Carbon fluxes in the equatorial Pacific: a synthesis of the JGOFS programme

Robert Le Borgne [1], Richard A. Feely [2] and Denis J. Mackey [3]
[1] *IRD (ex-ORSTOM), B.P. A5, Nouméa Cédex, New Caledonia*
[2] *Pacific Marine Environmental Laboratory, NOAA, 7600 Sand Point Way N.E., Seattle, WA 98115-0070, USA*
[3] *CSIRO Marine Research, P.O. Box 1538, Hobart 7001, Tasmania, Australia*

1. Background

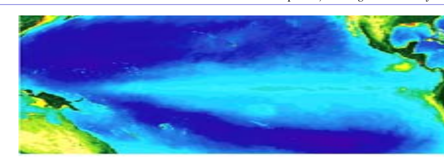
The Equatorial Pacific study was planned at the JGOFS meeting held in Honolulu in September 1989. Three questions were addressed as the basis for the programme:
(1) Does the equatorial Pacific biogeochemical cycling determine what happens in the global ocean?
(2) What is the capacity of the biological pump in the equatorial Pacific?
(3) What is the response of the equatorial Pacific to ENSO fluctuation?
Most of the field work finished in 1996 and during its Seattle meeting in September 1998, the JGOFS Equatorial Pacific Synthesis and Modeling Group decided to publish a synthesis in Deep-Sea Reserach II. The volume (Deep-Sea Research II, vol.49, Nos 13-14, 2002) was issued in June 2002 and includes synthetical chapters on different topics dealing with the carbon cycle in the region.
Here, we present the "synthesis" of the synthesis which appears in the Introduction of the volume.

2. Cruises and data resources

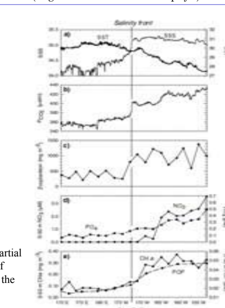
Oceanographic cruises were organized on an international basis by Australia, France, Japan and the United States. They explored the whole equatorial Pacific (42% of the world circumference), some being devoted to the eastern and central Pacific, others to the western part of it. Some consisted in meridional sections, others in zonal transects.The programme benefitted from the TAO mooring network (PMEL/NOAA) for the physical oceanography data, from sea color remote sensing data (Polder in 1996-1997 and SeaWIFS drom 1997), ships of opportunity measurements, underway measurements in the frame of the maintenance of TAO buoys and bio-optical and chemical sensors on some of the TAO moorings.
Data are distributed via the following web sites:
Australia: http://www.marine.csiro.au/datacentre/JGOFSweb/cmr_jgofs.htm
France: http://www.obs-vlfr.fr/jgofs/html/bdjgofs_eng.html
Japan: http://www.jodc.jhd.go.jp/JGOFS_DMO/index.html
United States: http://www1.whoi.edu/jgdms_info.html; http://www.pmel.noaa.gov/uwpco2/; http://aoml.noaa.gov/ocd/oaces/index.html; http://cdiac.esd.ornl.gov/ocd/oaces/index.html
JGOFS International Project Office: http://ads.smr.uib.no/jgofs/jgofs.htm

3. Two regions: the warm pool and the HNLC regions

The equatorial Pacific is subject to physical forcings that differ from west to east.In the western Pacific, the *warm pool* is an oligotrophic area with a deep thermocline and nutricline, combined with a barrier layer produced by shallow haloclines. In contrast, the region east of the *warm pool* is subject to the divergence of the South Equatorial Current, north and south of the equator. Such a divergence generates upwelling of waters from the Equatorial Undercurrent (EUC), which brings waters with higher salinity, dissolved inorganic carbon (DIC) and nutrients to the surface. Since phytoplankton pigment concentrations remain low and the macronutrients are not depleted, this region is usually called the *HNLC* (High Nutrient-Low Chlorophyll) area.



The two regions of the equatorial Pacific are clearly seen on ocean colour images. The warm pool is an oligotrophic region in the western Pacific. East of it, the HNLC region is characterized by higher seasurface chlorophyll concentrations (kindly provided by the SeaWIFS Project: http://seawifs.gsfc.nasa.gov).



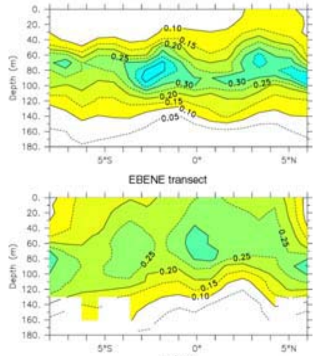
The border between the warm pool and the HNLC region is clearly delineated by an increase of the partial pressure of CO_2 (pCO_2), sea surface salinity (SSS), zooplankton biomass and higher concentrations of nitrate (NO_3), chlorophyll *a* (Chl*a*) and particulate organic phosphorus (POP). Note that variations in the sea surface temperature (SST) and phosphate (PO_4) are less pronounced (from Rodier et al., 2000).

4. Export of CO_2: 72% of outgassing from the world's ocean

The large number of CO_2 measurements since the beginning of the JGOFS equatorial Pacific process study indicate that as much as 72% of the outgassing of CO_2 from the world's ocean can be attributed to the equatorial Pacific. Most of this flux originates from the *HNLC* area so that its zonal extension, which is under the control of the climatic situation, will effect the amount of carbon dioxide being outgassed.

5. The biological pump in the warm pool and the HNLC regions

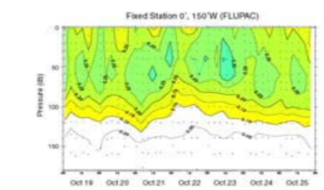
Both the level of primary production and the size strucutre of phytoplankton are related to the availability of macronutrients in the photic zone, which leads to significant differences in the strength of the biological pump between the *HNLC* and *warm pool* regions
The *warm pool* waters, which are essentially always depleted in macronutrients, are dominated by small phytoplankton cells and present a pronounced deep chlorophyll maximum at about 80-100m due to the competing requirements for light, which decreases with depth, and macronutrients, which increase in concentration with depth. Compared with the mid-ocean gyres, which are subject to downwelling, the warm pool has higher nitrate concentrations at 80-100m and there is usually uplifting of the nutricline, two features which lead to higher depth integrated chlorophyll concentrations in the *warm pool*.
The *HNLC* region is characterized by abundant macronutrients and comparatively high concentrations of chlorophyll in surface waters. As for the *warm pool*, the autotrophic community is also dominated by picoeukaryotes, but with a greater contribution of larger cells (>3µm), which appears to be constant along the equator west of the Galapagos islands, regardless of macronutrient concentrations, thus suggesting rather uniform populations. Whereas the biomass and production are clearly limited by the availability of macronutrients, the IronEx experiments in the eastern Pacific confirmed that iron limits production and the development of large cells in the *HNLC* region.The major source of iron is thought to be upwelled waters from the top of the EUC (Equatorial Undercurrent) in this region, although production of diatoms also may be limited by $Si(OH)_4$.
Export production, which is a function of the abundance and size-structure of the phytoplankton, was the focus of a wide range of studies conducted during the Equatorial Pacific JGOFS programme. In comparison with the *warm pool*, the average biological pump fluxes per unit area in the *HNLC* area, appear to be by a factor of 4 for sinking rates, 1-9 for new production and 2 for transfer by diel migration.Considering the "Wyrtki box" (i.e. 5°N-5°S; 180°-90°W), which corresponds to the average extent of the HNLC region for the period 1980-2000, Chavez et al. (1996) estimated the average new production. Their calculation, based on an estimation of upwelled nitrate and the assumption that 25-50% of this nitrate was advected out of the box, led to a new production of 0.65 - 0.98 Pg C yr^{-1}, which is comparable to the mean estimate of CO_2 evasion of 0.8 - 1.0 Pg C yr^{-1} during non-El Niño years (Feely et al., 2002). In addition, Chavez et al. (1996) provide an f ratio value ranging from 0.18 to 0.27, which indicates that the HNLC ecosystem works mainly on regeneration.



Chlorophyll a equatorial cross sections in the warm pool (Flupac transect, 165°E) and the HNLC (EBENE transect, 180°) regions. Note the deep chlorophyll maximum in the warm pool and the homogeneous distribution in the HNLC region between 4°S and 5°N.

6.The short-term variability and the steady state

One of the main characteristics of tropical ecosystems is low temporal variability and this is true also for both the *warm pool* and the equatorial upwelling systems. On time scales of less than a day, however, there can be substantial changes in abundance, cell size and *in situ* fluorescence due to active grazing at night by micrograzers, synchronized cell division, cell growth and changes in the chlorophyll to carbon content of individual cells as a function of irradiance. But, in spite of significant diel variations, planktonic biomasses remain the same from one day to another and this has been observed in the *warm pool* and the *HNLC* region. Such a steady state, however, requires an equilibrium between primary production and grazing or prey production and predators ingestion over a 24-h period. Most of the grazing on the microbial community is by micrograzers (Le Borgne and Landry, in press), since mesozooplankton only ingest a small fraction of the phytoplankton. The top-down control seems to be so strong that phytoplankton blooms have only been reported in the equatorial area on two occasions: one, during EqPac (1992) was in fact due to an accumulation on the leading edge of a Tropical Instability Wave (TIW). The second bloom occurred during the recovery of the equatorial upwelling in July-September 1998 and evidenced a temporay and insufficient grazing control together with a strong TIW activity.



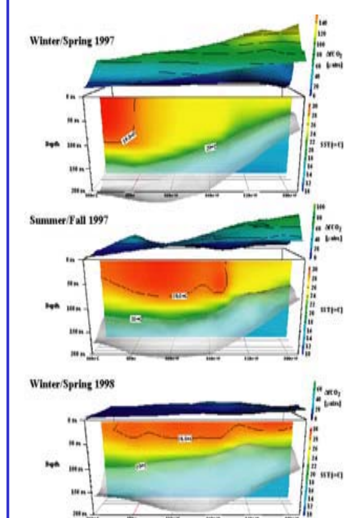
Time series of chlorophyll *a* at a 7-d long fixed station at 0°, 150°W, showing constant values from the beginning to the end in spite of clear diel variations.

7. Effects of wave activity

On time scales longer than a day, wave activity may have an effect on biomasses and fluxes. TIW and Kelvin waves affect primary production in the equatorial Pacific by changing the supply of macro- and micronutrients, including iron, to the photic zone.
The westward propagating TIW have periods of 20-30d, wavelengths of 1000-1500 km and are associated with higher concentrations of nutrients and chlorophyll due to enhanced upwelling along the southernmost front of the wave. TIW have been observed as far west as the dateline and may even occur in the western Pacific during strong La Niñas. Several observations of TIW effect on plankton biomass and production were made during the JGOFS field programme, but the processes involved (e.g. iron inputs) need further descriptions. At this stage, TIW activity appears to play a crucial role in the interpretation of the spatial variability of planktonic parameters in the *HNLC* area, even though the net effect on productivity (over a complete cycle of a TIW) still needs to be estimated.
Downwelling Kelvin waves, which have periods of 40-70 d, wavelengths of up to 10,000 km and travel from west to east at speeds of approximately 200 km d^{-1}, are generated by westerly wind bursts. The leading edge of a Kelvin wave deepens the thermocline (and nutricline) and reduces the supply of macro- and micronutrients to the euphotic zone. The mooring data of Foley et al. (1997) for the 1992-1993 El Niño indicate that primary production is reduced during the passage of the leading edge of these waves.

8. ENSO variability

An important finding of the JGOFS programme is that the interannual variability of CO_2 evasion in the equatorial Pacific is largely dependent upon the location of the eastern edge of the *warm pool*. The longitude of the border between the *warm pool* and the *HNLC* region is linked to the zonal displacement of the *warm pool* and is strongly corelated to the Southern Oscillation Index (SOI) (Inoue et al., 1996). During an El Niño, this warm water forms an eastward "flowing jet" that effectively caps the water containing high CO_2 east of the dateline. In contrast, during a La Niña, the warm pool retreats to the western Pacific exposing water with high pCO_2 to the surface. Thus, the major impact on the global carbon cycle is due to the changing area of the warm pool as it shrinks during La Niña events and expands during El Niño events. The complete set of JGOFS measurements to date, suggest that ENSO-related interannual variability in the equatorial Pacific efflux of CO_2, is about 0.3 - 0.7 Pg C yr^{-1} (Feely et al, 2002). These flux variations can account for the negative atmospheric anomalies during some El Niño periods and can explain, for example, up to approximately one-third of the decrease in the growth rate of atmospheric CO_2 during the 1991-1993 El Niño event. In addition, surface water pCO_2 data collected during the JGOFS era indicated significant seasonal variations.
As for estimates of the evasion of CO_2, estimates of the magnitude of the biological pump depend heavily on the overall surface area of the *HNLC* region. Temporal variations in the biological pump of the *HNLC* region have been summarized by Le Borgne et al (2002) for the 1°N-1°S equatorial band with a variable longitude of the western border. They found a smaller difference between strong El Niños and other periods (El Niño/other years ratio equals 0.67) than Feely et al (2002) found for the CO_2 evasion (ratio equals 0.25). This reflects the basic steady state nature of the biological pump, whih is an important consequence of *HNLC* conditions in which nitrate uptake by phytoplankton is very slow, due to both a limitation by micronutrients and strong control by grazers.



3-D view of the equatorial Pacific showing 6-month averaged temperature distributions and corresponding sea surface CO_2 fugacity (ΔfCO_2) distributions for the 1997-1998 El Niño event. The approximate location of the warm pool is indicated in orange colours and the 20°C isotherm surface is highlighted in grey. Notice the eastward migration of the warm pool.

9. PDO/ENSO/global warming impacts

It has been proposed (Feely et al.,2002) that the CO_2 flux anomalies associated with large-scale ocean-atmosphere reorientations, such as the ENSO phenomenon, will be modulated by the 18-30 yr cycle of the Pacific decadal oscillation (PDO) whih is a low-frequency pattern of Pacific climate variability. During the warm phase of the PDO, there are positive anomalies of the sea surface temperature (SST) in the equatorial Pacific. When the PDO and ENSO are both in the warm phase, as happened during the 1997-1998 ENSO event, the SST anomalies can be extremely large and lead to significant variations in the CO_2 flux from the equatorial Pacific. Global warming-induced increases in SST also could enhance the SST anomalies when the ENSO and PDO cycles are in phase with each other. Long-term changes in pCO_2 in this region could thus significantly influence the global budget for carbon by decreasing the amount of CO_2 that is outgassed to the atmosphere. The seasonal and interannual variability of surface water pCO_2 gives information on how the carbon cycle functions, and can be used in conjunction with other methods to help understand the regional and global patterns of CO_2 sources and sinks. A promising benefit of the JGOFS effort to improve the temporal resolution of data is the development of new autonomous chemical sensors that will make it possible to measure CO_2 and bioloical properties on moorings.

References

(Please, refer to Deep-Sea Research II, vol. 49, Nos 13-14 (2002)