# Decadal Changes of $CO_2$ in the North Pacific Ocean

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Acknowledgements:

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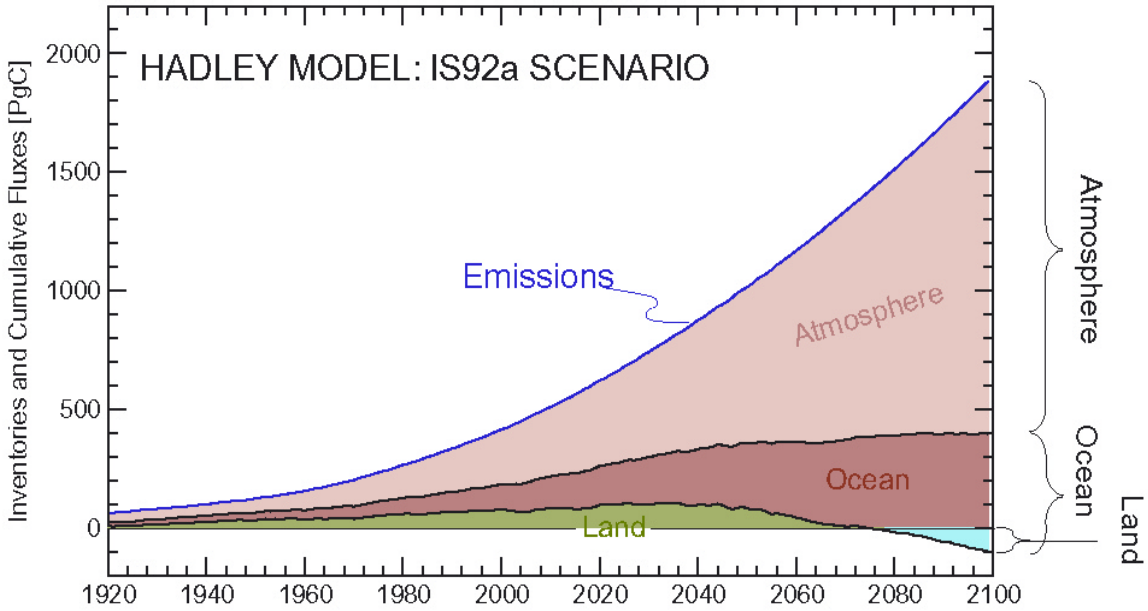
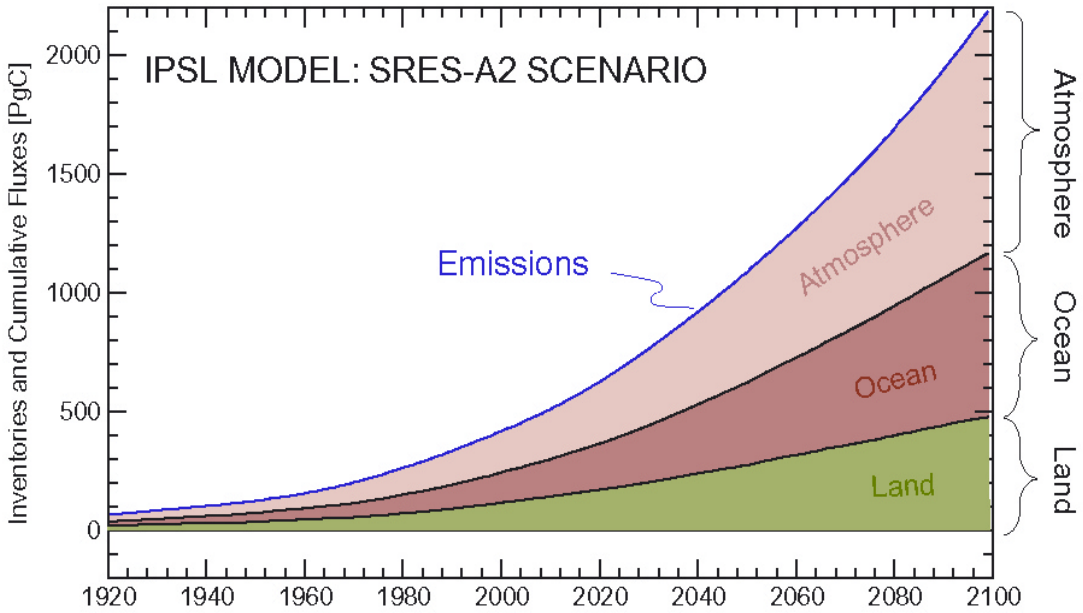
Tsueno Ono, Yutaka Watanabe,
Christopher Winn, Robert Key,
Marilyn Lamb and Dana Greeley

# CARBON-CYCLE / CLIMATE SYSTEM FEEDBACKS




**Current level of understanding, projected into the future:**

Predictive models about what will happen to carbon dioxide differ significantly.

Cannot improve predictions without better understanding of the controlling processes.

This is no longer just an academic issue …

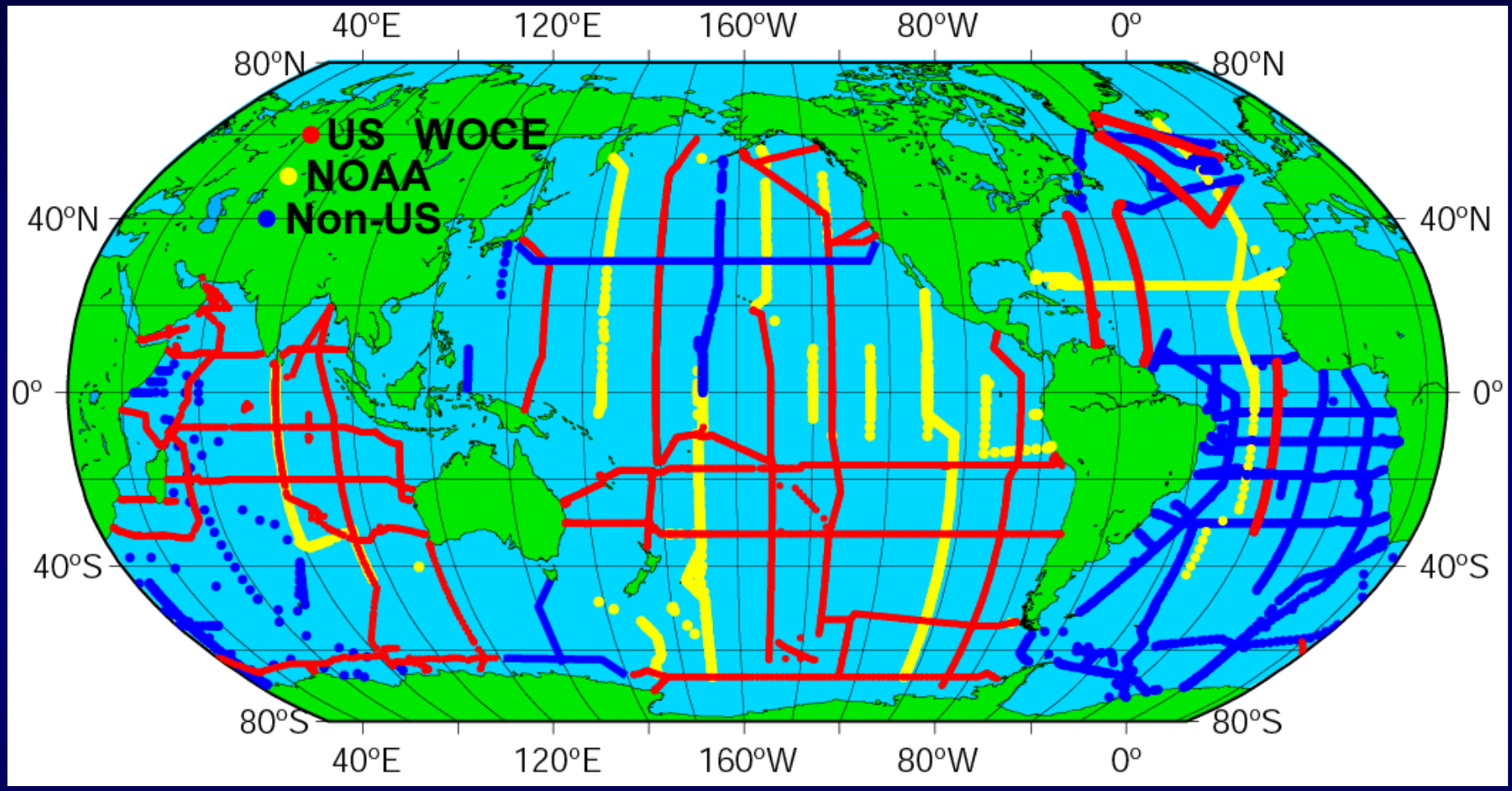
Disagreements in predictions impact baseline targets for emissions reduction.

Sequestration cost targets are $10-35/t of C.

Differences between models imply differences in ecosystem services of trillions of dollars.
*= big incentive for research.*

A.Gnanadesikan

# WOCE/JGOFS/OACES Global $CO_2$ Survey




~72,000 sample locations collected in the 1990s

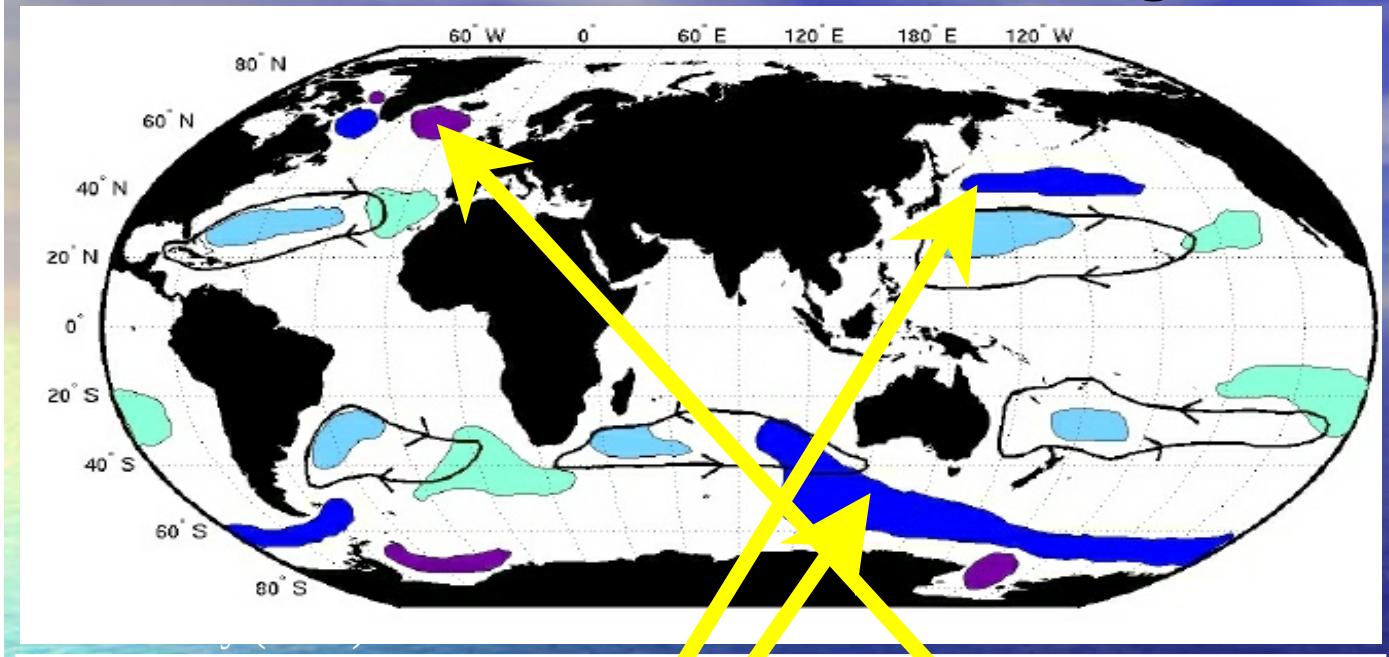
DIC ± 2 μmol $kg^{-1}$

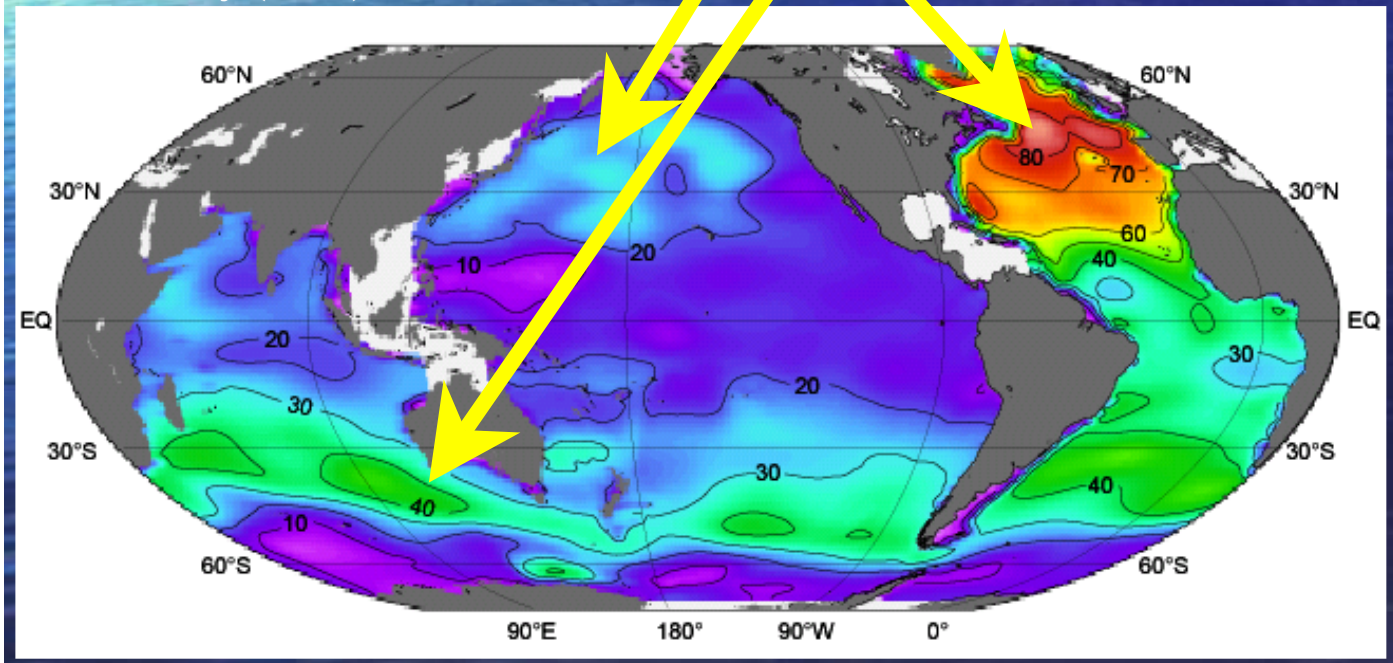
TA ± 4 μmol $kg^{-1}$

2004-12-07

Sabine et al (2004).

# Water Mass Formation Regions

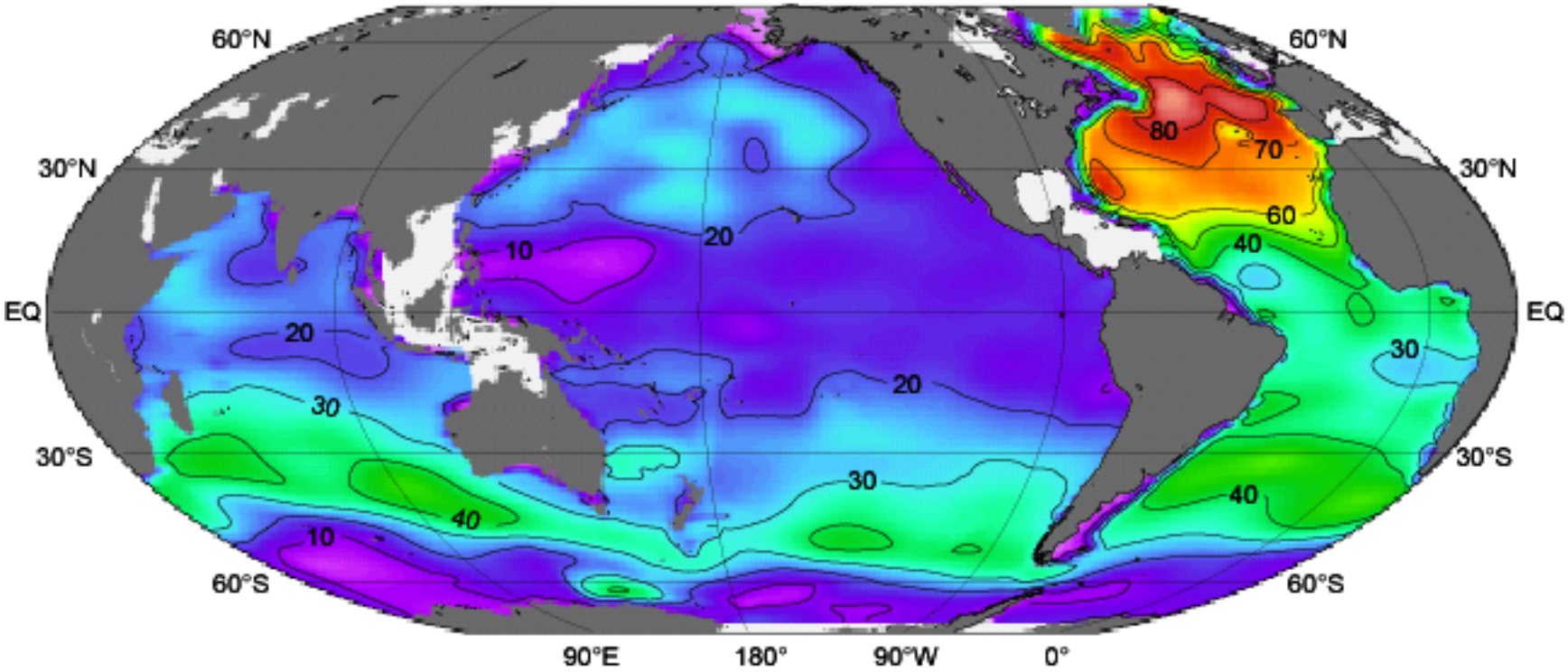



Anthropogenic $CO_2$ moves into the ocean interior with mode, intermediate, deep and bottom water.

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.

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

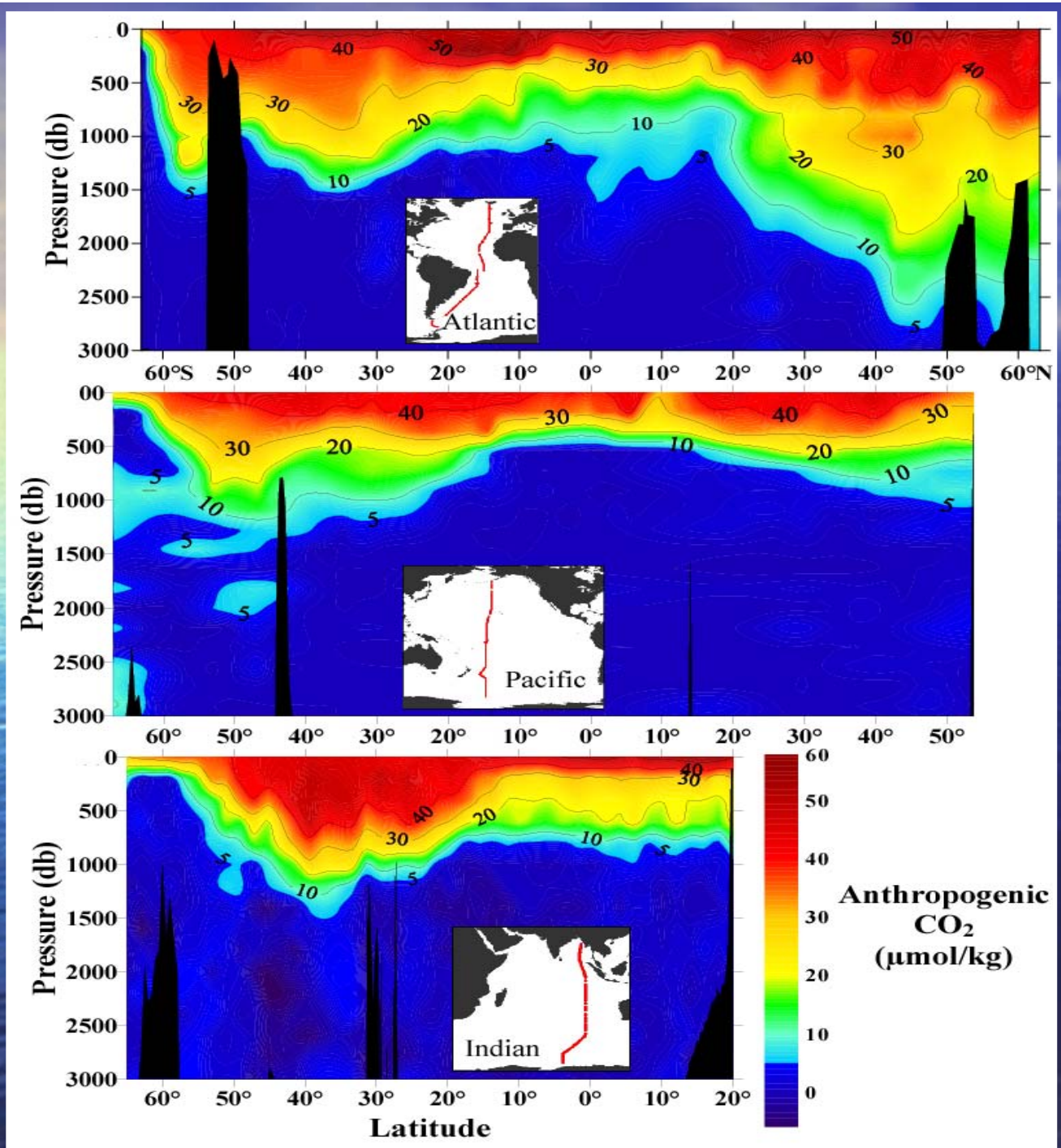



Mapped Inventory 106±17 Pg C
+ marginal seas 6± 6 Pg C
+ Arctic Ocean 6± 6 Pg C

Total Inventory 118±19 Pg C



Sabine et al. Science (2004)

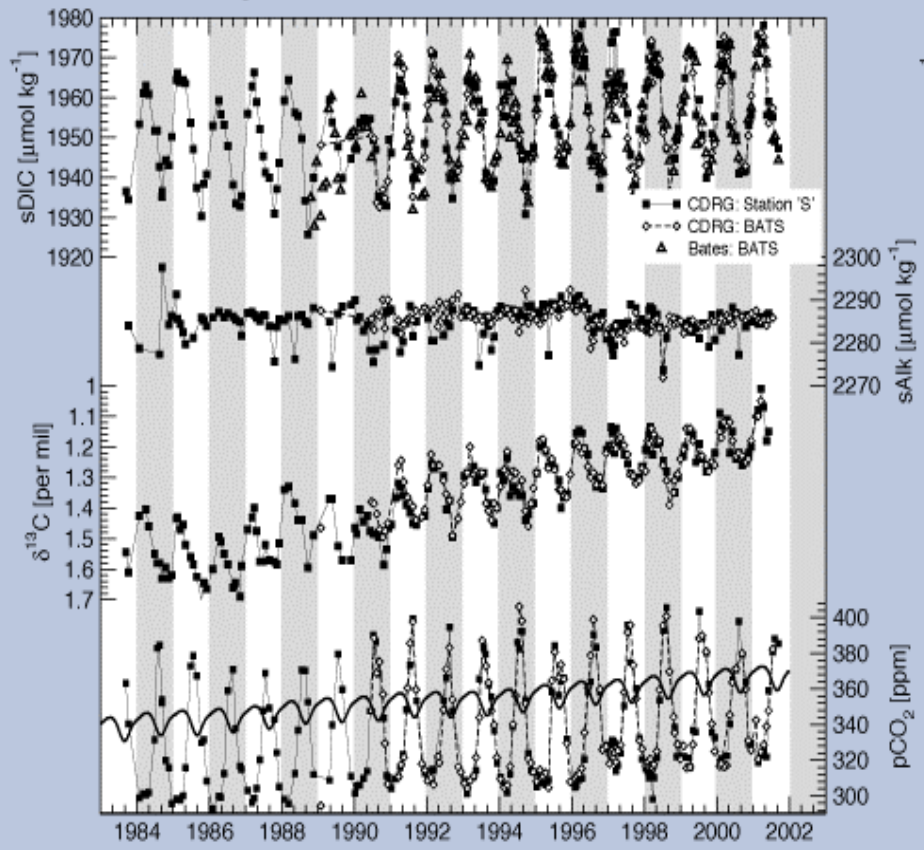



## Global Anthropogenic $CO_2$ Inventory = 118±19 Pg C

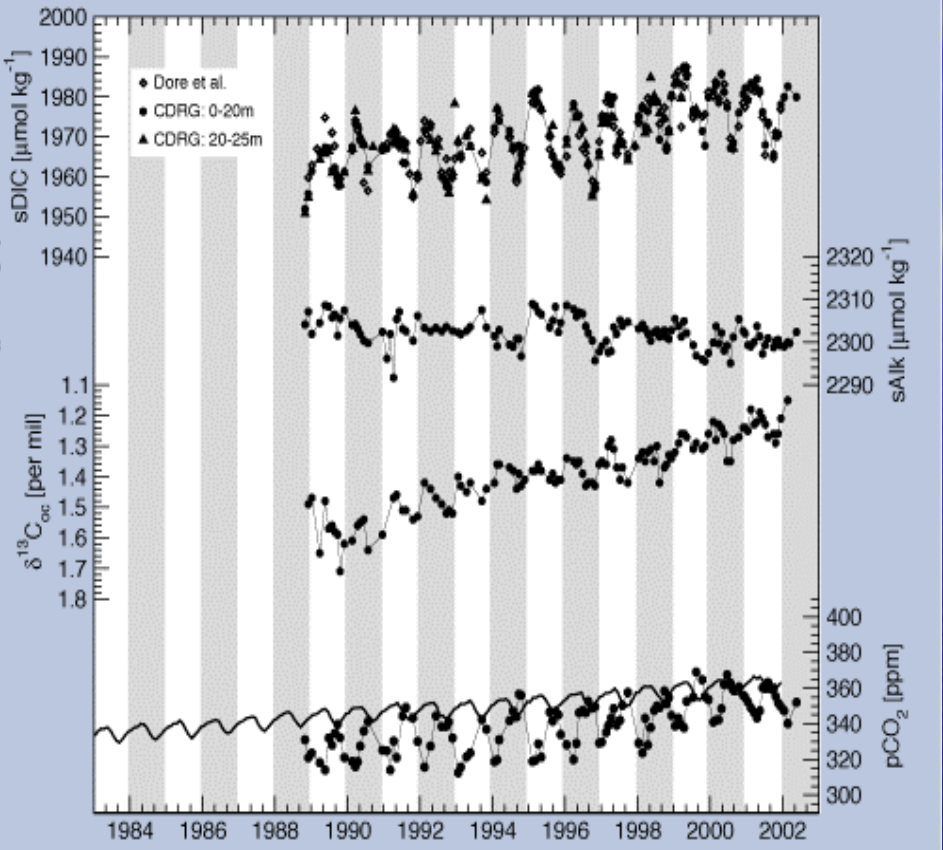
Because the ocean mixes slowly, half of the anthropogenic $CO_2$ stored in the oceans is found in the upper 10% of the ocean.

Sabine et al. Science (2004)

## BERMUDA




## HAWAII




## Time-rate of change:

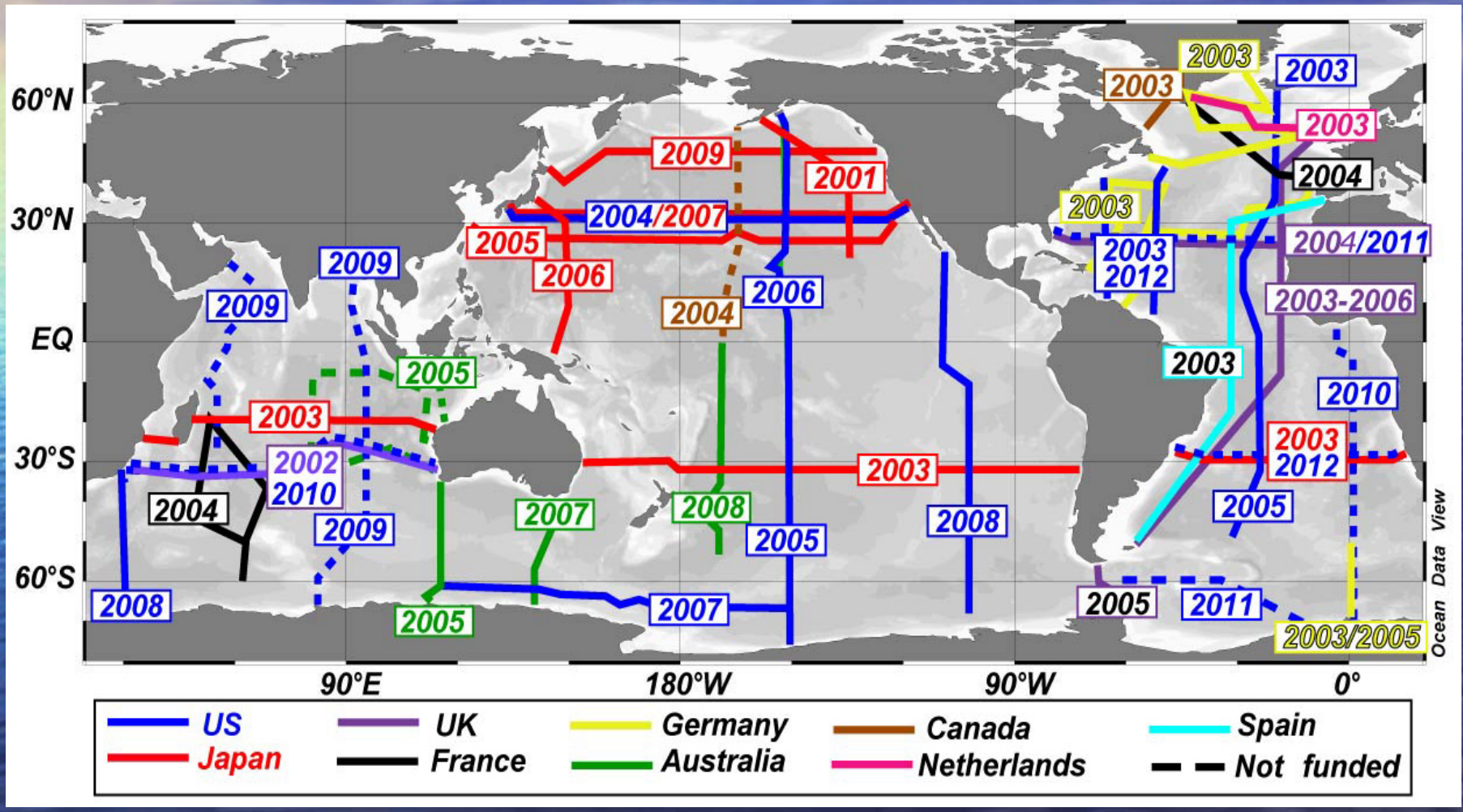
DIC: 0.68 µmol/kg/yr
$\partial^{13}$C: -0.024 permil/yr
pCO$_2$: 1.6 ppm/yr
*(1983-2000)*

DIC: 1.26 µmol/kg/yr
$\partial^{13}$C: -0.027 permil/yr
pCO$_2$: 2.3 ppm/yr
*(1988-2000)*

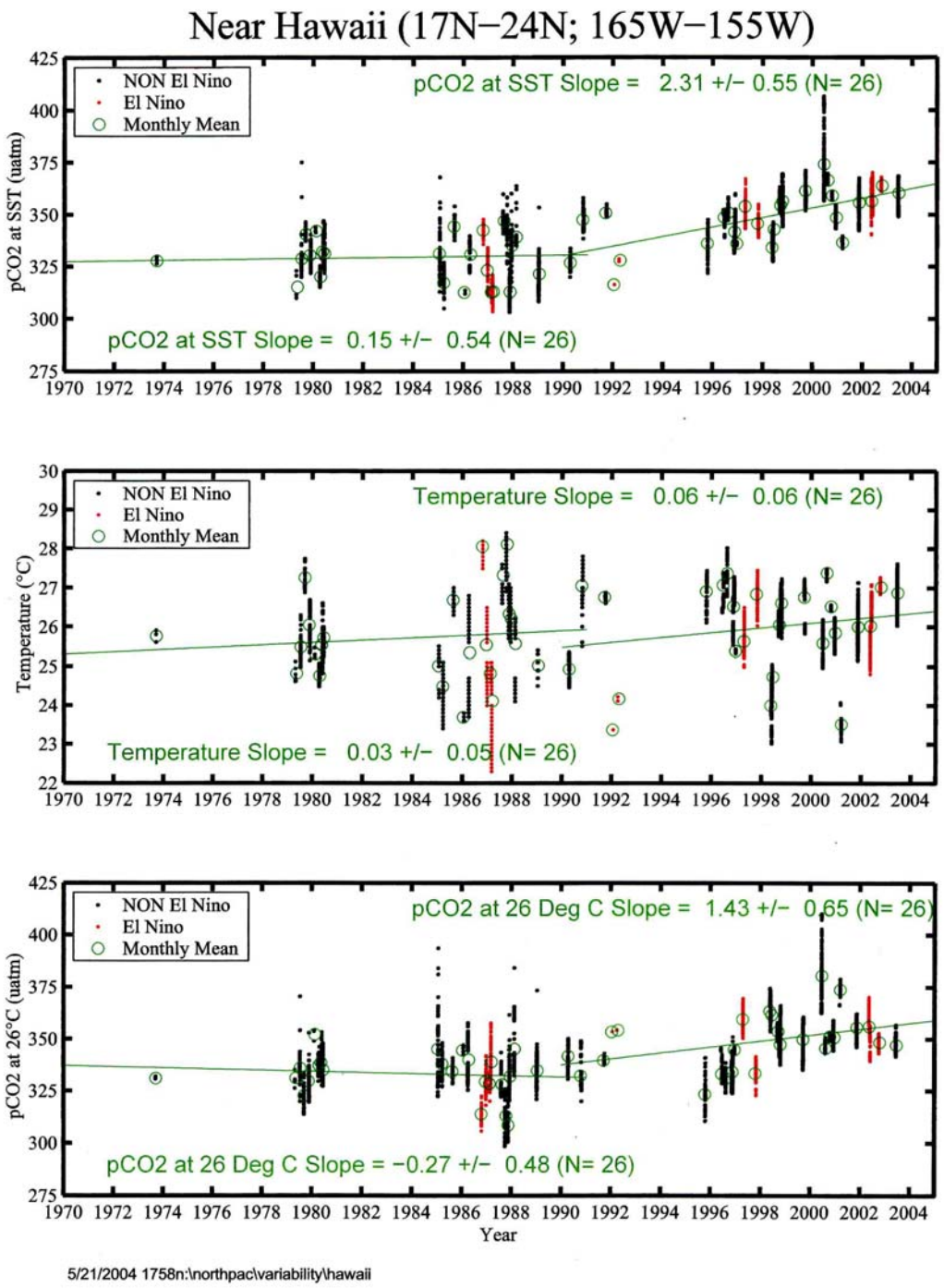


Nicolas Gruber and Holger Brix (2004)

# We must understand the temporal and spatial changes of the global ocean carbon system and the feedbacks to the climate system.

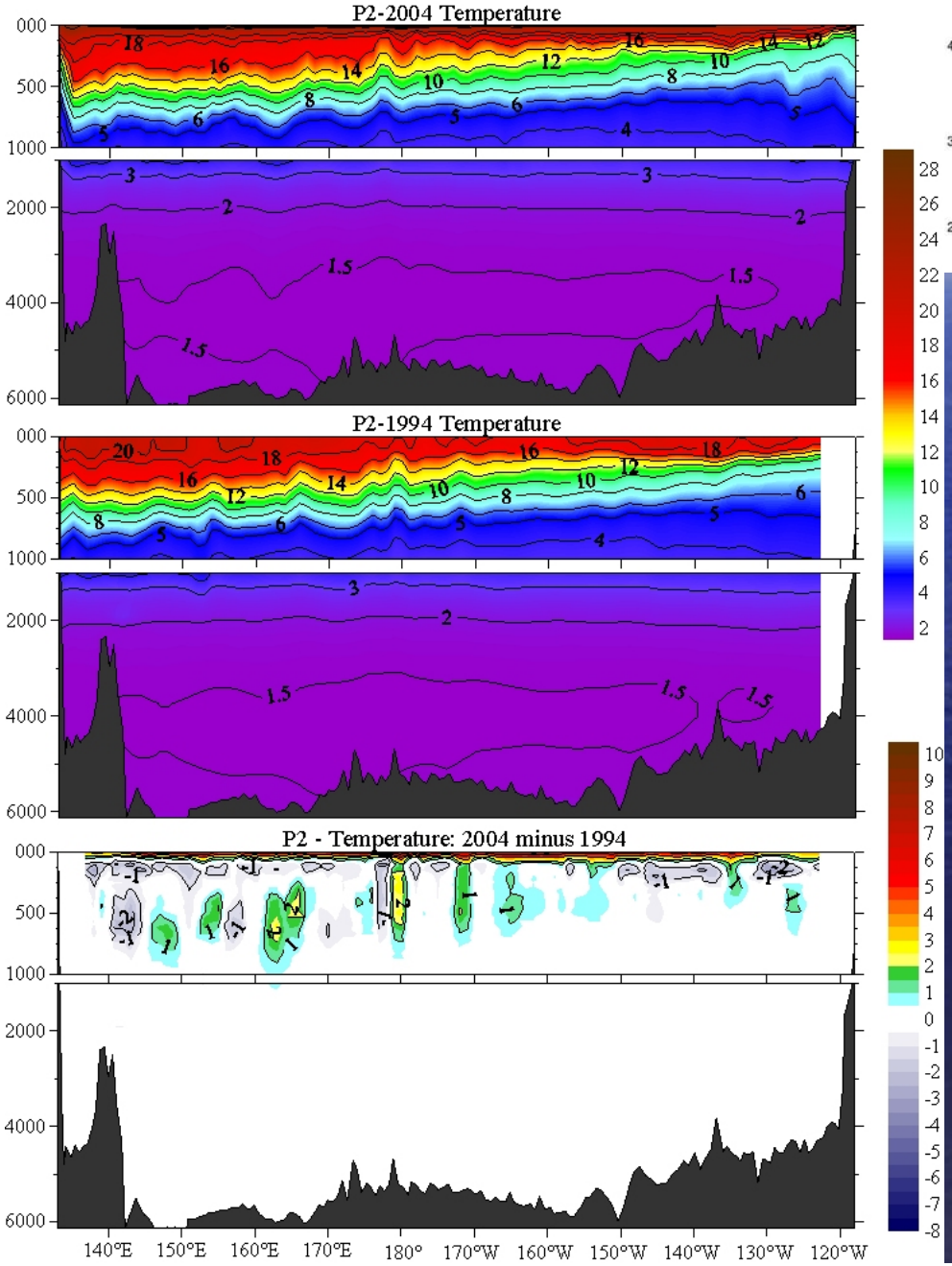


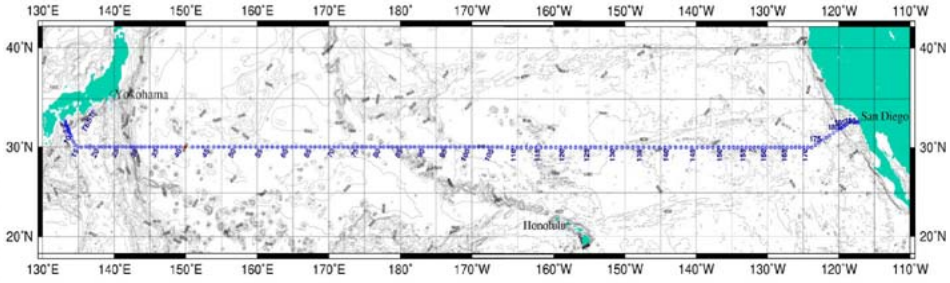

2004-12-07 CLIVAR/$CO_2$ Repeat Hydrography Program




Takahashi et al
(in preparation)

# North Pacific Temperature Changes (2004 - 1994)

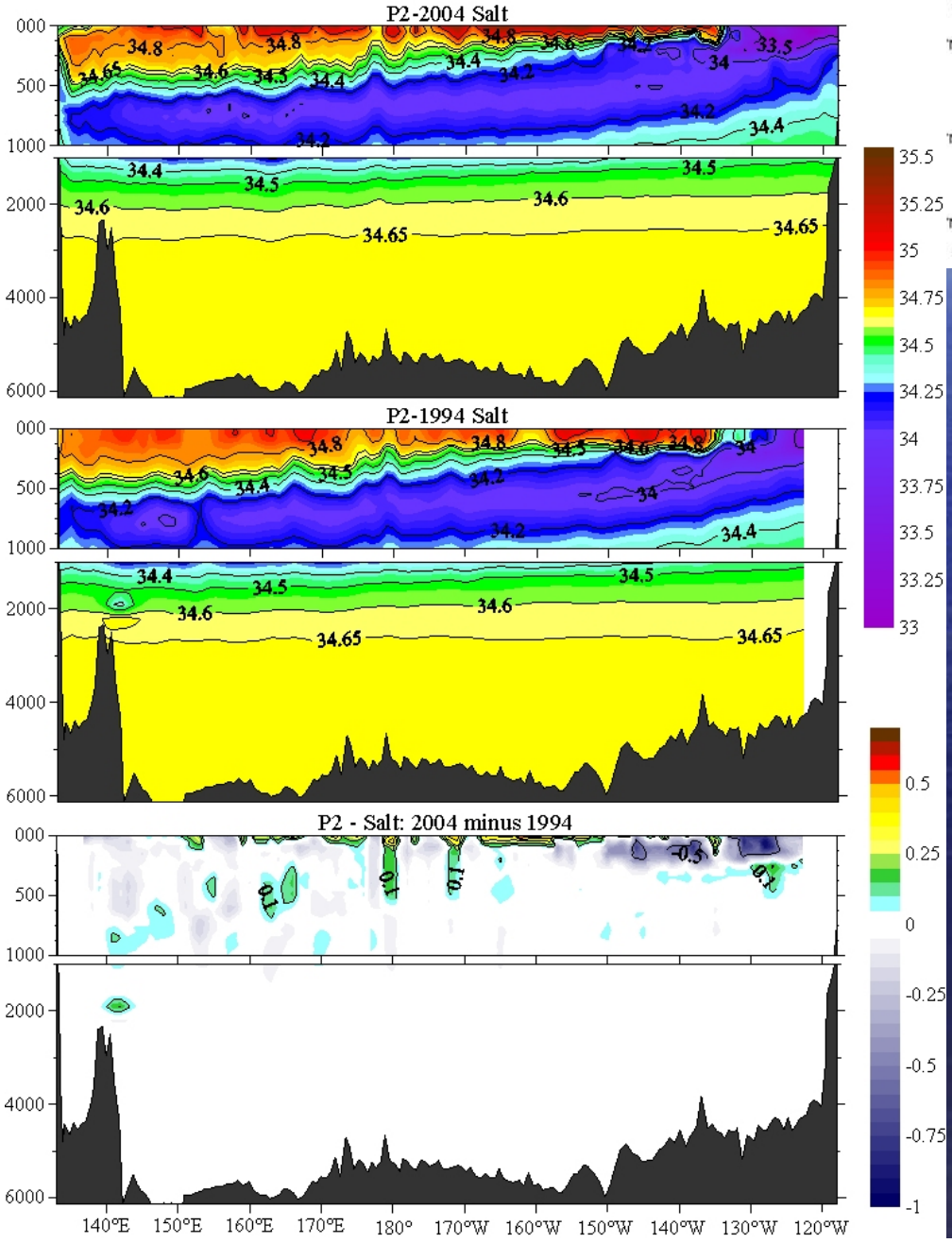


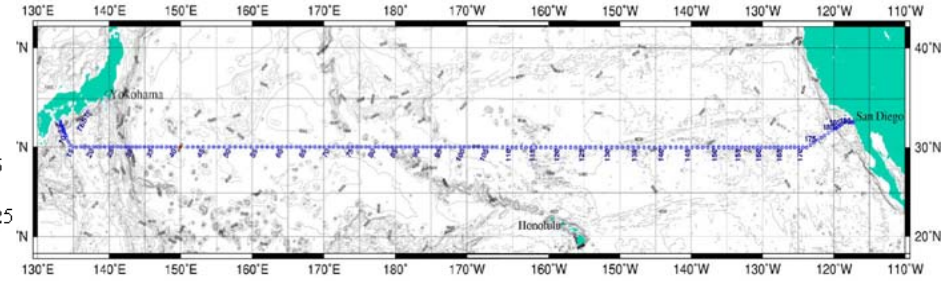




- Large positive and negative temperature differences in the upper 1000 m that correspond with salinity and AOU differences.

*2004 PICES XIII S8 - The Impacts of Climate Change on the Carbon Cycle in the North Pacific*

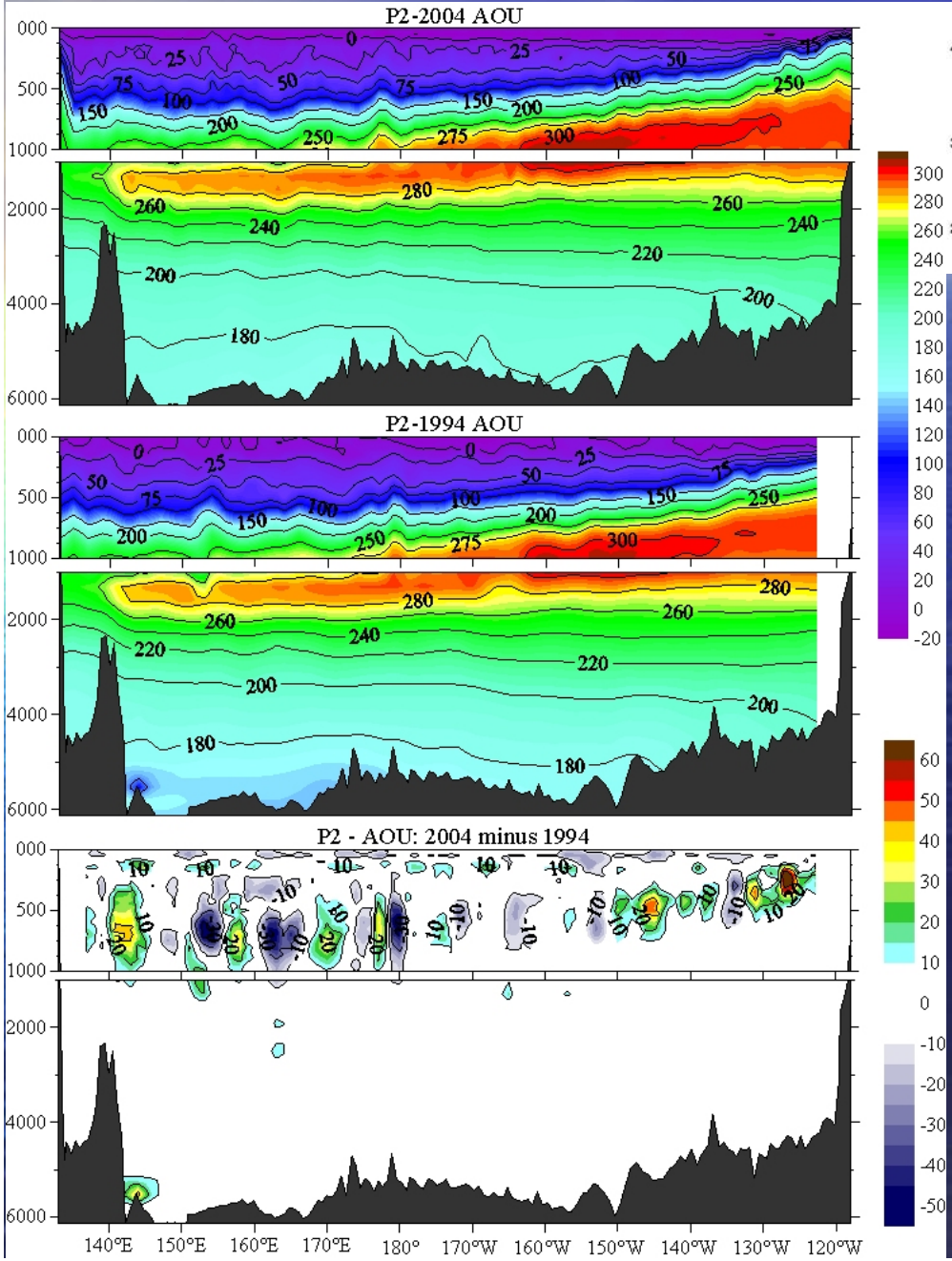
# North Pacific Salinity Changes (2004 - 1994)

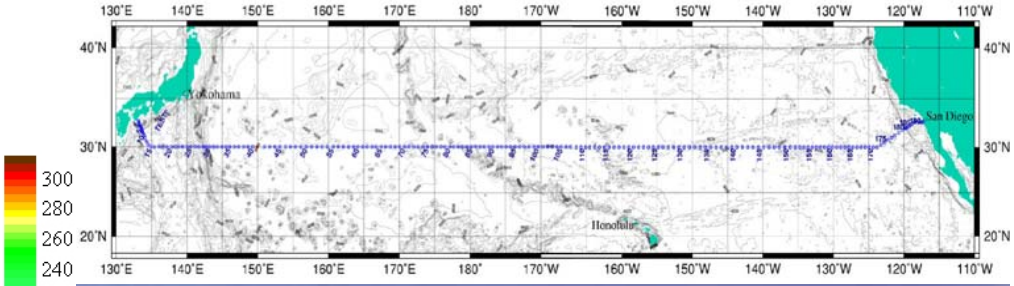



- Large positive and negative salinity differences in the upper 1000m that correspond with temperature and AOU differences.

# North Pacific AOU Changes (2004 - 1994)




- Large positive and negative AOU differences in the upper 1000 m that correspond with temperature and salinity differences.

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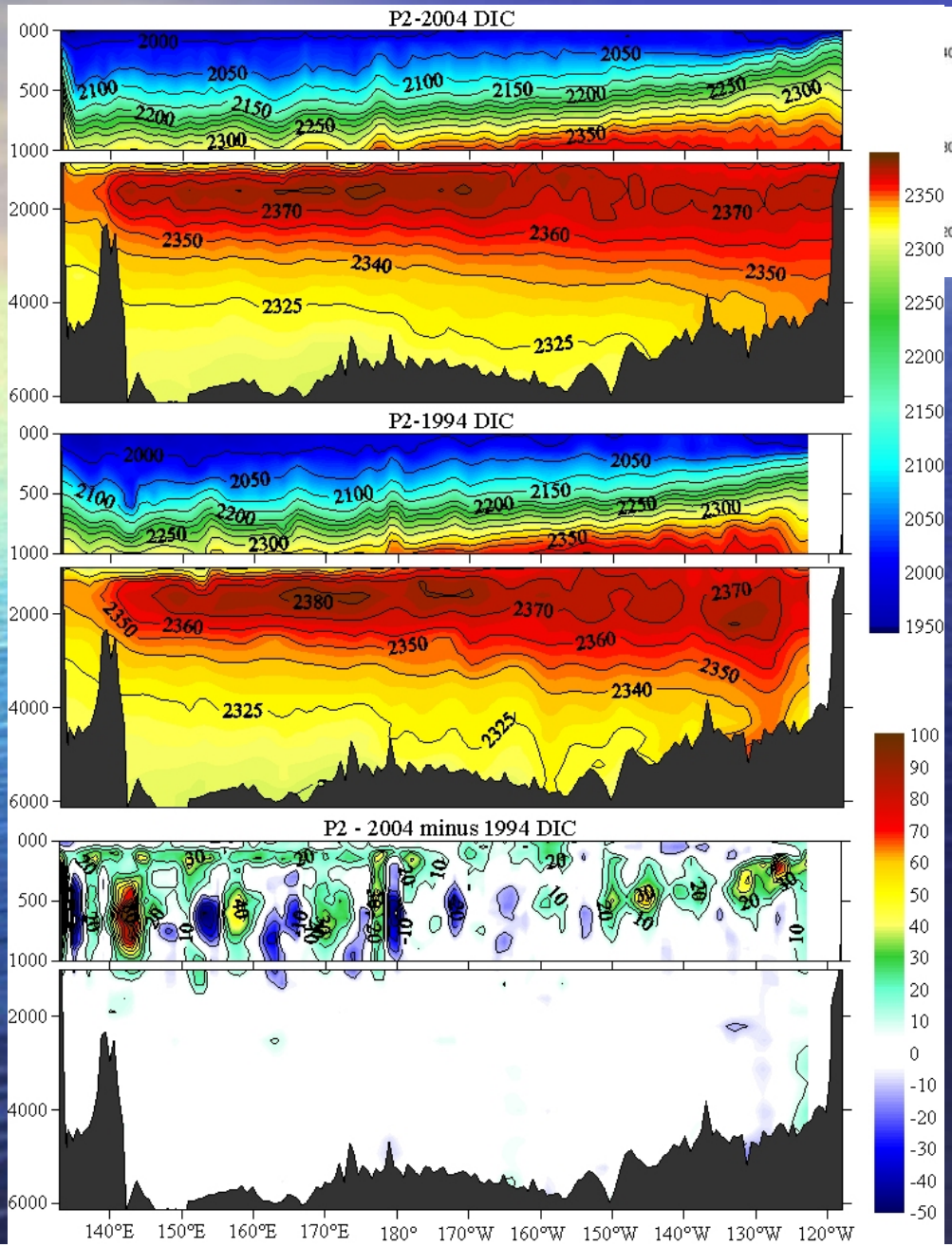
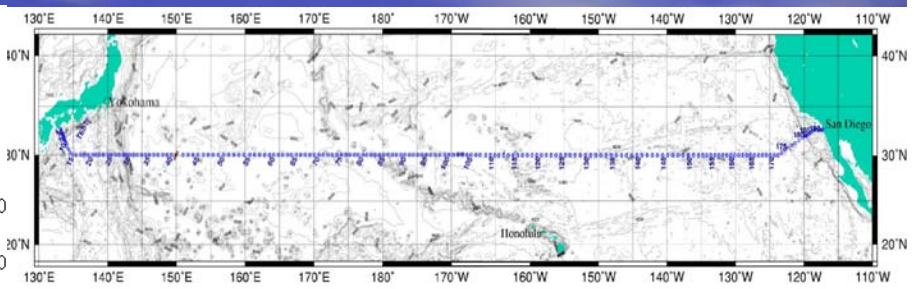
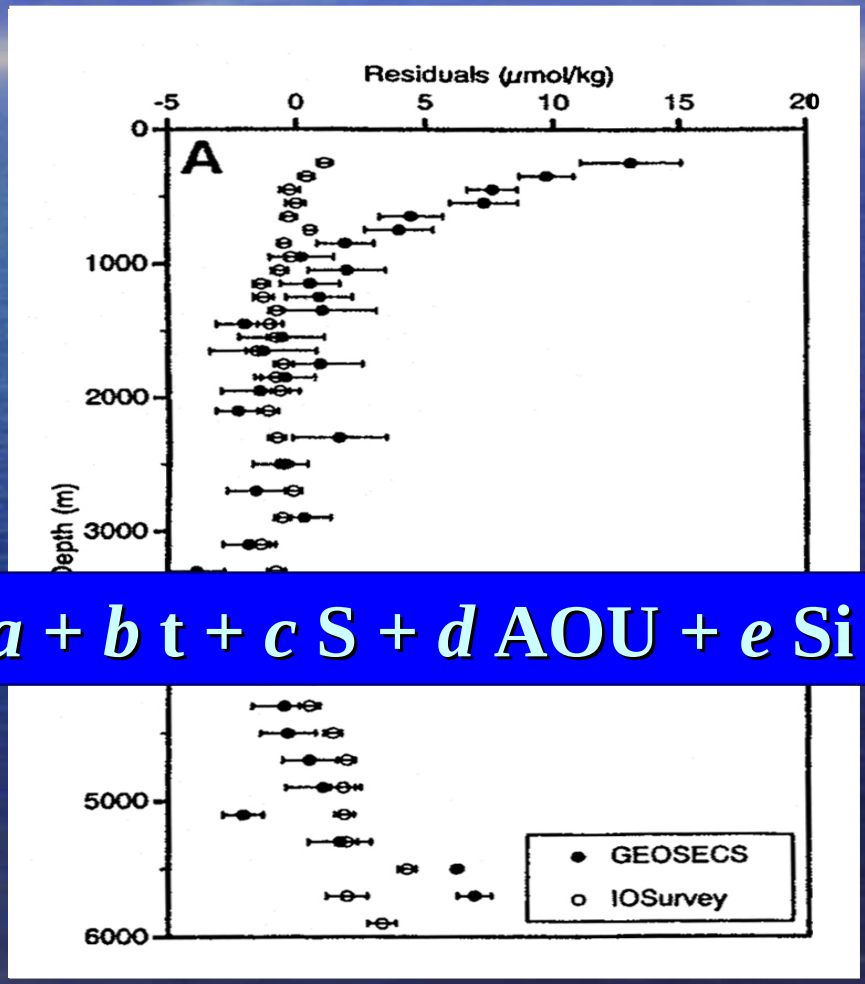
# North Pacific DIC Changes (2004 - 1994)




- Large positive and negative DIC differences in the upper 1000m that correspond with temperature, salinity, and AOU differences.

# Detecting changes in anthropogenic $CO_2$ in the ocean on decadal time scales




$$C_T = a + b\,t + c\,S + d\,AOU + e\,Si + f\,P$$

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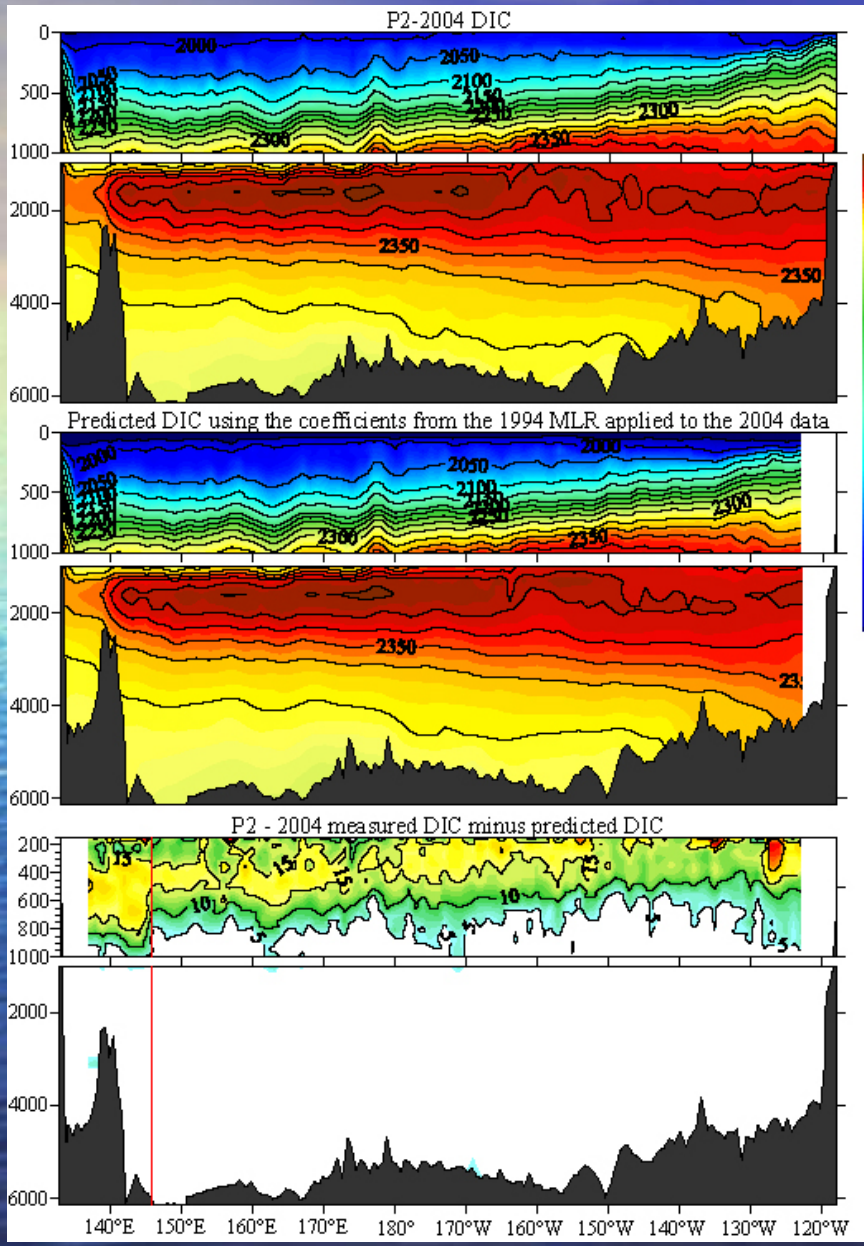
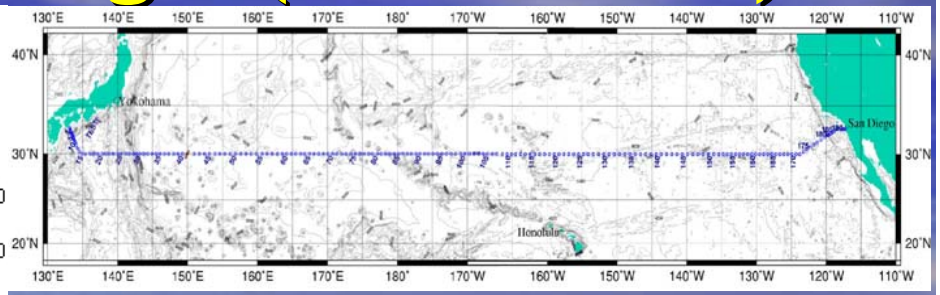
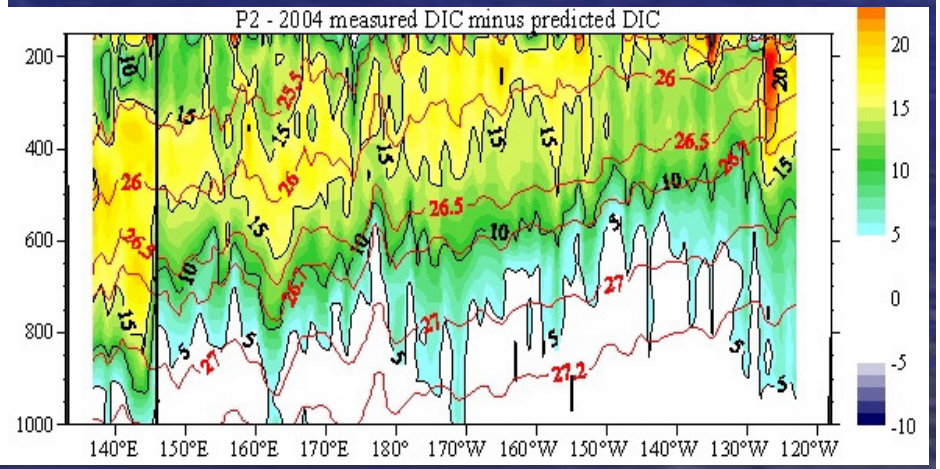
# North Pacific DIC Changes (2004 - 1994)



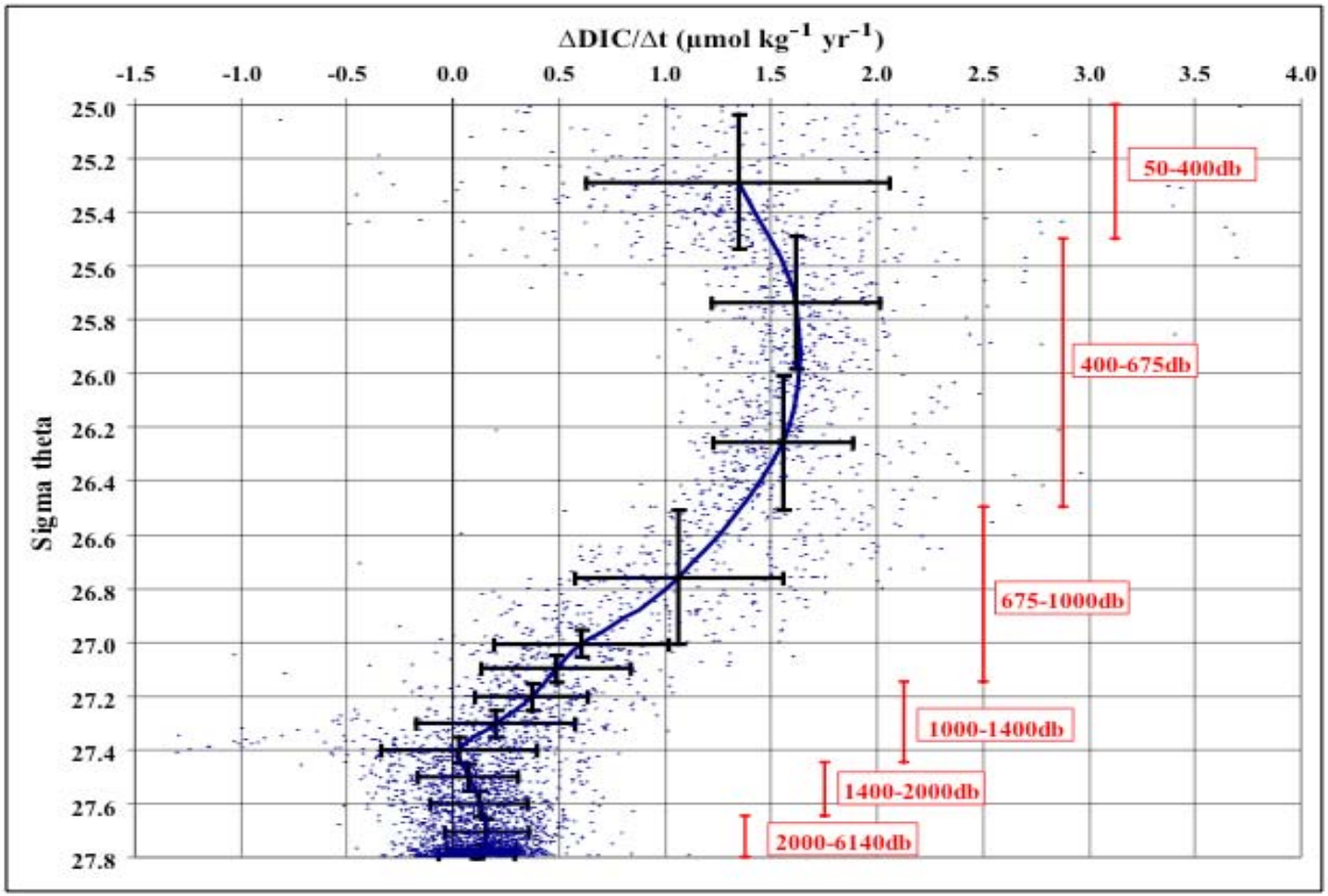

## MLR Procedure

- Large positive DIC differences in surface waters and 10 - 37 µmol/kg increases at intermediate depths between 200 - 800m.

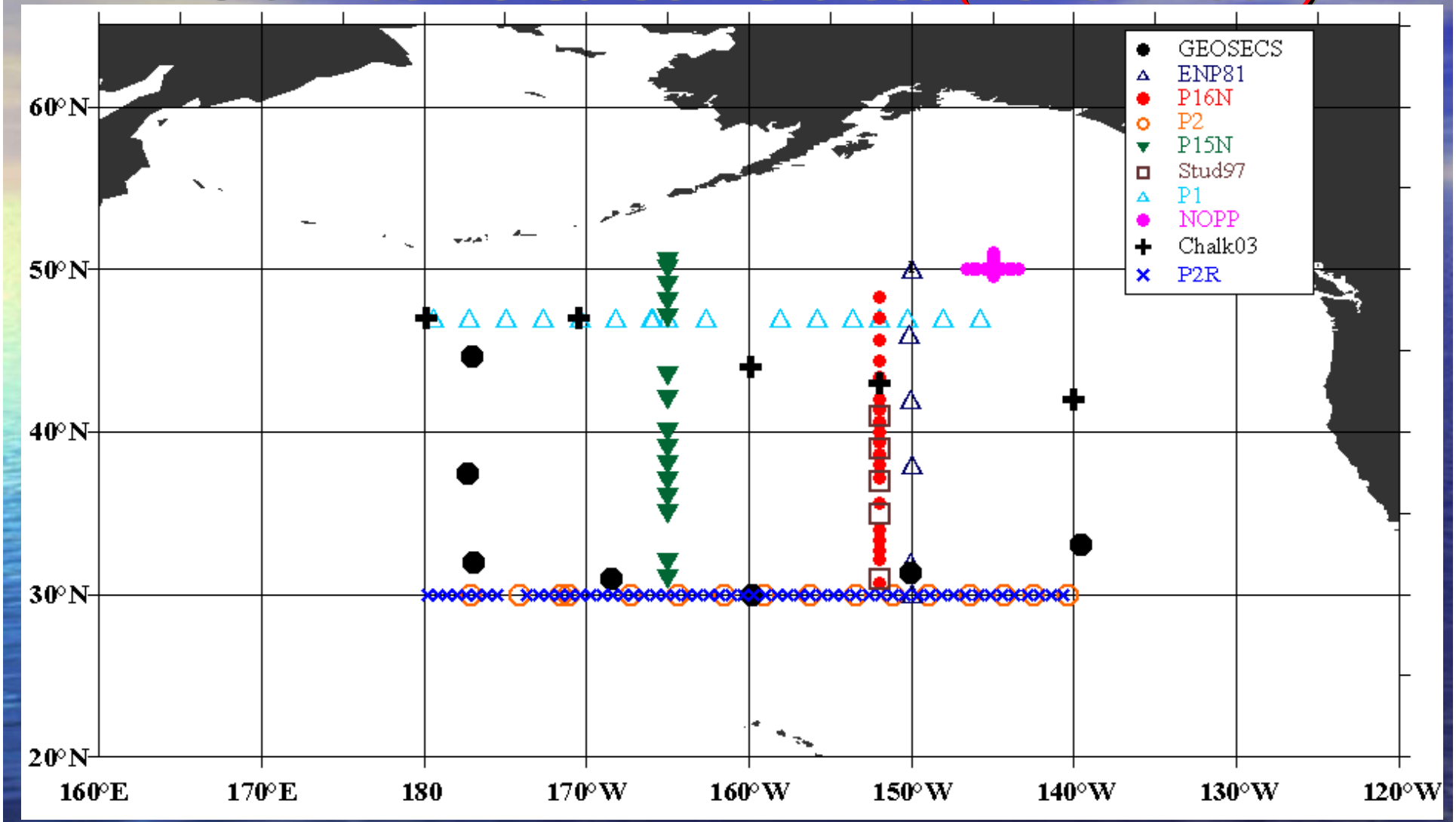


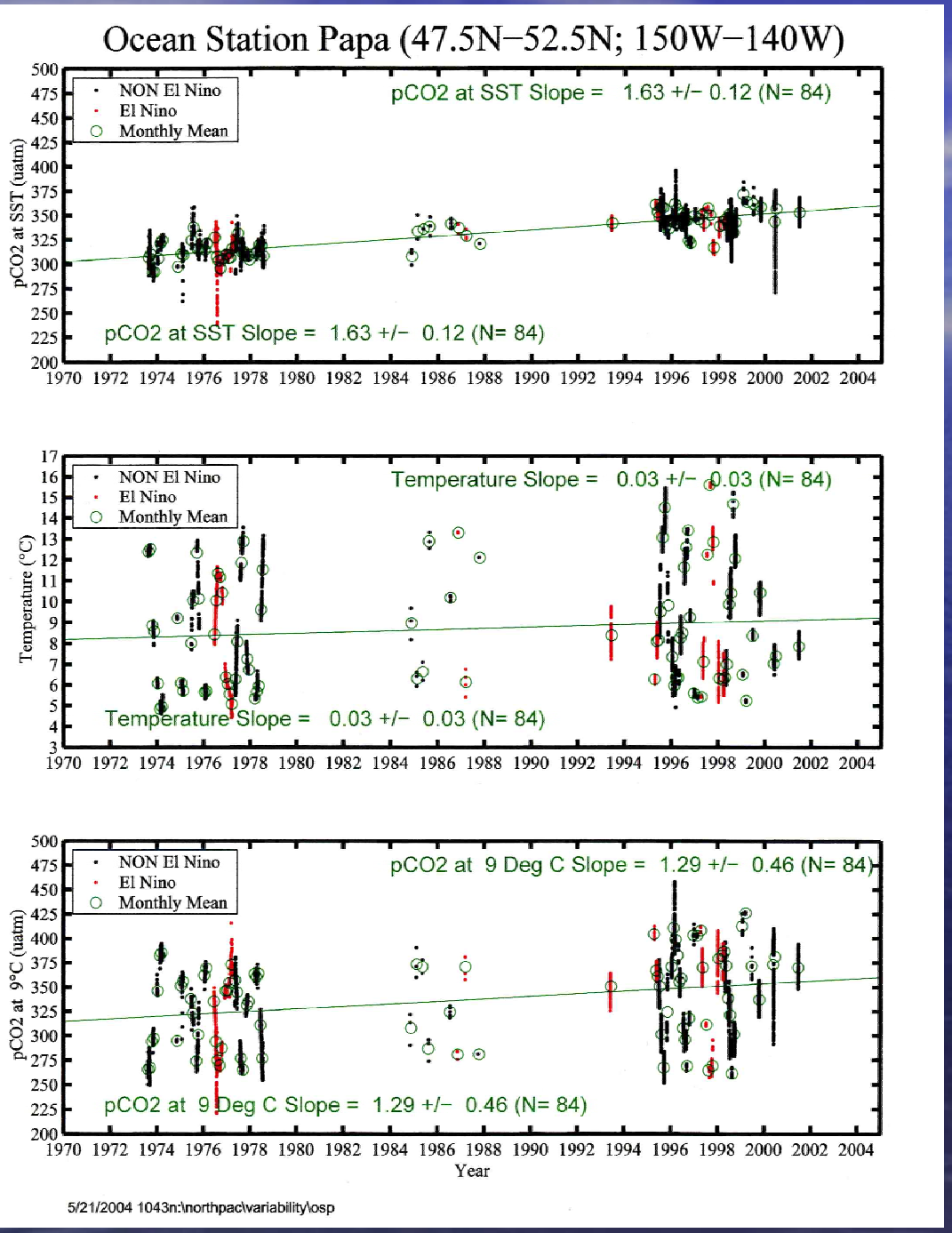

2004-12-07

# $CO_2$ Growth Rate on Isopycnal Surfaces along 30°N Based on P2 2004 - 1994 Comparison



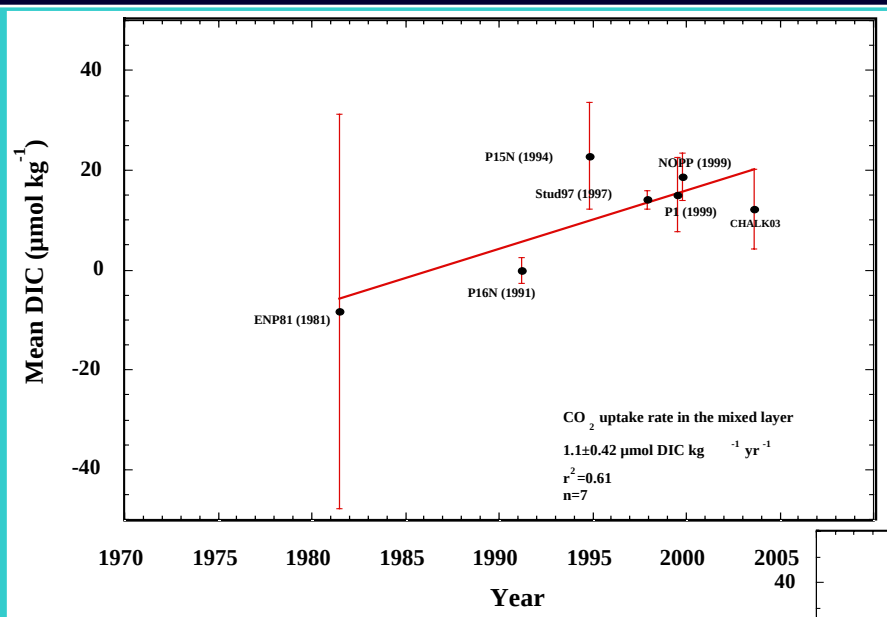
# North Pacific Carbon Cruises (1973 - 2004)






Takahashi et al
(in preparation)

# DIC increase in the mixed layer of the North Pacific Ocean

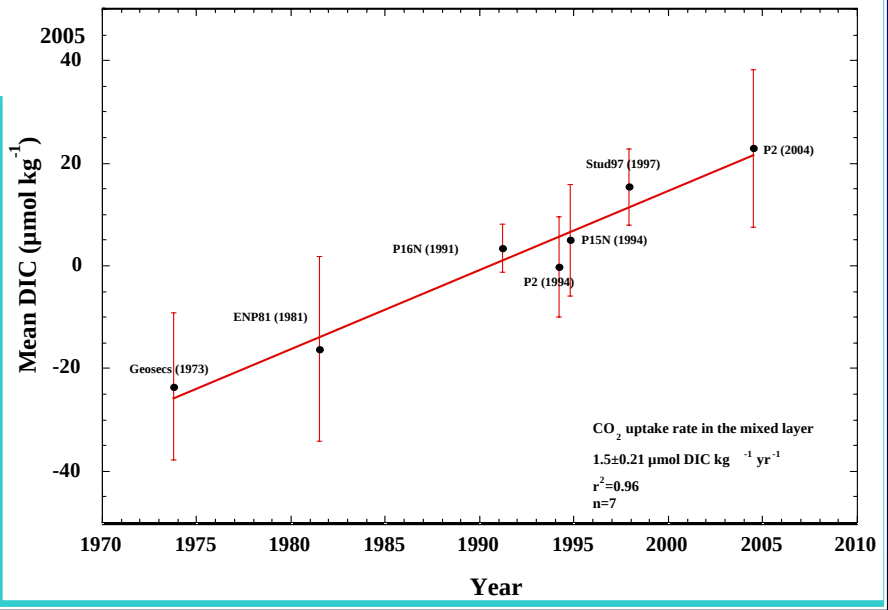



**N. Pacific Residual DIC**
**Mixed Layer >39°N**
**30-50°N/140-180°W**

**1.1 ±0.4 µmol kg$^{-1}$ yr$^{-1}$**

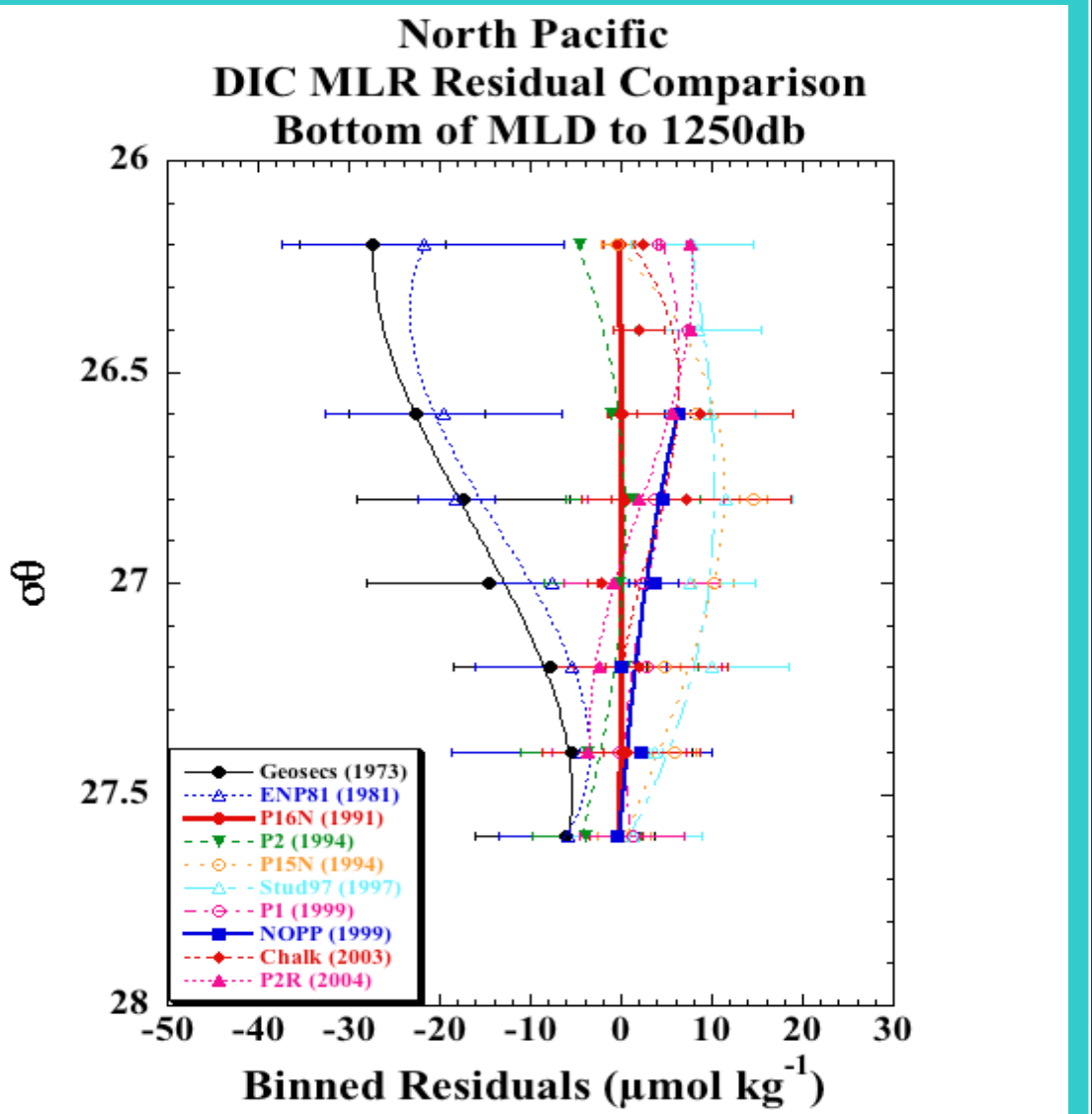
**N. Pacific Residual DIC**
**Mixed Layer <39°N**
**30-50°N/140-180°W**

**1.5 ±0.2 µmol kg$^{-1}$ yr$^{-1}$**




Feely et al. (in prep)

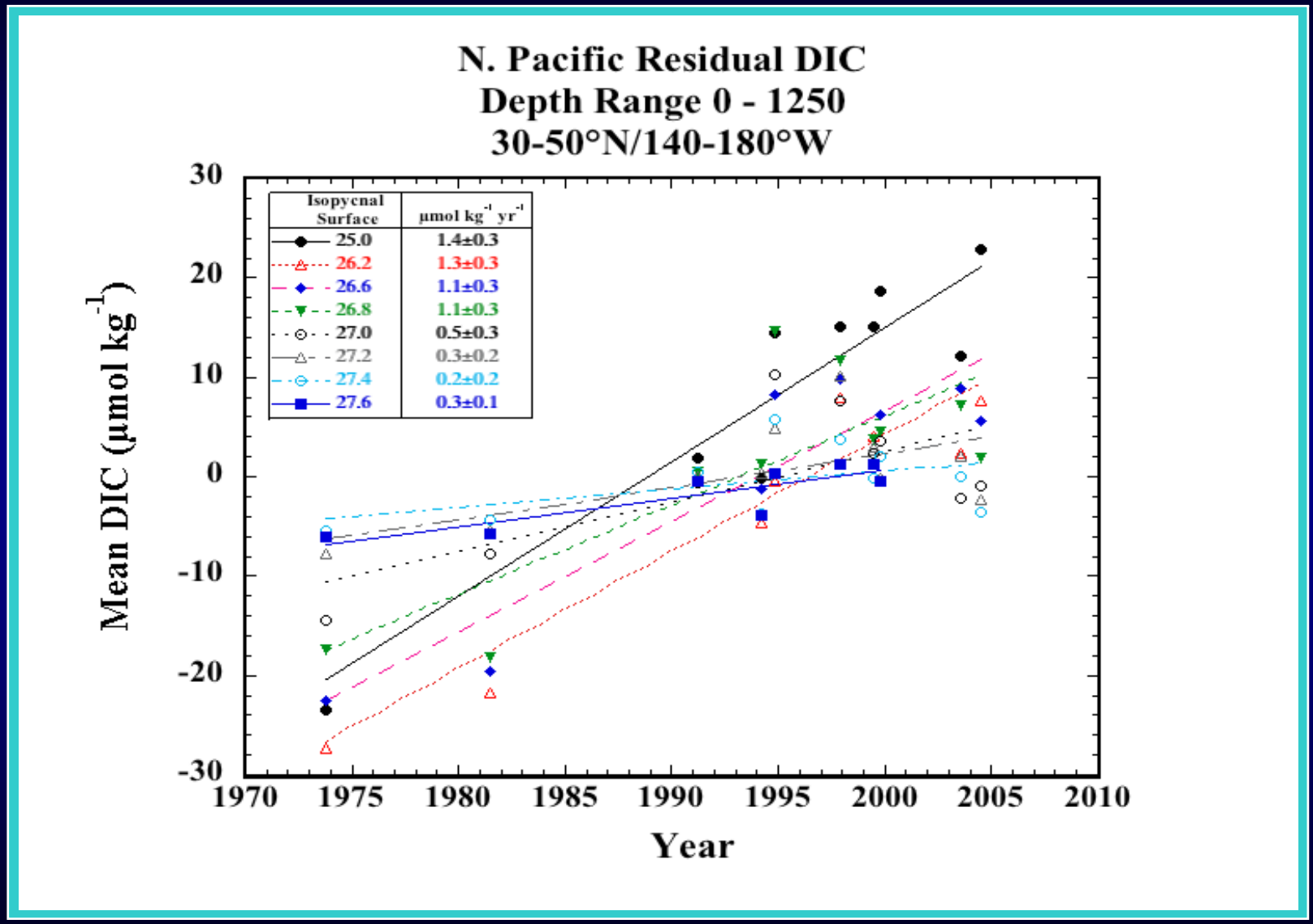
## MLR approach: $DIC = a\theta + bS + cAOU + dSi(OH)_4 + ePO_4$




**North Pacific DIC Residual Comparison Bottom of MLD to 1250db**

Feely et al. (in prep)

# DIC increase on Isopycnal Surfaces of the North Pacific Ocean




Feely et al. (in prep)

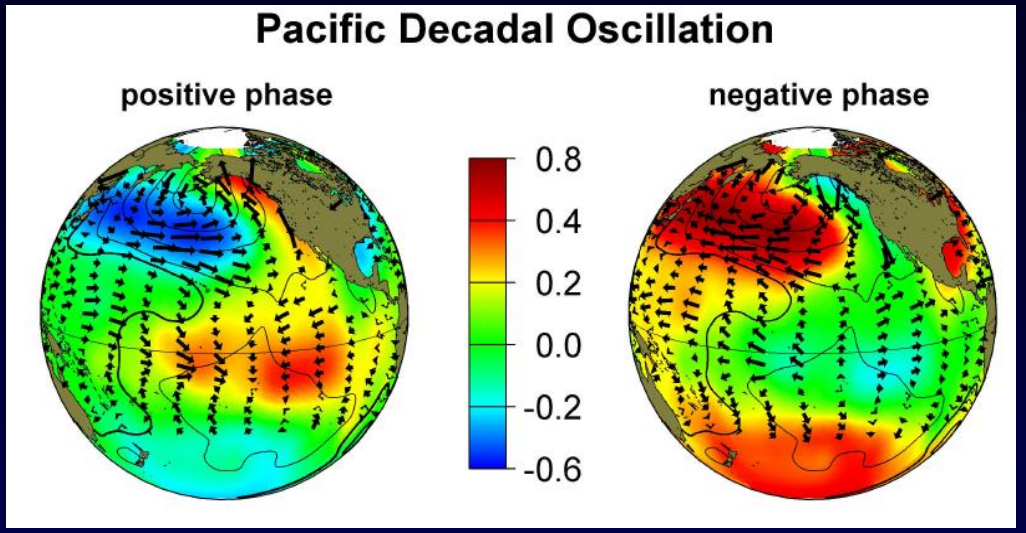
# Carbon Increases in the North Pacific Ocean (1968-2004)

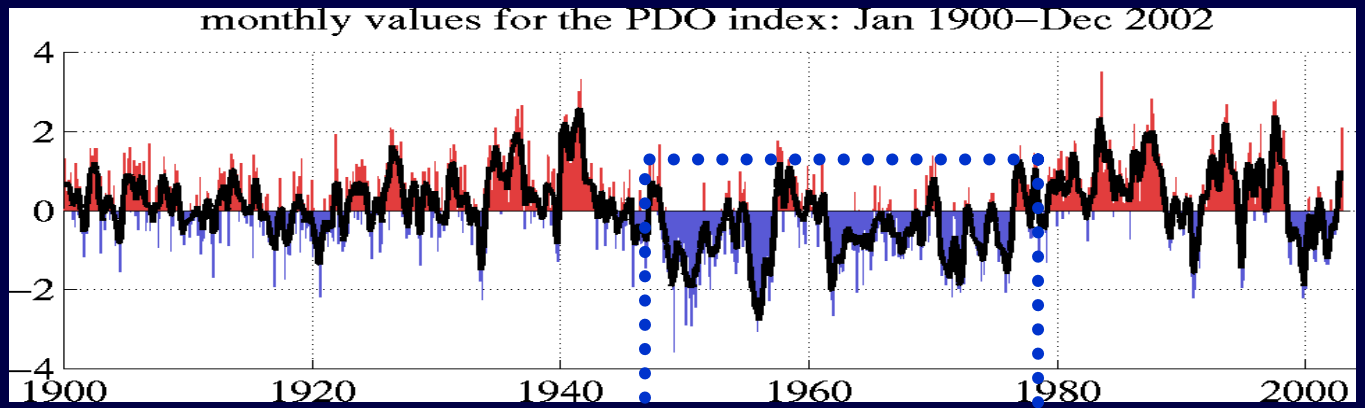
| Integrated uptake rate (mol $m^{-2}$ $yr^{-1}$) | DIC Mixed layer uptake (µmol $kg^{-1}$ $yr^{-1}$) | $pCO_2$ increase (µatm $yr^{-1}$) | Approach | Area of Study | Years | Depth range (m) | Reference |
|---|---|---|---|---|---|---|---|
| 0.83 ± 0.19 | — | — | OBS | Northwestern Pacific | 1973-1991 | 0-2000 | Tsunogai *et al.* (1993) |
| — | 0.4-1 | 1.8 ± 0.6 | OBS | 137°E, lat > 15°N | 1984-1993 | 0 | Inoue *et al.* (1995) |
| — | — | 0.5 ± 0.7 | OBS | 137°E, lat < 14°N | 1984-1993 | 0 | Inoue *et al.* (1995) |
| 0.63* ± 0.15 | 1.3 ± 0.7 | — | MLR | Central North Pacific | 1973-1991 | 125-1250 | Slansky *et al.* (1997) |
| 0.33 ± 0.05 | — | — | CFC | North Pacific | 1968-1978 | 0-cfc=0.02 | Watanabe *et al.* (2000) |
| 0.44 ± 0.07 | — | — | CFC | North Pacific | 1978-1988 | 0-cfc=0.02 | Watanabe *et al.* (2000) |
| 0.58 ± 0.09 | — | — | CFC | North Pacific | 1988-1998 | 0-cfc=0.02 | Watanabe *et al.* (2000) |
| 0.63 ± 0.2 | — | — | OBS | Pacific | 1973-1993 | 0-1000 | Ono *et al.* (2000) |
| 0.47 ± 0.2 | — | — | OBS | Pacific | 1982-1993 | 0-1000 | Ono *et al.* (2000) |
| 0.39 ± 0.1 | — | — | CFC | Pacific | 1980-1999 | 0-2000 | McNeil *et al.* (2003) |
| 1.0* ± 0.4 | — | — | OBS | KNOT | 1992-2002 | 200-700 | Wakita *et al.* (2003) |
| 0.7 | — | — | OBS | HOT | 1989-1992 | 0 | Winn *et al.* (1994) |
| — | 1.0 ± 2.9 | — | OBS | HOT | 1989-1995 | 0-60 | Winn *et al.* (1998) |
| 1.1 ± 0.1 | 1.2 ± 0.2 | 2.5 ± 0.3 | OBS | HOT | 1988-1999 | 0-225 | Dore *et al.* (2003) |
| 0.42 | — | — | INV | 13°S-13°N | 1990 | 0-btm | Gloor et al. (2003) |
| 0.25 | — | — | INV | 13°N-36°N | 1990 | 0-btm | Gloor et al. (2003) |
| 0.46 | — | — | INV | 36°N-62°N | 1990 | 0-btm | Gloor et al. (2003) |
| 0.9 ± 0.8 | — | — | MLR | South Pacific | 1973-1996 | 300-1250 | Peng *et al.* (2003) |
| 1.3 ± 2.1 | — | — | MLR | North Pacific | 1973-1991 | 300-1250 | Peng *et al.* (2003) |
| — | — | 1.8 ± 0.7 | OBS | Equatorial Pacific | 1990-2001 | 0 | Takahashi *et al.* (2003) |
| 1.1 ± 0.4 | 1.3 ± 0.2 | — | MLR | Central North Pacific | 1973-1999 | 0-1250 | Feely *et al.* (2003) |
| 0.74* | — | — | ΔC* | HOT | 1989-2000 | 100-800 | Sabine *et al.* (2004) |
| 1.0 ± 0.6 | 1.4 ± 0.3 | — | MLR | Central North Pacific | 1973-2004 | 0-1250 | This work |
| — | 1.5 ± 0.2 <39°N | — | MLR | Central North Pacific | 1973-2004 | 0-200 | This work |
| — | 1.1 ± 0.4 >39°N | — | MLR | Central North Pacific | 1973-2004 | 0-200 | This work |

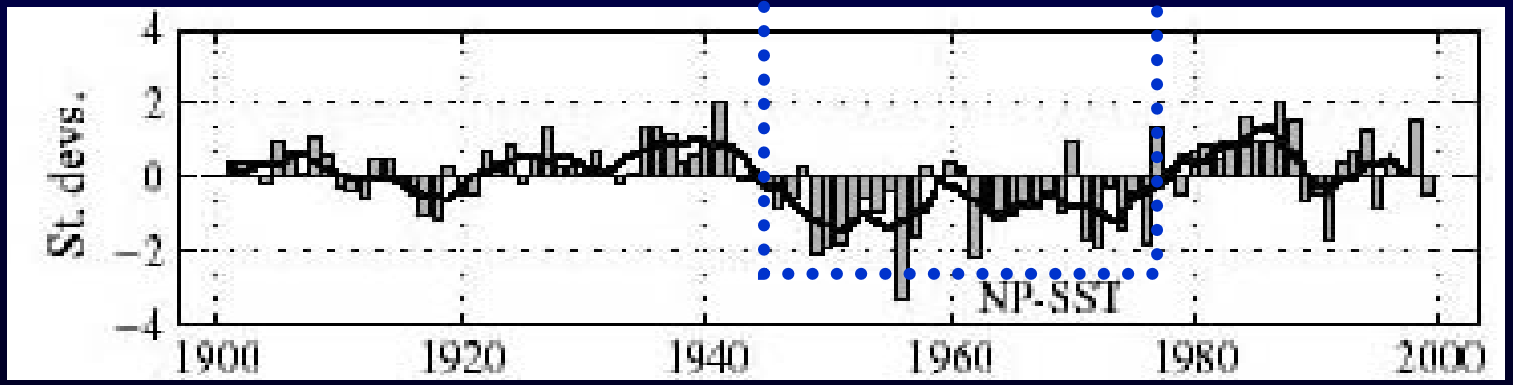
* = uptake not integrated all the way to the surface

**Temporal Changes in DIC based on the MLR procedure**

12/6/2004

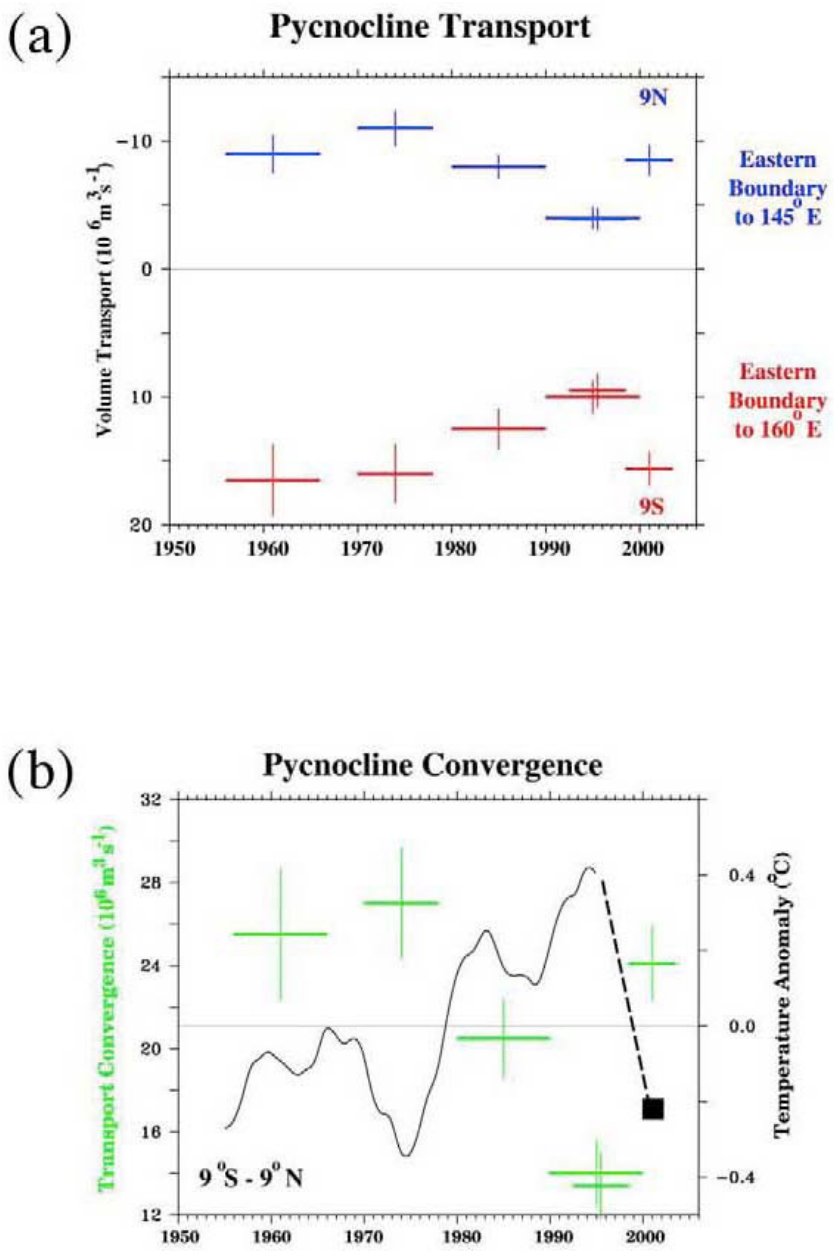



Nathan J.Mantua,

# McPhaden and Zhang (GRL, 2004)



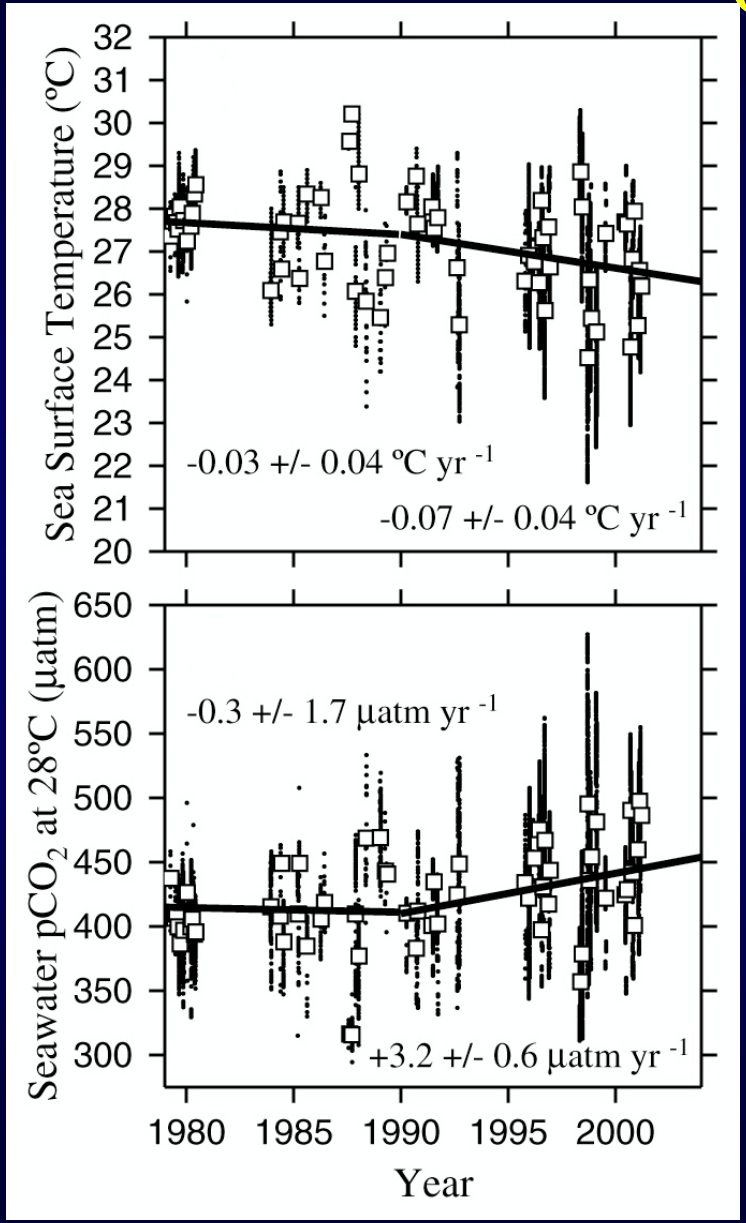

"Interior ocean pycnocline transports approximately doubled in Northern Hemisphere and intensified to levels not seen since before the 1976-77 regime shift in the Southern Hemisphere. Pycnocline transport convergence increased by approximately 10 Sv from 1992-1998 to 1998-2003 reaching its highest value since the mid-1970s"

-Mike McPhaden and Dongxiao Zhang

# Decadal Changes in the $CO_2$ Source from the equatorial Pacific Ocean after Takahashi et al (Science, 2003)

**A) Sea Surface Temperature in ˚C**

**B) $pCO_2$ in µatm corrected to 28˚C**




**Equatorial Pacific Nino 3.4 Region 5˚S - 5˚N, 170˚W -120˚W**

When these rates are corrected for the atmospheric increase =

1979-1990

-2.1 ± 1.4 µatm yr-1

1990 - 2001

1.3 ± 0.9 µatm yr-1

This suggests there has been a 7% increase in the $CO_2$ flux over the last decade

2004-12-07

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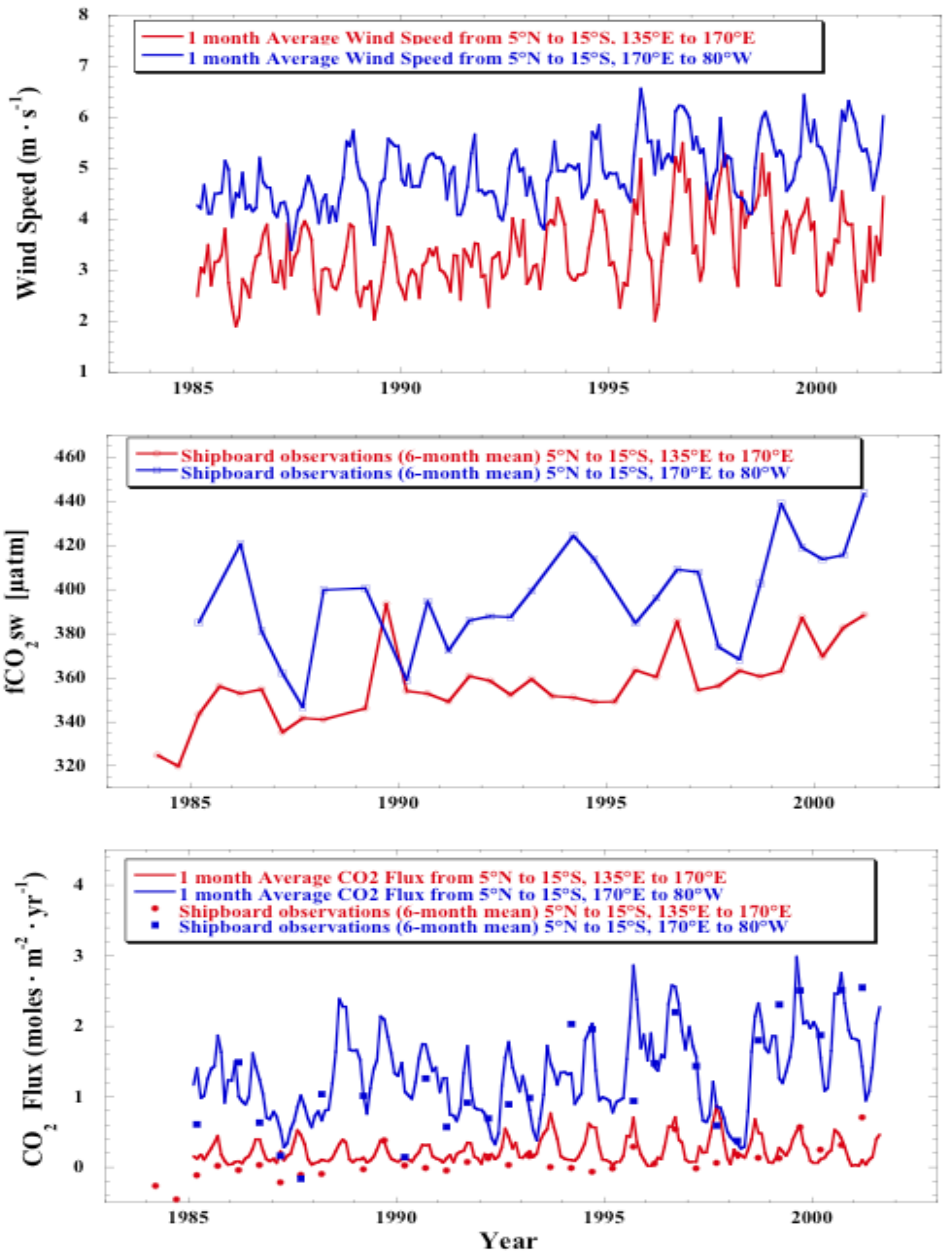
# Wind speeds, $pCO_2$ and $CO_2$ fluxes in the Equatorial Pacific




Wind speeds:

Slight increases after 1994

5.3 vs. 4.6 m $s^{-1}$ - east

3.7 vs. 3.1 m $s^{-1}$ - west

**$fCO_2$: slightly higher after 1994 in the eastern Pacific**

**408 vs. 384 ± 20 µatm**

**$CO_2$ flux: higher after 1994 in the eastern Pacific**

**1.5 vs. 1.2 ± .5 moles $m^{-2}$ $yr^{-1}$**

**This suggests there has been a 24% increase in the $CO_2$ flux over the last 10 years.**

# Conclusions

1. Air-sea exchange and ventilation processes are the primary control of DIC increases in the surface and intermediate waters of the North Pacific.
2. We have observed recent increases in the air-sea exchange flux of $CO_2$ in the tropical Pacific since about 1994, consistent with the rebound of the meridional overturning circulation reported by McPhaden and Zhang.
3. Decadal changes in $pCO_2$ distributions are consistent with PDO shifts.

# Thank You