Impact of upwelling events on the sea water carbonate chemistry and dissolved oxygen concentration in the Gulf of Papagayo (Culebra Bay), Costa Rica: Implications for coral reefs

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Abstract. The Gulf of Papagayo, Pacific coast of Costa Rica, is one of the three seasonal upwelling areas of Mesoamerica. In April 2009, a 29-hour experiment was carried out at the pier of the Marina Papagayo, Culebra Bay. We determined sea surface temperature (SST), dissolved oxygen concentration, salinity, pH, and the partial pressure of CO_2 (pCO_2). The aragonite saturation state (Ω_a) as well as the other parameters of the marine carbonate system such as the total dissolved inorganic carbon (DIC) and the total alkalinity (TA) were calculated based on the measured pH and the pCO_2. The entrainment of subsurface waters raised the pCO_2 up to 645 µatm. SSTs, dissolved oxygen concentrations decreased form 26.4 to 23.7°C and from 228 to 144 µmol l^{-1}. Ω_a dropped down to values of 2.1. Although these changes are assumed to reduce the coral growth, the main reef building coral species within the region (*Pocillopora* spp. and *Pavona clavus*) reveal growth rates exceeding those measured at other sites in the eastern tropical Pacific. This implies that the negative impact of upwelling on coral growth might be overcompensated by an enhanced energy supply caused by the high density of food and nutrients and more favorable condition for coral growth during the non-upwelling season. Rev. Biol. Trop. 60 (Suppl. 2): 187-195. Epub 2012 April 01.

Key words: pCO_2, dissolved oxygen, upwelling, Gulf of Papagayo, aragonite saturation state, Costa Rica, corals.

The eastern tropical Pacific (ETP) contains one of the most pronounced and largest mid-water oxygen minimum zones (OMZ) in the world's oceans (Conkright *et al.* 2002). Along the Californian coast, upwelling is known to carry oxygen-depleted and carbon-enriched subsurface waters into the surface layers, which leads to pCO_2's of ~ 1000 µatm and Ω_a of < 1 (Feely *et al*. 2008). Experiments have shown that calcification of many scleractinian corals decline with decreasing Ω_a. Accordingly ocean acidification caused by the rising CO_2 concentration in the atmosphere is assumed to be a significant threat to coral reefs (Kleypas *et al.* 2006). A tripling of the pre-industrial CO_2 concentration from 280 to 840 µatm which is predicted to occur within the forthcoming 100 years (Meehl *et al.* 2007) could decrease Ω_a from 3.44 to 1.81 and calcification of specific corals species by up to 85% (Kleypas *et al*. 2006). In order to study possible effects of upwelling on reef forming corals in Culebra Bay within the Gulf of Papagayo, SST, salinity, dissolved oxygen concentration, pH, and pCO_2 were measured during upwelling events triggered by the Papagayo winds at the end of April 2009 (Fig. 1).

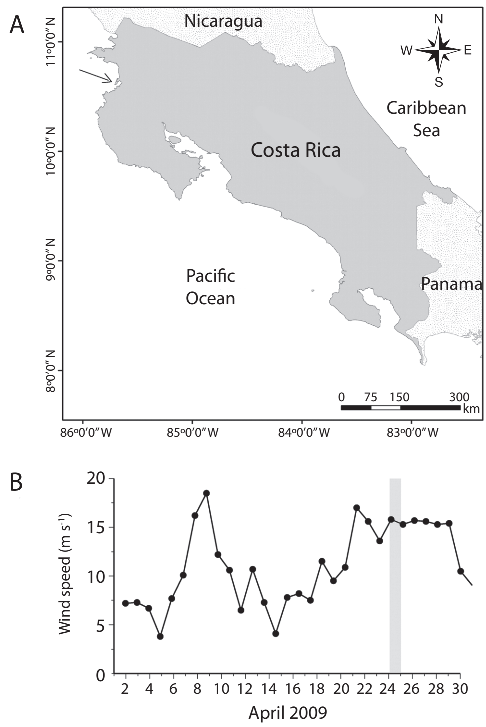


Fig. 1. A. Sampling site (black arrow). B. Daily wind speeds measured at the meteorological station Liberia, Costa Rica. The grey bar indicates the sampling period.

MATERIAL AND METHODS

Study site: The Papagayo wind is a strong north-easterly jet blowing through low elevation gaps of the Central American cordillera in southern Nicaragua and northern Costa Rica. The jet is driven by the sea level pressure difference between the Caribbean Sea and the eastern tropical Pacific (ETP) which develops during the boreal winter and the associated south-eastward migration of the subtropical Azores-Bermuda high (Clarke 1988, Amador *et al*. 2006, Romero-Centeno *et al.* 2007). Outbreaks of cold air masses from the North American continent into the Caribbean occasionally increase the sea level pressure difference between the two oceans and intensify the Papagayo winds (Clarke 1988, Alfaro & Cortés 2011). During such wind events, offshore-advecting cyclonic and anticyclonic eddies spin up south and north of the axis of the Papagayo Jet leading to upwelling of subsurface waters along the Nicaraguan coast and in the Gulf of Papagayo (McCreary *et al.* 1989, Ballestero & Coen 2004, Kessler 2006). The cyclonic eddies south of the Papagayo Jet intensify the shoaling of the thermocline within the Costa Rica Dome region, which is connected to the coast between March and April (Fiedler 2002, Fiedler & Talley 2006). Due to upwelling and wind mixing the SST can drop by up to 10°C within hours within the Gulf of Papagayo (Jiménez 2001, Alfaro & Cortés 2011). The coral habitats of the Gulf of Papagayo are of special interest due to the high abundance of large reefs built almost entirely by *Pavona clavus* and *Pocillopora* spp. and the presence of rare or endangered coral species with restricted distributions (Cortés & Jiménez 2003, Jiménez *et al*. 2010).

Methods: The SST and the mole fraction of CO_2 (xCO_2) was measured by an underway pCO_2 system (SUNDANS) at a water-depth of ~ 3 m. The system was set up on April 24th at 1:00 am at one of the outer piers of the Marina Papagayo (85°39'21.41"W; 10°32'32.89"N) in order to reduced impacts from the Marina at our sampling site. However, during the sampling period there was no ship traffic and the pier moved up and down with the tide so that water-depth from which we pumped the water remained constant throughout the experiment. SUNDANS was developed by "Marine Analytics and Data" (MARIANDA, Germany, www.marianda.com) according to the recommendations of the 2002 underway pCO_2 system workshop in Miami, Florida (NOAA & AOML 2002). It was equipped with a shower type equilibrator, an open pre-equilibrator and a non-dispersive dual cell infrared gas analyzer (LI-7000). The LI-7000 was calibrated by using nitrogen gas (zero CO_2) and a standard gas for CO_2. The CO_2 standard gases were checked against the standard gases provided by NOAA (CA07600 and CC311968) at the Institute for Baltic Sea Research in Warnemünde, Germany. The accuracy of the measured xCO_2 was ±1.6 ppm. The xCO_2 data were recorded every six seconds and subsequently averaged minute by minute. xCO_2 was converted into pCO_2 and the fugacity of CO_2 (fCO_2) according to equations provided by Zeebe and Wolf-Gladrow (2001). The SSTs were measured within the equilibrator. The atmospheric pressure and the wind speed were obtained from the meteorological station in Liberia approximately 30 km east of the sampling site (NCDC 2011). Salinity and the dissolved oxygen concentrations were determined by using WTW probes (Cond3310 and Multi 340i). The pH was measured using an Orion ROSS electrode and an Orion Star^{TM}. The Orion ROSS electrode was calibrated by using NBS standards and re-calibrated by using the RCM standards (Batch 82: http://andrew.ucsd.edu/co2qc/). Ω_a, DIC, and TA were calculated based on the fCO_2 and the pH. In order remove effects caused by temperature changes, DIC and TA were used to compute the $fCO_{2(DIC/TA)}$ using a constant salinity and temperature of 34.51 and 25.01°C.

RESULTS

During the experiment the salinity and temperature varied between 34.4 and 34.9 and 23.7 and 26.2°C. The mean salinity and temperature of 34.51 and 25.01°C were used to calculate $fCO_{2(DIC/TA)}$ as mentioned before. On April 24th between 05:00 and 06:00 am the SST dropped precipitously from 26.4°C to 24.1°C (Fig. 2). This drop was associated with decreases in pH and oxygen concentration from 8.01 to 7.86 and 228 to 144 µmol l^{-1}, respectively, as well as an increase in pCO_2 from 475 to 645 µatm. Between 06:00 and 12:00 am, the SST increased from 24.1°C to 25.9°C, and then steadily decreased to a minimum value of around 23.9°C at ~ 23:00. The first and the second period during which cold water occurred at the surface are referred to as the first and the second upwelling event during the following discussion (Fig. 2). The period prior to the first upwelling event is considered as pre-upwelling period. Wind speeds measured at the Meteorological Station Liberia indicate that the sampling period was characterized by an intensification of the Papagayo winds (Fig. 1).

DISCUSSION

The simultaneous drop of SST, dissolved oxygen, and pH indicate that oxygen-depleted and CO_2-enriched subsurface waters were entrained into the surface layer in the early morning hours on April 24th (Fig. 2). The observed SST drop of 2.3°C was associated with a decrease in the oxygen concentration of 84 µmol l^{-1} corresponding to a 37% reduction of the dissolved oxygen concentration. During the second upwelling event the decrease in oxygen concentration and pH was less pronounced but reveal as the data obtained during the first upwelling event and elsewhere (Feely *et al.* 2008, Manzello *et al.* 2008, Manzello 2010b), that wind-driven upwelling events in the ETP can deliver oxygen-poor, acidic waters to the surface along the coast. Continuous measurements of SST in the vicinity of our sampling site between 1993 and 1996, within a reef built by the massive coral species *Pavona clavus,* show as mentioned before, that SST can decrease by up 8-10°C for some hours during upwelling events (Jiménez 2001). This SST-record was extended until March 2009 and revealed a mean SST of 25°C in April (Fig. 3a) which almost equals the mean SST of 25.09°C measured during our experiment. As indicated by the 1x1 degree gridded World Ocean Atlas Data (WOA09 2009) a temperature of 25°C associated with oxygen concentrations of 209 µmol l^{-1} occur on average at water-depth between 20 and 30 m within the this region in April (Fig. 3b). Since this oxygen concentration is similar to those measured during our experiment (Fig. 2) it is assumed that the upwelled water was originated at this depth-range during our experiment. Oxygen concentrations between 40 and 80 µmol l^{-1} which are assumed to represent a range below which benthic fauna and reef fishes start to respond to oxygen depletion (Nilsson *et al.* 2007, Diaz & Rosenberg 2008) occurred at water-depth between 75 and 100 m (Fig. 3b). These oxygen concentrations are associated

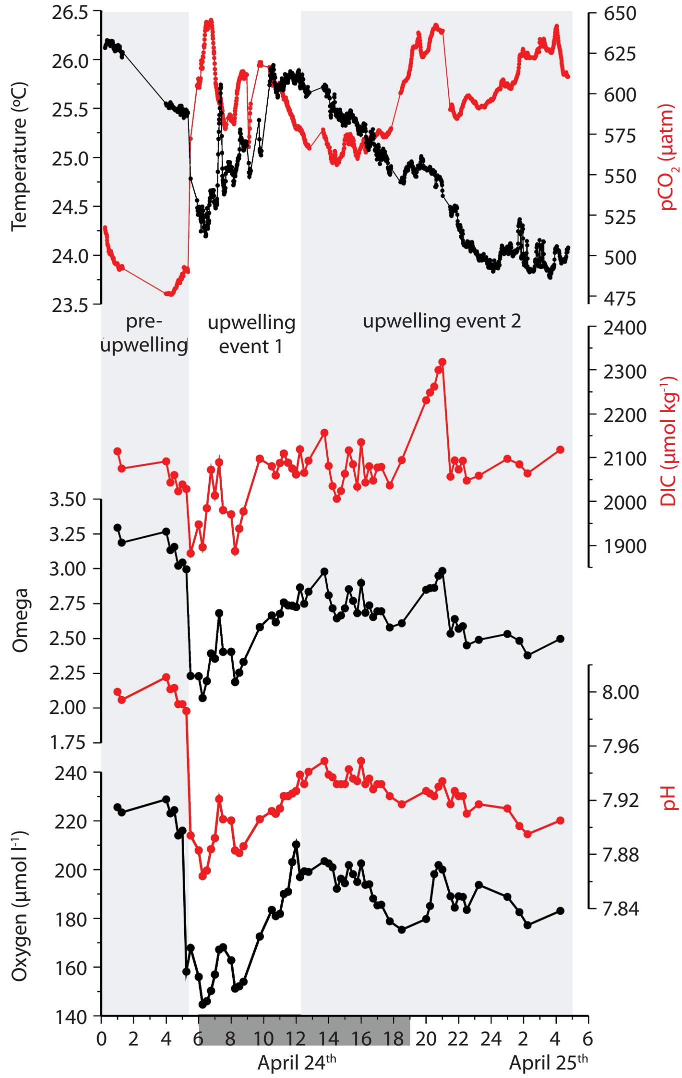


Fig. 2. Temperature, pCO_2, dissolved inorganic carbon (DIC) concentrations, omega (Ω_a), pH, and dissolved oxygen concentrations determined at the pier of the Marina Papagayo, Costa Rica. The light bars indicate the pre-upwelling period and the second upwelling event.

with temperatures between approximately 14.5 and 16.5 C°. Since such low SSTs occur only during extreme strong upwelling events at the surface (Fig. 3a) oxygen-depletion caused the entrainment of oxygen-poor subsurface water appears only occasionally be of importance at the study site. However, this might change in future because mid-water oxygen minimum zone are expanding in the ETA (Stramma *et al.* 2008, Stramma *et al.* 2010) and a strengthening of the trade winds system and the associated upwelling systems is assumed to be caused by global warming (Mitas & Clement 2005, 2006, Bakun *et al.* 2010).

SSTs correlate not only with the oxygen concentrations but also with the pH and DIC/TA ratios (Fig. 4 a, b). Varying values and relationships between these parameters and the

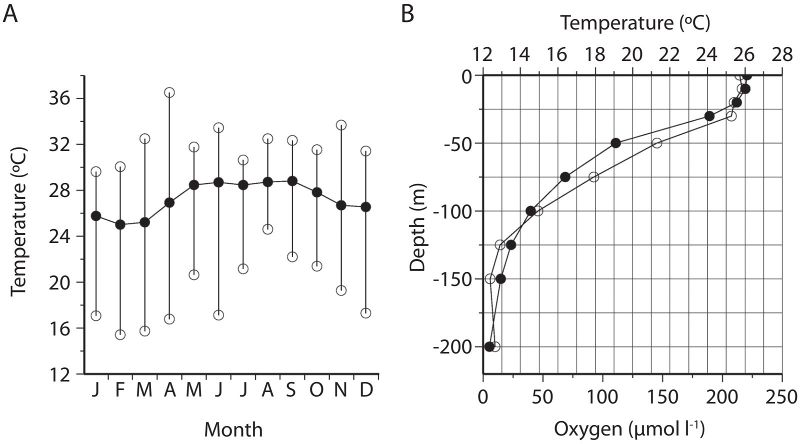


Fig. 3. (a) Monthly mean temperatures (black circle) as well as maxima and minima derived from measurements carried out in a reef close to our sampling site between December 1994 and March 2009. (b) Profiles showing the distribution of temperature (black circles) and dissolved oxygen concentrations (open circles) in the water column. This data were selected from the 1x1 degree gridded World Ocean Atlas for the grid box at 85°W and 10°N.

SSTs indicate a different history of the water masses, which were entrained into the surface waters during the pre-upwelling period and the two upwelling events. The main factor controlling the pH and the pCO_2 is the DIC/TA ratio as indicated by the correlation between this ratio, the pH and $pCO_{2(DIC/TA)}$ (Fig. 4 c, d). The DIC concentration and the TA are influenced by the precipitation and dissolution of calcium carbonate as well as by the photosynthesis and the respiration of organic matter (Fig. 5). In addition to these two biological processes wind-induced turbulent mixing of surface and subsurface water could be another important factor affecting these parameters at our sampling site. Contrary to biological processes and mixing, the CO_2 fluxes across the air-sea interface, which as assumed to be minor importance on the time scale considered here (Frankignoulle *et al.* 1996) influence the DIC concentration, only. Since respiration consumes oxygen and release DIC, oxygen-depleted subsurface waters are generally enriched in DIC. This appears not be the case at our study during the first upwelling event (Fig. 2). During this event water depleted in oxygen, DIC, and TA welled up and displaced surface waters enriched in all these parameters. Enhanced DIC concentrations and high TA imply that the dissolution of carbonates was a dominant process within the surface water during the pre-upwelling period. The much slower entrainment of subsurface water and resulting stronger effect of the carbonate dissolution on the carbonate chemistry within the upwelled water might also explain the higher pH values within the surface water during the second upwelling event. Ignoring physical effects, increases of the DIC concentration and the TA would imply a mean carbonate dissolution to respiration ratio of ~1.8 during the pre-upwelling period as indicated by the linear correlation between DIC and TA (Fig. 5). During the first upwelling event the mean carbonate dissolution to respiration ratio was 1.3. If this ratio would have been < ~1 due to reduced dissolution of calcium carbonate and an enhanced respiration an increase in DIC and TA would have reduces instead of increased Ω_a (Fig 5).

Prior to the first upwelling event between 1:00 and 5:00 am, Ω_a was ~3.2 with slightly lower than the values shown on maps (~3.5-3.6) derived from climatological data for the region off Costa Rica (Manzello *et al.* 2008). During the first upwelling event, Ω_a fell to values as

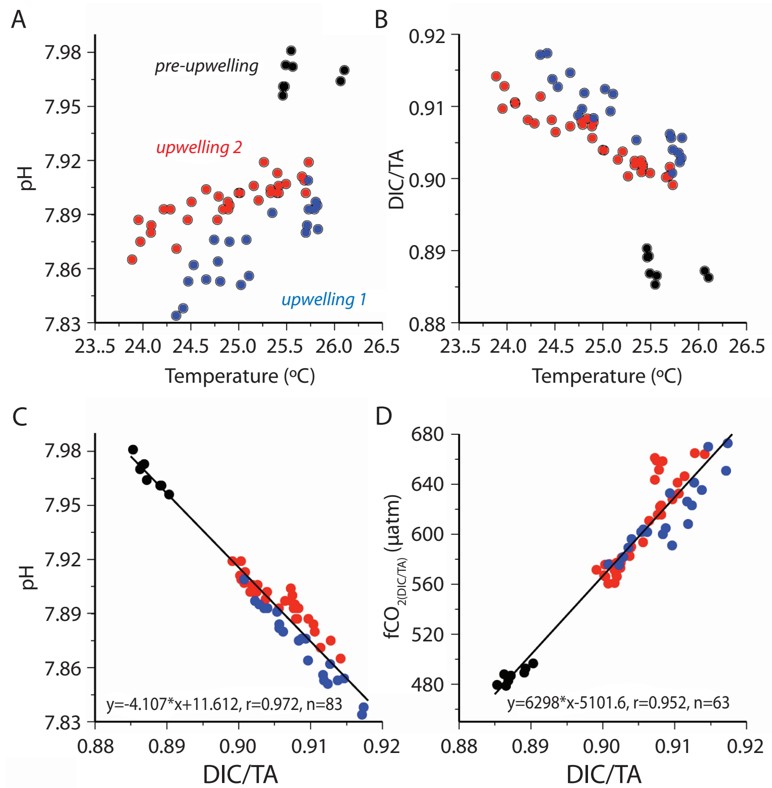
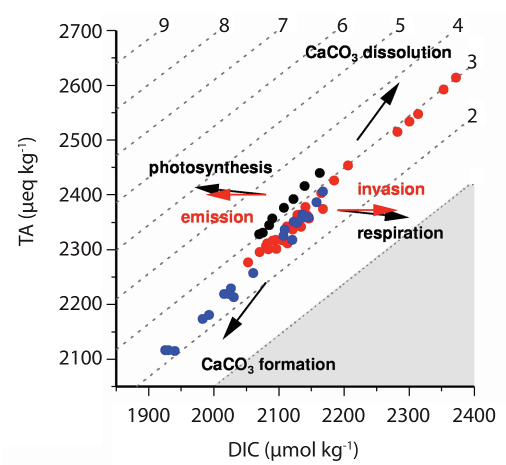


Fig. 4. Temperatures versus pH (a) and the DIC/TA ratios (b) as well as the DIC/TA ratio versus the pH (c) and the temperature corrected fCO_2 ($fCO_{2(DIC/TA)}$) (c). Black, red, and blue circles indicate the data measured during the pre-upwelling period, the first and the second upwelling event.



low as ~2.1. During the second, slower entrainment of subsurface waters, Ω_a reached a value of ~2.5 which is similar to those measured in reefs effected by upwelling in Galápagos (Fig. 6). Such low Ω_a's could reduce the growth of many coral species (Langdon & Atkinson 2005, Kleypas *et al.* 2006) and favor, at the same time, bioerosion within reefs by reducing the formation of carbonate cements (Manzello *et al*. 2008). Bioerosion could explain

Fig. 5. Dissolved inorganic carbon concentrations (DIC) versus the total alkalinity (TA) measured during the experiment. The arrows indicate the impacts of the mentioned processes on the DIC concentration and the TA. The dotted lines show constant levels of Ω_a and the number indicates the levels. The shaded area reveals the area characterized by an $\Omega_a < 1$. For calculating the constant Ω_a lines a mean temperature and salinity of 25.09 and 34.51 was considered. Black, red, and blue circles indicate as mentioned in figure 4 the data measured during the pre-upwelling period, the first and the second upwelling event.

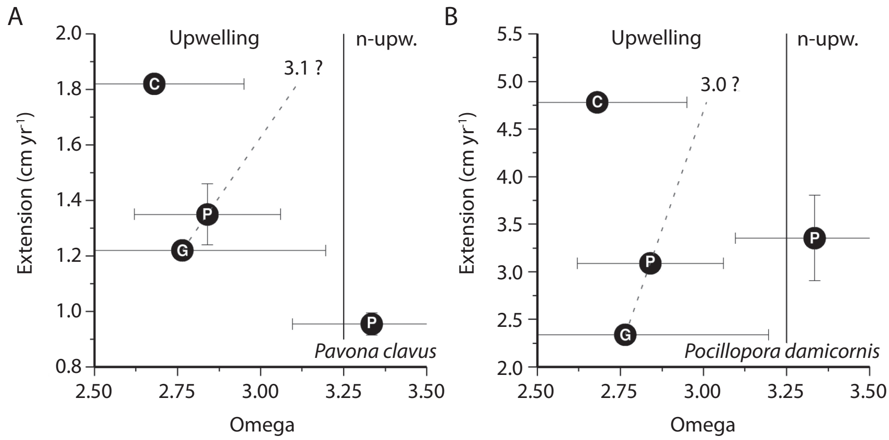


Fig. 6. Mean omega (Ω_a) versus mean linear extension rates derived from *Pavona clavus* and *Pocillopora damicornis* in Galápagos (G), Panamá (P), and at our study site in Costa Rica (C). The data from Galápagos (G), Panamá (P) were obtained from Manzello et al. (2010a,b) and the error bars indicate the standard deviations. The broken line shows regression equation derived from data obtained in the upwelling region and number shows the annual Ω_a at which the linear extension rates measured at our study site would meet the regression lines.

carbonate dissolution in water supersaturated with respect to calcium carbonates (Ω_a <1, Fig. 5) and lowers impacts of acidic water in reefs by increasing Ω_a during upwelling periods.

The main reef building corals in the vicinity of our study sites *Pocillopora* spp. and *Pavona clavus* reveal growth rates exceeding those measured in Galápagos, Panamá, and Colombia (Fig. 6, Jiménez & Cortés 2003). Coral calcification is an energy demanding process in the course of which proton pumps such as the Ca^{2+}-ATPase increase pH and the Ca^{2+} concentration within the calcifying cells (Al-Horani *et al.* 2003). Accordingly it was suggested that an enhanced energy supply could also counteract effects of a reduced Ω_a on the coral calcification by increasing the activity of the Ca^{2+}-ATPase (Cohen & Holcomb 2009). High density of nutrient and biomass and the resulting enhanced autotrophic and heterotrophic energy supply might in addition to hosting growth supporting thermally less tolerant zooxanthellae, be a process explaining the high growth rate of *Pocillopora* spp. and *Pavona clavus* at our study site (Manzello 2010a). However, in high productive regions shading caused by the high biomass density could reduce the penetration depth of light and thus the photosynthesis. Compared to *Pavona calvus, Pocillopora damicornis* seem to be less efficient in compensating a reduced energy supply of its zooxanthellae by an increased heterotrophic feeding (Houlbrèque & Ferrier-Pagès 2009). This might be a reason for the growth rates of *Pocillopora damicornis* which are lower in upwelling regions off Galápagos and Panamá than in the non-upwelling region off Panamá and their enhanced sensitively against ocean acidification in the ETA (Manzello 2010a). However, the high growth rates at our study site in Culebra Bay might additionally be favored by a higher Ω_a during the non-upwelling season, which needs to be proved in future studies. Such future studies should also consider impacts of reduced availability of dissolved oxygen on the heterotrophic energy supply, which is assumed to be of importance for counteracting ocean acidification effects in upwelling influence reef in future.

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RESUMEN

El Golfo de Papagayo, costa Pacífica de Costa Rica, es una de las tres regiones de afloramiento estacional de Mesoamérica. Las características físicas y químicas del agua que aflora no habían sido estudiadas. Durante 29 horas en Abril 2009, se estudiaron la temperatura superficial del mar (TSM), la concentración de oxígeno disuelto, salinidad, pH y la presión parcial de CO_2 (pCO_2), en la Marina Papagayo, Bahía Culebra. Con base en las mediciones de pH y pCO_2 se calculó el estado de saturación de la aragonita (Ω) y otros parámetros del sistema de carbonatos como lo es el carbono orgánico disuelto (COD) y la alcalinidad total (AT). Los resultados indican que el arrastre por convección del agua sub-superficial durante los eventos de afloramiento aumenta la pCO_2 y disminuye la TSM, la concentración de oxígeno disuelto y Ω. Aunque se asume que estas condiciones reducen el crecimiento coralino, las principales especies constructoras de arrecife en la región de Papagayo (*Pocillopora* spp. y *Pavona clavus*) tienen las mayores tasas de crecimiento en el Pacífico Tropical Oriental. Esto posiblemente implica que el efecto negativo del afloramiento es compensado por el crecimiento durante la época de no afloramiento.

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