Australian Government
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Marine and Tropical Sciences Research Facility Milestone Report, 31 January 2009

Program 5(i): **Climate Change: Great Barrier Reef**

Project 2.5i.2: **Early warning and assessment system for thermal stress on the Great Barrier Reef**

Project Leader: **Professor Ove Hoegh-Guldberg,**
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Summary

(a) Thresholds and coral response

Calibrate stress response models for interactions between temperature, light and time in multi-factorial experiments and meta-data analysis. Model analyses of coral population and community changes for under projected climate-change scenarios

- *New model for predicting coral mortality risk during and following bleaching events:*

  Key findings were that the timing of the onset of coral mass mortality is determined by a combination of bleaching severity (loss rate of photopigments), duration of the bleaching event, heterotrophy and the size of energy reserves before bleaching occurs.
- *Colony geometry and tissue characteristics modulate light levels in corals at multiple scales:*

  Key findings provide new insight into the adaptive mechanisms (via phenotypic plasticity) for how corals control their internal light environments and alleviate light stress.
- *Predictive models of warming and acidification effects on coral bleaching:*

  Our projections indicate that ocean acidification will lead to dramatically increased levels of severe bleaching overtaking the importance of ocean warming by mid century.
- *Major bleaching events can lead to reduced bleaching in subsequent events:*

  We demonstrated that one bleaching event can increase the thermal tolerance of the remaining coral population to a subsequent thermal stress event.
- *Seasonal thermal baselines improve the predictions of coral bleaching:*

  Predictions of coral bleaching from space-based sensors are greatly improved if seasonal thermal variation of corals is accounted for in the analysis.
- *Recovery from large scale bleaching and mortality within an annual cycle:*

  Large scale bleaching and mortality resultant from large seasonal anomalies, but only small diversions from summer maxima, are recoverable within an annual cycle through coral tissue regeneration and seasonal algal dynamics.
- *Heating rate and symbiont productivity are key factors in identifying thermal threshold flexibility in reef-building corals:*

  Heating rate differential affects corals, but the response is non linear with some factors such as O2 evolution responding positively to rapid heating.

Remnant cells in bleached corals can be orders of magnitude more efficient at evolving O2 than cells in unbleached corals.

Observations of reduced Fv/Fm are not sufficient to demonstrate photosynthetic dysfunction at either the level of the symbiont or the host.

- *Expanding the paradigm of stress and health on coral reefs:*

  We show that response models that build on multiple, nested layers of biological and ecological information have more power to predict sublethal stress, mortality risk, and probability of population and community recovery than existing models

Complete experiment and analysis of ^{13}Carbon acquisition and translocation by clade D and clade C Acropora millipora exposed to thermal stress. Analyse composition of labelled secondary metabolites and host cellular response

- *Seasonal and regional differences in the carbon cycle of A. millepora:*

  Seasonal and regional field experiments have been concluded, respirometry analysed, 13C-labelled metabolites to be analysed by LC-MS.

- *Latitudinal differences in O_2 flux-temperature response curves:*

  The key observation to date is that maximal net O_2 evolution occurs at maximal regional sea surface temperature even for coral sampled in winter.

- *Effect of temperature on cell fates (apoptosis, autophagy or necrosis):*

  Consistent transcriptional changes in genes involved in apoptosis have been observed to occur in rapidly heated corals.

(b) Heritability and genetics

This task investigates the ability of the coral-algal symbiosis to adapt to the predicted rise in ocean temperatures over this century. Two sets of experiments have been conducted to determine the underlying genetic variation in thermal tolerance traits upon which natural selection can act. The experiments were conducted on two populations of Acropora millepora, one from Magnetic Island which hosts thermo-tolerant type D, and one from Orpheus Island which hosts thermo-sensitive symbiont type C2. During the current reporting period, laboratory analyses were completed on samples from the second heat tolerance experiment (Orpheus Island). These included quantifying ratios of zooxanthellar pigments which have a photoprotective function, coral growth and the expression of selected host coral stress and antioxidant genes. The results are being analysed and a manuscript is in preparation.

(c) Diversity of naturally occurring symbiont types

The abundance and host-specificity of the subcladal symbiont types identified thus far suggests that identification at the lowest possible taxonomic level, with use of current methodologies, is ecologically relevant and will help to increase our understanding of the complex responses displayed by each distinct host-symbiont combination.

Oceanography, bleaching and higher trophic effects

This task investigates the role of mesoscale oceanographic patterns and variability to better understand their link to, and influence on, mass coral bleaching and higher trophic animals, especially sea birds. Modis satellite SST and chlorophyll climatologies and time series have been generated, showing distinct "environmental provinces" across the GBR region. The higher resolution (1km) time series have provided unique insights into coral bleaching patterns in the southern GBR, particularly for the inshore Keppel Islands reefs.

Datasets have been identified to investigate broad-scale climate change impacts on the GBR ecosystem. Specific key environmental variables have mapped in space and time across the scale of the GBR ecosystem. The spatial-temporal variability of the physical dynamics in the southern GBR has been investigated and reefs impacts on the meso- and smaller-scale described.

Furthermore, this task aims to explore the basis for the link between bleaching and upwelling, by investigating the relationship between upwelling and the activity of the EAC and in particular, its intrusion into the GBR. Relevant data sets have been selected and data acquisition is being undertaken. Data analysis and manuscript preparation for submission to scientific journals is continuing.

Impact on higher trophic levels

An analysis of levels of adult behavioural and chick developmental plasticity has been completed for one off-shore foraging species – the black noddy (*Anous minutus*) and a manuscript arising from this work is currently in review. Similar work is to be initiated on a second species this season – the wedge-tailed shearwater and is to be continued during the 2010 breeding. It is anticipated that two seasons data will be required before statistically robust conclusions can be drawn for this species.

An analysis examining the effects of large-scale and long-term among-season, oceanographic variation in SST, thermocline depth and productivity (chlorophyll-a) on breeding participation in Sooty terns has been completed. A manuscript arising from this work has been accepted for publication (refer to *Project Results*). This work is continuing to further refine the functional relationships identified in this analysis. In addition, preliminary analyses combining foraging success data with satellite and hydrodynamic information at local inter-reefal scales is currently underway.

Agreed Project Outputs / Milestones

Targeted Activity

(a) Thresholds and coral response

To improve our ability to detect coral stress and predict coral mortality risks in the future, we will develop new predictors and models that incorporate knowledge about how key environmental factors interact in the coral stress response, and to what extent potential acclimatization and historical adaptation may affect such risk. The models will be calibrated using controlled laboratory and raceway experiments in which the responses of a range of coral species to combinations of temperature, light and water quality will be determined. These laboratory experiments will be complimented with detailed analyses of how thermal history, bleaching severity, carbon acquisition/translocation and recovery interact in order to better understand the associated risks of mortality. These thresholds will be incorporated into projection models of how reefs might change as seas warm (Project 2.5i.1*: Regional climate scenarios* and Project 2.5i.4: *Tools to support resilience-based management in the face of climate change*). An important outcome is to the development of an expanded framework for how climate-change stressors impact on coral communities at levels ranging from cell biology to community ecology.

(b) Heritability and genetics

How corals are likely to respond to selection for increased thermal tolerance will be investigated by exploring the heritability of key genetic traits within corals and their symbionts. This information will be fed back into this objective to provide more accurate estimates of the trajectory of GBR coral communities under rapid climate change.

(c) Oceanography, bleaching and higher trophic effects

The role of mesoscale oceanographic patterns and variability will be investigated to better understand their link to, and influence on, mass coral bleaching and higher trophic animals, especially sea birds. MODIS SST and chlorophyll remote sensing data will be used to explore the GBR oceanography and it influence on biological systems. SST and chlorophyll climatologies have been generated (ARP2) as a 1km resolution baseline essential for future studies, showing distinct “bio-geographic provinces” across the GBR region. The higher resolution time series have provided unique insights into coral bleaching patterns in the southern GBR, particularly for the inshore Keppel Islands reefs. Further to this, we will investigate how broad-scale climate change phenomena translate into changes within the GBR ecosystem and impact reefs on the meso- and smaller-scale. Key environmental variables will be mapped in space and time to improve our understanding ‘of climate change impacts across the scale of the GBR ecosystem. The spatial-temporal variability of the physical dynamics will be investigated to determine the biological response, and also whether particular reef systems may be heated or cooled (flushed) and hence likely to experience coral bleaching and mortality or not.

Seabird foraging and reproductive success is explicitly linked to both local and large-scale oceanographic variation. We will investigate the relationships between prey availability/accessibility and specific physiochemical oceanographic parameters at different scales. These data will be combined with satellite and hydrodynamic information on meso-scale oceanographic variability to better predict how seabirds will respond to projected increases in both SST and other ENSO associated phenomena. Further, we will aim to assess both behavioural and developmental plasticity in multiple seabird species under fluctuating resource availability. These project components will allow determination of the likely range of oceanographic and climatic conditions within which seabird reproduction on the GBR will remain viable.

Project Results

Description of the results achieved for this milestone

(a) Thresholds and coral response

Calibrate stress response models for interactions between temperature, light and time in multi-factorial experiments and meta-data analysis. Model analyses of coral population and community changes for under projected climate-change scenarios. Team Member: Ken Anthony [UQ]

During this reporting year, our team of senior researchers and postgraduate students have conducted a series of experimental studies and model analyses focusing on a deeper understanding of the biological and ecological processes underlying stress responses of coral reefs to climate change. Our efforts have resulted in a series of papers and submitted manuscripts aimed at high-profile journals. The following is a detailed list of specific objectives and outcomes.

- ***New model for predicting coral mortality risk during and following bleaching events***

  A key objective of this was to develop a model that links the functional response of colony energy balance and energy-store dynamics to coral mortality risk and recovery during and following bleaching events. The rationale for this work was that, although the onset of mass bleaching events can be predicted using simple temperature stress metrics (e.g. NOAA Hotspots), no models are available for predicting coral mortality risk or sub-lethal stress associated with bleaching. In a series of simulations based on calibrated response functions and parameter values from experimental studies and meta-analyses, we demonstrate that prior energy-costly disturbances and alternative energy sources are both important determinants of coral mortality risk during and following bleaching. Key findings were that the timing of the onset of coral mass mortality is determined by a combination of bleaching severity (loss rate of photopigments), duration of the bleaching event, heterotrophy and the size of energy reserves before bleaching occurs (Figure 1). Depending on initial energy reserves, model results showed that high rates of heterotrophy could delay the onset of mortality in the two coral species by up to three weeks. Survival following bleaching was also strongly influenced by remaining lipid reserves, rates of heterotrophy, and rates of photopigment (or symbiont) recovery. Our results indicate that energy-costly disturbances and low availability of food, prior to and during bleaching events, respectively, work to increase bleaching-induced coral mortality risk for acroporid corals on Indo-Pacific reefs. The work resulted in a large modelling / review paper published in *Function Ecology*.

  Journal Articles:

  Anthony, K. R., Hoogenboom, M. O., Maynard, J. A., Grottoli, A. and Middlebrook, R. (2009) Energetics approach to predicting mortality risk from environmental stress: A case study of coral bleaching. *Functional Ecology* 23(3): 539-550 [doi:10.1111/j.1365-2435.2008.01531.x] [June 2009]

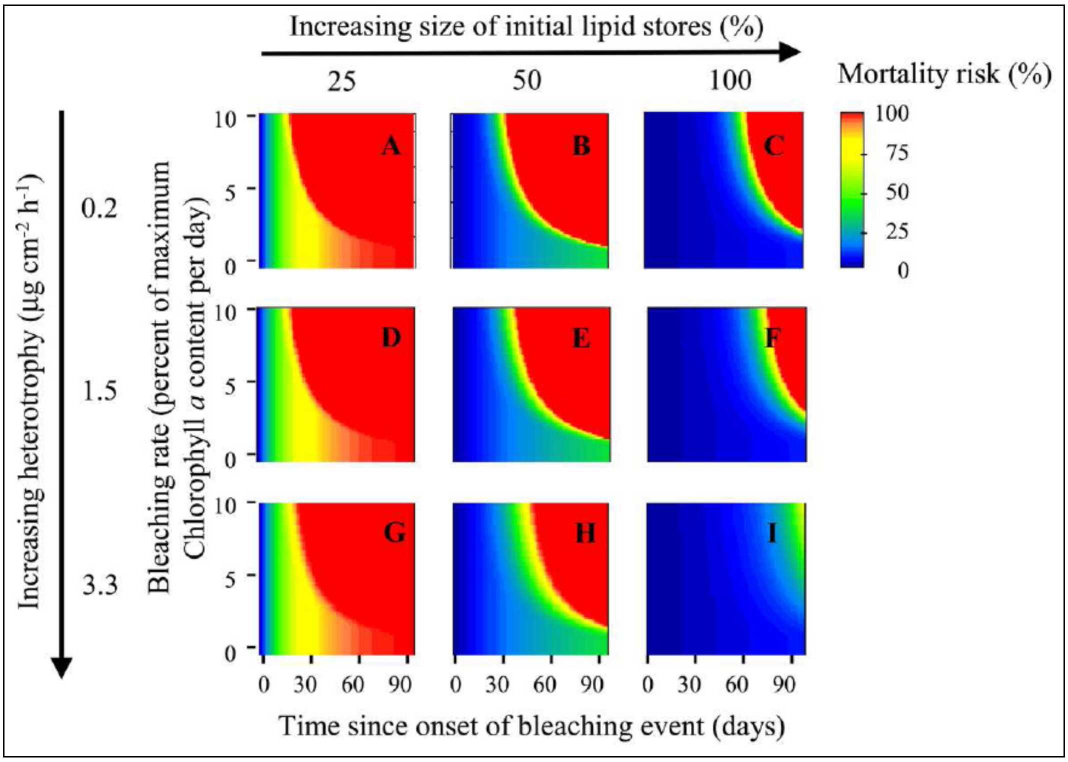

Figure 1: Effects of the size of initial lipid stores (prior to bleaching, *Es0*), rate of heterotrophy and bleaching rate ($dChl_n(t) / dt$) on accumulated coral mortality risk (colour bar, percent) during a three-month bleaching event. Initial percentages of lipid content of 25, 50 and 100% correspond to 0.5, 1.0 and 2.0 mg lipid cm^{-2}, respectively. From Anthony et al. (2009), *Functional* Ecology 23(3): 539-550.

- ***Colony geometry and tissue characteristics modulate light levels in corals at multiple scales***

  In two collaborative studies led by Paulina Kaniewska, we determined analytically how adaptive variation in coral morphology and characteristics at colony, branch and polyp level provides varying degrees of self-shading and thereby offer protection from supra-optimal light fields. Because light is a key co-factor in coral bleaching, light control has important implications for coral bleaching risk. In one study now published in *Marine Biology* (Kaniewska, Anthony and Hoegh-Guldberg 2008), we found that variation in branch length and branch spacing across light habitats in *Acropora* and *Pocillopora* are effective mechanisms of reducing light pressure at the level of tissue and symbionts. In a second related paper, now submitted to *Limnology and Oceanography* (See References: Kaniewska, Magnusson, Anthony, Reef, Kühl and Hoegh-Guldberg, *submitted*), the team found that coral species from across a wide spectrum of morphological types are able to modulate internal light regimes. These finding provide new insight into the adaptive mechanisms (via phenotypic plasticity) for how corals control their internal light environments and alleviate light stress. The studies complement recent publications (Dove *et al.* 2008, Smith-Keune and Dove 2008, and the PhD thesis of J. Deckenback 2008) that show that host pigmentation is highly susceptible to fluxes in light and temperature. In a follow-on modelling study (Anthony and Dove), we are currently investigating the significance of such light control for the bleaching susceptibility of corals under future warming scenarios.

  Journal Articles:

Dove, S. G., Lovell, C., Fine, M., Deckenback, J., Hoegh-Guldberg, O., Iglesias-Prieto, R. and Anthony, K. R. N. (2008) Host pigments: Potential facilitators of photosynthesis in coral symbioses. *Plant, Cell and Environment* 31(11): 1523-1533 [doi:10.1111/j.1365-3040.2008.01852.x] [November 2008]

Kaniewska, P., Anthony, K. R. N. and Hoegh-Guldberg, O. (2008) Variation in colony geometry modulates internal light levels in branching corals, *Acropora humilis* and *Stylophora pistillata*. *Marine Biology* 155(6): 649-660 [doi:10.1007/s00227-008-1061-5] [November 2008]

Smith-Kuene, C. and Dove, S. (2008) Gene expression of a green fluorescent protein homolog as a host-specific biomarker of heat stress within a reef-building coral. *Marine Biotechnology* 10(2): 166-180 [doi:10.1007/s10126-007-9049-6]

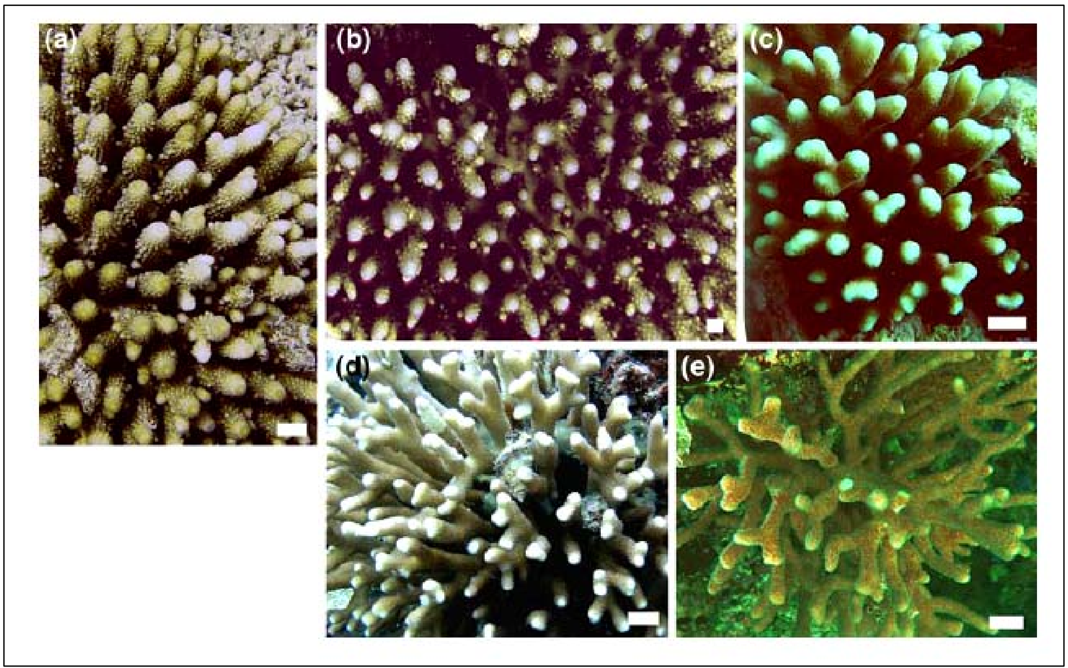

Figure 2: Type morphologies of two branching coral species from different light habitats (shallow, deep, cave) on Heron Island, GBR. In high-light habitats, tight packaging and branch elongation and **(a)** *Acropora humilis* at 5 m (shallow); **(b)** *A. humilis* at 18 m (deep); **(c)** *Stylophora pistillata* at 5 m (shallow); **(d)** *S. pistillata* at 18 m (deep); **(e)** *S. pistillata* at 5 m (cave). *Scale bars* represent 1 cm.

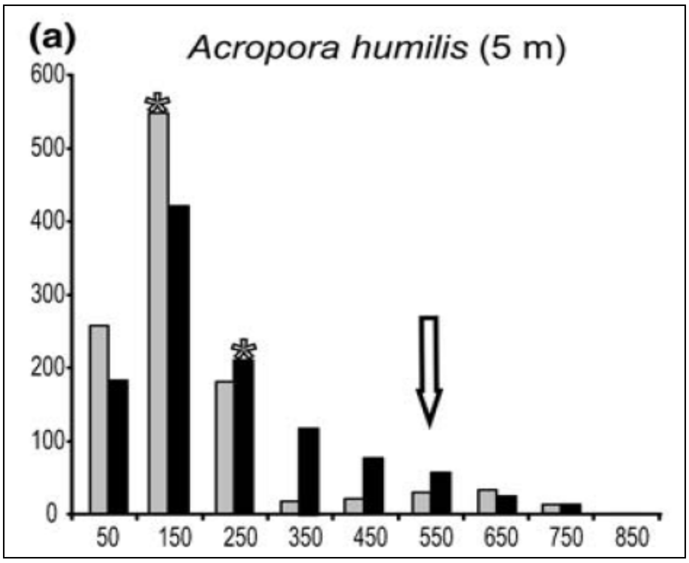

Figure 3: The role of colony morphology in modulating internal light regimes in *Acropora humilis*. Grey bars are for shallow water (5 m) and black bars are for the deep model (18 m). The difference in the shapes of the distributions is attributable to variation in structural self shading – protecting shallow-water corals from damaging light levels. The arrow indicates the ambient irradiance level and the asterisks indicate the modes of the light distributions in shallow and deep water.

- ***Predictive models of warming and acidification effects on coral bleaching***

  Building on our recent finding that high CO_2 is a bleaching agent for corals (Anthony *et al.* 2008), the team developed a new projection model of coral bleaching risk for the century. The work was led by UQ (Anthony, Hoegh-Guldberg, Dove, Diaz-Pulido, Weeks) and was a collaborative modelling study involving Stanford University (Caldeira and Cao), the NOAA Coral Reef Watch Program (Eakin), Melbourne University (Maynard) and AIMS (Berkelmans and Lough). Our projections indicate that ocean acidification will lead to dramatically increased levels of severe bleaching under both emission scenarios (Figure 4). Comparing projections with and without the CO_2 effect for the A1FI scenario (red versus light blue areas in Figure 2), our model suggests the CO_2 effect will increase the probability of full bleaching from 40-60% to 70-100% of corals during the late half of this century. Even more dramatically, for the B1 scenario, CO_2 was projected to be 2-4 fold more important than temperature as a coral bleaching agent beyond year 2040 (yellow versus blue areas in Figure 4). Effectively, on southern GBR reefs, increased coral bleaching risk as a result of acidification will result in annual severe bleaching events occurring twenty to thirty years earlier than expected from temperature projections. Importantly, our bleaching risk projections are likely to be underestimates since we constrained CO_2 bleaching effects to the heating, and high-irradiance, season only. A paper from this work is being submitted to *Science* in early February 2009 (See References: Anthony *et al.* 2009).

  Journal Articles:

  Anthony, K. R. N., Kline, D. I., Diaz-Pulido, G., Dove, S. and Hoegh-Guldberg, O. (2008) Ocean acidification causes bleaching and productivity loss in coral reef builders. *Proceedings of the National Academy of Sciences of the United States of America* 105(45): 17442-17446 [doi:10.1073/pnas.0804478105]

- ***Major bleaching events can lead to reduced bleaching in subsequent events***

  In a study comparing bleaching severities in three coral genera (*Acropora*, *Pocillopora* and *Porites*) following the thermal stress event on the central GBR in 1998 and 2002, we demonstrated that one bleaching event can increase the thermal tolerance of the remaining coral population to a subsequent thermal stress event (Figure 5). Specifically, following severe thermal stress in 2002, bleaching severity was 30-100% lower than predicted from the relationship between severity and thermal stress in 1998, despite higher solar irradiances during the 2002 thermal event. Coral genera most susceptible to thermal stress (*Pocillopora* and *Acropora*) showed the greatest increase in tolerance. Although bleaching was severe in 1998, whole colony mortality was low at most study sites suggesting that the observed increase in thermal tolerance cannot be explained fully by selective mortality. Our analyses suggest that such increase in thermal tolerance may buy reefs valuable, however short, time before the predicted onset of mass coral mortalities during this century. The work was published by Maynard, Anthony, Marshall and Masiri in the journal *Marine Biology*.

  Journal Articles:

  Maynard, J. A., Anthony, K. R. N., Marshall, P. A. and Masiri, L. (2008) Major bleaching events can lead to increased thermal tolerance in corals. *Marine Biology* 155(2): 173-182 [doi:10.1007/s00227-008-1015-y]

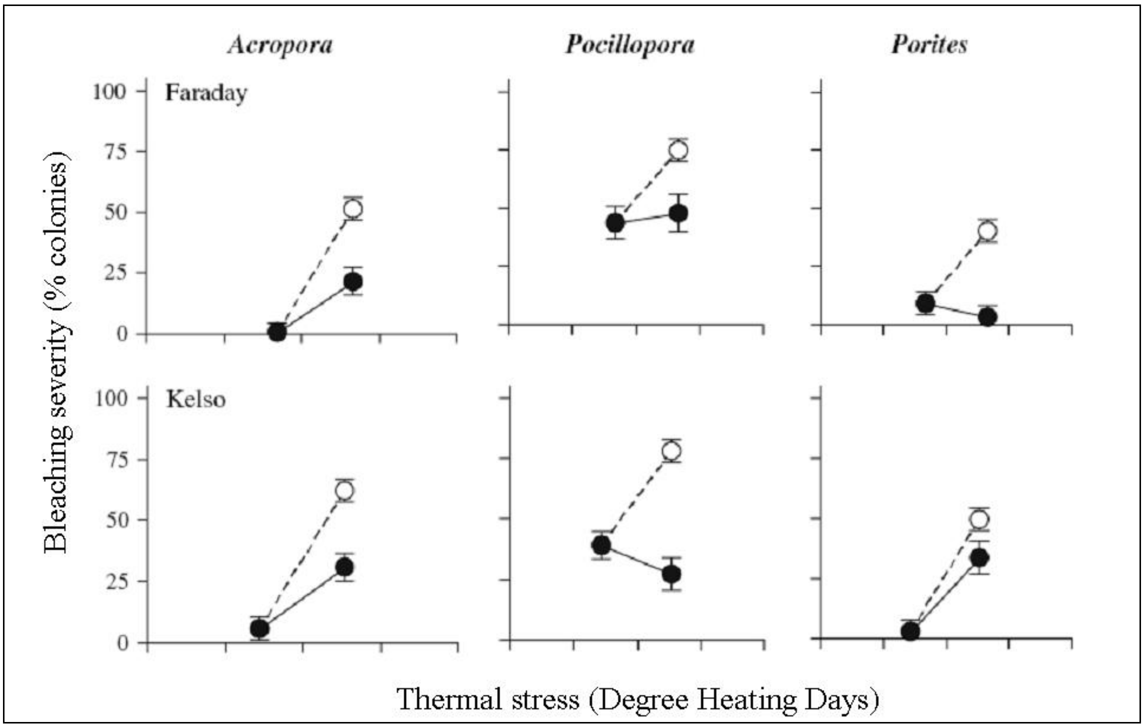

Figure 5: Bleaching responses of the three study genera as a function of accumulated heat stress (degree heating days) at five sites in 1998 and 2002. Solid markers are observed bleaching severities in 1998 (left markers) and 2002 (right markers), respectively. Predicted bleaching severities in 2002 (open markers) were calculated based on the empirical relationship between bleaching severity and accumulated heat stress for fifteen surveyed sites in 1998. Confidence limits (95%) for predicted bleaching severities in 2002 were estimated using Monte Carlo analyses.

- ***Seasonal thermal baselines improve the predictions of coral bleaching***

  This study, led by Scarla Weeks and published in *Limnology and Oceanography* (Weeks, Anthony, Feldman, Bakun and Hoegh-Guldberg, 2008), demonstrated that predictions of coral bleaching from space-based sensors are greatly improved if seasonal thermal variation of corals is formally accounted for (Figure 6). The team concluded that the development of remote thermal sensing models that incorporate information about seasonal biological processes and varying sensitivities to environmental variables is likely to produce more accurate tools for predicting thermal stress to coral reefs under ocean warming.

  Journal Articles:

  Weeks, S. J., Anthony, K. R. N., Bakun, A., Feldman, G. C. and Hoegh-Guldberg, O. (2008) Improved predictions of coral bleaching using seasonal baselines and higher spatial resolution. *Limnology and Oceanography* 53(4): 1369-1375.

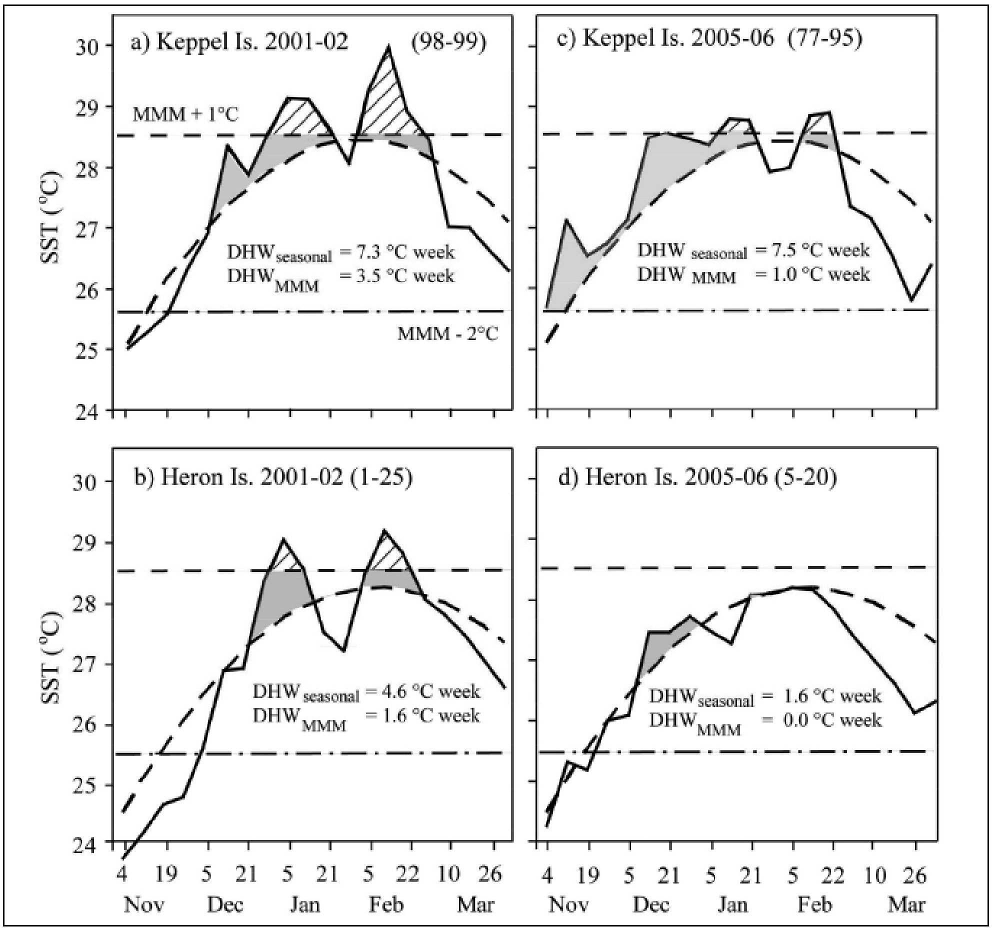

Figure 6: Adapted from Weeks et al. (2008) Limnology and Oceanography 53(4): 1369-1375.

- ***Recovery from large scale bleaching and mortality within an annual cycle. Keppel Island. Following major +7.5 DHW Seasonal Impact, but minimal +1 DHW MMM***

  See References: Diaz-Pulido et al. (In Review)

  Mass bleaching of corals on inshore reefs of the southern Great Barrier Reef, particularly in the Keppel Islands, caused high coral mortality in early 2006. This coral mortality led to an unprecedented bloom of a single species of unpalatable seaweed (*Lobophora variegata*), colonizing dead coral skeletons. However, corals on these reefs recovered dramatically, in less than a year. The cover of branching *Acropora* corals at most studied sites showed an extremely rapid recovery after the seaweed bloom, reaching pre-bleaching levels by December 2006 to April 2007 (ca. 12-14 months after the onset of bleaching. This represents a 100-200% increase in cover of *Acropora* in approximately six months. This rapid reversal was driven by rapid regeneration rates of remnant coral tissue, very high competitive ability of the corals allowing them to out-compete the seaweed, a natural seasonal decline in the particular species of dominant seaweed. The seaweed decline occurred during the warmer months (December through May), potentially providing the corals a window for recovery. This study provides a key example of the recovery potential of a highly resilient reef, and new insights into the variability and mechanisms of reef resilience under rapid climate change.

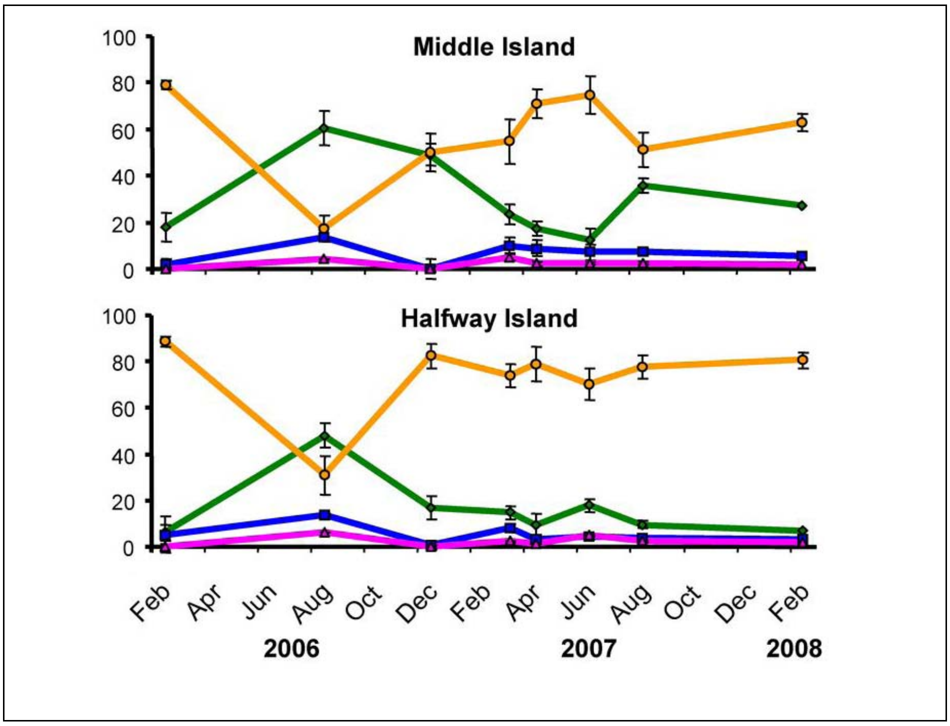

Figure 7: Coral-algal dynamics in response to the 2006 warming-induced coral bleaching event. Data from the reef slopes of four islands in the Keppel Islands, southern Great Barrier Reef. Percent cover data are means (n=10) ±SE, except for February 2006 (n=25-26). CCA = Crustose calcareous algae.

- ***Heating rate and symbiont productivity are key factors in identifying thermal threshold flexibility in reef-building corals***

  See References: Middlebrook, R., Anthony, K., Hoegh-Guldberg, O. and Dove, S. (In Review).

  Effect of heating rate – rapid (1°C per day) vs. slow progressive (0.5°C per day) from winter ambient temperature of 23°C, to +3-4°C anomalous temperature of 33°C – on a variety of photosynthetic indices in the symbiotic coral *Acropora formosa* from Orpheus Island. At the highest temperature of 33°C, *Symbiodinium* densities where reduced to 0.5 million cells cm^{-2} irrespective of treatment. Interestingly, only rapidly heated corals incurred further losses in symbiont cells when returned to the ambient winter temperature. Remnant cells however were highly productive if few in number. Between 30-32°C, remnant cells in rapidly heated corals were evolving O_2 at a rate greater than either corals slowly heated to this temperature range or control corals at 23°C. Reductions in dark adapted Fv/Fm have previously been defined as reductions in "symbiont photosynthetic fitness" (Berkelmans and van Oppen 2006), and argued to reflect the status of holobiont O_2 flux and hence the ability of the host to maintain its autotrophic status (Rowan 2004). The data from this study however suggest that reductions in the efficiency of converting absorbed photons to photochemical energy at PSII (Fv/Fm) do not necessary coincide with reductions in the efficiency with which O_2 is evolved either at the level of the symbiont or the host. This observation is perhaps not surprising given that photochemistry involves at least four pathways inclusive of non-carbon assimilatory pathways that consume oxygen.

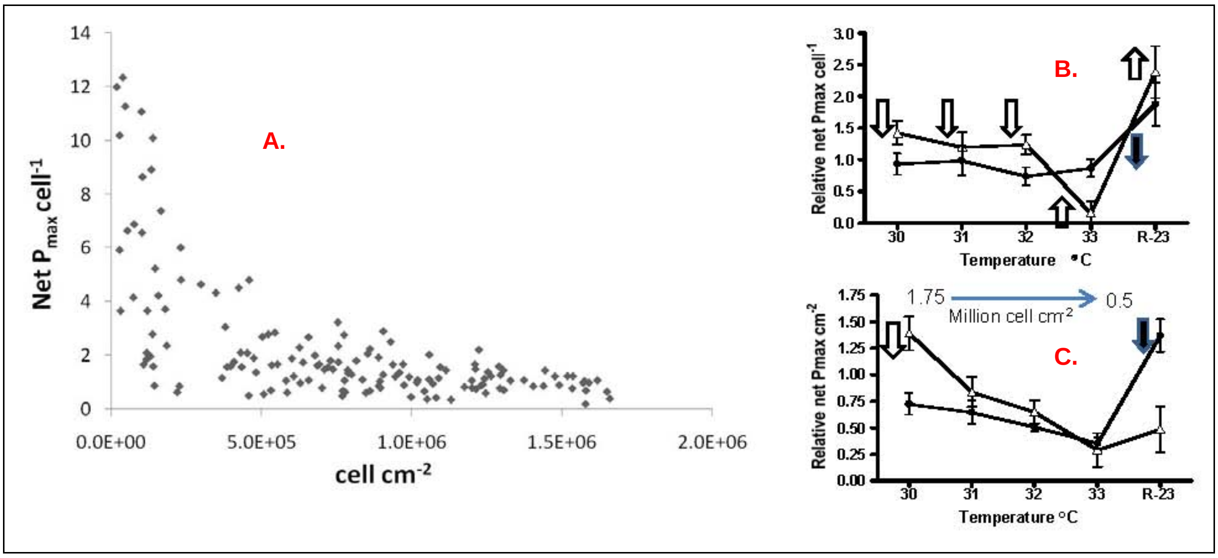

Figure 8: Adapted from Middlebrook *et al.* (In Review) (See References). **A.** Net O_2 evolution per symbiont cell for *Acropora formosa* as a function of symbiont density. **B.** Effect of temperature on O_2 evolution for symbiont cells hosted by *A. formosa* as a function of temperature. **C.** Areal O_2 evolution for *A. formosa* as a function of temperature. **B. and C.** Data are normalised to response of corals held at ambient winter of 23°C. *Open symbols*, rapid heating; *closed symbols*, slow heating; *down arrows*, observed reductions in Fv/Fm, *up arrows*, observed increases in Fv/Fm prior to O_2 flux measurements; *R-23*, Response of corals to a fairly rapid reintroduction to 23°C.

- ***Expanding the paradigm of stress and health on coral reefs***

To help determine the location of environmental thresholds beyond which coral reefs show declining health and function we (Anthony, Dove, Dunn, Caley, Hoegh-Guldberg) are compiling and analysing metadata for coral and reef responses within a new framework. We expand the existing stress (or health) paradigm for coral reefs by integrating information across levels of cell, organism, population, community and ecosystem (Figure 9). Using climate-change and water-quality stressor as case studies, we show that response models that build on multiple, nested layers of biological and ecological information have more power to predict sublethal stress, mortality risk, and probability of population and community recovery than existing models. As a specific case, we examine the efficacy of using organism energetics as a metric for quantitatively linking cellular to population-level stress responses as the flow of energy determines resources available for growth, maintenance and survival. With information on differential species-specific responses, stressors at organism and population levels can drive stress responses predictively at the community level. We show that this expanded framework for environmental stress provides reef managers with improved ability to predict mortality risk and recovery potentials under complex environmental scenarios, and thereby improved opportunities to undertake proactive management to lessen impacts on a local scale. The analyses and the manuscript are far progresses and we expect to submit the paper in early April.

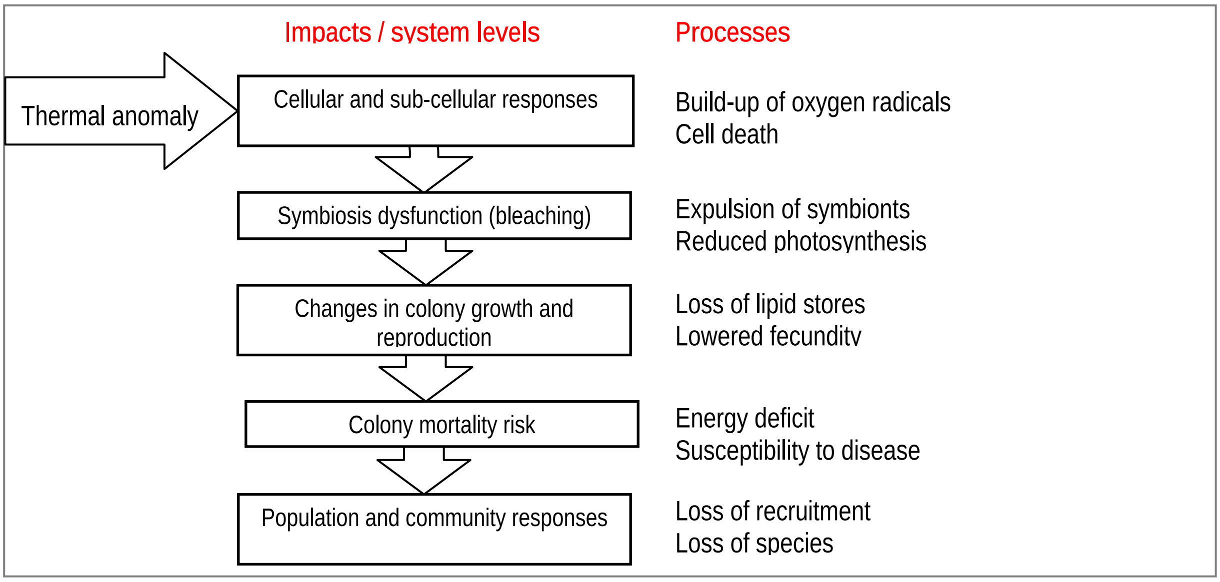

Figure 9: Summary of how a direct impact at the lowest (cellular) level flows on to produce secondary impacts on higher organisational levels. The diagram highlights only deterministic processes and thereby ignores other scale-dependent influences such as stochastic demographic processes (e.g. recruitment) and species interactions

Description of the results achieved for this milestone (cont'd)

Complete experiment and analysis of ^{13}Carbon acquisition and translocation by clade D and clade C Acropora millepora exposed to thermal stress. Analyse composition of labelled secondary metabolites and host cellular response. Team Member: Sophie Dove [UQ]

- ***Seasonal and regional differences in the carbon cycle of A. millepora***

  The experiments on seasonal changes to the acquisition and translocation of carbon are underway. Experiments have involved the incorporation of ^{13}Carbon (in place of ^{14}Carbon) on sunny days in chambers deployed in less than 0.5 m of water in reef flat locations. To date, experiments have been performed in the field with *Acropora millepora* from Lizard Island and Heron Island. Late summer experiments have been conducted on Heron Island, and winter experiments on both Heron and Lizard Islands. Analyses of these samples have been delayed so that ^{13}C incorporation into metabolites can be analysed by our newly acquired LC-MS.

- ***Latitudinal differences in O_2 flux-temperature response curves***

  The key observation to date is that maximal net O_2 evolution occurs at maximal regional sea surface temperature even for coral sampled in winter. These data suggest enzyme-temperature response curves for enzymes involved in O_2 evolution are not subject to seasonal acclimation

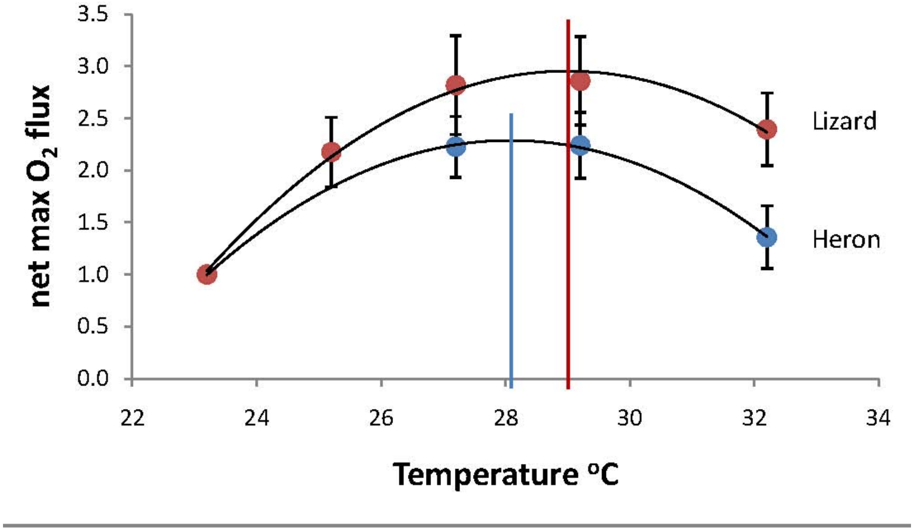

Figure 10: O_2 flux-temperature response curves for colonies serially exposed to increases in temperature in fifteen-minute steps. Mean ± SE for five colonies with the response normalised to the response observed at 23°C. NOAA website: Max Monthly temp = 27.3°C (Heron Island), 29°C (Lizard Island); Bleaching Threshold = 28.3°C (Heron Island), 30°C (Lizard Island).

- ***Effect of temperature on cell fates (apoptosis, autophagy or necrosis)***

Recently, functional studies have suggested the key role of multiple cell death pathways, such as apoptosis and autophagy in coral bleaching process. However, despite the importance of bleaching phenomenon, the interconnectivity between these major cellular pathways and physiological responses to environmental stress remains unresolved in the case of coral-dinoflagellate symbiosis. This study aimed to specify the influence of elevated temperature on the molecular regulation of apoptotic cellular processes of the reef building coral *Acropora millepora*. The effects of rapid thermal change on the level of expression of two pro-apoptotic genes (Bax, Bak) and two anti-apoptotic genes (Bcl-2, Bcl-L1) were investigated experimentally in *A. millepora* cells by using real time PCR. The results indicated clear expression patterns associated with severe thermal stress conditions (fast treatment: increase of 8°C in sea water temperature in eighteen hours), both pro and anti-apoptotic genes showing a significant increase in their level of expression. The important change in Bcl-2 expression level (16 fold greater) as well as in Bcl-2/Bax and Bcl-2/Bak ratio (2.3 and 2.9 fold greater) suggest a major role of the Bcl-2 protein in the cellular processes occurring in the coral host tissue during thermal stress conditions. These results are in accordance with previous studies in mammals reporting over-expression of Bcl-2 as a potential protective mechanism against heat induced apoptosis.

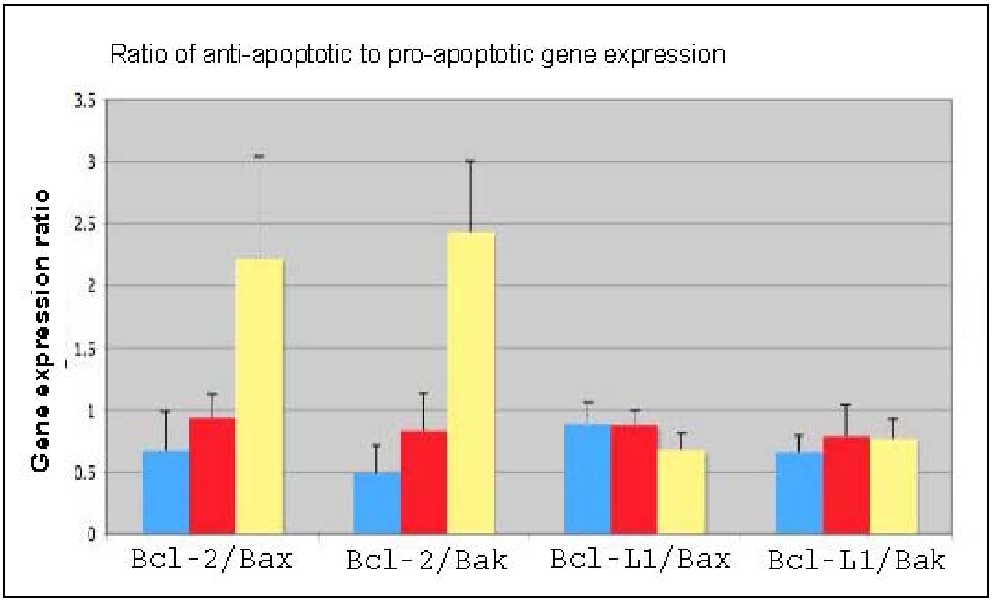

Figure 11: Increased coral host anti-apoptotic gene expression (Bcl-2, Bcl-L1) versus pro-apoptotic gene expression (Bak, Bax) as a mechanism of damage mitigation under hyperthermic induced cell stress. *Blue*, Control time 0; *Red*, Control time 18 hours; *Yellow*, Hyperthermic stress time 18 hours.

(b) Heritability and genetics

Complete laboratory analysis of samples from the second heritability heat tolerance experiment (van Oppen/Csaszar)

In the previous report we presented preliminary findings of the relative adaptive potential of two *Acropora millepora* populations to thermal stress. These results concerned the photophysiology traits of the Magnetic Island population which hosts symbiont clade D and the Orpheus Island population which hosts clade C2.

In this reporting period the laboratory analyses were completed for the second experiment (Orpheus Island population). These variables included, (i) quantifying symbiont pigment ratios (diathoxanthin (DT) to diadinoxanthin (DD)), which have a photo protective function; (ii) coral growth rates (a 'holobiont' trait); and (iii) quantifying the host coral expression of the stress and antioxidant genes Ferritin, Hsp70, MnSOD and Zn^{2+}-metalloprotease.

The results from the laboratory analyses are currently being analysed with a view to comparing the adaptation potential in traits of the zooxanthellae versus those of the coral host and the populations with contrasting zooxanthella types. A manuscript on this work is in preparation.

Diversity of naturally occurring symbiont types **(Hoegh-Guldberg/ Tonk/ Sampayo)**

The genotype of dinoflagellates (*Symbiodinium*) residing within the tissues of many reef invertebrates appears to be highly diverse and plays an important role in determining environmental tolerance ranges of their host. A database of existing literature on *Symbiodinium* diversity has been compiled that contains approximately 3,500 entries of a wide range of host taxa (such as hard corals, soft corals, anemones, hydroids fire corals and clams) and covers 62 collection sites along the GBR. The majority of hosts contained a single symbiont type of which ~ 90% belong to clade C, 9% to clade D and 1% to clades A, B and G. The occurrence of clade D appears to be higher in the more northerly sections of the GBR as well as inshore locations within the central section and the Mackay/Capricorn section. However, few inshore and northern locations have been included. To supplement the existing database inshore collections have already been done in 2008 and further collections are planned in 2009.

A substantial amount of variability was found across the GBR on a taxonomic level lower than the cladal level. Approximately eighty distinct subcladal types were identified based on the internal transcribed spacer regions of the ribosomal genes. Previous work has shown that subcladal types are ecologically relevant and play an important role in determining host tolerance ranges. Preliminary findings of the samples (~720) collected around Lizard Island during November 2007 also have shown that a wide diversity of subcladal symbiont types exists. All samples from soft corals (~18%) have been analysed and this has effectively doubled the amount of entries in our database for soft coral hosts. Across the thirteen genera of soft corals sampled at least fourteen different symbionts subcladal types were identified. Eighty percent of these were members of clade C. Across the fourteen genera of hard corals approximately 45 different symbiont subcladal types were identified. Approximately 45% were belonged to clade C. Subcladal symbiont types were largely specific to the host genus from which they were isolated although some types were shared between closely related host genera. The abundance and host-specificity of the subcladal symbiont types identified thus far suggests that identification at the lowest possible taxonomic level, with use of current methodologies, is ecologically relevant and will help to increase our understanding of the complex responses displayed by each distinct host-symbiont combination.

Oceanography, bleaching and higher trophic effects

Evidence of provision of MODIS SST and Ocean Colour data and interpretation to GBRMPA on bleaching conditions during summer (Weeks, UQ)

Bleaching risk output reports have been provided to the Great Barrier Reef Marine Park Authority and further interested parties on a fortnightly basis since the beginning of November 2008. These have been assembled from an array of satellite and in situ data, as well as selected bleaching forecast models. The reports include a brief analysis of the current conditions. An example is included as an Appendix 1 to this report.

Evidence of ongoing provision of MODIS satellite data from NASA to UQ (Weeks, UQ)

Acquisition of daily one-kilometre resolution MODIS satellite data from NASA remains ongoing, as does generation of geophysical parameters -SST, chlorophyll *a* concentration and Kd490. Three regions have been mapped in space and time: the GBR and Coral Sea regional waters, the northern and the southern GBR regions, for analysis. Climatologies have been generated to include eight years' MODIS data. The processes driving the formation of mesoscale anti-cyclonic and cyclonic eddies are identified by analysing the MODIS SST and chlorophyll concentration imagery together with the long and intensive oceanographic deployment in the southern GBR.

Two papers based on this work are about to be submitted:

Weeks, S. J., Bakun A., Steinberg, C. and Hoegh-Guldberg, O. (2009) The Capricorn Eddy: a prominent driver of the ecology and and future of the southern Great Barrier Reef.

Weeks, S. J., Bakun A., Congdon B. and Steinberg, C. (2009) Mesoscale ocean eddy dynamics and seabird ecology in the southern Great Barrier Reef: Observations from the 2005-2006 coral bleaching event.

EAC dynamics during bleaching and their influence on upwelling on the GBR (Steinberg, AIMS; Berkelmans, AIMS; Weeks, UQ)

Meetings were held at AIMS in September 2008 and January 2009 to progress the identification and acquisition of relevant data sets. It was decided to concentrate initially on the activity of the EAC dynamics, which directly influences the GBR through it inflows, eddies, upwelling and along-shelf transport. The dynamics of the SEC can't be done justice within the scope of this task and will be undertaken separately in ARP4.

The following long-term observational data sets are being compiled for analysis for this project from current and historical studies, concentrating on the warm bleaching summers of 2001-2002 and 2005-2006, the warm non-bleaching summer of 2003-2004 and the cool non-bleaching summer of 2002-2003:

- Meteorological data from the AIMS and Bureau of Meteorology (BoM) automatic weather stations (Berkelmans and Steinberg);
- Sea level from AIMS loggers and BoM National Tidal Centre (Steinberg);
- Temperature Loggers (Berkelmans);
- Current Meter Moorings from the outer and mid-shelf (Steinberg);
- The Bluelink ReAnalysis (BRAN 2.1) hydrodynamic model subset was acquired from CSIRO and is now available locally at UQ and AIMS. This covers the period 1992-2008

and is a daily three-dimensional view of the ocean (currents, temperature and salinity) at a 10x10km spatial resolution (Steinberg);

- MODIS satellite SST – Day, Night and merged (Weeks);
- MODIS satellite chlorophyll concentration (Weeks);
- SeaWiFS satellite PAR (photosynthetically available radiation) (Weeks); and
- NOAA AVHRR Pathfinder data (Weeks).

Analysis of levels of adult behavioural and chick developmental plasticity within one off-shore foraging species (Brad Congdon, JCU)

An analysis of levels of adult behavioural and chick developmental plasticity has been completed for one off-shore foraging species – the black noddy (*Anous minutus*) and a manuscript arising from this work is currently in review:

Devney C. A., Caley, M. J. and Congdon, B. C. (In Review) Flexibility of responses by parent and offspring noddies to sea-surface temperature anomalies. *Oikos.*

Abstract: Determining whether species can resist predicted climate change associated shifts in temperature through behavioural and/or developmental plasticity is crucial for predicting outcomes of potential environmental stress. We investigated the plasticity of sex-specific adult foraging behaviour and chick development of black noddies (*Anous minutus*) during two breeding seasons. The first season had anomalously high sea-surface temperatures and low prey availability (low food treatment). The second breeding season was a year with periods of slightly below average sea-surface temperature (normal food treatment). During this second season, supplementary feeding of chicks was used to manipulate offspring nutritional status in order to mimic conditions of high prey availability (medium-high and high supplementation food treatments). Chicks from the low food treatment were fed smaller meals by both male and female parents but at the same rate as chicks in the normal food treatment. Supplementary feeding of chicks also resulted in delivery of smaller meals by males and females, but again did not influence feeding frequency. Chick begging and parental responses to cessation of supplementation suggest smaller meals fed to artificially supplemented chicks resulted from a decrease in chick demands associated with satiation, rather than adult behavioural responses to chick condition. During periods of low prey abundance chicks maintained structural growth while sacrificing body condition and were unable to take advantage of periods of high prey abundance by increasing growth rates. These results suggest that this species expresses limited plasticity in provisioning behaviour and development of offspring, implying that black noddies currently have restricted capacity to resist environmental variation associated with climate change. Consequently, responses to future changes in sea-surface temperature and other environmental variation may be dependant on evolutionary responses to natural selection in these birds.

Similar work is to be initiated on a second species this season – the wedge-tailed shearwater and is to be continued during the 2010 breeding. It is anticipated that two seasons data will be required before statistically robust conclusions can be drawn for this species.

Preliminary analysis of the relationship between among-season variation in SST/thermocline depth / productivity and foraging success / reproductive output (Congdon, JCU)

An analysis examining the effects of large-scale and long-term among-season, oceanographic variation in SST, thermocline depth and productivity (chlorophyll-a) on breeding participation in Sooty terns has been completed. A manuscript arising from this work has been accepted for publication:

Devney C. A., Short, M. and Congdon, B. C. (2009) Sensitivity of tropical seabirds to El Niño precursors. *Ecology* (In Press)

Abstract: Intense El Niño events severely impact seabird populations, often months in advance of peak temperature anomalies. The trophic mechanisms responsible for these impacts are unknown, but are assumed to operate at seasonal scales and to be linked to ocean productivity changes. Precursors to El Niño events include changes in both sea-surface temperature and the depth of the 20°C thermocline. Foraging piscivorous seabirds are known to be sensitive to both thermocline depth and sea-surface temperature change, but the potential influence of these phenomena on breeding dynamics is unknown. Using eighteen years of data on three seabirds of the western tropical Pacific, we show that pelagic seabird breeding participation is directly and independently related to changes in both surface chlorophyll concentration and thermocline depth that occur well in advance of El Niño generated sea-surface temperature anomalies. In contrast, breeding in an inshore foraging species is not correlated with any environmental/biological parameters investigated. These findings demonstrate that El Niño related phenomena do not affect seabird prey dynamics solely via productivity shifts at seasonal scales, nor in similar ways across different seabird foraging guilds. Our results also suggest that population declines observed in western tropical Pacific may be directly related to the frequency and intensity of El Niño anomalies over the study period.

This work is continuing to further refine the functional relationships identified in this analysis. In addition, preliminary analyses combining foraging success data with satellite and hydrodynamic information at local inter-reefal scales is currently underway.

Explanation of Activity Changes

Diversity of naturally occurring symbiont types (Hoegh-Guldberg/ Tonk)

The trip to the Far Northern section in collaboration with AIMS was rescheduled and could therefore not be attended. We will now try to schedule this trip in October 2009 by joining the Undersea Explorer on their Far Northern expedition. The trip to the Swains is scheduled in March/April 2009. However, due to the potentially upcoming bleaching event rescheduling may take place as well.

Oceanography, bleaching and higher trophic effects

For the upwelling and current dynamics component of this task, it was initially envisaged that both the SEC and the EAC dynamics be investigated together. However, it has since become clear that doing both is too ambitious in the current ARP3 and that we should be concentrating our efforts on the EAC in the first instance. We therefore propose that the SEC dynamics, it's bifurcation on the northern GBR shelf and subsequent flows to the EAC (south) and the Hiri current (north) should be investigated separately in ARP4. This will be part of a PhD project for a UQ student, Ana Redondo-Rodriguez, jointly supervised by S. Weeks, J. Lough, R. Berkelmans and C. Steinberg.

Problems and Opportunities

Database applicability and future direction: (Hoegh-Guldberg/Tonk/Sampayo)

As mentioned in the previous report, the analysis of the *Symbiodinium* database has shows apparent incompatibility of the different methodologies commonly used to assess symbiont diversity, in particular on the finer taxonomic level. Gaining information on symbiont identity on the lowest taxonomic level (species) is important because identification of symbionts at the cladal level (high taxonomic level) appears to overlap with physiological performance. The majority of currently identified GBR symbionts have been identified using the internal transcribed spacer regions 1 or 2 of the ribosomal genes. One of the few examples where these two marker regions have been directly compared is with subcladal ITS1 type C2 that corresponds with ITS2 type C3 (a generalist). The majority of currently identified symbionts are based either on the ITS1, ITS2 or higher taxonomic level (clades) and information from the different markers regions has not been linked; thus the dataset cannot be analysed to its full extent due to these incompatibilities.

To allow the currently compiled dataset to be fully analysed across multiple environmental layers, it is essential to streamline approaches and cross-correlate available symbiont identities based on different marker regions. We propose to streamline available data by analysing both the ITS1 and ITS2 region of each representative symbiont type found in the additional collections that have been undertaken thus far or are planned during the remainder of the project. It is likely that a large proportion of the symbionts identified to date will be represented in these newly collected samples. However, to gain information on the types that are not represented we will liase with authors of the currently published data to obtain representative samples of most symbiont types present on the GBR. In taking this approach it is envisaged that the majority of the data compiled from literature to date will become directly comparable between marker regions and thus provide some exiting avenues for data analysis across a wide range of host taxa along various environmental gradients on the GBR. The task is expected to be completed by June 2010.

Higher trophic order effects (Congdon)

The birds have not bred again and so no additional field work has been undertaken since the previous reporting period. Therefore, no additional problems or opportunities have arisen.

Communications, major activities and events

Description of the results achieved for this milestone

Journal Articles

Anthony, K. R., Hoogenboom, M. O., Maynard, J. A., Grottoli, A. and Middlebrook, R. (2009) Energetics approach to predicting mortality risk from environmental stress: A case study of coral bleaching. *Functional Ecology* 23(3): 539-550 [doi:10.1111/j.1365-2435.2008.01531.x] [June 2009]

Anthony, K. R. N., Kline, D. I., Diaz-Pulido, G., Dove, S. and Hoegh-Guldberg, O. (2008) Ocean acidification causes bleaching and productivity loss in coral reef builders. *Proceedings of the National Academy of Sciences of the United States of America* 105(45): 17442-17446 [doi:10.1073/pnas.0804478105]

Devney, C. A., Caley, M. J. and Congdon, B. C. (In Review) Flexibility of responses by parent and offspring noddies to sea-surface temperature anomalies. *Oikos*.

Devney, C. A., Short, M. and Congdon, B. C. (In Press) Sensitivity of tropica seabirds to El Niño precursors. *Ecology*.

Dove, S. G., Lovell, C., Fine, M., Deckenback, J., Hoegh-Guldberg, O., Iglesias-Prieto, R. and Anthony, K. R. N. (2008) Host pigments: Potential facilitators of photosynthesis in coral symbioses. *Plant, Cell and Environment* 31(11): 1523-1533 [doi:10.1111/j.1365-3040.2008.01852.x] [November 2008]

Kaniewska, P., Anthony, K. R. N. and Hoegh-Guldberg, O. (2008) Variation in colony geometry modulates internal light levels in branching corals, *Acropora humilis* and *Stylophora pistillata*. *Marine Biology* 155(6): 649-660 [doi:10.1007/s00227-008-1061-5] [November 2008]

Maynard, J. A., Anthony, K. R. N., Marshall, P. A. and Masiri, L. (2008) Major bleaching events can lead to increased thermal tolerance in corals. *Marine Biology* 155(2): 173-182 [doi:10.1007/s00227-008-1015-y]

Sampayo, E. M., Dove, S. and Lajeunesse, T. C. (2009) Cohesive molecular genetic data delineate species diversity in the dinoflagellate genus *Symbiodinium*. *Molecular Ecology* 18(3): 500-519 [doi:10.1111/j.1365-294X.2008.04037.x]

Smith-Kuene, C. and Dove, S. (2008) Gene expression of a green fluorescent protein homolog as a host-specific biomarker of heat stress within a reef-building coral. *Marine Biotechnology* 10(2): 166-180 [doi:10.1007/s10126-007-9049-6]

Weeks, S. J., Anthony, K. R. N., Bakun, A., Feldman, G. C. and Hoegh-Guldberg, O. (2008) Improved predictions of coral bleaching using seasonal baselines and higher spatial resolution. *Limnology and Oceanography* 53(4): 1369-1375.

Conference Presentations

Berkelmans, R. (2008) Shifting bleaching thresholds: acclimatization or a flawed model? Proceedings of the 11th International Coral Reef Symposium, 7-11 July, Fort Lauderdale, Florida.

Congdon, B. C. (2008) Climate change and the seabirds of Raine Island. Raine Island Workshop: A climate change risk assessment. Great Barrier Reef Marine Park Authority (GBRMPA), Townsville, Australia.

Congdon, B. C. (2008) Climate change and the seabirds of the GBR. Coastal Seabird Atlas Workshop: Great Barrier Reef Marine Park Authority (GBRMPA), Townsville, Australia.

Dove, S., Roff, G. and Dunn, S. (2008) When Is Not Bleaching "Unhealthy" For Corals and/or Coral Reefs? Proceedings of the 11th International Coral Reef Symposium, 7-11 July, Fort Lauderdale, Florida.

Dunn, S. and Dove, S. (2008) Suicide is painless, It brings on many changes: Apoptosis and Autophagy in Cnidarian-Dinoflagellate Symbiosis. Proceedings of the 11th International Coral Reef Symposium, 7-11 July, Fort Lauderdale, Florida.

Steinberg, C. R., Andrefouet, S., Brinkman, R., Choukroun, S., Heron, S., Herzfeld, M., Skirving, W. and Weeks, S. (2008) The physical oceanography of Heron Island, Great Barrier Reef, Eos Trans. AGU, 89(23), West. Pac. Geophys. Meet. Suppl., Abstract OS52A-04.

Weeks, S. J., Bakun, A., Congdon, B., Feldman, G. C. and Steinberg, C. (2008) Whirlpools, hot water and hungry seabirds in the southern GBR. Proceedings of the 11th International Coral Reef Symposium, 7-11 July, Fort Lauderdale, Florida.

Workshops and Meetings

Workshops held at AIMS 5 September 2008 and 22 January 2009 to discuss the *oceanography, bleaching and higher trophic effects* progress and plans amongst team members.

Participation in monthly chart discussions with Australian Meteorologists and Oceanographers with the contribution focussing on Coral Sea and GBR impacts. Published quarterly in the Significant Mesoscale Oceanography in the Bulletin of the Australian Meteorological and Oceanographic Society: http://www.amos.org.au/publications

During next milestone reporting period

Journal Articles (Currently In Review)

Anthony, K. R. N., Maynard, J. A., Cao, L., Caldeira, K., Diaz-Pulido, G., Weeks, S., Dove, S., Crawley, A. and Hoegh-Guldberg, O. (Submitted) Ocean acidification will double coral bleaching risk. *Science*.

Diaz Pulido, G., McCook, L. J., Dove, S., Berkelmans, R., Roff, G., Kline, D. I., Weeks, S., Evans, R. D., Williamson, D. H. and Hoegh-Guldberg, O. (In Review) Doom and boom on a resilient reef: Climate change, algal overgrowth and coral recovery. *PLOS One.*

Kaniewska, P., Magnusson, S. H., Anthony, K. R. N., Reef, R., Kuhl, M. and Hoegh-Guldberg, O. (Submitted) The importance of macro versus micro structure in modulating irradiance inside coral colonies. *Limnology and Oceanography.*

Middlebrook, R., Anthony, K., Hoegh-Guldberg, O. and Dove, S. (In Review) Heating rate and symbiont productivity are key factors in identifying thermal threshold flexibility in reef-building corals. *Functional Ecology.*

Conference Presentations

Presentations made at the Third Annual Conference of the Marine and Tropical Sciences Research Facility, 28-30 April 2009, Townsville, Queensland:

Dove, S. (2009) Effects of temperature and CO_2 on the physiology of acroporids: Should we be looking beyond bleaching when assessing the health status of corals?

Csàszàr, N. (2009) (Student presentation) Estimating the potential for adaptation of corals to climate change.

Steinberg, C. (2009) East Australian Current and upwelling influences on the thermal environment of the Great Barrier Reef.

Tonk, L. (2009) *Symbiodinium* diversity on the Great Barrier Reef: Biogeography, specificity and patterns of host community sensitivity.

van Oppen, M. (2009) Climate change threats, ecosystem impacts and mitigation for the Great Barrier Reef (MTSRF Program 5i Overview).

Appendix 1 – Current bleaching risk conditions

See following graphics.