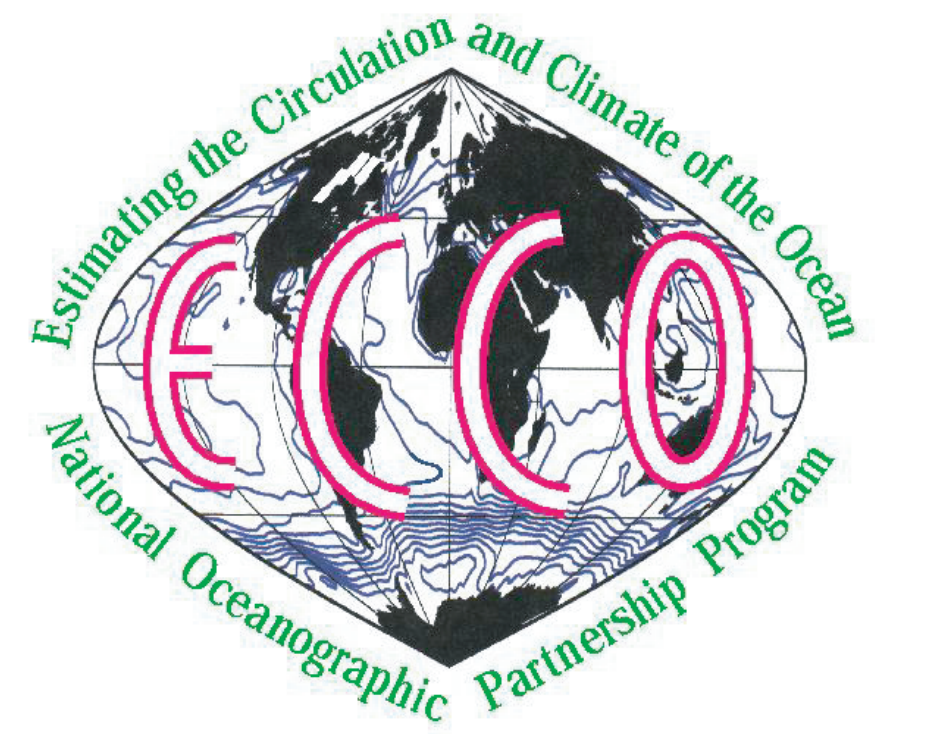




Interannual Variability in Air-Sea Fluxes of O₂ and CO₂

Galen A. McKinley, Michael J. Follows, and John Marshall
 Massachusetts Institute of Technology
 Cambridge, MA 02139 USA



Motivation:

Observed year-to-year changes in the growth rate of atmospheric CO₂ indicate large interannual variability of the global carbon sinks in terrestrial biota and the ocean. However, sink partitioning and driving mechanisms for both sinks remain elusive. The use of atmospheric O₂/N₂ to infer CO₂ sinks¹ has made air-sea O₂ flux variability also important to quantify.

Previously, estimates of interannual variability (IAV) of the ocean CO₂ sink from ocean models have been smaller than estimates from atmospheric data inversions.² However, recent atmospheric results show smaller ocean IAV.³

We use an ocean GCM to study air-sea O₂ and CO₂ fluxes. Variability is quantified and driving mechanisms are evaluated. The model estimate of O₂ air-sea flux IAV is applied as a constraint on the O₂/N₂ method to estimate the previously unquantified error associated with this variability. Finally, we illustrate an increasing agreement in CO₂ sink estimates between ocean models and atmospheric data inversions.

MITgcm Offline Biogeochemical Model:

Physical:⁴

- longitude 1°, latitude 0.3°-1°, 47 vertical levels
- KPP upper ocean mixing and GM eddy parameterizations
- 12 hr meteorological forcing
- 10 day average output for 1980-1998

Biogeochemical:

- Tracers: P, O₂, CO₂
- Upper ocean only, 32 levels to 1265m with restoring below
- Spatially varying export, modified by light and nutrients: $\frac{dP}{dt} = \square \square \frac{I}{I+I_0} \frac{P}{P+P_0}$
- Air-sea exchange following Wanninkhof, 1992

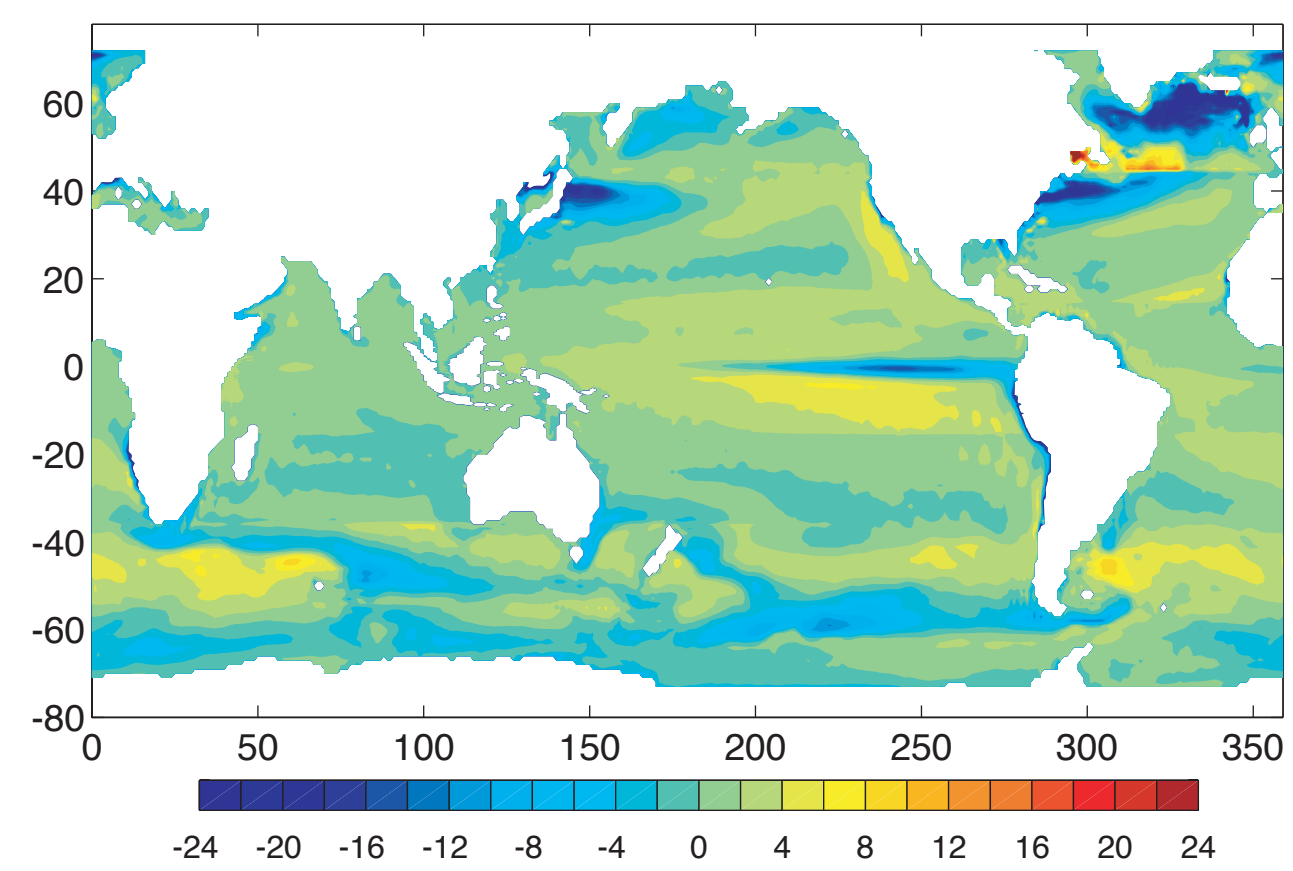


Figure 1: 19 yr mean fluxes of O₂ (top) and CO₂ (bottom) Positive to the atmosphere fluxes in mol/m²/yr. Change in the export parameter (□)(x,y) from the subtropical to subtropical Atlantic at 45°N cause the notable flux gradients in this region.

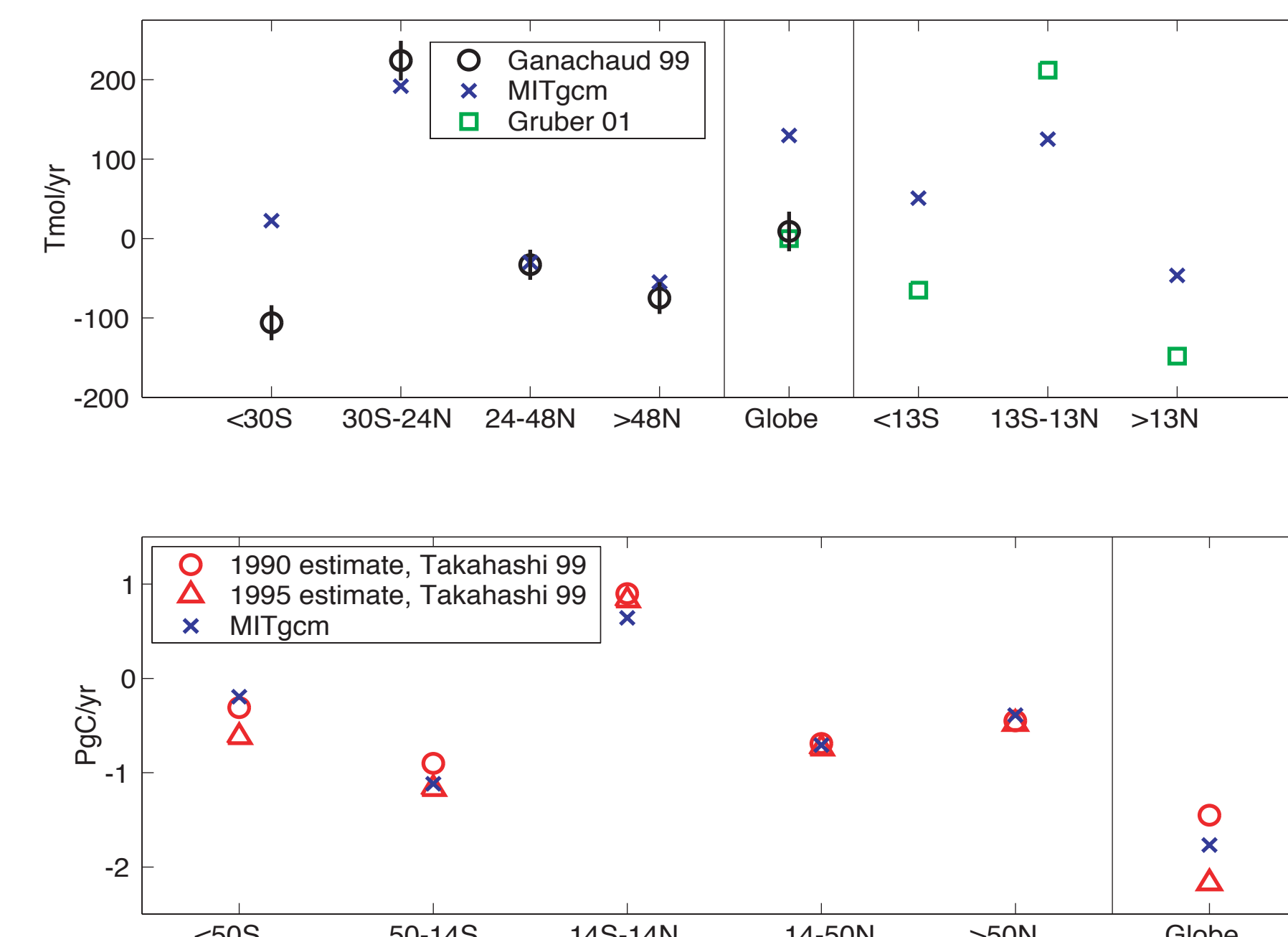


Figure 2: Zonally averaged mean fluxes of O₂ (top) and CO₂ (bottom) vs. data and model/data estimates.

Mean Fluxes

Figure 1: Mean CO₂ fluxes outgas in the tropics and ingas in the high latitudes. O₂ is expelled to the atmosphere across most of the globe, with limited areas of uptake primarily associated with deep mixing and equatorial upwelling. **Figure 2:** The model agrees well with data estimates for mean CO₂ and O₂ fluxes, except for O₂ in the Southern Ocean. The model exhibits smaller mean O₂ fluxes than the model/data inversion of Gruber et al.⁵

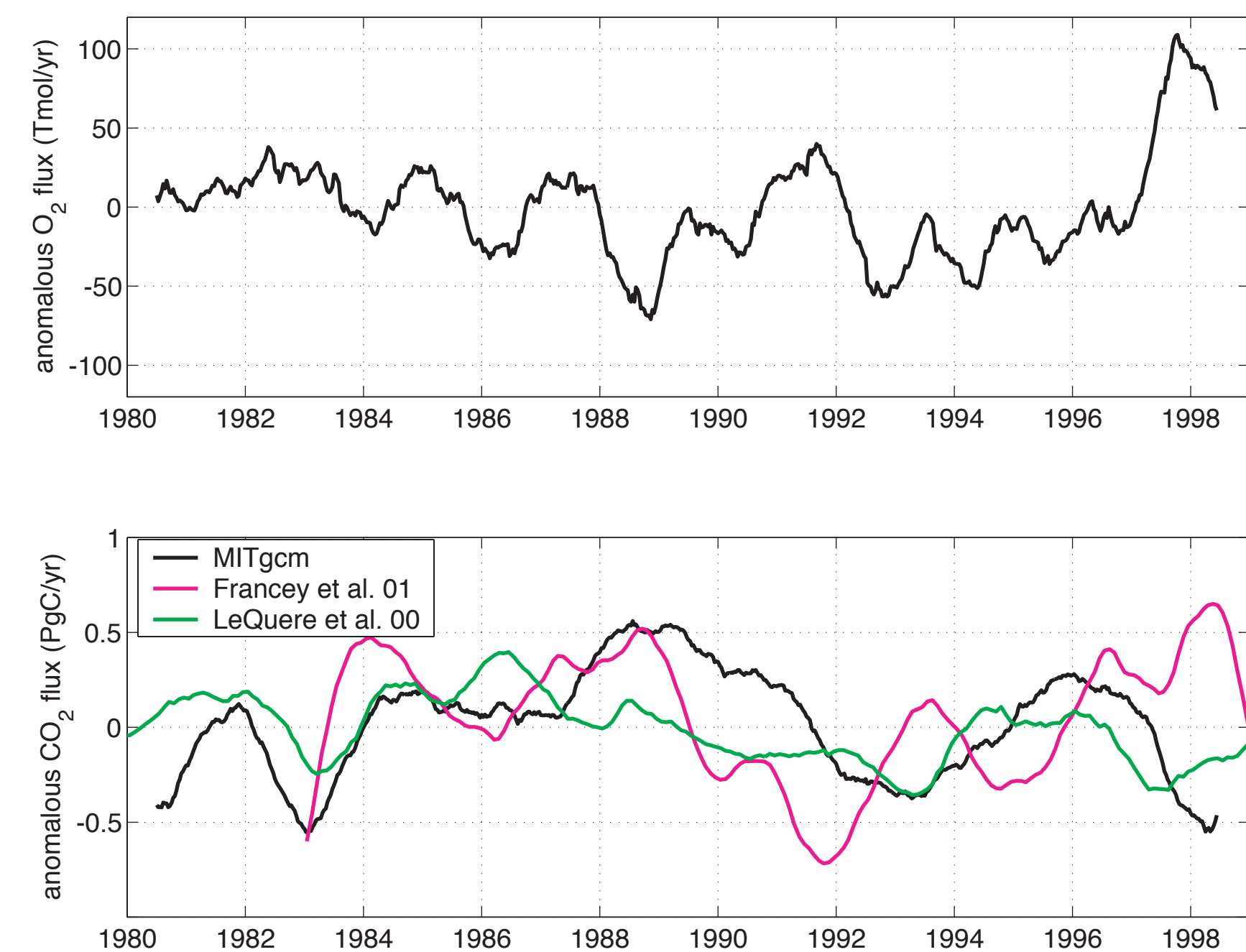


Figure 3: Interannual flux anomalies of O₂ (top) and CO₂ (bottom). All have been 12-month smoothed.

Global Interannual Variability

Figure 3: Interannual anomalies of O₂ fluxes have a maximum amplitude of ± 100 Tmol/yr (rms = 35 Tmol/yr) and CO₂ of ±0.5 PgC/yr (rms = 0.28 PgC/yr). While this estimate of CO₂ flux IAV agrees qualitatively with the ocean modeling result of LeQuéré et al.², it is notably larger in magnitude, and approaches the magnitude of the atmospheric $\delta^{13}C$ data inversion of Francey et al.³. We believe this is due to greater physical variability of this high-resolution, fully prognostic model. Nevertheless, comparison of model SSH to TOPEX altimetric data indicates that the model captures only up to 40% of upper ocean variability at the large scale. Thus, flux variability estimates are likely to be lower bounds.

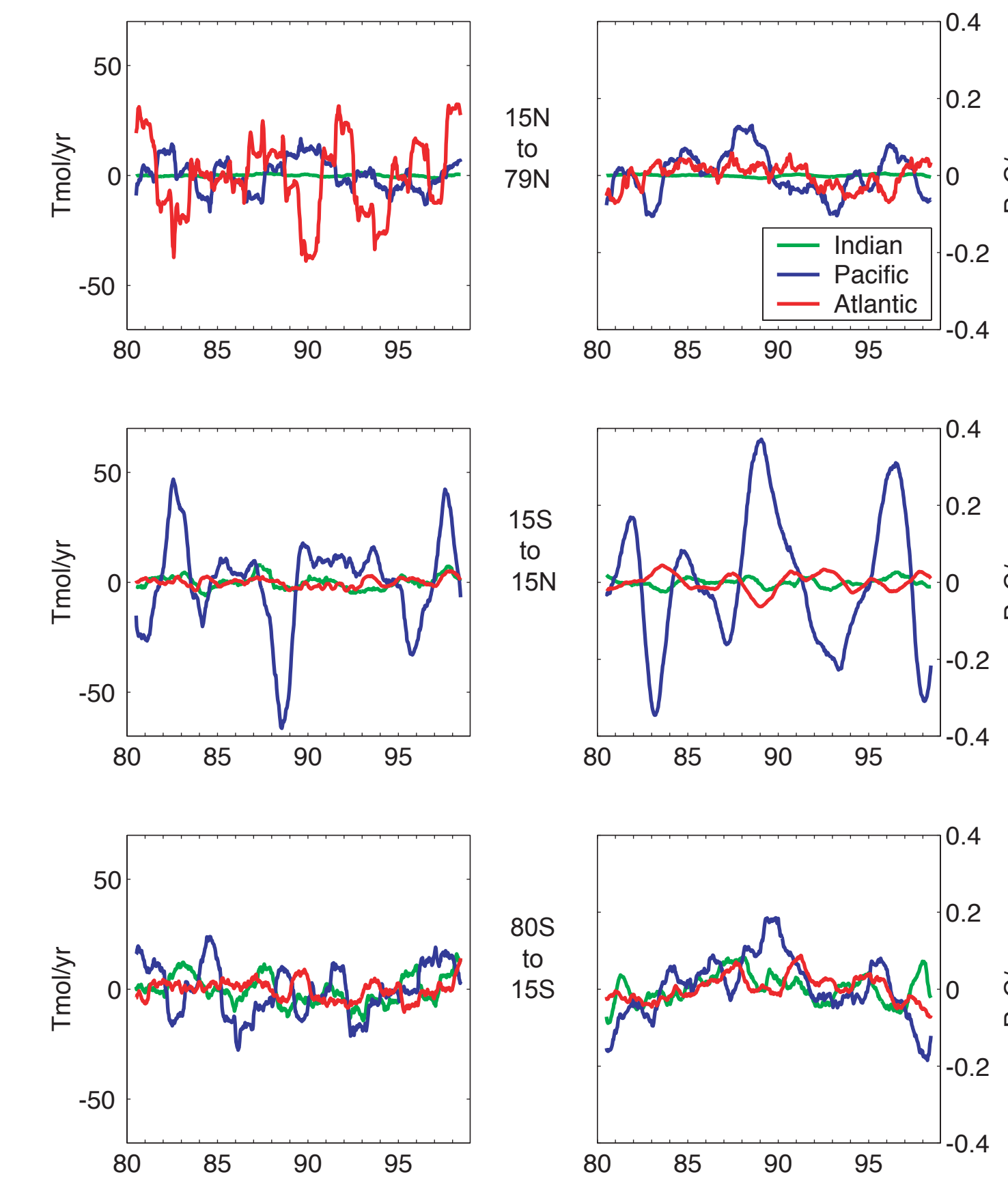


Figure 4: Regional fluxes of O₂ (left) and CO₂ (right).

Regional Flux Variability

Figure 4: A regional breakdown of the anomalous O₂ and CO₂ fluxes illustrates that the global flux variability of both gases is strongly influenced by flux variability in the equatorial Pacific. For O₂ only, the North Atlantic is also particularly important to the global flux IAV.

Figure 5: Flux EOFs in these regions indicate that physical changes associated with ENSO and NAO drive flux IAV. EOF1 for CO₂ (O₂) in the Equatorial Pacific explains 50% (73%) of the interannual variance, and the normalized principle component correlates with the SOI index at r=0.84 (r=0.80) when the flux lags by 1-2 months (leads by 2-3 months). In the North Atlantic, EOF1 explains 28% of the O₂ variance and the PC1 correlates with the NAO index at r=0.73 with no lag. Changes in thermocline slope and upwelling with ENSO and convective variability with NAO drive flux IAV. The faster gas equilibration timescale for O₂ allows it to respond to the rapid physical changes of the N. Atlantic, while the buffering of CO₂ by seawater inhibits the CO₂ response.

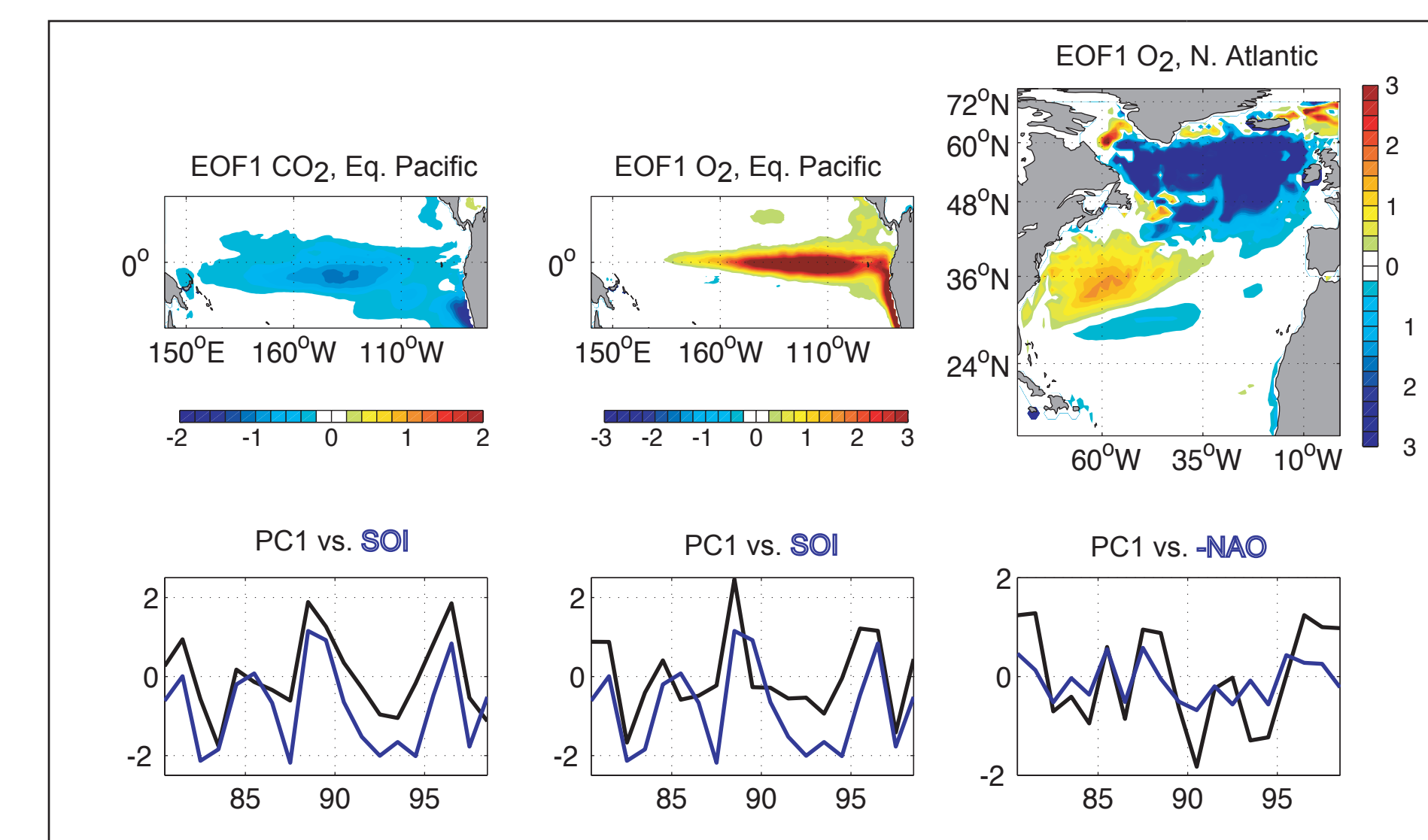


Figure 5: First Empirical Orthogonal Functions (top) and normalized principle components (PC1) compared to climate indices (bottom). In the Equatorial Pacific: CO₂ (far left) and O₂ (middle). O₂ in the North Atlantic (far right). Flux EOFs in mol/m²/yr.

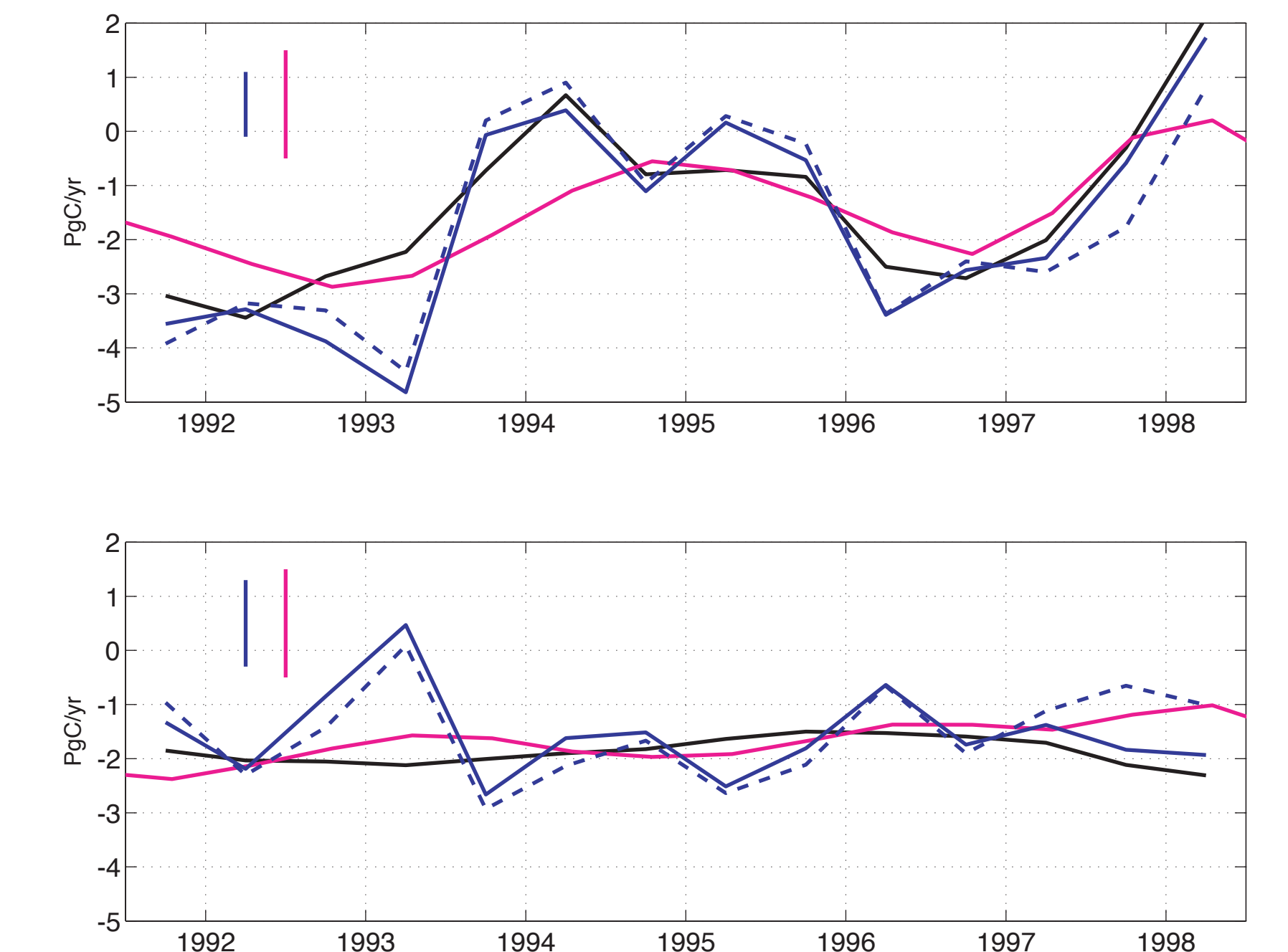


Figure 6: Land (top) and ocean (bottom) CO₂ sinks for 1992 - 1998. MITgcm (black), Francey et al. (pink), O₂/N₂ method without (dashed blue), and with (solid blue) O₂ flux IAV.⁶

Land and Ocean Sinks

Figure 6: Land and ocean CO₂ sink estimates are compared. We find: (1) ocean modeling and atmospheric $\delta^{13}C$ data inversion studies³ are converging toward an ocean sink variability of ±0.5 to 1 PgC/yr and a larger land sink variability of ±1.5 to 2 PgC/yr; and (2) O₂ air-sea flux IAV imparts an error to the O₂/N₂ method of up to ±1 PgC/yr on interannual timescales. However, O₂ IAV imparts an insignificant error (±0.02 PgC/yr) when the calculation is performed based on atmospheric changes integrated over the entire 1991.75-1998.25 period.

Conclusions:

- IAV in air-sea CO₂ flux = ± 0.5 PgC/yr
- IAV in air-sea O₂ flux = ±100 Tmol/yr
- ENSO is the primary driver of CO₂ flux variability.
- ENSO and NAO drive O₂ flux variability.
- O₂ IAV imparts significant error to the O₂/N₂ method only on short (2-3 year) timescales.
- We find increasing convergence in land and ocean sink estimates from independent methods.

References and Acknowledgements

- (1) Keeling et al. 1996. *Nature* 381 p.218.
- (2) Bender et al. 1996. *Global Biogeochem. Cycles*, 10 p.9.
- (3) Manning, 2001. PhD Thesis, UCSD.
- (4) LeQuéré et al. 2000. *Global Biogeochem. Cycles*, 14, p.1247.
- (5) Francey et al. 2001. *Extended Abstracts, 6th Int. CO2 Conference*.
- (6) Lee et al. *J. Phys. Oceanogr.* in press
- (7) Ganachaud, 1999. ScD Thesis, MIT/WHOI Joint Program.
- (8) Gruber et al. 2001. *Global Biogeochem. Cycles*, 15, p. 783.
- (9) Takahashi et al. 1999. *Proc. of the 2nd Int. Symposium on CO2 in the Oceans*.
- (10) Calculations performed following Manning '01. We use CO₂ and O₂/N₂ data from Alert, La Jolla and Cape Grim (A. Manning, pers. comm.), and fossil fuel data from Marland et al. '01. This calculation is sensitive up to 1 PgC/yr to the CO₂ data choice.
- (11) We thank I. Fukimori, D. Menemenlis, and T. Lee at JPL for physical model results. We thank C. Hill, A. Adcroft, and S. Dutkiewicz for model development and assistance.
- (12) For more information, please contact GAM, galen@mit.edu.