Air-Sea Flux of Carbon Dioxide in the Coastal Eastern Pacific

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ABSTRACT

This project seeks to first quantify and then understand the magnitude, spatial pattern, and variability of air-sea carbon dioxide (CO_2) flux in the coastal waters of the eastern Pacific. The strategy includes measurements from drifters, moorings, and ships. Underway partial pressure of CO_2 sensors have been deployed on ships off North, central and South America in collaboration with institutions/projects that have regular sampling programs. Drifters and moorings have been deployed to determine temporal variability and quantify the impact of biological and physical processes on the air-sea CO_2 flux. Satellite data have been used to estimate wind speed for flux calculations and the wind data are being integrated with altimetry to estimate fluxes of nutrients and carbon. Results for California suggest that this upwelling system is a region of zero net flux. Peru on the other hand is a large source. We speculate that these differences are associated with circulation, denitrification and iron supply.

CALIFORNIA (Alta and Baja)

The northeast Pacific Ocean off western North and Central America can be divided into three regions. Offshore, the warm and salty North Pacific Central Gyre (NPCG) waters form a southward-flowing layer about 250 m deep. Second, between the NPCG and 150-200 km west of North America, the California Current (CC) also flows southward at 0.6-1.2 km/hr as a 1200 km broad and 250 m deep surface current. Thirdly, inshore of the CC there is a region dominated by coastal upwelling-the Coastal Upwelling System (CUS). The wind-driven equatorward circulation overlies the poleward-flowing California Undercurrent, which has maximum velocity near 100 m but reaches to at least 1000 m. The CC and CUS with its California Undercurrent, Inshore Countercurrent and coastal upwelling circulation are together termed the California Current System (CCS).

The sampling program off Monterey Bay, in the heart of the CCS, has been in place for a decade. Recently we have expanded this program to include CalCOFI and IMECOCAL cruises (Figures 1 and 2). The highly dynamic CUS off central California (Figure 3A) can be further subdivided into a region of active upwelling and CO_2 venting (Figure 3B, RR) and a region offshore where biological uptake turns the ocean into a CO_2 sink (CTZ). The CC is also a CO_2 sink but this is associated with larger scale processes in the north Pacific. Monterey Bay is a strong sink due to increased biological activity. The net annual air-sea flux of CO_2 for the CUS, including Monterey Bay is essentially zero. The combined CalCOFI and IMECOCAL pCO_2 surveys have been ongoing for less than a year so we cannot make annual estimates. During a recent winter survey (Figure 2) we estimated an average CO_2 flux into the ocean of 0.4 moles CO_2 m^{-2} $year^{-1}$. During the Spring and Summer of 2005 there have been several cruises covering the same region. Preliminary results indicate that during the upwelling season there is a flux from the ocean to the atmosphere. The positive flux is driven by a combination of upwelling of CO_2 enriched waters and seasonal warming. In the northern portion of this region the estimated flux out of the ocean was 1 mole CO_2 m^{-2} $year^{-1}$,while in the southern portion where he seasonal warming is more significant fluxes to the atmosphere may be as high as 2 moles CO_2 m^{-2} $year^{-1}$.

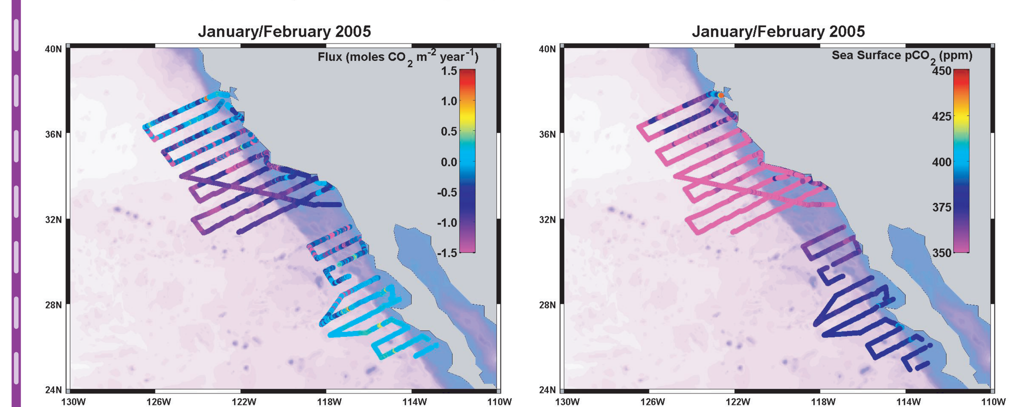


Figure 2. Estimates of sea surface pCO2 and air-sea CO2 flux (positive out of the ocean, negative into the ocean) for two recent CalCOFI and IMECOCAL cruises. The background for the maps is bottom depth.

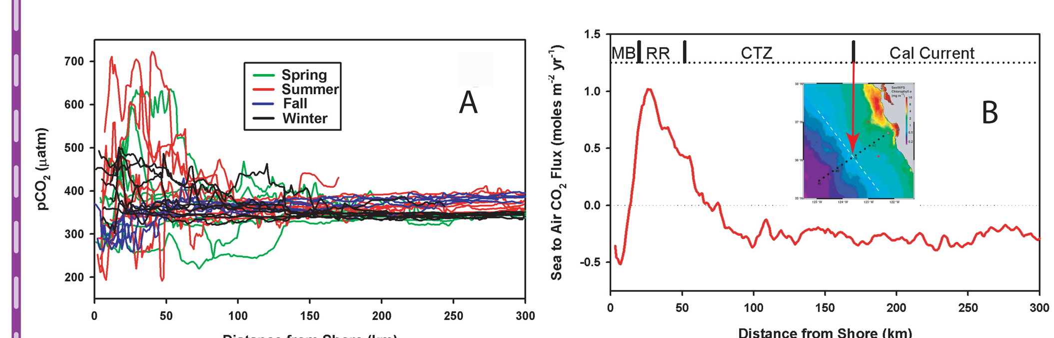


Figure 3. (**A**) Sea surface pCO2 versus distance offshore. Variability is high inshore due to intermittent coastal upwelling which is most intense in spring (green) and summer (red). Offshore variability is due primarily to seasonal temperature differences. (**B**) Estimate of annual sea to air CO2 flux based on approximately 150 cruises covering the inner 60 km and 30 cruises covering the remainder of the section. The top of the bottom figure delineates subregions of the section: Monterey Bay (MB), the first Rossby radius region of active upwelling (RR), the coastal transition zone (CTZ), and the CC (offshore of the CUS). Mean annual air/Sea CO2 flux is near-zero within the CUS.

Seasonal cycle in the California Current based on the average of data collected between 200 km and 300 km from shore

The increase of sea surface pCO2 from Winter/Spring to Summer can be directly related to the rise in temperature. The values observed in Fall are slightly lower than those expected due to the increased temperature. The average flux of CO2 is into the ocean at a rate of 0.28 moles m^{-2} $year^{-1}$.

Season	pCO2	Air/Sea Flux	Temperature	Salinity
Winter	345	-0.63	13.89	32.88
Spring	346	-0.85	13.91	32.81
Summer	370	0.02	15.45	32.84
Fall	378	0.31	17.04	33.10

Trends of Sea Surface CO2 in the coastal upwelling zone

Observations gathered between the coast and 60 km offshore since 1993 indicate that the mean annual sea surface pCO2 values appear to be related to the mean upwelling index which is a measure of upwelling favorable winds. This is not necessarily true on shorter time scales since enhanced upwelling also will also favour increased biological carbon uptake. During the upwelling season sea surface pCO2 can range from 150 to 1000 ppm in this zone. (These data have been de-trended for the anthropogenic CO2 increase.)

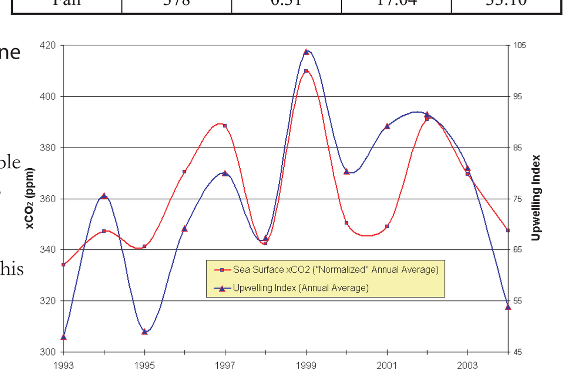


Table 1. Air-sea fluxes of pCO_2 (positive out of the ocean, negative into the ocean) for regions of the coastal Eastern Pacific in moles CO_2 m^2 y^{-1}.

California	0
Central America	0.35
Peru	6.6
Chile	3.0

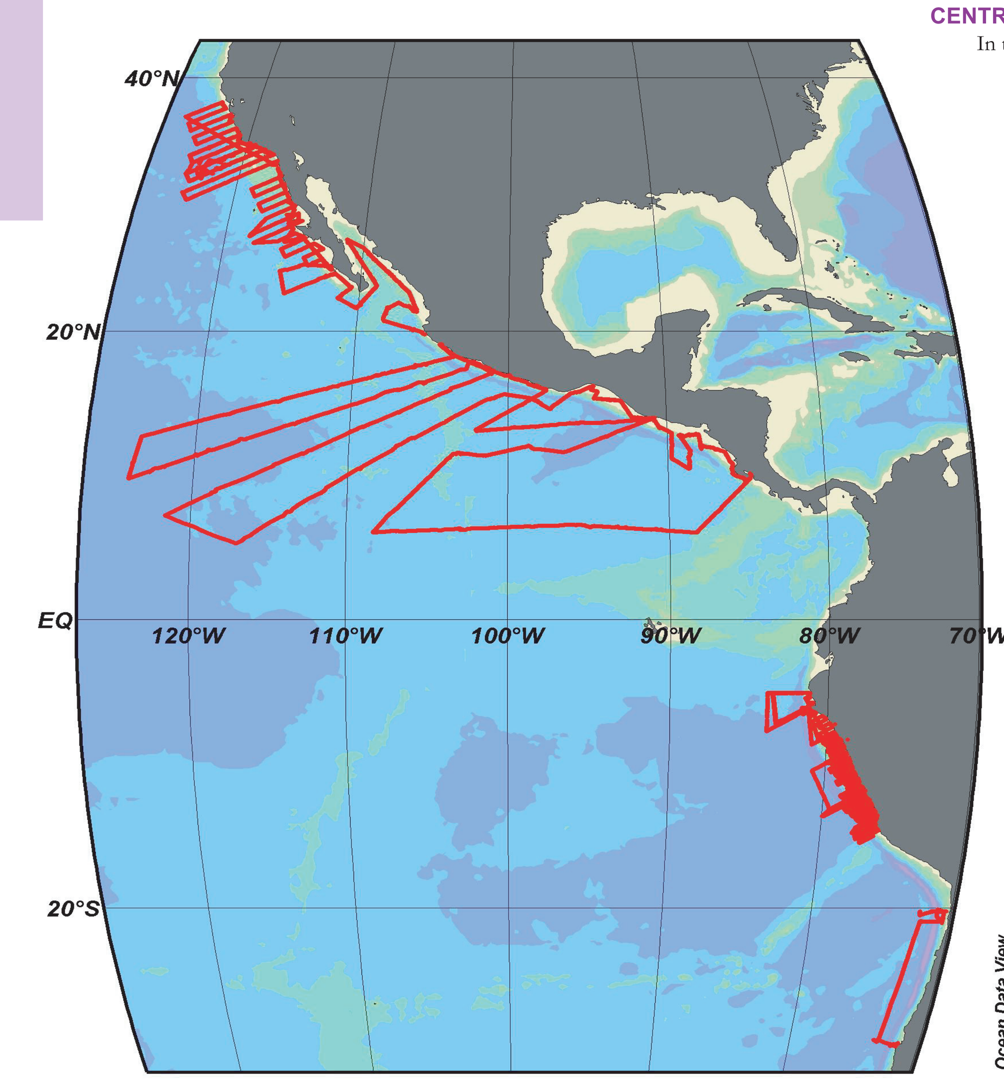


Figure 1. Map of the eastern Pacific showing the cruises where pCO2

DRIFTERS

As part of a technology development effort we have built moorings and drifters that are capable of measuring pCO_2 in the sea surface and the atmosphere. The drifters are capable of other measurements as well as pCO_2 (see Figures 7 and 8), have a GPS receiver and transmit their data in near real-time via the Orbcomm satellite system. The drifters have been tested in Monterey Bay (Figure 7) and off Baja California (Figure 8). Off Peru our deployment was interrupted by a fisherman who recovered the drifter; the satellite communications allowed us to follow the drifter to shore and recover it. We have also deployed one of the drifters in a moored configuration off Chile in support of a field campaign.

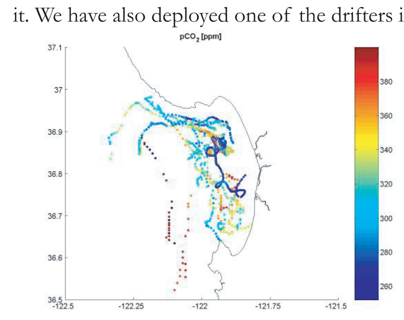


Figure 7. Estimates of sea surface pCO_2 and air-sea pCO_2 flux (positive out of the ocean, negative into the ocean) along drifter trajectories in Monterey Bay, California.

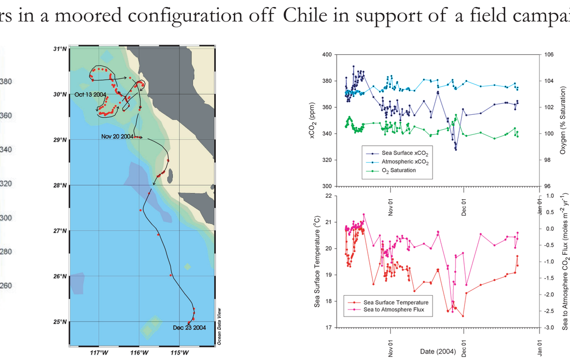
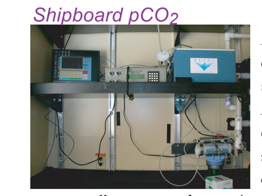


Figure 8. Trajectory of a drifter deployed off Baja California together with time series of sea surface pCO_2 and air-sea pCO_2 flux (positive out of the ocean, negative into the ocean), oxygen saturation, temperature and salinity for the two month drifter deployment.

METHODS

Shipboard pCO_2

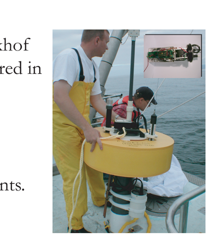


A nondispersive infrared gas analyzer (LI-COR model 6262) was utilized to determine the mixing ratio of CO_2 in the atmosphere and in air equilibrated with surface seawater. Commercial CO_2 in dry air standards were calibrated with primary gas standards obtained from the National Oceanic and Atmospheric Administration Climate Monitoring and Diagnostics Laboratory. A membrane equilibrator with a total volume of 100 ml and a water flow of about 1 liter per minute was utilized for air-seawater equilibration. Water vapor, pressure and temperature were measured and appropriate dilution and solubility corrections were applied to estimate in-situ values. The equilibrator temperature was usually measured or estimated within ± 0.02 C°.

Drifter

The drifter and mooring CO_2 systems measure sea surface and atmospheric CO_2 with an infrared gas analyzer. The analyzer and an integrated gas sampling and equilibration system are operated in a relatively low power mode (~1.5 W) for a few minutes during each sampling cycle. In addition sea surface oxygen saturation, temperature, salinity and position data are collected. Prior to deployment the instruments are calibrated over the temperature and CO_2 range that they are likely to encounter in their projected path. Data telemetry is accomplished using the Orbcomm satellite system with a Quake modem.

Sea to Atmosphere CO_2 Flux Estimates



The sea to atmosphere gas exchange rates are based on the wind speed dependent formulation of Wanninkhof (1992) which appears to provide a reasonable relationship at the low to intermediate wind speeds encountered in the regions of our investigation. We used one-month wind speed averages to obtain a more representative match with sea surface variability. Wind data used in the flux calculation are from Quikscat at 0.25 degree resolution obtained from ftp://ftp.ssmi.com/qscat/bmaps_v03/. The atmospheric CO_2 data for these calculations was obtained by combining our shipboard observations with estimates based on GLOBALVIEW-CO_2 (2004), a NOAA-CMDL product derived from high quality atmospheric measurements.

Wanninkhof, R. (1992). Relationship Between Wind Speed and Gas Exchange Over the Ocean. Journal of Geophysical Research, 97(C5), 7373-7382.

GLOBALVIEW-CO_2: Cooperative Atmospheric Data Integration Project - Carbon Dioxide. CD-ROM, NOAA CMDL, Boulder, Colorado [Also available on Internet via anonymous FTP to ftp.cmdl.noaa.gov, Path: ccg/co2/GLOBALVIEW], 2004.

This research was supported by the David and Lucile Packard Foundation and NASA via grant NAG5-12392. We thank Mark Harlan for drifter support and Jeannette Fink for assembling the poster.

CONCLUSIONS

1) Results to date suggest strong differences between coastal upwelling regions.
2) North Pacific upwelling systems have an average air-sea flux of CO_2 of close to zero.
3) South Pacific upwelling systems are a strong source of CO_2 to the atmosphere.
4) The reason for the strong differences require further study.
5) Our offshore results are consistent with the global map constructed by Takahashi et al. (2002) but we have extended their results in to the coast.

CENTRAL AMERICA

In the 1950s and 1960s, the northeastern tropical Pacific received attention due to the abundance of yellowfin tuna and its associated commercial fishery. The fishery led to significant mortality of porpoises because of the association between the marine mammals and the fish. The area also encompasses the Costa Rica Dome and the upwelling areas associated with the Gulfs of Tehuantepec, Papagayo and Panama. NOAA NMFS conducts annual porpoise surveys in the warm waters of the north eastern tropical Pacific to track recovery of these organisms from the early fishery losses. We were able to deploy one of our pCO_2 systems during one of those surveys (Figure 4). The mean for that survey was an average CO_2 flux out of the ocean of 0.4 moles CO_2 m^{-2} $year^{-1}$.

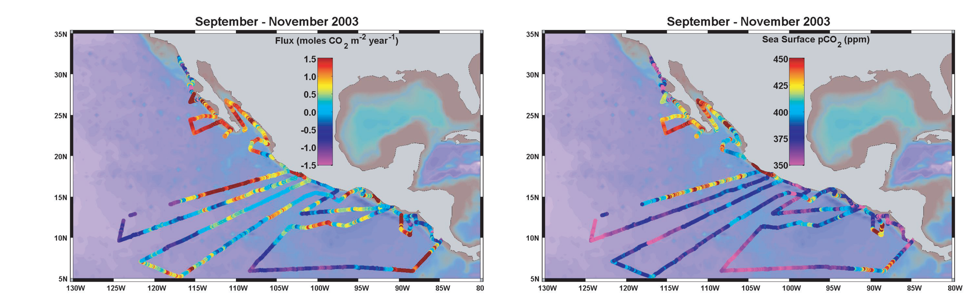


Figure 4. Estimates of sea surface pCO_2 and air-sea pCO_2 flux (positive out of the ocean, negative into the ocean) for several legs of a porpoise survey cruise off central America.

PERU

The interest in biological production in the coastal waters of Peru, beginning in the 1960s, was due to the large abundance of living sources. The eastern boundary system of the Peru Current has some similarities and differences to that found off California. The Peruvian portion of the coastal upwelling system is particularly different for several reasons: 1) it is associated with waters of very low oxygen and high denitrification; 2) the upwelling volume is significantly larger due to the proximity to the equator; 3) heating rates are significantly higher.

The surveys off Peru, in collaboration with IMARPE, show that pCO_2 in surface waters is almost always higher than the atmosphere (Figure 5). The mean air-sea flux for the high upwelling, low production period was out of the ocean at 10.25 moles CO_2 m^{-2} $year^{-1}$. The mean flux for the period of weak upwelling, high production was also out of the ocean at 2.5 moles CO_2 m^{-2} $year^{-1}$.

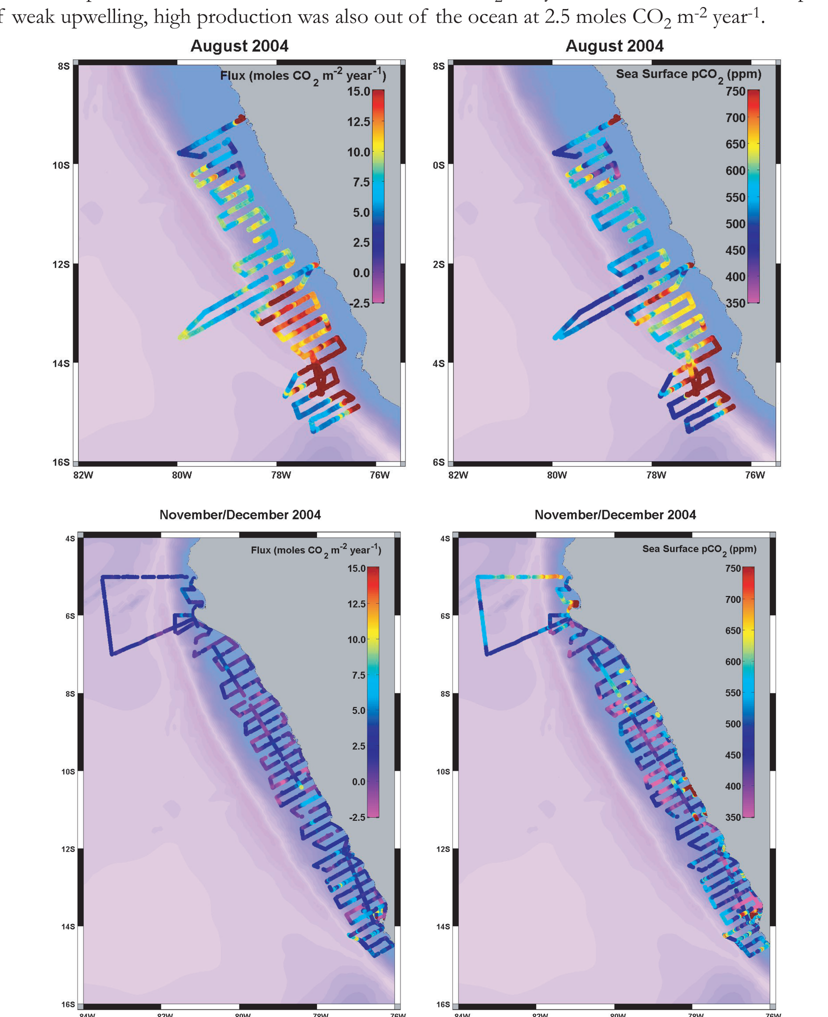


Figure 5. Estimates of sea surface pCO_2 and air-sea pCO_2 flux (positive out of the ocean, negative into the ocean) for two cruises off Peru during strong (August) and weak (Nov/Dec) upwelling.

CHILE

One cruise off Chile has been completed and during that period the mean flux was out of the ocean at 3 moles CO_2 m^{-2} year (Figure 6). A mooring has been placed off the coast of northern Chile and the initial data indicate that this region has the potential for high sea to atmosphere CO_2 fluxes (Figure 7).

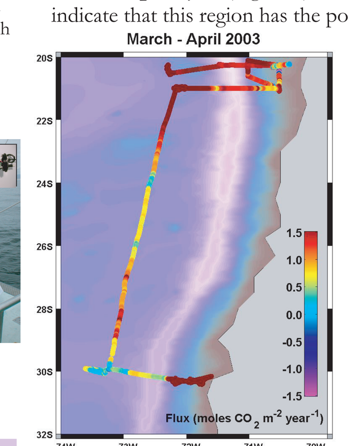


Figure 6. Estimates of sea surface pCO_2 and air-sea pCO_2 flux (positive out of the ocean, negative into the ocean) for a cruise off the coast of northern Chile.

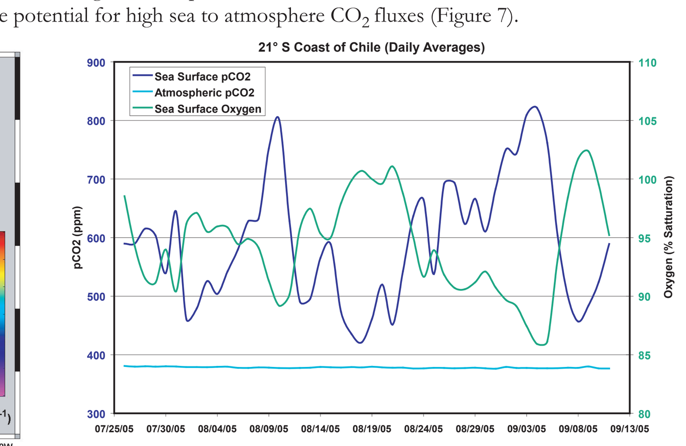


Figure 7. Preliminary results from a mooring placed in the northern Chilean coastal upwelling system. This mooring is located very close to the coast and may primarily observe freshly upwelled waters before significant biological carbon uptake occurs.