Ocean Constraints on the Atmospheric Inverse Problem: The contribution of Forward and Inverse Models

Nicolas Gruber

Institute of Geophysics and Planetary Physics & Department of Atmospheric Sciences, University of California, Los Angeles

Ackowledgements

Manuel Gloor [1], J. L. Sarmiento [2], C. Sabine [3], R. F. Feely [4], J. C. Orr [5] and the OCMIP members

(1) Max Planck Institute for Biogeochemistry, Jena, Germany

(2) Program in Oceanic and Atmospheric Sciences, Princeton University

(3) JISAO, University of Washington, Seattle

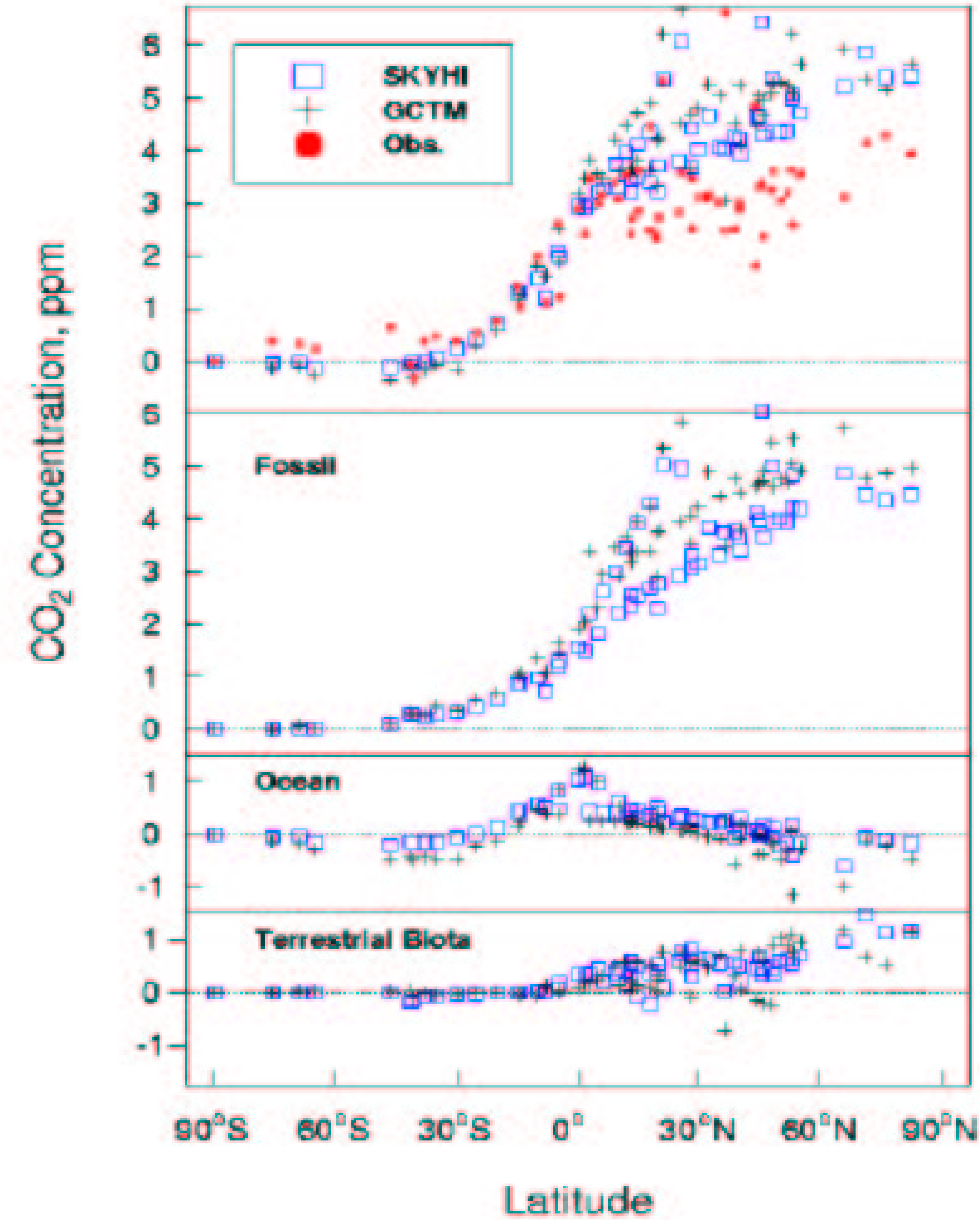
(4) Pacific Marine Environmental Laboratory, Seattle

(5) Lab. des Sciences du Climat de l'Environment, Gif-sur-Yvette, France

Outline

1. Introduction: A short historical overview
2. Observational approaches
3. Forward Modeling
4. Inverse Modeling
5. Regionalization
6. Summary and Conclusion

INTERHEMISPHERIC GRADIENT OF ATMOSPHERIC CO_2

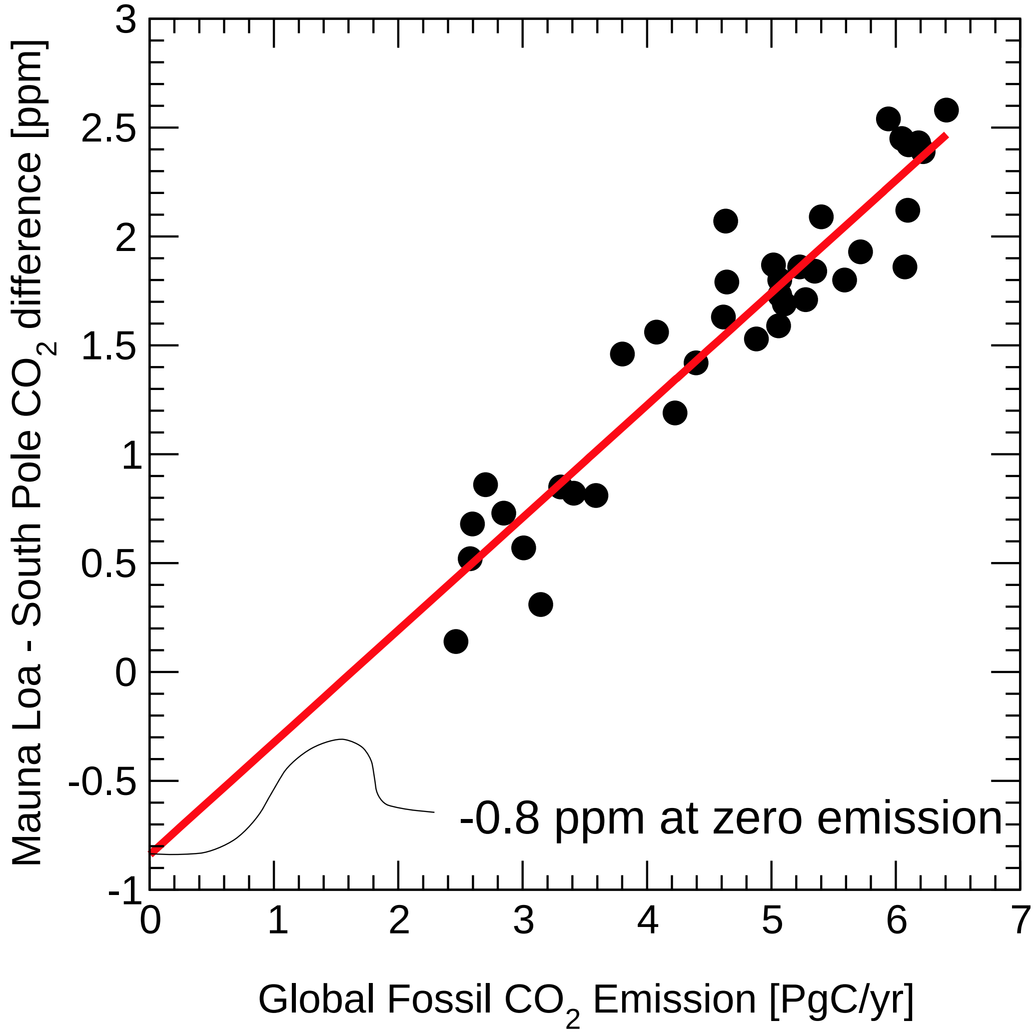


Fan et al. (1999)

Interhemispheric ocean CO_2 transport

[*Keeling et al.*, 1989]

PREINDUSTRIAL INTERHEMISPHERIC CO_2 GRADIENT

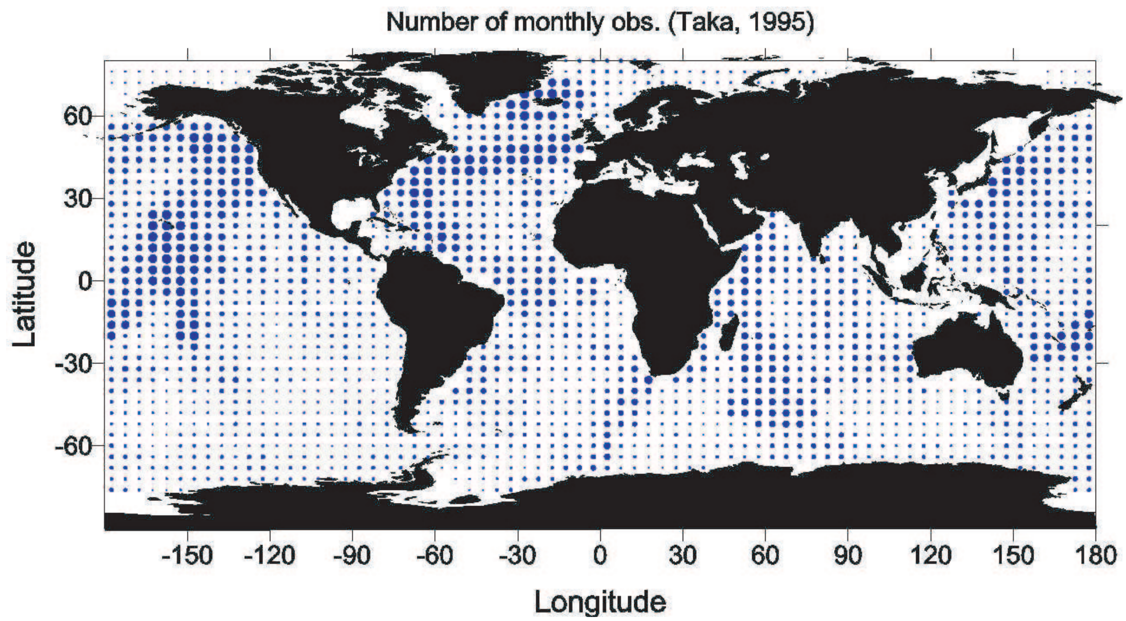


adapted and updated from Keeling et al. (1989)

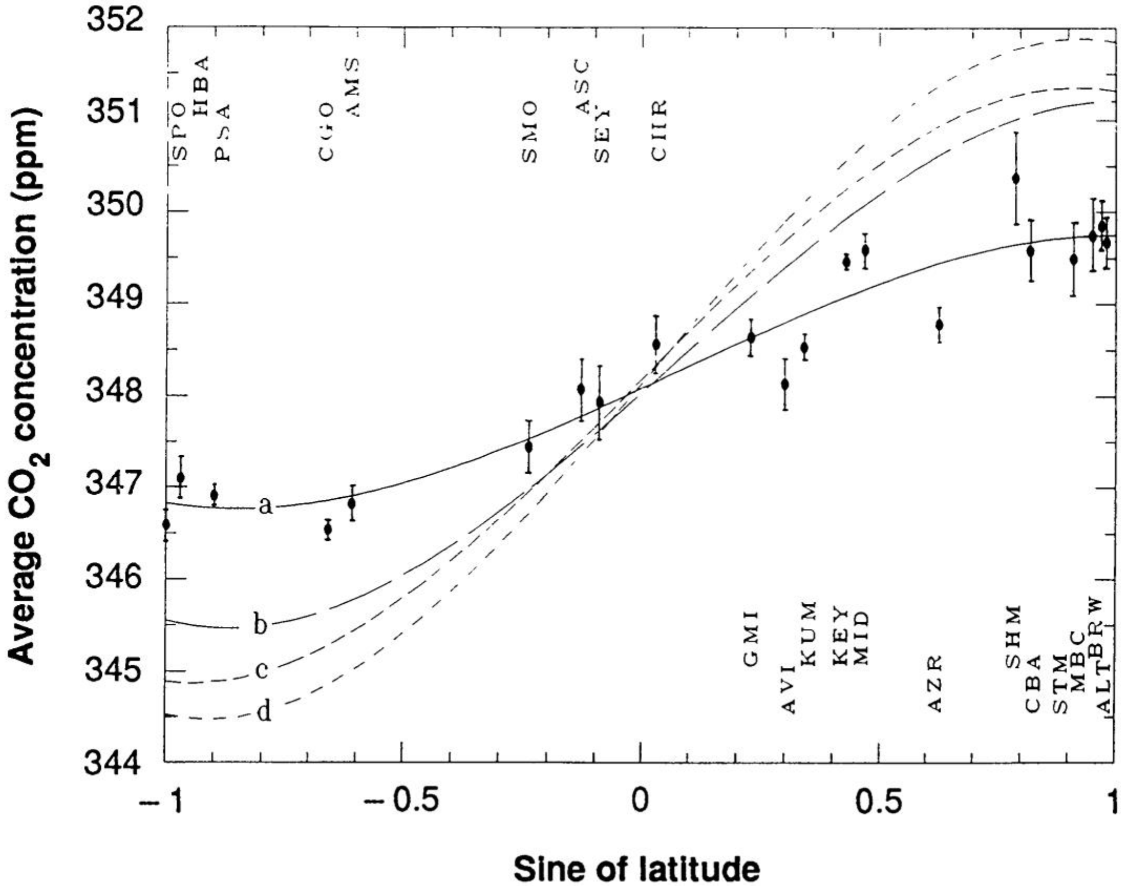
EVOLUTION OF OCEANIC pCO_2 NETWORK

TANS ET AL. (1990)

TAKAHASHI ET AL. (1999)

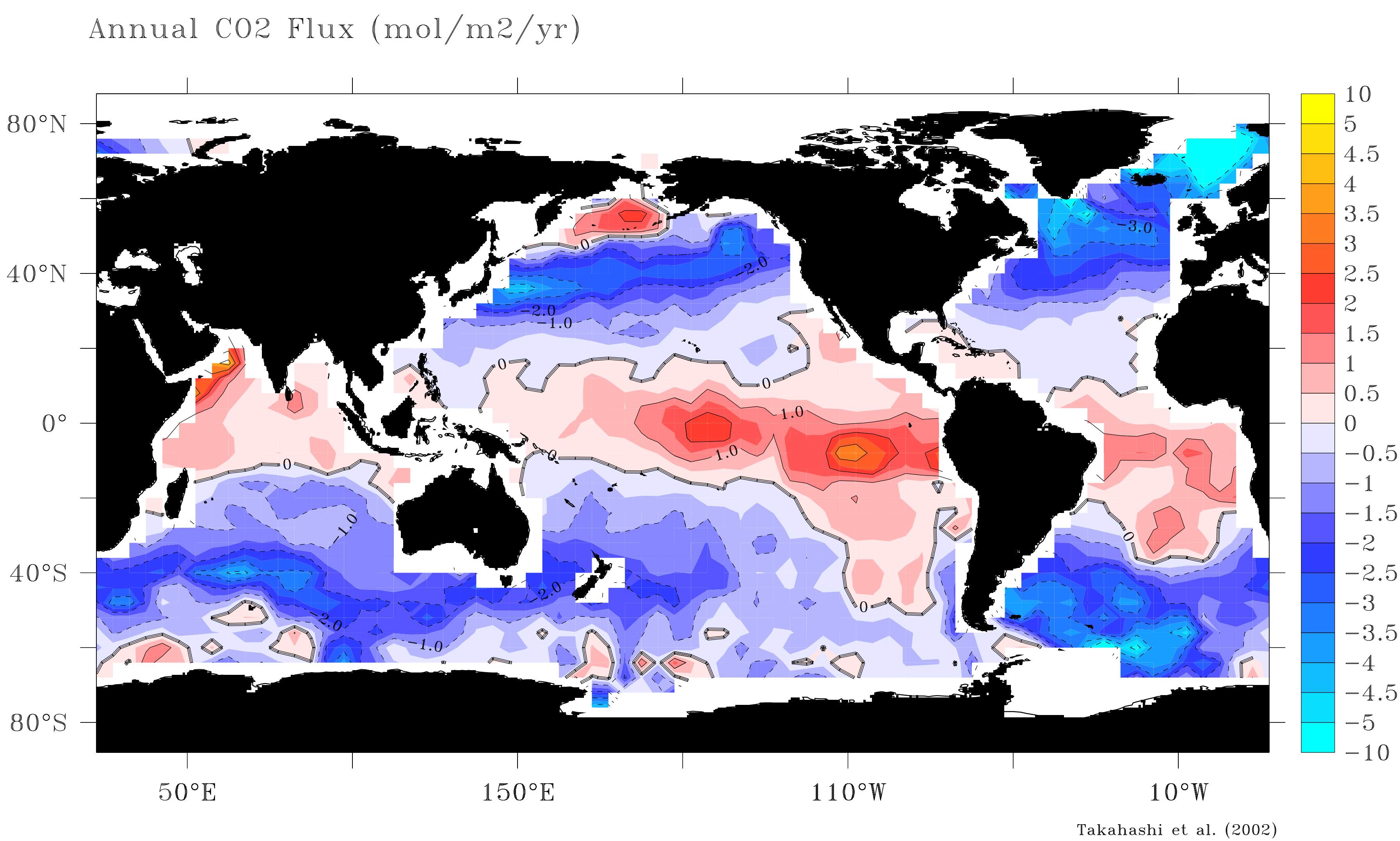


OBSERVED AND PREDICTED ATMOSPHERIC CO_2

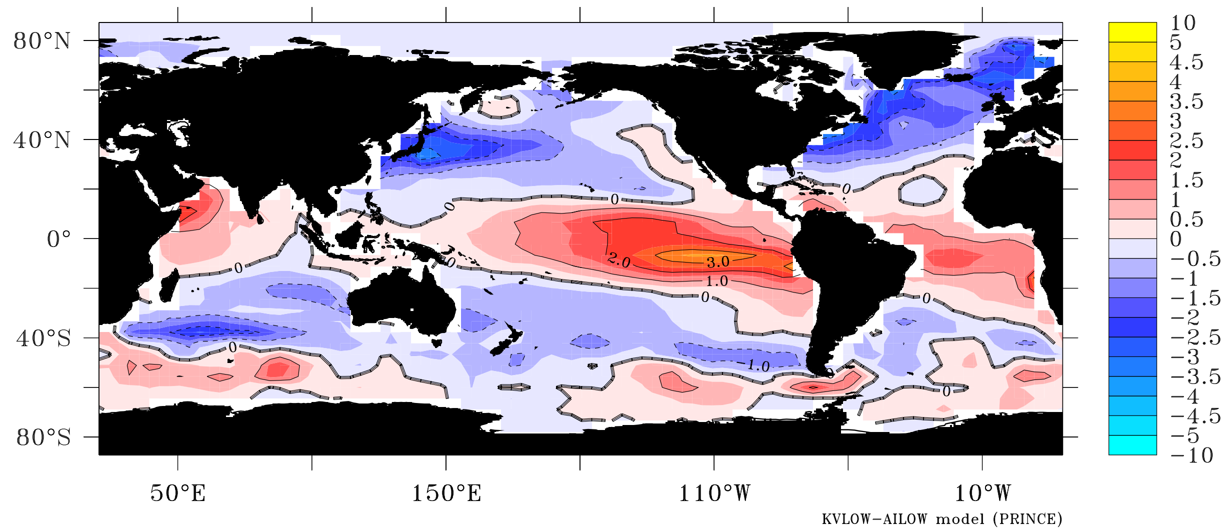


Tans et al. (1990)

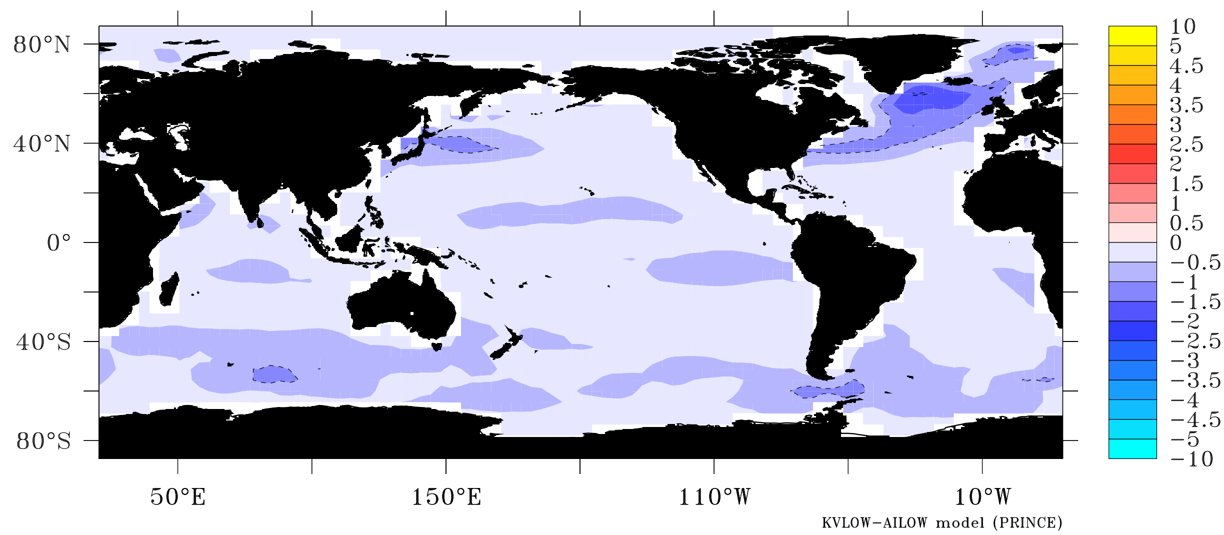
a) fit to data
b) predicted CO2 concentration with fossil fuel emission, sesonal vegetation tropical deforestation, and ocean flux computed using LM gas transfer coefficient
c) as b, except for ocean flux computed using Tans et al. gas transfer coefficient
d) as b, except for ocean flux computed using previous estimates


Annual CO2 Flux (mol/m2/yr)
80°N
40°N
0°
40°S
80°S
50°E
150°E
110°W
10°W
10
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2.5
−3
−3.5
−4
−4.5
−5
−10
Takahashi et al. (2002)

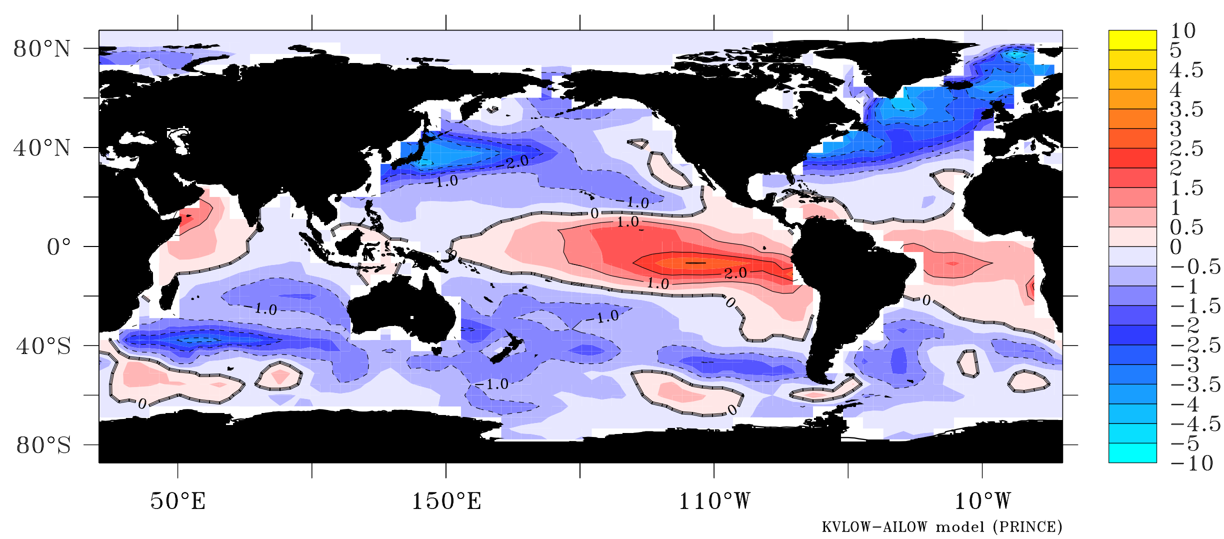
Pre-Industrial CO2 Flux (mol/m2/yr)



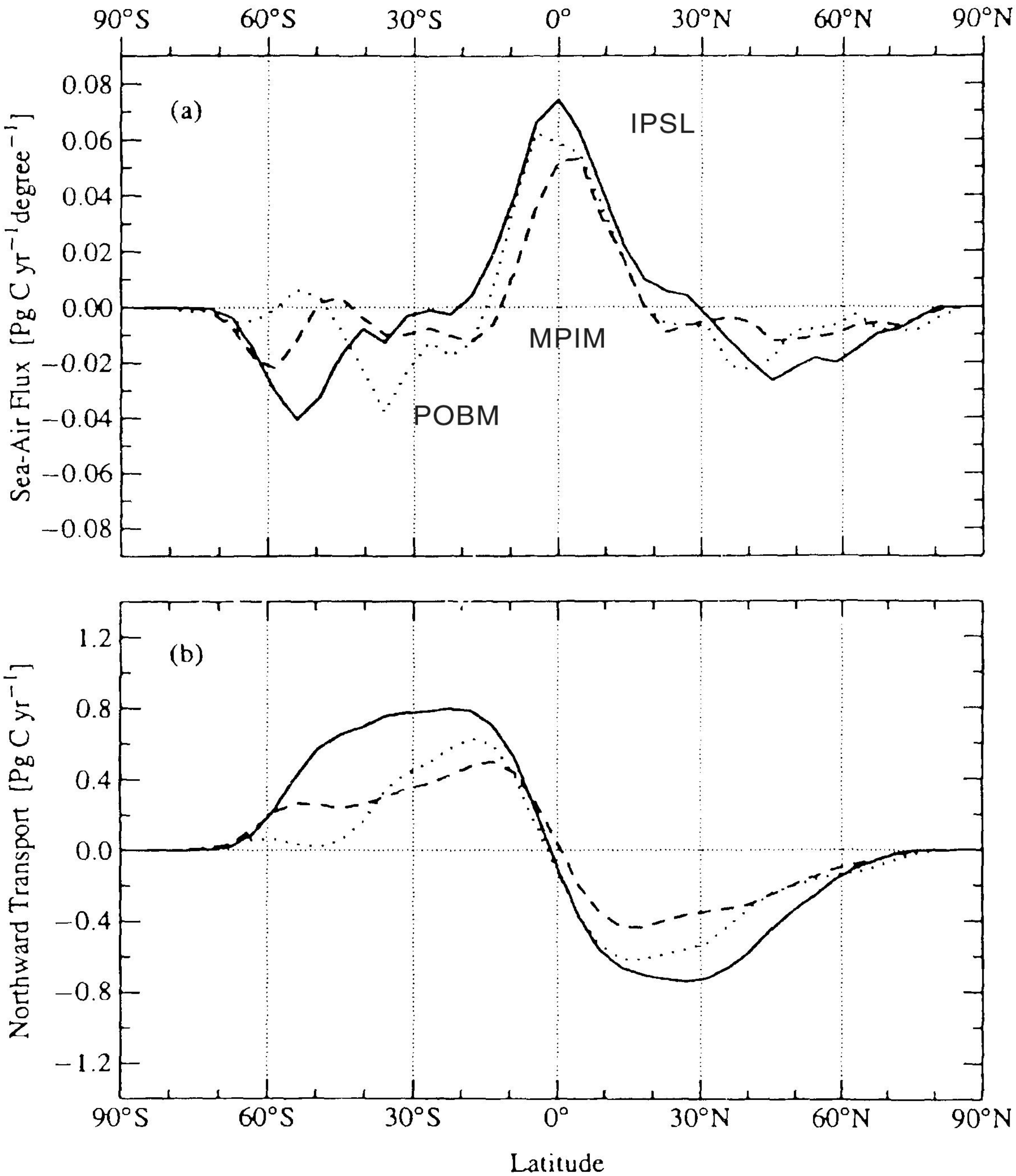
Anthropogenic CO2 Flux (1990) (mol/m2/yr)



Contemporary CO2 FLux (1990) (mol/m2/yr)

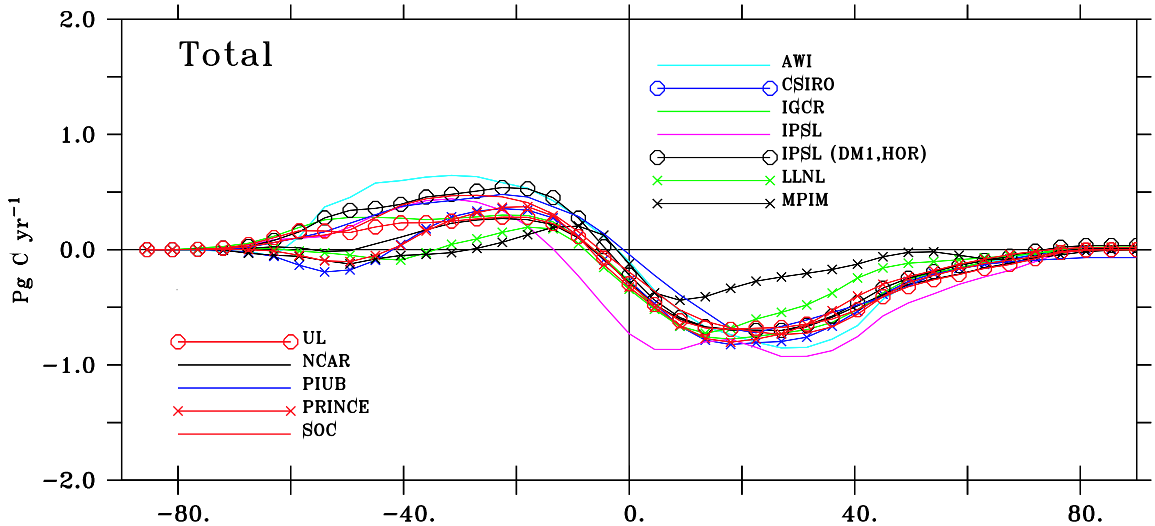


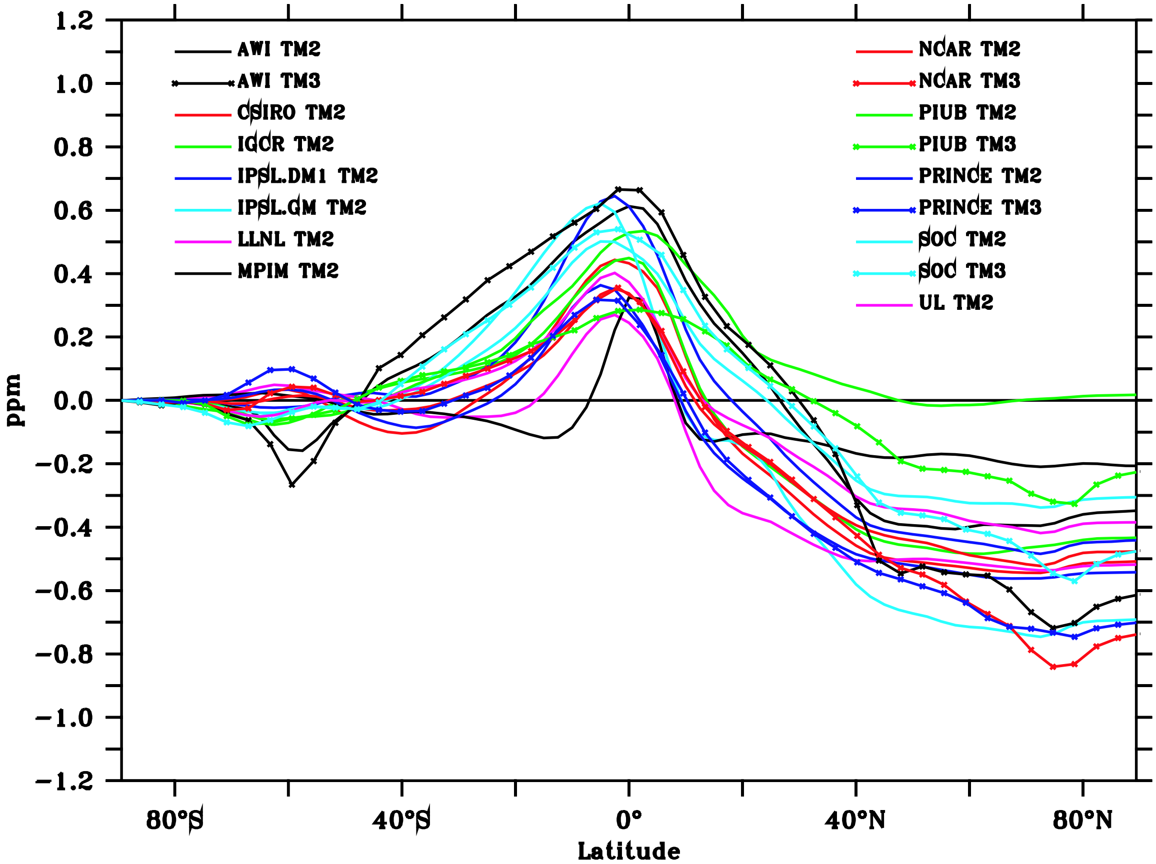
OCMIP-1: CO_2 FLUXES AND OCEAN TRANSPORT



Sarmiento et al. (2000)

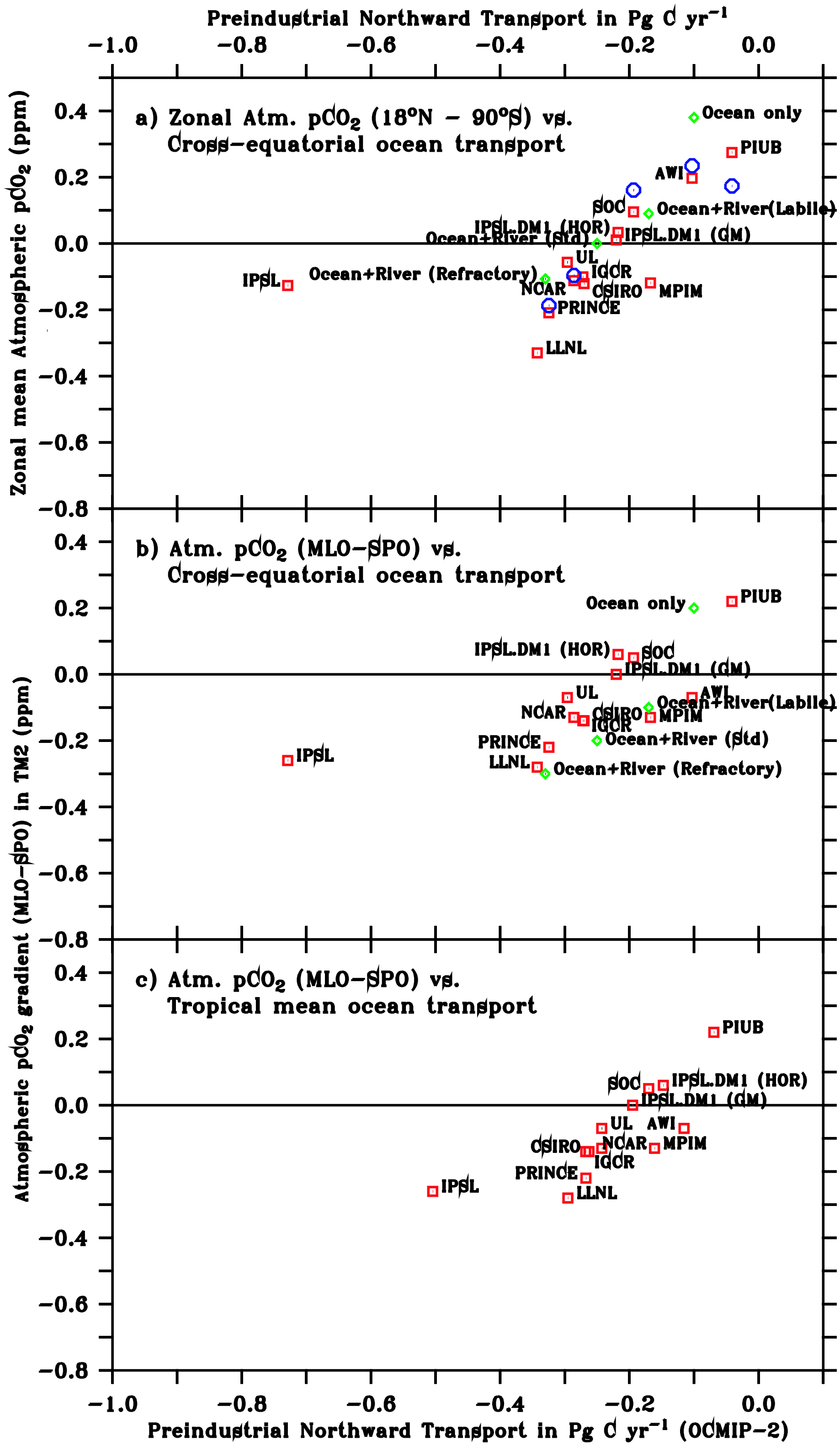
OCMIP-2: OCEAN CO_2 TRANSPORTS AND ATM. RESPONSE





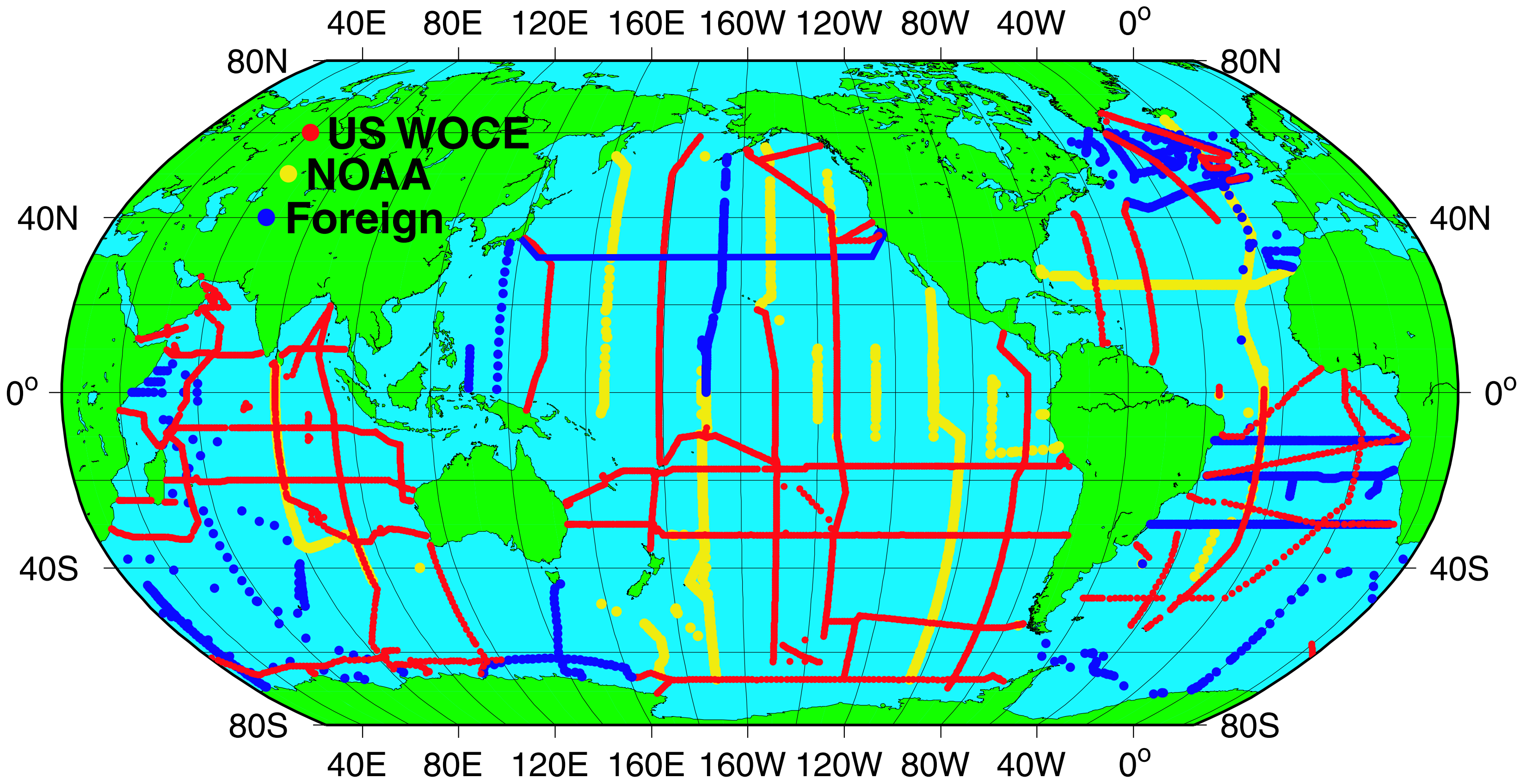
J. Orr and OCMIP-2 (pers.comm)

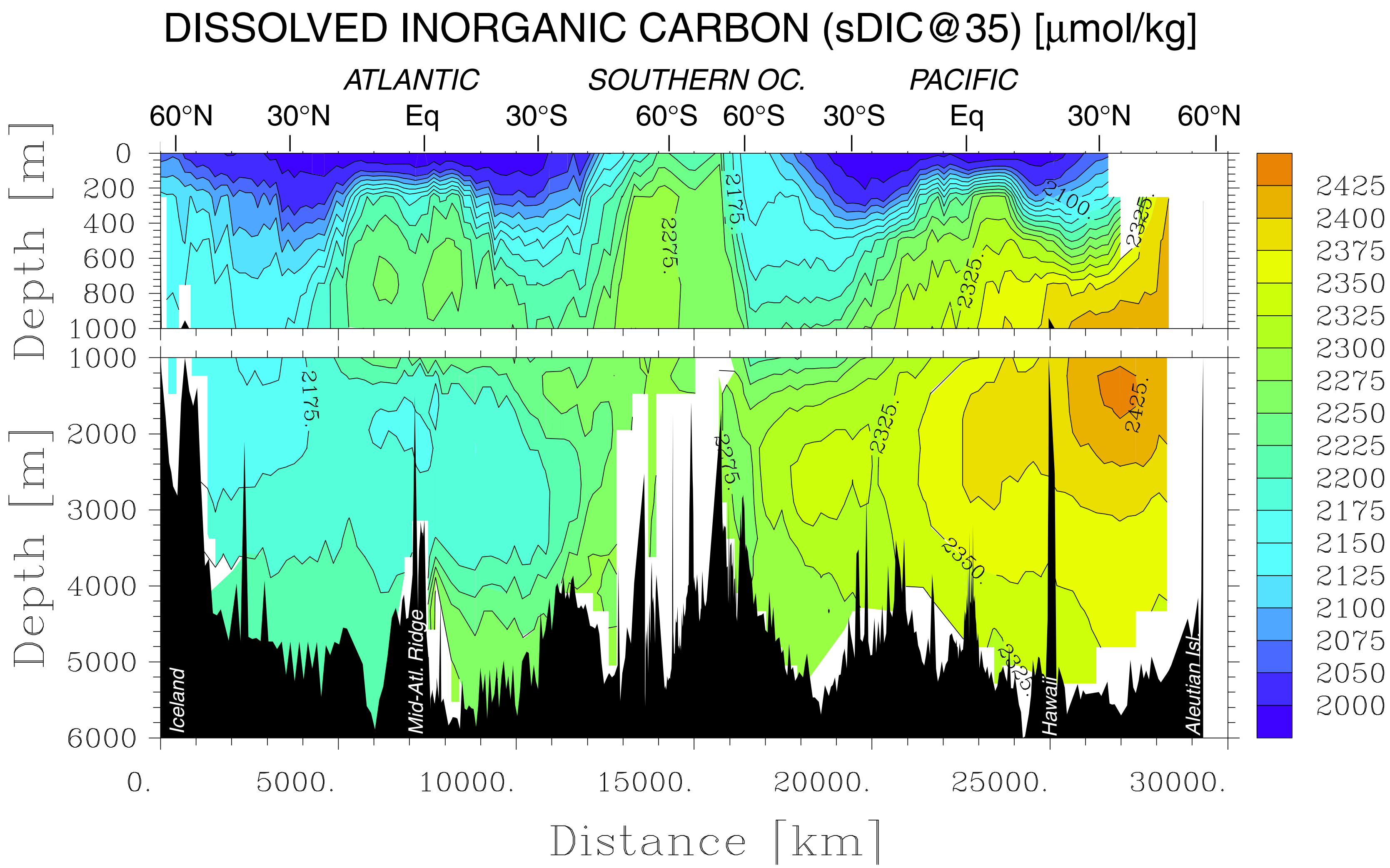
OCMIP-2: OCEAN CO_2 TRANSPORT VERSUS ATMOSPHERIC GRADIENT



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

WOCE/JGOFS 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
Hawaii
Aleutian Isl.
0.
5000.
10000.
15000.
20000.
25000.
30000.
2425.
2400.
2375.
2350.
2325.
2300.
2275.
2250.
2225.
2200.
2175.
2150.
2125.
2100.
2075.
2050.
2000.

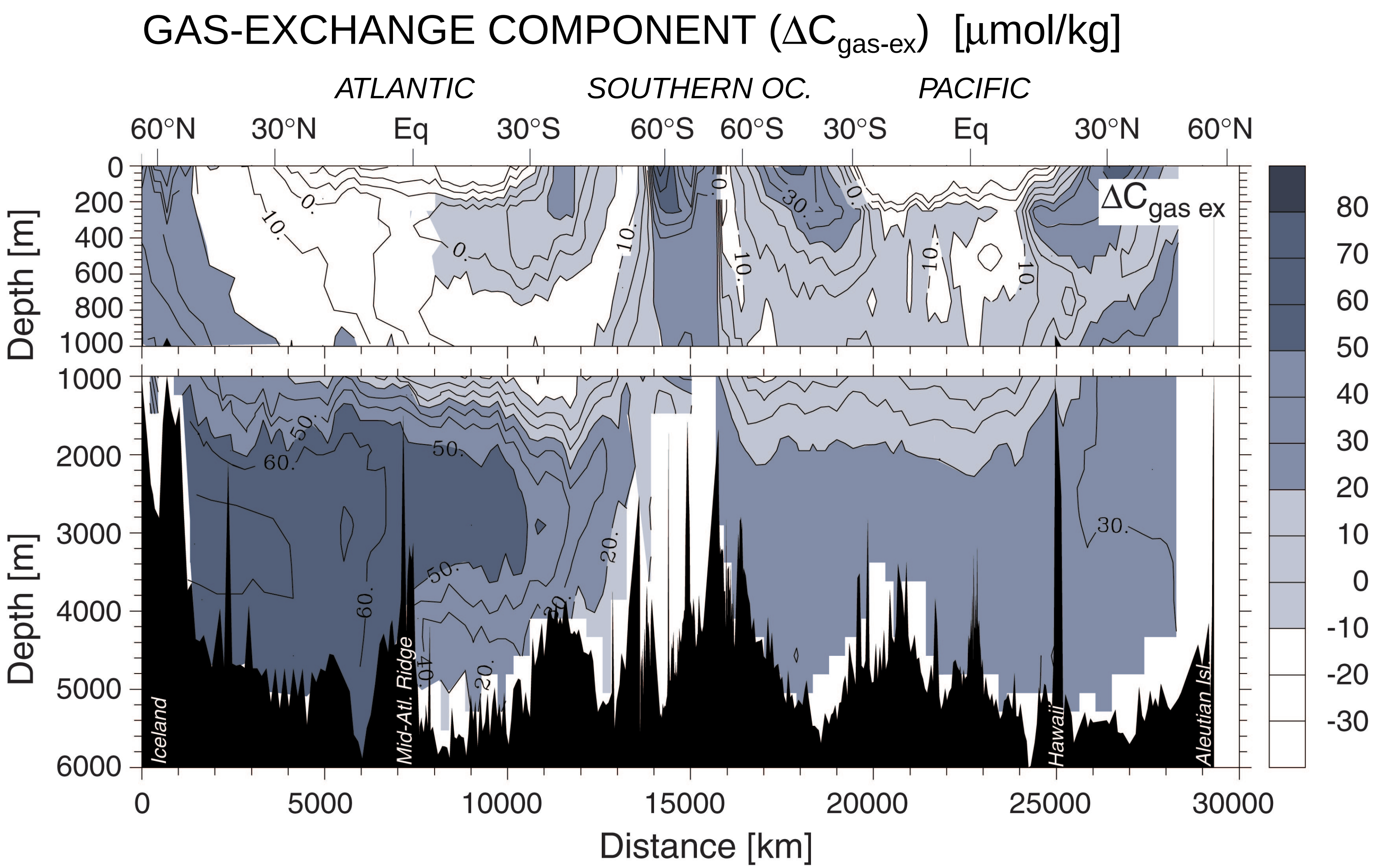
What $\Delta C_{\text{gas ex}}$ can tell us about the air-sea gas exchange of CO_2

- Definition of $\Delta C_{\text{gas ex}}$:

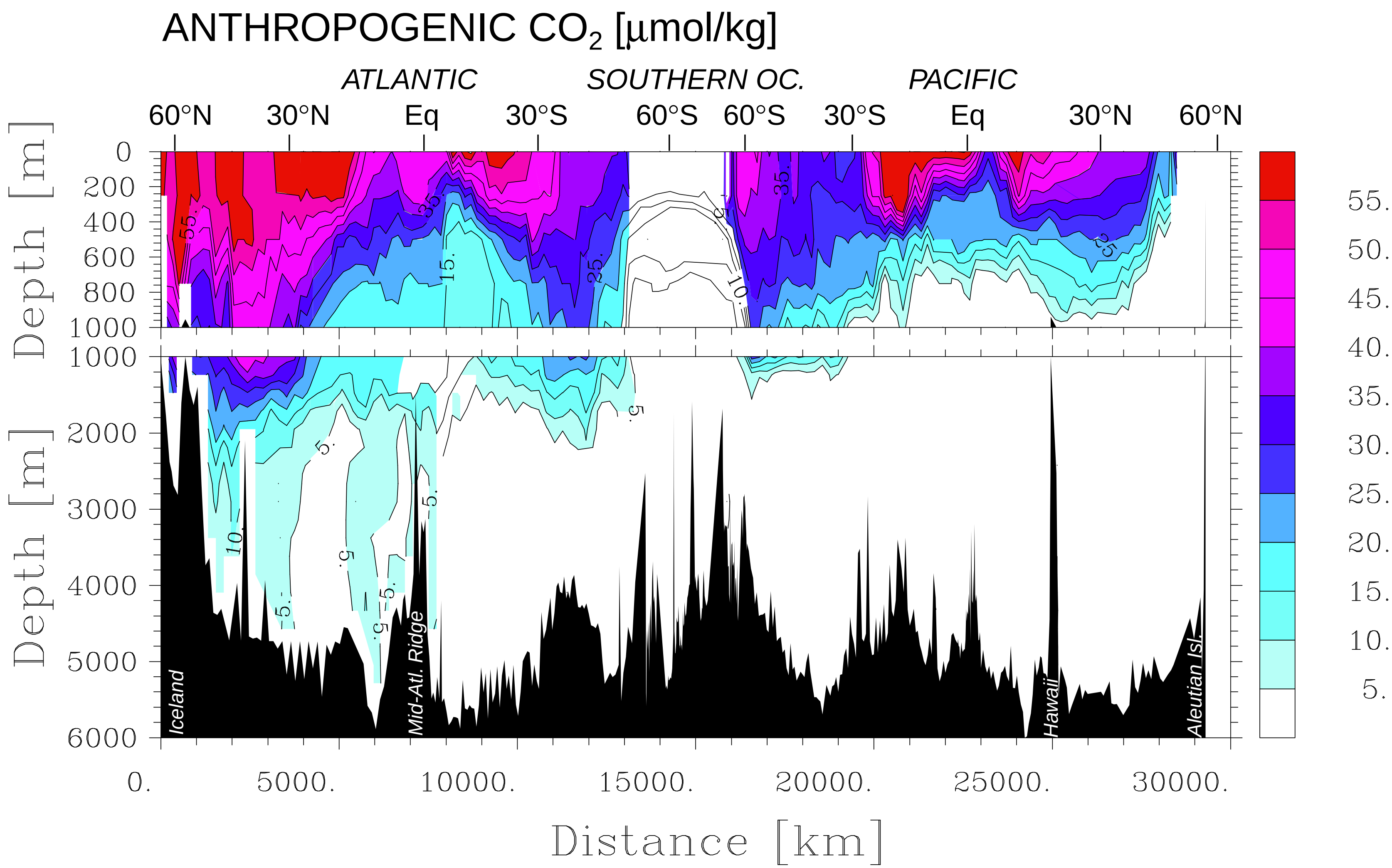
$$\Delta C_{\text{gas ex}} = \frac{S^o}{S}\left(DIC - r_{C:P}P - \frac{1}{2}\left(Alk + r_{N:P}P\right)\right) - \Delta C_{\text{ant}},$$

$$\Gamma(\Delta C_{\text{gas ex}}) = 0.$$

- Explanation and Interpretation :
  - The normalization to constant Phosphate (P) and Alkalinity (Alk) removes the contribution of the soft-tissue and carbonate pumps.
  - The remaining variability is due to the exchange of natural CO_2 between the ocean and atmosphere as well as the uptake of anthropogenic CO_2 (ΔC_{ant}).
  - After removing ΔC_{ant} as well, we end up with a tracer just reflecting the air-sea exchange of natural (i.e. pre-industrial) CO_2.



GAS-EXCHANGE COMPONENT (ΔC_{gas-ex}) [µmol/kg]
ATLANTIC
SOUTHERN OC.
PACIFIC
60°N
30°N
Eq
30°S
60°S
60°S
30°S
Eq
30°N
60°N
$\Delta C_{gas\ ex}$
Depth [m]
Depth [m]
Distance [km]
Iceland
Mid-Atl. Ridge
Hawaii
Aleutian Isl.
80
70
60
50
40
30
20
10
0
-10
-20
-30



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]
0
200
400
600
800
1000
1000
2000
3000
4000
5000
6000
Iceland
Mid-Atl. Ridge
Hawaii
Aleutian Isl.
0.
5000.
10000.
15000.
20000.
25000.
30000.
Distance [km]
55.
50.
45.
40.
35.
30.
25.
20.
15.
10.
5.

Principle of Oceanic Inversion

- The ocean surface is partitioned into n regions.
- Basis functions
  - *Steady-State Inversion*

    In a OGCM, constant fluxes of dye tracers (Φ) are imposed in each of the n regions, and the model is run until the spatial patterns of the dyes attain a quasi steady-state.
  - *Transient-tracer Inversion*

    Analogous to the *steady-state* inversion except that the dye fluxes are time-varying, i.e. for CO_2,

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

- The model predictions of the dye concentrations are sampled at the observation stations and arranged as a vector $\vec{\chi}_{\mathrm{OGCM}}$. The model therefore provides us with a transport matrix A_{OGCM} that relates the fluxes to the distribution,

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

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

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

The Models

- coarse resolution model: 3.75° meridionally, 4.5° zonally and 24 layers vertically

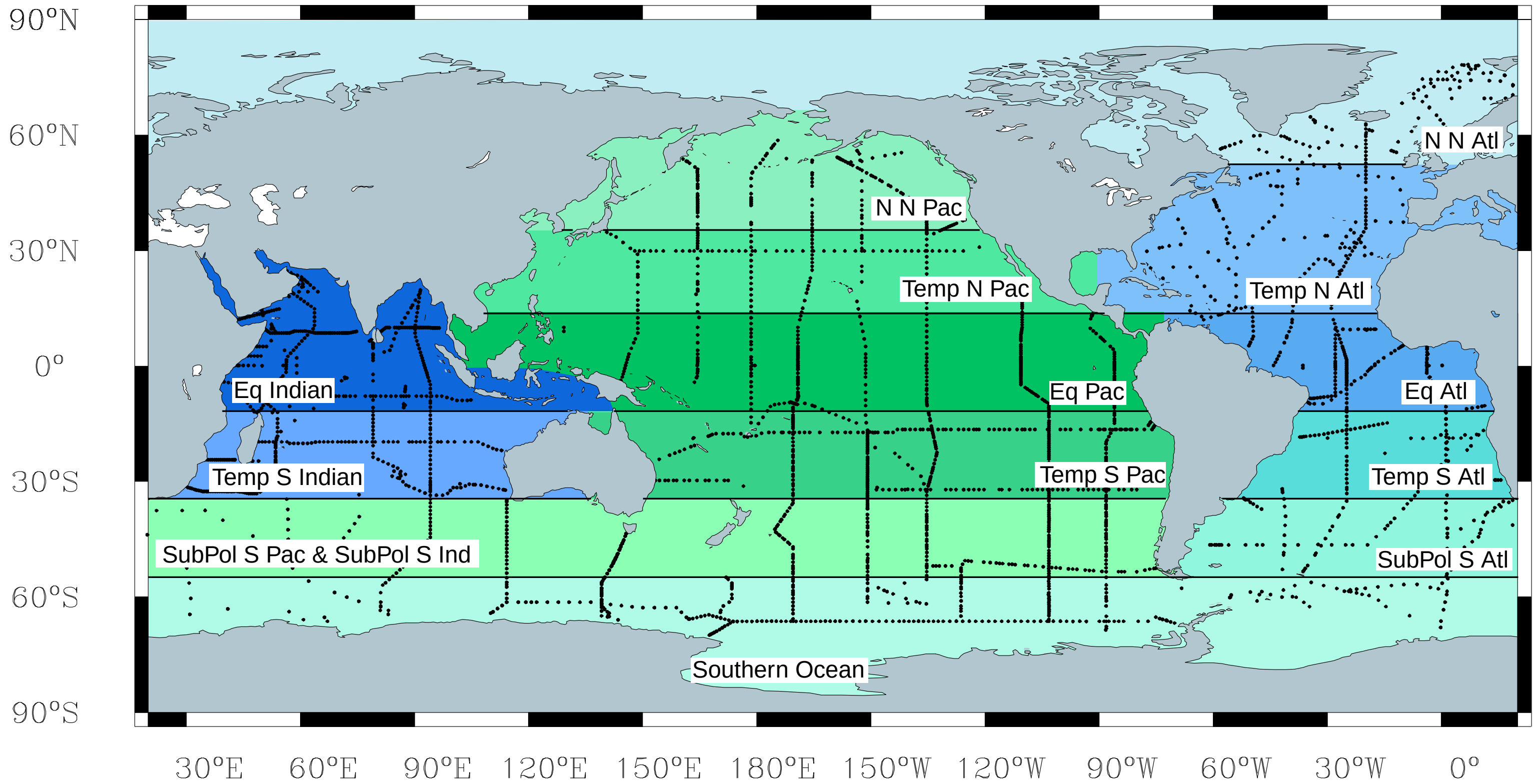
- seasonal forcing at the surface with observed wind-stress, [Hellermann and Rosenstein, 1983] and heat and freshwater fluxes [DaSilva et al., 1994] with weak restoring towards observed temperature and salinity fields from Levitus et al. [1994].

- Sub-grid scale parameterization of eddies according to Gent and McWilliams [1990]

- KvLOW-AiLOW: Low vertical diffusivity everywhere; KvHISouth-AiLOW: Enhanced vertical diffusivity in the Southern Ocean.

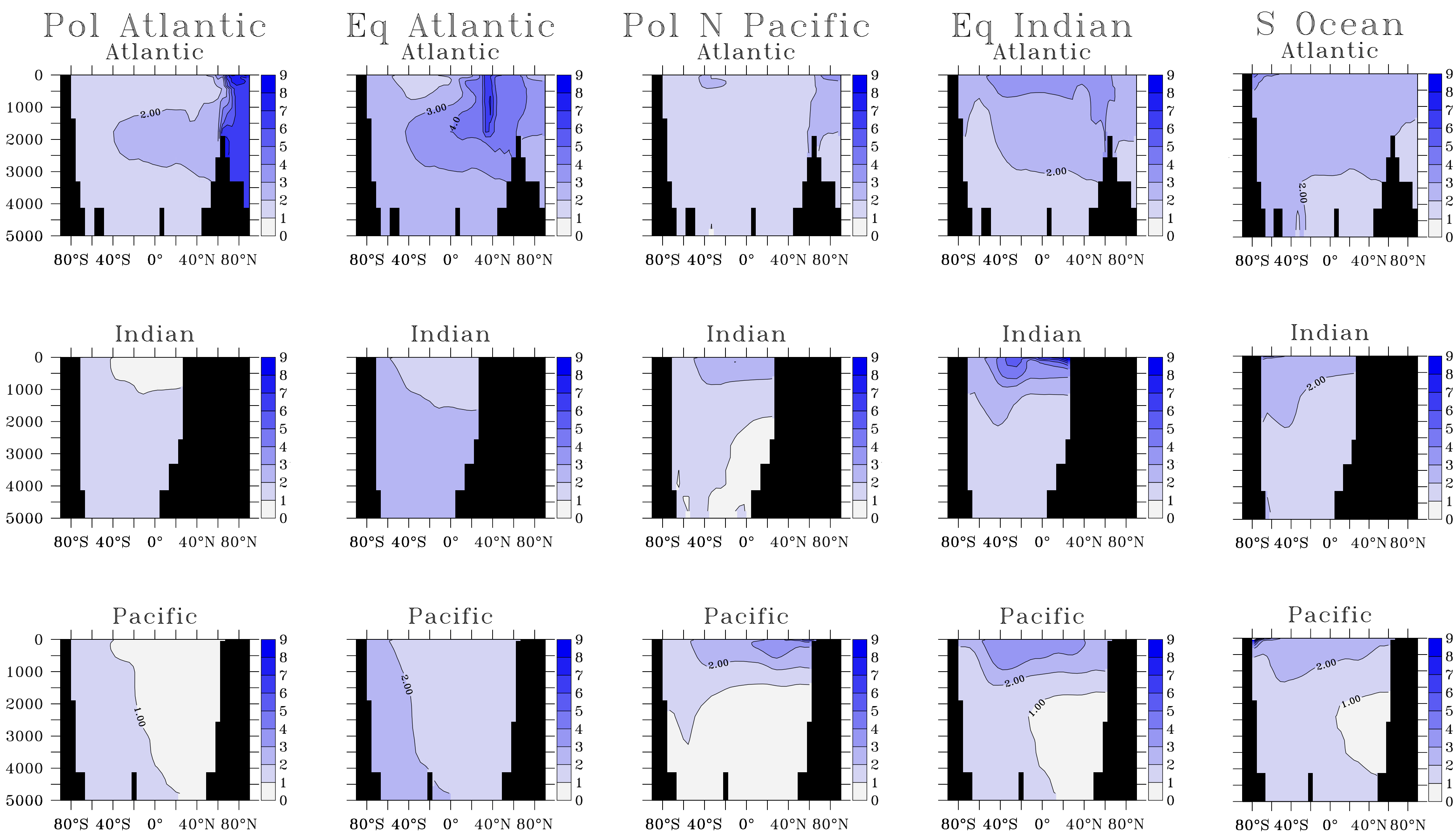
- Surface ocean has been divided into 15 regions and unit fluxes have been applied for a total runtime of 3000 years. For the time-dependent inversion, the unit fluxes were scaled in time according to the evolution of the atmospheric CO_2 perturbation.

OCEAN REGIONS AND NETWORK

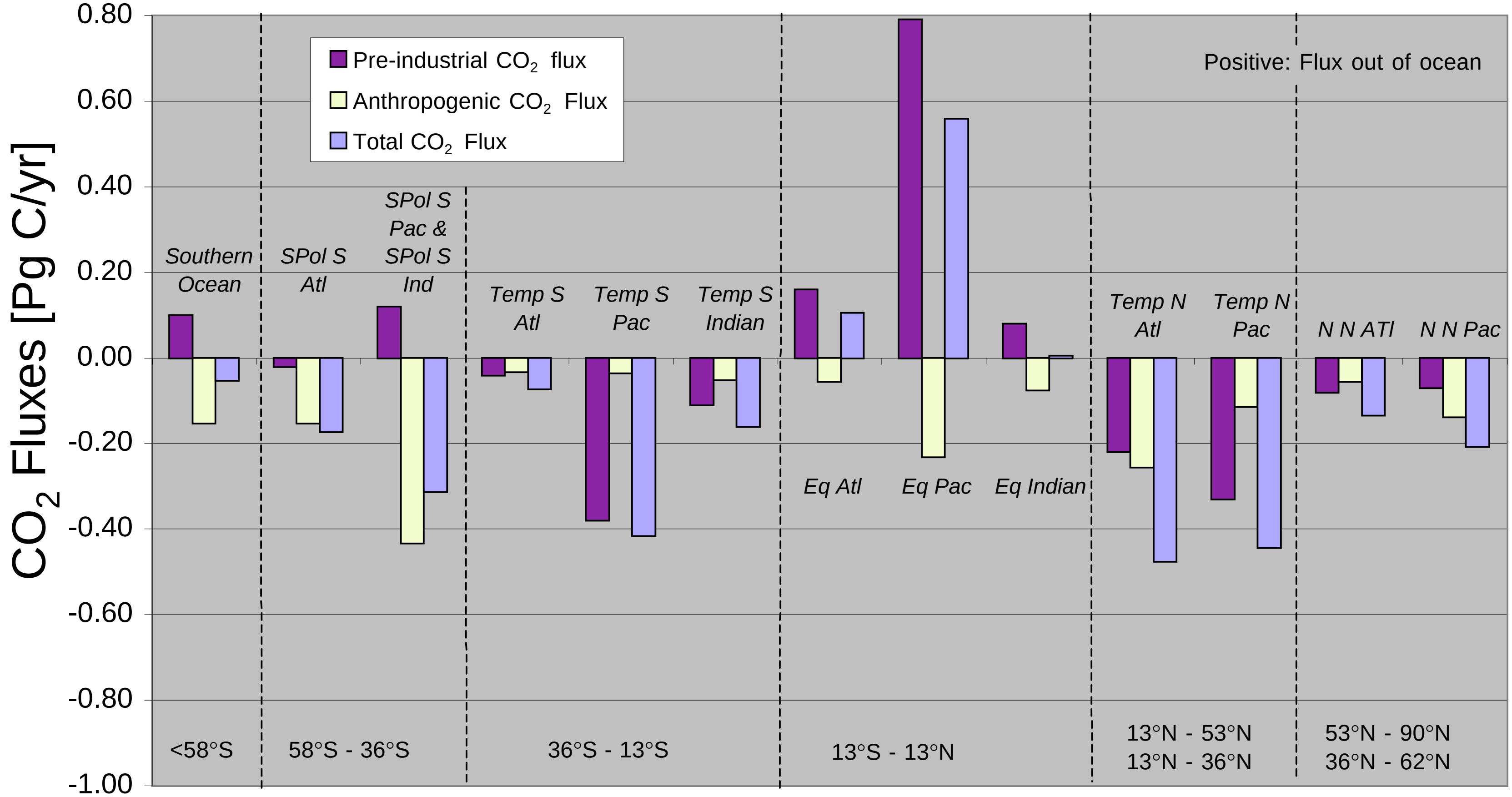


WOCE/JGOFS/OACES SURVEY

Basis Functions: Color Tracer Distribution

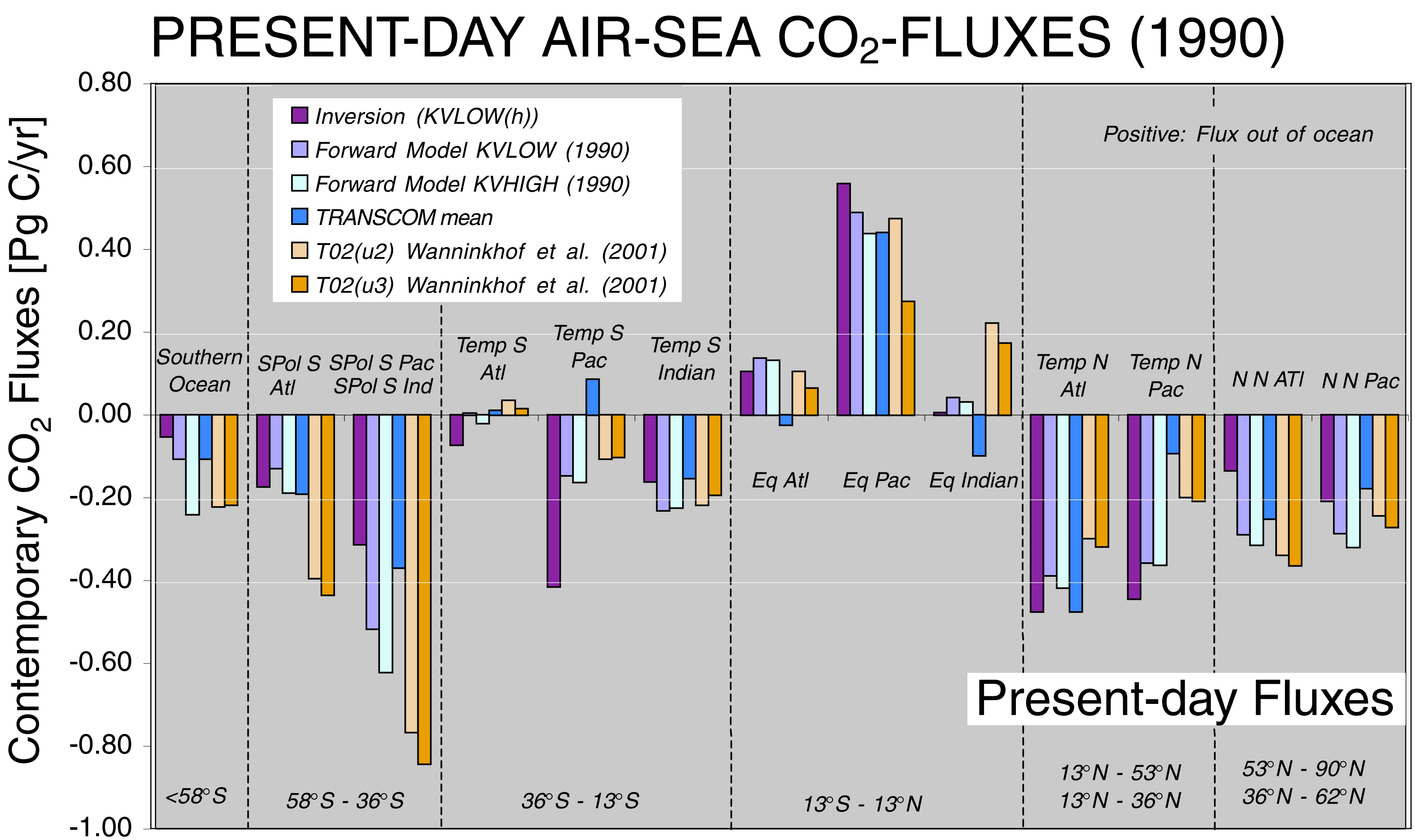


INVERSE AIR-SEA CO_2-FLUXES



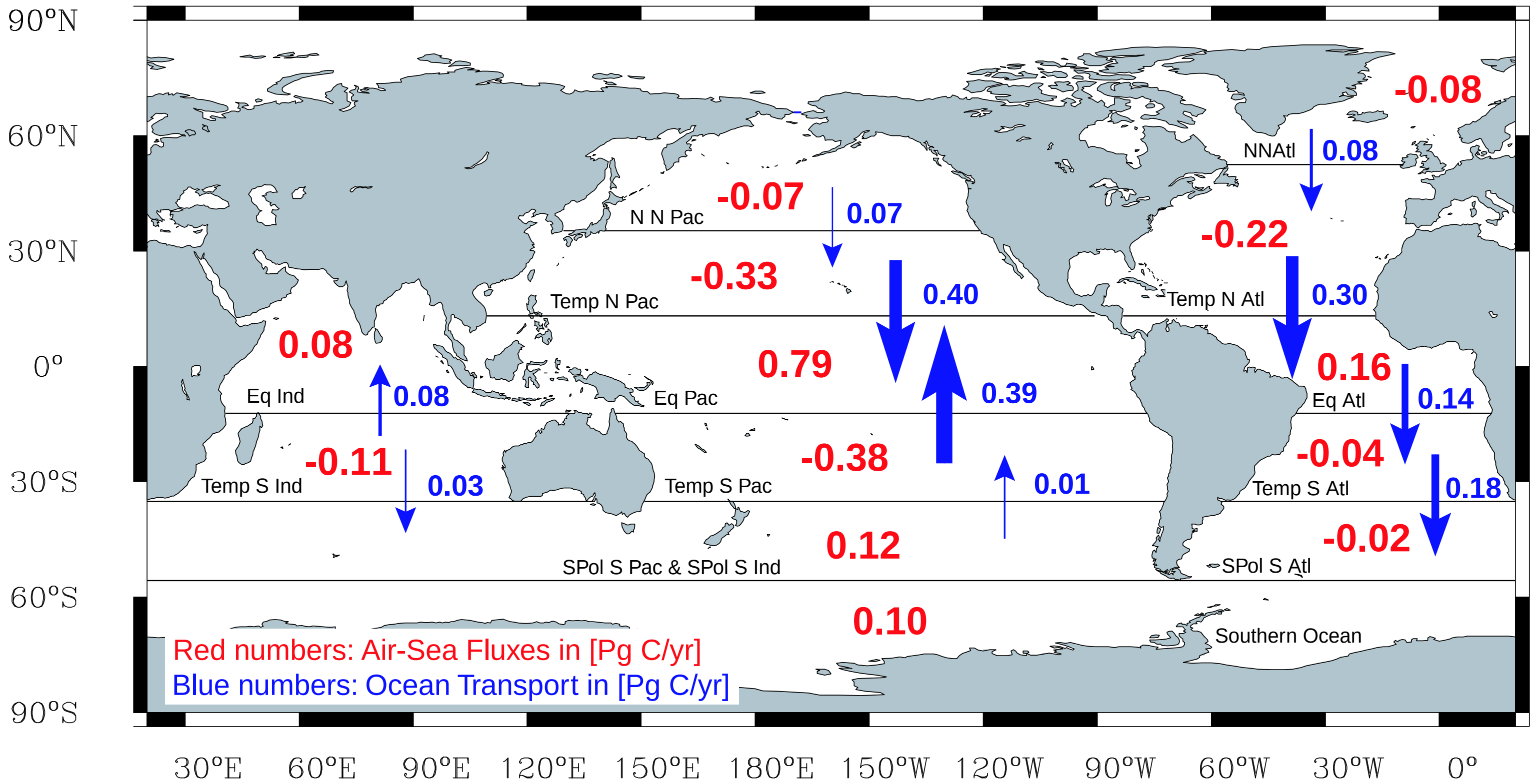
Anthropogenic CO_2 Flux: 1.8 PgC yr^{-1}

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



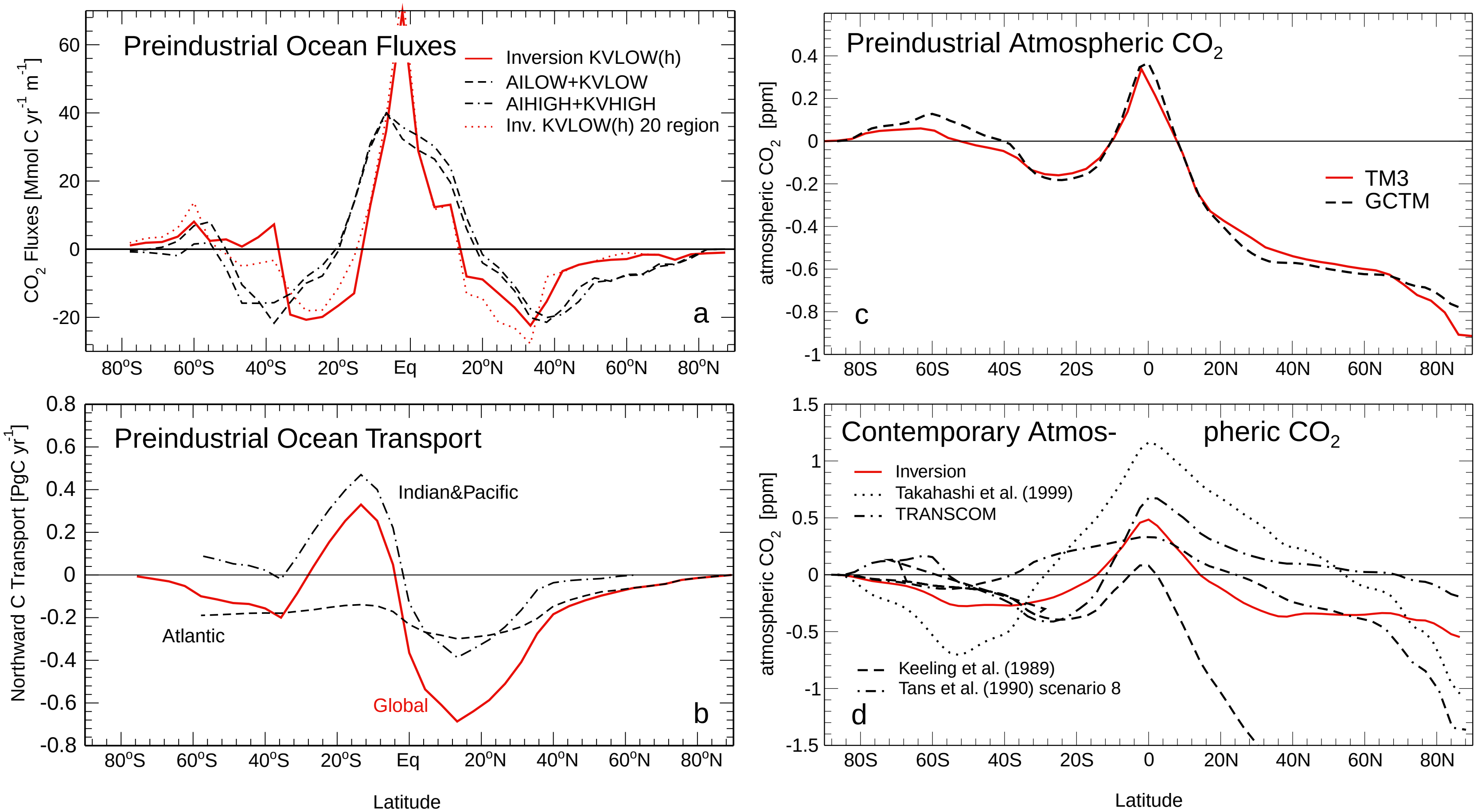
Gloor et al. (submitted)
Gruber et al. (in prep.)

PRE-INDUSTRIAL AIR-SEA FLUXES AND TRANSPORT

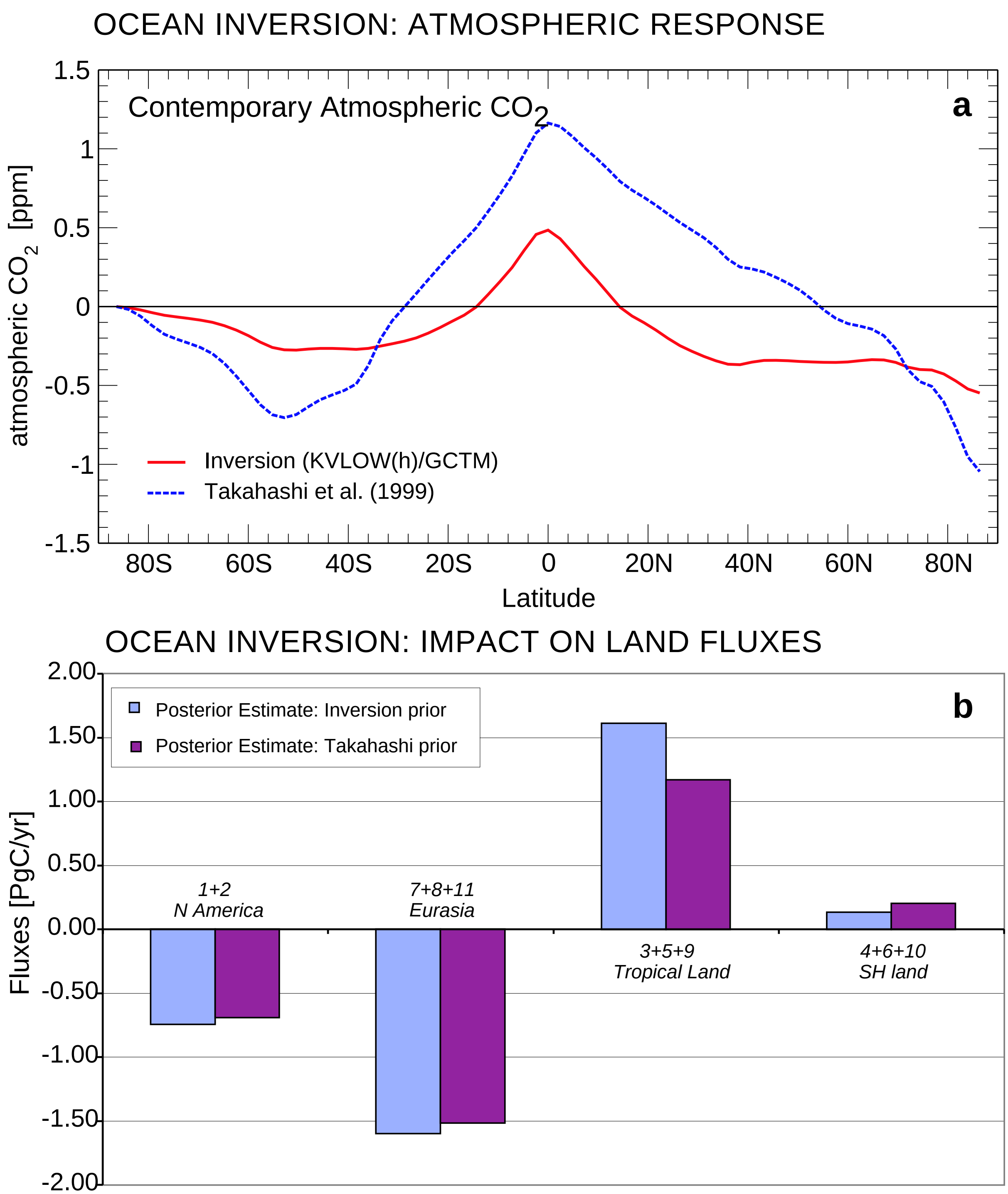


Transport across Equator: 0.4 PgC yr^{-1}
Transport vanishes at about 3°S

OCEAN INVERSION

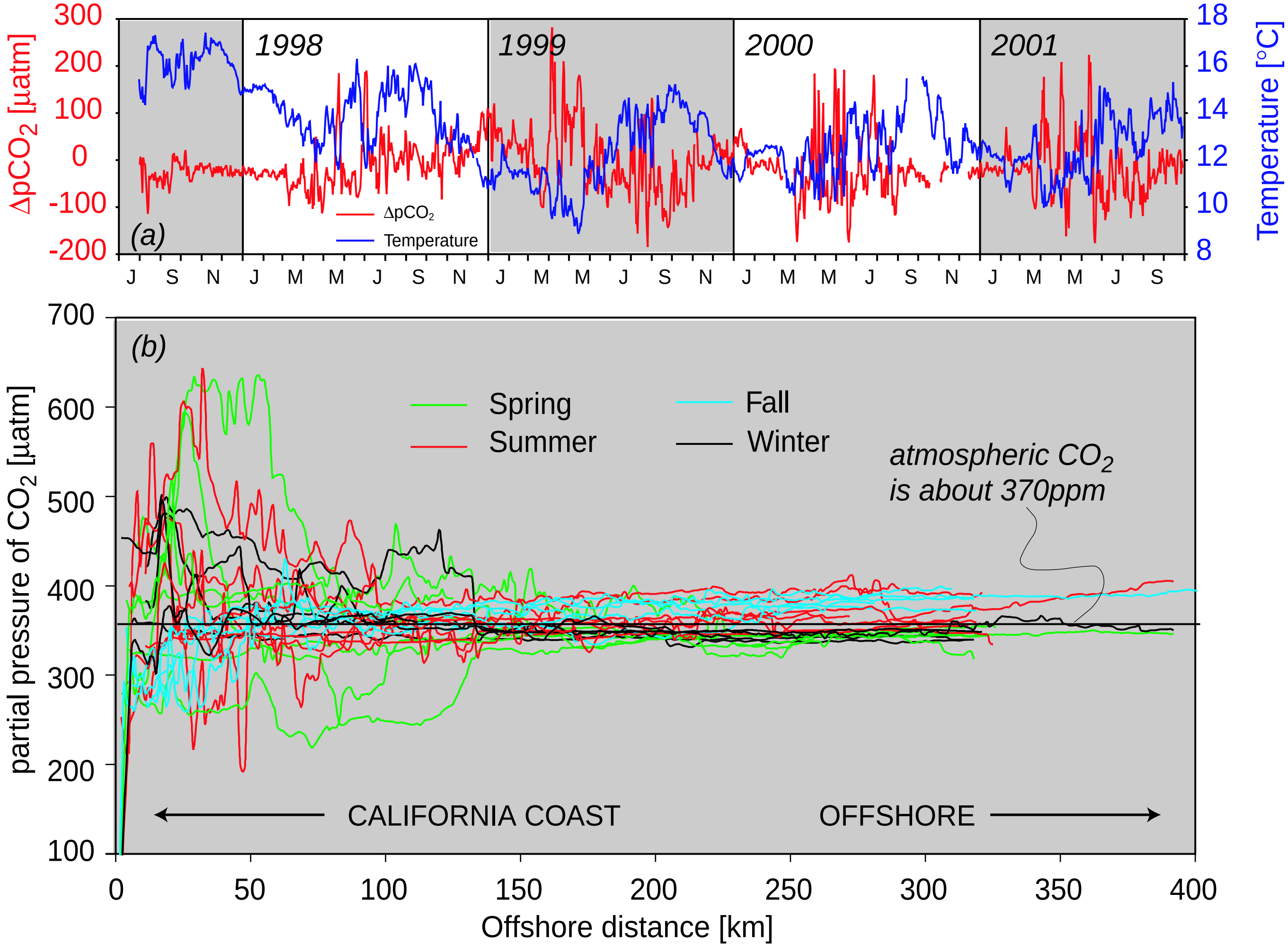


Gloor et al. (submitted)
Gruber et al. (in prep.)



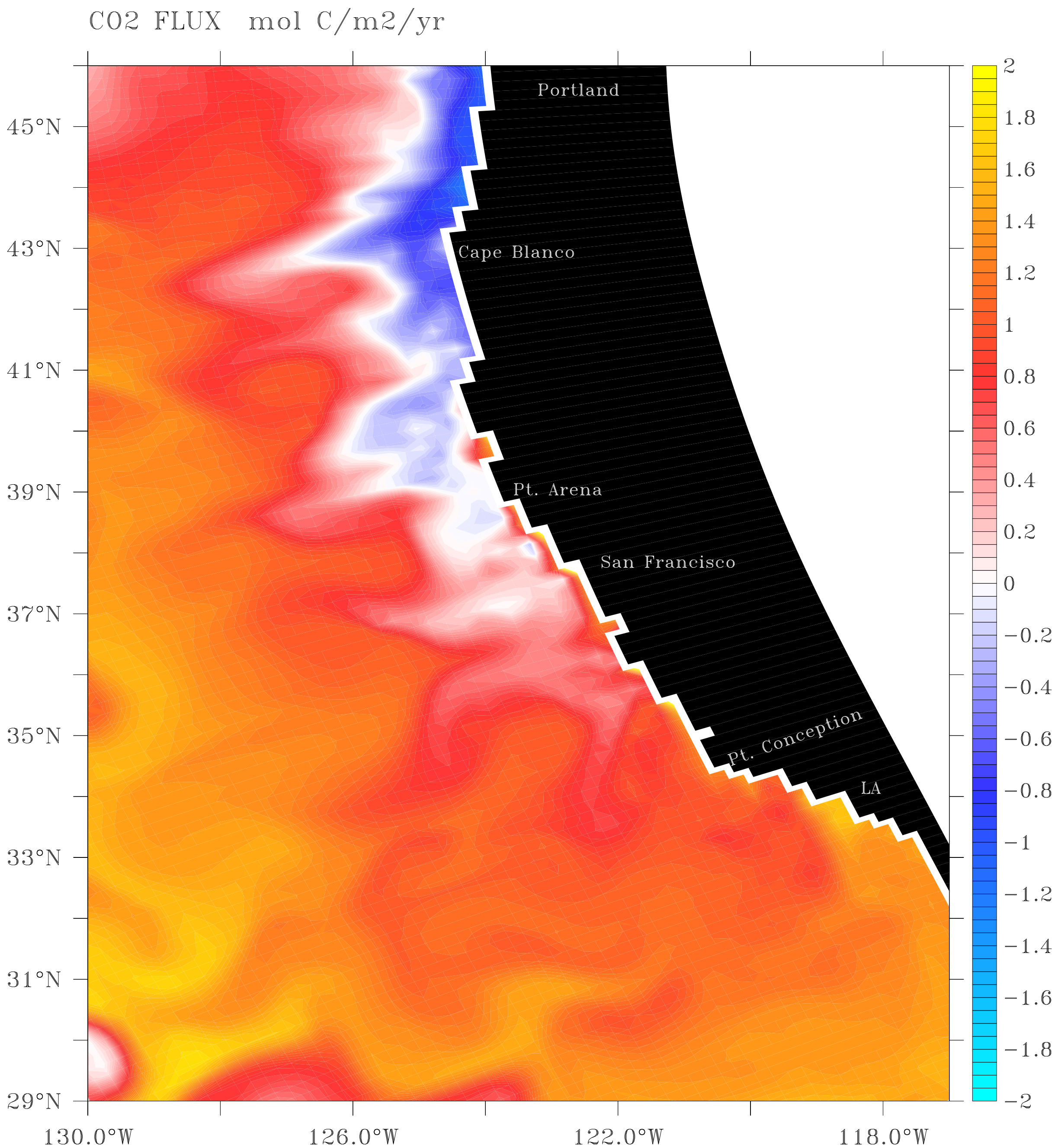
Gruber et al. (in prep.)

pCO$_2$ VARIABILITY NEAR MONTEREY BAY



Friederich et al. (in press)
Chavez et al. (in prep.)

Regional Ocean Modeling System (ROMS)



Gruber et al. (in prep.)

Summary and Outlook

- Forward and inversely based estimates of the pre-industrial and anthropogenic CO_2 fluxes show overall very similar patterns and magnitudes, which are generally similar to observationally based estimates.

- However, this agreement breaks down in the Southern Hemisphere. In particular, the inversely based estimates indicate a substantially smaller CO_2 uptake in the subpolar regions than indicated by ΔpCO_2 based estimates. Atmospheric inversions tend to come to similar conclusions.

- OCMIP forward models and our inverse models find a southward CO_2 transport of the order of 0.4 Pg C yr^{-1} across the equator. This is considerably smaller than has been proposed by *Keeling et al.* [1989], and *Broecker and Peng* [1992]. We nevertheless find an interhemispheric gradient in atmospheric CO_2, but primarily driven by the within hemisphere asymmetry in the fluxes.

- We find that our inversely estimated CO_2 fluxes, when used as priors in an atmospheric CO_2 inversion instead of those by *Takahashi et al.* [1999], lead to a relatively small change in the northern hemisphere terrestrial fluxes, but large changes in the tropical and southern hemisphere land regions.

- Regional ocean modeling advances have made it possible to address also the highly variable CO_2 flux dynamics of the coastal ocean, which might be important for regional atmospheric CO_2 inversions.
- There is large potential in further exploring how inverse techniques can be used to fuse at the same time oceanic and atmospheric data with models.