Cold water bleaching of *Pocillopora* in the Gulf of California

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Abstract. Changes in sea-water temperature on coral reefs can cause mass coral bleaching events resulting in widespread coral mortality. In the last five years, coral communities of the Gulf of California have had bleaching events caused by temperatures below 19 °C. A cold water bleaching event occurred in February 2011, providing an opportunity to assess the bleaching response and verify bleaching susceptibility among *Pocillopora* morphospecies. Across three surveyed locations, 84% of corals showed visual signs of bleaching to a minor or major degree. The southern-most location was the least affected by cold water bleaching; possibly due to the exposition of high levels of wave and current that could diminish the effects of high sea surface temperatures, acclimation of colonies to seasonal upwelling of cold water from the California current, and the frequency of cold-resistant *Symbiodinium glynni* in coral colonies, which all suggest adaptation to harsh temperature conditions. High significant bleaching to cold water was found between *P. damicornis* and the rest of *Pocillopora* morphospecies (*P. verrucosa*, *P. meandrina, and P. capitata*). High bleaching susceptibility of *P. damicornis* could be due to intra-specific differences in symbiont or genotypic variation among colonies, and other factors such as local water circulation and/or flow velocity that can also influence bleaching and morphological plasticity in *Pocillopora* corals. A better understanding of bleaching events and the ability of corals to respond to periods of thermal stress (cold or warm) will allow managers to target particular reef ecosystems for protection.

Key words: Coral bleaching, Cold stress, Bleaching susceptibility, Eastern Pacific, *Pocillopora,* Morphospecies.

Introduction

Changes in sea temperature on coral reefs can cause mass coral bleaching events resulting in widespread coral mortality. Bleaching is a response by corals to stressful conditions and results in a paling or whitening caused by photo-inhibition and expulsion of microalgae endosymbionts (*Symbiodinium* spp.) (Hoegh-Guldberg 1999). Depending on the intensity and duration of the thermal stress, bleaching can result in differential mortality among taxa (depending of host-symbiont association) or between locations (Hoegh-Guldberg 1999, Lesser 2011, Lirman et al. 2011).

Research on coral bleaching impacts caused by extreme sea temperature events have concentrated almost entirely on elevated temperatures because the majority of bleaching events have been correlated with these conditions and the increasing concern about global warming (Hoegh-Guldberg 1999, Lirman et al. 2011). However, impacts of cold temperature events on coral physiology and mortality can be identical or even higher than warm-water events (Saxby et al. 2003, Hernández et al. 2010, Lirman et al. 2011). For example, catastrophic impacts were recorded in the Florida Reef Tract during an extreme cold water event (<16°C) in January 2010 (Lirman et al. 2011). Coral mortality was as 1-2 times greater than previous that caused by warm temperatures in the region. The impacts were species-specific; taxa with high resistance to warm-water events were more affected by the cold water event than more susceptible spp. (Lirman et al. 2011).

In the Gulf of California, the first record of cold water bleaching was in February 1988, near Los Cabos (23°N), where 95% of *Pocillopora* corals, the main component of coral communities in the middle and southern gulf, were dead by July 1989 (Wilson 1990). More recently, in the south-western Gulf of California, cold water bleaching of 10–60% was reported in 2006, with temperatures below 19°C. Only two years later, more extreme temperatures (~17°C) caused severe coral bleaching of up to 90% of *Pocillopora* corals in some locations (Hernández et al. 2010, LaJeunesse et al. 2010). General recovery of colonies was visible five months after the bleaching event, except in the northern locations (around Bahía de Loreto National Park, 25°50’N), where 90% of the *Pocillopora* community was dead due to the bleaching event (Hernández et al. 2010, LaJeunesse et al. 2010).

Here, we assess the February 2011 cold water bleaching event in the Gulf of California in terms of susceptibility to bleaching among the dominant coral group (*P. capitata, P. damicornis, P. meandrina,* and *P. verrucosa*), and discuss the differences in bleaching among three locations at the southern Baja California Peninsula.

Material and Methods

Field surveys

Field surveys were conducted in April 2011 at three locations near the city of La Paz (24°05'N, 110°20'W; Fig. 1). To quantify *Pocillopora* corals bleaching, five replicate 20 × 2 m belt transects, parallel to the shoreline, were surveyed at each site (Fig. 1); except in Punta Arenas where two transects were surveyed. On each side of the transect line, a 1 m^2 quadrat was photographed every 1 m. In addition, *Pocillopora* colonies were recorded and assigned to one of four morphospecies (*P. capitata, P. damicornis, P. meandrina,* and *P. verrucosa*) according to their morphological characteristics (Veron, 2000; Ketchum and Reyes-Bonilla, 2001). Here, we refer to these corals as *Pocillopora* morphospecies because they comprise one genetic group in the Gulf of California (*Pocillopora* type 1, *sensu* Pinzón and LaJeunesse 2011).

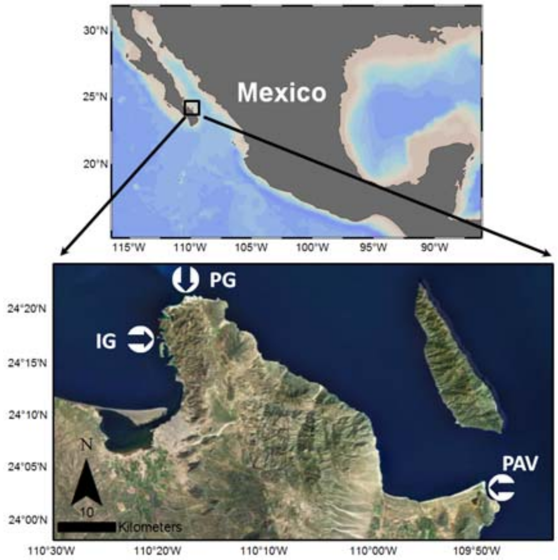

Figure 1: Map of surveyed locations in the southern Baja California Peninsula, Mexico. (IG) Isla Gaviotas, (PG) Punta Galeras, and (PAV) Punta Arenas de la Ventana.

A random point count method was used to estimate coral bleaching in each photo-quadrat using Coral Point Count estimate with Excel extensions (CPCe, Kohler and Gill 2006). The stratified random method (two rows and two columns with five random points in each cell for a total of 20 points in each quadrant) was used to determine the distribution of random points.

Degree of bleaching of each *Pocillopora* morphospecies was recorded from the photo-quadrats and assigned to one of three categories (0 = healthy, 1 = minor bleaching [<50% bleached tissue], and 2 = major bleaching [>50% bleached tissue]). The three categories were ranked using a Kruskal-Wallis test to determine statistical differences in the degree of bleaching of colonies among *Pocillopora* morphospecies and among locations. For all significant results, a Mann-Whitney post-hoc test with Bonferroni correction was performed.

Temperature data

To record changes in sea surface temperature (SST) during cold water bleaching, satellite and *in situ* data were used. Data from the AVHRR sensor (resolution of 11 km) were accessed (Kilpatrick *et al.* 2001; http://las.pfeg.noaa.gov/oceanWatch). Temperature data corresponded to geographic coordinate 24.4154°N, 110.097°W. *In situ* water temperature was recorded by an underwater data logger (HOBO Pendant, Onset Computer Corporation) from March 2003 through February 2008 at 3 km and 8 km from the Isla Gaviotas and Punta Galeras reefs, respectively (HOBO location was 24.3123°N, 110.3363°W at 5 m). Linear regression of daily satellite-derived SST data vs. *in situ* sea temperature data between March 2003 and February 2008 showed close agreement between these two data sources ($r^2 = 0.8136$, $P < 0.001$).

To compare the magnitude of recent cold water bleaching events in the Gulf of California, Oceanic Niño Index (ONI) data were accessed from 1986 to 2011 through the Climate Prediction Center (www.cpc.ncep.noaa.gov).

Results

Temperature data

Average monthly SSTs when no cold water bleaching occurred between 2004 and 2010 were characterized (Fig. 2B). The normal cold season is between December and April with an average monthly temperature of 21 ± 1 °C (Mean ± S.D.) in the south of the Gulf of California. January, February and March were consistently the coldest months in this period (20 ± 1 °C).

During the cold water bleaching event in the Gulf of California in February 2011, SSTs dropped to less than 18 °C and the average of SSTs of January to March for cold water bleaching years was 19 ± 1 °C (2006, 2008, and 2011). SSTs during cold water bleaching were significantly lower than SSTs observed in non-bleaching years during the 2004–2010 period ($P < 0.001$, Mann-Whitney *U*-test).

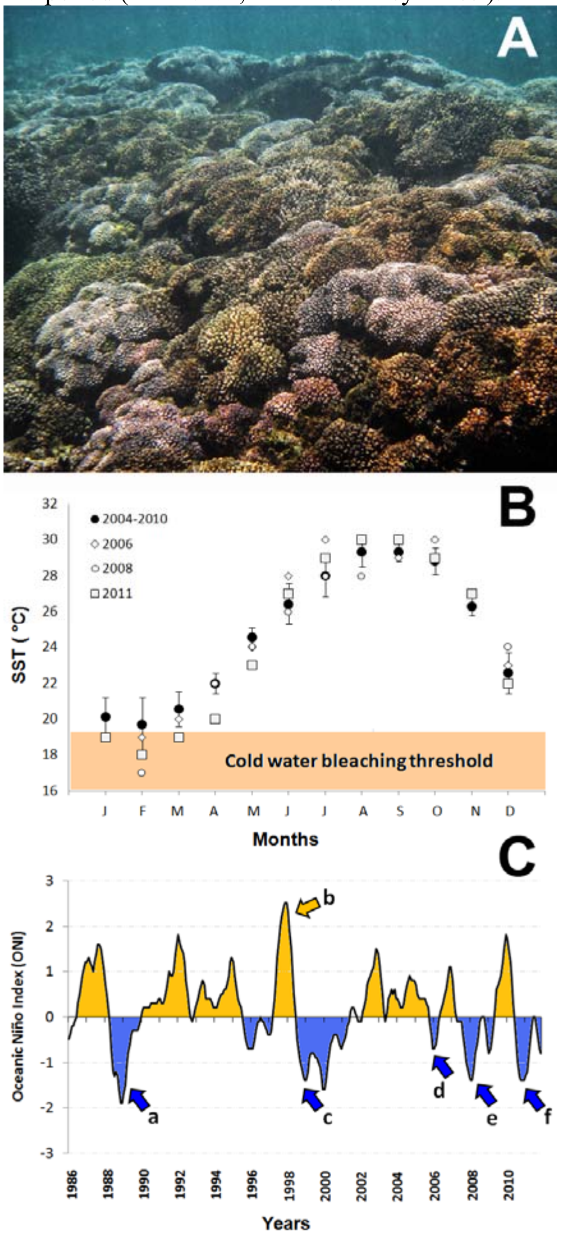

Figure 2: Cold water bleaching event in 2011 in the southern Gulf of California. (A) Bleaching event of *Pocillopora* colonies in Punta Galeras (B) Average monthly SSTs between 2004 and 2010 (black circles), and of years of recent cold water bleaching in 2006, 2008, and 2011 (open symbols). Squares represent the cold water bleaching threshold (<19 °C) for *Pocillopora* corals in the Gulf of California. (C) Oceanic El Niño Index (ONI) from 1986 to 2011. Letters indicate high bleaching events in the Gulf of California in the last 25 years according to: (a) Wilson 1990; (b) Reyes-Bonilla 2002; (d, e) LaJeunesse 2007, 2010; and (f) this study. According to Reyes-Bonilla (2001), no cold water bleaching occurred at (c), despite of ONI values.

The cold water bleaching threshold for *Pocillopora* corals in the Gulf of California is around of 19 °C. The occurrence of cold water bleaching was distinguished by Oceanic Niño Index (ONI), which indicated five cold water events in the last 23 years in the Gulf of California (Fig. 2C). For these five events, four cold water bleaching events were documented, but during the period 1998-1999 no cold water bleaching occurred despite of ONI values.

Cold water bleaching

Eighty four percent of surveyed *Pocillopora* colonies showed signs of bleaching during the cold water bleaching event. The percent of bleaching was twice as high in the northern locations of Isla Gaviotas (30%) and Punta Galeras (35%) compared with the southern Punta Arenas (15%) where there were more colonies with normal coloration (9%; Fig. 3). The Kruskal Wallis test revealed a significant effect of locations on conditions of colonies ($\chi^2_{(2, n=1726)} = 36.44$, $P < 0.001$). A post-hoc test using Mann-Whitney *U*-tests with Bonferroni correction showed the significant differences between Punta Arenas and Isla Gaviotas ($P < 0.001$) and between Punta Arenas and Punta Galeras ($P < 0.001$). No significant differences were found between northern locations (Isla Gaviotas vs. Punta Galeras).

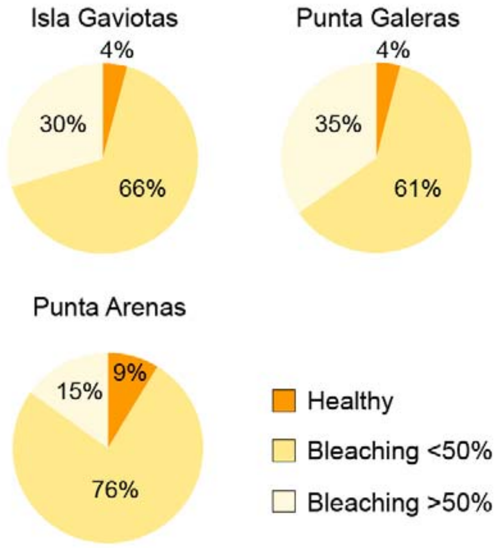

Figure 3: Condition of *Pocillopora* morphospecies colonies at three locations after the 2011 cold water bleaching event in the south-western Gulf of California. Isla Gaviotas, *n* = 1009; Punta Galeras, *n* = 465; Punta Arenas, *n* = 252.

Differences in cold water bleaching susceptibility were observed among *Pocillopora* morphospecies (Kruskal-Wallis test, $\chi^2_{(3, n=1726)}=111.32$, $P < 0.001$, Fig. 4). *P. damicornis* was the species most affected with an average of 36% colonies bleached among sites. Bleaching was observed for *P. verrucosa* (19%), *P. meandrina* (12%), and *P. capitata* (8%). The post-hoc Mann-Whitney *U*-test showed significant differences in all comparison between *P. damicornis* and other species ($P < 0.005$), and no significant differences were found among other species (*P. verrucosa vs. P. meandrina vs. P. capitata*, all comparisons $P > 0.05$).

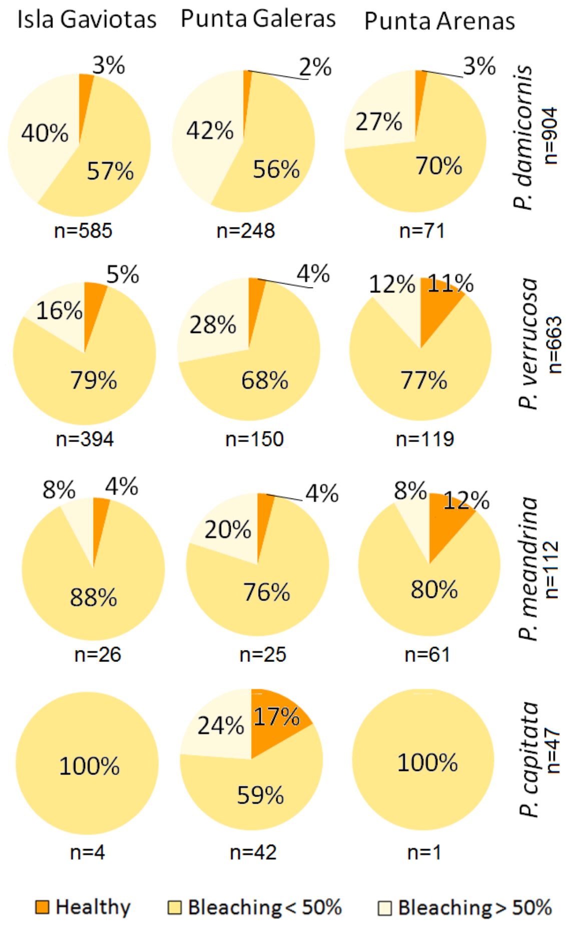

Figure 4: Percentage of bleached *Pocillopora* morphospecies at three locations in the south-western Gulf of California during the 2011 cold water bleaching event. The condition of *P. damicornis* was significantly different to the other *Pocillopora* morphospecies (Mann-Whitney *U*-tests in all comparison, $P < 0.005$).

Discussion

The 2011 cold water bleaching event was the fourth event since the first report of bleaching in the Gulf of California 23 years ago (Wilson 1990, Fig. 2). Bleaching occurred in 84% of *Pocillopora* corals in the region. Similar cold water stress occurred in 2008, when 90% of corals were bleached (Hernandez et al. 2010).

Taxa-specific bleaching susceptibility to cold water has been observed in laboratory experiments and during natural bleaching events in the field (Saxby et al. 2003, Hoegh-Guldberg et al. 2005, Lirman et al. 2011). In this study, significantly higher bleaching was observed between *P. damicornis* and the rest of *Pocillopora* morphospecies (Fig. 4). *Pocillopora* corals show a high specificity for *Symbiodinium glynni* (ITS2 rDNA type D1 *sensu* LaJeunesse et al. 2008) and/or type C1b-c in the Gulf of California (LaJeunesse et al. 2008, 2010); colonies with *S. glynni* are resistant to bleaching and mortality, while colonies harboring type C1b-c are susceptible to bleaching (LaJeunesse et al. 2008, 2010). Although *Symbiodinium* type was not identified in the surveyed corals in this study, the proportions of bleaching-sensitive type C1b-c and *S. glynni* in *Pocillopora* morphospecies were similar to previous studies and seem to be stable through the years (LaJeunesse et al. 2008, 2010). High bleaching susceptibility of *P. damicornis* could be due to intra-specific differences in symbiont or genotypic variation among colonies. Alternatively, other factors such as local water circulation and/or flow velocity can also influence differential bleaching susceptibility and morphological plasticity in *Pocillopora* corals (Veron 2000, Nakamura and Yamasaki 2006). Recently, Pinzón and LaJeunesse (2011) suggested that *Pocillopora* corals in the Gulf of California form one host-symbiont genetic lineage and that morphological variation of this group corresponds to phenotypic plasticity. Colonies exposed under moderate to high levels of water flow velocity would develop thicker branches (e.g. *P. verrucosa* and *P. meandrina* morphological variations), and this level of flow has been demonstrated to suppress bleaching during high SST condition (Nakamura and Yamasaki 2005, 2006). Conversely, colonies exposed under low flow conditions develop branches less thick such as *P. damicornis* and possibly have higher bleaching susceptibility as we found in this study in this morphospecies. Nevertheless, further research is required to investigate the effect of flow and morphological plasticity on cold water bleaching in *Pocillopora* corals.

The southern location of Punta Arenas was less affected by cold bleaching in 2006 and 2011 (LaJeunesse et al 2007) compared with northern locations in the Gulf of California. The resistance of *Pocillopora* colonies to bleaching in this location could due to several aspects: 1) location in an area exposed to high levels of wave and current could diminish the effects of SSTs on coral communities; 2) Punta Arenas is influenced by cold water of the California current which is localized close to a zone of seasonal upwelling where possible acclimation of colonies could occur (Glynn and Aunt 2000, Reyes-Bonilla 2001); and 3) most *Pocillopora* colonies harbored the resistant *Symbiodinium glynni* suggesting adaptation to harsh temperature conditions (LaJeunesse et al 2008, 2010). In addition, colonies from northern locations in the Gulf of California may be more susceptible to cold water bleaching than colonies living further south (Fig. 3, LaJeunesse et al. 2007, Hernández et al. 2010), due to higher proportion of *Symbiodinium* type C1b-c (LaJeunesse et al 2010), and also due to differences in local oceanographic conditions during the year that could raise the acclimation of colonies (e.g. temperature and chlorophyll a levels) (Halfar et al. 2006, LaJeunesse et al. 2010).

Cold water events can produce similar or higher bleaching events than warm water stress events. Cold water bleaching events have showed higher mortalities in *Pocillopora* corals at the northern and southern limits of their distribution in the Baja California Peninsula (90%, Wilson 1990, Hernández et al. 2010) than warm bleaching events (<20%, Reyes-Bonilla 2001, Reyes-Bonilla et al. 2002); perhaps because upwelling zones intensifies the stressful conditions on coral reefs by decreasing light penetration and the temperature of the water (e.g. by mixing of upwelling cold water and masses of cold water during thermal stress).

At our survey locations, 20% mortality of *Pocillopora* morphospecies corals occurred in 2008 (Hernandez et al. 2010). We were not able to record mortality in April 2011, but visits in August 2011 and January 2012 showed that most corals had recovered.

The coexistence of two host–symbiont combinations in *Pocillopora* corals in the Gulf of California can serve as a model to infer how more complex coral communities elsewhere may respond to episodes of environmental stress. Further work is required to determine the underlying factors contributing to differential bleaching susceptibility in closely related *Pocillopora* morphospecies during cold stress events.

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