

Acclimation to predicted ocean warming through developmental plasticity in a tropical reef fish

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Abstract

Determining the capacity of organisms to acclimate and adapt to increased temperatures is key to understand how populations and communities will respond to global warming. Although there is evidence that elevated water temperature affects metabolism, growth and condition of tropical marine fish, it is unknown whether they have the potential to acclimate, given adequate time. We reared the tropical reef fish *Acanthochromis polyacanthus* through its entire life cycle at present day and elevated (+1.5 and +3.0 °C) water temperatures to test its ability to thermally acclimate to ocean temperatures predicted to occur over the next 50–100 years. Fish reared at 3.0 °C greater than the present day average reduced their resting oxygen consumption (RMR) during summer compared with fish reared at present day temperatures and tested at the elevated temperature. The reduction in RMR of up to 69 mg O₂ kg⁻¹ h⁻¹ in acclimated fish could represent a significant benefit to daily energy expenditure. In contrast, there was no acclimation to summer temperatures exhibited by fish reared at 1.5 °C above present day temperatures. Fish acclimated to +3.0 °C were smaller and in poorer condition than fish reared at present day temperatures, suggesting that even with acclimation there will be significant consequences for future populations of tropical fishes caused by global warming.

Keywords: acclimation, climate change, coral reef fish, developmental plasticity, global warming, metabolism, oxygen consumption, respirometry

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Introduction

Average sea surface temperatures are expected to increase up to 3.0 °C by the end of this century due to global warming (Meehl *et al.*, 2007; Poloczanska *et al.*, 2007; Munday *et al.*, 2009). Whether marine organisms have the capacity to cope with such a rapid increase in temperature is critical to understanding the likelihood of species persistence and population sustainability (Donner *et al.*, 2005; Brierley & Kingsford, 2009; Hofmann & Todgham, 2010). There is increasing evidence that species located in tropical regions might be sensitive to temperature increases of just a few degrees, due to them having evolved in a relatively thermally stable environment (Tewksbury *et al.*, 2008; Nilsson *et al.*, 2009; Wright *et al.*, 2009). Specifically, some tropical species exhibit a narrower thermal reaction norm than related temperate species and this is expected to reduce their

ability to cope with temperatures above their thermal optimum (Stillman, 2003; Pörtner & Farrell, 2008; Tewksbury *et al.*, 2008). Consequently, understanding the potential for species to acclimate or adapt to rapid temperature change will be especially important for predicting the consequences of global warming for populations and communities of tropical species.

Poikilotherms, like fish, are strongly influenced by increases in environmental temperature (Fry, 1967; Hazel & Prosser, 1974; Houde, 1989; Clarke & Johnston, 1999). A wide range of attributes may be affected including resting metabolic rate (RMR), maximum oxygen uptake, growth rate, lipid composition and enzyme activity (Hazel & Prosser, 1974; Clarke & Johnston, 1999). RMR, generally measured as resting oxygen consumption, and maximal oxygen uptake have been suggested to be critical factors in determining persistence at locations during climate change (Pörtner & Knust, 2007). Specifically, at higher temperatures, the maximum capacity for oxygen uptake can no longer keep pace with the rise in resting metabolism, causing a reduction in the scope for processes like feeding and reproduction (Brett, 1971; Pörtner & Knust, 2007; Farrell *et al.*, 2008; Pörtner & Farrell, 2008). Furthermore, the

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temperature for optimal metabolic scope is believed to coincide with optimal growth (Del Toro-Silva *et al.*, 2008), and optimal growth rate does not readily shift with acclimation temperature (Brett, 1971; Guderley *et al.*, 2001). For some tropical reef fishes, recent research has shown that aerobic scope (the difference between maximum and resting metabolism) decreases when water temperature is raised above normal summer temperature (Nilsson *et al.*, 2009), and that increased seawater temperature can limit the growth of juvenile and adult reef fishes (Munday *et al.*, 2008b), as well as their reproductive capacity (Hilder & Pankhurst, 2003; Donelson *et al.*, 2010). Therefore, most of the available evidence suggests that populations of tropical reef fish will be significantly affected by global warming.

Thermal acclimation is one means of coping with increased temperature. Acclimation involves the phenotypic altering of physiological, behavioral or morphological characteristics to better suit an environment (Fry, 1967; Hazel & Prosser, 1974; Randall *et al.*, 2000; Woods & Harrison, 2002). Two general classes of acclimation are recognized: reversible and developmental acclimation. Developmental acclimation consists of permanent responses to the environment during early ontogeny whereas reversible acclimation includes controlled responses in relation to daily or seasonal environmental fluctuations (Angilletta, 2009). While either form of acclimation has the potential to produce some benefits to the individual, neither is likely to be cost free. There are possible energetic costs associated with modifications for which the energy used could have been spent on other functions (Hoffmann, 1995; Angilletta *et al.*, 2003). For example, physiological acclimation to increased temperature may reduce the energy available for growth or reproduction. Furthermore, acclimation to elevated maximum temperatures might have consequences for performance at minimum temperatures (Dulai *et al.*, 1999; Seebacher *et al.*, 2005; Glanville & Seebacher, 2006) if there is a trade-off between performance at maximum and minimum temperatures.

Previous research on temperature acclimation in marine fishes has primarily involved temperate species, which are likely to have a greater scope for acclimation than tropical species as they naturally experience a greater range of temperature fluctuations (Stillman, 2003). Moreover, the main focus has been on cold acclimation and its effects to mitochondrial densities, metabolic rate, swimming performance and muscular development (Johnston & Dunn, 1987; Johnston *et al.*, 1998; Johnston & Temple, 2002; Sylvestre *et al.*, 2007). Research on polar species, which have evolved in a thermally stable environment, primarily indicate a very low capacity for acclimation (Steffensen, 2002),

although some evidence for thermal acclimation has been found (Franklin *et al.*, 2007; Robinson & Davison, 2008).

So far, only three studies have investigated thermal acclimation in tropical coral reef species, and no metabolic acclimation was observed (Tullis & Baillie, 2005; Nilsson *et al.*, 2009, 2010). However, since these studies only investigated the potential for acclimation in juveniles and adults over a short period (up to 3 weeks), the question of whether coral reef fishes are capable of developmental thermal acclimation remains unanswered.

We tested the ability of a common reef fish, *Acanthochromis polyacanthus*, to undergo developmental metabolic acclimation as a means of coping with tropical ocean temperatures that are predicted to occur over the next 50–100 years due to global warming. Specifically, fish were reared from shortly after hatching to maturity in present day and elevated temperatures (+1.5 and +3.0 °C) to determine if continuous exposure to elevated temperatures induced an acclimation response in their RMR at maximum (summer) and minimum (winter) temperatures. The experimental temperatures were chosen to represent tropical ocean warming that could occur around 2050 (+1.5 °C) or by 2100 (+3.0 °C) (Preston & Jones, 2006; Lough, 2007). In addition, the physical characteristics of the fish were measured to determine if acclimation had a significant physiological cost.

Materials and methods

Experimental design

Established pairs of *A. polyacanthus* were collected from the Palm Island region (18°37'S, 146°30'E) of the central Great Barrier Reef in July to August 2007 and maintained in 60 L aquariums inside an environmentally controlled facility at James Cook University, Townsville, Australia. Pairs were maintained at the mean present day ocean temperature for the collection location (Fig. 1) and provided with the average food consumed by wild pairs (0.376 g per fish Aquaculture Nutrition NRD 12/20 pellets: 1.0% body weight, see Donelson *et al.*, 2010 for more details). In *A. polyacanthus* care is provided to the benthic eggs by both parents and after hatching the young remain with the parents for 30–45 days (Kavanagh, 2000). The geographic range of *A. polyacanthus* is from 15°N–26°S to 116°E–169°E, which encompasses a total temperature span (inclusive of seasons) of approximately 20–31 °C across this range. Similar temperature ranges are experienced by many other broadly distributed coral reef fishes (Munday *et al.*, 2008a).

During the austral summer 2007–2008, breeding bouts from eight pairs were used for the current study. Offspring from these pairs were kept with their parents for 30 days posthatching. At this time, individuals from each clutch were divided

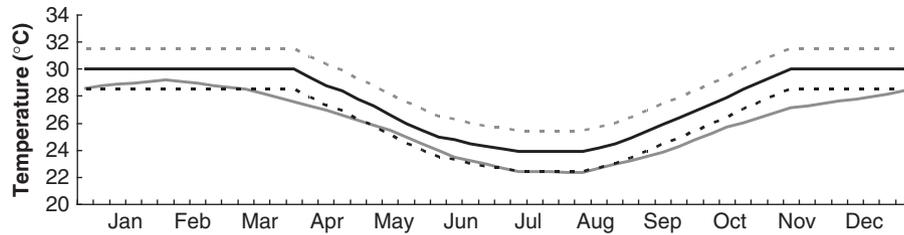


Fig. 1 Seasonal water temperature at the Palm Island Region and in experimental treatments. The solid grey line shows average weekly water temperature at Orpheus-Palm Island based on 14 years of daily water temperature records from the JCU/AIMS weather station. Experimental treatment temperatures were: present day (black dashed), +1.5 °C (solid black) and +3.0 °C (grey dashed).

into three groups of 18 and gradually adjusted (>5 h) to one of the three treatment temperatures: either the present day mean temperature at the collection location, +1.5 or +3.0 °C treatment (Fig. 1). Temperature was kept within ± 0.3 °C of the desired treatment mean. Temperatures at the collection location have fluctuated between 0.2 and 2.5 °C in a single day over the last 14 years, but on average vary only 0.45 °C on a daily basis (JCU/AIMS weather station). Splitting clutches in this way ensured that each experimental treatment contained similar genetic diversity and controlled for possible genetic effects on acclimation ability. Sibling fish were kept in groups of six in 40 × L aquaria until 6 months old when the smallest two fish were removed to reduce density in aquaria. No differences in mortality were observed among treatments, with close to 100% survival attained at each temperature. At 8 months, individuals were sorted into pairs consisting of one male and female nonsibling fish and maintained in 40 L aquaria for the duration of the experiment to limit aggressive interactions between same sex individuals. Fish were fed to satiation a mixture of newly hatched *Artemia nauplii* and Aquaculture Nutrition NRD with increasing size.

Resting metabolism

RMR was estimated at the end of summer during March and April 2009 (fish were approximately 1 year old and $13.5 \text{ g} \pm 0.3$ SE) and during winter in July and August 2009 (fish were approximately 1.5 years old and $16.2 \text{ g} \pm 0.4$ SE). Fish were starved for 24 h before testing to remove any effects of digestion on oxygen consumption. The test temperatures used during these periods were 28.5, 30.0 and 31.5 °C in summer and 22.5, 24.0 and 25.5 °C in winter. These temperatures are the summer and winter averages for the three treatments: present day, +1.5 and +3.0 °C, respectively. Fish were initially tested at their temperature treatment and then given at least 3 days of rest. All tested fish were then divided equally in two groups and gradually adjusted to one of the other two treatment temperatures over a 2 h period. Fish were maintained at the new temperature for 7 days before RMR was tested again at the new temperatures. All experiments were conducted within a temperature-controlled room and during respirometry temperatures did not vary more than 0.3 °C from the intended temperature. For measurements undertaken from March to

April a total of 170 trials were completed with 28 fish from present day, 33 from +1.5 °C and 30 from +3.0 °C treatments. During the July to August measurement period, 111 trials were completed with 19 fish from current day, 20 fish from +1.5 °C and 19 fish from +3.0 °C. Wet weight (nearest mg) and standard length (mm) of all fish were measured during March–April 2009, when acclimation was found to occur. These measurements were taken directly following RMR measurements, when fish has not fed for 24 h, thereby ensuring that feeding activity did not affect wet weight measures.

Respirometry methods were modified from Nilsson & Östlund-Nilsson (2004) and Nilsson *et al.* (2009). Each fish was allowed to acclimatize in the respirometer (a 1000 mL Perspex cylinder with 68 mm inner diameter) for 1 h with a constant water flow. A longer acclimatization time of 3 h did not alter respiration values obtained (ANOVA: $F_{3,16} = 0.701$, $P = 0.565$). Following acclimatization the chamber was sealed and oxygen concentrations were monitored with an oxygen electrode (WTW OXI 340i or OXI 3310, Germany) for 30 min or until oxygen concentrations had fallen to 60% of air saturation. The respirometer was submerged in a temperature-controlled aquarium to maintain a stable temperature. Subsequently, the wet weight of each fish was measured to the nearest mg.

Statistics

RMR ($\text{mg O}_2 \text{ consumed kg}^{-1} \text{ h}^{-1}$) for each fish was calculated from the recorded fall in oxygen concentration in the respirometer (measured as % of air saturation), taking into account the O_2 solubility in sea water at each test temperature. One-way and factorial ANOVA, with rearing temperature and/or testing temperature as fixed factors, was used to compare RMR in summer and winter test periods. Summer data were square root transformed before analysis to improve the homogeneity of variances. Fisher's LSD *post hoc* tests were completed where necessary.

To determine whether acclimation had a cost to growth of body condition, regression analysis was used to examine the relationship between standard length and weight of fish in each temperature treatment during summer, as this was when acclimation was found to occur. A power function was fitted as this best described the relationship between standard length and weight. Additionally, the length–weight relation-

ship converted to Fulton's *K* condition factor [equation: $(10\,000 \times \text{weight})/L^3$] was used as an indicator of condition. An increase in weight proportional to length has been found to relate significantly to muscle and liver energy content (Lambert & Dutil, 1997), survival time in stressful conditions (Robinson *et al.*, 2008) and fecundity (Lambert & Dutil, 2000), and is thus considered to be a good general indicator of physiological condition. ANOVA was used to test for differences in both Fulton's *K* and standard length between the temperature treatments. Fisher's LSD *post hoc* tests were executed where necessary. All statistics were completed with STATISTICA 8.0 – (StatSoft Inc., Tulsa, OK, USA).

Results

Resting metabolism at rearing temperatures

When resting oxygen consumption (RMR) for each treatment group was measured at their rearing temperatures (present day, +1.5 and +3.0 °C), it increased with temperature at both the summer maxima ($F_{2,82} = 16.77$, $P < 0.001$; Fig. 2a) and winter minima ($F_{2,53} = 22.89$, $P < 0.001$; Fig. 2b). During winter, all three treatments were significantly different from each other and each increase of 1.5 °C caused an increase of approximately $30 \text{ mg O}_2 \text{ kg}^{-1} \text{ h}^{-1}$ in oxygen consumption.

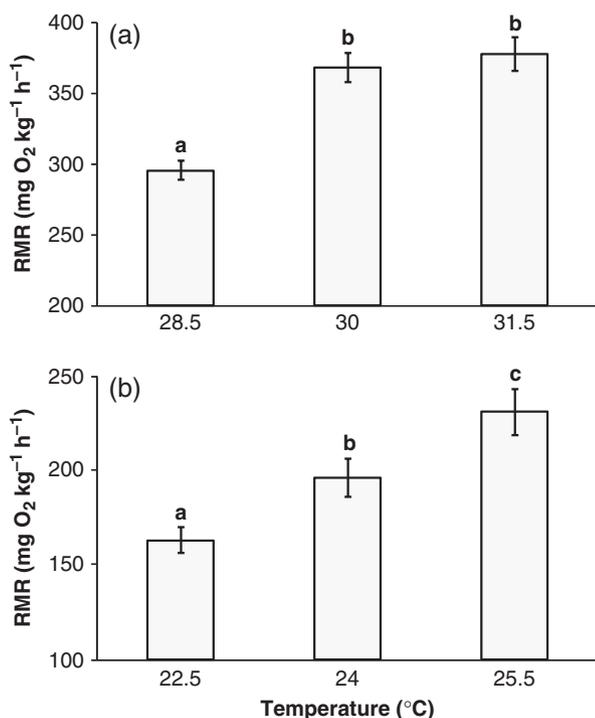


Fig. 2 Resting metabolic rate (\pm SE) of fish reared and tested at their average summer (a) and winter (b) temperatures. Letters above bars represent significant differences at $P < 0.05$ determined by Fisher's LSD.

However, during summer differences were only found between fish at the present day temperature and the two elevated temperatures, but not between the elevated temperature groups. Thus, the +1.5 and +3.0 °C treatment groups showed similar RMR values of approximately $370 \text{ mg O}_2 \text{ kg}^{-1} \text{ h}^{-1}$ (Fig. 2a).

Resting metabolism with acute temperature change

Fish were tested for potential RMR differences between the three treatments throughout the range of summer and winter average temperatures (Fig. 3). When exposed to acute temperature changes RMR values of the groups were similar at all temperatures in the winter series, regardless of acclimation temperature, revealing no effect of long-term acclimation (Fig. 3b). This was also the case in the summer series at both 28.5 and 30.0 °C (Fig. 3a). However, differences in RMR were seen at 31.5 °C, with both the present day and +1.5 °C fish showing significantly higher RMR (up to $69 \text{ mg O}_2 \text{ kg}^{-1} \text{ h}^{-1}$ higher) than the +3.0 °C fish (Fig. 3a). Thus, the data provides evidence of thermal acclimation in the +3.0 °C treatment group to the elevated temperature experienced during summer, without affecting RMR at winter minimum temperatures.

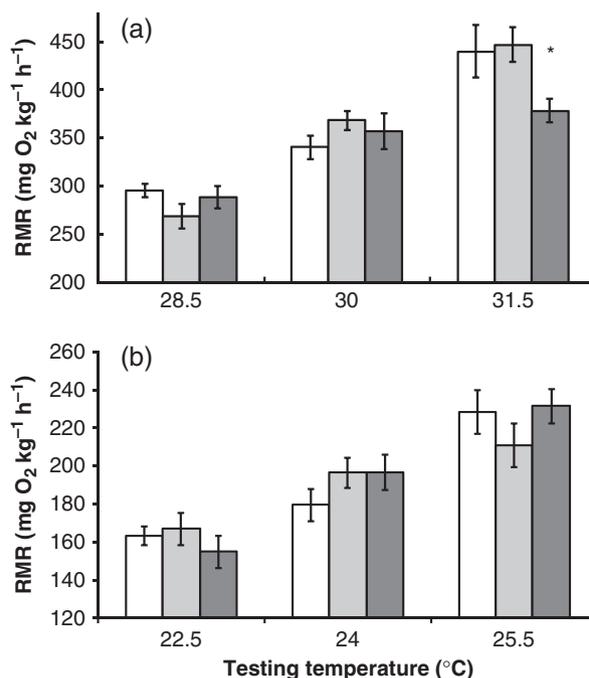


Fig. 3 Resting metabolic rate (\pm SE) of fish reared under present day (white), +1.5 °C (light grey) and +3.0 °C (dark grey) and tested at the summer (a) and winter (b) averages of temperatures. *Significant differences within a testing temperature at $P < 0.05$ determined by Fisher's LSD.

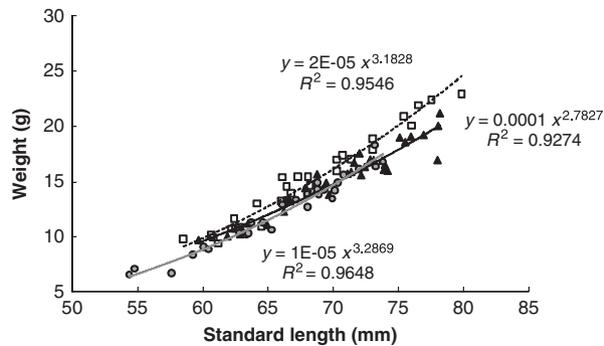


Fig. 4 Weight of fish after 1 year in present day (squares, dashed), +1.5 °C (triangles, black) and +3.0 °C (circles, grey) temperature treatments. Lines of best fit are power functions.

Body condition and growth

There was a close relationship between body mass and standard length for fish in each temperature treatment (Fig. 4; $r^2 > 0.92$ for all relationships). The physical condition (i.e. body mass at a given length) of fish depended on the temperature treatment they were reared at for 1 year ($F_{2,92} = 29.27$, $P < 0.001$; Fig. 4). Fish kept under present day conditions (mean Fulton's K : 0.468 ± 0.0051 SE) were heavier for a given length than fish from either the +1.5 (mean Fulton's K : 0.431 ± 0.0040 SE) or +3.0 °C (mean Fulton's K : 0.422 ± 0.0043 SE) treatment ($P < 0.001$). In contrast, there was no difference in the length-weight relationship between +1.5 or +3.0 °C treatment fish ($P = 0.149$). The differences in condition between fish at present day temperatures compared with the +1.5 or +3.0 °C treatments were more pronounced at lengths > 65 – 70 mm (Fig. 4).

The average length of fish also varied depending on treatment ($F_{2,92} = 28.5$, $P < 0.001$), with fish reared at +3.0 °C (mean: 66.1 mm ± 0.96 SE) being on average shorter than fish from either present day (mean: 67.9 mm ± 1.06 SE) or +1.5 °C treatments (mean: 70.4 mm ± 0.81 SE; $P < 0.001$).

Discussion

Acclimation is an important mechanism for coping with a changing or fluctuating environment. Previous studies have found no evidence for thermal acclimation of metabolic rates in tropical reef fishes (Tullis & Baillie, 2005; Nilsson *et al.*, 2009, 2010). In contrast, we detected thermal acclimation through a reduction in resting oxygen consumption (RMR) in fish that had been reared from shortly after hatching to 1.5 years old at 3 °C above average temperatures (but not in fish reared at 1.5 °C above average temperatures). This indicates that at least

some tropical reef fishes can undertake developmental plasticity to acclimate their RMRs as water temperatures increase due to global warming. The reduction in daily metabolic demands is likely to be beneficial by allowing redistribution of saved energy to other activities. However, fish acclimated to a higher than normal temperature were on average smaller than fish kept at present day temperatures, suggesting that increased temperature, or acclimation *per se*, incurred some physiological cost. Furthermore, fish at both elevated temperatures were in poorer condition than fish reared at present day temperatures. This demonstrates that even with acclimation, warmer sea temperatures are likely to have significant impacts on reef fish populations.

The low RMR exhibited by +3.0 °C fish at the summer temperature (31.5 °C) compared with present day and +1.5 °C fish tested at this temperature indicates that these fish spent less energy on daily maintenance than fish that exhibited acute temperature responses. This acclimation would potentially provide individuals with extra energy for a range of activities, including feeding and reproduction. The RMR of +3.0 °C fish tested at 31.5 °C was not different from the RMR of +1.5 °C fish tested at 30.0 °C and these two groups had similar body condition (body mass at a given length). This suggests that the additional energy made available through acclimation at 31.5 °C was possibly used to maintain body condition. Further support for this notion is seen in the comparison of RMR between fish at elevated temperature treatments (+1.5 and +3.0 °C) and the present day temperature treatment. The RMR of +1.5 and +3.0 °C fish in their respective temperatures was higher than that of fish reared at present day temperatures, and both these groups had lower body condition than fish reared in the present day temperature treatment. In combination, these comparisons indicate that elevated temperature has an effect on body condition, but this effect was reduced at the highest temperatures through acclimation of RMR.

Despite acclimation of RMR to the summer average in fish reared at 3.0 °C above present day averages, there was no evidence for acclimation in fish reared at 1.5 °C above. The absence of acclimation to 30.0 °C in the +1.5 °C fish is likely to be related to the costs and benefits of acclimation. Previous studies have shown that for this population of *A. polyacanthus* a reduction in growth, body condition and reproduction occurs at ≥ 31.0 °C, regardless of food availability (Munday *et al.*, 2008b; Donelson *et al.*, 2010). Although reductions in growth and reproduction have also been observed at 30.0 °C (Donelson *et al.*, 2010) they are less severe than at 31.5 °C. The smaller loss of performance caused by exposure to 30.0 °C compared with 31.5 °C may explain

why physiological acclimation only occurred in the higher temperature treatment.

The reduced average length of + 3.0 °C fish compared with fish reared at + 1.5 °C and present day temperatures suggests that metabolic acclimation during development may have incurred a physiological cost. Energy used for acclimation and maintenance of body condition may have otherwise been used for somatic growth. It is also likely that physiological processes involved in growth, like protein synthesis and cell proliferation, influence RMR. Such processes may have to be suppressed during developmental acclimation to allow for a maintained (i.e. reduced) RMR at an elevated water temperature, thereby retarding growth. Alternatively, reduced growth may have occurred because + 3.0 °C fish could only partially compensate for temperature effects through RMR (Fry, 1967). This is suggested by the fact that RMR was still significantly higher in the + 3.0 °C acclimated group compared with those reared at present day temperatures. RMR is expected to be mirrored by metabolic scope, which coincides with optimum growth (Del Toro-Silva *et al.*, 2008). Therefore, the reduced growth rate might have occurred because only partial compensation was possible. Regardless of the specific cause, our results suggest that future populations living at + 3.0 °C conditions will consist of smaller individuals that are in poorer condition than present day populations at the same location.

Reduced physical condition at elevated temperatures is likely to have important ramifications for reef fish populations in a natural setting. It is well documented that survival rates are positively associated with body condition in juvenile reef fishes (Hoey & McCormick, 2004; Grorud-Colvert & Sponaugle, 2007; Holmes & McCormick, 2009). Therefore, fewer fish will potentially survive to maturity at elevated temperatures, because they will be in poorer condition. Reduced condition will also affect reproductive output, with fewer and smaller offspring being produced compared with good condition counterparts (Marteinsdottir & Steinarsson, 1998; Donelson *et al.*, 2008). In addition, fish from the + 3.0 °C treatment group were shorter on average, which also has ramifications for individual fitness, including reduced size at maturity which in turn may reduce reproductive output (Morita & Takashima, 1998; Vallin & Nissling, 2000; Johnston & Leggett, 2002). Alternatively, maturity may be delayed until a size threshold is reached, which could increase the likelihood of mortality before maturity and reduce the size of the breeding population (Morita *et al.*, 2005).

Although acclimation to maximum temperatures might be expected to affect performance at minimum temperatures, this is not always the case. Acclimation to one temperature extreme often does not coincide with

poor performance at the opposite temperature extreme (Gvoždík *et al.*, 2007; Angilletta, 2009; exceptions Seebacher *et al.*, 2005; Glanville & Seebacher, 2006). Consistent with these observations, thermal acclimation observed in the 31.5 °C treatment group did not affect RMR at any of the predicted winter temperatures. This suggests that acclimation may be an important process whereby tropical reef fish can cope with increased average summer temperatures in the future without a loss of performance at winter temperatures. The reduction in RMR of $\sim 70 \text{ mg O}_2 \text{ kg}^{-1} \text{ h}^{-1}$ in acclimated fish represented a Q_{10} (the rate of change depending on temperature) reduction of 1.31, which is similar to that observed when acclimation in polar fishes occurs (Q_{10} change: 0.62–1.29; Franklin *et al.*, 2007; Robinson & Davison, 2008), but is less than that recorded for temperate species (Q_{10} change: 1.55–3.97; Morris, 1965; Walsh *et al.*, 1983; Sébert *et al.*, 1995). This demonstrates that acclimation potential of some tropical fishes may not be as large as species that experience greater seasonal variation in maximum and minimum temperatures.

While the present study only investigates the potential for acclimation in one species it is expected that developmental acclimation will be common among coral reef fishes. In many ectotherms developmental acclimation, or developmental plasticity, is known to be critical to producing phenotypes suited to specific environments (Beck, 1983; Seebacher, 2005). This plasticity is common in the dispersive larval stage of reef fish, because they are likely to experience environmental unpredictability (Warner, 1997; West-Eberhard, 2003). Here we have shown that *A. polyacanthus*, a species without a dispersive larval phase, can exhibit thermal acclimation during its lifetime. Thus, it is likely that other species of reef fish will exhibit thermal acclimation because developmental plasticity in other traits is well documented (Munday *et al.*, 2006), although this remains to be tested.

One-hour acclimatization to the metabolism chamber is relatively short time compared with other studies and a longer time can be required to obtain accurate RMR values of some species (Sloman *et al.*, 2000; Nilsson & Östlund-Nilsson, 2004). However, it is unlikely that our RMR values are inflated by the relatively short acclimatization as the values obtained are similar to those reported in Nilsson *et al.* (2009) for the same species. Additionally, it is possible that a greater acclimation time is needed at warmer temperatures or at temperatures different to rearing conditions. However, it would then be expected for the + 3.0 °C group at 31.5 °C (where acclimation was found to occur) to have a greater RMR than when it was tested at 30.0 °C or for groups tested at their rearing temperature to obtain lower RMR than the other treatment groups. We suggest that the reduced

acclimatization time required is due to the fish being habituated to their aquarium conditions since birth. Furthermore, this habituation may also influence RMR values, but again this is not likely since present metabolism estimates are similar to wild estimates (Nilsson *et al.*, 2009).

Our study is one of the first to demonstrate that acclimation to high temperature may come at the cost of reduced somatic growth. Other research to identify costs associated with thermal acclimation (quantified as the production of heat shock proteins) has been conducted on *Drosophila* with differences found in cell growth (Feder *et al.*, 1992), fecundity (Krebs & Loeschcke, 1994) and survival (Krebs & Feder, 1997). To our knowledge, ours is the first study on an organism outside the Insecta to suggest that energy employed to facilitate acclimation could have been utilized on another function. This emphasizes the need to explore the costs as well as the benefits associated with thermal acclimation.

Thermal acclimation provides a mechanism that could assist tropical fish populations to cope with warming ocean temperatures. It seems likely that developmental acclimation will play a role in reducing the impacts of global warming, improving the chances that populations will persist across their present geographic ranges. However, acclimation has limitations and may not be sufficient for populations already living close to their thermal maximum, thus selection of thermally tolerant genotypes over multiple generations will also be vital. Even with acclimation, our results demonstrate that individuals in future populations will have reduced fitness, which will have significant ramifications for population sustainability.

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