Interannual Variability of Equatorial Pacific CO_2 Fluxes Estimated from Temperature and Salinity Data

H. Loukos[1,2], F. Vivier[3], P. P. Murphy[4], D. E. Harrison[5] and C. Le Quéré[6]

Abstract

Based on atmospheric data and models, the tropical CO_2 source anomaly reaches up to 2 GtC yr^{-1}, but the respective contributions of the terrestrial biosphere and the oceans to this flux are difficult to quantify. Here we present a new method for estimating CO_2 fluxes from oceanic observations based on the surprisingly good predictive skill of temperature and salinity for surface dissolved inorganic carbon. Using historical temperature and salinity data, we reconstruct the basin scale CO_2 flux to the atmosphere in the equatorial Pacific from 1982 to 1993. We find that interannual anomalies do not exceed 0.4 $\pm$0.2 GtC yr^{-1} which suggests that up to 80% of the tropical CO_2 source anomaly is due to the terrestrial biosphere.

Introduction

The largest natural source of CO_2 to the atmosphere is the tropical ocean [*Takahashi et al.,* 1997]. Upwelling of subsurface waters rich in dissolved inorganic carbon (DIC) maintains a higher partial pressure of CO_2 (pCO_2) in the surface ocean than in the overlying atmosphere, which results in a CO_2 outgassing from the ocean. As the largest tropical ocean and the main scene of upwelling variability forced by El Niño–Southern Oscillation events (ENSO), the equatorial Pacific is a major contributor to the global interannual fluctuations of oceanic CO_2 evasion rates [*Lee et al.,* 1998; *Le Quéré et al.,* 1999].

The most direct approach to determine the mean regional value of pCO_2 and its interannual variability is from *in situ* measurements. In the equatorial Pacific, pCO_2 has been measured regularly on five longitudinal sections since 1992 [*Feely et al.,* 1999]. Despite increasingly better data coverage, basin scale estimates are still affected by the need of significant interpolation. An alternative approach is to infer pCO_2 from other water properties (mainly temperature) for which more data is available. *Lee et al.* [1998] use a SST-pCO_2 relationship for seasonal to interannual estimates in the equatorial Pacific. However, because of the coarse resolution of their method ($4°\times5°$), the spatial structure of pCO_2 within its high-gradient region is weakly captured, particularly at the edge of the warm waters of the western pacific (the Warm Pool). *Boutin et al.* [1999] propose to modulate the CO_2 flux by the zonal displacement of the Warm Pool, but this method is only valid between the equator and 5° South.

Here we propose to estimate pCO_2 from both SST and sea surface salinity (SSS) observations. In the equatorial Pacific, surface variability of nutrients and DIC is primarily controlled by the physical structure of the upper water column because biological activity closely follows the variability of dynamical processes that supply surface waters with the essential nutrients [*Archer et al.,* 1996; *Garside and Garside,* 1995]. Because SST and SSS variability reflect those physical changes, they can be used to estimate the surface concentrations of DIC, from which pCO_2 can be calculated. We show that a single SST-SSS-DIC relationship can be used in the equatorial Pacific for both ENSO and non-ENSO conditions. This allows us to estimate CO_2 evasion rates at the spatial and temporal coverage of the SST and SSS observations.

Method

We calculate a polynomial approximation of DIC by linear least square fitting to surface data (< 20m depth) from six surveys between 10°N–10°S and 170°W–96°W covering both ENSO and non-ENSO conditions of the early 1990's (WOCE sections P17C, P17S/P16S, P16C of 1991, EQPAC cruises of 1992, and WOCE section P18 of 1994). We limit our study to DIC measurements made using similar methods and calibrated against standard reference materials[1]. A fourth order polynomial is selected, since increasing order does not significantly decrease quadratic error.

$$\begin{aligned} dic &= 0.4665 - 0.7004t + 0.6352s - 0.1841t^2 \\ &\quad +0.1021ts - 0.4304s^2 - 0.0349t^3 + 0.0757t^2s \\ &\quad +0.0899ts^2 - 0.1831s^3 + 0.0181t^4 - 0.0341t^3s \\ &\quad +0.0884t^2s^2 + 0.0211ts^3 - 0.0220s^4 \end{aligned} \quad (1)$$

where dic = (DIC-2000)/50, t = (SST-25)/3, and s = (SSS-35)/0.5. $\sigma=\pm$ 9 μmol kg^{-1}, with 435 samples. This fit is remarkable given the range of SST and SSS and the seasonal-to-interannual variability encountered during those cruises (17–30°C and 33.7–35.9). The SSS dependency accounts mainly for the south-north gradient of DIC, while upwelled waters with high DIC content have SST-SSS characteristics much more scattered with increasing temperature. Data from the same cruises show that pCO_2 and (SST, SSS) couples have no one-to-one relationship. Thus, pCO_2 is calculated from the estimated DIC and alkalinity (TA) using a thermodynamic model for the carbonate system in sea-water [*Murphy,* 1996] where TA is also expressed as a function of SST and SSS according to *Millero et al.,* [1998]. Figure 1 illustrates the satisfactory agreement between measured and estimated surface DIC and pCO_2.

Figure 1

To evaluate the potential of this method, we estimate the bulk pCO_2 difference between the ocean and the atmosphere (ΔpCO_2) on a $1.5°\times1.5°$grid (140°E – 95°W and 5°N – 10°S, Figure 2a) from surface DIC and TA inferred from basin scale monthly SST [*Reynolds and Smith,* 1994] and SSS [*Delcroix,* 1998]. However, like DIC, the estimated pCO_2 does not include changes induced by anthropogenic CO_2 emissions (≈ 5 μmol kg^{-1}yr^{-1} or 1.25 μatm yr^{-1}). Therefore, to estimate ΔpCO_2 we assume a similar anthro-

Figure 2

[1] Reported standard deviations for DIC measurements from each cruise are ± 2 μmol kg^{-1}. Certified reference material for DIC developed by A. Dickson (UNESCO Report 60, 1990) were used to control the quality of the measurements. In consequence, the between-cruise bias was estimated to be < 4 μmol kg^{-1}

pogenic CO_2 increase in the ocean and in the atmosphere, which agrees with the observed trend [*Feely et al.,* 1999].

The CO_2 flux to the atmosphere (F_C) is estimated from ΔpCO_2 as $F_C = GEC \times \Delta pCO_2$ where GEC is the gas exchange coefficient which depends primarily on the wind speed [*Wanninkhof,* 1992] (Figure 2b). We use monthly values from the wind speed reanalysis (1979–1993) by the European Centre for Medium Range Weather Forecasts, a consistent product that assimilates wind speed data measured by the TAO array. The beginning of our study period is set by the SST field and the end by the wind product.

The flux estimates (Figure 2c) are subject to errors from (1) DIC (σ=$\pm$9 μmol kg^{-1}) and TA (σ=$\pm$5 μmol kg^{-1}); (2) uncertainties in the SST ($\pm$0.5°C) and SSS ($\pm$0.1) fields; (3) accuracy of the pCO_2 calculation ($\pm$5 μatm); (4) uncertainties in the wind dependency of GEC and wind forcing (25%); and (5) the ocean skin temperature effect ($\pm$0.3°C). Only (1) and (3) are specific to this study. The DIC fit will be improved as more data become available, especially for La Niña events, in order to include large SST-DIC anomalies. Considering all the above errors and after comparison with field data, we estimate a 50% uncertainty on the CO_2 fluxes.

Results and discussion

High ΔpCO_2 (high DIC) values occur in the cool-salty central and eastern equatorial Pacific, and low ΔpCO_2 (low DIC) cover the warm-fresh western Pacific (Figure 2a). During ENSO events, the eastward advection of western waters is reflected in the appearance of low ΔpCO_2 along the equator. The most dramatic change for the 1982-93 period occurs during the 1982–1983 El Niño. Moreover, periods of low ΔpCO_2 coincide with low GEC since reduced upwelling is associated with a relaxation of the Trade Winds. Those two parameters act together to modulate F_C.

The evasion rate (R_C, the basin integral of F_C, Figure 3) is in agreement with field estimates (Table 1). Indeed, our estimate of F_C falls within the uncertainties of the observations. The only substantial discrepancy is for the 1982–83 El Niño: we estimate a minimum evasion rate of 0.3 Gt yr^{-1} while *in situ* data suggest no-flux conditions. Because the field estimate did not include observations south of the equator, where recent data indicate relatively higher pCO_2, we find no cause for concern over the difference in flux estimate.

Negative anomalies of R_C follow the Southern Oscillation Index (SOI) with several months lag (3–4 months like SST). They occur during 1982–83, 1986–87 and almost continuously after 1989. Positive anomalies do not always correlate with the SOI. Even though R_C was high during the 1988–89 La Niña (highest SOI of the period), its highest values occurred between the 1982–83 and 1986–87 ENSO events, when the SOI did not record anomalous conditions. During the cold event of 1988–89, estimated DIC reached a maximum, but the potential increase in ΔpCO_2 was reduced by a SSS-driven TA maximum centered in 1988–89 (not shown).

The variability of R_C inferred from this study and from the model simulation of *Le Quéré et al.* are in excellent agreement (Figure 3). These authors use the same wind product to evaluate the GEC for the model predicted pCO_2. Therefore differences are mostly related to pCO_2 estimates. Our results also support those of *Lee et al.,* 1998 and *Boutin et al.,* 1999 that suggest a relatively small interannual variability of R_C in the equatorial Pacific. Such a satisfactory agreement between four inherently different approaches (*in situ* data, SST-SSS-DIC relationship, SST-pCO_2 relationship, model study) strongly sugests that ENSO-related anomalies of CO_2 evasion rates do not exceed $\pm$ 0.4 Gt yr^{-1} in the equatorial Pacific.

Another way to evaluate the oceanic contribution to interannual CO_2 variations is from inverse methods using the ^{13}C ratio of atmospheric CO_2. These methods allow to distinguish between oceanic and terrestrial contributions to atmospheric CO_2 variability (e.g. [*Francey et al.,* 1995; *Keeling et al.,* 1995]). On a global scale, ^{13}C inversions attribute a much greater role to the ocean than is infered from oceanic studies [*Lee et al.,* 1998; *Le Quéré et al.,* 1999]. This remains true for the tropics. A recent study by [*Rayner et al.,* 1999] estimates the ENSO-related tropical CO_2 source anomaly as 1–2 Gt yr^{-1} from which 1 Gt yr^{-1} is attributed to the ocean. Our flux estimate is 0.5 $\pm$0.3 GtC yr^{-1} with anomalies of 0.4 $\pm$0.2 GtC yr^{-1} (we increase R_C by 20% to roughly estimate the contribution of the tropical Atlantic and Indian oceans [*Takahashi et al.,* 1997]).

Do oceanic/atmospheric based estimates under/over-estimate oceanic uptake variability? The answer is certainly not straightforward, but we would argue in favour of a greater role played by the terrestrial biosphere, compared to that of the ocean as to ENSO-

related changes of tropical sources of CO_2. Although we recognize that ocean-based methods may underestimate the variability on ENSO timescales due for instance to unsufficient spatio-temporal coverage in the data, or underestimation of interannual variability by geochemical models, recent improvements of atmospheric-based methods either by reducing uncertainties in the ^{13}C method [*Fung et al.,* 1997] or by inversions that do not use ^{13}C data but only the spatial distribution of CO_2 [*Bousquet et al.,* 1999], show better agreement with ocean-based estimates such as the one presented here.

The use of SST and SSS data to reconstruct spatial and temporal variability of ocean pCO_2 is shown to be reasonable in the equatorial Pacific. The developing ability to remotely sense SSS [*Lagerloef,* 1999] and of pCO_2 algorithms similar to that presented here could provide useful tools for global mapping of time dependent pCO_2 in the equatorial Pacific and possibly elsewhere.

Acknowledgments. We are grateful to T. Delcroix for providing the SSS data, to all the carbon PIs for collecting the data and to CDIAC for distributing the data. HL and FV thank S. Hankin and K. Kelly for their support. This publication was supported by JISAO under NOAA Cooperative Agreement NA67RJO155, contribution 747.

References

Archer, D. E., *et al.*, Daily, seasonal, and interannual variability of sea surface carbon and nutrient concentration in the equatorial Pacific Ocean, *Deep Sea Res. Part II, 43,* 779-808, 1996.

Bousquet, P., P. Peylin and P. Ciais, Interannual changes in CO_2 sources and sinks from 1980 to 1998: results of an inversion of CO_2 atmospheric data and comparison with ocean and land ecosystems models, paper presented at AGU 1999 Fall Meeting, S. Francisco, Dec. 13-17, 1999.

Boutin, J., *et al.*, Satellite sea surface temperature: a powerfull tool for interpreting in situ pCO_2 measurements in the equatorial Pacific Ocean, *Tellus, 51B,* 490-508, 1999.

Delcroix, T., Observed surface ocean and atmospheric variability in the tropical Pacific at seasonal and ENSO timescales: A tentative overview, *J. Geophys. Res., 103,* 18,611-18,633, 1998.

Feely, R. A., *et al.*, Distributions of chemicals tracers in the eastern tropical Pacific during and after the 1982-1983 El Ni1o/Southern Oscillation event, *J. Geophys. Res., 92,* 6645-6558, 1987.

Feely, R. A., *et al.*, CO_2 distributions in the equatorial Pacific during the 1992–91 ENSO event, *Deep Sea Res. Part II, 42,* 365-386, 1995.

Feely, R. A., R. Wanninkhof, T. Takahashi and P. Tans, Influence of El Niño on the equatorial Pacific contribution to atmospheric CO_2 accumulation, *Nature, 398,* 597-601, 1999.

Francey, R. J., *et al.*, Changes in oceanic and terrestrial carbon uptake since 1982, *Nature 373,* 326-330, 1995.

Fung, I., *et al.*, Carbon 13 exchanges between the atmosphere and biosphere, *Global Biogeochem. Cycles, 11,* 507-533, 1997.

Garside, C., and J.C. Garside, Euphotic zone nutrient algorithms for the NABE and EqPac study sites, *Deep Sea Res. Part II, 42,* 335-347, 1995.

Keeling, C. D., T.P. Whorf, M. Wahlen and J. van der Plicht, Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980, *Nature, 375,* 666-670, 1995.

Inoue, H. and Y. Sugimura, Variations and distribution of CO_2 in and over the equatorial Pacific during the period from the 1986/88 El Niño to the 1988/89 La Niña event, *Tellus, 44B,* 1-22, 1992.

Lagerloef, Progress toward salinity remote sensing satellite missions, *Second Workshop of the Salinity Sea Ice Working Group*, NASA Goddard Space Flight Center, Grennbelt MD, USA, 19-21 April 1999.

Lee, K., *et al.*, Low interannual variability in recent uptake of atmospheric carbon dioxide, *Nature, 396,* 155-159, 1998.

Le Quéré, C, *et al.*, Interannual variability of the oceanic sink of CO_2 from 1979 to 1997, *Global Geochem. Cycles,* in press.

Millero, F.J., K. Lee and M. Roche, Distribution of alkalinity in the surface waters of the major oceans, *Mar. Chem., 60,* 111-130, 1998.

Murphy, P.P., The carbonate system in seawater, laboratory and field studies, Ph.D. Dissertation, 297 pp., Univ. of Washington, 1996.

Rayner, P.J., R.M. Law, R. Dargaville, The relationship between tropical CO_2 fluxes and the El Niño-Southern Oscillation, *Geophys. Res. Lett., 26,* 493, 1999.

Reynolds, R.W., and T.M. Smith, Improved global sea surface temperature analysis using optimum interpolation, *J. Clim., 7,* 929-948, 1994.

Takahashi, T., *et al.*, Global air-sea flux of CO_2: An estimate based on sea-air pCO_2 differences, *Proc. Natl. Acad. Sci., 94,* 8292-8299, 1997.

Volk, T., Effect of the equatorial Pacific upwelling on atmospheric CO_2 during the 1982-83 El Niño. *Global Geochem. Cycles, 3,* 267-279, 1989.

Wanninkhof, R., Relationship between wind speed and gas exchange over the ocean, *J. Geophys. Res., 97,* 7373-7382, 1992.

Wong, C. S., *et al.*, Changes in equatorial CO_2 flux and new production estimated from CO_2 and nutrients levels in Pacific surface waters during the 1986-87 El Niño. *Tellus, 45B,* 64-79, 1993.

H. Loukos, Laboratoire d'Océanographie Dynamique et de Climatologie, UPMC Boite 100, 4 Place Jussieu, Paris 75252 Cedex 05, France. (e-mail: loukos@ipsl.jussieu.fr)

F. Vivier, Applied Physics Laboratory, University of Washington, 1013 NE 40^{th} St, Seattle, WA 98105. (e-mail: fvi@apl.washington.edu)

P.P. Murphy, National Oceanographic Data Center, NOAA, 1315 East-West Highway Silver Spring, MD 20910. (e-mail: pmurphy@nodc.noaa.gov)

D.E. Harrison, Pacific Marine Environmental Laboratory, NOAA, 7600 Sand Point Way N.E., Seattle, WA 98115. (e-mail: harrison@pmel.noaa.gov)

C. Le Quéré, Laboratoire des Sciences du Climat et de l'Environnement, CEA Saclay, 91191 Gif sur Yvette, France. (e-mail: lequere@lsce.saclay.cea.fr)

Received August 26, 1999; revised December 23, 1999; accepted February 24, 2000.

[1]Laboratoire d'Océanographie Dynamique et de Climatologie, Institut Pierre Simon Laplace, Paris, France

[2]Formerly at the Joint Institute for the Study of the Atmosphere and Ocean, University of Washington

[3]Applied Physics Laboratory, University of Washington

[4]National Oceanographic Data Center, NOAA, Silver Spring, Maryland

[5]Pacific Marine Environmental Laboratory, NOAA, Seattle, Washington

[6]Laboratoire des Sciences du Climat et de l'Environnement, Institut Pierre Simon Laplace, Gif sur Yvette, France

This preprint was prepared with AGU's LaTeX macros v5.01. File LOUKOSTEX formatted February 28, 2000.

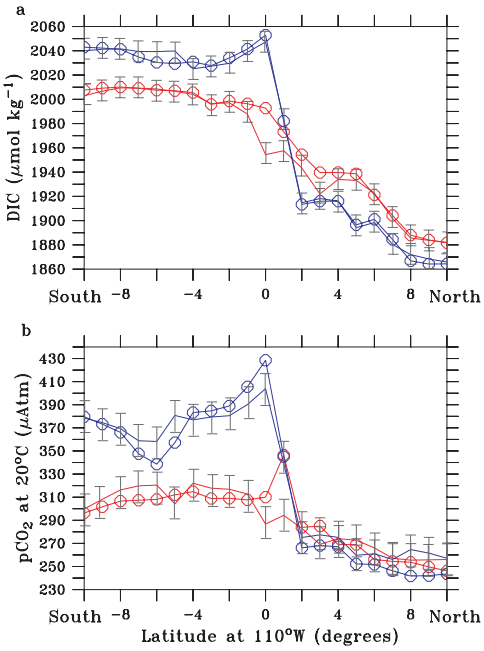

Figure 1. DIC and pCO_2 at 20° C at 110° W. Data (circles) and estimates (line) for ENSO (Spring of 1992) in red and non ENSO conditions (Fall of 1992) in blue.

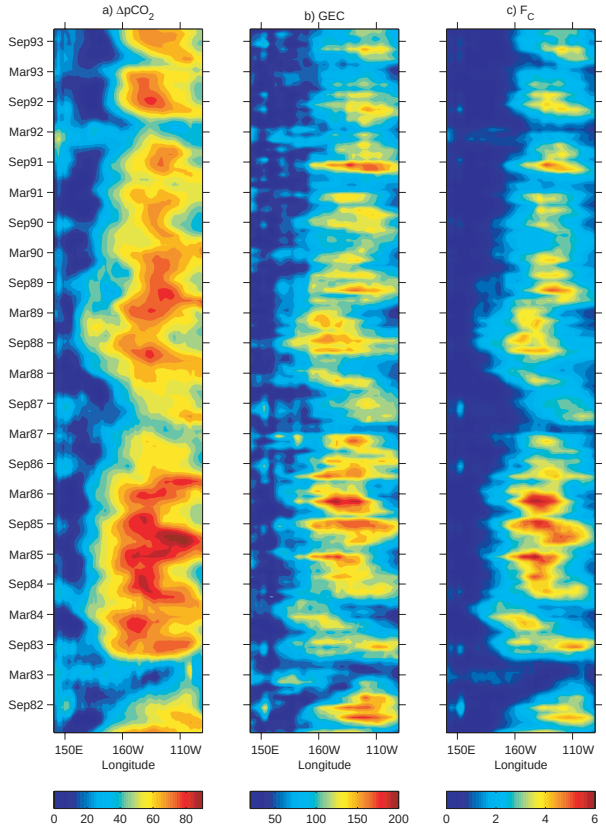

Figure 2. (a) ΔpCO_2: air-sea CO_2 gradient (μatm), (b) GEC: gas exchange coefficient (moles m^{-2} day^{-1} atm^{-1}), and (c) F_C: CO_2 evasion rate (moles m^{-2} day^{-1}) averaged between 5°N–10°S.

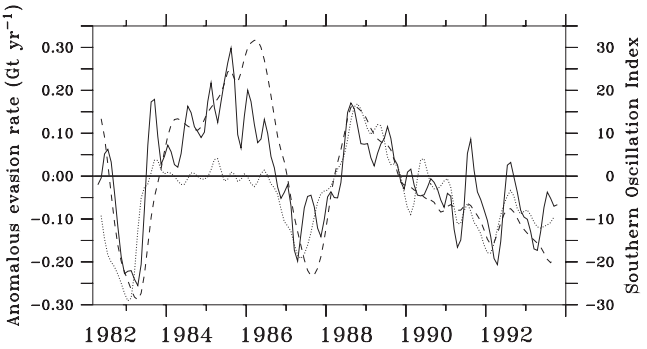

Figure 3. Anomaly of the CO_2 evasion rate between 140°E–90° W and 5°N–10°S (thick line). The estimate from *Le Quéré et al.* (dashed line) and the Southern Oscillation Index (dotted line) are plotted for comparison. Errors are ±50% (see text). All data is smoothed with 3-month Hanning filter.

Table 1. Comparison of ΔpCO_2 and CO_2 evasion rates

Region	Year	Field estimate (μatm/GtC y^{-1})	This study
Non-ENSO conditions			
10°S–10°N, 80°W–135°E	1984	60/0.6 (1)	50/0.7
10°S–10°N, 80°W–120°E	1984	60/0.8 (2)	51/0.8
10°S–10°N, 80°W–135°E	1989	50/0.4 (3)	44/0.7
5.5°S–5.5°N, 80.5°W–134.5°E	1989	79/1.0 (4)	53/0.5
ENSO conditions			
10°S–10°N, 80°W–135°E	1983	2/0.02 (1)	24/0.3
10°S–10°N, 80°W–135°E	1987	5/0.09 (3)	30/0.4
5.5°S–5.5°N, 80.5°W–135.5°E	1987	31/0.4 (4)	31/0.2
10°S–10°N, 80°W–135°E	1992	27/0.3 (5)	32/0.4

ΔpCO_2 estimates are directly comparable while part of the discrepancies in CO_2 fluxes can be attributted to differences in formulations and wind forcing. Sources: 1, [*Feely et al.,* 1987]; 2, [*Volk et al.,* 1989]; 3, [*Wong et al.,* 1993]; 4, [*Inoue and Sigimura*, 1992]; 5, [*Feely et al.,* 1995].