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The uptake, transport, and storage of anthropogenic CO_2 by the ocean

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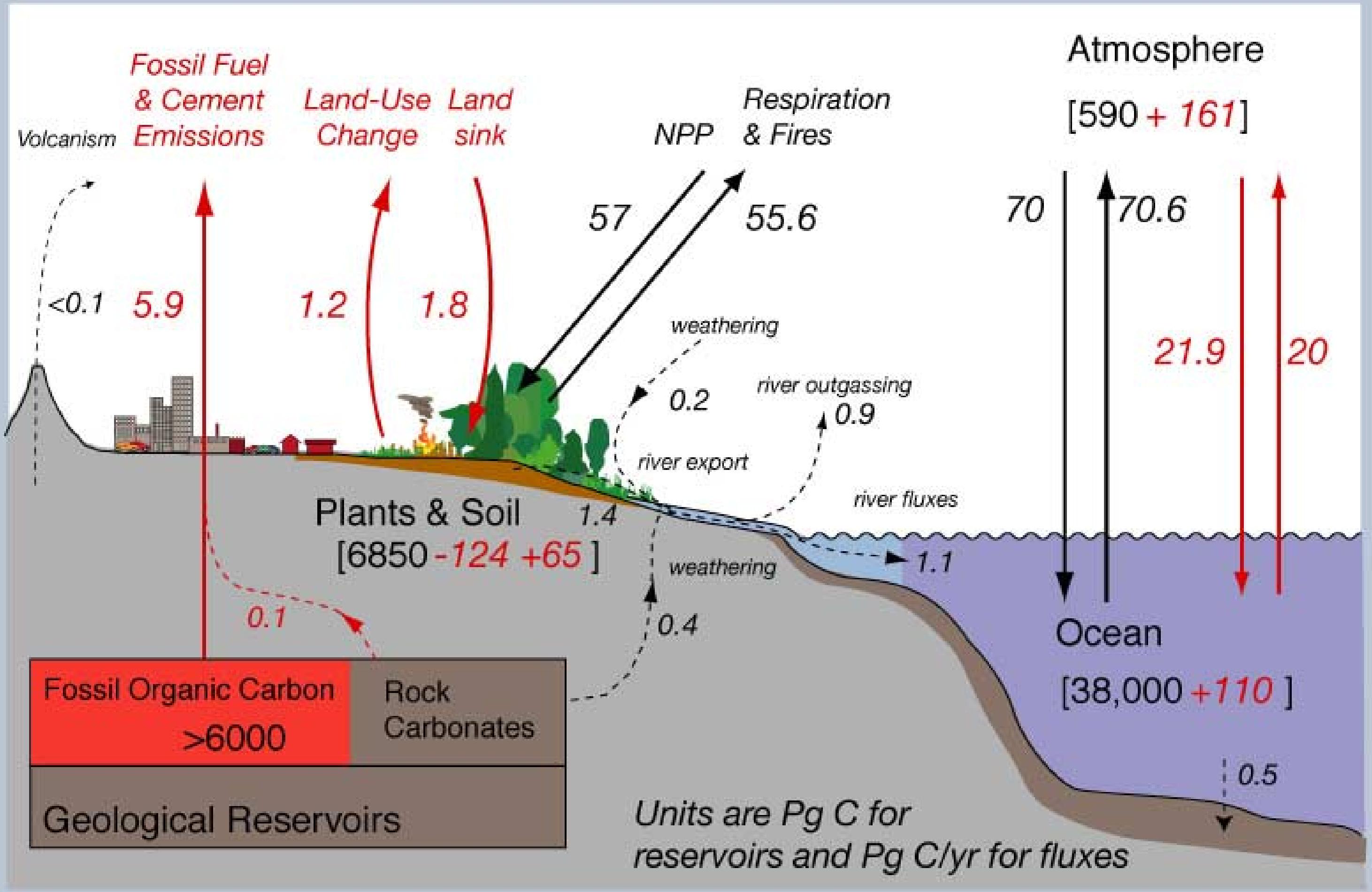
- The many people that made the Global CO_2 survey a success!
- NSF, NOAA, and NASA for their funding

THE ANTHROPOGENIC PERTURBATION

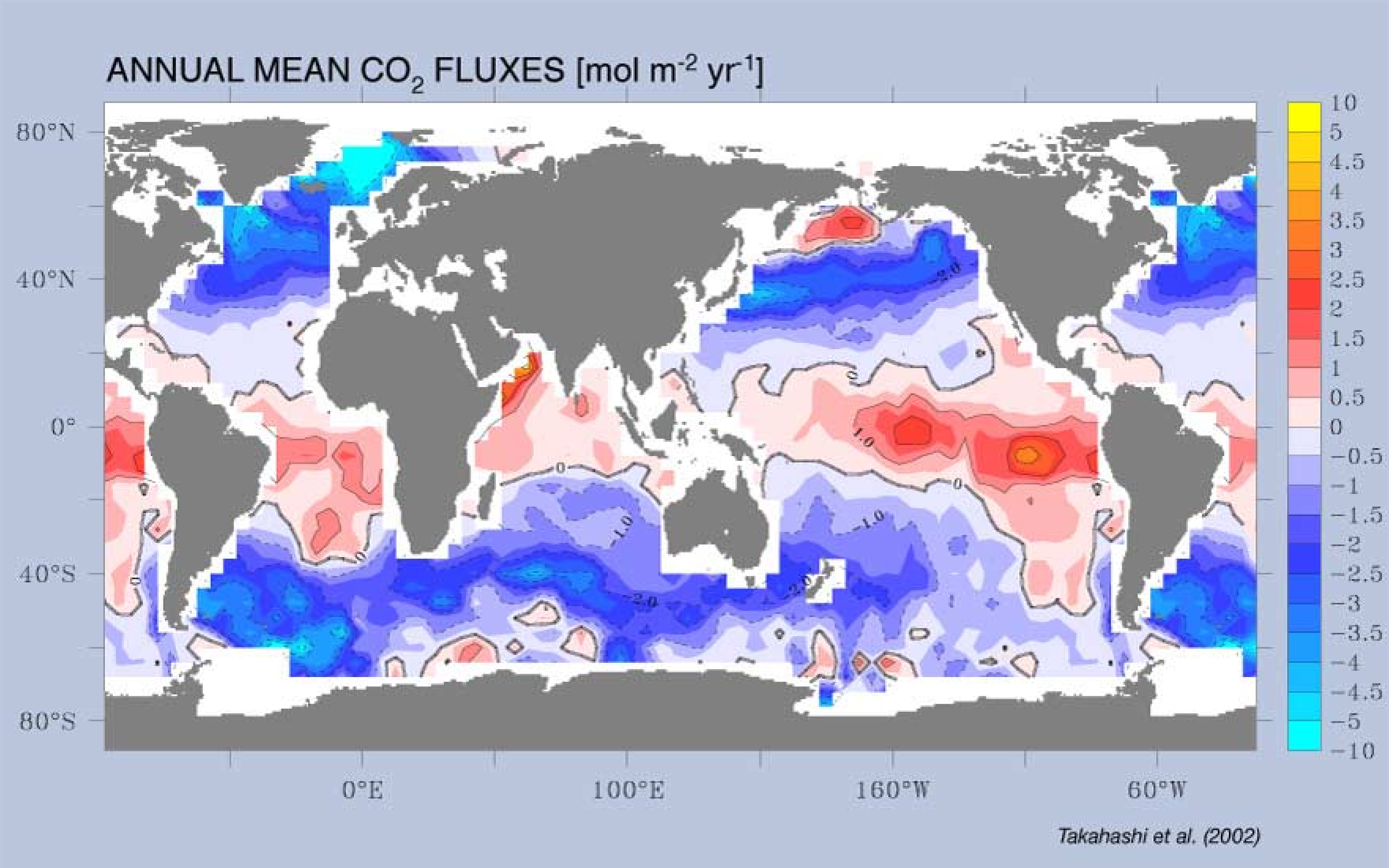
IN THE CONTEXT OF THE NATURAL C CYCLE



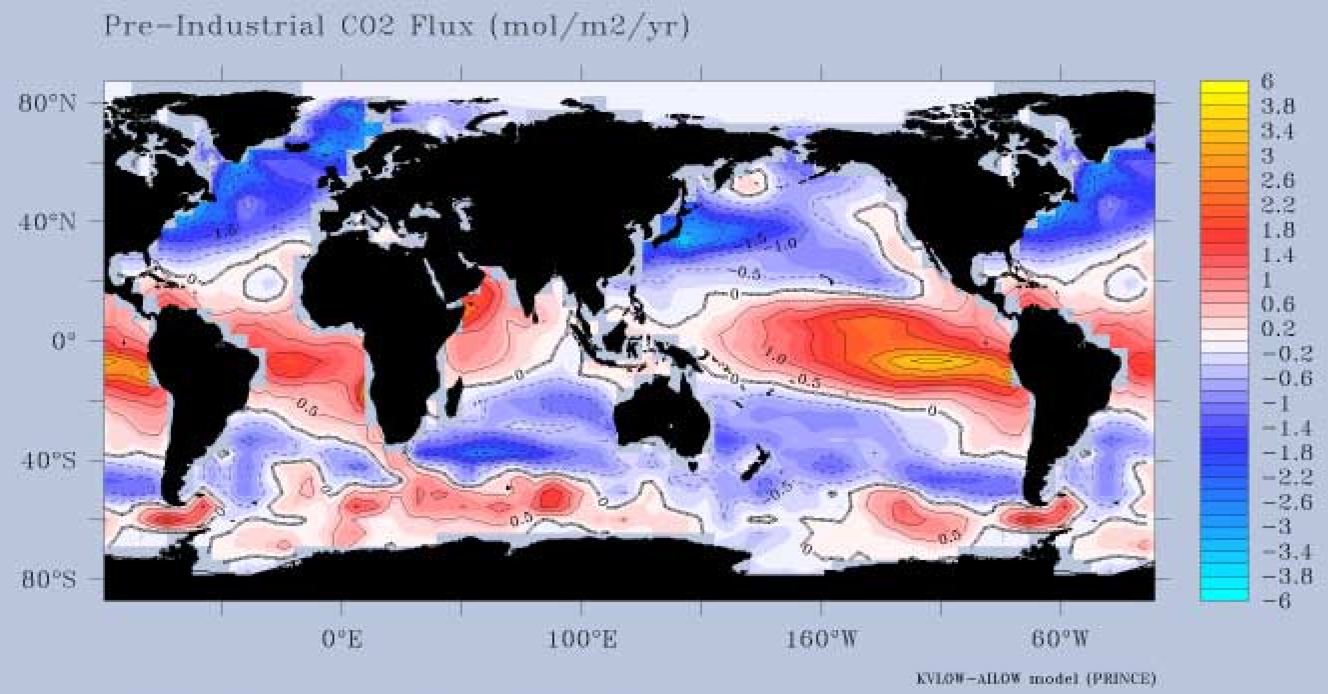
Sabine et al. (2003)
SCOPE/GCP

Outline

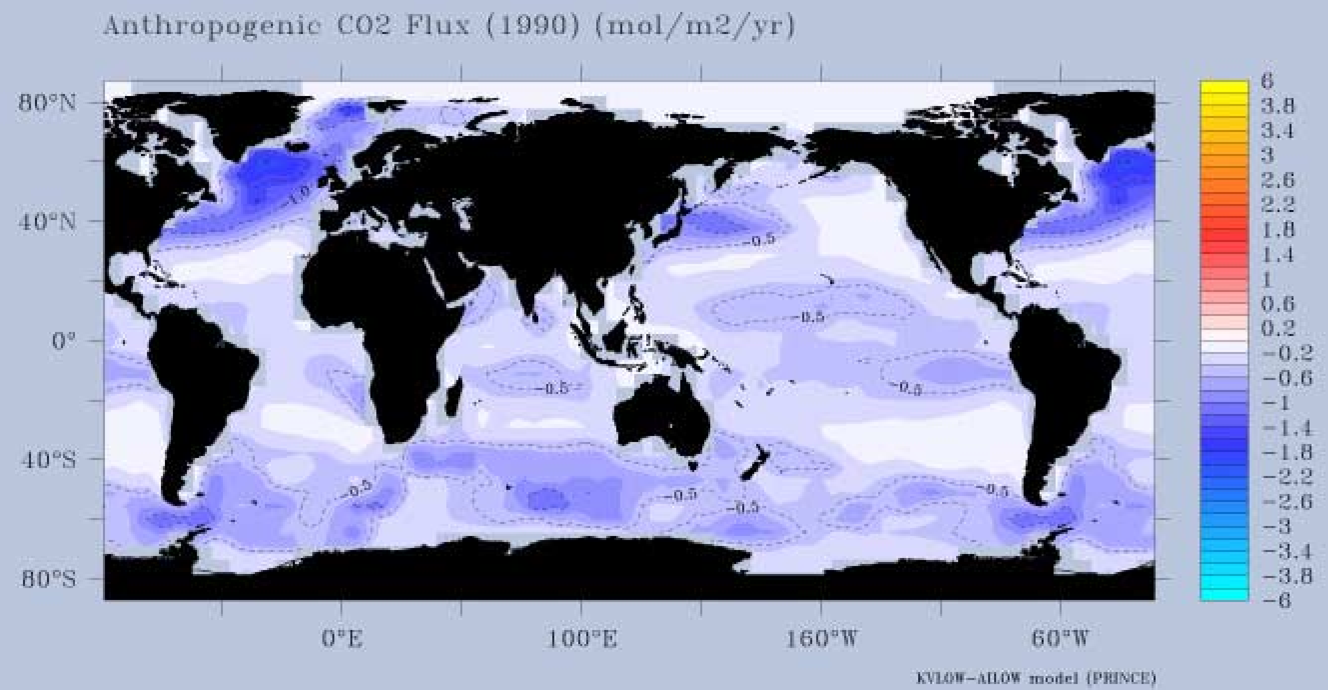
- Introduction
- Air-sea CO_2 fluxes *or the problem of separating the natural from the anthropogenic fluxes*
- The importance of the ocean as a sink for anthropogenic CO_2
- How do we obtain fluxes from storage? An inverse approach
- On the role of anthropogenic CO_2 transport
- What do the OCMIP-2 models find?
- Summary and Outlook



Globally integrated flux: 2.2 PgC yr^{-1}

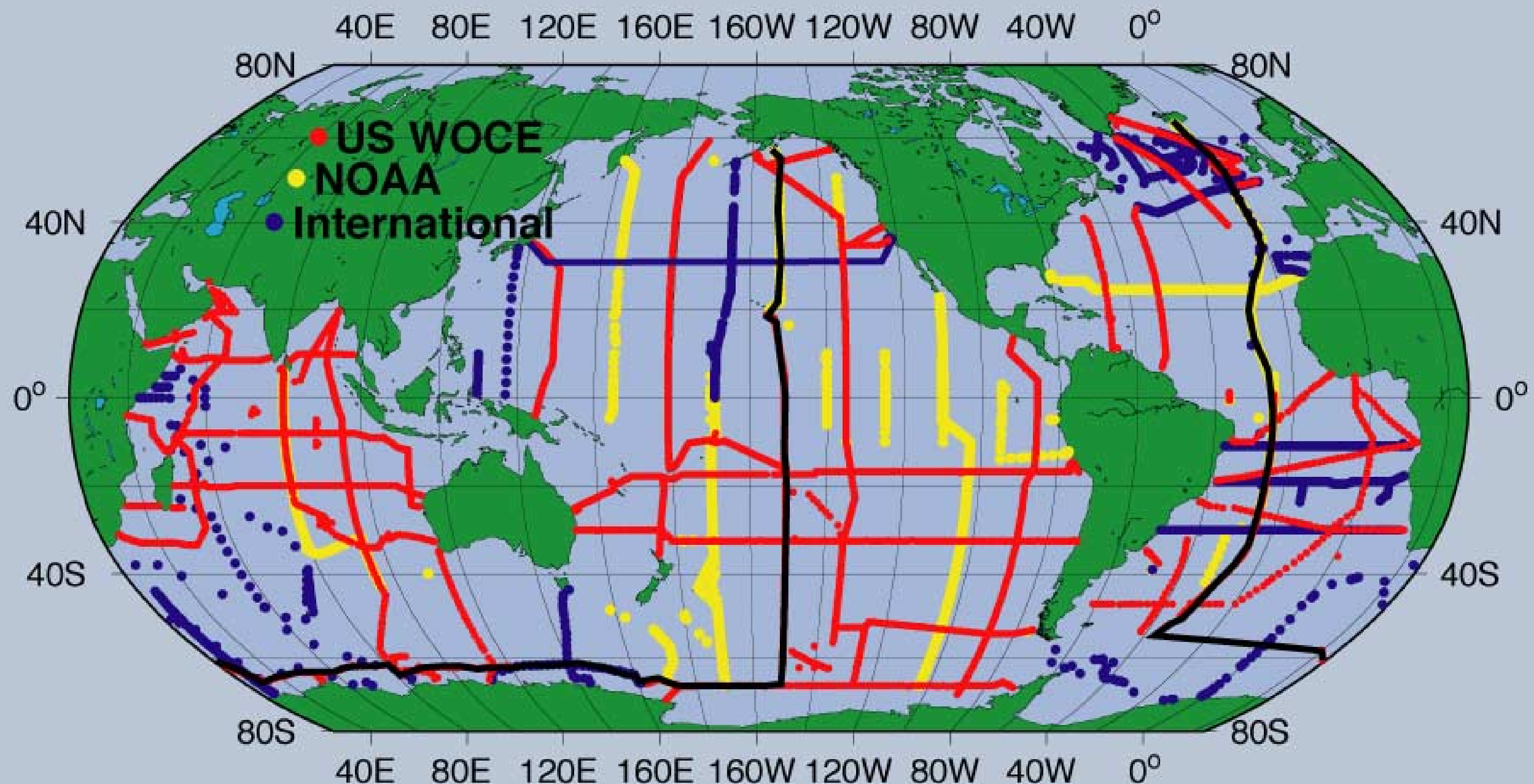


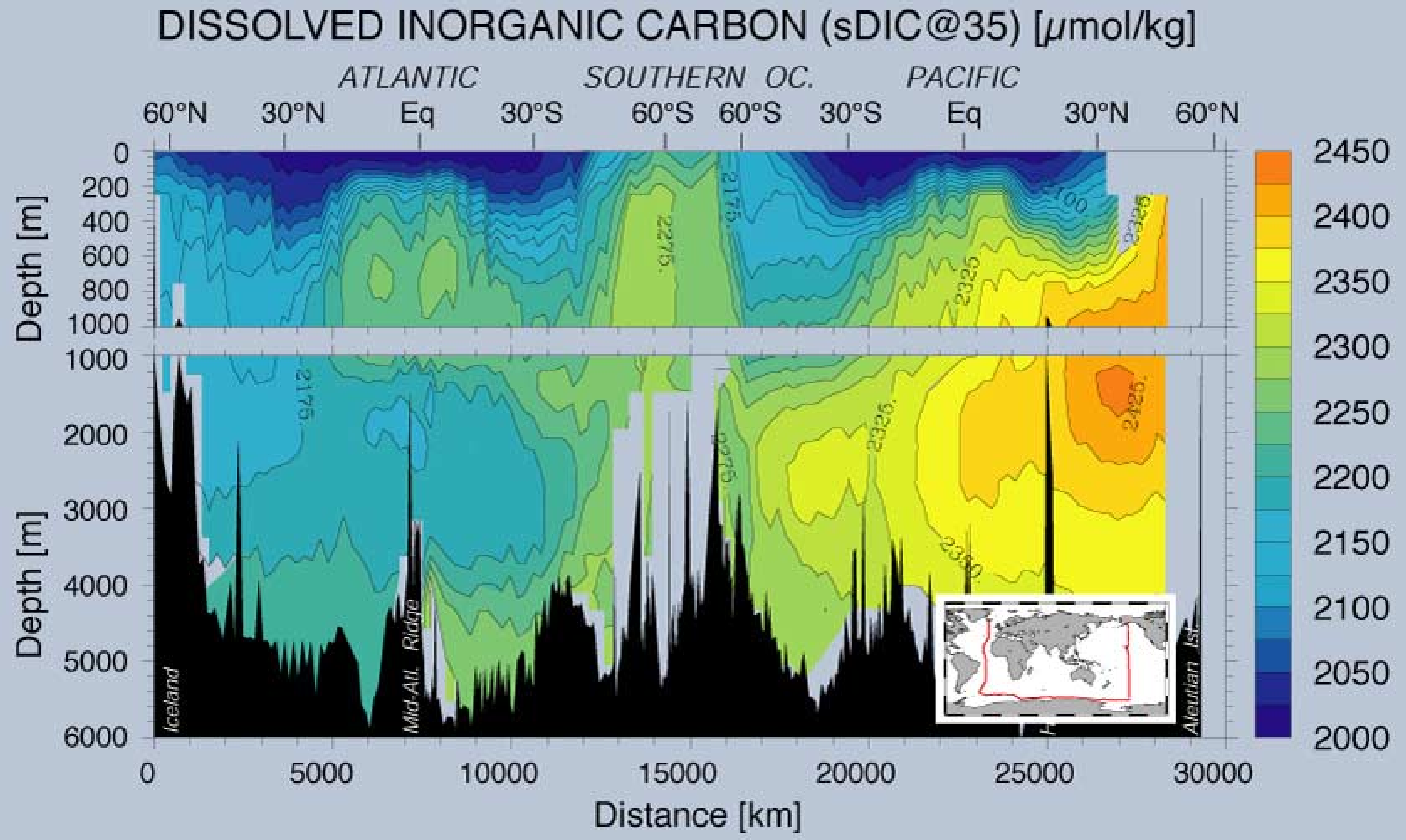
Preindustrial Flux



Anthropogenic Flux

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 Is.
2175.
2275.
2100
2325
2325.
2175.
2325.
2275.
2425.
2350
2450
2400
2350
2300
2250
2200
2150
2100
2050
2000

Determination of anthropogenic CO_2

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

i) the change in DIC that incurred since the water left the surface ocean due to remineralization of organic matter and dissolution of $CaCO_3$ (ΔDIC_{bio}), and

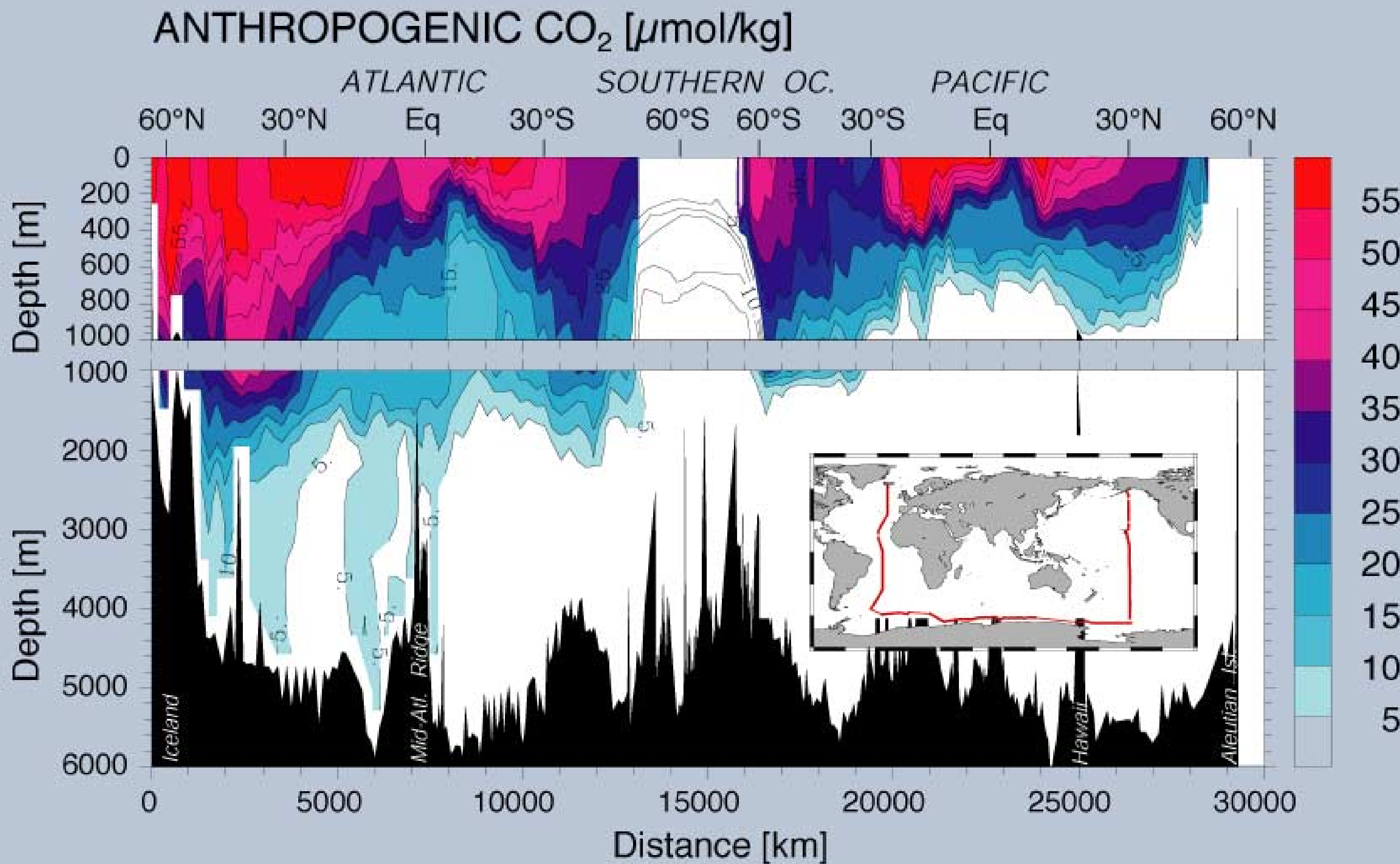
ii) a concentration, $DIC_{sfc\text{-}pi}$, that reflects the DIC content a water parcel had at the outcrop in pre-industrial times,

Thus,

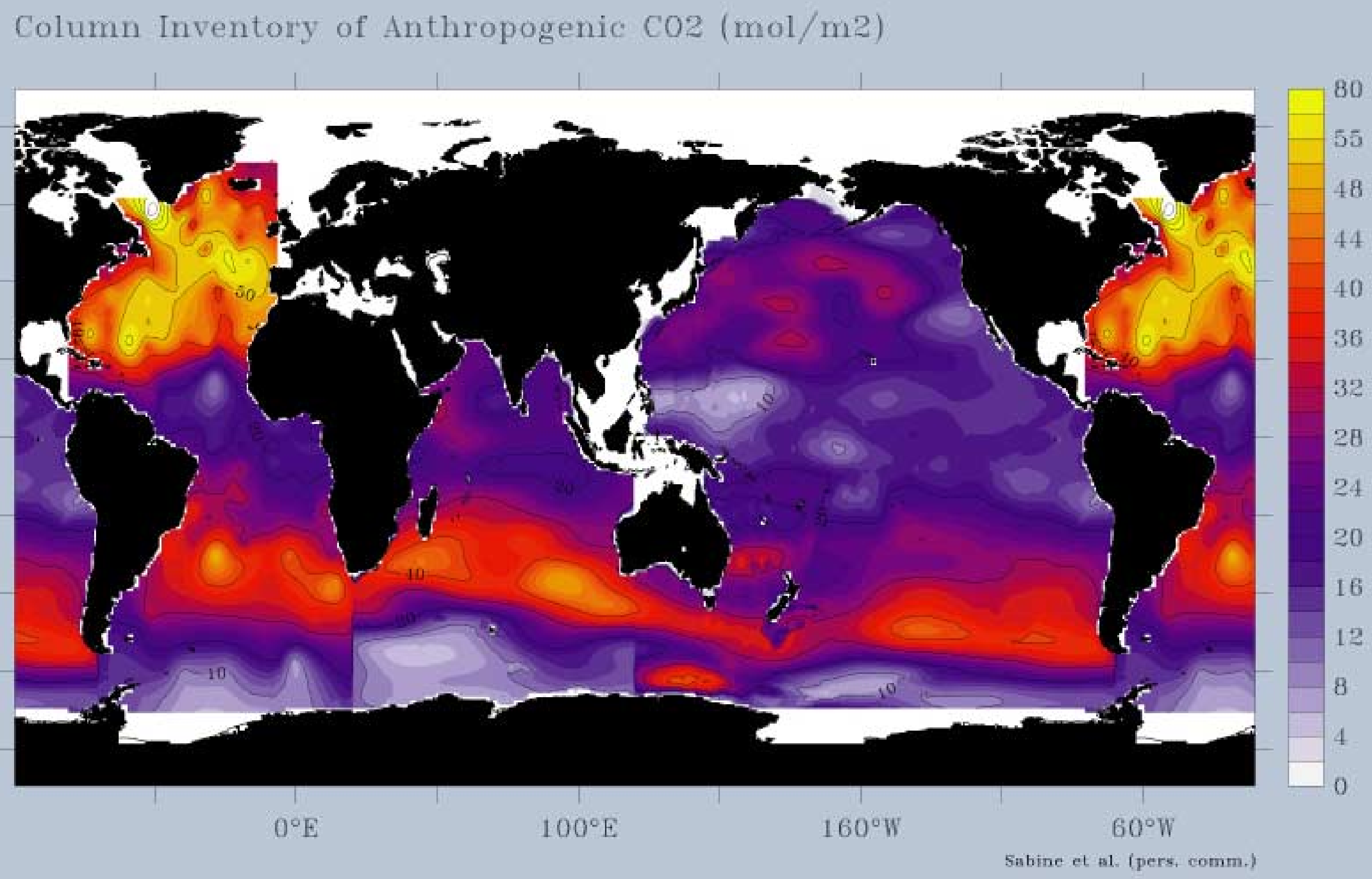
$$\Delta C_{ant} = DIC - \Delta DIC_{bio} - DIC_{sfc\text{-}pi}$$

Assumptions:

- natural carbon cycle has remained in steady-state

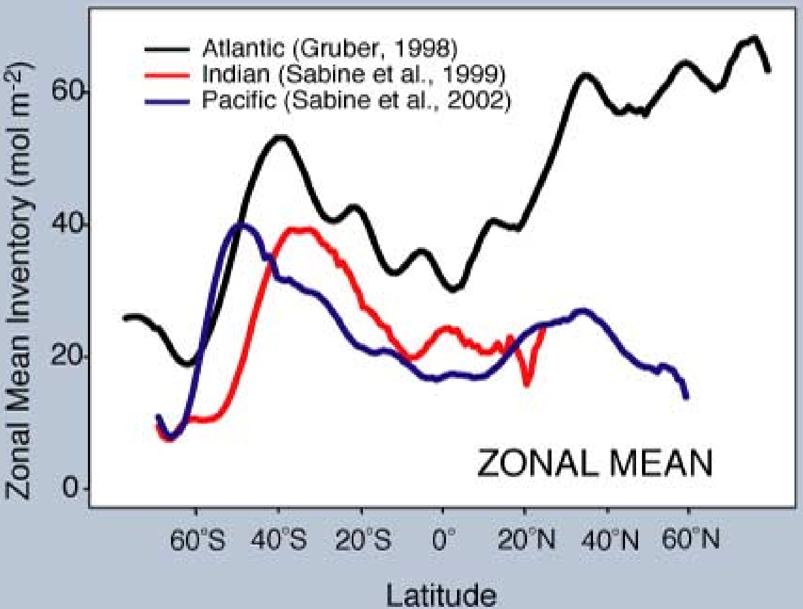


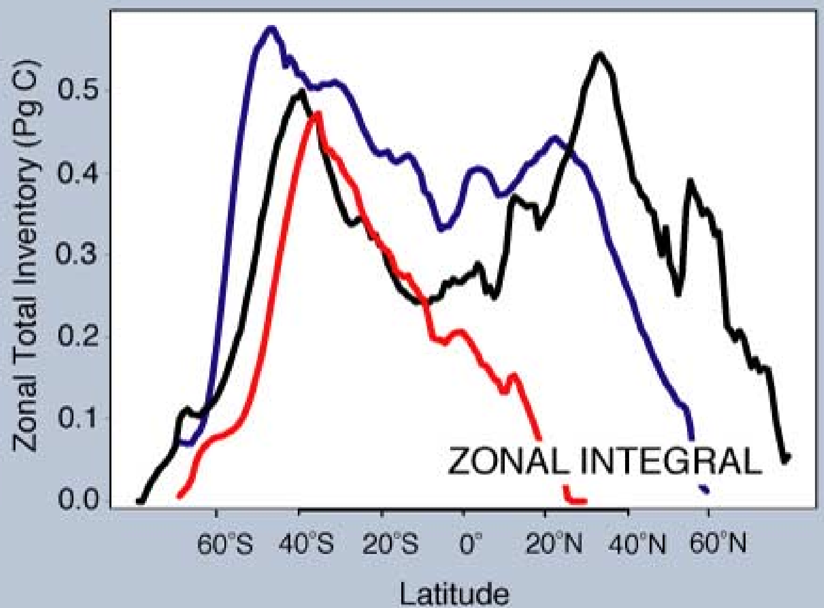
ANTHROPOGENIC CO_2 [μmol/kg]
ATLANTIC
SOUTHERN OC.
PACIFIC
60°N
30°N
Eq
30°S
60°S
60°S
30°S
Eq
30°N
60°N
Depth [m]
Depth [m]
Iceland
Mid-Atl. Ridge
Hawaii
Aleutian Isl.
Distance [km]
55
50
45
40
35
30
25
20
15
10
5



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
Sabine et al. (pers. comm.)

ANTHROPOGENIC CO_2 INVENTORIES





Anthropogenic CO_2 Inventories in ~1994

	Atlantic[a] Inventory [Pg C]	Pacific[b] Inventory [Pg C]	Indian[c] Inventory [Pg C]	Global Inventory [Pg C]
Southern hemisphere	19	28	17	62
Northern hemisphere	28	17	3	48
Global	47 (42%)	45 (40%)	20 (18%)	112

a) *Lee et al.* (submitted)
b) *Sabine et al.* (2002)
c) *Sabine et al.* (1999)

See also poster by Sabine et al.

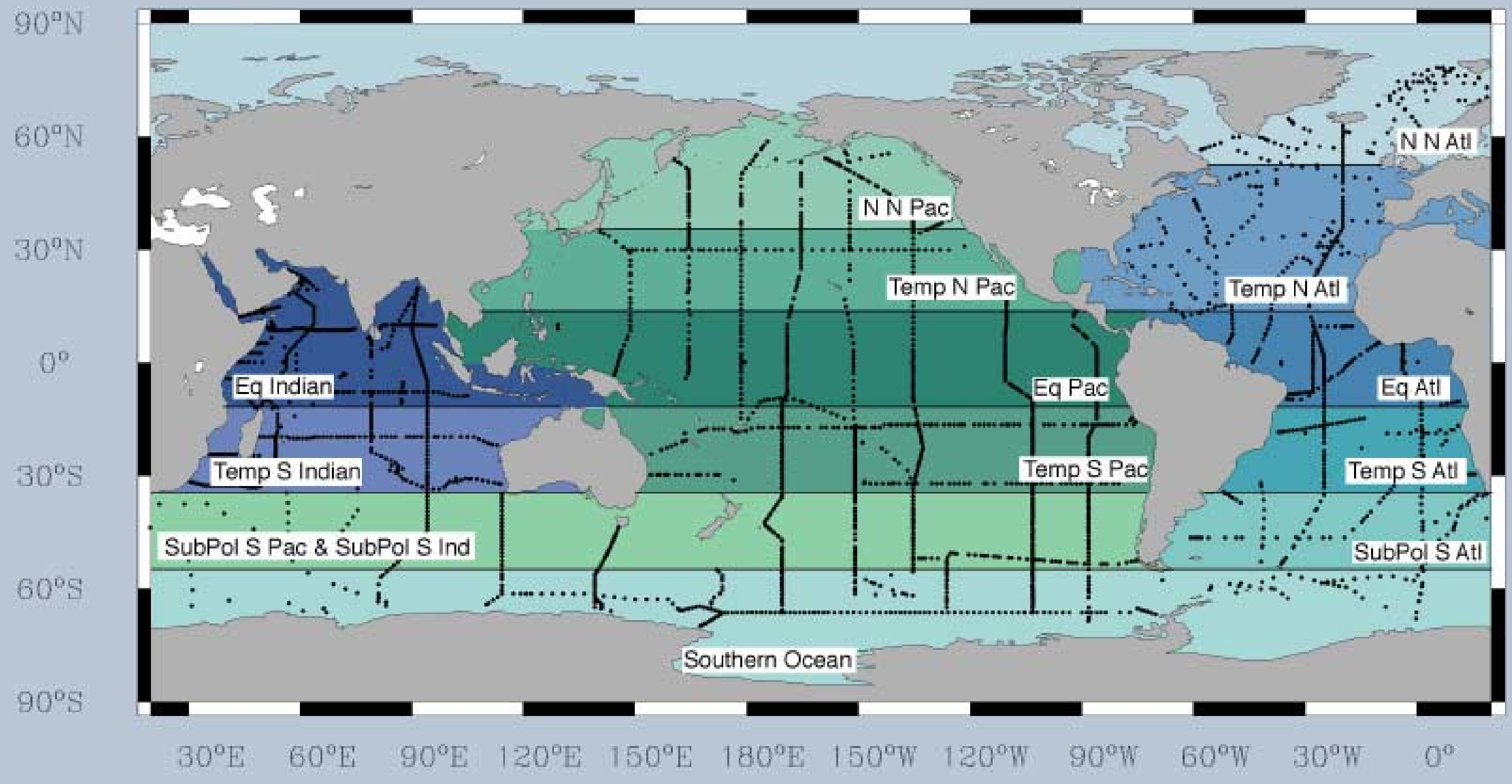
Anthropogenic CO_2 Budget 1800 to 1994

CO_2 Sources	[Pg C]
(1) Emissions from fossil fuel and cement production[a]	244
(2) Net emissions from changes in land-use[b]	110
(3) Total anthropogenic emissions = (1) + (2)	354
Partitioning among reservoirs	**[Pg C]**
(4) Storage in the atmosphere[c]	159
(5) Storage in the ocean[d]	112
(6) Terrestrial sinks = [(1)+(2)]-[(4)+(5)]	83

a: From *Marland and Boden* [1997] (updated 2002)
b: From Houghton [1997]
c: Calculated from change in atmospheric pCO_2 (1800: 284ppm; 1994: 359 ppm)
d: Based on estimates of *Sabine et al.* [1999], *Sabine et al.* [2002] and *Lee et al.* (submitted)

Ocean Inversion method

- The ocean is divided into n regions (n = 13)



Ocean Inversion method (cont.)

- Basis functions:

  In an OGCM, time-varying fluxes of dye tracers (Φ) of the form

  $$\Phi(t) = \Phi(t_o) * (pCO_2(t) - pCO_2(t_o))$$

  are imposed, and the model is run forward in time.

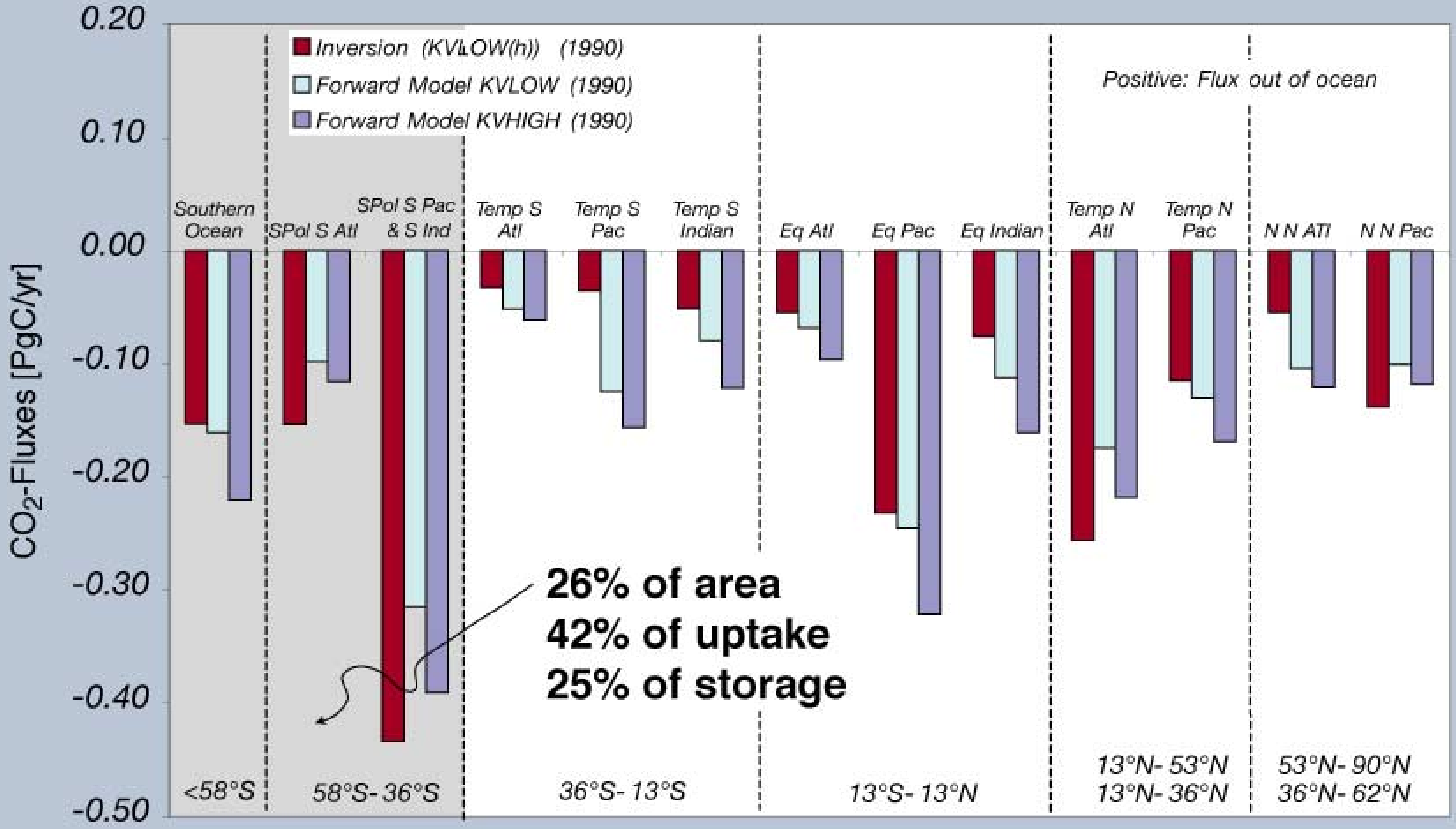
- By sampling the modeled distribution at the observation stations, χ, we obtain a transport matrix (A_{OGCM}) that relates the fluxes to the distribution:

  $$\chi_{OGCM} = A_{OGCM} * \Phi.$$

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

  $$\Phi_{est} = (A_{OGCM})^{-1} \ \chi_{obs}$$

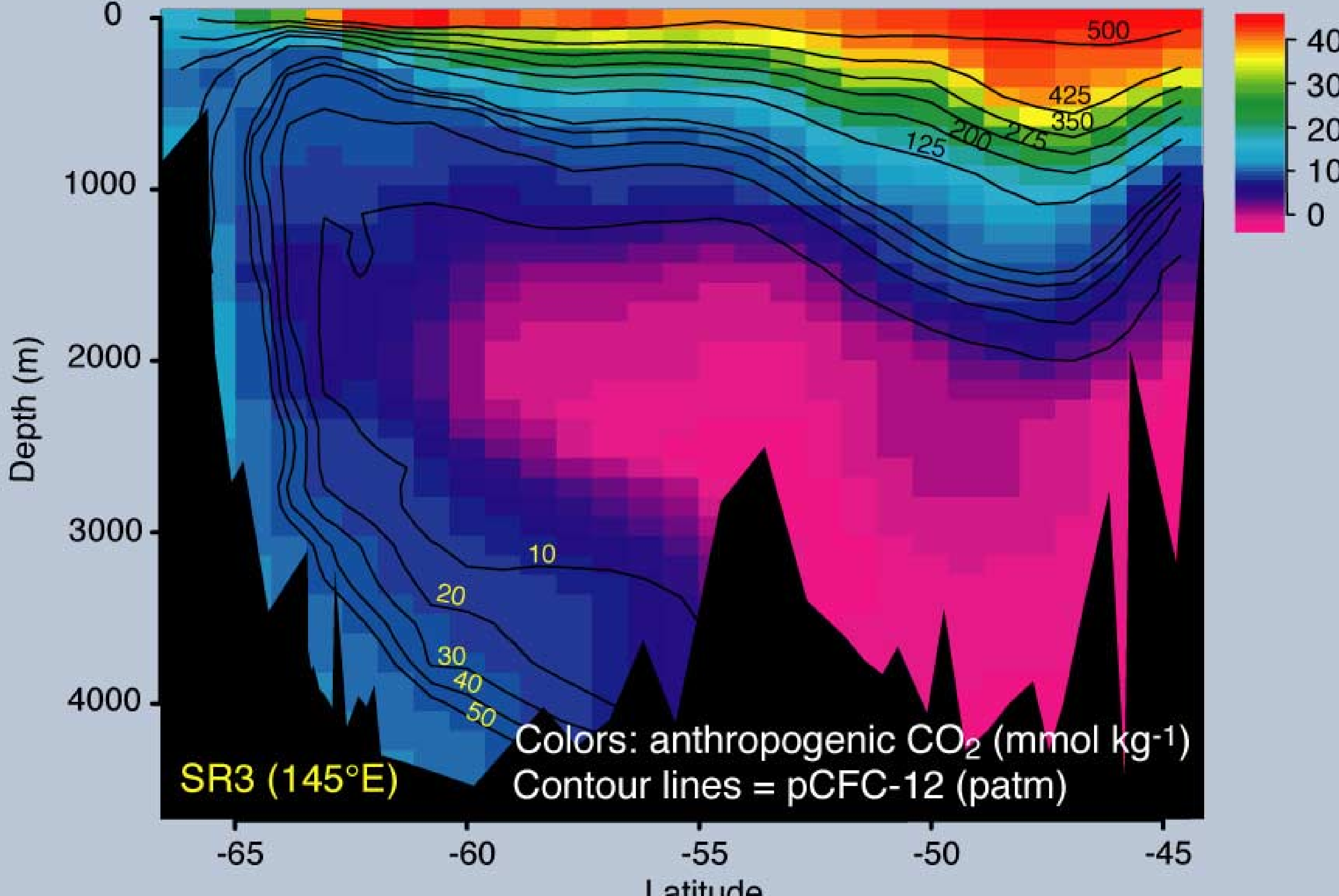
AIR-SEA FLUXES OF ANTHROPOGENIC CO_2



Anthropogenic CO_2 Flux for 1990: 1.8 PgC/yr

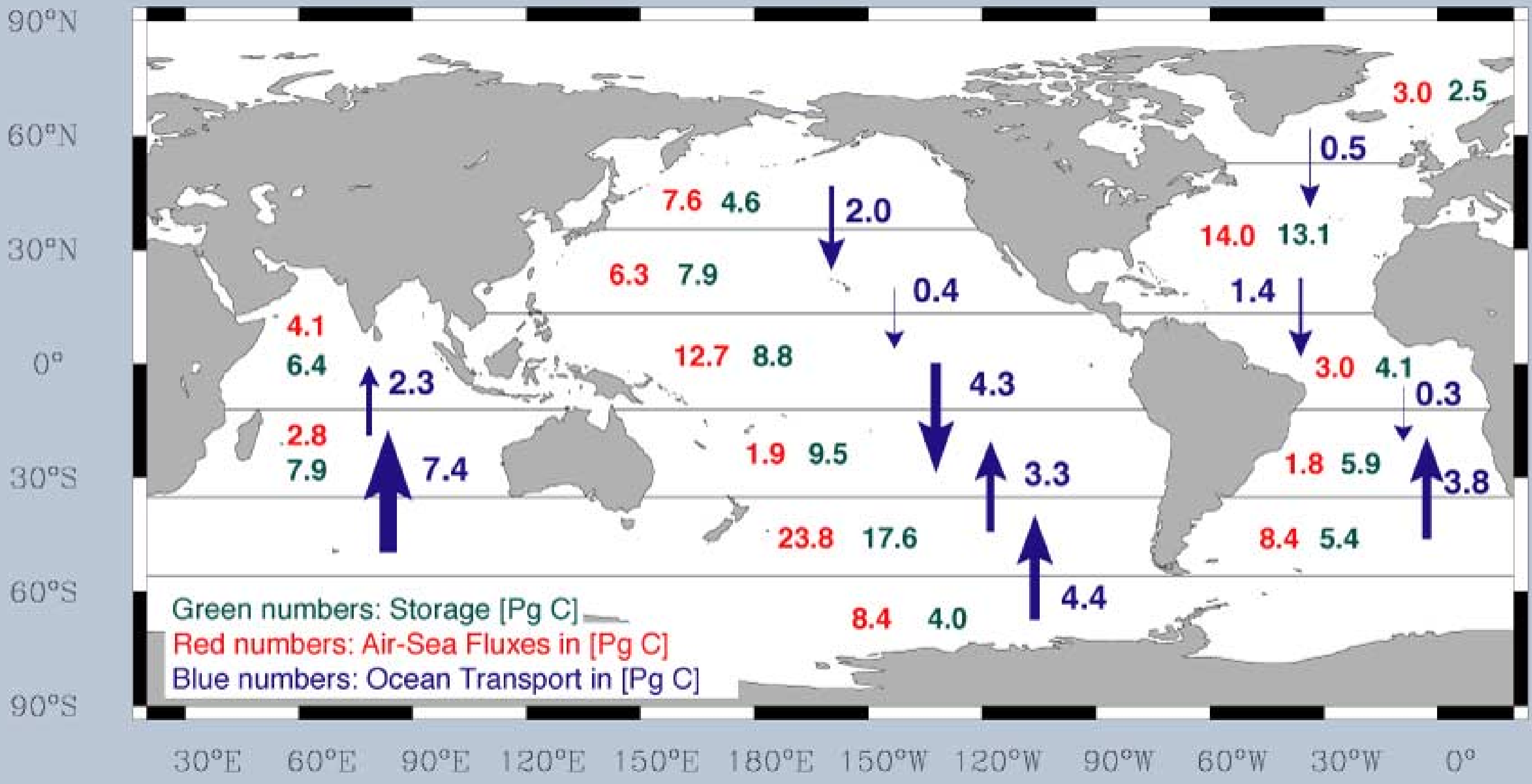
Gloor et al. (2003)
Gruber et al. (in prep.)

SR3: ANTHROPOGENIC CO_2 AND pCFC-12



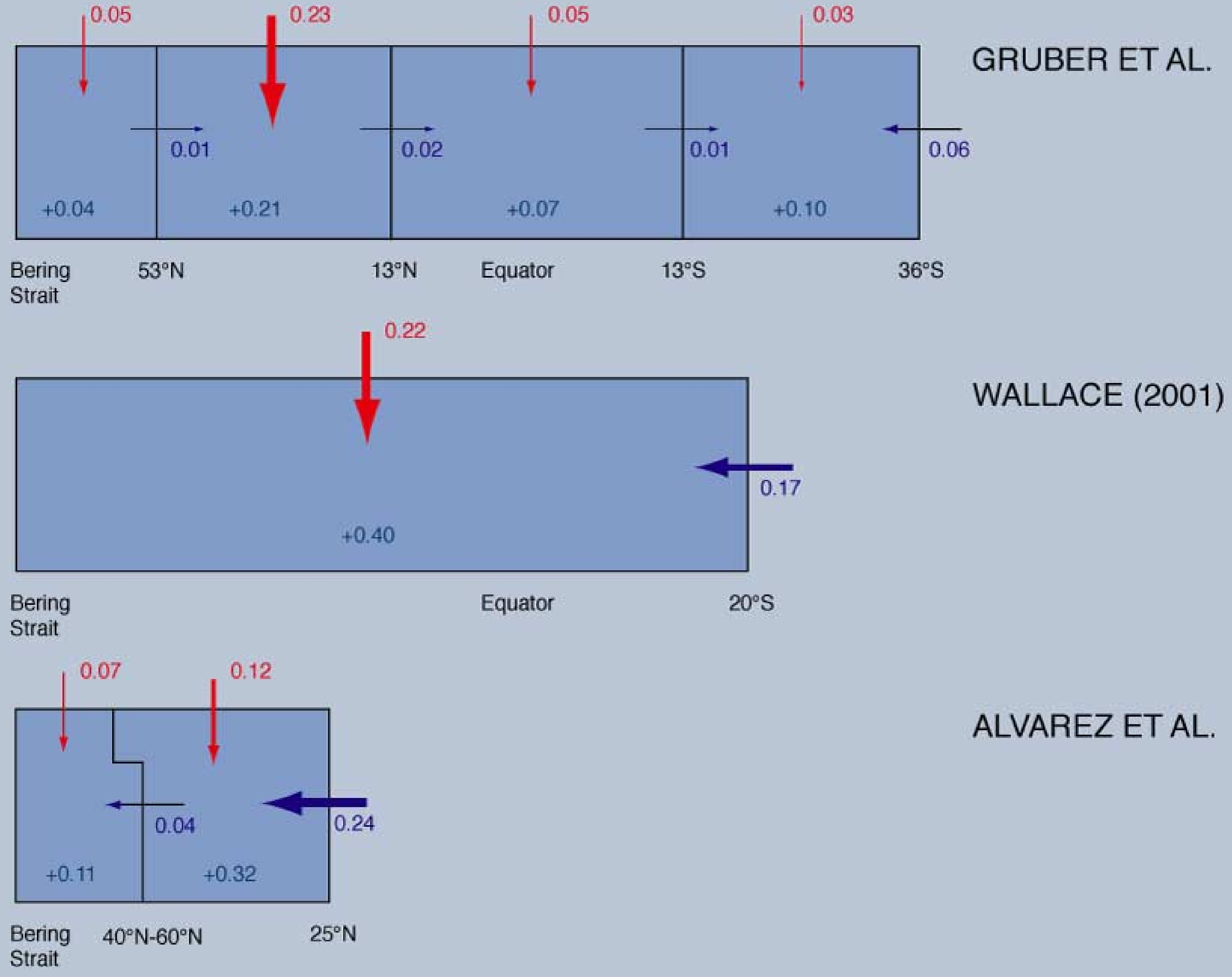
Sabine et al. (2002)

ANTHROPOGENIC CO_2 FLUXES, STORAGE AND TRANSPORT

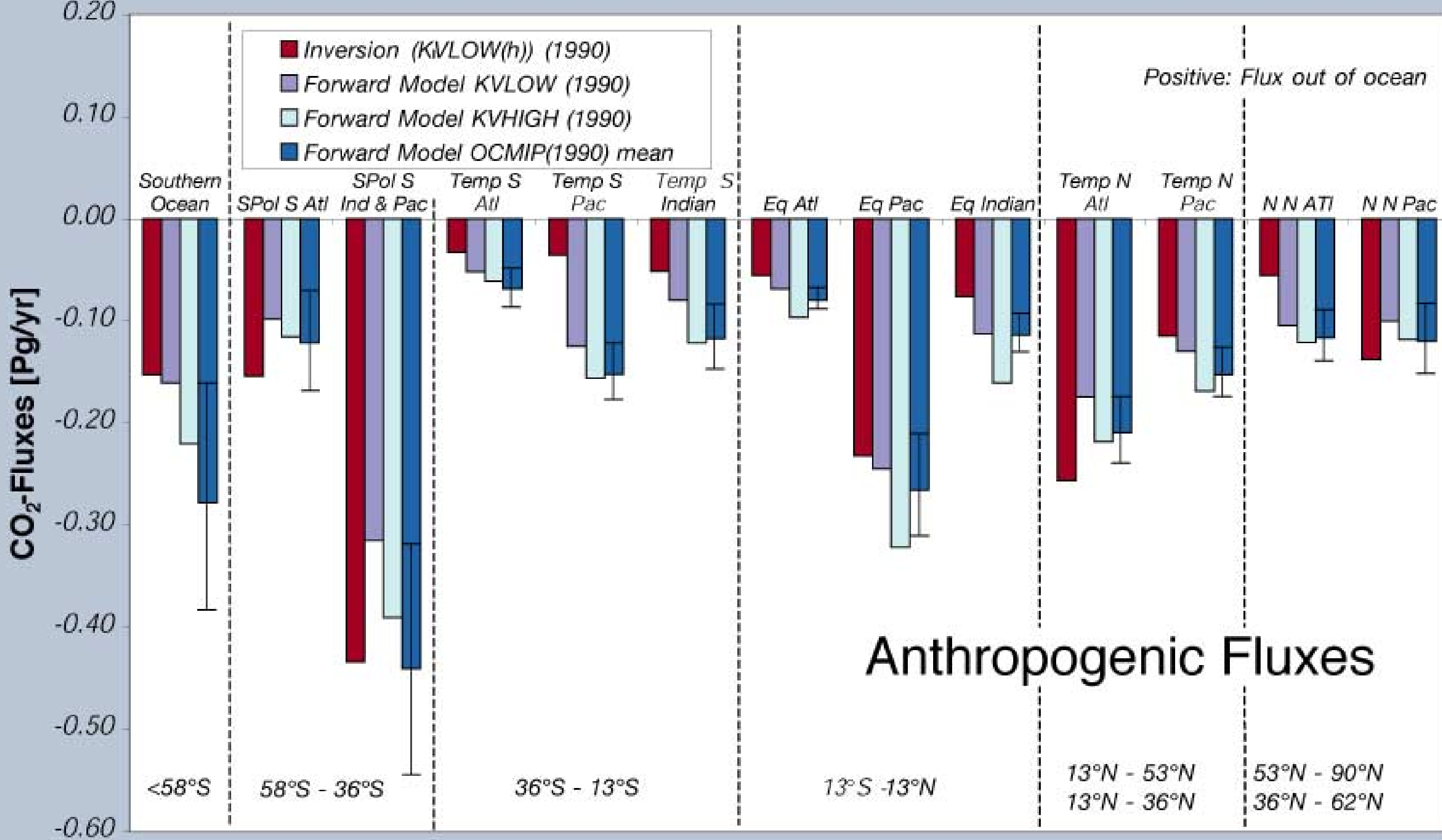


preliminary results: Gruber et al. [in prep.]

ATLANTIC: ANTHROPOGENIC CO_2 BUDGETS

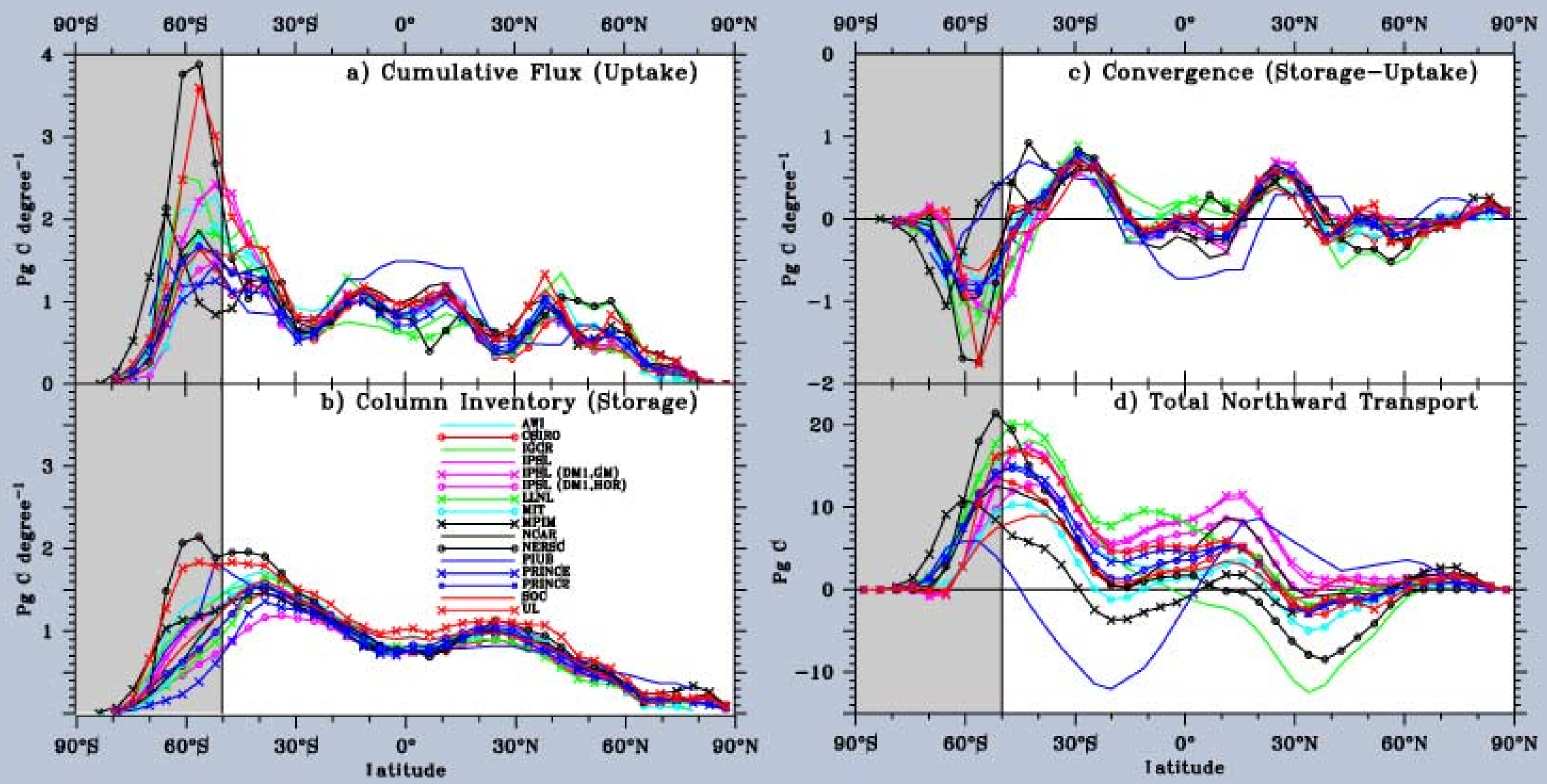


ANTHROPOGENIC AIR-SEA CO_2-FLUXES



Gloor et al. (2003)
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

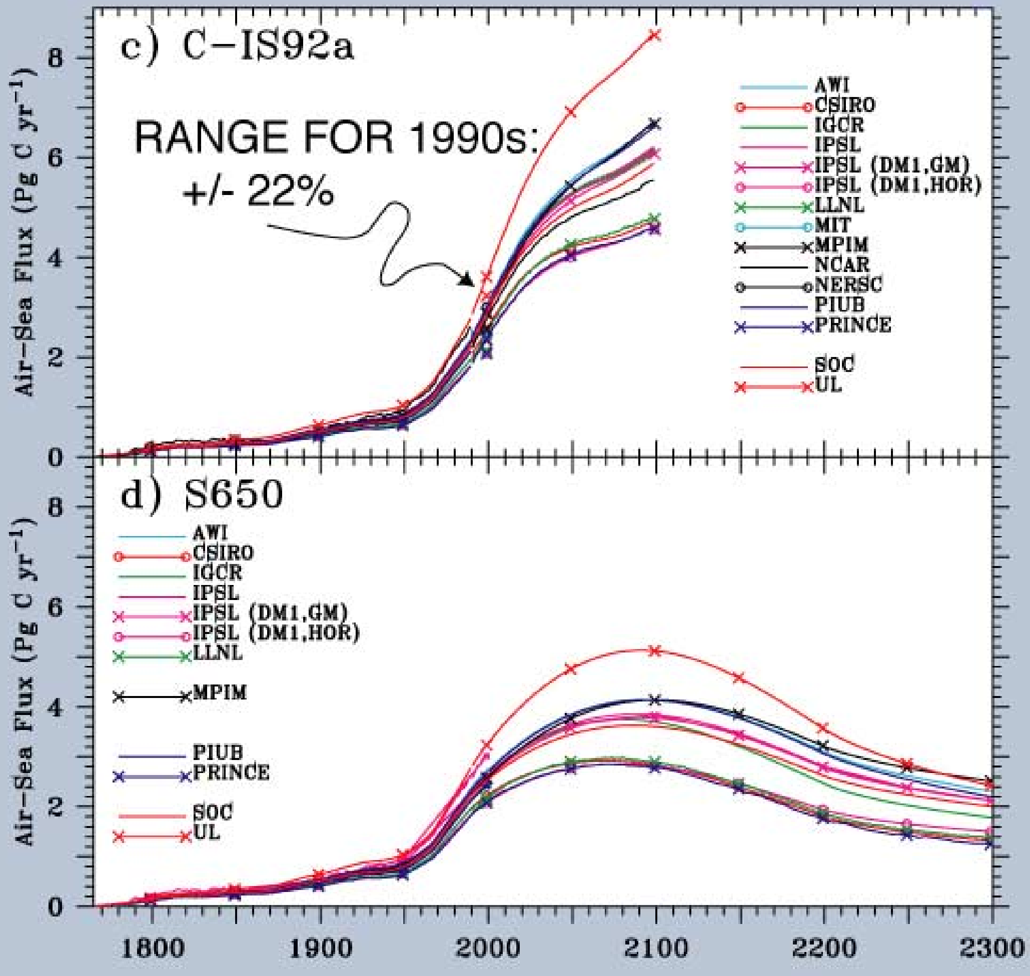
Model	Uptake Rate (PgC/yr) 1980-1989	Uptake Rate (PgC/yr) 1990-1999 (S650)	Inventory (Pg) 1765-1990
PRINCE	1.65	1.98	102
IPSL.DM1 (HOR)	1.67	1.98	
LLNL	1.78	2.08	108
CSIRO	1.78	2.11	108
MIT	1.91	2.29	117
NCAR	1.93	2.30	115
PRINC2	1.93	2.32	
IPSL (GM)	1.97	2.36	
MPIM	2.01	2.43	124
SOC	2.01	2.39	123
IPSL.DM1 (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*"			104 +/- 20

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

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

Models tend to be on the high side relative to data reconstruction

OCMIP-2: FUTURE ANTHROPOGENIC CO_2 UPTAKE



IS92a: RANGE FOR 2100:
+/- 33%

S650: RANGE FOR 2100:
+/- 30%

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

Summary

- By taking up about a third of the total emissions, the ocean has been the largest sink for anthropogenic CO_2 during the anthropocene.

- The Southern Ocean south of 36°S constitutes one of the most important sink regions, but much of this anthropogenic CO_2 is not stored there, but transported northward with Sub- Antarctic Mode Water.

- 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 and thus for the evolution of climate.

Outlook and Challenges

While we have made substantial advances in our understanding of the role of the ocean as a sink for anthropogenic CO_2, there remain a number of important challenges.

- The magnitude and role of natural variability
- The response to climate change and other ant. perturbations

These problems need to be addressed by a combination of long-term monitoring of the ocean and the development of a hierarchy of models that are based on a mechanistic understanding of the relevant processes.

The End.