

Mechanisms of CO₂ Air-Sea Flux Variability in the North Atlantic and Equatorial Pacific

Galen A. McKinley*, Michael J. Follows, and John Marshall

Massachusetts Institute of Technology, Cambridge, MA 02139, USA

*Instituto Nacional de Ecología, Mexico City, 04530, Mexico galen@alum.mit.edu

I. Abstract

A global ocean general circulation model is used to estimate the magnitude and understand the mechanisms of interannual variability in air-sea fluxes of CO₂. The global variability in the flux ($\pm 0.5 \times 10^{15}$ PgC/yr for 1980-1998) is dominantly forced by the ENSO cycle. The model indicates that air-sea CO₂ flux variability in the North Atlantic is comparatively small, and without significant association to the NAO. Flux variability estimates agree with mean atmospheric inversion results of Bousquet et al. (2000) only in the Equatorial Pacific. The model indicates significant spatial coherence of the flux variability in the Equatorial Pacific that is consistent with a priori estimates of the geographical flux pattern used in the atmospheric inversion. However, results indicate that the inversion may over-represent CO₂ flux variability in the North Atlantic through its a priori assumption of large-scale spatial coherence of the flux variability.

II. Model, Data Comparisons

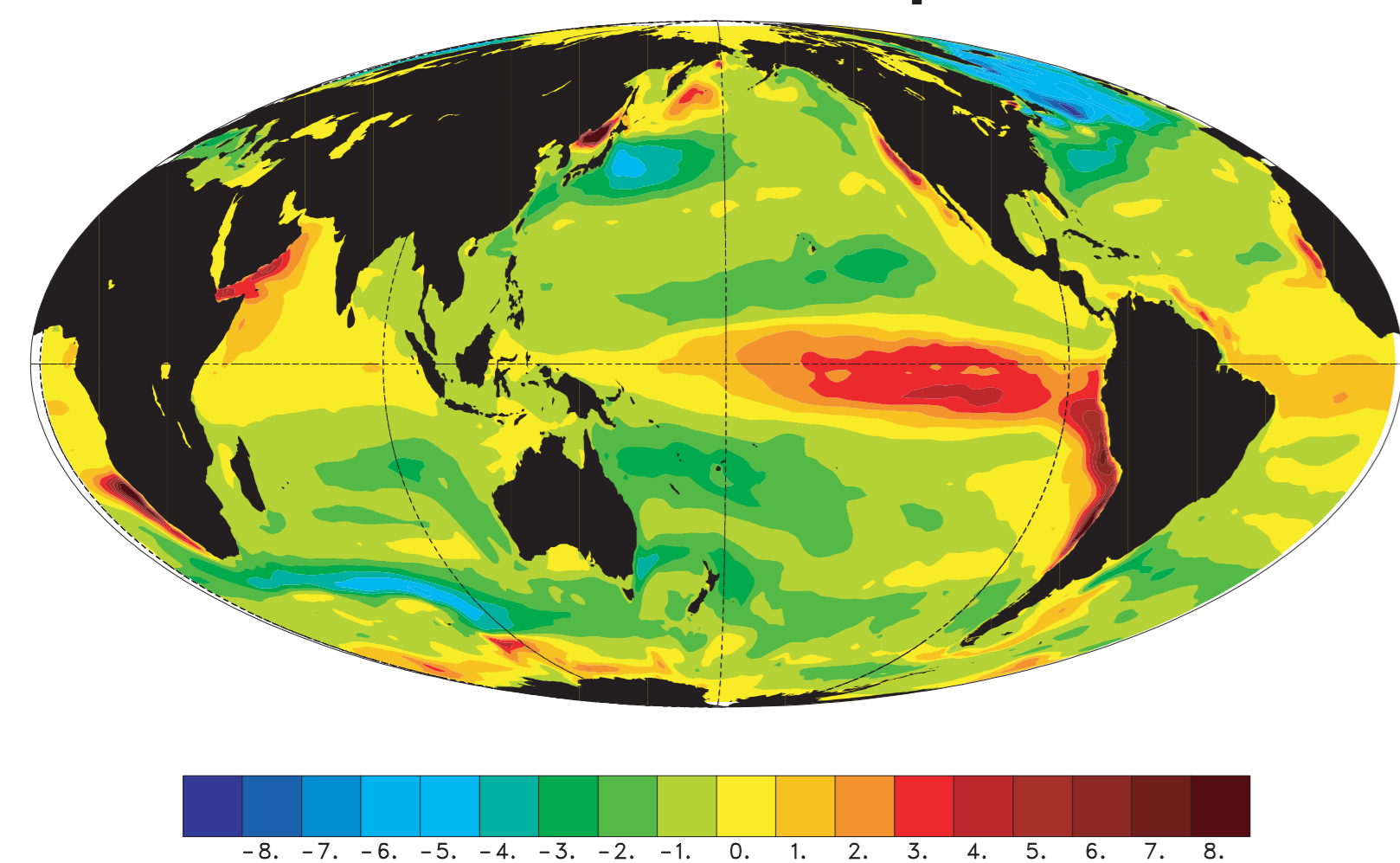


Figure 1: Model mean air-sea CO₂ flux (mol/m²/yr)

MITgcm Offline Biogeochemical Model:

Physical (Lee et al. 2002):

- 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
- Air-sea exchange following Wanninkhof, 1992

Figure 1 illustrates the mean air-sea CO₂ flux of the model. Zonal means agree well with results of Takahashi et al. (2002). **Figure 2** shows that the model captures much of the flux variability estimated from observations at BATS and HOT.

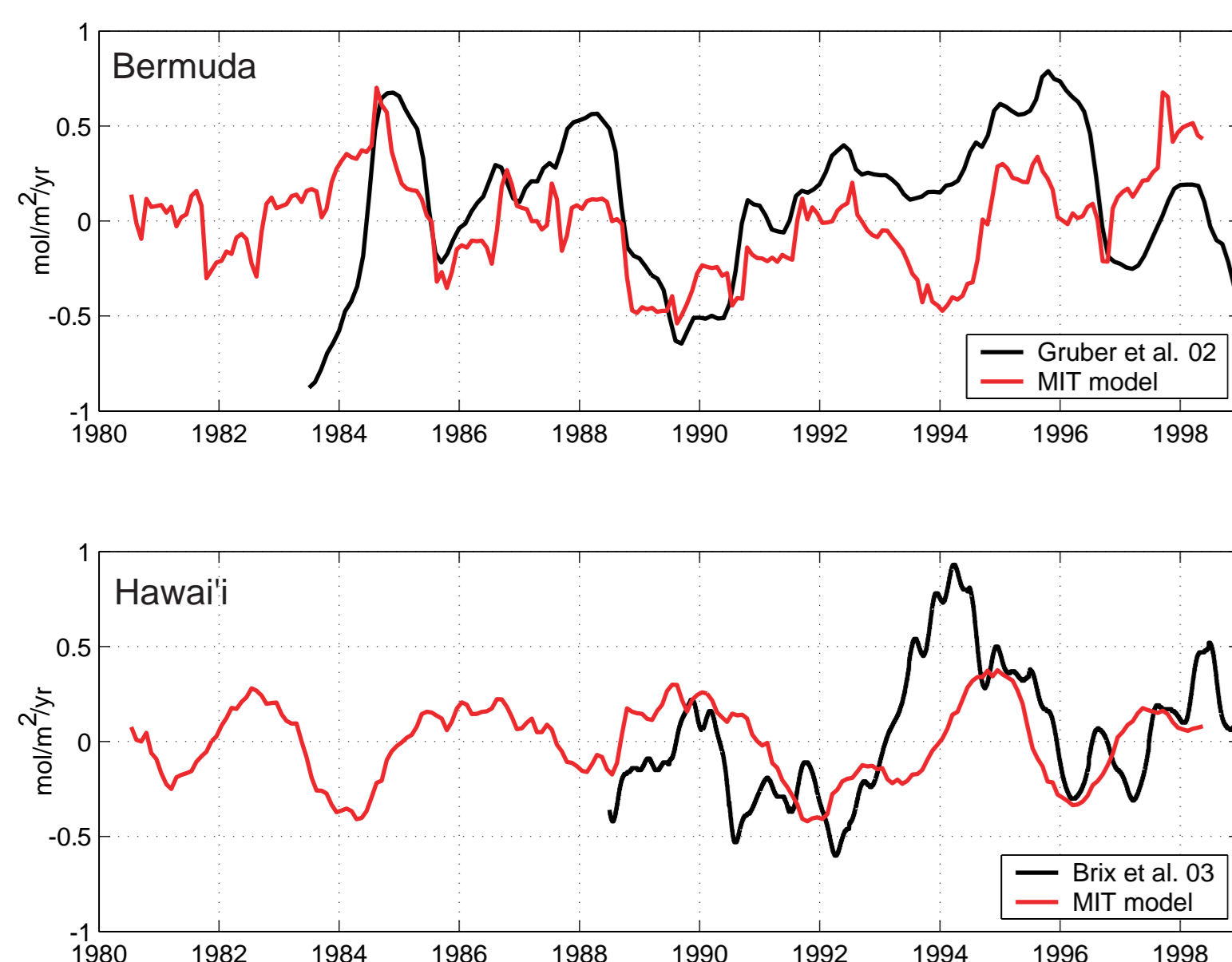


Figure 2: Comparisons to timeseries fluxes

III. Mechanisms

The Equatorial Pacific dominates the global CO₂ flux variability (**Figure 3**).

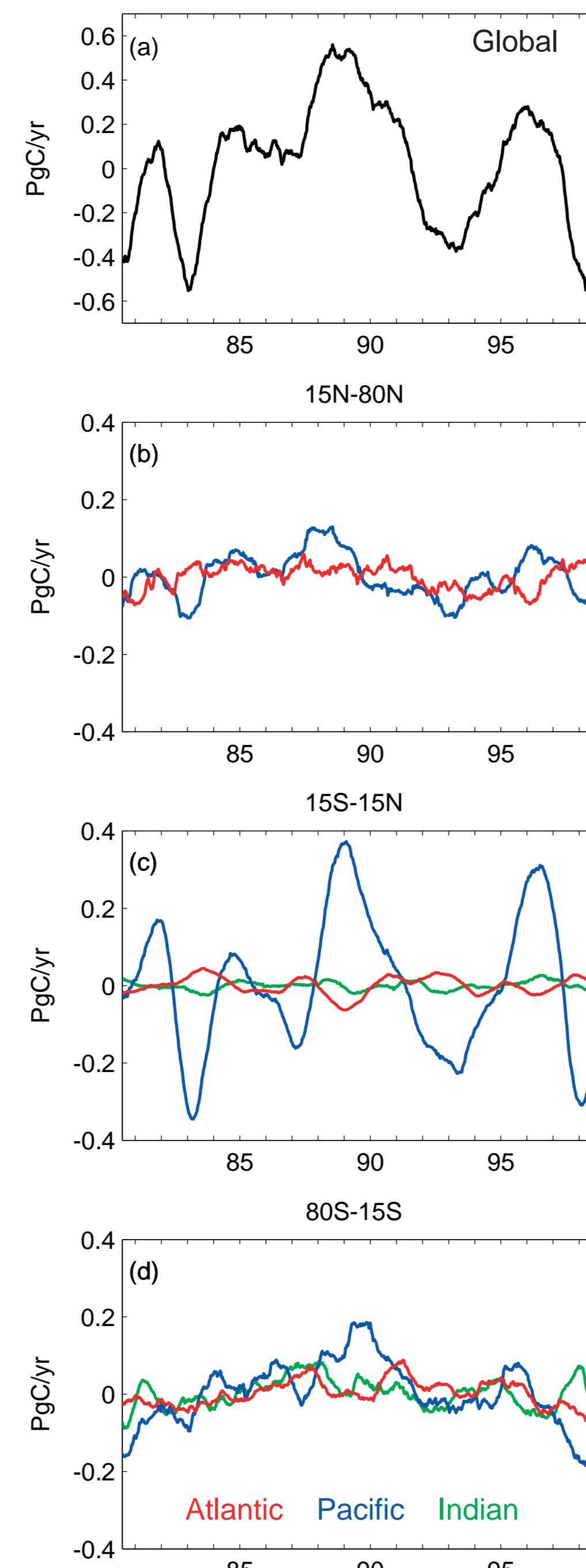


Figure 3: Anomalies: (a) globe, (b-d) regions.

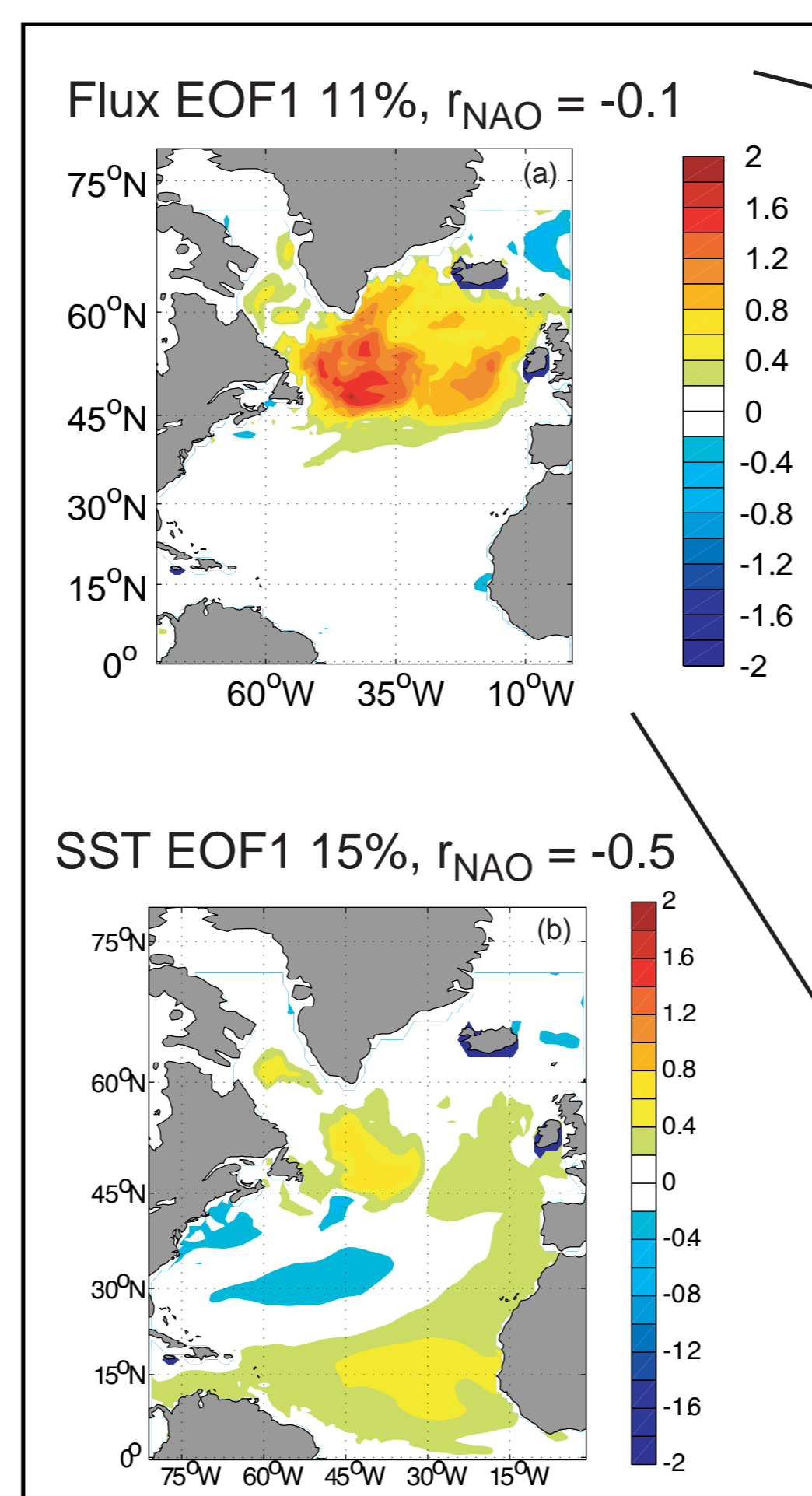


Figure 4: EOF1: (a) flux (mol/m²/yr) and (b) SST (°C)

North Atlantic Mechanisms

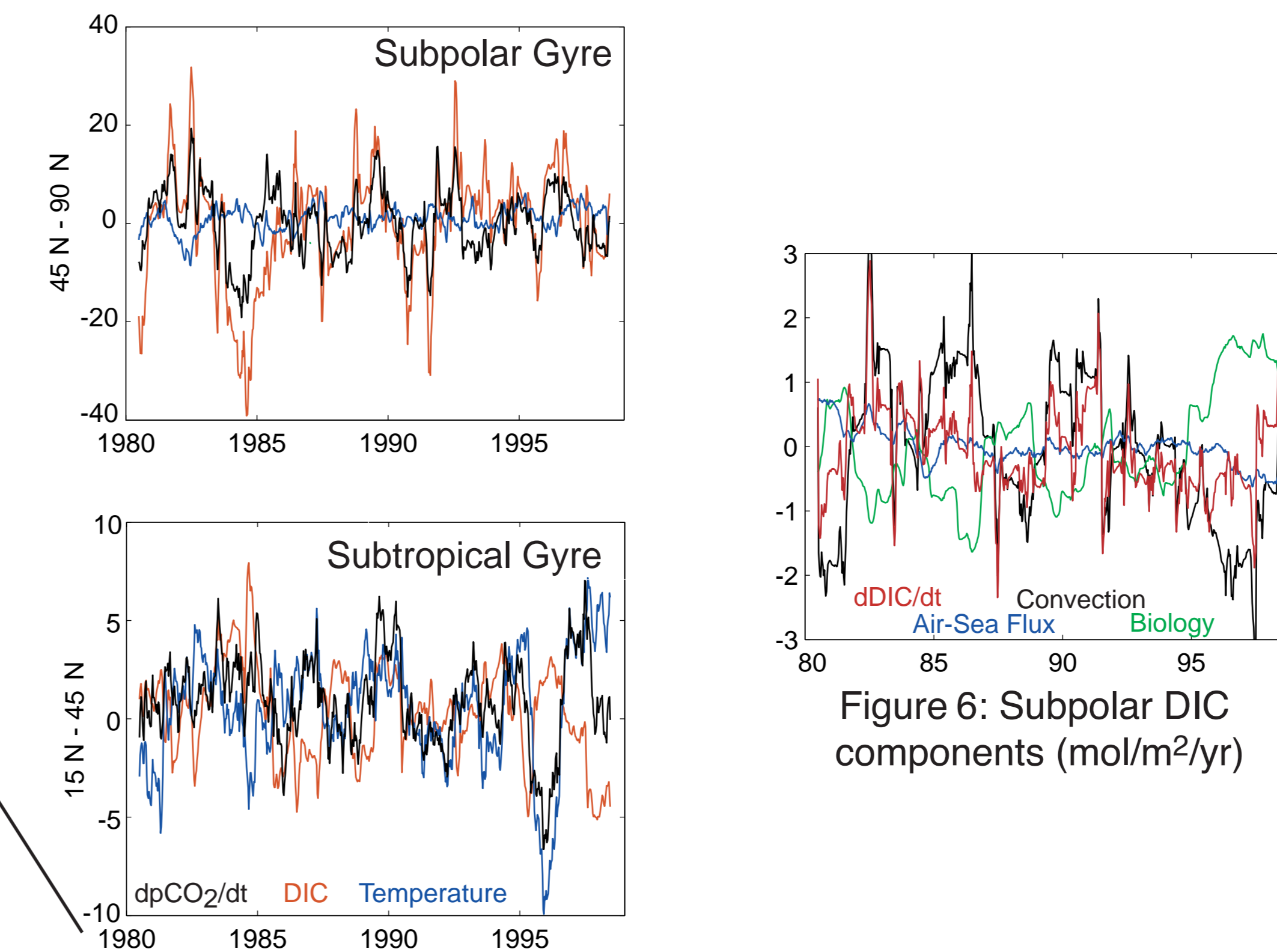


Figure 5: pCO₂ components (uatm/yr) (alkalinity and salinity impacts small and not shown)

In **Figure 3**, we show that the CO₂ flux variability is small in the North Atlantic. Further, EOF1 for the air-sea CO₂ flux in the North Atlantic explains 11% of the variance (**Figure 4a**). It has been postulated that the NAO has a major influence on basin-scale air-sea CO₂ flux in the North Atlantic (Gruber et al., 2002). In this model, the corresponding principle component for EOF1 is uncorrelated with the NAO, despite the fact that EOF1 of SST correlates at $r = -0.5$ (**Figure 4b**).

To understand what causes a decoupling of air-sea CO₂ flux variability from the major driver of physical variability in ocean surface pCO₂ (**Figure 5**). In the subpolar gyre, the total pCO₂ is driven by the DIC term ($r = 0.78$), with temperature damping the variability. In the subtropical Atlantic, temperature determines pCO₂ variability ($r = 0.69$), consistent with findings of Gruber et al. (2002).

In the subpolar gyre, surface DIC variability is primarily controlled by convection (**Figure 6**). Export production counters the convective DIC supply with shifts in carbon export. The slow air-sea exchange timescale for CO₂ allows this biological export substantial time to address the DIC excess delivered by convection, and thus the net impact on the air-sea flux of the convective DIC changes is small.

Equatorial Pacific Mechanisms

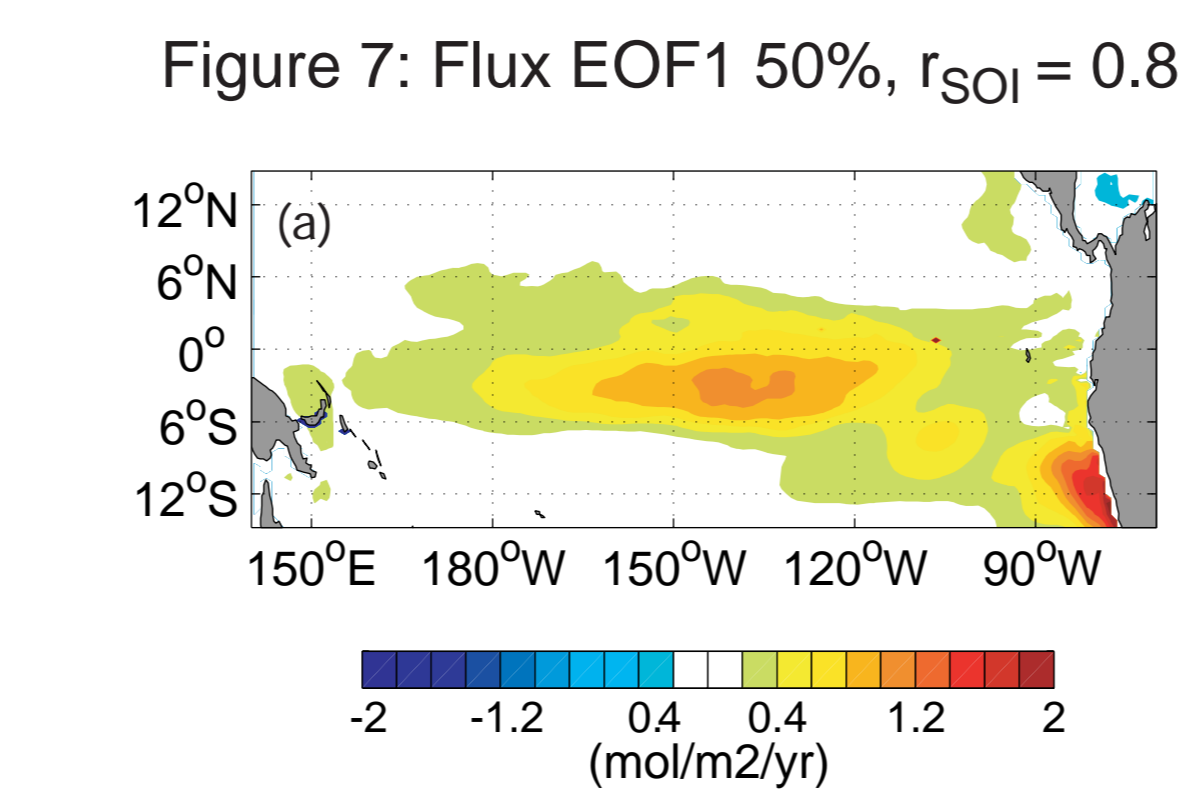


Figure 7: Flux EOF1 50%, $r_{SOI} = 0.8$

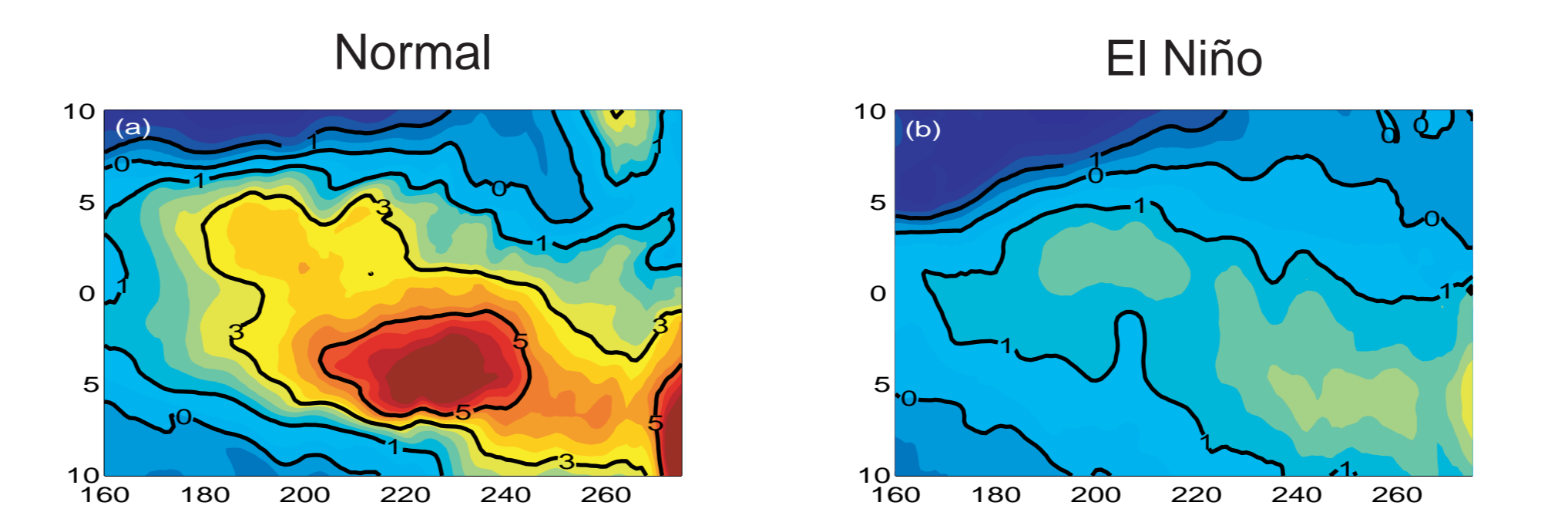


Figure 8: Flux (mol/m²/yr) in (a) Dec '95-Jun '96 and in (b) Nov '97-May '98

The first EOF for the air-sea flux of CO₂ in the Equatorial Pacific explains 50% of the variance (**Figure 7**). The corresponding first principle component has high correlation with the SOI ($r = 0.8$).

ENSO impacts air-sea fluxes of CO₂ primarily by altering DIC supply to the surface, through changes in both the upwelling strength and the depth of high DIC waters below the thermocline. Similar to the observational results of Chavez et al. (1999), **Figure 8** illustrates the dramatic changes in CO₂ fluxes during the El Niño of 1997-1998 and a non-El Niño period in 1995-1996.

IV. Implications for Inversions

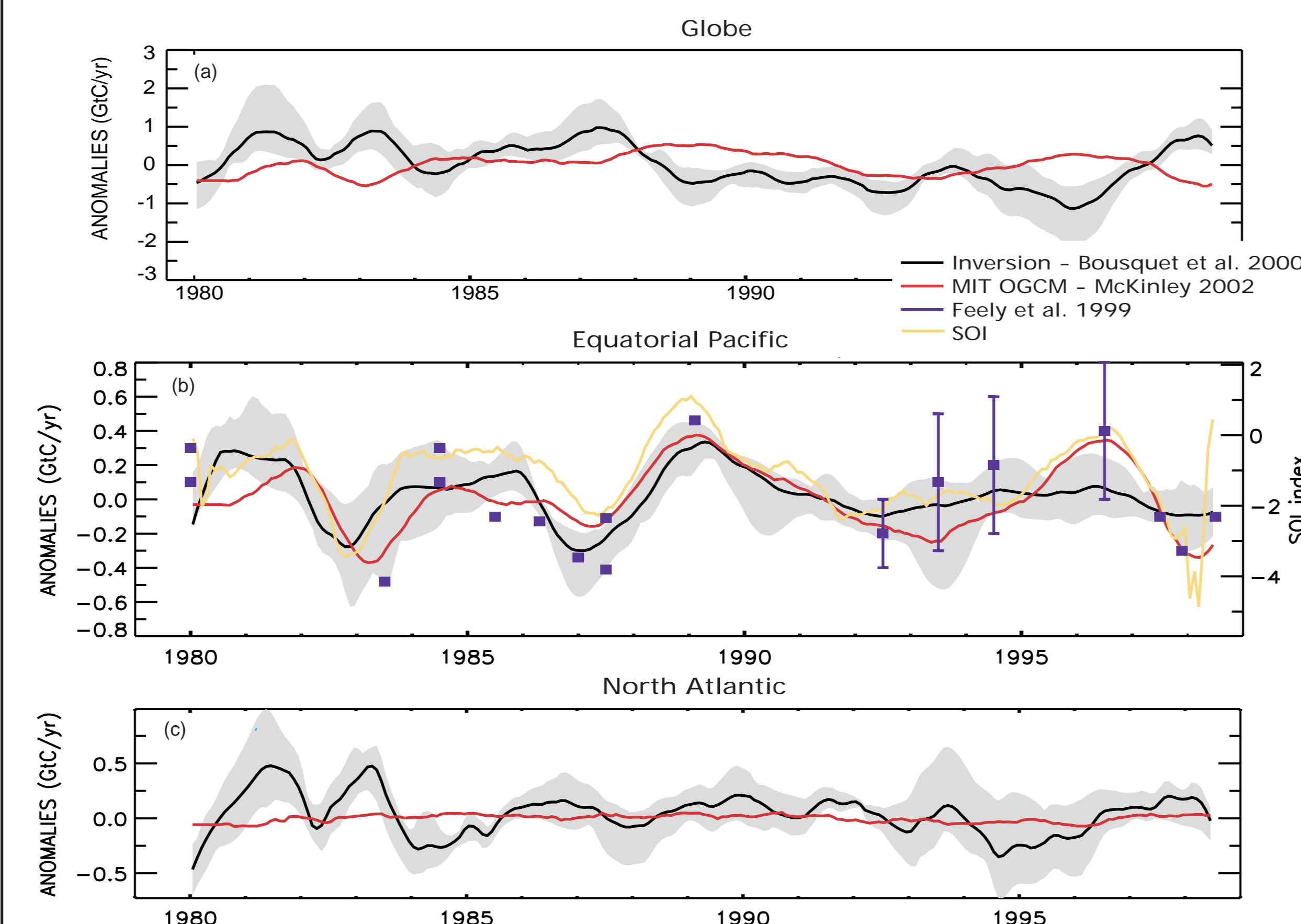


Figure 9: Model compared to inversion of Bousquet et al. 2000

The model's global timeseries is compared to the inversion of Bousquet et al. (2000) in **Figure 9(a)**. Though the magnitude of the flux variability is similar in the two methods, there is essentially no relationship of the temporal structure. Yet, in Equatorial Pacific region the results of the two methods agree very well with each other and with observations. However, in the North Atlantic the mean inversion shows much more variability than the model (**Figure 9(b,c)**). In the inversion, the temporal structure of the global timeseries is dominated by the high latitudes, while this model, consistent with previous modeling studies (LeQuere et al. 2000), indicates that the Equatorial Pacific is dominant.

Why is there such a difference between estimates in the North Atlantic, while at the same time agreement is extremely good in the Equatorial Pacific? We propose that the atmospheric inversions may be biased to overestimate high latitude air-sea flux variability by assuming that variability occurs as a modulation of fixed spatial patterns across large ocean regions. This model indicates that while this assumption may be appropriate for the Equatorial Pacific, it is not applicable to the North Atlantic region. That EOF1 in the North Atlantic captures only 11% of the variance indicates that variability does not occur with the kind of basin-scale coherence that is assumed.

V. Conclusions

For the period 1980-1998, this ocean model indicates that the global air-sea flux variability of CO₂ flux has extremes of ± 0.5 PgC/yr (RMS = 0.28 PgC/yr). Physical variability in the equatorial Pacific associated with ENSO is the primary driver of global air-sea flux variability of CO₂. In the North Atlantic, air-sea CO₂ flux variability is small because biogenic export counters flux tendencies created by convective variability before significant CO₂ air-sea exchange can occur.

Ocean model estimates of air-sea CO₂ flux variability compare well to the atmospheric inversion of Bousquet et al (2000) only in the Equatorial Pacific. Drawing on the model's illustration of large-scale spatial coherence of the flux variability in the Equatorial Pacific and a lack of coherence in the North Atlantic, we speculate that a priori assumptions about the geographic patterns of the flux variability may be responsible for biasing the atmospheric inversion toward overrepresentation of high-latitude air-sea CO₂ flux variability.

References

- Bousquet et al. 2000. *Science* 290. 1342-1346.
- Brix et al. 2003. *in preparation*.
- Chavez et al. 1999. *Science* 286.2126-2130.
- Gruber, Keeling, and Bates. 2002. *Science* 298. 2374-2378.
- Lee et al. 2002. *J. Phys. Ocean.* 32(5). 1404-1429.
- LeQuere et al. 2000. *Global Biogeo. Cycles*. 15. 1247-1265.
- McKinley, Follows and Marshall. 2003. *in preparation*.
- Takahashi et al. 2002. *DSR II*. 49. 1601-1622.
- Peylin et al. 2003. *in preparation*.
- Wanninkhof. 1992. *J. Geophys. Res.* 97 (C5). 7373-7382.

Acknowledgements

We thank I. Fukimori, D. Menemenlis, and T. Lee at JPL for physical model results; C. Hill, A. Adcroft, and S. Dutkiewicz for model development and assistance; P. Peylin, N. Gruber, and H. Brix for providing data and figures; and A. Fernandez and J. Martinez of INE for their support.