

Thermal stress physiology and mortality responses in scleractinian corals of Mauritius

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Abstract: Photo-physiological and climate change - related bleaching were studied in eight selected species of scleractinian corals, namely *Acropora cytherea*, *Acropora hyacinthus*, *Acropora muricata*, *Acropora* sp., *Pocillopora damicornis*, *Pocillopora eydouxi*, *Galaxea fascicularis* and *Fungia* sp. from October 2008 to December 2009 around Mauritius. PSII functioning was measured in partially bleached (PB), pale (P), bleached (B) and non-bleached (NB) corals using a pulse-amplitude-modulated (PAM) fluorometer. Temperature records from January to March 2009 showed that the surface seawater temperature was at least 30°C. The recorded physical parameters in May 2009 indicated a temperature, dissolved oxygen, salinity, and pH of 27.52 ± 0.33 °C, 20.38 ± 0.77 mgL⁻¹, 33.5 ± 1.45 ‰, and 7.10 ± 0.15 , respectively. PSII functioning (F_v/F_m) was lower in PB, P and B samples as compared to the NB ones in *A. cytherea* and *A. hyacinthus*. In *A. muricata* PB and B were lower than the NB F_v/F_m , except for the P ones. Pale colonies of *P. damicornis* and *G. fascicularis* did not differ from their non-bleached ones. F_v/F_m measured in *P. eydouxi* and *Fungia* sp. was normal and no recorded bleaching occurred. Tabular corals, *A. cytherea* and *A. hyacinthus*, showed the highest levels of recent mortalities while *A. muricata* exhibited high levels of partial colony mortalities and *P. damicornis*, *P. eydouxi*, *G. fascicularis* and *Fungia* sp. did not show any signs of mortality. *A. cytherea* and *A. hyacinthus* were the most vulnerable while *P. damicornis*, *P. eydouxi*, *G. fascicularis* and *Fungia* sp. were the most tolerant coral species.

Keywords: Coral bleaching, Climate change, PAM, Scleractinian, Mauritius.

Introduction

Coral reef bleaching originally referred to as the loss of pigment by corals (Yonge & Nichols 1931) is characterized by the loss of algae (Hoegh-Guldberg & Smith 1989a; Glynn & D'Croz 1990; Lesser et al. 1990; Le Tissier & Brown 1996) and/or loss of photosynthetic pigment (Kleppel et al. 1989). This phenomenon is a common stress response of corals usually associated with anthropogenic and natural disturbances, for instance, extreme low/high temperatures, solar irradiance, sedimentation, xenobiotics (Cu, herbicides and oil), subaerial exposure, inorganic nutrients (nitrate and ammonium), freshwater dilution, and pathogens. Since the zooxanthellae increase the fitness of their host by enhancing calcification, mediating elemental nutrient flux and providing photosynthetically fixed carbon, their loss results in a loss of fitness (Jones & Berkelmans 2011) and often mortality.

Recent studies have shown that zooxanthellae densities within the coral host vary in relation to exogenous factors such as nitrogen enrichment (Muscatine et al. 1989), copper enrichment (Jones 1997a), iron enrichment (Harland & Brown 1989), cyanide (Cervino et al. 2001),

starvation and osmotic shock (Titlyanov et al. 2001a), increases in sea water temperature (Coles & Jokiel 1978), lowered seawater temperature (Gates et al., 1992), ultraviolet light (Jokiel et al. 1982) and Photosynthetic Active Radiation (PAR) (Titlyanov et al. 2001b). Furthermore, field studies have shown that there are seasonal cycles in zooxanthellae densities in response to variations in environmental factors (Fagoonee et al. 1999). The leading factors responsible for large-scale coral reef bleaching are increased sea temperatures and solar radiation (Stone et al. 1999; Glynn 1993; Brown 1997).

Coral bleaching and subsequent mortality is becoming more frequent worldwide. The coral bleaching process takes place due to the breakdown of the photosynthetic machinery (photosystem II, PSII) of the endosymbiotic dinoflagellates (genus *Symbiodinium*) commonly called zooxanthellae, which is then released from the coral host, leaving behind the whitish coral animal (Warner et al. 1999). Differential bleaching/ mortality of corals have also been documented. Baird and Marshall (2002) reported that whole colony mortality due to thermal stress was high in *A. hyacinthus* (88%) and *A. millepora* (32%) and partial mortality rare, *Platygyra*

daedalea and *P. lobata* took longer to bleach, longer to recover and longer to die. Mortality data after thermal stress experiments (Bhagooli & Hidaka 2004) indicated differential bleaching susceptibilities in *Seriatopora caliendrum*, *Montipora digitata*, *Porites cylindrica* and lastly *Platygyra ryukyuensis* in order of most susceptible to least.

The coral reefs of Mauritius surround most of the island as fringing reefs (150 km) except with breaks on the southern and western coasts. The coastline of the island of Mauritius is complex and comprises bays, estuaries and semi-enclosed lagoons where human population, recreational activities and industrial development are concentrated. Our reefs are, thus, exposed to significant of environmental stress arising from inshore (point source) and inland (non-point source) anthropogenic activities. These activities include hotel and marina developments, sewage disposal, effluent discharge from textile industries, seepage, terrestrial runoff containing pollutants such as herbicides, pesticides and fertilizers, coastal erosion and sedimentation. The reefs are also regularly impacted by cyclones, and there is good evidence that the lagoon patch reefs seasonally exhibit partial bleaching during the summer months (Fagoonée et al. 1999) due to increased sea surface temperatures. Coral reefs of Mauritius escaped the widespread mass coral bleaching/mortality phenomenon in 1998; however, temperature records from October 2008 till March 2009 show that the surface seawater temperature in Belle Mare lagoon on the eastern coast of Mauritius was at least 30°C.

Materials and Methods

In situ survey of bleaching

Four permanent transects were laid in the lagoon of Belle Mare, each comprising 3 stations at near-shore, mid-lagoon and back-reef habitats. A visual survey of the status of bleaching was observed on a monthly basis for the period of study October 2008 – May 2009. The survey was done by snorkeling, skin-diving and photo-recording by placing 1m X 1m quadrats along the permanent transects. A total of 12 stations with 20 colonies of the eight reef-building corals, *Acropora cytherea*, *Acropora hyacinthus*, *Acropora muricata*, *Acropora* sp., *Pocillopora damicornis*, *Pocillopora eydouxi*, *Galaxea fascicularis* and *Fungia* sp., were surveyed.

Field collection

Colonies of the eight reef-building corals of varying conditions (partially bleached (PB), pale (P), bleached (B) and non-bleached (NB)) were collected from the eastern reef of Mauritius island, namely at

Belle Mare public beach. The observed conditions were based on the visual estimates of the extent of bleaching as compared to coloured photographs of the normal states of corals. Thus, partially bleached condition is less than 30% of the colony white; pale condition indicates overall paling of the colony; bleached condition indicates >90% of the colony bleached; non-bleached condition means healthy looking colonies with normal coloration. All collections were done at a depth of 1 – 2 m. Coral tips of 2 – 3 cm were collected and kept in seawater in 250 ml sampling bottles. The coral samples were brought to the laboratory and dark-adapted for about 4 hours to allow the photosynthetic endosymbionts to relax all their PSII reaction centers before measurement of maximum quantum yield, F_v/F_m .

Chlorophyll a fluorescence measurements

Chlorophyll fluorescence was measured using a teaching PAM fluorometer. The initial fluorescence (F_0) was measured by applying pulses of weak red light ($< 1 \mu\text{mol quanta m}^{-2} \text{s}^{-1}$) and a saturating pulse ($3000 \mu\text{mol quanta m}^{-2} \text{s}^{-1}$, 0.8 s duration) was applied to determine the maximal fluorescence (F_m) when all the PSII centers were closed. The ratio of the change in fluorescence ($F_v = F_m - F_0$) caused by the saturating pulse to the maximal fluorescence (F_m) in a dark-adapted sample, is correlated to the maximum quantum yield of PSII and thus represent the PSII functioning (Genty et al. 1989).

In-situ measurements and chemical analyses

Temperature (OAKTON pH/mv/°C meter pH300 series) and other physical parameters such as dissolved oxygen (Hach Sension 6), salinity and pH (OAKTON waterproof pH300 series) were measured *in situ* and recorded on a monthly basis from October 2008 until May 2009. Samples of seawater were collected at each station during each sampling for the laboratory measurement of nitrates and phosphates in seawater. Nitrate determination was done by the cadmium reduction method (Wood et al. 1967) and analysis of inorganic phosphate in seawater by the colorimetric method by Murphy and Riley (1962).

Statistical analysis

Measured data for the maximum quantum yield for the 4 different conditions (PB, P, B and NB) in the 8 species of coral was arcsine square root transformed and analysed by One-way ANOVA followed by Post Hoc Tukey Test using the Statistica (version 10.0) software.

Results

The recorded physical parameters in May 2009 indicated an average temperature, dissolved oxygen,

salinity, and pH of 27.52 ± 0.33 °C, 20.38 ± 0.77 mgL⁻¹, 33.5 ± 1.45 ‰, and 7.10 ± 0.15 , respectively (Fig. 1).

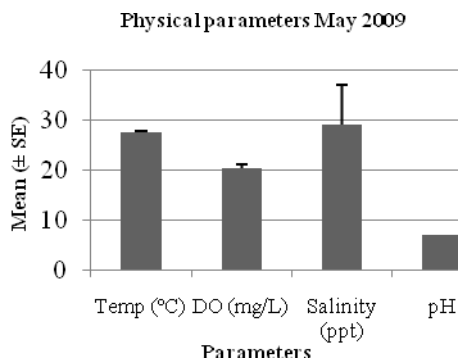


Figure 1: Mean values of physico-chemical parameters (temperature, dissolved oxygen, salinity and pH) measured *in situ* in May 2009.

It was also observed that nitrate concentrations were at or below 0.2 mg/L throughout the sampling period from October 2008 to May 2009. Observations also indicate a decrease in nitrates with distance from the shore. Concentrations of phosphate above 0.04 mg/L have been implicated in coral stress (Connel & Hawker 1991). Results indicated phosphate levels in samples less than 0.04 mg/L. Detailed data are not presented in this paper.

Results indicate that sea surface temperatures increased gradually from September 2008 to February 2009 where they peaked at 31.5°C, and then decreased to 27.4°C by May 2009 (Fig. 2).

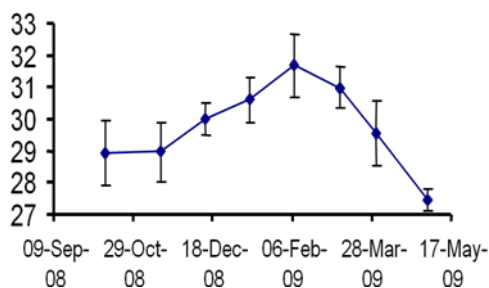


Figure 2: Temperature (°C) recorded at Belle Mare lagoon from October 2008 till May 2009.

Complete mortality was highest in *A. hyacinthus* and highest partial mortality in *A. cytherea*, *A. formosa* and *Acropora* sp. whilst no mortality was observed in *P. damicornis*, *G. fascicularis*, *Fungia* sp. and *P. eydouxi*. (Fig. 3).

Maximum quantum yield (F_v/F_m) was highest (0.6) in non-bleached colonies in the eight species under study and lowest in bleached colonies of *A. cytherea*, *A. hyacinthus* and *A. formosa*, indicating direct relationship between chlorophyll *a*

fluorescence and bleaching (Fig. 4). There is no significant difference in F_v/F_m in pale and non-bleached colonies of *P. damicornis* ($p > 0.05$, one-way ANOVA test) and *G. fascicularis* ($p > 0.05$, one-way ANOVA test). Pale colonies in *A. hyacinthus*, *A. formosa* and *A. sp.* showed $F_v/F_m \leq 0.4$. The pale colonies of *P. damicornis* and *G. fascicularis* did not differ from their non-bleached ones ($p > 0.05$, one-way ANOVA test).

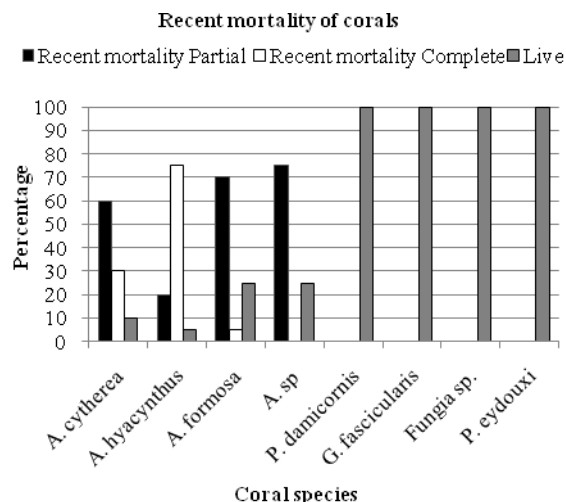


Figure 3: Percentage recently partially and completely dead colonies and live (out of 20 observed colonies) of the eight studied coral species at Belle Mare in May 2009.

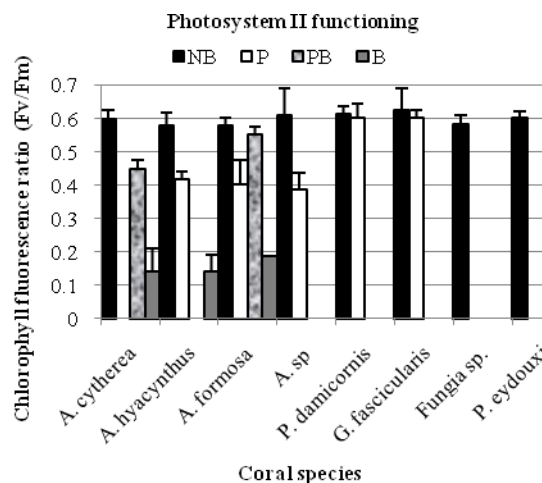


Figure 4: Maximum quantum yield (F_v/F_m) in non-bleached (NB), pale (P), partially bleached (PB), and bleached (B) coral samples (n=4-11) in eight studied coral species at Belle Mare in May 2009.

PS II functioning, measured as F_v/F_m , was lower in partially bleached (PB), pale (P) and bleached (B) samples as compared to the non-bleached (NB) ones in *A. cytherea* ($p < 0.05$, Post Hoc

Tukey test) and *A. hyacinthus* ($p < 0.05$, Post Hoc Tukey test) (Fig 4). For *A. cytherea*, there was significant differences between NB and B ($p < 0.05$, Post Hoc Tukey test), PB and B ($p < 0.05$, Post Hoc Tukey test), and no significant difference between PB and NB conditions ($p > 0.05$, Post Hoc Tukey test). In *A. hyacinthus*, there were significant differences among and between all conditions ($p < 0.05$, Post Hoc Tukey test).

In *A. formosa* PB, B and P were lower than the NB F_v/F_m , with significant differences between B and NB ($p < 0.05$, Post Hoc Tukey test), PB and NB ($p < 0.05$, Post Hoc Tukey test), but no significant differences between P and PB ($p > 0.05$, Post Hoc Tukey test). In *Acropora* sp., F_v/F_m was lower in P compared to NB samples. No visual bleaching was recorded in *Fungia* sp. and *P. eydouxi*. All the F_v/F_m values measured in *P. eydouxi* and *Fungia* sp. were normal (Fig. 4).

In situ survey of coral bleaching from October 2008 to May 2009 revealed ~70% of corals bleached and 40 - 50% mortality of corals were recorded between January and March 2009. The tabular corals, *A. cytherea* and *A. hyacinthus*, showed the highest levels of recent mortality, while *A. formosa* and *A. sp.* exhibited high levels of partial colony mortalities and *P. damicornis*, *P. eydouxi*, *G. fascicularis* and *Fungia* sp. did not show any signs of mortality (Fig. 3).

Discussion

Although bleaching of corals is a general response to stress, much of the extensive bleaching observed in the field is thought to be due to elevated seawater temperatures which in turn increase the susceptibility of symbiotic dinoflagellates to high irradiance (Warner et al. 1996; Brown, 1997). This study demonstrates the variable susceptibility to coral bleaching among eight different species in the Belle Mare Lagoon, Mauritius, Indian Ocean.

Our results suggest that the tabular corals, *A. cytherea* and *A. hyacinthus* are thermally the most susceptible to bleaching while *P. damicornis*, *P. eydouxi*, *G. fascicularis* and *Fungia* sp. are among the most tolerant reef-building coral species in the studied lagoon. This is observed in May 2009 results for coral mortality where 100% of *P. damicornis*, *P. eydouxi*, *G. fascicularis* and *Fungia* surveyed exhibited live colonies. *A. cytherea*, *A. hyacinthus*, *A. formosa* and *A. sp.* showed varying conditions (NB, B, P and PB) or susceptibilities to thermal stress (Fig 4). Maynard et al. (2008) found that coral genera generally most susceptible to thermal stress (*Pocillopora* and *Acropora*) showed the greatest increase in tolerance between bleaching events (2002 v/s 1998). Dunne and Brown (2001) found similar

results in the Andaman Islands in 1998 as compared to 1995. The range in bleaching tolerances among corals inhabiting different thermal realms suggest that at least some coral symbioses have the ability to adapt to much higher temperature fluctuations than they originally experience (Maynard et al. 2008; Coles & Brown 2003; Riegl 2002).

Reduction in the photosynthetic capacity of *in hospite* zooxanthellae under thermal stress has been reported in several coral species (e.g. Warner et al 1999; Bhagooli & Hidaka 2002). Warner et al. (1999) also reported the temperature-dependent loss of PSII activity from naturally and experimentally bleached corals as well as in cultured zooxanthellae treated at 32°C. These findings strongly suggest that damage to photosynthetic apparatus in zooxanthellae is a determinant of coral bleaching.

The present results show that the most susceptible corals (tabular and branching *Acropora*), zooxanthellae had the lowest F_v/F_m (< 0.2) in bleached (B) corals indicating damage to their photosynthetic machinery in the B corals. However, zooxanthellae of lightly pale (P) corals of *P. damicornis* and *G. fascicularis* had normal F_v/F_m level when compared to NB condition, thus indicating non-selective release of zooxanthellae with respect to their PSII functioning.

The above findings also suggest that the symbionts as well as the host play an equally important role in its resistance/ susceptibility to bleaching. Baird et al. (2009) suggested that the coral host has several potential ways to reduce UV and light flux to symbionts, including production of fluorescent pigments, acquisition of mycosporine-like amino acids, and several antioxidant systems and stress enzymes to deal with oxygen stress originating in the animal cell. The differences among the host species in their capacity to utilize these mechanisms might therefore determine differences among species in response to stress.

Also, differences in sensitivity among corals are determined, in some species, by the symbiont. Oliver and Palumbi (2011) reported that physiologically distinct lines of dinoflagellate symbionts, *Symbiodinium spp.*, may confer distinct thermal tolerance thresholds on their host corals. If a coral host may alternately host distinct symbionts, changes in their *Symbiodinium* communities might allow corals to better tolerate increasing environmental temperatures. The *Symbiodinium* genotype was not examined in this paper. However, Baker et al. (2004) reported that only 3% of the coral colonies in Mauritius in years 2000 – 2002 contained Clade D and that corals containing thermally tolerant *Symbiodinium* Clade D are more common on reefs after episodes of severe bleaching and mortality. Mc

Clanahan et al (2005) reported most scleractinian corals (Acroporidae, Pocilloporidae, Oculinidae, Poridae and Agariciidae) contained *Symbiodinium* Clade C from the northeast coast of Mauritius, except one sample of *Galaxea fascicularis* containing *Symbiodinium* Clade D from the north-west coast, indicating that the observed differences in response among coral taxa and sites were unlikely to be affected by the type of symbiont they contain. Rowan (2004) reported that *Pocillopora* spp. living in frequently warm (more than 31.5°C) habitat host only *Symbiodinium* D and perhaps explains why those living in cooler habitats predominantly host *Symbiodinium* Clade C. The diverse response of corals to thermal anomalies has been related to host and/or symbiont factors but the combined physiology of the two organisms likely determines the tolerance range of the holobiont (Sampayo et al, 2008).

In conclusion, the results of this study highlight the variable responses among the eight studied coral species. The order of susceptibility/ mortality is as follows: Tabular *Acropora* > Branching *Acropora* > Massive-like Corals/ Solitary Corals.

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