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Seawater temperature measured at the surface and at two depths (7 and 12 m) in one coral reef at Culebra Bay, Gulf of Papagayo, Costa Rica

Carlos Jiménez [1-2]
[1]Centro de Investigación en Ciencias del Mar y Limnología (CIMAR), Universidad de Costa Rica, 2060 San José, Costa Rica. Fax (506) 207-3280.
[2]Present address: Zentrum für Marine Tropenökologie (ZMT), Universität Bremen, Fahrenheitstr. 6, D-28359 Bremen, Germany. Fax (049) 0421-2380-030; carlos.jimenez@zmt.uni-bremen.de

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Abstract: Superficial seawater temperature (SST) and at two depths (7 and 12 m) were measured non-continuously during the study of the corals and coral reefs of Culebra Bay (1993-1996). SST showed seasonal variations of ~4°C. The highest average temperatures (27.0 ± 0.1, range 23-29°C) were during the rainy season from May to November and the lowest (22.9 ± 0.3°C, 15.5-29°C) during the dry season from December to April. Cold fronts with 2-3°C differences in SST frequently pass into the bay and remain there for several hours according to the tidal cycles. Differences of ~3°C between SST and the bottom (5-10 m depth) were usually found, particularly at locations where bottom topography and tidal circulation produced tidal bores. The average temperatures recorded by data loggers placed at 7 and 12 m depth on a coral reef at the outer shores of Culebra Bay, were 27.1 ± 0.02ºC (20.5 – 31.6ºC) and 25.8 ± 0.04 (9.9-31.5ºC) respectively. The seasonal pattern of higher and lower temperatures corresponds respectively to the rainy and dry season of the northern Pacific coast of Costa Rica. Water temperature at 12 m was <14ºC for some hours during an upwelling event whilst minimum temperatures at 7 m were ≥ 22ºC. Negative temperature anomalies coincided with an increase of the NE-E winds intensity and there is a lunar and tidal component which influence diurnal variations of temperature. These results suggest that coral reefs built by branching species (e.g. *Pocillopora* spp.) in Culebra Bay could be limited by both the influence of cold fronts and by seasonal upwellings which affect negatively those coral species, as reported for other locations in the tropical eastern Pacific.

Key words: Corals, upwelling, eastern Pacific, Costa Rica, Guanacaste, temperature.

In the tropical eastern Pacific there are coastal upwellings of considerable dimensions (»300 km) at the gulfs of Tehuantepec (México), Papagayo (Costa Rica) and Panamá (Hubbs & Roden 1964), where the most productive waters of the region are located (Fiedler *et al.* 1991). In the region of Papagayo, the continental platform is relatively narrow, favoring the influence of oceanic waters on the coastal waters (Brenes *et al.* in prep.). Additionally, there is a topographical gap (>70 km) between the Guanacaste volcanic mountain range and the region of the Nicaraguan Lakes, affecting the local meteorology by canalizing the wind flow along the gap's axis (Stumpf & Legeckis 1977). This occur with more intensity during the displacement of the polar air masses over the Caribbean Sea as the pressure gradient NE-SO is incremented in the gap's axis (Clarke 1988). The shallow water currents produced by those winds along their trajectory, displace superficial water in the opposite direction of the Nicaraguan and Costa Rican coast (McCreary *et al*. 1989), diminishing the superficial seawater temperature (SST) by as much as 10°C in a few hours (Legeckis 1988) and maintaining low temperatures (<21°C) for 3-10 days for several months (Stumpf & Legeckis 1977, Clarke 1988, Brenes *et al*. 1995).

Temporal or transitory oceanographic environment with marginal temperatures for marine organisms such as corals occurs due to the intensity and duration of the upwelling. Low seawater temperatures *per se* cause mortality in corals and other marine invertebrates (Glynn & D'Croz 1990, Gates *et al*. 1992), although sublethal or indirect effects on the corals' reproduction, growth and reef accretion have been reported (Glynn 1977, Richmond 1990, Pennings 1997).

Culebra Bay, located in the Gulf of Papagayo, is one of the most important reservoirs in the Costa Rican Pacific coast for coral species, and has several unique coral reefs which have not been observed elsewhere (Jiménez 1997, 2001, this volume). Therefore, it is important to characterize the local water temperature settings in the reefal environs of the bay, and to discuss the possible role of the seasonal upwelling in the distribution and growth of the coral reefs in this area.

MATERIAL AND METHODS

Sea surface temperature (SST) was recorded from 1993 to 1996 in different locations at Culebra Bay utilizing a calibrated mercury thermometer. Recordings were made several times during the day (6-12 days depending on the month), and taken directly at the surface from the boat or by divers while surfacing from the working sites at the reefs. Additionally,

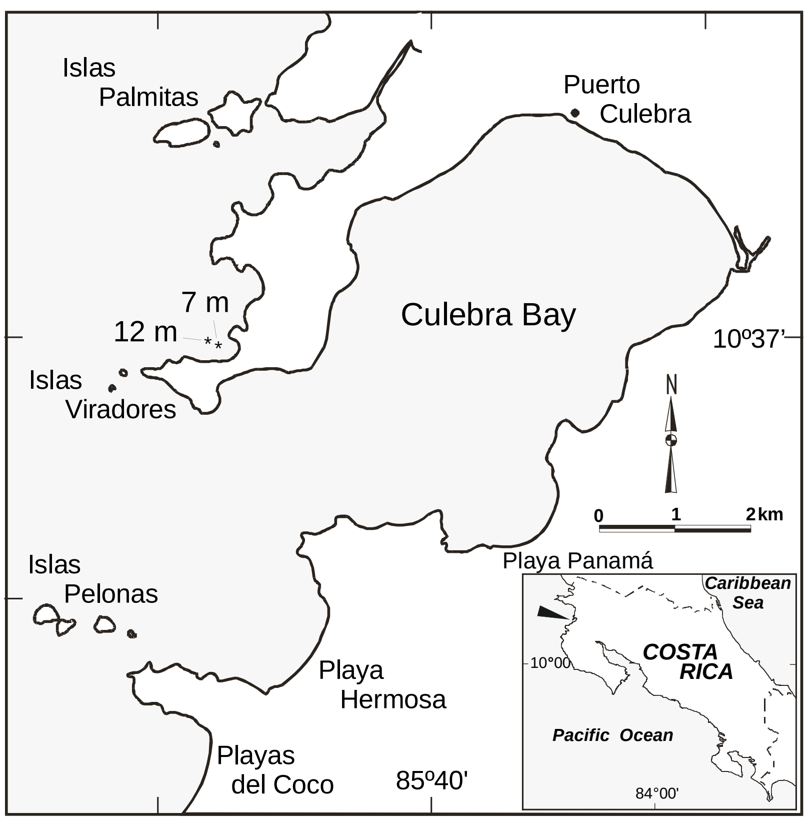

Fig.1. Location of the Güiri-Güiri reef at Culebra Bay, Gulf of Papagayo, where the data loggers for temperature at 7 (one unit) and 12 m (two units) depth were deployed.

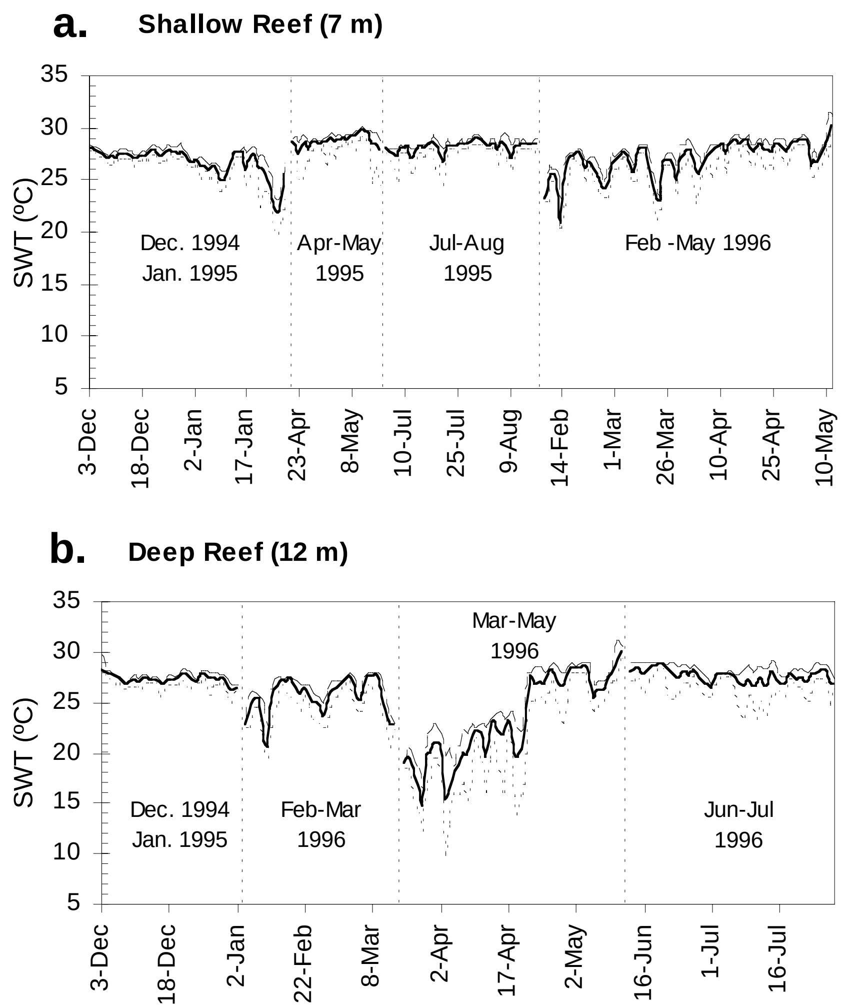

Fig. 2. Average seawater temperature (SWT) at 7 (a.) and 12 m (b.) depth taken at Güiri-Güiri coral reef, Culebra Bay. See text for temperature measurements frequency.

submersible data loggers for temperature (Hobotemp®, Onset Computer Corp.) were placed at 7 and 12 m depth in a reef known locally as Güiri-Güiri, in the external shores of the bay (Fig. 1), and replaced during the next 30-35 days. Continual readings were taken every 24 min for the period of time from 3-XII-1994 to 28-I-1995 (7 and 12 m depth) and every 36 min from 21-IV-1995 to 11-V-1996 (7 m depth) and 28-VII-1995 to 28-VII-1996 (12 m). It was not possible to have a continuous temperature record from 1994 to 1996 due to problems with the loggers' batteries and loss of one unit.

RESULTS

The average SST temperature (± standard error) measured in Culebra Bay during the upwelling season (December-April) was 22.9 ± 0.3 °C (range: 15.5 - 29°C, n= 134) and 27.0 ± 0.1°C (23 – 29.5°C, n= 162) for the rest of the year. Occasionally during the non-upwelling season (May-November), strong eolic streams of short duration (5-6 hrs) generated cold fronts that suppress SST by 3°C for some hours. Also the formation of numerous Lagmuir cells has been recorded during periods of moderate

TABLE 1

Average ± standard error of monthly temperatures (°C) at 7 and 12 m depth in the Güiri-Güiri coral reef, Culebra Bay. Average monthly differences (Diff.) between both depths are indicated as well as the number of measurement (N). Paired T-test showing degrees of freedom (df), descriptor (t) and probability (p)

Year	Month	7 m	12 m	Diff.	N	df	t	p
1994	Dec	27.4 ± 0.01	27.3 ± 0.01	0.13	1714	1713	25.27	<0.01
1995	Jan	26.6 ± 0.02	26.3 ± 0.04	0.25	87	86	5.59	<0.01
	Apr	28.3 ± 0.03	--	--	--	--	--	--
	May	28.9 ± 0.03	--	--	--	--	--	--
	Jul	28.0 ± 0.02	--	--	--	--	--	--
	Aug	28.2 ± 0.02	--	--	--	--	--	--
1996	Feb	25.5 ± 0.06	25.1 ± 0.07	0.37	820	819	27.78	<0.01
	Mar	26.5 ± 0.05	23.5 ± 0.11	3.1	750	749	21.5	<0.01
	Apr	27.8 ± 0.03	22.5 ± 0.11	5.3	1200	1199	54.7	<0.01
	May	28.1 ± 0.05	27.6 ± 0.06	0.5	458	457	17.57	<0.01
	Jun	--	27.9 ± 0.02	--	--	--	--	--
	Jul	--	27.3 ± 0.02	--	--	--	--	--

winds. This elliptic circulation, which is produced near the surface, usually produces fronts parallel to the wind direction (Wolanski & Hamner 1988). Because Langmuir cells could be recognized by their size and by the appearance of the water at the surface of the front (result of differences in density, Le Fèvre 1986), it was possible to measure SST inside and outside (~2.5 m apart) of one of such well defined fronts, resulting in a difference of 3.5°C. Not infrequently, SST was 2-3°C higher than at 5-10 m depth during the rainy season, this being more common at the inner littoral of the bay and in sheltered or semi-enclosed coves of the outer littoral.

Average temperature at 7 m depth in the Güri-Güiri reef was 27.1 ± 0.02°C (range 20.5 – 31.6°C, n= 5029), and 25.8 ± 0.04°C (9.9 – 31.5°C, n= 6829) at 12 m. Higher temperatures at both depths (Fig. 2) generally occurred during the rainy season months (May-November) and low temperatures during the dry season (December-April). Considering the months with simultaneous temperature recordings at both depths (Table 1), average differences between the shallow and deep reefs (0.13 to 5.33°C) are significant for the whole study period, markedly for April 1996. On April 4, temperature at the deep reef was less than 14°C during almost four hours (17:00-21:30 hrs), while at the shallow reef (<80 m apart) minimum temperatures were significantly higher (>22°C) during the same time. Northeast winds intensified around that day, triggering an upwelling comprising the Papagayo Gulf and San Juan del Sur (Nicaragua) (Fig. 3). The

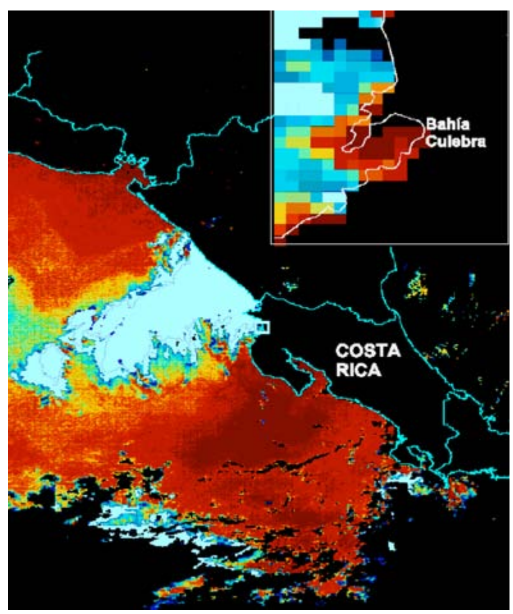

Fig. 3. Satellite image during an upwelling event (4-IV-1996, 13:00 hrs). Scale of grays for SST: dark corresponds to warm waters (>26°C), and increasing light patterns to cold (<22°C) waters. Center of the upwelling enhanced to facilitate recognition. Upwelled waters were located a few kilometers from the reef with the data loggers (insert). NOAA-Laboratorio de Oceanografía y Manejo Costero, Universidad Nacional, Heredia.

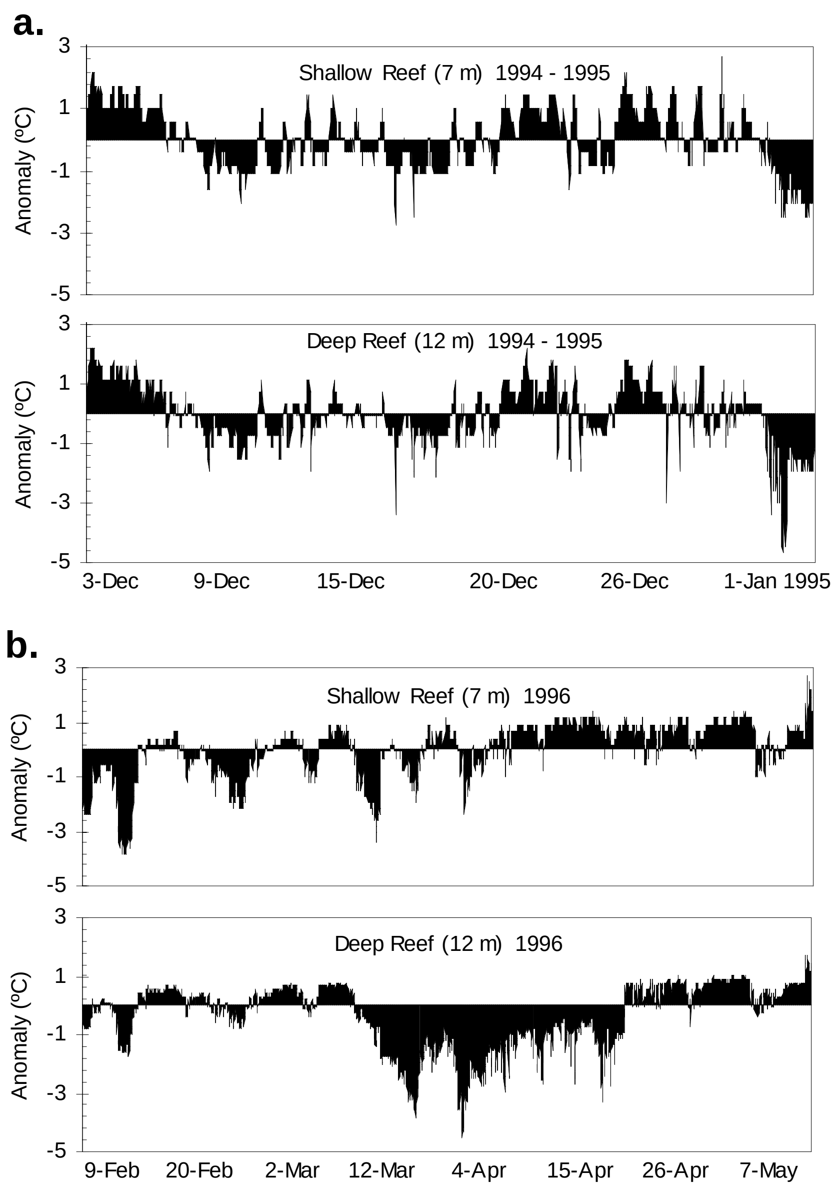

Fig. 4. Thermal anomalies (1994-1996 average) at the beginning (a.) and during (b.) the upwelling season of 1996 at 7 and 12 m depth at Güiri-Güiri coral reef, Culebra Bay.

satellite image (13:00 hrs) shows the upwelled waters located 3-5 km from Culebra Bay, and it is wasn't until 17:00 hr of the same day that the data logger at 12 m depth registered the arrival of the incoming cold waters (<14°C) which remained there until 21:30 hr. During this period, water temperature at 7 m remained over 20°C. The cold water front incursion into the deep reef was short (related with the tidal change) but a minimal temperature of 9.9°C over 30 min was recorded.

Comparing temperature anomalies during December 1994, when the eolic events which trigger the coastal upwelling were not fully

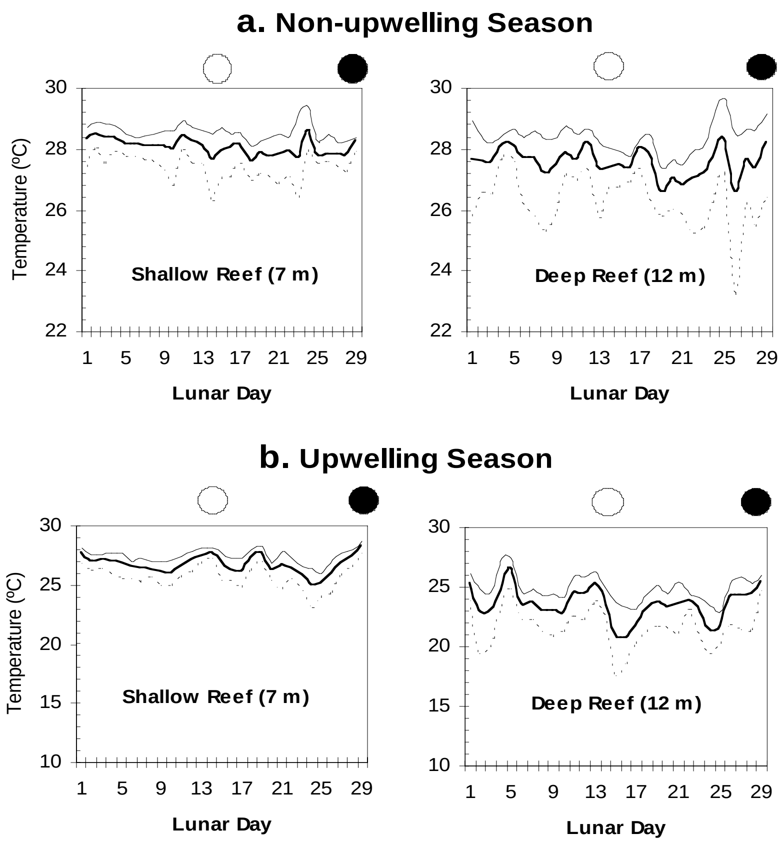

Fig. 5. Average seawater temperature (°C) for each day of the lunar cycle for non-upwelling months (a.) and during (b.) the upwelling season at 7 and 12 m depth at Güiri-Güiri coral reef, Culebra Bay. White and black circles are full and new moon respectively. Temperature averages considered three or more lunar days. Higher temperatures= thin line; Average= thick; Lower= broken. Note different temperature scales.

present, both depths showed similar distribution of temperature anomalies (Fig. 4a), although greater at the deeper reef. The contrary is observed for on April 1996 (upwelling) negative temperature anomalies at 12 m depth were again greater lasted for several days (Fig. 4b).

All temperature data were related with the lunar cycle in order to establish its relation with the tides (Pineda 1991), and separated according to the season (months with or without upwelling) and depth (Fig. 5). Generally, high and low water temperature fluctuated slightly with the lunar day during the months where the upwelling was absent (Fig. 5a), and fluctuated more during the upwelling (Fig. 5b). Tide contribution to these temperature fluctuations becomes apparent when comparing the upwelling of April 1996 and its corresponding lunar day (full moon) in may 1996 (non-upwelling) (Fig. 6). Low temperatures tend to couple with the high tide for both months and depths, indicating the arrival of the tidal wave with cold waters, a process that is strengthened during the strong NE wind season.

DISCUSSION

Seawater temperature at Culebra Bay and in the Gulf of Papagayo in general, present significant seasonal differences related with the occurrence of upwelling events. Typically, the Papagayo upwelling is produced by the intensification of the trade winds (NE-E) during the northern Hemisphere winter and is coincident with the dry season in Costa Rica (Stumpf & Legeckis 1977, Clarke 1988, McCreary *et al.*

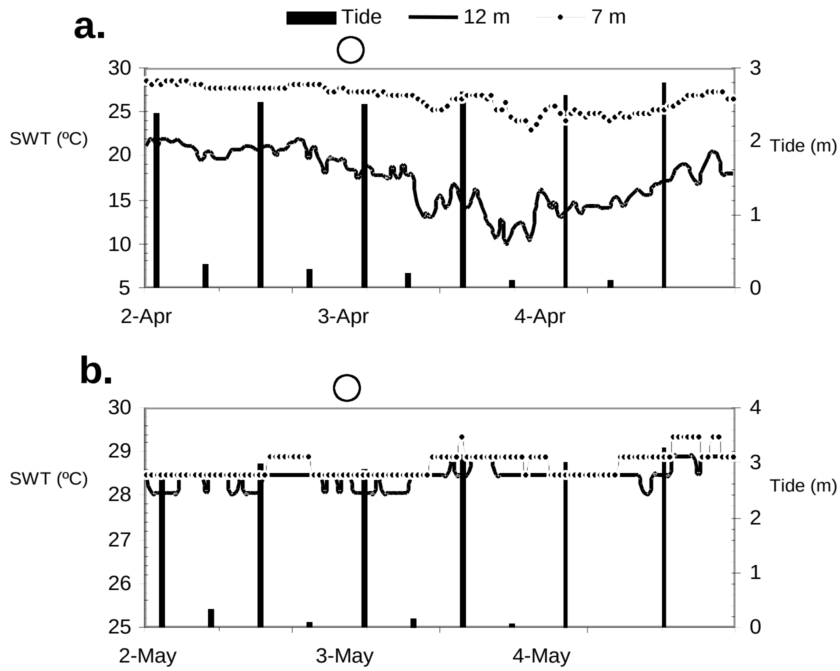

Fig. 6. Seawater temperature (lines) according to tidal cycle (bars) of lunar day 14 (full moon, open circle) in presence (a.) and absence (b.) of an upwelling event at 7 and 12 m depth at Güiri-Güiri coral reef, Culebra Bay. Note different scales of temperature and tide.

1989), producing average seasonal variations of ~ 3.5°C between the rainy and dry season (Brenes & Lizano 1994, Brenes *et al*. 1995).

The majority of those observations mentioned above are based on oceanographic cruises conducted more than 10 km offshore (C. Brenes, pers. com. 1997) and in water masses with probably different characteristics than those present at the shores of Culebra Bay. For example, SST in the bay showed a seasonal variation (~ 4°C) slightly higher than the one reported for oceanic waters (~ 3.5°C, Brenes *et al*. 1995). The difference is probably due to the localized effect of the runoff during the rainy season, for the creation of a temporal thin strata of less dense water at the sea surface is common. Additionally, the incursion into the bay of cold water fronts with differences of 3°C is normal and remain there for several hours. Therefore, SST in the bay is influenced by several factors that produce significant local variations to those temperatures reported for nearby oceanic waters.

Likewise, water temperature at two depths in the Güiri-Güiri reef showed seasonal variations corresponding to the upwelling events and the tidal cycles. The majority of the negative anomalies are associated with an increase in the intensity of the NE-E winds at the bay, being more common during the dry season. At both depths, low temperatures (<23°C) occurred consistently during the dry season (upwelling), and the minimal (<15°C) were recorded during one upwelling event. It is plausible that the light coral bleaching (<15% of colony tissue) observed two weeks later in colonies at 12 m depth was related to this cold front.

It is possible that at Güiri-Güiri reef an increase of height of the tidal wave front is produced by the combined effect of the wave entry (as a well defined cold front) with a pronounced bottom topography in deeper waters (A. Gutiérrez, pers. com. 1997). Those tidal bores (Wolanski & Hamner 1988) markedly decrease seawater temperature in the lower strata and they normally do not mix with the superficial layers or reach the coast.

The fact that the cold fronts depressed water temperature at 12 m depth and not at 7 m, suggests that low temperatures are one of the limiting factors controlling reef growth at that depth. Negative effects of cold water on corals (bleaching, mortality) have been documented under controlled and natural conditions. For example, some reef building coral species in the eastern Pacific (e.g. the branching *Pocillopora* spp.) are susceptible to low water temperature. Extensive bleaching and mortality related to low temperatures (<15°C) during upwelling events, have been reported for this species (Glynn & Stewart 1973, Glynn *et al*. 1983, Eakin *et al*. 1989, Glynn 1990, Glynn & D'Croz 1990, Richmond 1990). Corals' low tolerance to cold water during seasonal upwelling events, poor light penetration and its effects on coral growth and survivorship, are all limiting factors restricting reef building by branching species at the Gulfs of Papagayo and Panamá (Dana 1975, Glynn & Steward 1973, Glynn 1977, Glynn & Macintyre 1977, Glynn *et al*. 1983, Guzmán & Cortés 1993, Glynn & Maté 1997).

It is possible that seawater temperature in other reefs at Culebra Bay follows similar patterns as observed at Güiri-Güiri, for there is no reef construction by branching species at depths beyond 10 m (Jiménez 1997, 1998, 2001, this volume). Therefore, seasonal fluctuations in physical parameters, such as seawater temperature, due to upwelling events may have an important role in structuring and limiting coral reef growth at Culebra Bay and other regions of the eastern Pacific with seasonal upwelling of cold waters.

RESUMEN

Se midió la temperatura superficial del mar (TSM) y a dos profundidades (7 y 12 m), durante el estudio de los ambientes arrecifales de Bahía Culebra (1993-1996). La TSM en la mayor parte de la bahía presenta variaciones estacionales de ~ 4ºC. La temperatura promedio más alta (27 ± 0.1ºC, ámbito 23 - 29ºC), se presenta en la época de lluvias de mayo hasta noviembre y las mínimas (22.9 ± 0.3ºC, 15.5 - 29ºC) en la época seca de diciembre hasta abril. Frecuentemente ingresan en la bahía frentes fríos con diferencias de TSM de 2 a 3ºC y permanecen por varias horas de acuerdo a los cambios mareales. En varias oportunidades se registraron diferencias entre la TSM y el fondo (5 - 10 m) de ~ 3ºC, especialmente en zonas donde la topografía del fondo y la marea producen saltos hidráulicos (Tidal Bores). El promedio de mediciones de temperatura en un arrecife de la bahía y a 7 y 12 m de profundidad fue de 27.1 ± 0.02ºC (20.5 - 31.6ºC) y 25.8 ± 0.04ºC (9.9 - 31.5ºC) respectivamente. El patrón estacional de las mayores y menores temperaturas corresponde respectivamente a la estación lluviosa y seca de la costa Pacífico norte de Costa Rica. Durante un evento de afloramiento la temperatura a 12 m fue menor a 14ºC durante cuatro horas, en tanto que a 7 m las temperaturas mínimas no disminuyeron de 22ºC en el mismo período. La distribución de las anomalías de temperatura negativas coincide con aumentos en la intensidad del viento NE-E, y existe un componente lunar y mareal que influye en las variaciones diurnas de temperatura. Los resultados indican que en Bahía Culebra, al igual que en otras localidades del Pacífico oriental, el desarrollo de arrecifes coralinos construidos por especies ramificadas (*Pocillopora* spp.) puede estar limitado por la incidencia de frentes fríos que afectan negativamente estas especies.

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