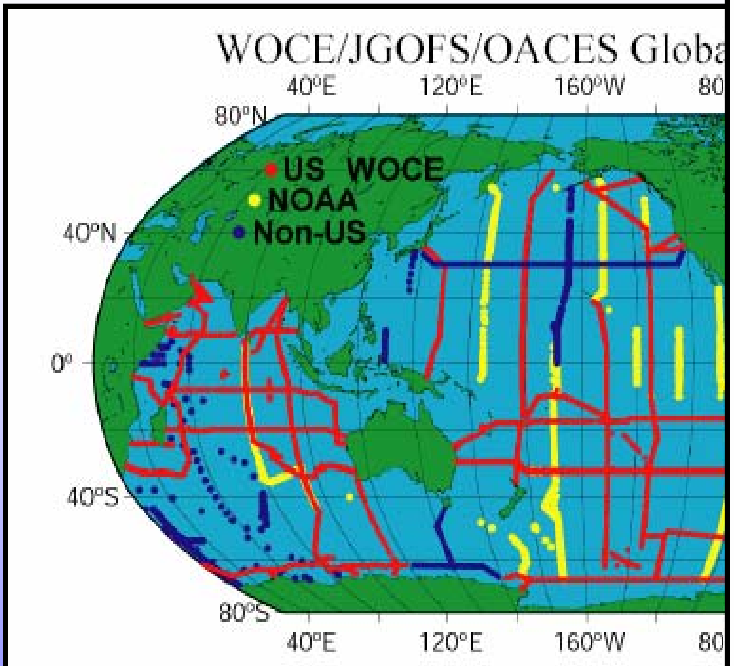
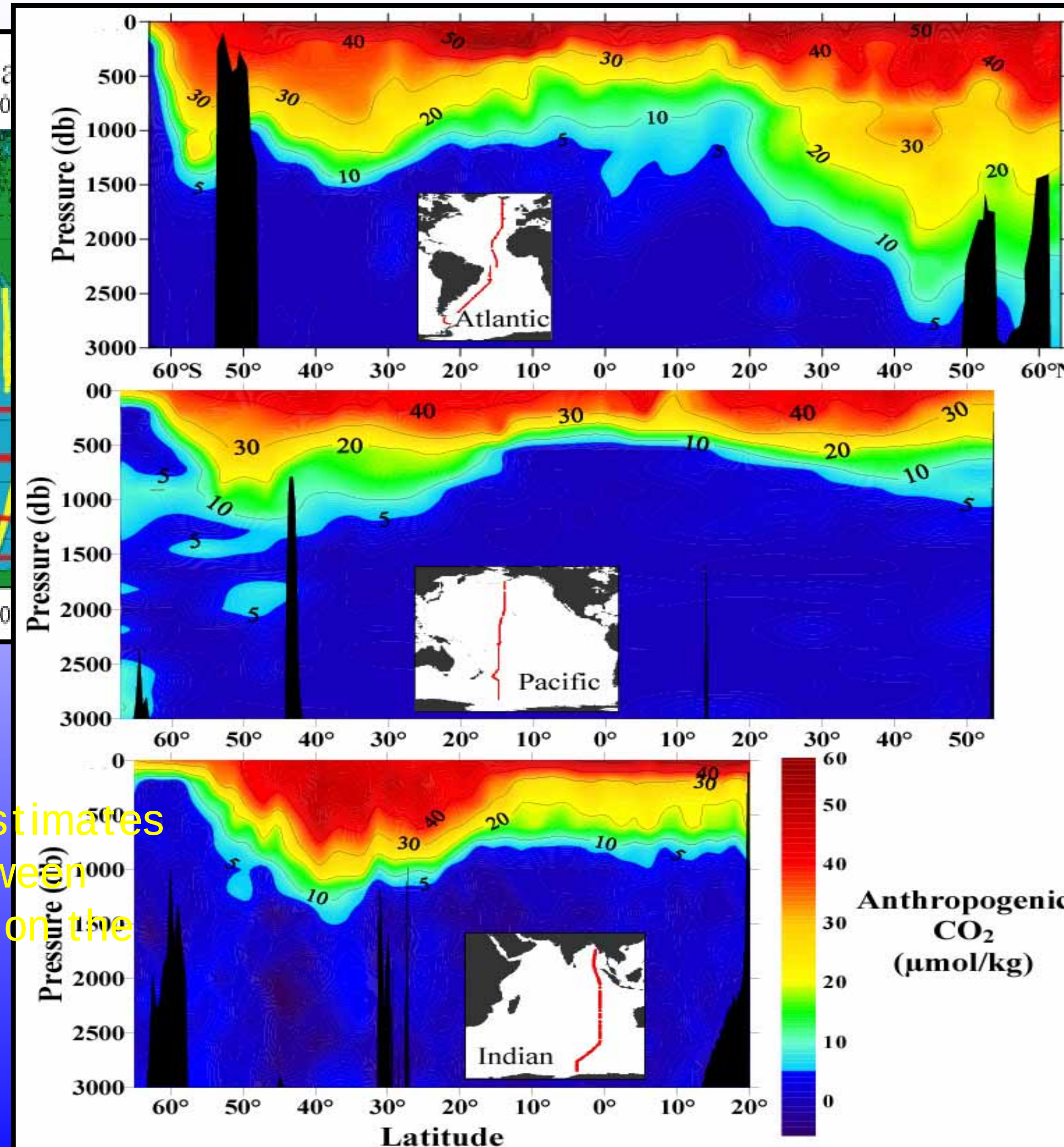


A first look at the distribution of anthropogenic CO_2 in the ocean was based on the WOCE/JGOFS/OACES global survey of carbon conducted in the 1990s.





We see deep penetration in the North Atlantic compared to the North Pacific.
Generally deeper penetration in subtropics vs. tropics.
Relatively little penetration in the high latitude S.O.

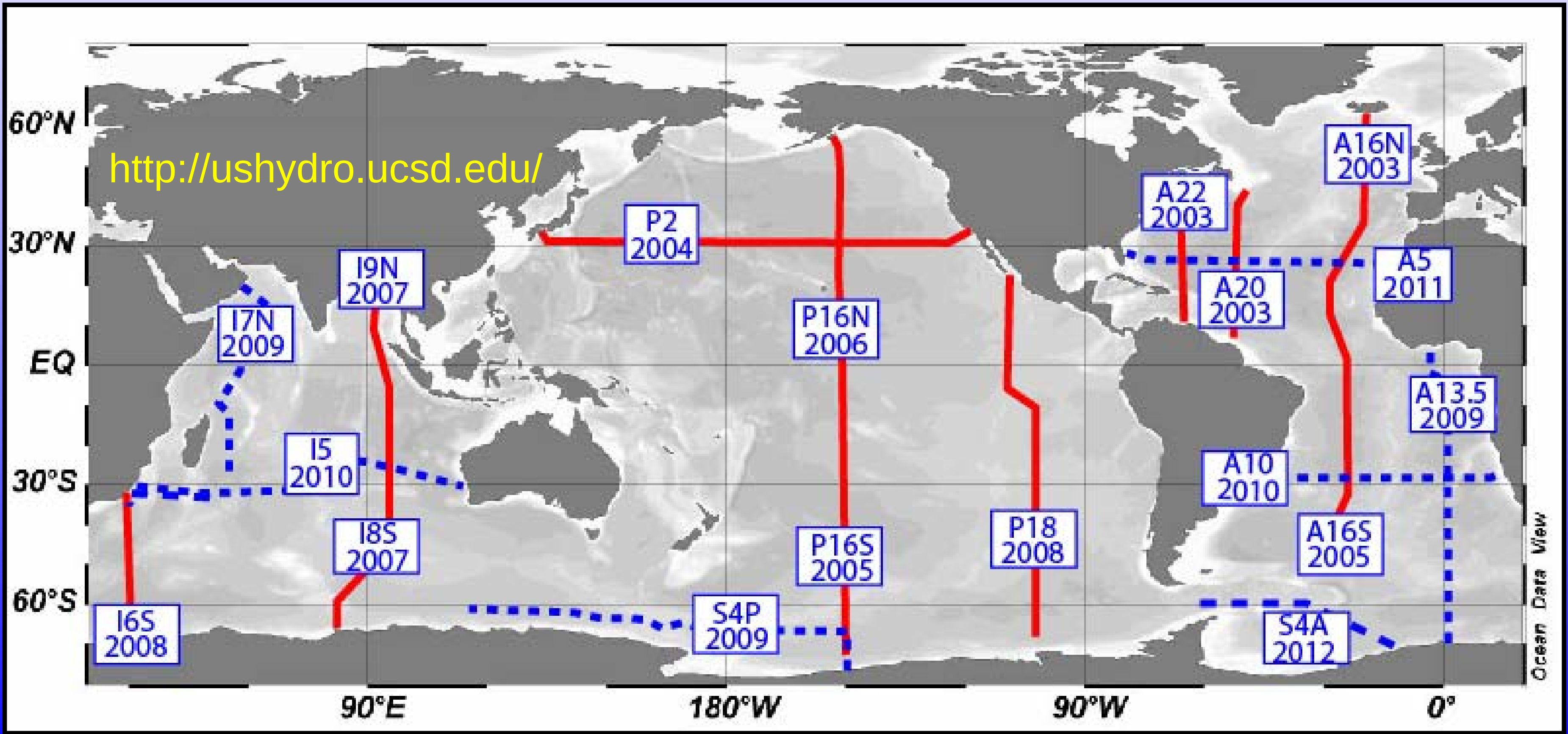
Anthropogenic CO_2 estimates are accumulation between 1800 and 1994 based on the ΔC^* approach.

CLIVAR/CO_2 Repeat Hydrography

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.

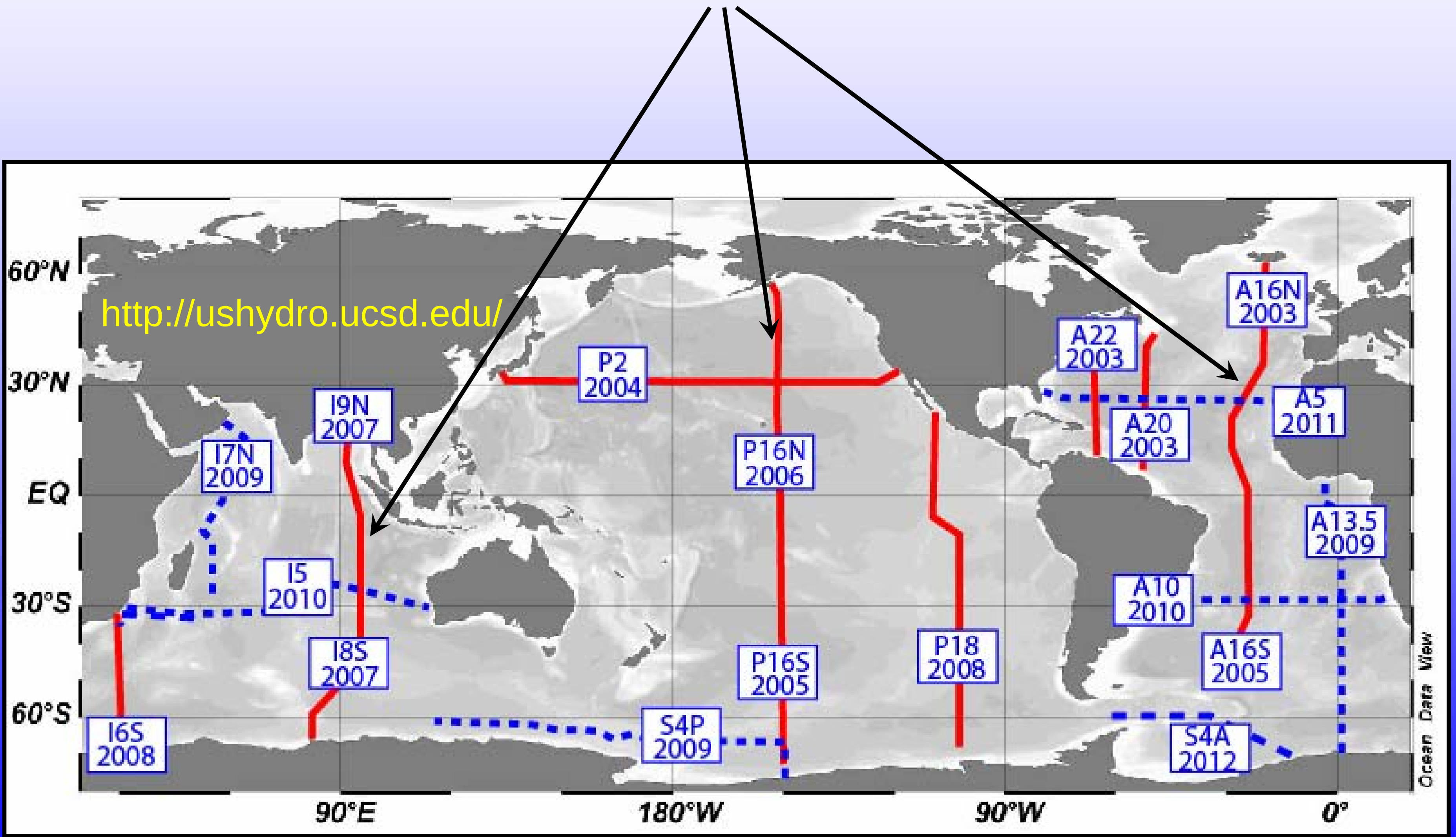
Approach: The sequence and timing of the U.S. CLIVAR/CO_2 Repeat Hydrography cruises have been selected so that there is roughly a decade between them and the WOCE/JGOFS global survey.

Achievements: The U.S. CLIVAR/CO_2 Repeat Hydrography Program has completed 11 of 18 lines and is on schedule to complete global survey by 2012.

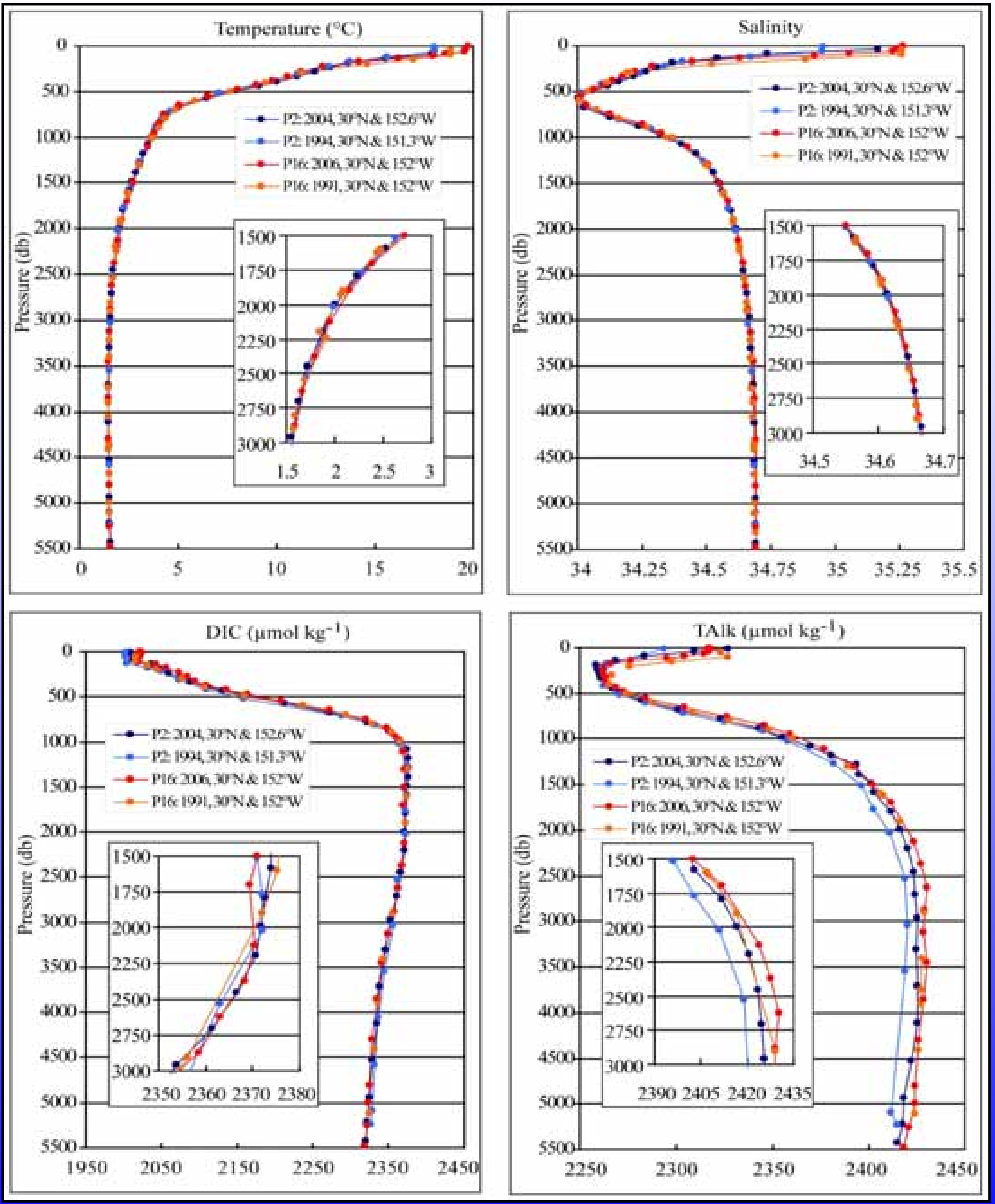


CLIVAR/CO_2 Repeat Hydrography

Today's talk will focus primarily on three representative lines

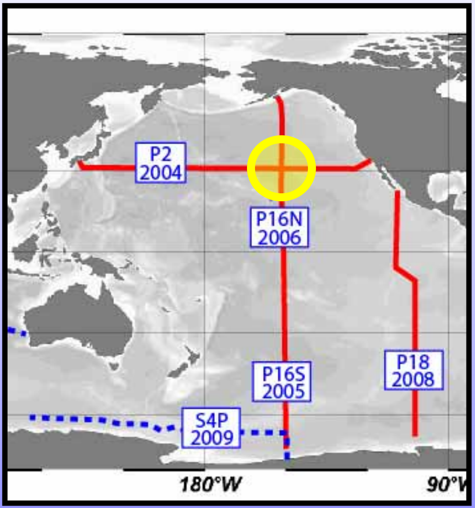


Comparison of profiles from stations near the intersection of P2 and P16N.



Repeat Hydrography Data Are Very High Quality

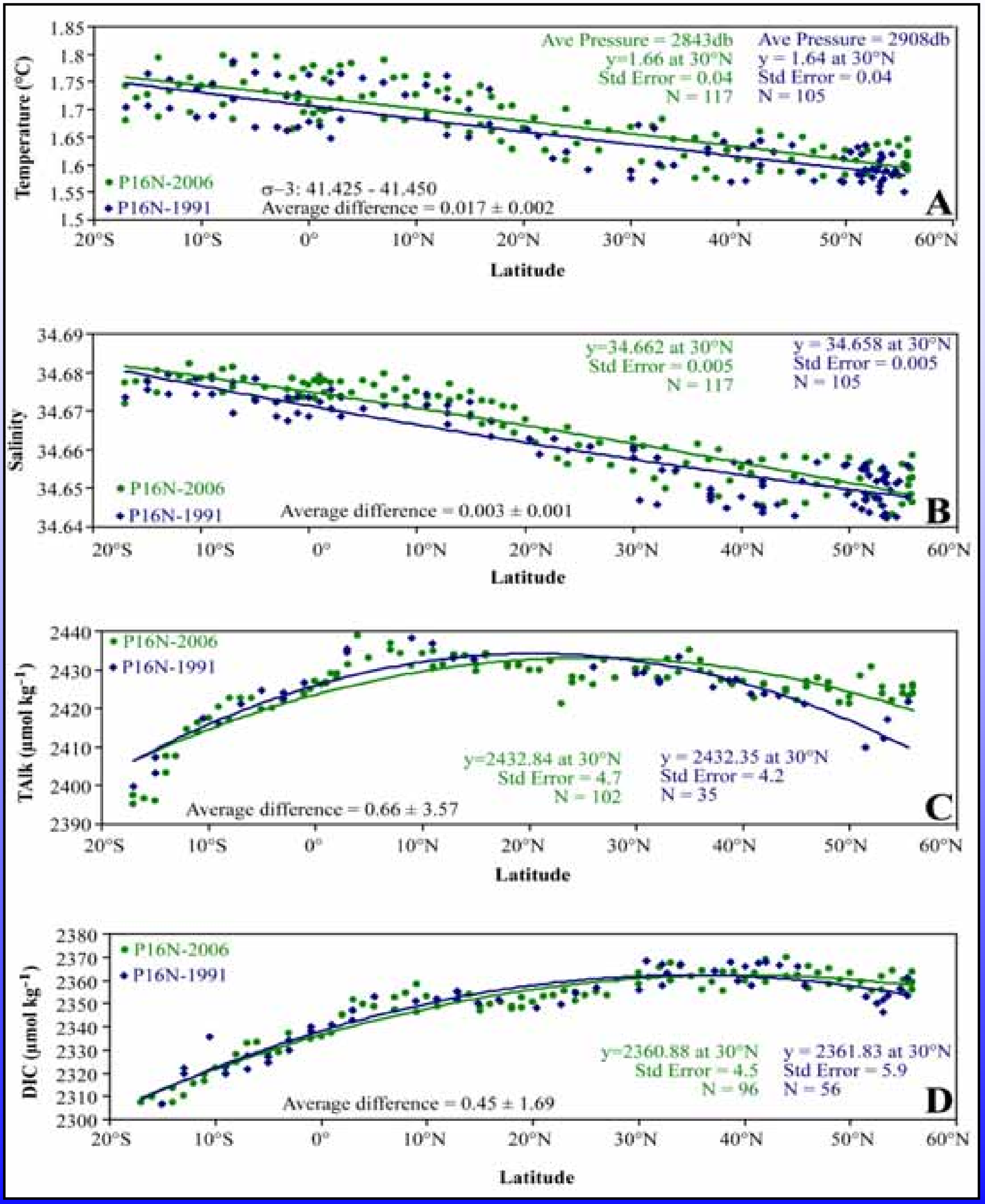
P02 along 30°N
Japan to San Diego, CA
June-August 2004



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

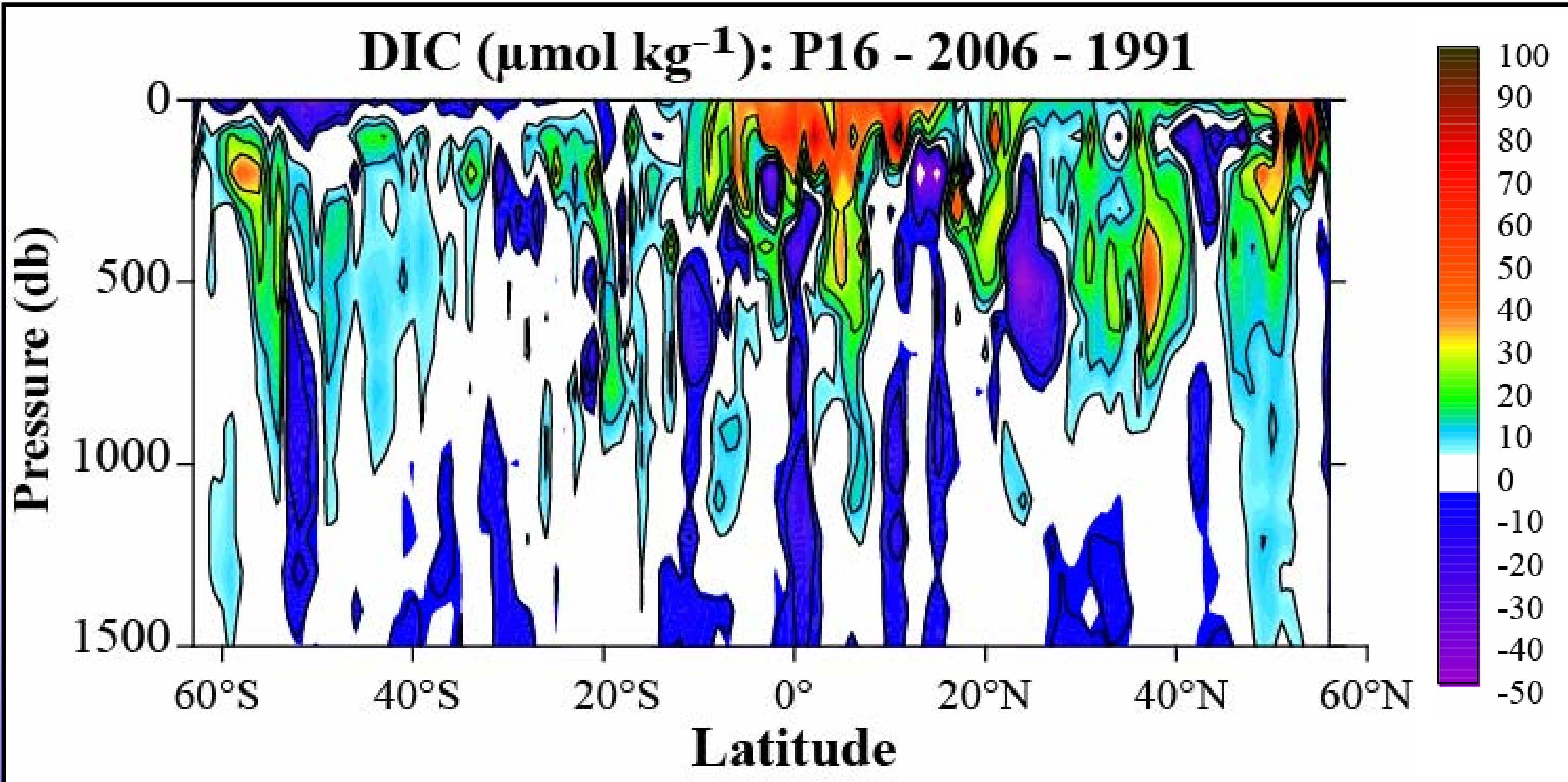
Comparison of crossover and overlap stations indicate the DIC data are good to +/- 1 $\mu mol\ kg^{-1}$ and alkalinity data are good to +/- 2 $\mu mol\ kg^{-1}$

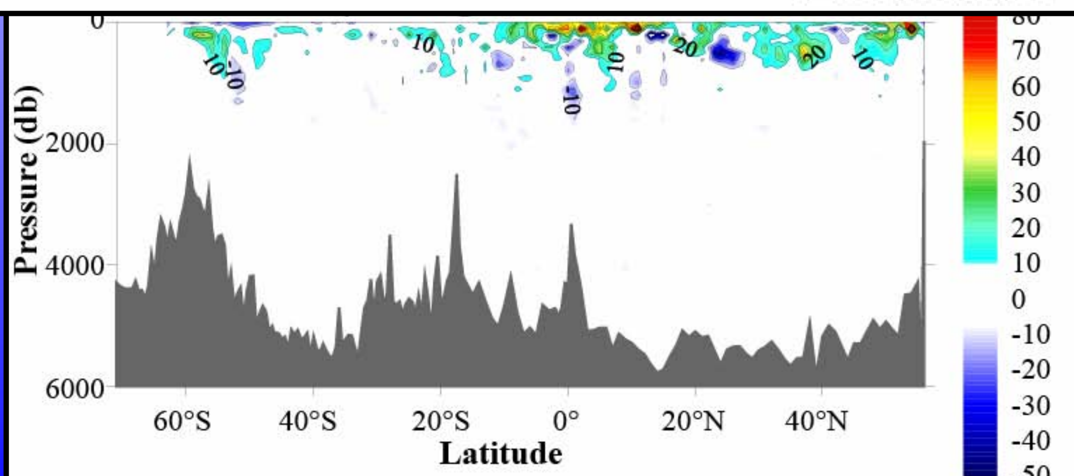
Comparison of 1991 P16N data with 2006 P16N data along 41.425-41.450 σ_3 isopycnal surface.



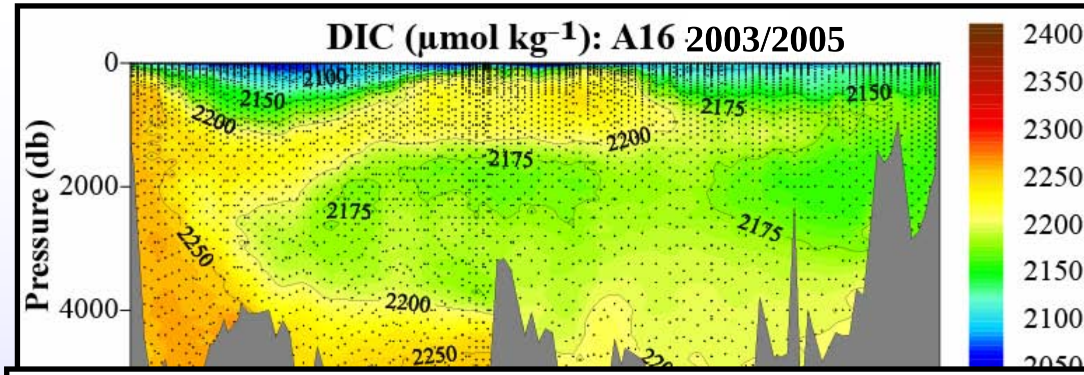
Repeat Hydrography Data Agree Well With Historical Data

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

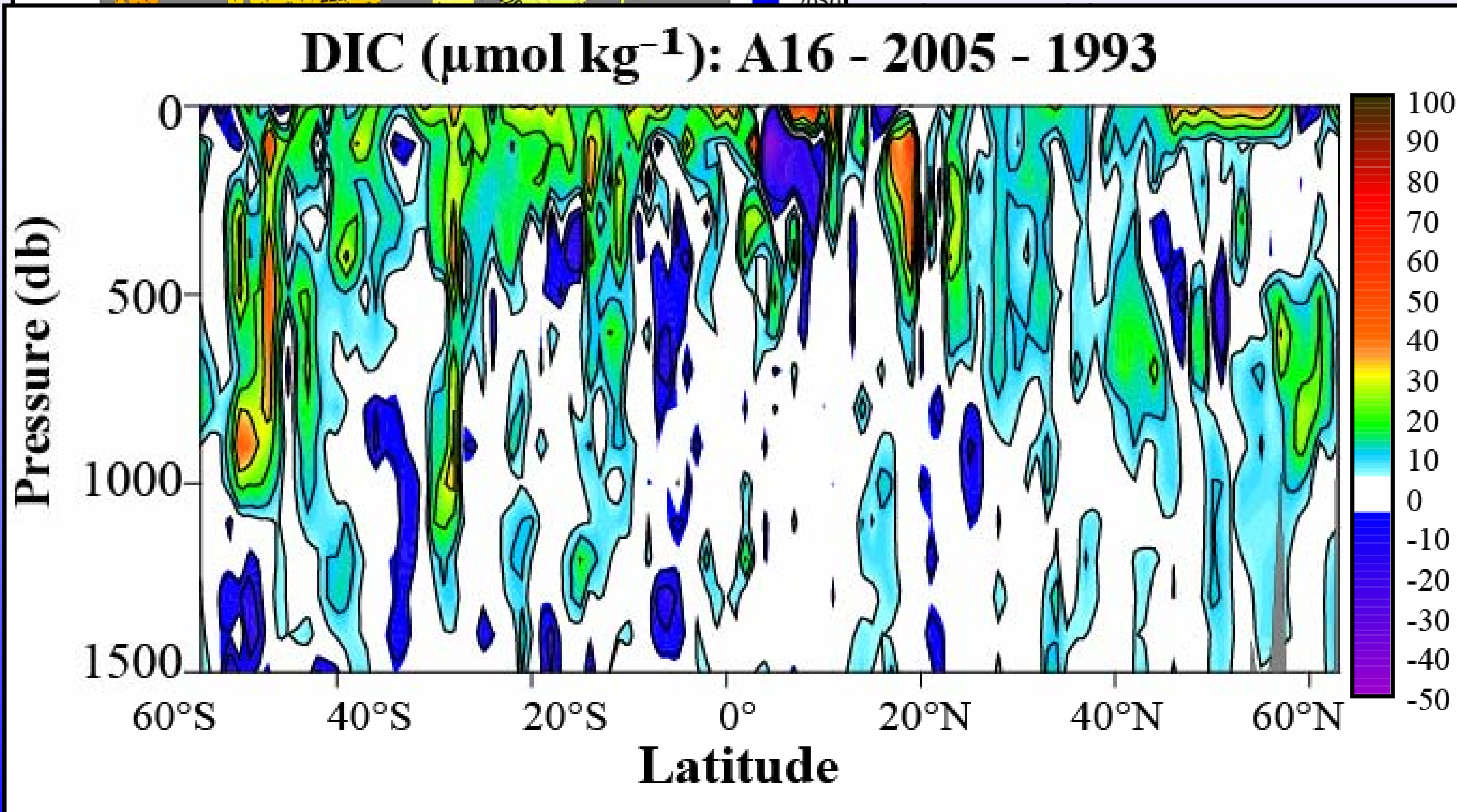


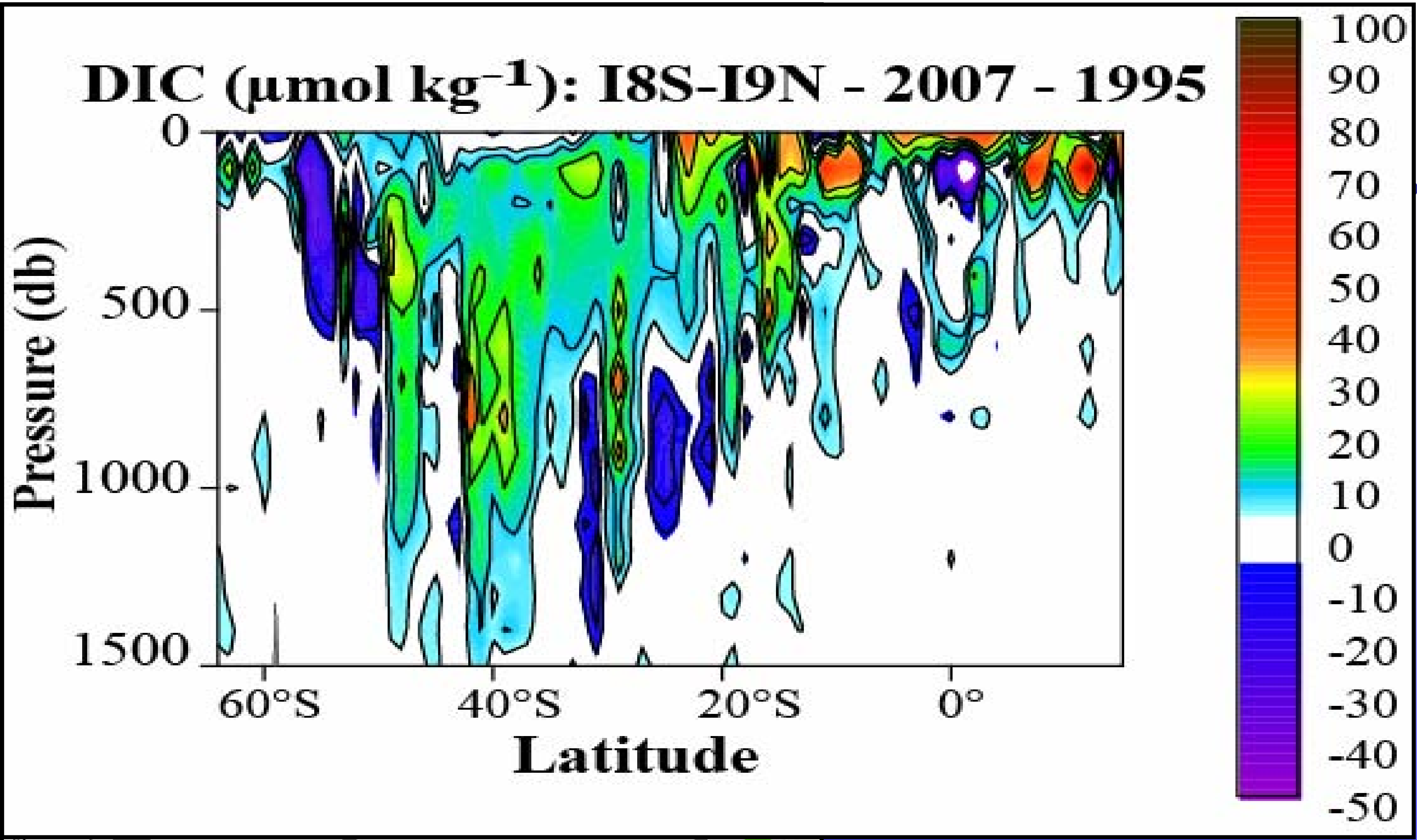


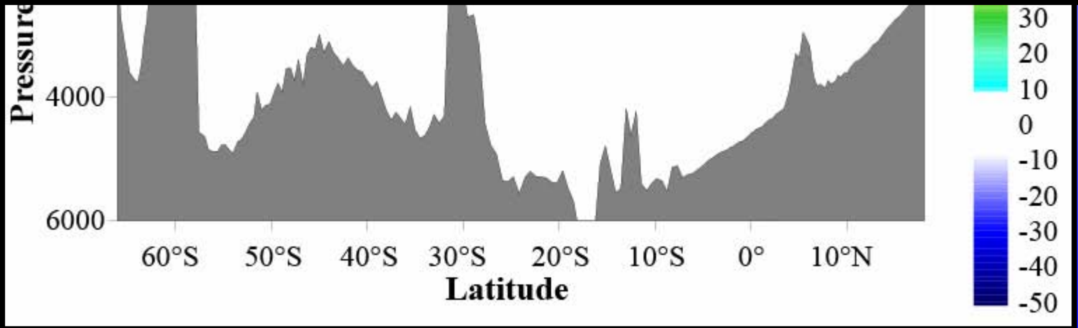
But the changes are very patchy and do not show consistent trends.



As with the Pacific, the first order Atlantic DIC distributions look very similar but there are significant differences



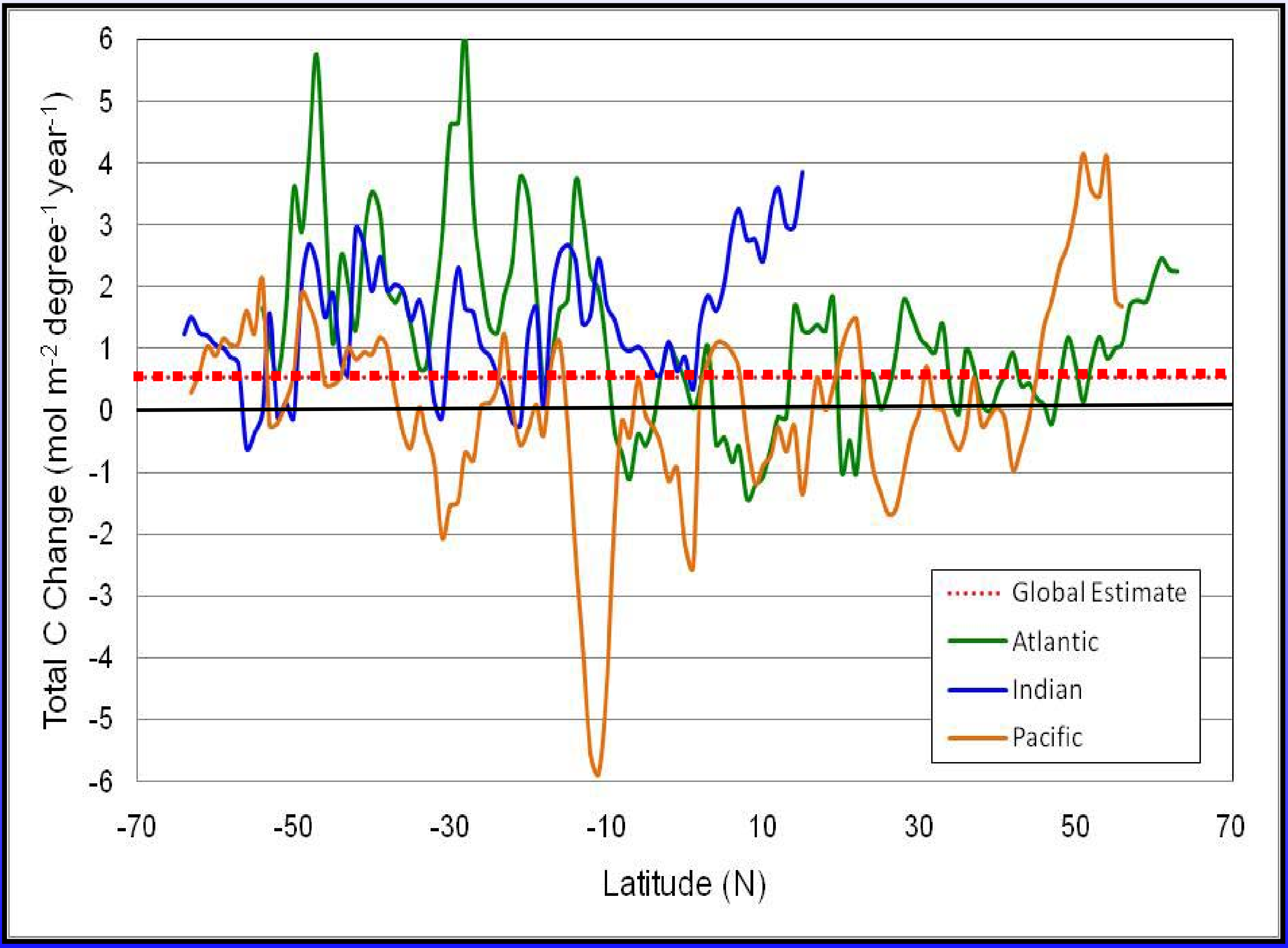




There are still some negative values, but there are more areas of coherent positive change

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



<u>Average:</u>

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 335.2×10^9 km^2

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

Use 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.

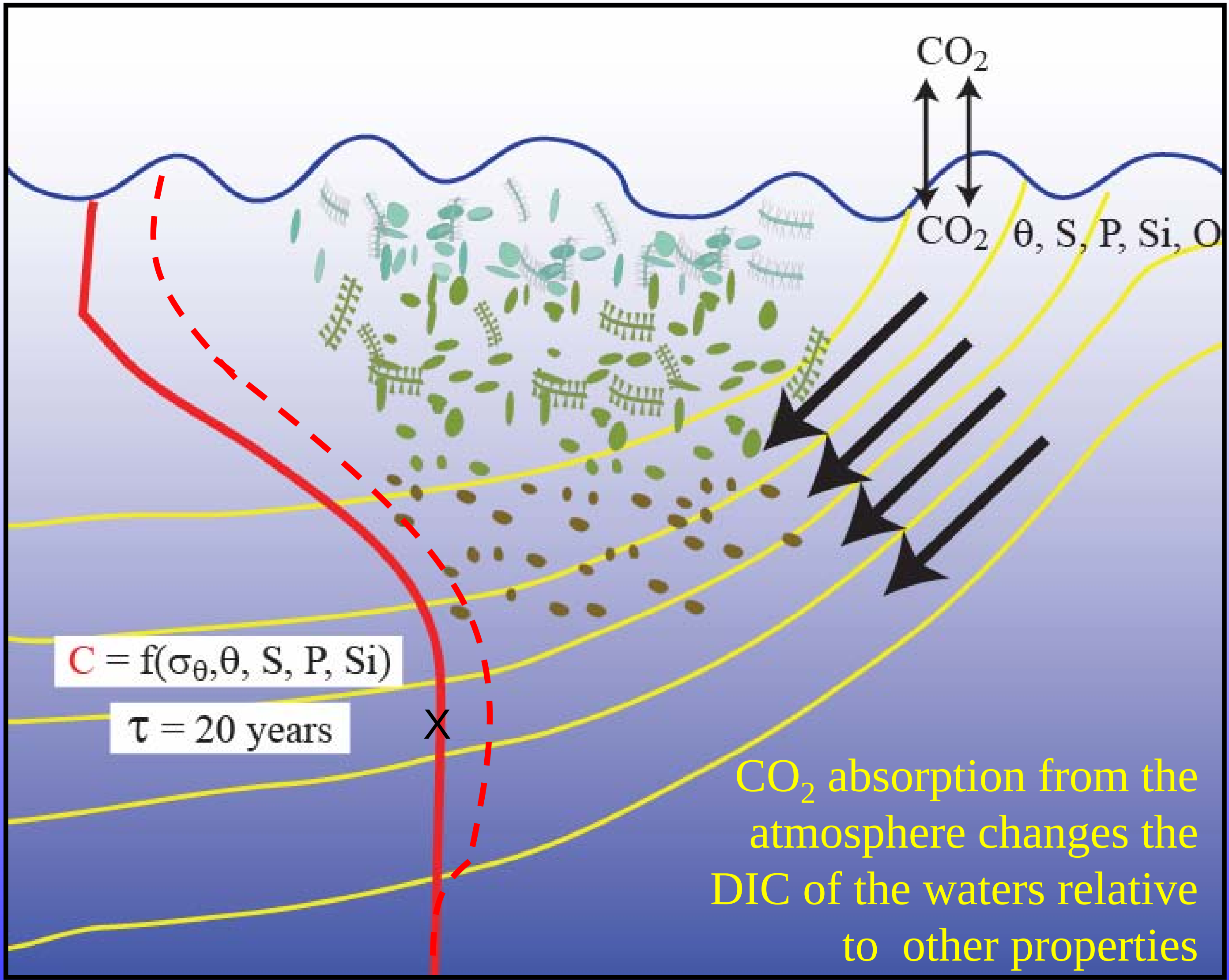
Friis et al. (2005, Deep Sea Res.) refined this approach with the extended MLR where both cruises are fit and take difference in fits.

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

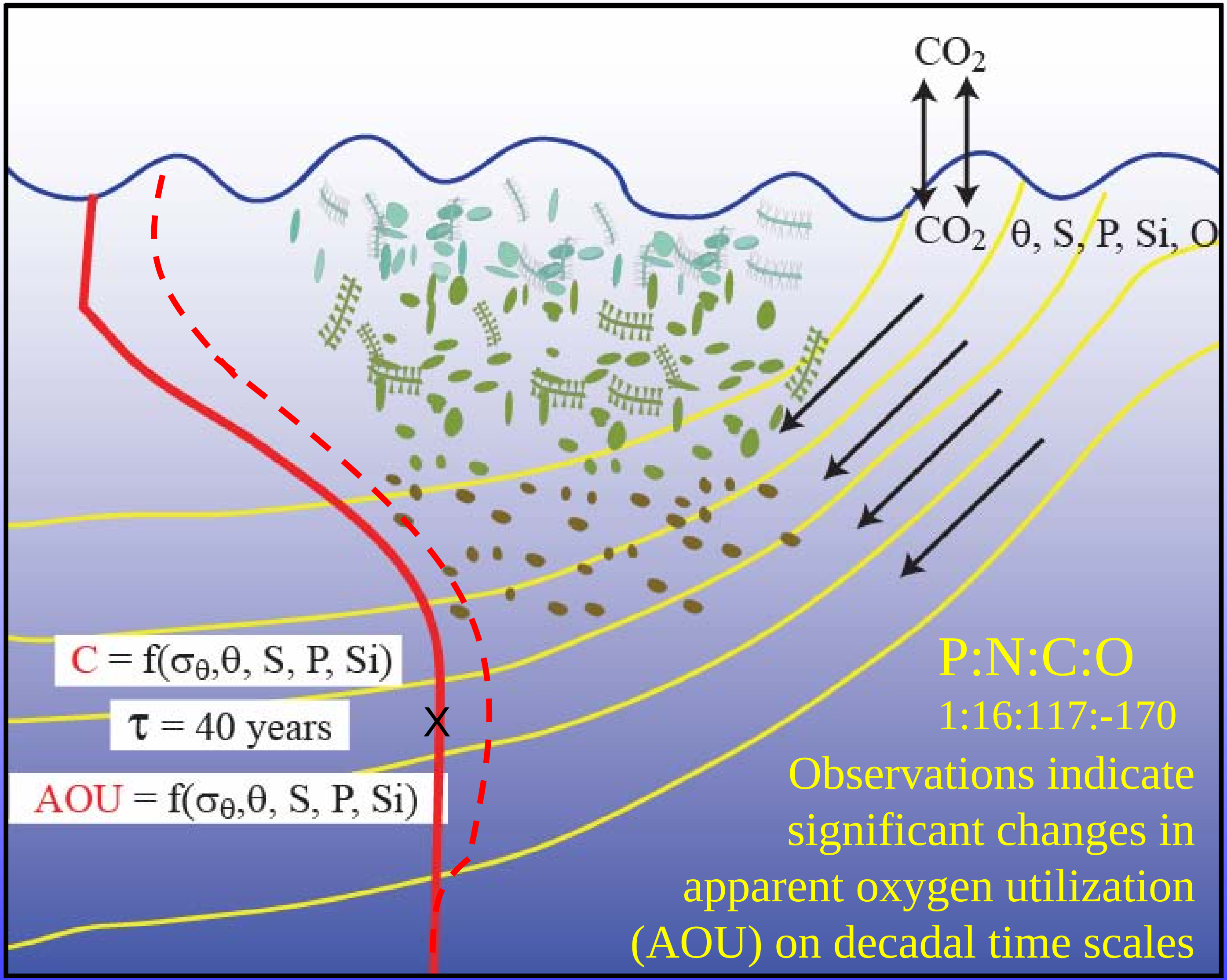
$$DIC_{(2006)} = A*\sigma_\theta + B*\theta + C*S + D*Si + E*P + F$$

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

What Does the MLR Tell us About Carbon Changes?

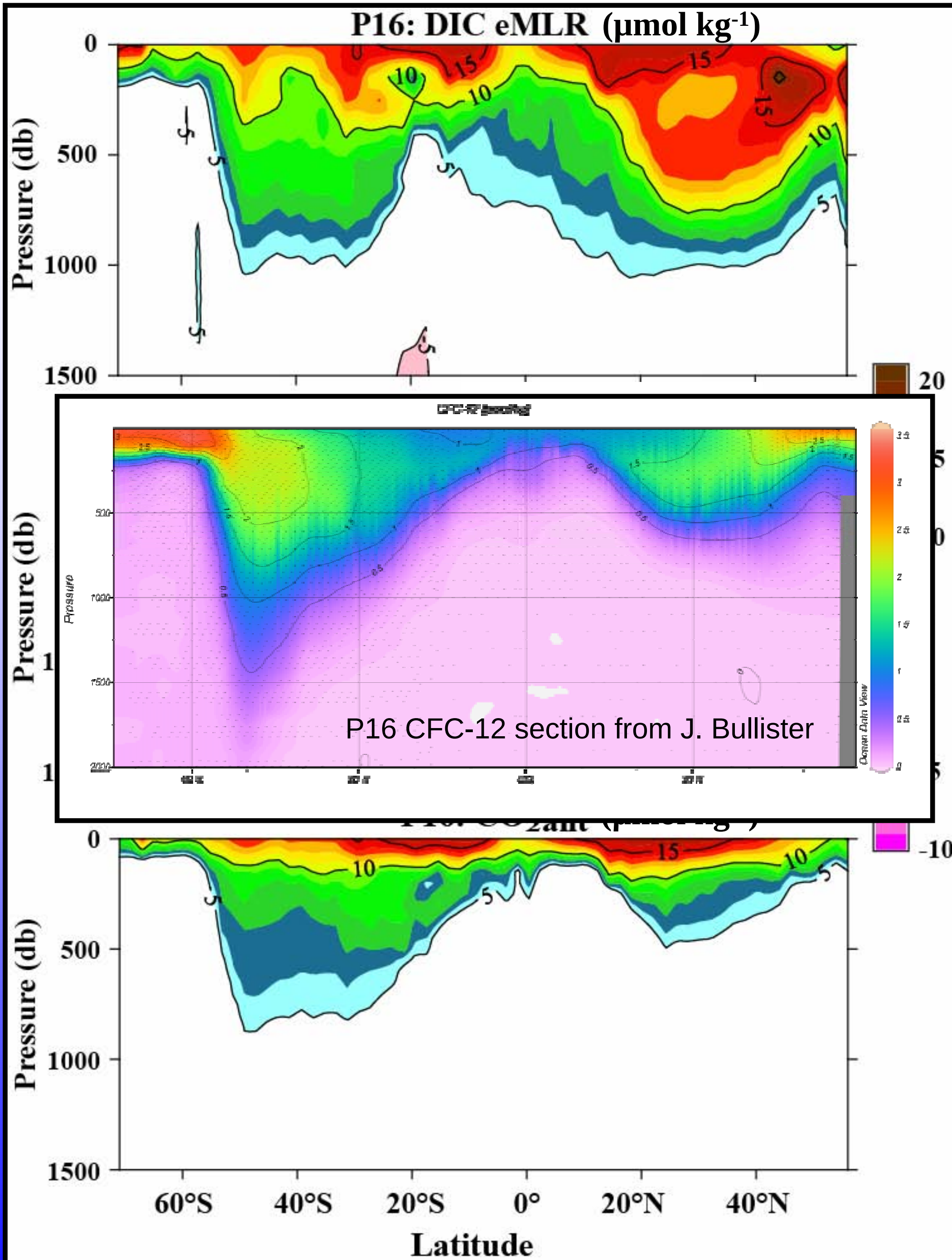


What Does the MLR Tell us About Carbon Changes?



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 rate

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



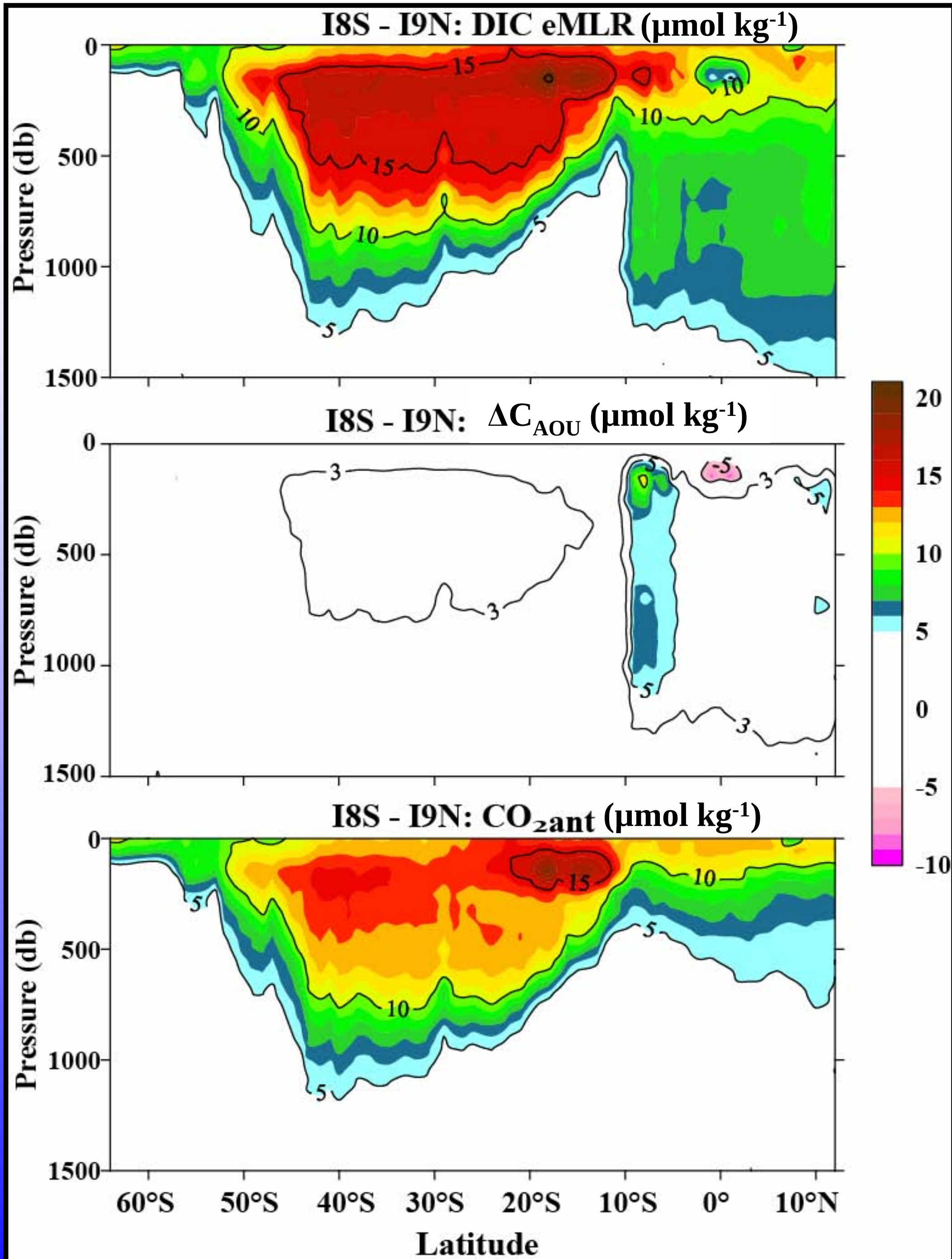
Pacific eMLR Sections Show Much More Coherent Patterns of Change

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

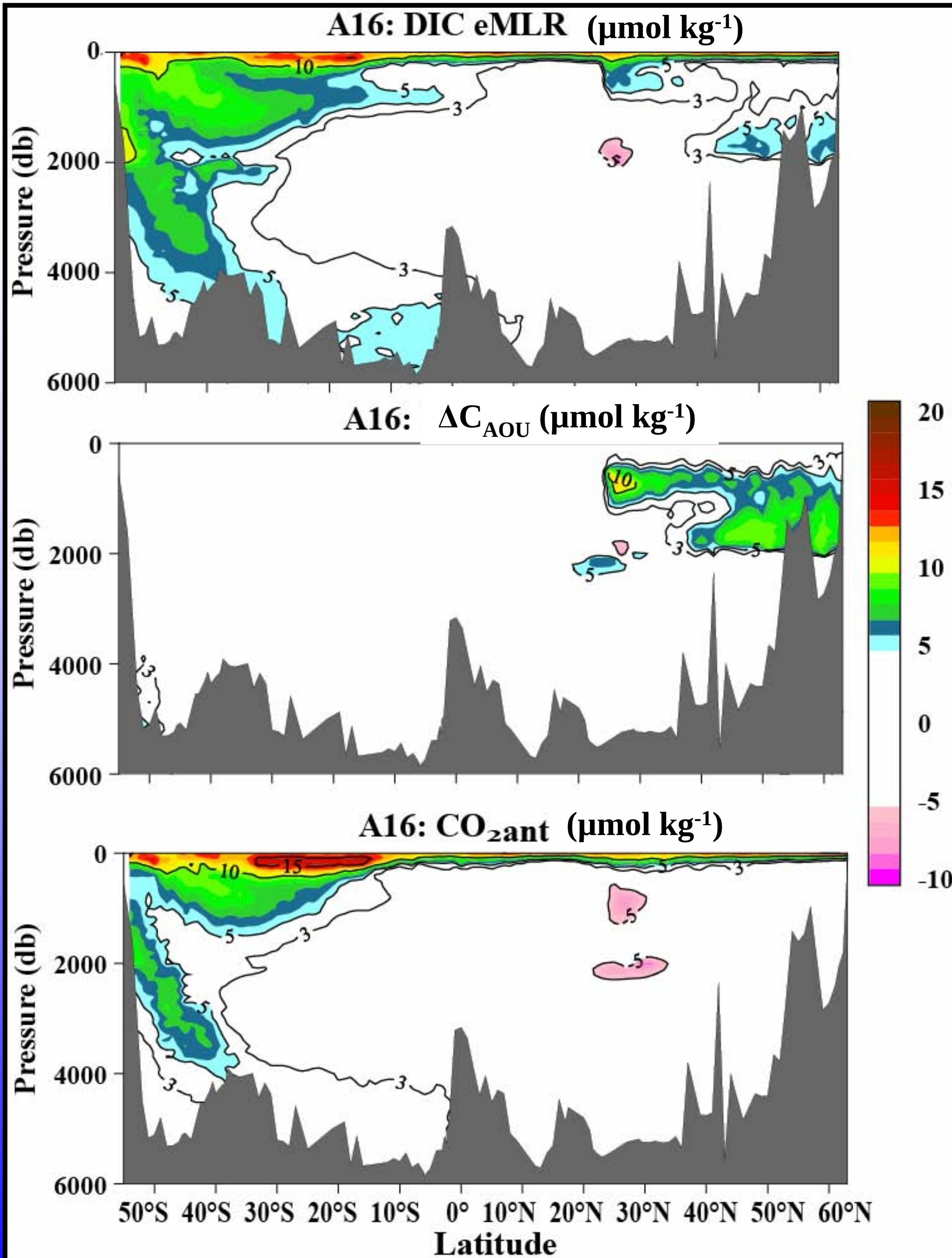


Indian eMLR Sections Are Similar To The Pacific

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



Atlantic eMLR Sections Were Much More Difficult to Derive A Coherent Picture

eMLR function without AOU shows a deep carbon change signal

The AOU eMLR function gives substantial changes in the northern intermediate waters

Atlantic anthropogenic carbon signal shows no deep penetration in the North Atlantic over the last decade, but big changes in the South Atlantic

Comparison of Atlantic Inventories along the A16 section (64 ˚N - 54 ˚S) in mol m^{-2} yr^{-1}

Method	N. Atlantic	Eq. Atl	S. Atlantic	Full Section
	(> 15 ˚N)	(15 ˚N- 15 ˚S)	(> 15 ˚S)	
ΔDIC	0.82	0.23	0.56	0.58
ΔDIC_{AOU}	0.92	0.60	0.86	0.82
ΔDIC_{NO3}	0.59	-0.28	0.66	0.39
$\Delta DIC_{e\text{-}mlr}$	0.59	0.68	0.78	0.68
$\Delta DIC_{e\text{-}mlr\text{-}sectional}$	0.69	0.17	0.96	0.65
$\Delta DIC_{e\text{-}mlr\text{-}dens}$	0.57	0.20	0.76	0.53
$\Delta DIC_{C\text{-}13}$[a]	0.63 ± 0.16			
$\Delta DIC_{e\text{-}mlr}$[b]	1.22± 0.27			

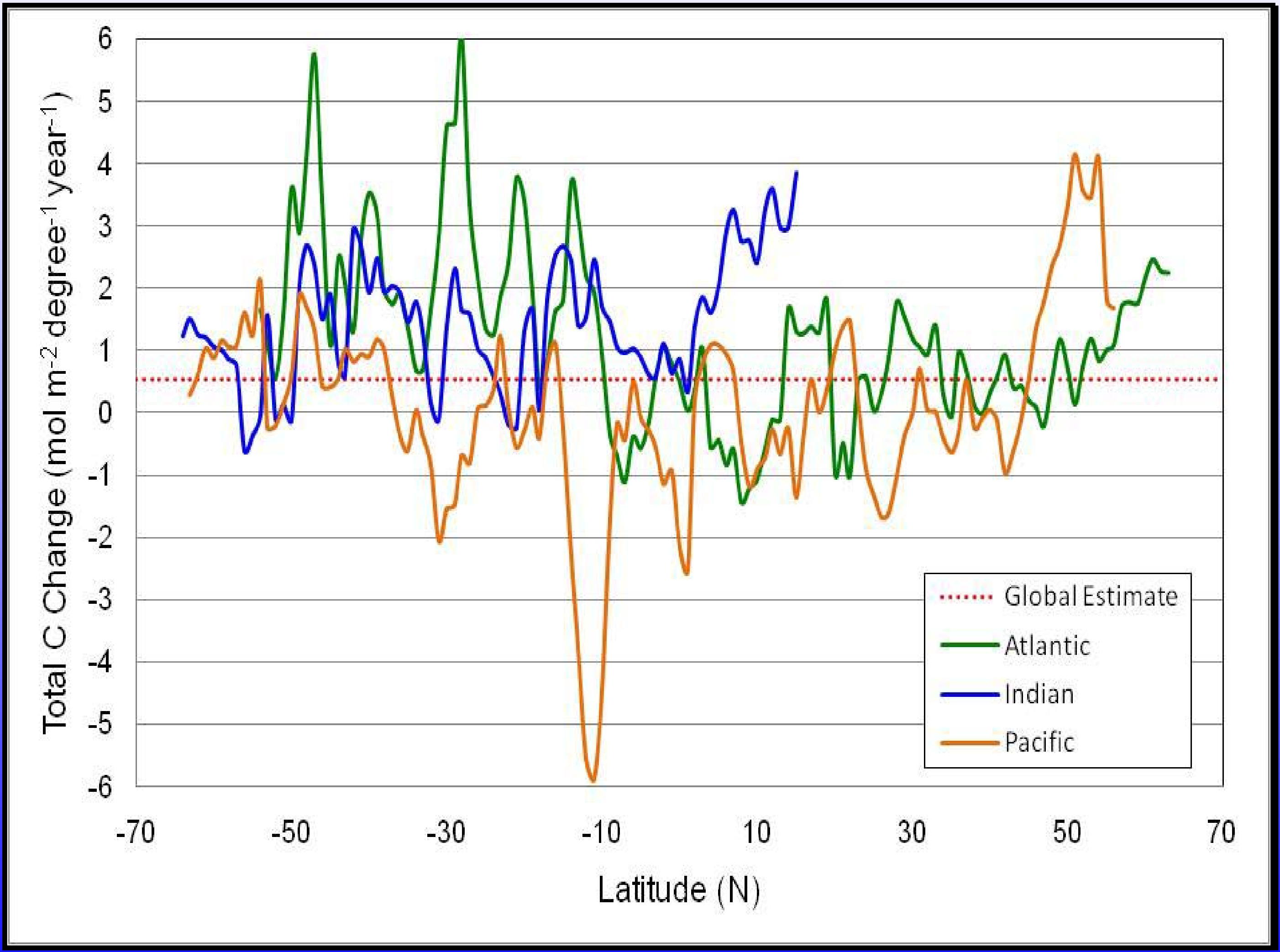
a: From Quay et al., 2007
b: From Tanhua pers. Comm.

From R. Wanninkhof

Different MLR approaches seem to give different regional results in the Atlantic. We are currently trying to understand the reasons for this.

Measured DIC changes show large variability on small spatial scales

But eMLR DIC changes give much more consistent patterns of change



Average change:

Atl NH: 0.6±?

Atl SH: 0.8±?

Pac NH: 0.25±0.1

Pac SH: 0.41±0.2

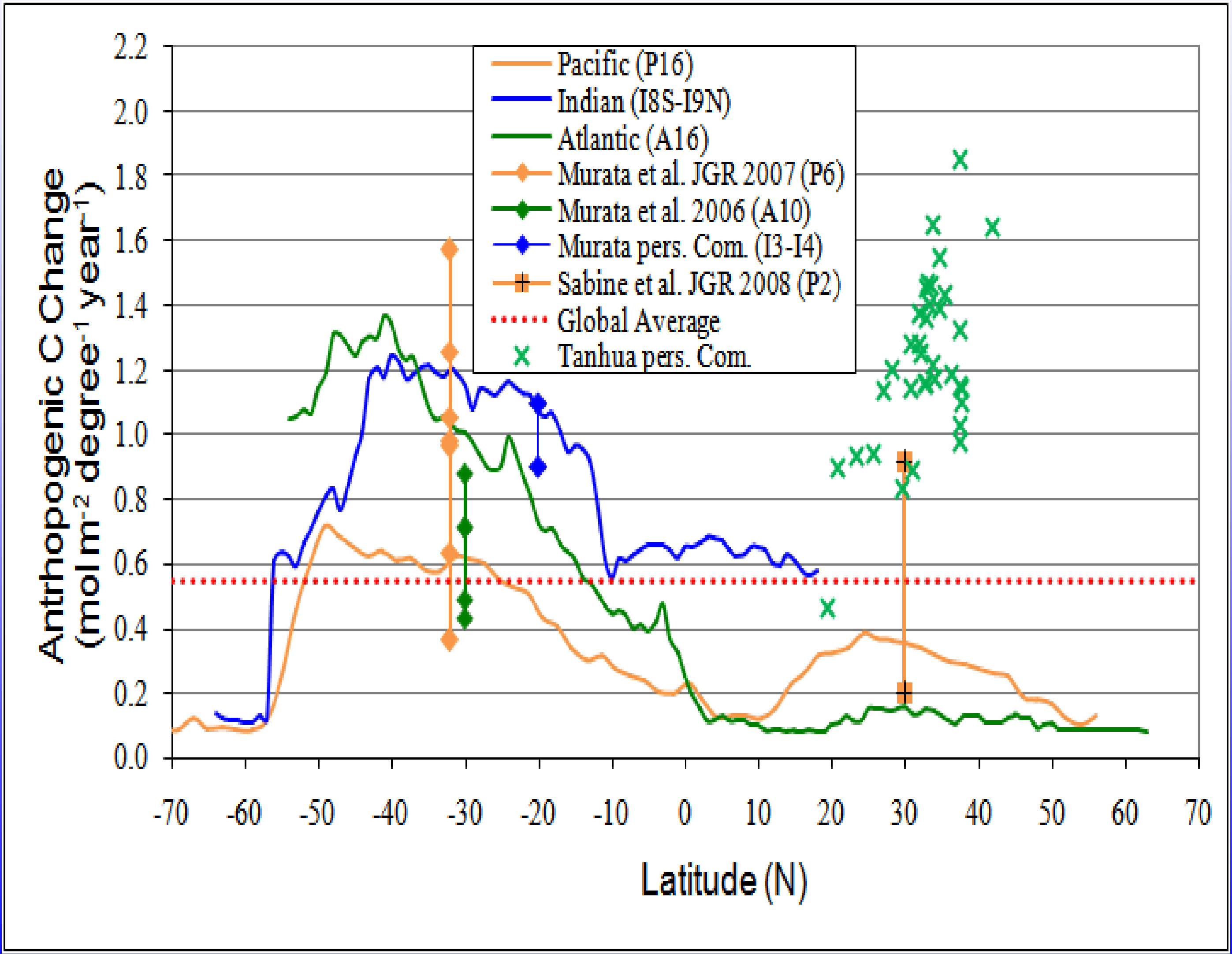
Ind SH: 0.83±0.3

Total: 0.5±0.3

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

Additional Anthropogenic DIC Change Estimates Show Significant Variability Within Each Basin

The decadal survey is not complete, additional sampling and evaluation is needed to properly determine the global ocean CO_2 uptake and storage

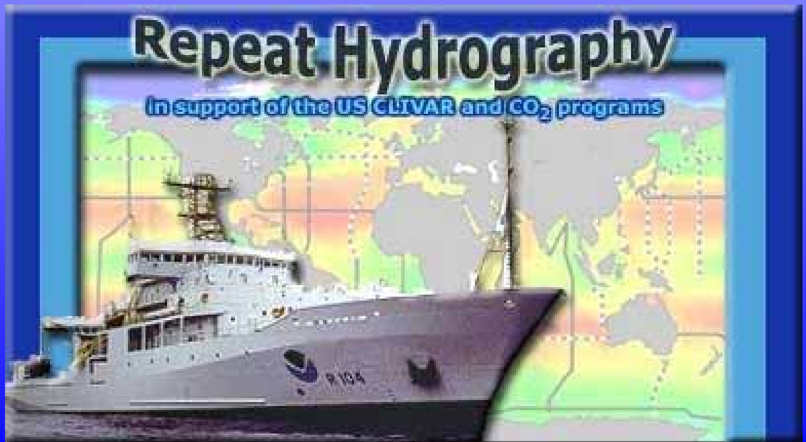


Additional work is needed to understand Atlantic carbon changes

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

Conclusions

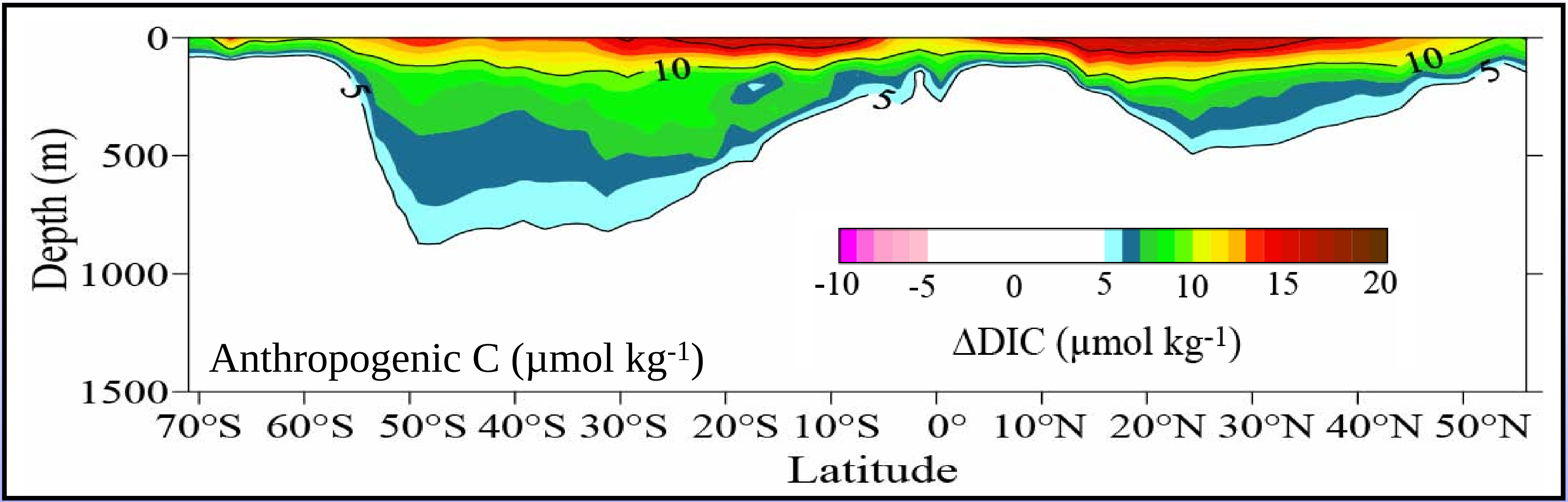
1) The Repeat Hydrography program is providing high quality data that is essential for detecting inventory changes
2) The observations reveal very large changes in carbon concentrations on decadal time scales
3) Changes in apparent organic remineralization rates can have a significant impact on total carbon changes on decadal time scales
4) Both the anthropogenic and organic carbon changes show patterns of variability consistent with other work on ocean tracer changes
5) The full international repeat hydrography data set will be required to properly constrain the global decadal carbon change signal.



Thank you for your time!

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

Total - AOU DIC Change Compares Well With CFC-12 Distributions Along P16 (150°W) 2005/6 – 1991/2



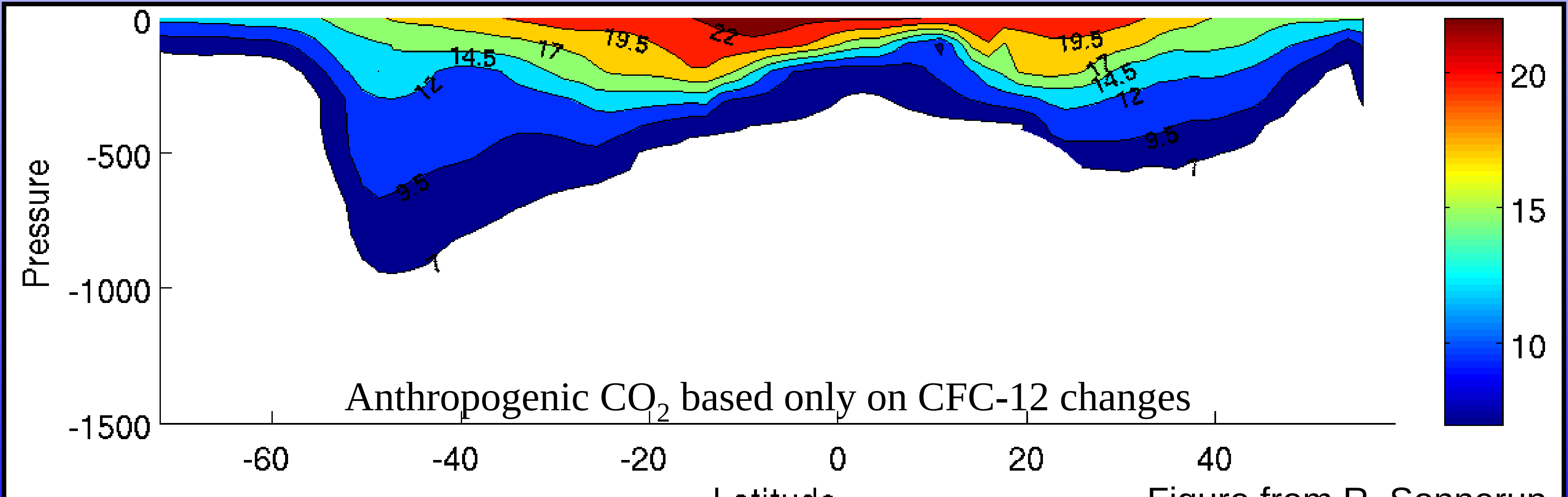
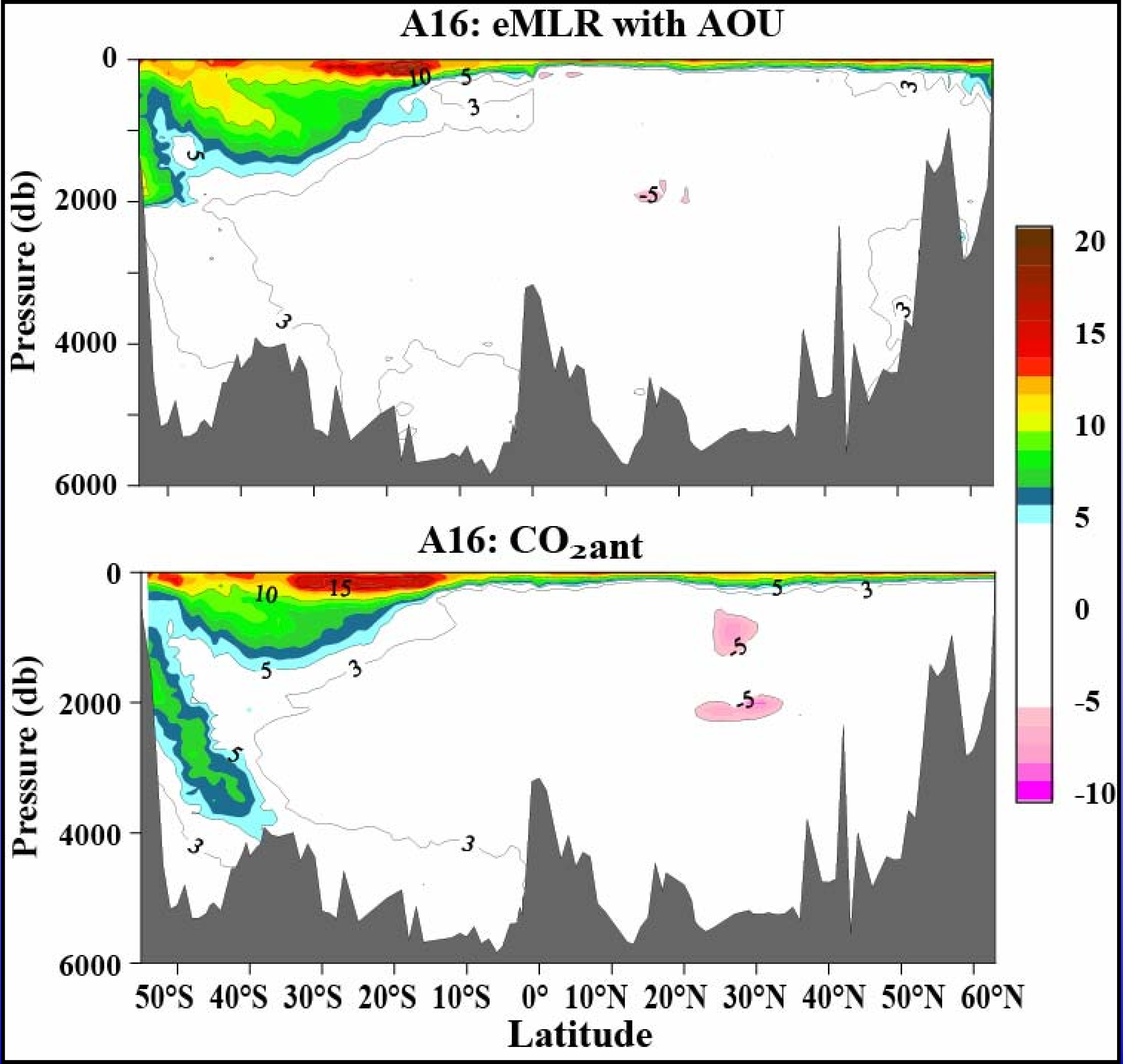


Figure from R. Sonnerup



A16: eMLR with AOU
Pressure (db)
0
2000
4000
6000
10
5
3
-5
A16: CO₂ant
15
Latitude
50°S 40°S 30°S 20°S 10°S 0° 10°N 20°N 30°N 40°N 50°N 60°N
20
15
10
5
0
-5
-10