BIOGEOCHEMISTRY GROUP
IGPP/AS UCLA

# Uptake, transport, and storage of anthropogenic $CO_2$ by the ocean: implications for the global carbon cycle


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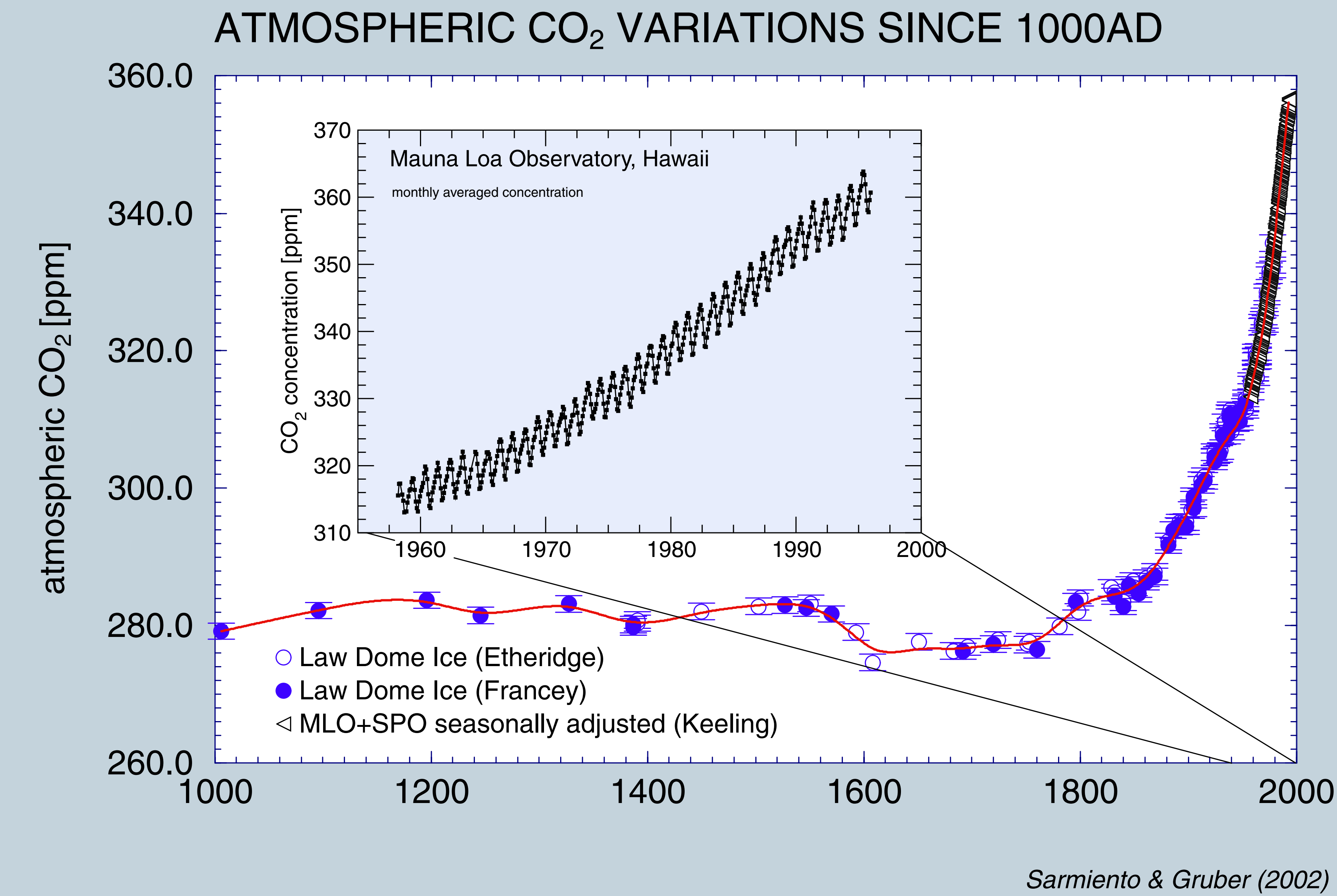
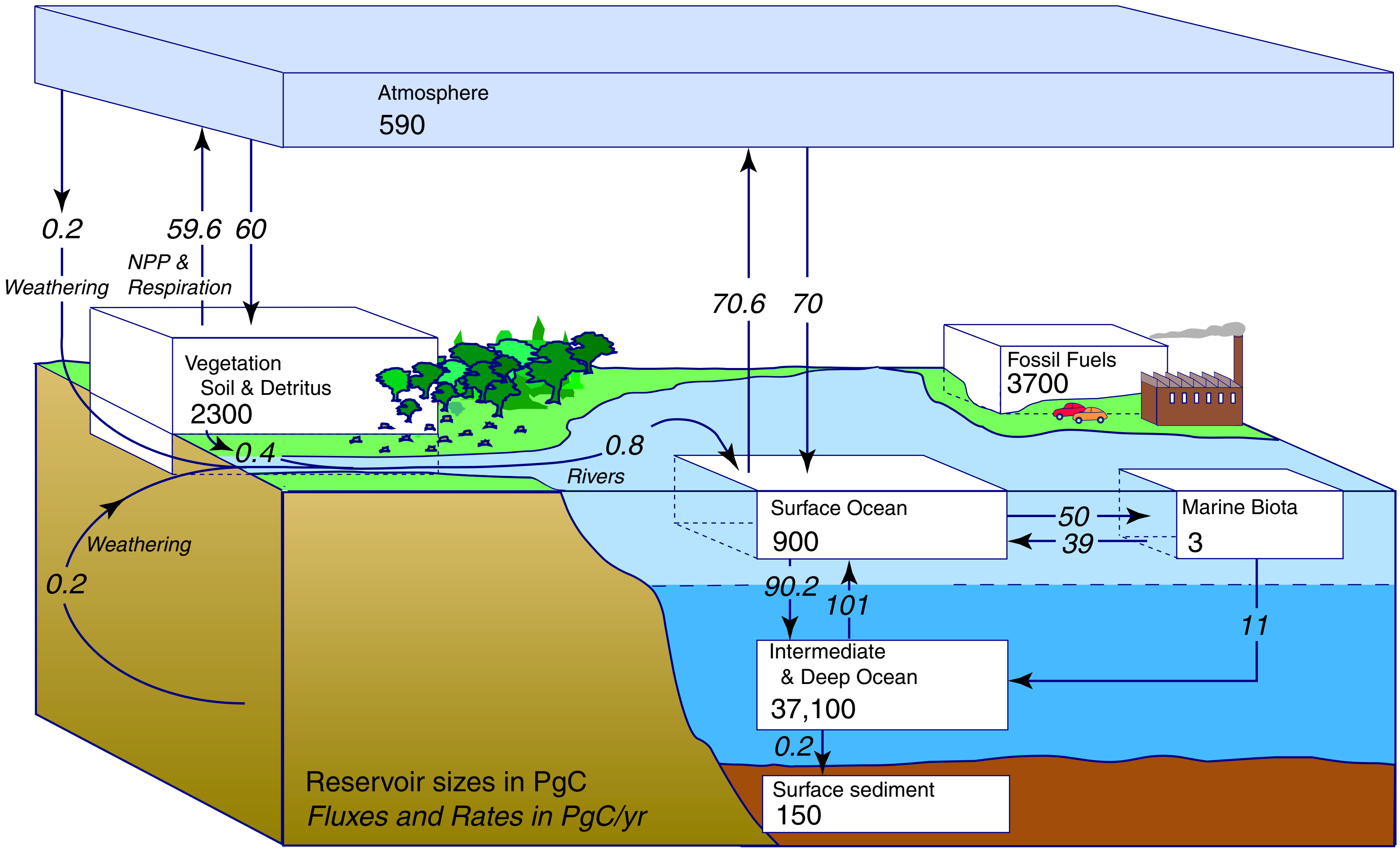
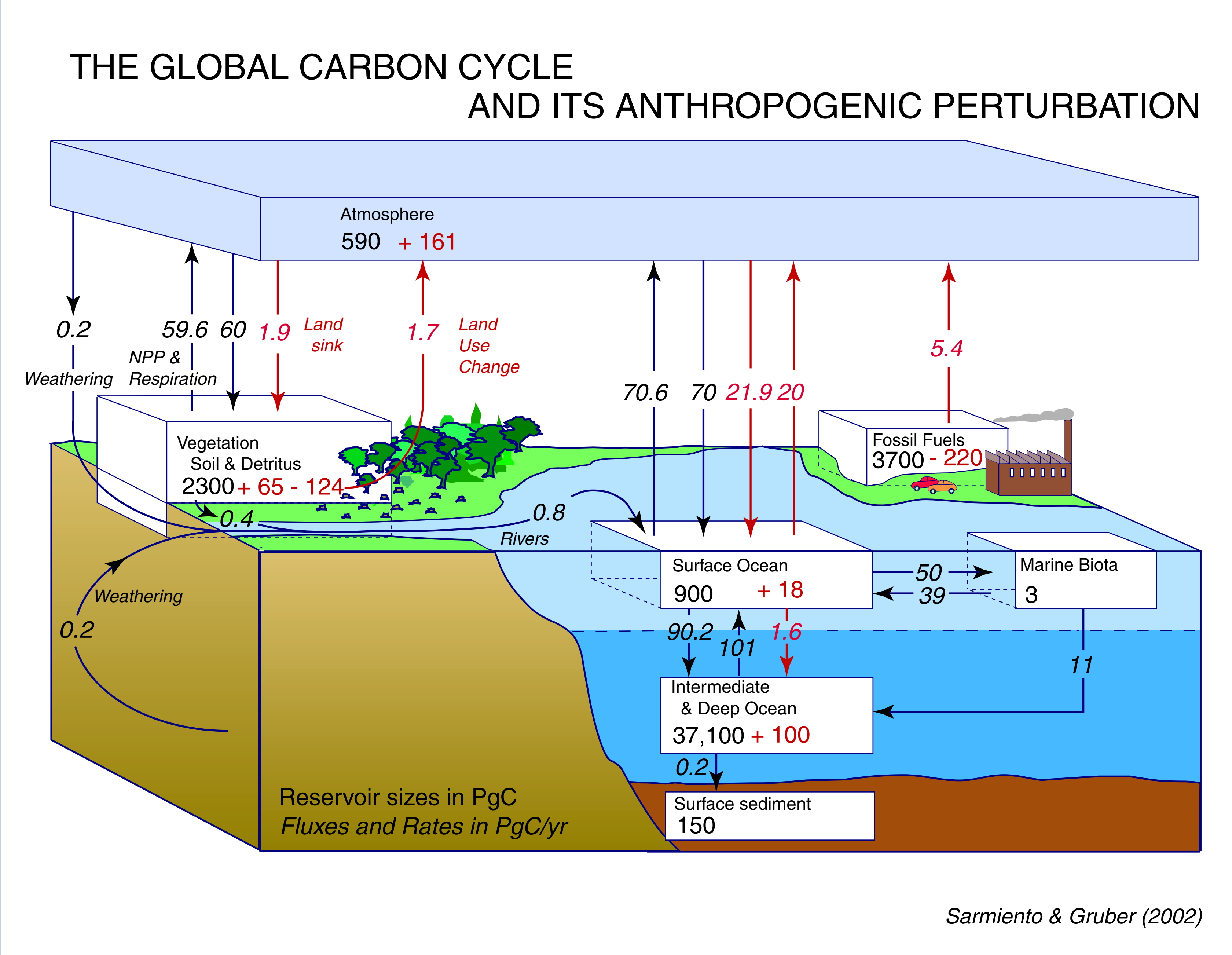

ATMOSPHERIC $CO_2$ VARIATIONS SINCE 1000AD
atmospheric $CO_2$ [ppm]
360.0
340.0
320.0
300.0
280.0
260.0
1000
1200
1400
1600
1800
2000
Mauna Loa Observatory, Hawaii
monthly averaged concentration
$CO_2$ concentration [ppm]
370
360
350
340
330
320
310
1960
1970
1980
1990
2000
Law Dome Ice (Etheridge)
Law Dome Ice (Francey)
MLO+SPO seasonally adjusted (Keeling)
Sarmiento & Gruber (2002)

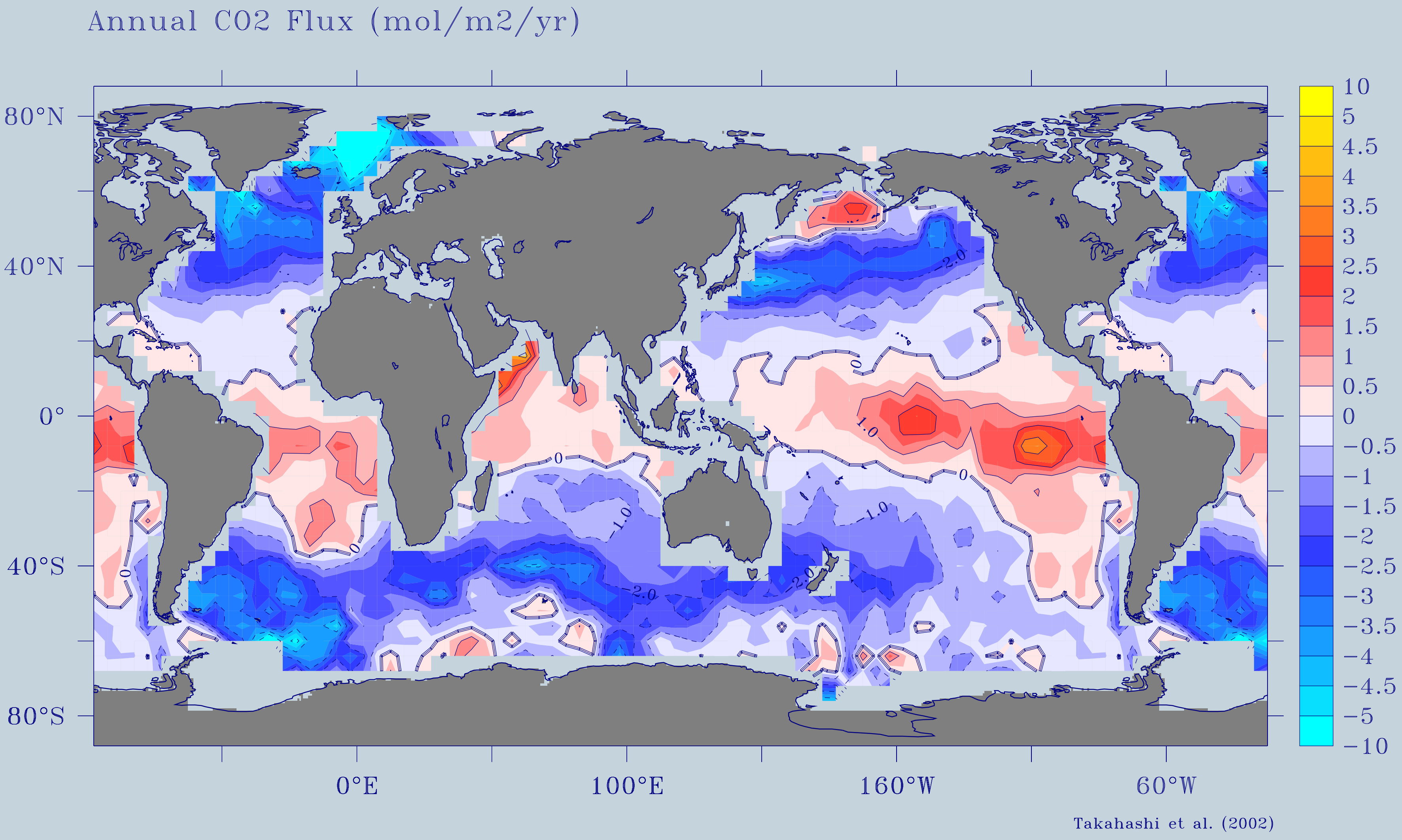
THE GLOBAL CARBON CYCLE



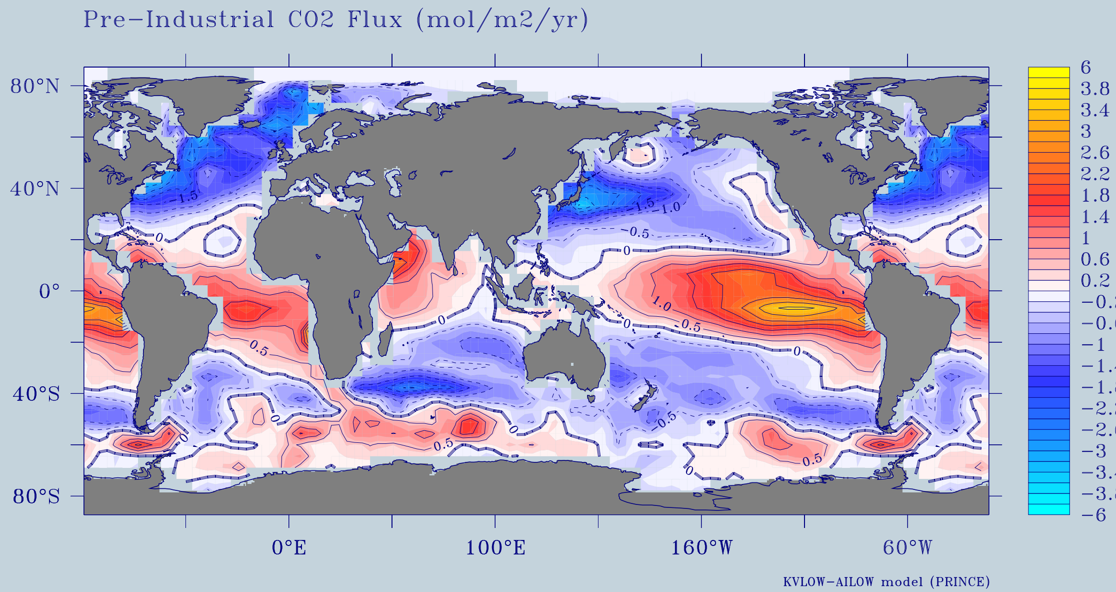

THE GLOBAL CARBON CYCLE
AND ITS ANTHROPOGENIC PERTURBATION
Atmosphere
590 + 161
0.2
Weathering
59.6
60
NPP &
Respiration
1.9
Land
sink
1.7
Land
Use
Change
70.6
70
21.9
20
5.4
Vegetation
Soil & Detritus
2300 + 65 - 124
0.4
0.8
Rivers
Fossil Fuels
3700 - 220
Surface Ocean
900 + 18
50
39
Marine Biota
3
90.2
101
1.6
11
Intermediate
& Deep Ocean
37,100 + 100
0.2
Surface sediment
150
Weathering
0.2
Reservoir sizes in PgC
Fluxes and Rates in PgC/yr
Sarmiento & Gruber (2002)

# Outline

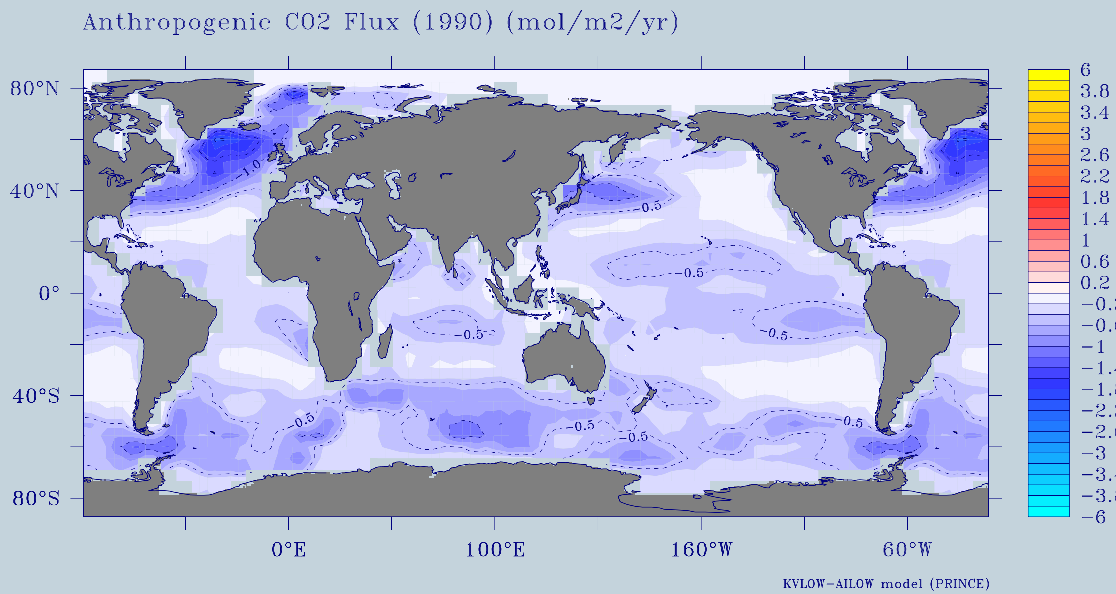
- Introduction
- Air-sea $CO_2$ fluxes *or the problem of separating the anthropogenic from the natural component*
- The importance of the ocean as a sink for ant. $CO_2$
- How do we obtain fluxes from storage? An inverse approach
- On the relationship between transient tracers and anthropogenic $CO_2$
- Summary and outlook




Globally integrated flux into the ocean: 2.2 PgC $yr^{-1}$

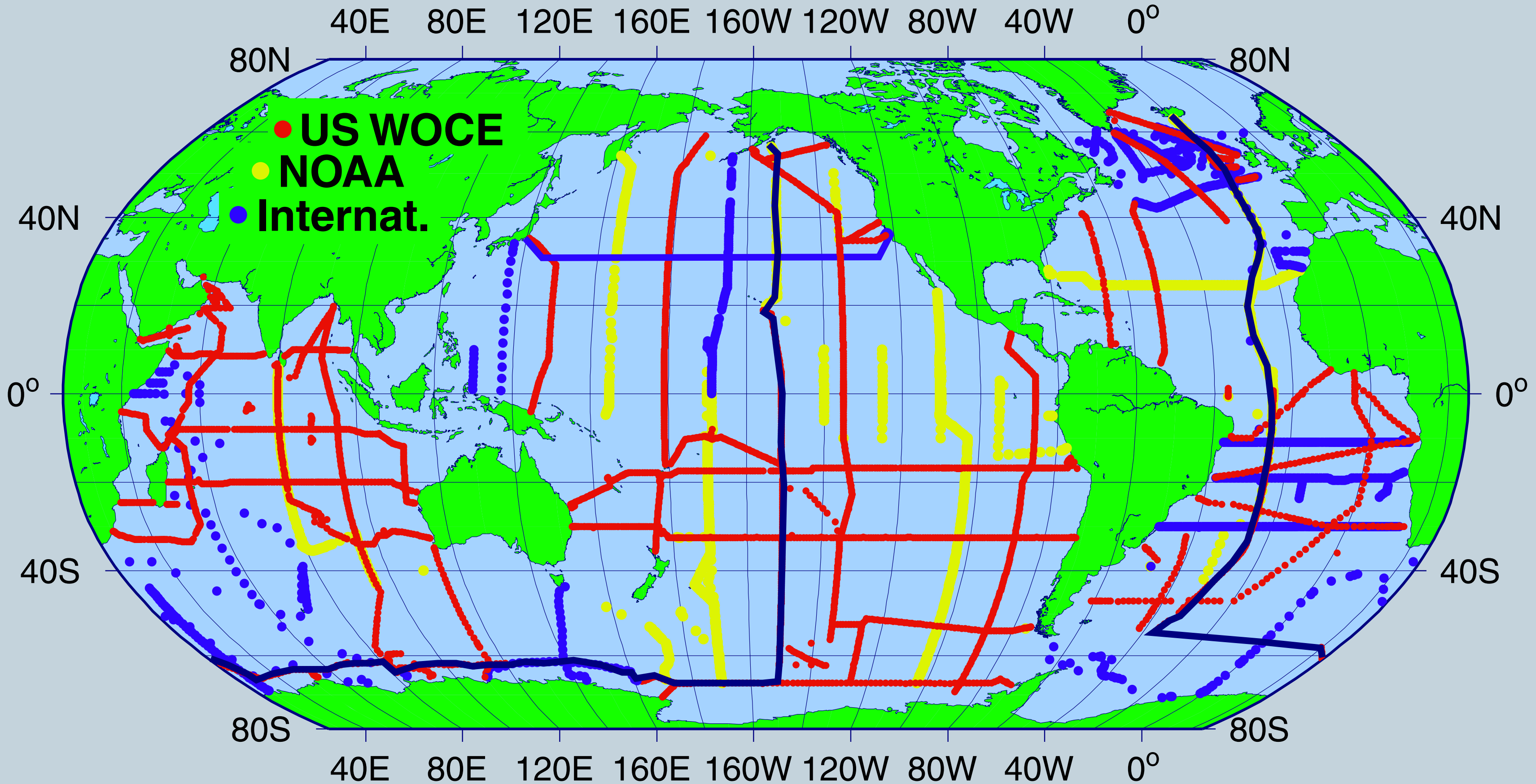


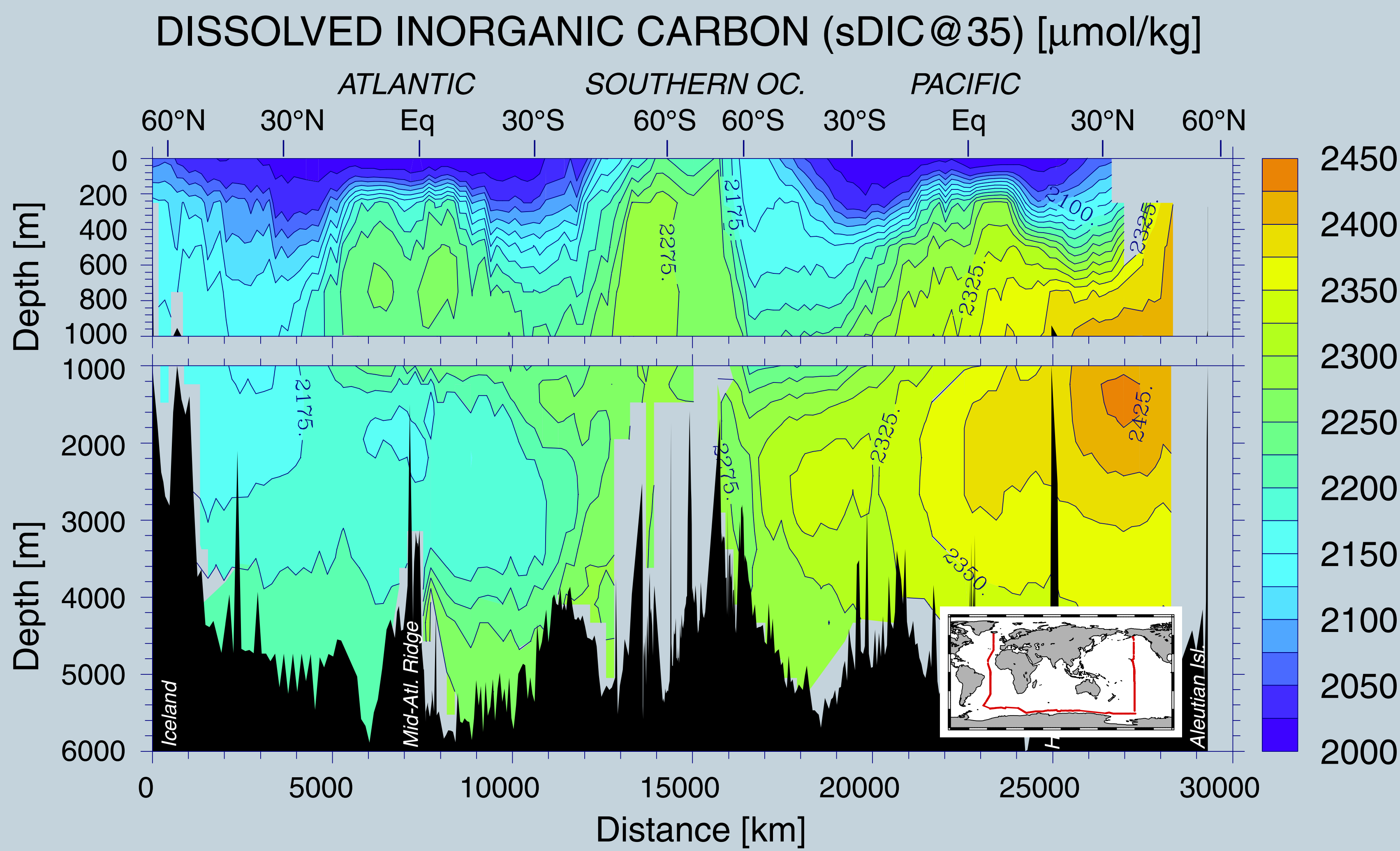

# Pre-industrial $CO_2$ fluxes




# Anthropogenic $CO_2$ fluxes

# WOCE/JGOFS/OACES $CO_2$ SURVEY





DISSOLVED INORGANIC CARBON (sDIC@35) [µmol/kg]
ATLANTIC
SOUTHERN OC.
PACIFIC
60°N
30°N
Eq
30°S
60°S
60°S
30°S
Eq
30°N
60°N
Depth [m]
Depth [m]
Distance [km]
Iceland
Mid-Atl. Ridge
Aleutian Isl.
2175.
2275.
2100.
2325.
2425.
2350.
2450
2400
2350
2300
2250
2200
2150
2100
2050
2000

# Determination of the anthropogenic $CO_2$ signal

We follow the method of *Gruber et al.* [1996] to separate the anthropogenic $CO_2$ signal from the large natural variability in oceanic DIC. This method requires the removal of

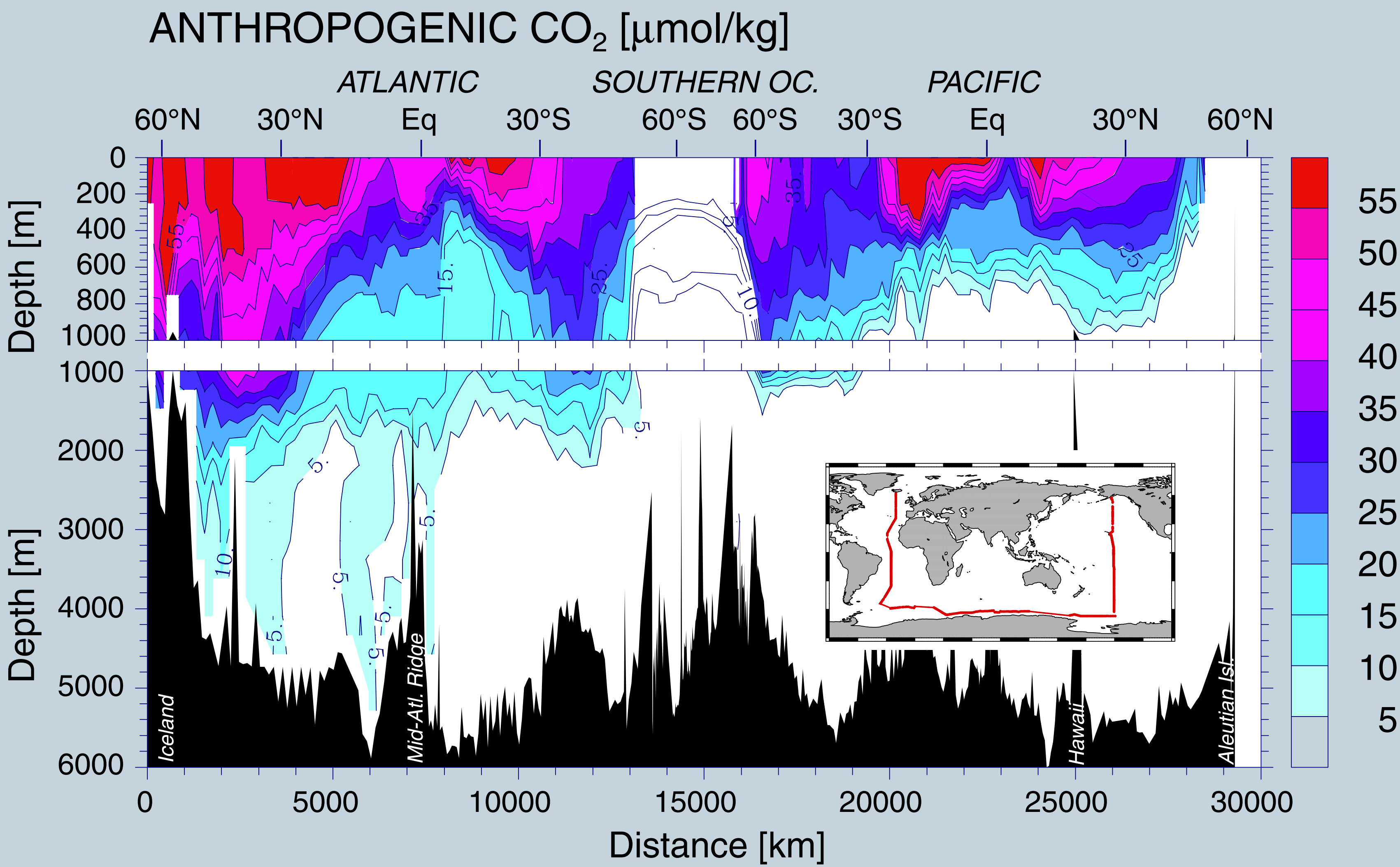
(i) the change in dissolved inorganic carbon (C) that incurred since the water left the surface ocean due to remineralization of organic matter and dissolution of $CaCO_3$ ($\Delta C_{\text{bio}}$), and

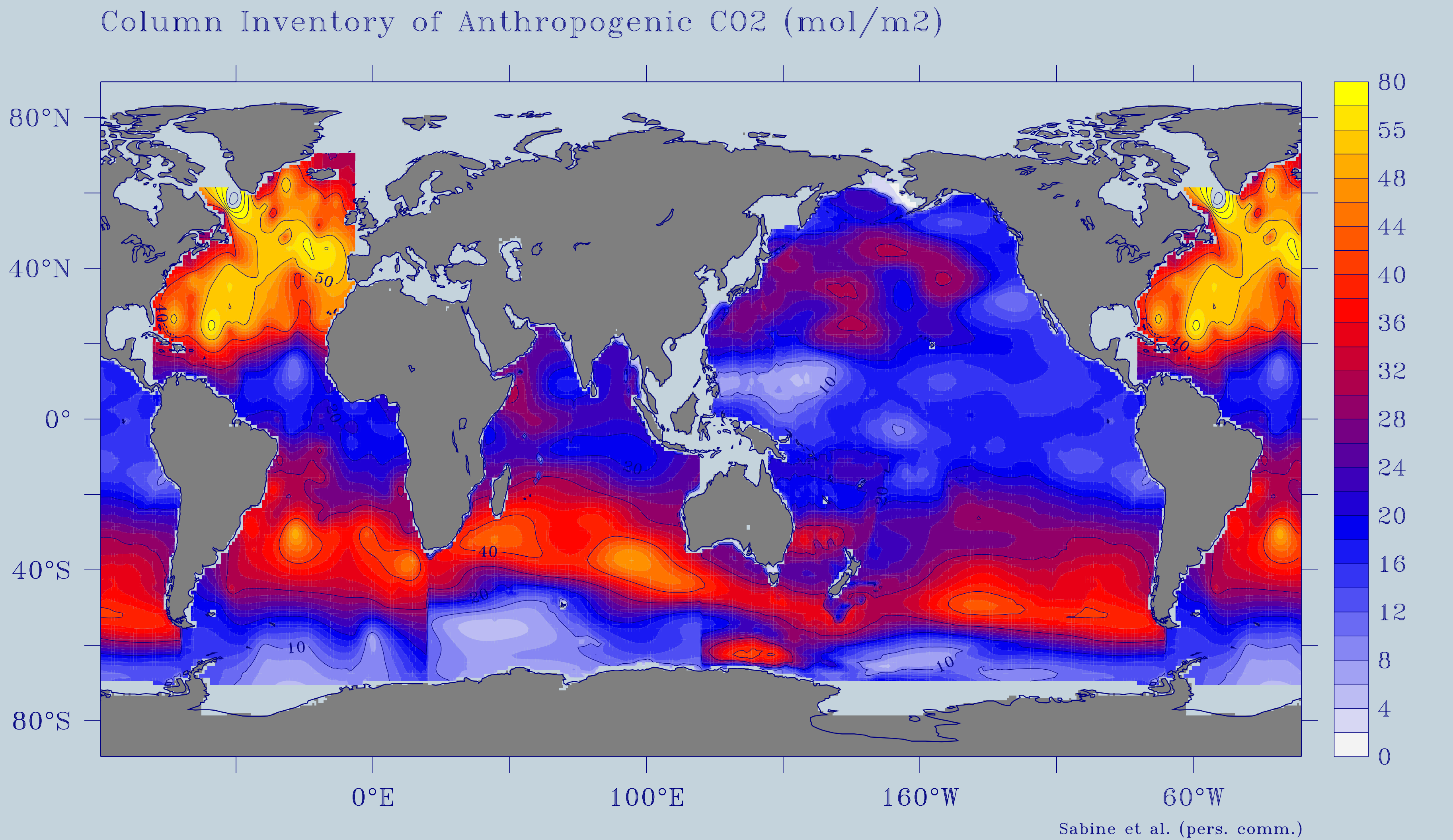
(ii) of a concentration $C_{\text{sfc-pi}}$ that reflects the DIC content a water parcel had at the outcrop in pre-industrial times

Thus,

$$\Delta C_{\text{ant}} = C - \Delta C_{\text{bio}} - C_{\text{sfc-pi}}$$

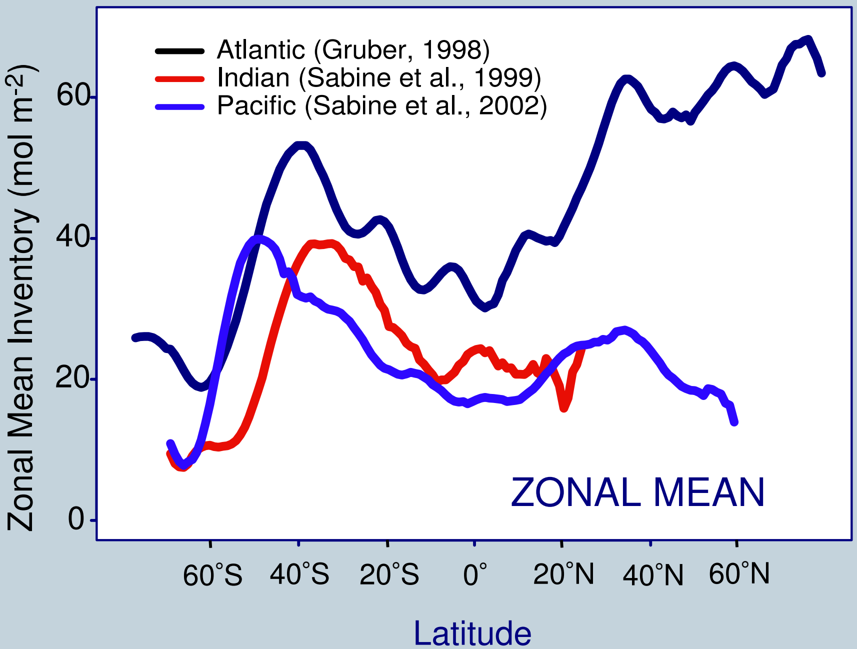
- Assumption:
  Natural carbon cycle has remained in steady-state.

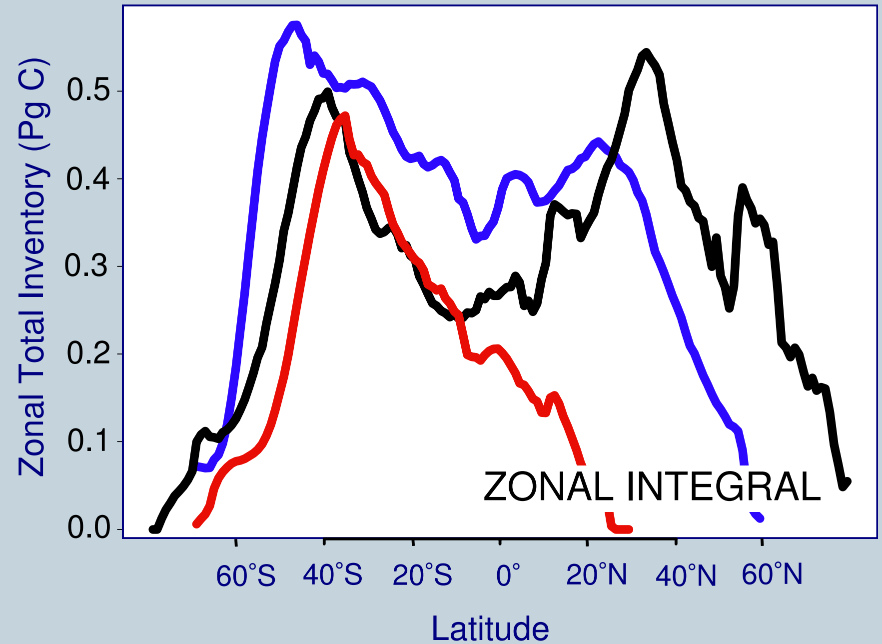

ANTHROPOGENIC $CO_2$ [μmol/kg]
ATLANTIC
SOUTHERN OC.
PACIFIC
60°N
30°N
Eq
30°S
60°S
60°S
30°S
Eq
30°N
60°N
Depth [m]
Depth [m]
Distance [km]
Iceland
Mid-Atl. Ridge
Hawaii
Aleutian Isl.
0
200
400
600
800
1000
1000
2000
3000
4000
5000
6000
0
5000
10000
15000
20000
25000
30000
55
50
45
40
35
30
25
20
15
10
5



Column Inventory of Anthropogenic CO2 (mol/m2)
80°N
40°N
0°
40°S
80°S
0°E
100°E
160°W
60°W
80
55
48
44
40
36
32
28
24
20
16
12
8
4
0
50
40
10
20
Sabine et al. (pers. comm.)

## ANTHROPOGENIC $CO_2$ INVENTORIES




large storage in subtropical gyres!

# Anthropogenic $CO_2$ Inventories during WOCE era

| | Atlantic Inventory[†] [Pg C] | Pacific Inventory[‡] [Pg C] | Indian Inventory[⋆] [Pg C] | Global Inventory [Pg C] |
|---|---|---|---|---|
| Southern Hemisphere | 17 | 28 | 17 | 62 (56%) |
| Northern Hemisphere | 28 | 17 | 3 | 48 (44%) |
| Total | 45 (41%) | 45 (41%) | 20 (18%) | 110 |

[†] Lee et al. (in prep.)

[‡] Sabine et al. (2002)

[⋆] Sabine et al. (1999)

# Anthropogenic $CO_2$ Budget (1800 to 1990)

| *$CO_2$ sources* | Gt C |
|---|---|
| (1) Emissions from fossil fuel and cement production [a] | 230 |
| (2) Net emissions from changes in land-use [b] | 110 |
| (3) Total anthropogenic $CO_2$ emissions = (1) + (2) | 340 |
| *$CO_2$ partitioning amongst reservoirs* | Gt C |
| (4) Storage in the atmosphere [c] | 145 |
| (5) Ocean uptake [d] | 107 |
| (6) Terrestrial sinks = [(1)+(2)]-[(4)+(5)] | 82 |

$a$: From *Marland and Boden* [1997]

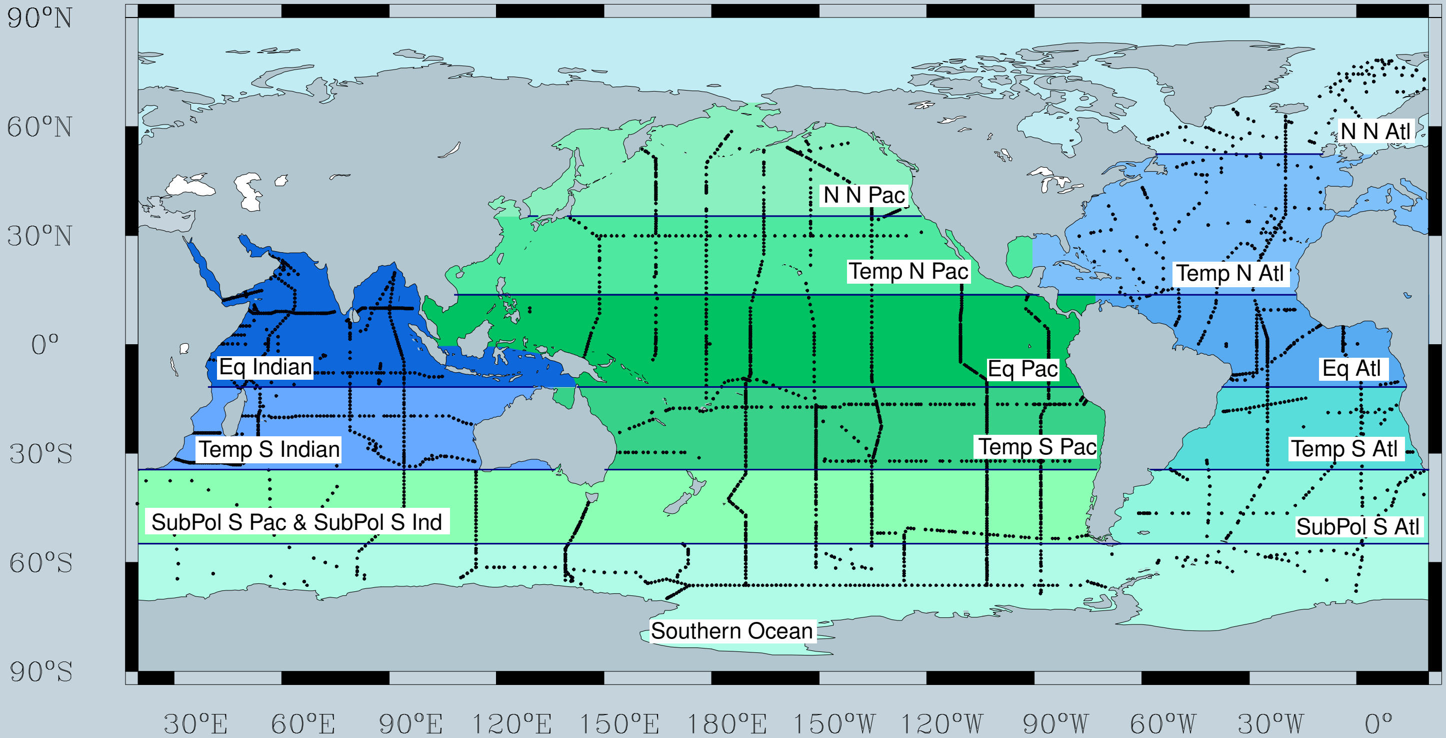
$b$: From *Houghton* [1997]

$c$: Calculated from change in atmospheric $pCO_2$

$d$: Based on estimates of *Sabine et al.* [1999], *Sabine et al.* [2002] and *Lee et al.* (in prep.), adjusted to 1990

# Principle of Oceanic Inversion

- The ocean surface is partitioned into $n$ regions ($n$=13).



## Principle of Oceanic Inversion (Cont.)

- Basis functions:
  In a OGCM, time-varying fluxes of dye tracers $(\Phi(t))$ of the form

$$\vec{\Phi}(t) = \vec{\Phi}(t=0) * (p\mathsf{CO}_2(t) - p\mathsf{CO}_2(t=0))$$

  are imposed in each of the $n = 13$ regions, and the model is run forward in time.

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- By sampling the modeled distribution at the observations stations, we obtain a transport matrix $A_{\mathsf{OGCM}}$ that relates the fluxes to the distribution,

$$\vec{\chi}_{\mathsf{OGCM}} = A_{\mathsf{OGCM}} \vec{\Phi}.$$

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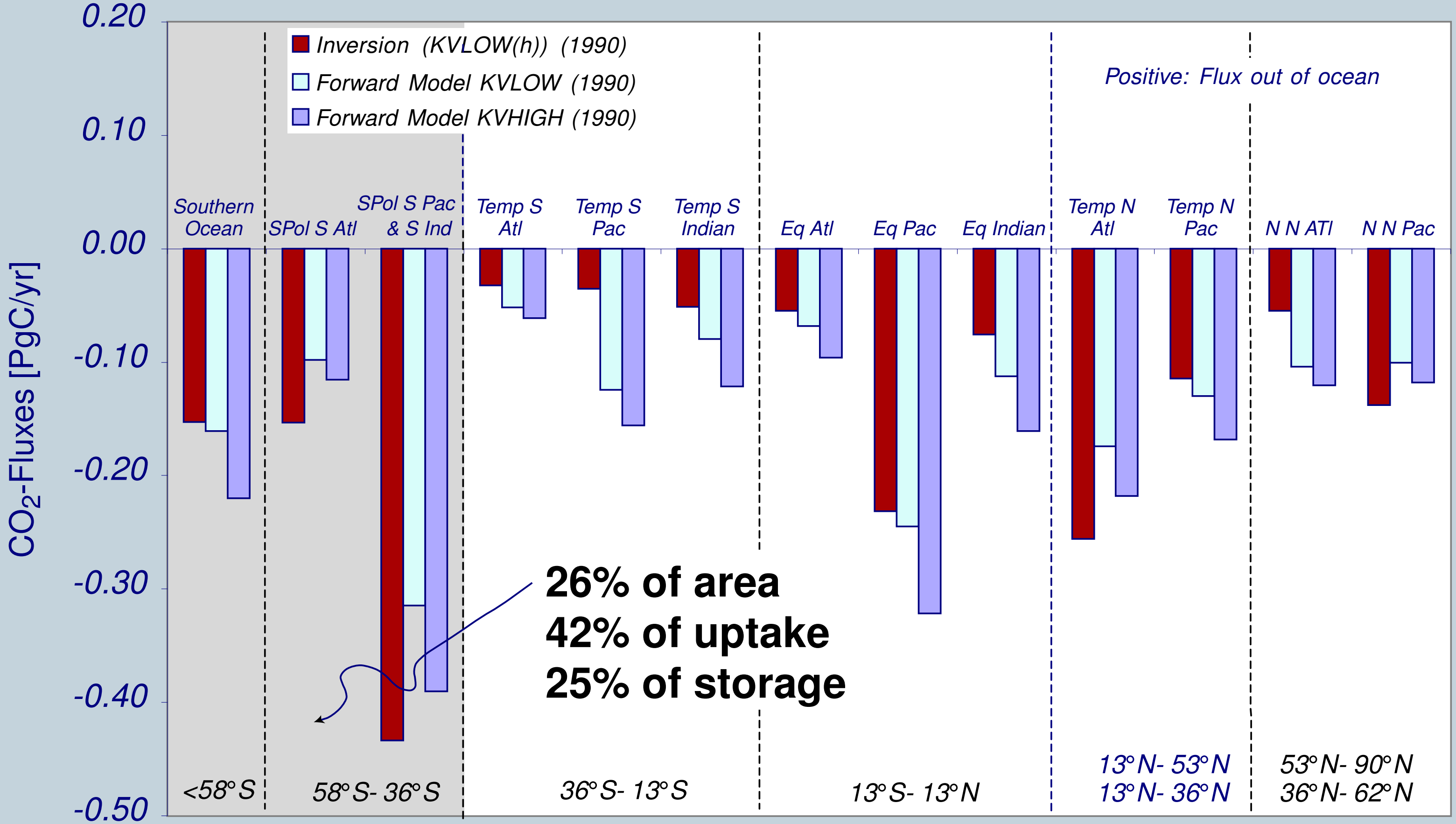
- By sampling the modeled distribution at the observations stations, we obtain a transport matrix $A_{\mathsf{OGCM}}$ that relates the fluxes to the distribution,

  $$\vec{\chi}_{\mathsf{OGCM}} = A_{\mathsf{OGCM}} \vec{\Phi}.$$

- Modeled distributions are then substituted with observed ones and the matrix $A$ is inverted to get an estimate of the surface fluxes $(\vec{\Phi}_{\mathsf{est}})$ :

  $$\vec{\Phi}_{\mathsf{est}} = A^{-1}_{\mathsf{OGCM}} \, \vec{\chi}_{\mathsf{obs}}.$$

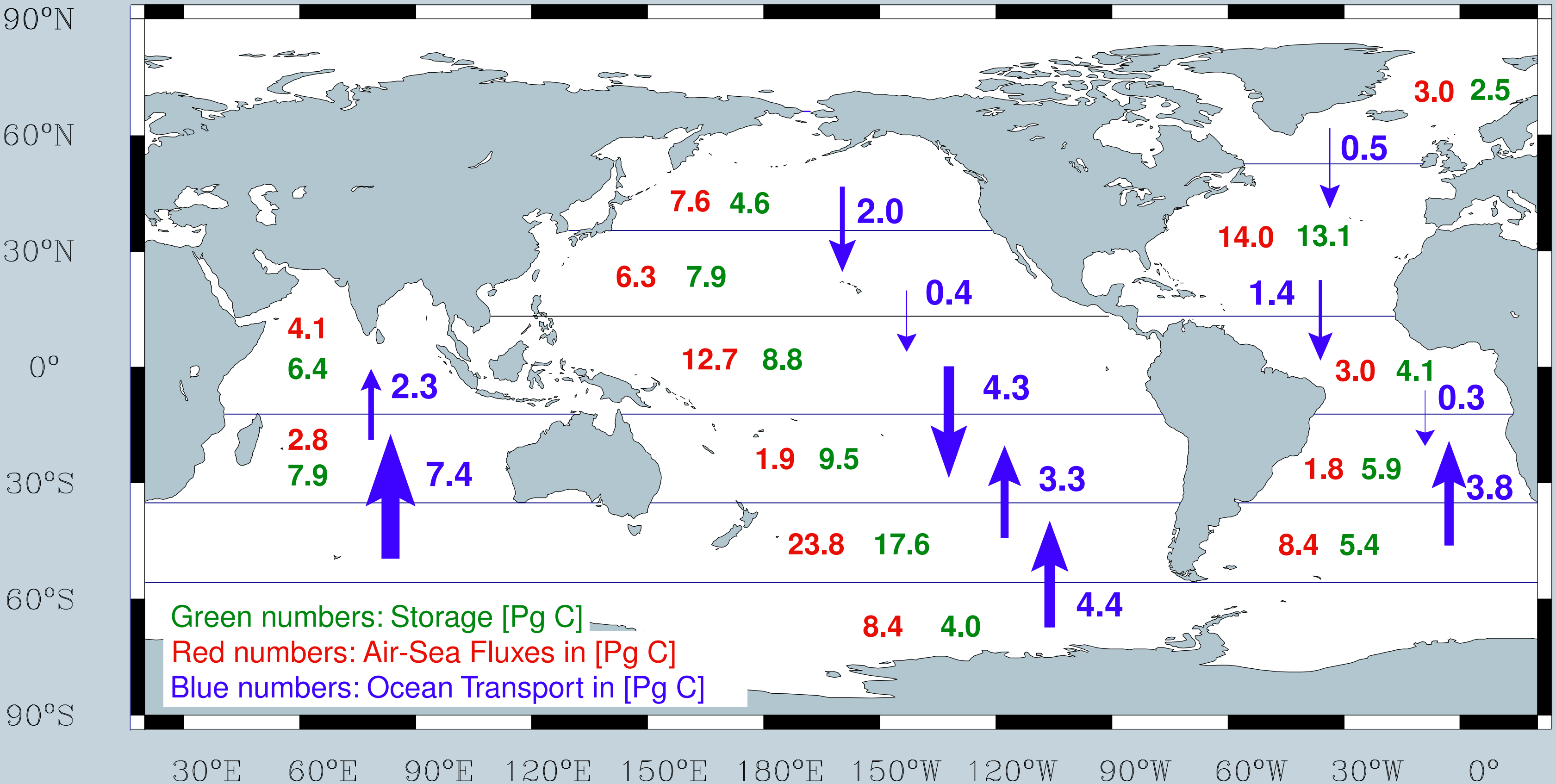
# AIR-SEA FLUXES OF ANTHROPOGENIC $CO_2$



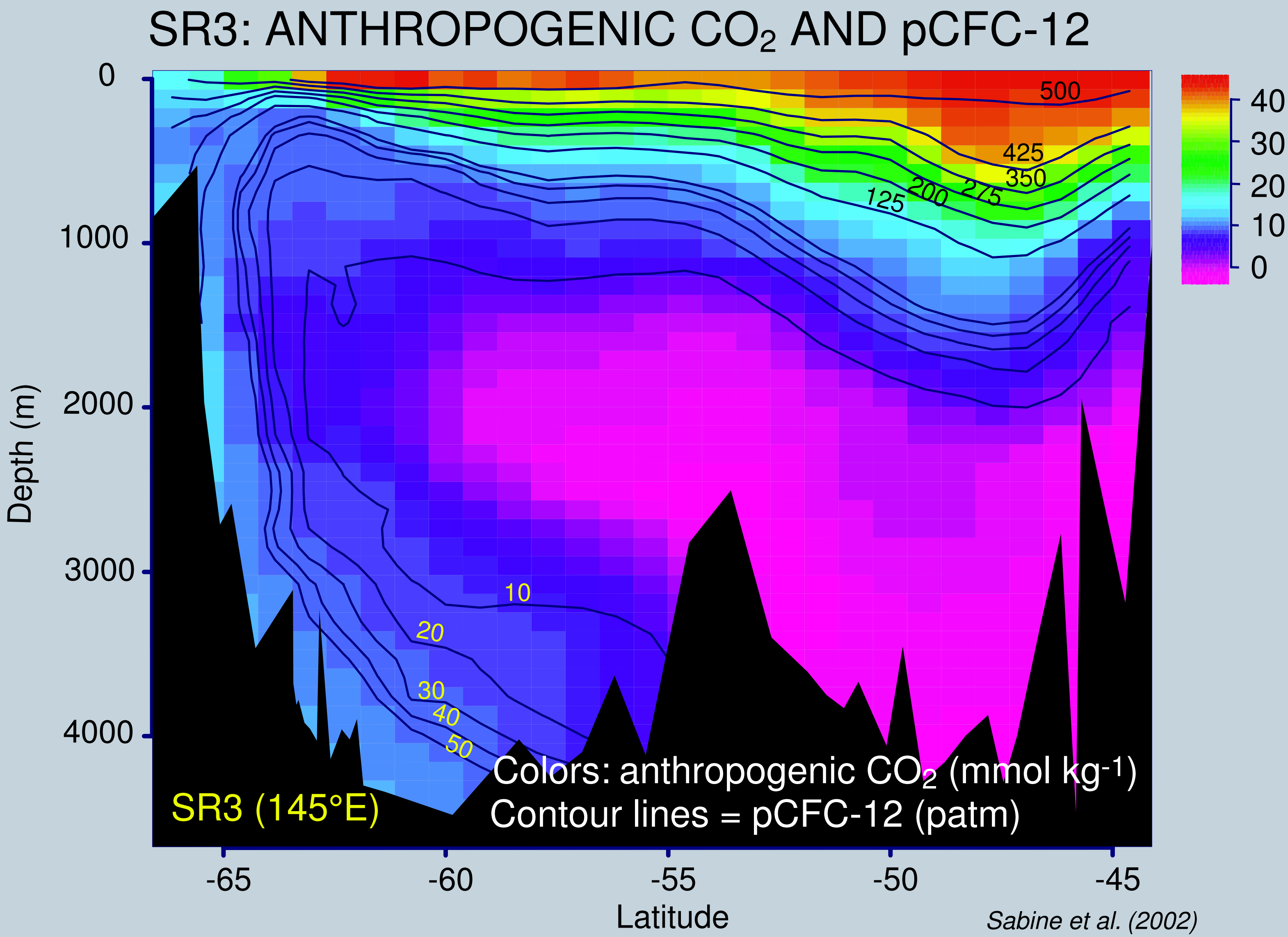

Anthropogenic $CO_2$ Flux for 1990: 1.8 PgC/yr

*Gloor et al. (in press)*
*Gruber et al. (in prep.)*

# ANTHROPOGENIC $CO_2$ FLUXES, STORAGE AND TRANSPORT

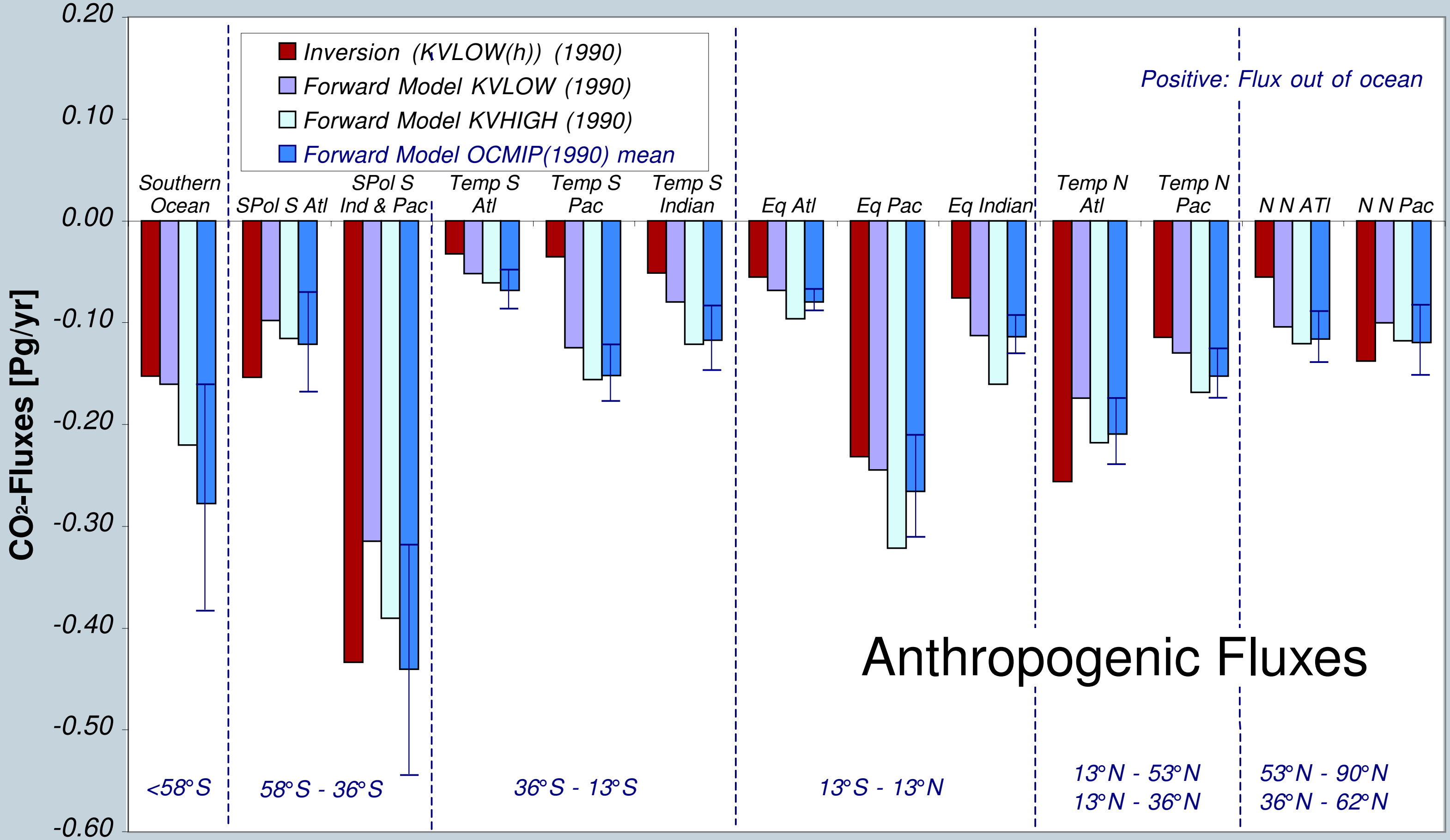



*preliminary results: Gruber et al. [in prep.]*



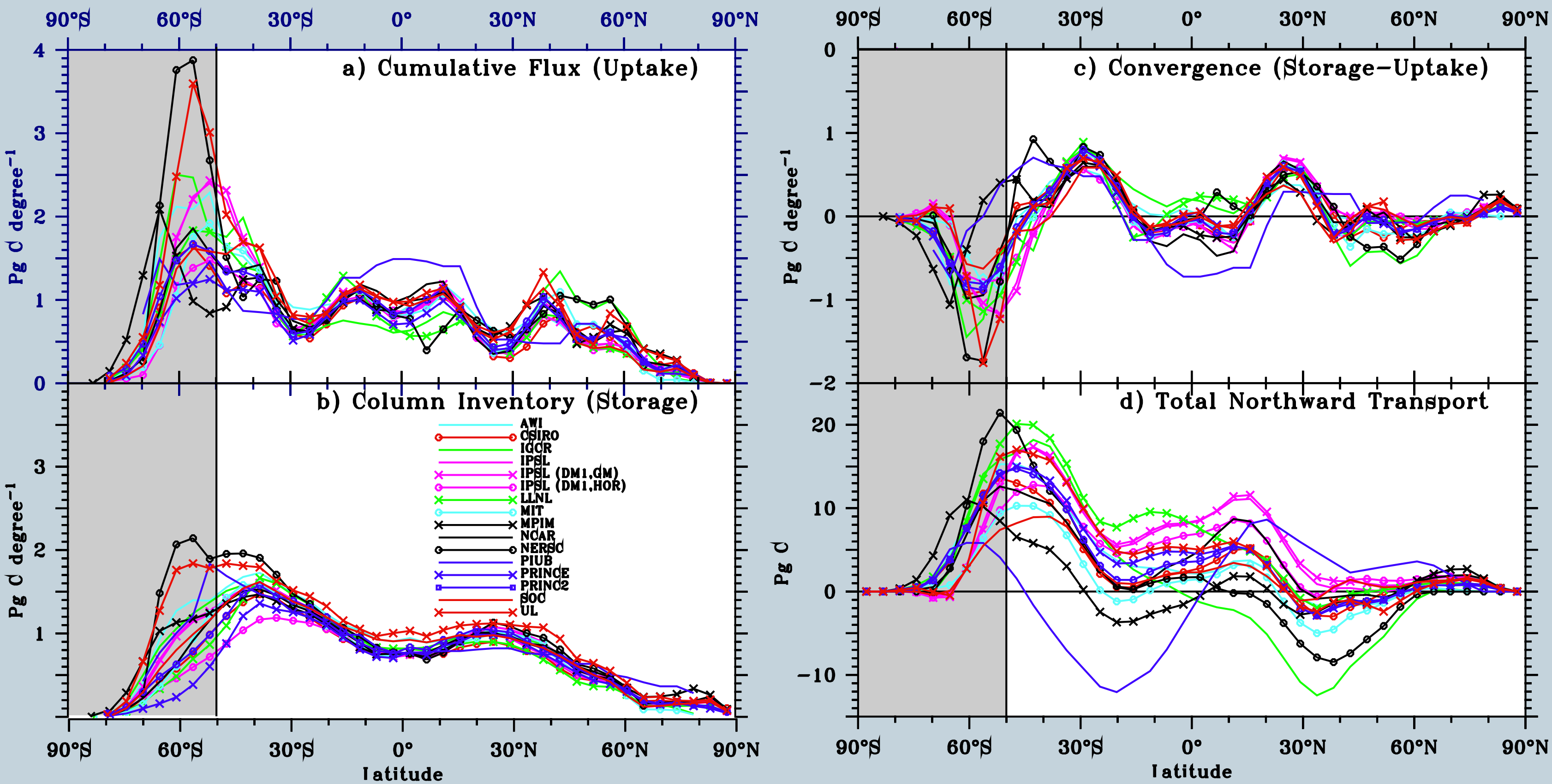
SR3: ANTHROPOGENIC $CO_2$ AND pCFC-12
Depth (m)
0
1000
2000
3000
4000
-65
-60
-55
-50
-45
Latitude
40
30
20
10
0
500
425
350
275
200
125
10
20
30
40
50
SR3 (145°E)
Colors: anthropogenic $CO_2$ (mmol kg$^{-1}$)
Contour lines = pCFC-12 (patm)
Sabine et al. (2002)

# ANTHROPOGENIC AIR-SEA $CO_2$-FLUXES




Gloor et al. (in press),
Gruber et al. (in prep.)

# OCMIP-2: ANTHROPOGENIC $CO_2$ FLUXES, STORAGE, AND TRANSPORT




*J. Orr and OCMIP-2 (pers. comm)*

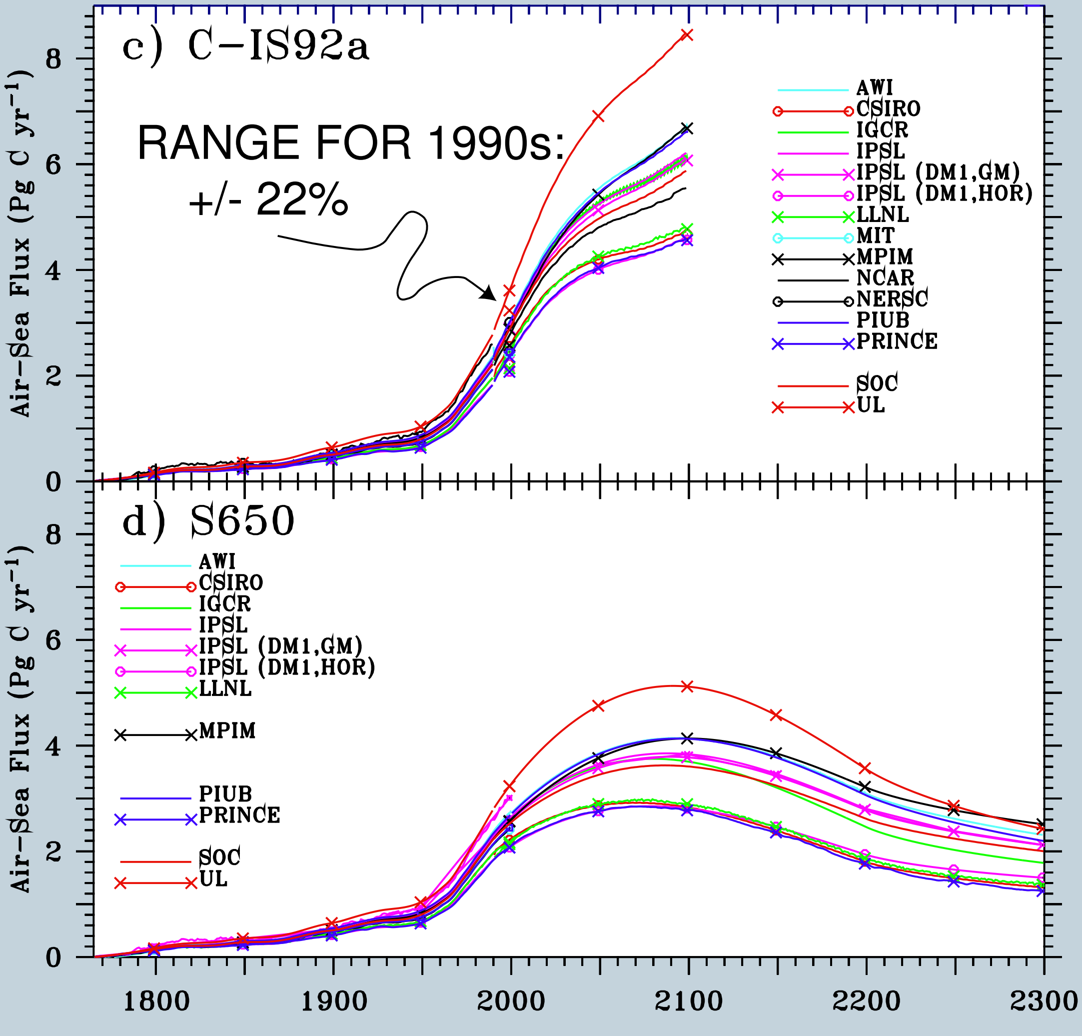
# OCMIP-2: ANTHROPOGENIC $CO_2$ UPTAKE

| Model | Uptake Rate (PgC/yr) 1980-1989 | Uptake Rate (PgC/yr) 1990-1999 (S650) | Inventory (Pg) 1765-1990 |
|---|---|---|---|
| PRINCE | 1.65 | 1.98 | 102 |
| IPSL.DM1 (HOR) | 1.67 | 1.98 | |
| LLNL | 1.78 | 2.08 | 108 |
| CSIRO | 1.78 | 2.11 | 108 |
| MIT | 1.91 | 2.29 | 117 |
| NCAR | 1.93 | 2.30 | 115 |
| PRINC2 | 1.93 | 2.32 | |
| IPSL (GM) | 1.97 | 2.36 | |
| MPIM | 2.01 | 2.43 | 124 |
| SOC | 2.01 | 2.39 | 123 |
| IPSL.DM1 (GM) | 2.03 | 2.43 | 125 |
| IGCR | 2.05 | 2.47 | 127 |
| PIUB | 2.11 | 2.52 | 135 |
| AWI | 2.14 | 2.58 | 127 |
| NERSC | 2.38 | 2.84 | 146 |
| UL | 2.51 | 3.04 | |
| MEAN | 1.99+/- 0.23 | 2.38+/- 0.29 | 121+/- 12 |
| RANGE | 1.65-2.51 | 1.98-3.04 | 102-146 |
| "DATA RECONSTRUCTION*" | | | 107 +/- 20 |

** Sabine et al. (pers. comm)*

*J. Orr and OCMIP-2 (pers.comm.)*

# OCMIP-2: FUTURE ANTHROPOGENIC $CO_2$ UPTAKE

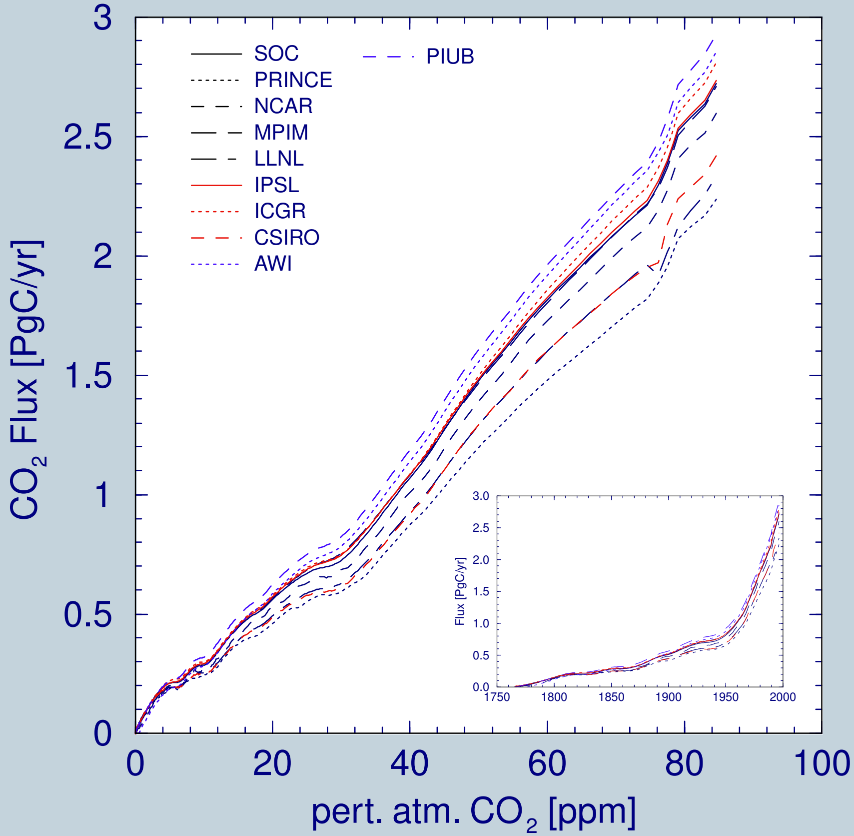


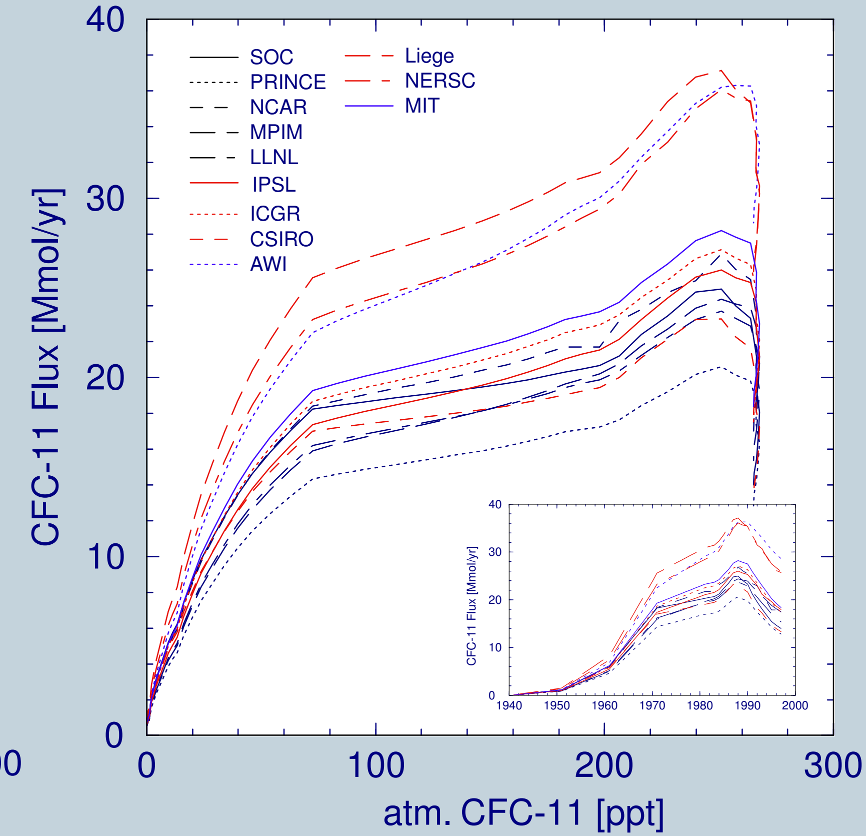

*J. Orr and OCMIP-2 (pers. comm)*

IS92a: RANGE FOR 2100:
+/- 33%

S650: RANGE FOR 2100:
+/- 30%

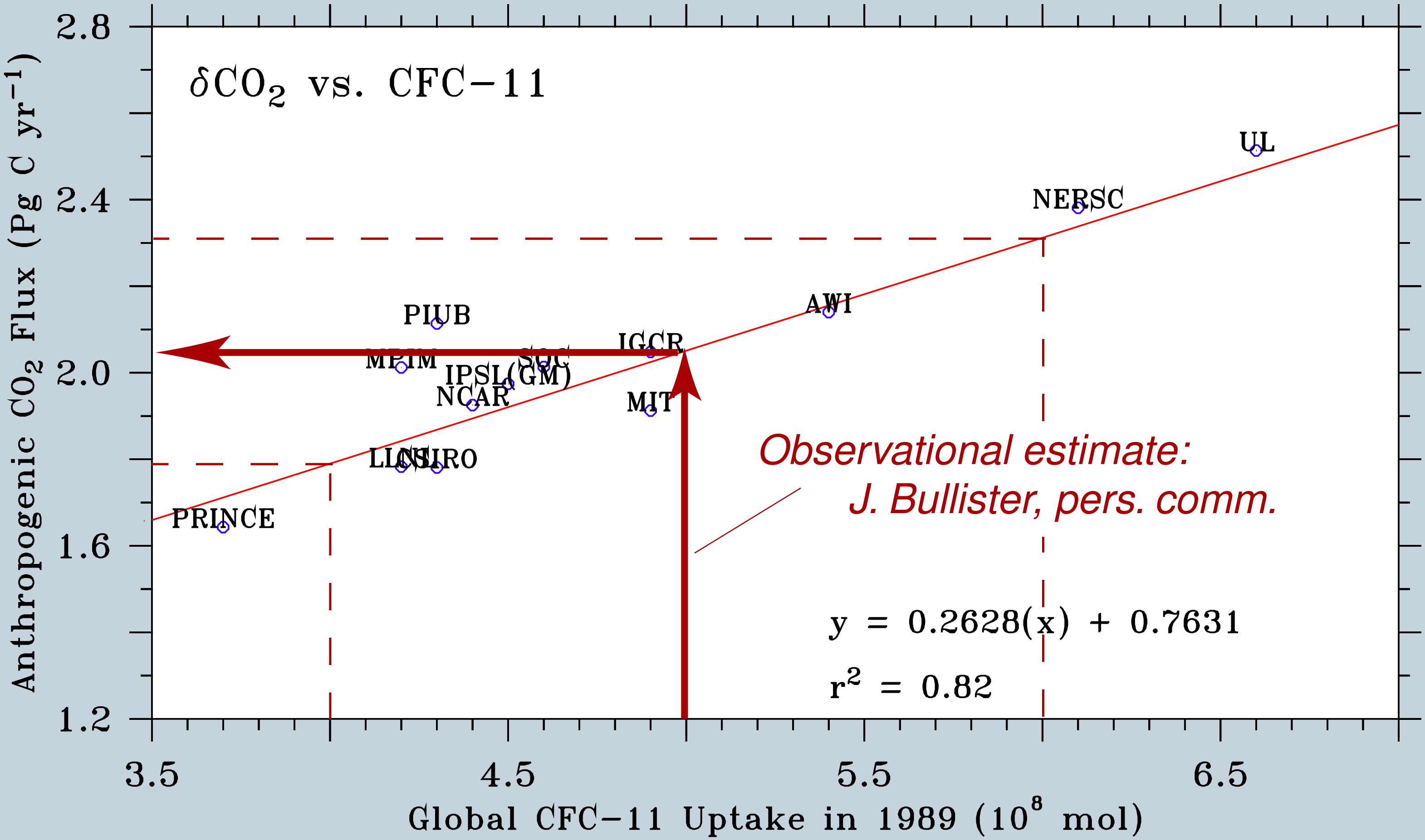
# OCMIP-2: OCEANIC UPTAKE OF ANT. $CO_2$ AND CFC-11




*N. Gruber and OCMIP-2*

# OCMIP-2: ANTHROPOGENIC $CO_2$ FLUX VERSUS CFC-11 INVENTORY




J. Orr and OCMIP-2 (pers.comm.)

## Summary

- Reconstructions of the oceanic inventory of anthropogenic $CO_2$ as well as ocean models indidate that the ocean has been the the largest sink for anthropogenic $CO_2$ during the anthropocene (taking up about a third of the total anthropogenic $CO_2$ emissions).

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- Models show a similar pattern, but they differ widely in the magnitude of their Southern Ocean uptake. This has large implications for the future uptake of anthropogenic $CO_2$ even in the absence of climate change.
- Transient and anthropogenic tracers are very helpful in better constraining the oceanic sink for ant. $CO_2$.

## Outlook and challenges

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- Both require a detailed understanding not only of the anthropogenic $CO_2$ perturbation, but also of the natural carbon cycle, i.e. the interaction of biological and solubility pumps.

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  - Response to climate change and other ant. perturbations
- Both require a detailed understanding not only of the anthropogenic $CO_2$ perturbation, but also of the natural carbon cycle, i.e. the interaction of biological and solubility pumps.
- These problems need to be addressed by a combination of long-term monitoring of the ocean and the development of a hierarchy of diagnostic and prognostic models that are based on a mechanistic understanding of the relevant processes.

# Acknowledgements


- Chris Sabine and the GLODAP members
- Jim Orr and the OCMIP members
- Jorge Sarmiento, Manuel Gloor, Andy Jacobson
- Katsumi Matsumoto
- Taro Takahashi and oceanic p$CO_2$ community
- all the people that made the WOCE/JGOFS/OACES cruises a success