CLIMATE CHANGE AND BIODIVERSITY IN MELANESIA

Series editors:
Stephen J. Leisz and J. Burke Burnett

Potential Climate Change Impacts on Corals and Coral Reefs in Melanesia from Bleaching Events and Ocean Acidification

Steve Coles
Department of Natural Science, Bishop Museum

CCBM Paper 5

Funding provided by:
John D. and Catherine T. MacArthur Foundation

Bishop Museum Technical Report 42(5)
June 2008

This paper is produced as part of the Climate Change and Biodiversity in Melanesia Project, funded by the John D. and Catherine T. MacArthur Foundation. The aim of this project is to assess the vulnerability of Melanesian marine and terrestrial ecosystems to projected climate changes. The CCBM Paper Series, listed below, are published as part of the larger Bishop Museum Technical Report Series.

Paper No.	Author	Title
1	Kelvin Richards and Axel Timmermann, IPRC, SOEST, University of Hawaii	Climate change projections for the Southwestern Pacific with a focus on Melanesia
2	Peter G. Brewer, Monterey Bay Aquarium Research Institute	Climate Change and Biodiversity in Melanesia: Biophysical science – ocean acidification
3	Dan A. Polhemus, Department of Natural Sciences, Bishop Museum	Climate change in New Guinea and its potential effects on freshwater ecosystems
4	Geoffrey Hope, The Australian National University	Palaeoecology and resilience in Melanesia: How can palaeoecology contribute to climate change response planning?
5	Steve Coles, Department of Natural Sciences, Bishop Museum	Potential Climate Change Impacts on Corals and Coral Reefs in Melanesia from Bleaching Events and Ocean Acidification
6	Terry J. Donaldson, University of Guam Marine Laboratory	Climate Change and Biodiversity in Melanesia: Implications for and impacts upon reef fishes
7	Rodney V. Salm and Elizabeth Mcleod, The Nature Conservancy	Climate Change Impacts on Ecosystem Resilience and MPA Management in Melanesia
8	Shelley A. James, Department of Natural Sciences, Bishop Museum	Climate Change Impacts on Native Plant Communities in Melanesia
9	Andrew L. Mack, Carnegie Museum of Natural History	Predicting the effects of climate change on Melanesian bird populations: probing the darkness with a broken flashlight

Introduction

The world's atmosphere is undergoing changes that are unprecedented in the post-glacial period of the last 10,000 years that are apparently related to the emissions which began increasing with industrial development in the mid 19^{th} century. Although it is only one of a suite of "greenhouse gases" that have increased dramatically in the last 150 years, CO_2 (carbon dioxide) is the most pervasive and most studied. Continuous measurements of this compound, a natural component of the earth's atmosphere, at the Mauna Loa observatory on the island of Hawaii since 1958 has shown a steady increase from an annual average of about 315 ppm to about 380 ppm in 2005 (Figure 1). Comparison of these increases with proxy records derived from ice cores indicates that this increase is an extension of an exponential increase in CO_2 from pre-industrial levels of about 280 ppm that had been previously rising at a much slower rate from about 260 ppm approximately 7000 years ago (IPCC 2007).

CO_2 and water are essential for life's processes, and they are the basic components for the formation of organic matter through photosynthesis. However, increasing levels of CO_2 and other industrial emissions-related gases in the atmosphere are of major concern, since they reduce the back radiation of heat from the earth's lower atmosphere, i.e. result in a "greenhouse effect" similar to a car with it's windows closed on a sunny day. International Panel for Climate Change estimates (IPCC 2007) indicate that the earth's atmosphere has warmed about 1°C since 1850, with the major portion of this warming and the years of highest temperatures occurring in the last decade (Figure 2). A variety of IPCC models have been developed to estimate further global atmospheric warming that may result from various estimates of atmospheric CO_2 concentrations by the end of this century (Figure 3). The most conservative of these models projects an average 2.0°C (range 1.8-2.9) above present levels, based on an estimated pCO_2 concentration of 800 ppm by 2100.

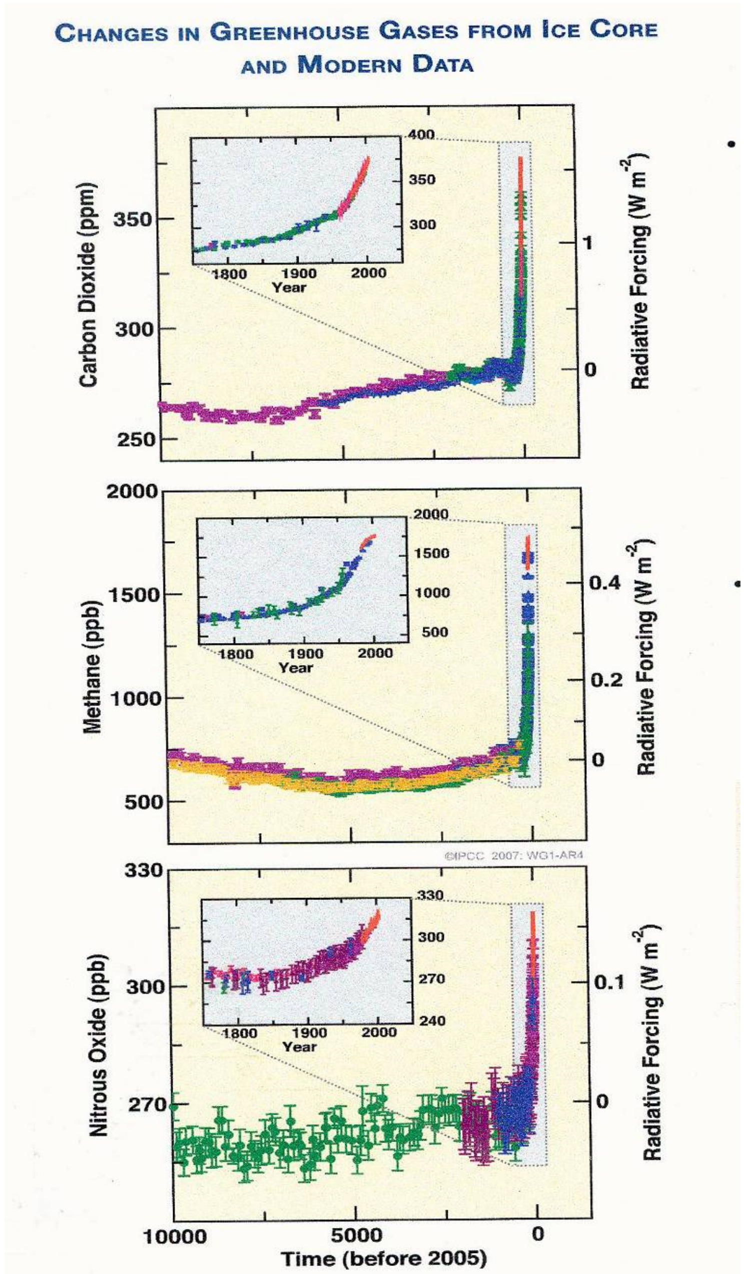

Figure 1. CO_2 and other greenhouse gases to 2005 determined from Mauna Loa measurements and ice core estimates. (IPCC 2007).

These increases in atmospheric temperature and CO_2 concentrations are very relevant to the earth's ocean system since a portion of both are introduced into the ocean and affect its physical-chemistry, biology and ecology The atmospheric warming that has occurred since 1850 is reflected by an approximate 0.5°C in ocean temperature and a pH reduction (acidity increase) of 0.1 to the present average pH level that averages about 8.1, with some regional variation. Although these small changes may at first

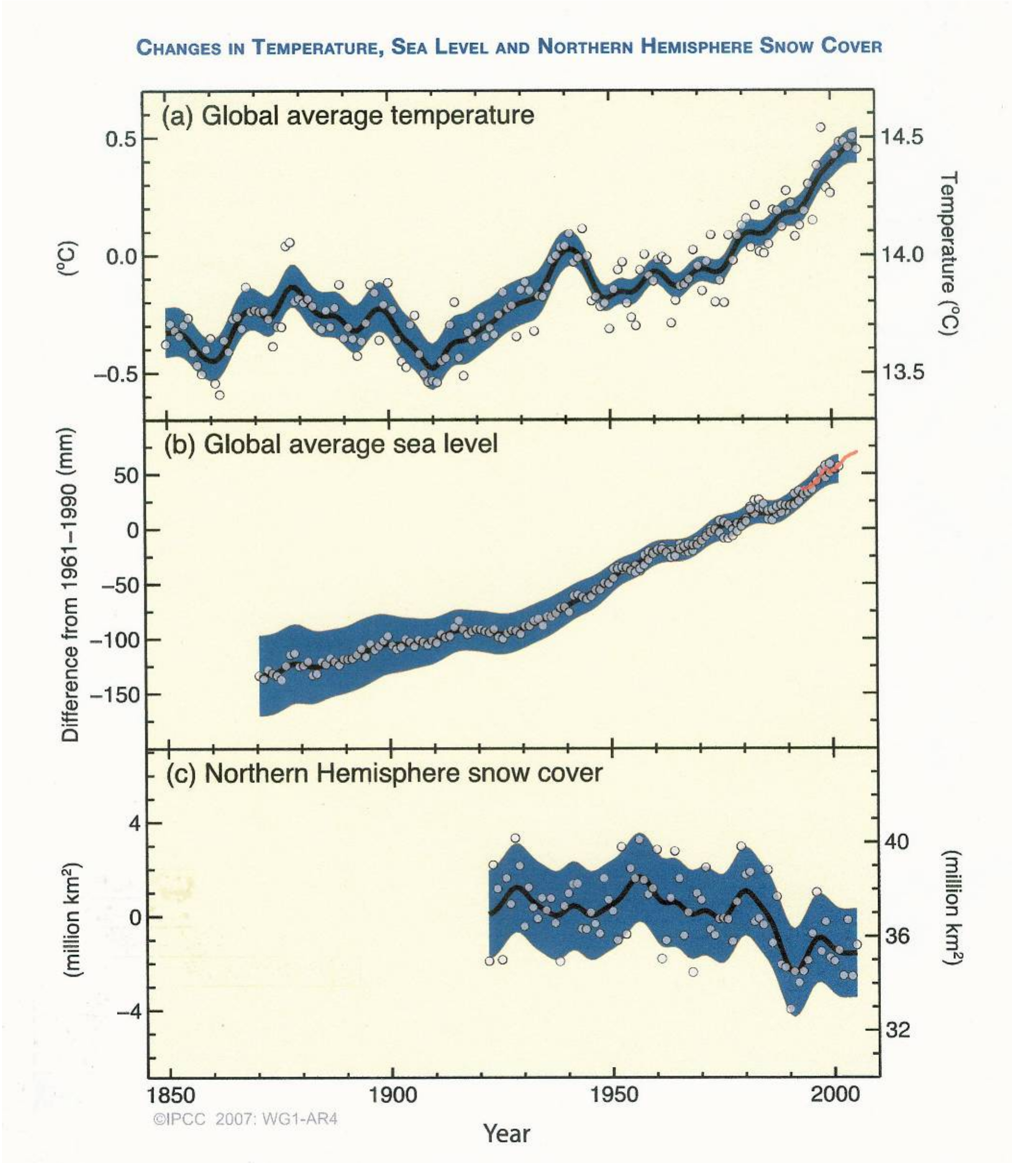

Figure 2. Estimated global atmospheric temperature, seal level and northern hemisphere snow cover 1850-2000 (IPCC 2007).

seem trivial, they have already been reflected in sometimes dramatic events related to temperature, while increasing acidity due to elevated CO_2 may have even more serious consequences, especially in tropical regions dominated by coral reef systems.

The primary impact of elevated temperature on coral reefs is manifested as a phenomenon known as "coral bleaching", and the primary impact of increased ocean acidity is on the calcium carbonate deposition and dissolution processes of corals and other calcareous organisms that form the structure of coral reefs. Sufficient information exists for coral bleaching and ocean acidification on reef calcifies exists so that the impacts for these can be projected with some confidence for both the tropical oceans as

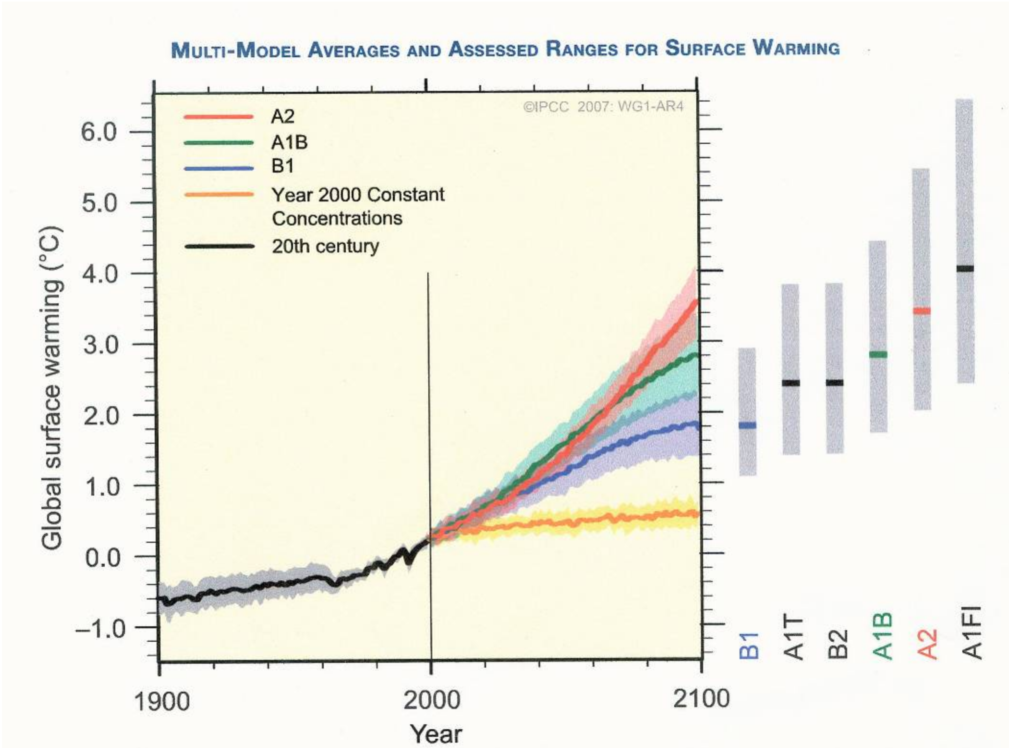

Figure 3. Projected atmospheric global temperature average increases from various IPCC models (IPCC 2007).

a whole and for Melanesia as a region. A third topic to have been covered for this project, that of diseases of corals and other marine organisms, is a science still in its development and lacks specific information that can be projected for the tropics, with no specific information existing for Melanesia. It will therefore not be covered here except for this general comment and summary references (Peters 1997, Richardson 1998, Willis et al. 2004).

Coral Bleaching

Although the awareness of coral bleaching has increased dramatically in the last 20 years because of the occurrence of a number of worldwide bleaching events, bleaching has apparently been a natural process occurring on reefs for an indeterminate time and was first described from observations made during the Australian Great Barrier Reef Expedition in the late 1920s (Coles and Brown 2003). Understanding of the processes and thresholds leading to coral bleaching was increased from work in the 1970s related to evaluating the impact of thermal effluents from power plants (Figure 4, Jokiel and Coles 1974) (Coles and Jokiel 1977). Two major concepts were developed from these studies: 1) Coral bleaching results from the combined and synergistic effects of elevated light and temperature impacting the coral-algal symbiotic association. 2) Threshold temperatures leading to coral bleaching are not fixed limits, but rather closely tied to the ambient annual maximum temperature normally occurring in the local environment of the coral.

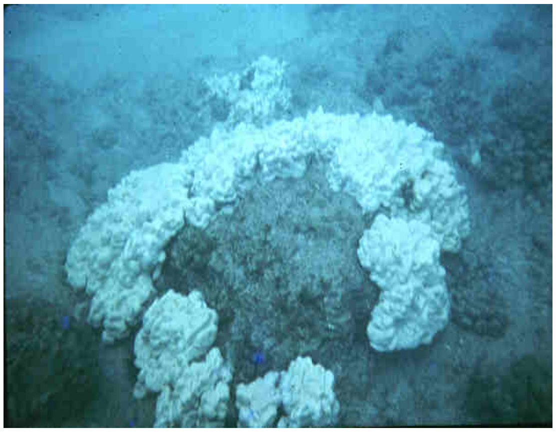

Figure 4. Bleached coral in the path of the thermal outfall from the Kahe Power Station in 1971 (Coles and Jokiel 1974).

The latter concept was derived from comparison of results of experiments and observations comparing corals from Hawai‘i where ambient maximum temperature is ca. 27°C with those from the mid-Pacific atoll Enewetak where annual maximum is about 29°C. (Figure 5). These results were summarized in the statement: “in both subtropical and tropical environments large populations of corals are exposed to temperatures precariously close (within 1 to 2°C) to their upper lethal limit during the summer months” (Coles, Jokiel and Lewis 1976). The existence of this 1-2°C temperature threshold has been confirmed repeatedly in the past 30 years by determinations derived from multiple bleaching events ranging from The Arabian Gulf, where temperatures of 1-2°C above historic ambient maxima of 33-34°C in 1998 and Rapa Nui (Easter Island) where a similar elevation above normal maxima of about 25°C produced extensive coral bleaching and mortality (Coles 1983, Coles and Brown 1983). This wide range of the temperature threshold for coral bleaching indicates a long term acclimatization and adaptation of the processes that maintain the symbiotic association, This is important for evaluating the potential for future adjustments to climate change induced thermal stress. The National Oceanic and Atmospheric Administration (NOAA) has combined this temperature threshold concept with a duration factor to develop the “degree heating weeks” alert system which uses satellite imagery of sea surface temperature to detect potential areas of coral bleaching http://coralreefwatch-satops.noaa.gov/SBA.html. Generally, a DHW value of >4-5 for an area is considered sufficient to result in extensive coral bleaching and a DHW of 10 to correspond to massive coral mortality.

Figure 5. Bleached coral on Enewetak fringing reef, 1974 (Coles unpublished).

Unfortunately rising seawater temperature in the last 30 years have coincided with repeated major bleaching events throughout the world. Most, but not all have been linked with years of El Nino Southern Oscillation (ENSO) (Figure 6, Hoegh-Guldberg 1999). The most dramatic of these occurred in 1998-99 when massive bleaching and mortality occurred in the Caribbean, Indian Ocean including Indonesia, and in the Pacific along the Great Barrier Reef and northwestern areas such as Okinawa and Palau (Figure 7). This was the sixth major bleaching event that had occurred since 1979, with the number of reef regions where bleaching occurred increasing with time.

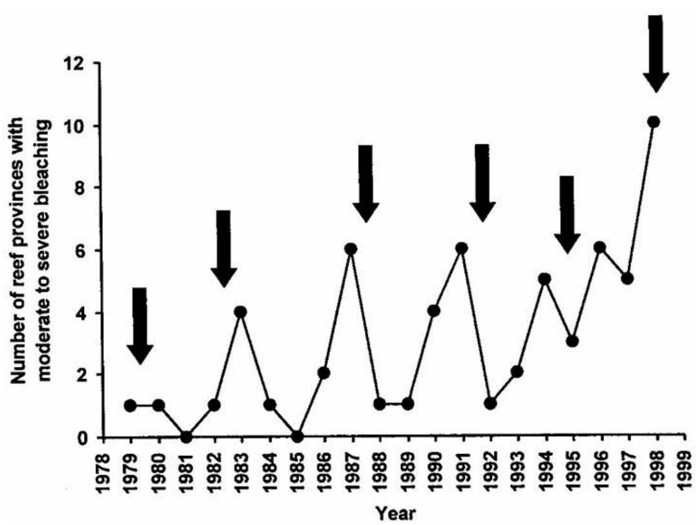

Figure 6. Major bleaching events occurring worldwide 1978-1999 (Hoegh-Guldberg 1999).

Interestingly, no areas in Melanesia were affected by the 1998 event, and coral bleaching-related temperature stress appears to be more closely related to La Niña years than El Nino in Melanesia. Three major bleaching episodes have been reported in the Papua New Guinea (PNG) region of Melanesia since 1982 (Figure 8). The first was a minor event in the waters of Kimbe Bay and Port Moresby (Srinivasan 2000). The major event for PNG occurred in 1996, when four months of elevated temperatures of 1.3°C above the normal maxima of about 30.5 resulted in bleaching and mortality of 54% of the corals surveyed down to 20 m (Davies et al. 1997, Foale 2006) and bleaching was also observed in areas near Motupore and Madang and the Lihir Islands and Lak region near New Ireland (Srinivasan 2000). In 1999-2000 increasing bleaching with depth was observed to 20 m at some areas in Kimbe Bay and Milne Bay (Srinivasan 2000).

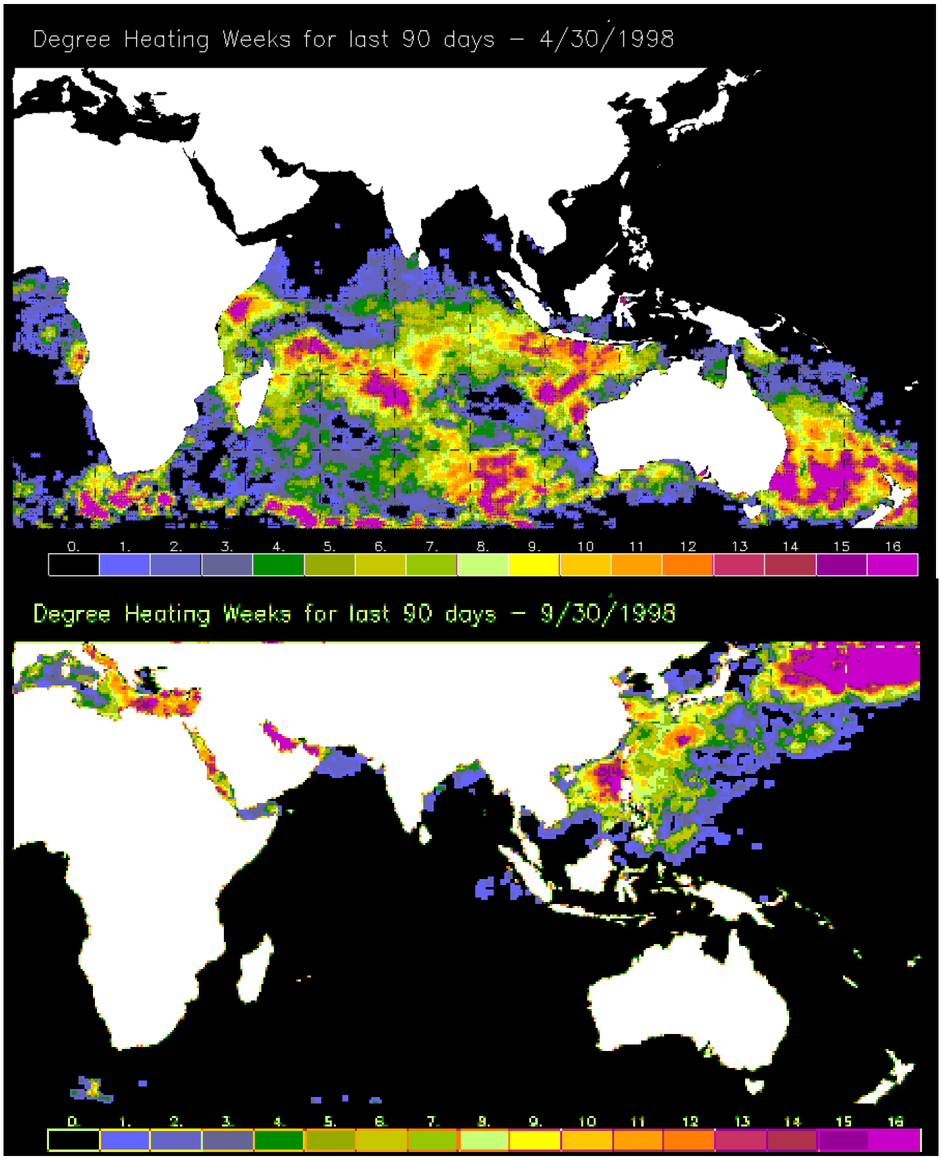

Figure 7. Degree Heating Week projections for South and North Pacific during 1998 El Nino event when extensive coral bleaching occurred outside of Melanesia.

The 1999-2000 La Nina also coincided with the most extensive bleaching event that has been observed in the Fiji islands (Cumming et al. 2002). Moderate coral bleaching was observed in Suva Bay in 1999 (E. R. Lovell, pers. com.) but the major bleaching occurred in early 2000 when water temperatures exceeded normal summer maxima for

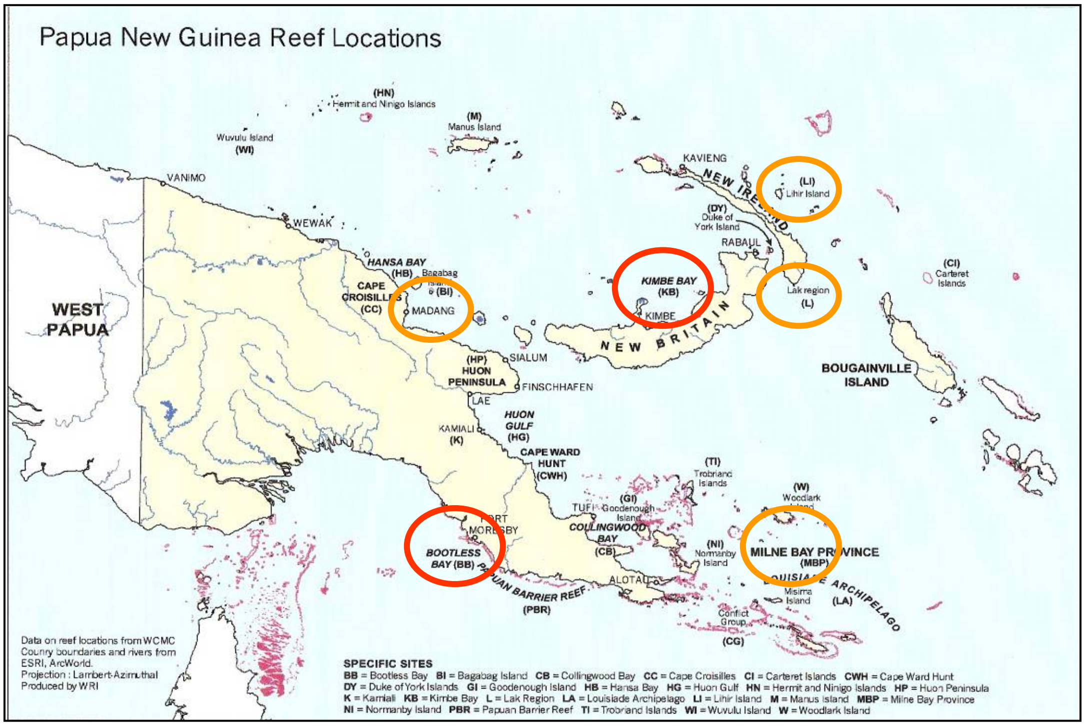

Figure 8. Areas of coral bleaching reported for Papua New Guinea in 1993, 1996 and 1999 (Davies et al. 1997, Srinivasan 2000, Foale 2006)

five months, with the highest temperatures occurring in March and April (Figure 9). Six DHWs, with highest values of 30.5°C, produced >80% mortality on the southern and eastern Fiji reefs. Coral recovery from this event was highly variable, with rapid recovery and growth observed in Suva Harbor and Beqa Lagoon (Coles and Brown 2003, Coles pers. obs.), but long term damage was reported by J. Koven (pers. com.) for the Great Astrolabe Reef near the Kandavu Islands.

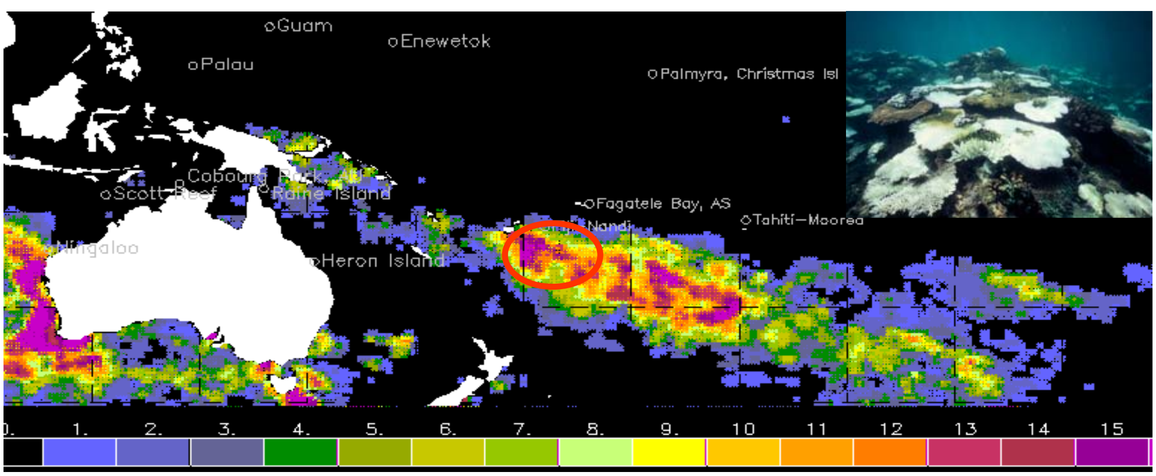

Figure 9. Degree Heating Weeks projection for Fiji Islands region of Melanesia during 2000 La Nina belaching event. Inset: Bleached corals near the entrance to Suva Harbor in March 2000 (Coles and Brown 2003).

The limited available information therefore indicates that areas of Melanesia are subject to major coral bleaching events, but at different times than much of the Indo-Pacific region, possibly related to La Nina rather than El Nino periods. Atmospheric and sea surface temperature models have been developed to project the probability of coral bleaching events throughout the 21st century. Models developed by A. Timmerman for various reef areas around the world suggest, based upon assumed thermal thresholds for corals of those areas and SST temperature projections, a consistent pattern worldwide where annual temperature maxima will exceed coral bleaching temperature tolerances by about 2030 (Heogh-Guldberg 1999) resulting in annual bleaching and mortality that has in the past been confined to El Nino or La Nina years (Figure 10).

Projections for the western Pacific that can be used to evaluate possible future trend for Melanesia are available in Guinotte et al. (2003). Using an annual maximum monthly temperature of 31.1°C as a threshold for coral bleaching for the region and a projected pCO_2 atmospheric rise of 517 ppmv by 2069 (more conservative than the IPCC estimates of 600 ppmv) their models suggest relative stability until mid 21st century and rapid increases in temperature stress thereafter, with large areas of Melanesia subject to annual coral bleaching (Figure 11). Similar results are shown by an unpublished DHW model for New Guinea and Indonesia developed by A. Timmerman using IPCC temperature projections, where DHW of 4 begins to occur in 2040-49 and DHW of >10 in 2060-69 for waters of PNG (personal communication). Further extrapolation of model results suggests that DHW values of up to 20 could occur during the last decade of this century.

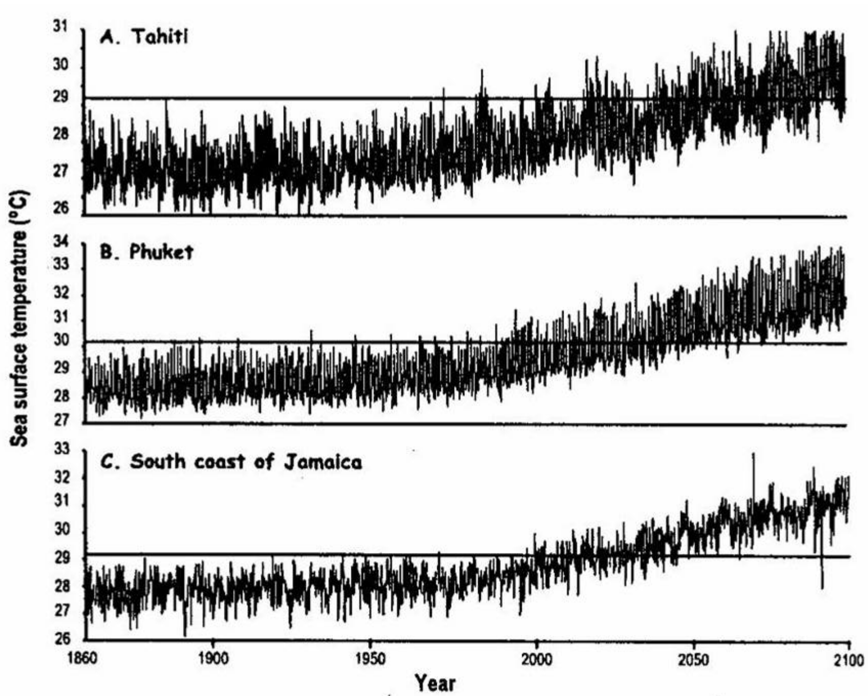

Figure 10. Projections of annual seawater temperatures based on climate change models developed by A. Timmerman for three reef locations worldwide (Hoegh-Guldberg 1999).

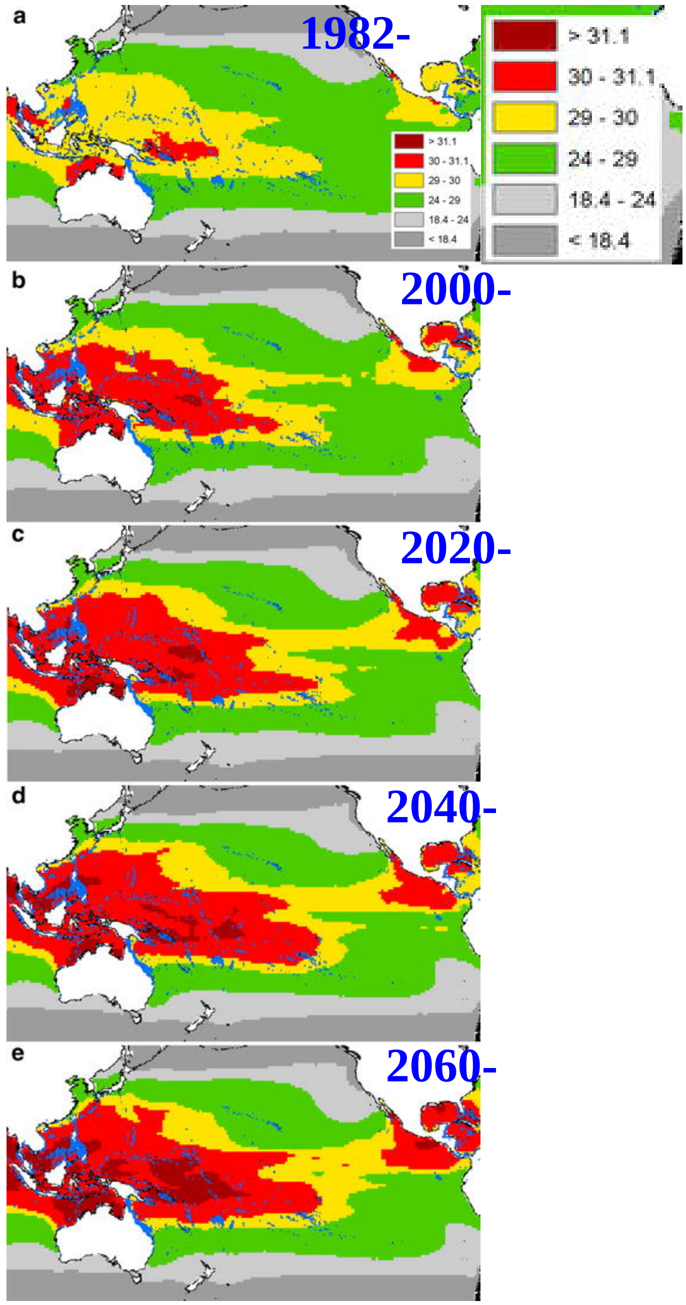

Figure 11. Projected future water temperature conditions for Melanesia. a-e: Maximum monthly water temperatures per decade from Guinote et al. (2001) through 2069.

It should be noted that these projections are regional downscales of models developed for worldwide or oceanic estimates and that they all have the underlying assumption that upper thermal threshold for coral bleaching are fixed values. Clearly this is not the case when, worldwide, temperatures inducing coral bleaching range up to nearly 10°C. Further, when a bleaching event occurs, not all corals are affected equally and there is a substantial interspecific and intraspecific variation in the degree to which coral bleaching and mortality occurs for corals in the same area and subject to the same stresses. Extrinsic factors such as water turbidity, circulation, shading and pre-exposure to elevated temperatures are a major influence on susceptibility to bleaching. Intrinsic factors associated with both corals and their zooxanthellae are indicated to play a major role in selection of corals that are resistant and resilient to stresses inducing coral bleaching (Coles and Brown 2003). Guinote et al. (2001) conclude that their projected temperatures should be within the adaptive range of corals within the region, but if the DHW projections of Timmerman shown here by the end of the century occur, there will be severe stress on corals of the region that will probably exceed any adaptive mechanisms of reef corals for the region.

Acidification

CO_2 is highly soluble in seawater, forming an intermediary state of carbonic acid before disassociating to bicarbonate (HCO_3^-), carbonate (CO_3^{2-}) and hydrogen (H^+) ions. The relative concentrations of (HCO_3^-) and (CO_3^{2-}) are highly pH dependent, with the proportion favoring (HCO_3^-) at present ocean pH of 8.1 (Figure 12). Higher concentrations of CO_2 in the atmosphere and increased oceanic dissolved CO_2 result in increasing (H^+) ions that are buffered by available (CO_3^{2-}), with lower concentrations of that ion thus available to combine with calcium ions (Ca+) for the process of calcification. Therefore, increasing dissolved CO_2 results in decreasing saturation of dissolved calcium carbonate ($CaCO_3$) in seawater, more energy required for deposition of $CaCO_3$ by calcifying organisms, and higher rates of dissolution of $CaCO_3$ that has already been formed.

The $CaCO_3$ saturation state (Ω) of the oceans varies with latitude and is maximal in tropical regions where organisms with calcareous structures predominate over those with siliceous structures. CaCO3 is deposited by organisms in one of three crystalline forms: calcite, aragonite and high magnesium calcite, and the saturation state of each of these is defined by the formula:

$$\Omega = \frac{[Ca^{2+}]\,[CO_3^{2-}]}{k}$$

where *k* is the solubility product for a given mineral phase of CaCO3. This results in Ω saturation values of Calcite>Aragonite>high Mg Calcite at any given ocean pH.

Calcite is the dominant form of CaCO3 deposited by most tropical plankton and reef-forming organisms including calcareous algae, but aragonite is deposited by reef corals in their skeletal growth, and aragonite is generally the form referenced in demonstrating the effects of ocean acidification. Pre-industrial aragonite Ω was estimated to have been about 4.6, and the present value is at 4.0. It is expected that the value will be 3.1 by 2065 and 2.8 by 2100 based on IPCC pCO2 modeling estimates available prior to 1999 (Kleypas et al 1999).

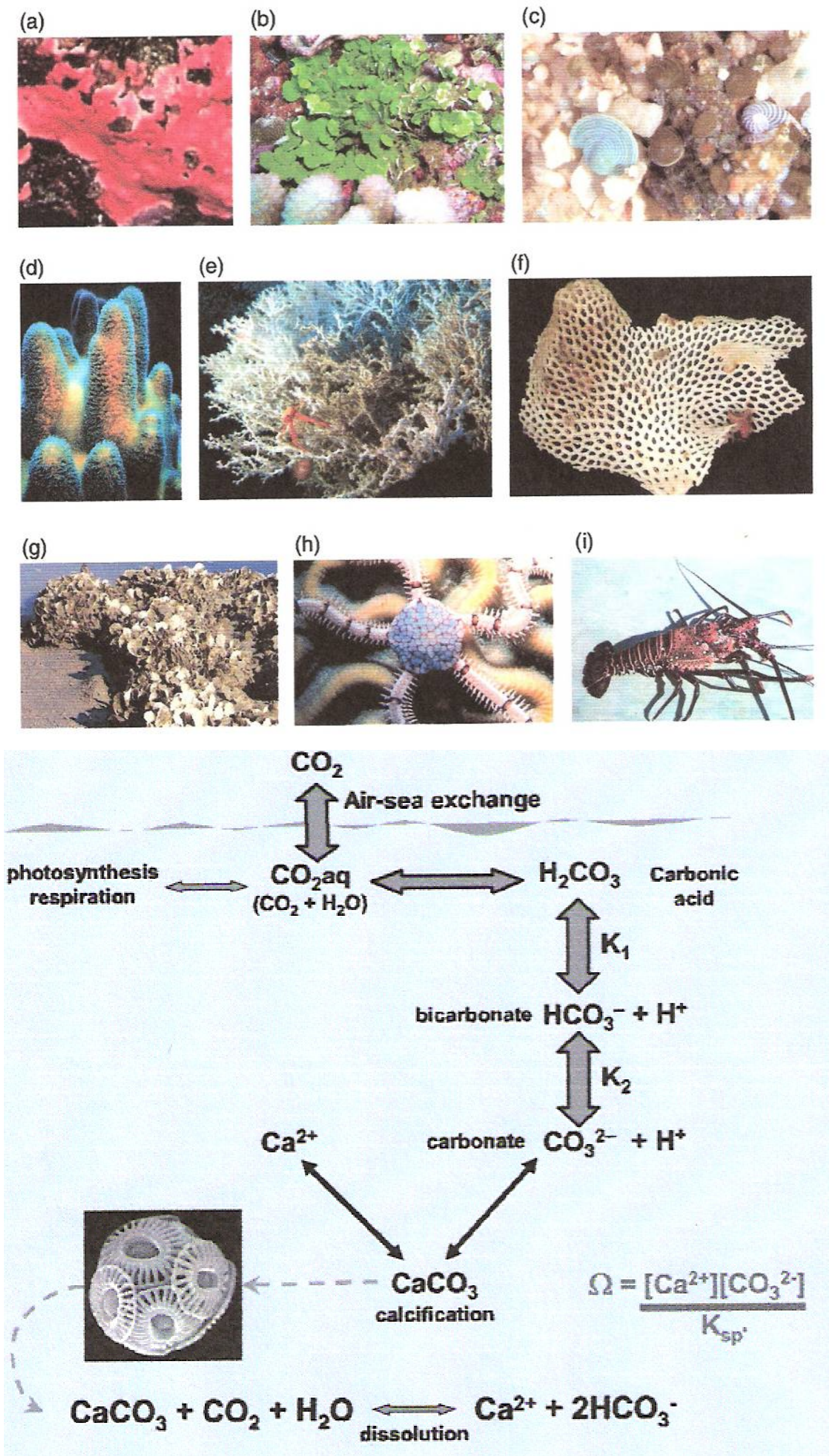

Figure 12. Examples of reef calcifying organisms and the effect of increased CO_2 on seawater acidification and the calcification/dissolution processes. a-b: red and green calcareous benthic algae, c: foraminifera, d-e: shallow and deep-water reef corals, f: bryozoan, g: oysters. h: brittle star echinoderm, i: lobster (from Kleypas el 2005).

The anticipated result of this reduction of ocean pH and Ω saturation values in tropical water is reduced calcification rates world-wide, especially for reef-forming corals. The projections are based on results from controlled laboratory experiments, simulations of atmospheric CO2 concentrations in mesocosms such as the Biosphere Project, and mass balance calculations. Aragonite and high-calcite deposition in the tropics has been estimated to have already decreased 6-11% from pre-industrial conditions (Kleypas et al. 1999a), and a further decrease of 3-60% is projected for a range of benthic organisms with a doubling of pre-industrial CO2 by about 2065 (Kleypas et al. 2001). An average 30% decline has been shown experimentally for reef coral calcification at an Ω equivalent to double pre-industrial pCO_2 values (Kleypas et al. 2005, unpublished), which could result in a 14-30% overall decrease in reef calcification (Kleypas et al 2001). Reduced calcification rates will also result in weaker calcareous structures and increased susceptibility to erosion, and pH reduction has been shown experimentally to result in complete loss of coral skeletal by an apparently otherwise healthy coral that can resume calcifying when pH is restored to normal levels (Fine and Tchernov 2007).

These proposed reductions in reef calcification rates pose a significant potential deficit for coral reefs world-wide, and those projected to have the greatest deficits are those in currently high saturation conditions, e.g. the Red Sea, Caribbean and the west central Pacific, including Melanesia (Kleypas et al. 1999a). A detailed projection for this area for SST, calcification, and their combined effects (Guinotte et al 2003) provides a view of possible conditions for Melanesia up through 2069 (Figure 13). Their projections may be considered conservative since they were based on a 2060-2069 estimate of atmospheric pCO2 of 515 ppmv, compared to the latest IPCC estimates of 600 ppmv by that time.

The (Guinotte et al 2003) projections, based on NCAR Community Climate System Model CCSM v. 1.0, indicate the entire Indo-Pacific region to have had optimal aragonitic saturation (Ω>4) during pre-industrial times, but by the first decade of the 21st century, optimal conditions to have diminished to an area eastward from Melanesia, with most of the Melanesian region covered by adequate saturation (Ω=3.5-4) of aragonite. Saturation conditions are projected to continue to decrease through the second and third decade and by 2040-49 marginal (Ω=3.0–3.5) conditions are shown for most of New Guinea and adequate saturation for the rest of Melanesia. By 2060-69 and a projected pCO_2 of 517 ppmv marginal conditions are shown for all Melanesia and all of the Indo-Pacific tropics except areas where saturation is extremely low (Ω=<3.0).

Combining temperature and saturation projection estimates shows patterns of even greater difficulty for Melanesian and other Pacific coral reefs. Using a threshold monthly temperature of >31.1°C for coral bleaching, by 2020-29 thermal stress is indicated to be a factor for reefs north of the Solomon and Vanuatu Island groups, and by 2040-49 this area expands to include waters and reefs north of PNG. By 2060-69 both thermal stress and marginal to submarginal saturation are indicated to affect reefs throughout most of the Melanesian region, as well as large areas throughout Indonesia and north Australia. Therefore, by the second half of the 21st century, large reef areas in

Melanesia and elsewhere are projected to become marginal i.e. pushed beyond their normal environmental limits (Keypas et al. 1999b)

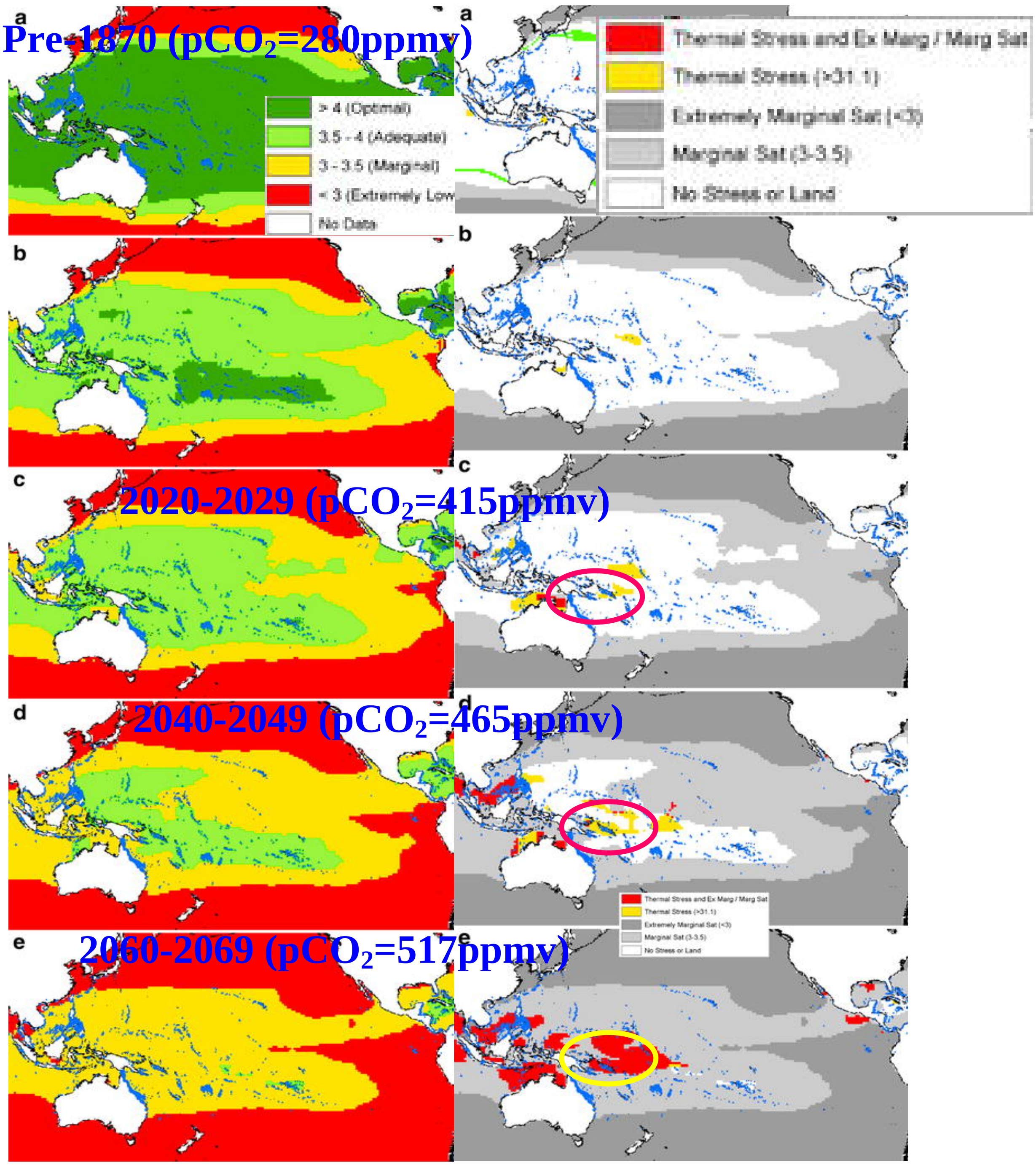

Figure 13. Projections of $CACO_3$ saturation sat by decade through 2069 (from Guinote et al 2003).

Environmental and Human Consequences of Coral Bleaching

It should be emphasized that the previous scenarios and projections are estimates based on large-scale models and assume that rates of CO_2 uptake in ocean water will continue at present rates relative to atmospheric concentrations. This may not necessarily be the case if higher CO_3^{2-} concentrations in the water column, due to $CaCO_3$ dissolution, provide some increased buffering capacity in the system. This may happen as CO_2 moves closer to its saturation state in seawater with increasing pCO_2 concentrations in the atmosphere. The total affect of coral bleaching and ocean acidification by the end of the century is impossible to predict at this time and there are large areas of uncertainty that still need to be addressed. The following are some of these questions concerning organism and ecosystem response to bleaching and acidification, and their resulting impacts on coral reef systems that need to be addressed:

- Will thermal adaptation occur fast enough to counter the worst effects of coral bleaching, and do mechanisms exist for adaptation by corals and other reef calcifiers to reduced saturation?
- What will be the effect of elevated temperature and reduced saturation state of CO_3^{2-} on reef bioerosion rates? Will increased dissolution of reef materials already deposited be an additional major factor in the total reef carbonate budget dynamics.
- The actual role of reef building in coral reef ecosystem functioning is complex and not fully understood, and the effects of changing calcification and dissolution rates on reef ecosystem function are unknown. If reef structures and rugosity decrease due to climate change, will this be reflected in decreased reef biotic diversity and biomass, especially of harvestable reef fishes?
- What will be the impact of elevated temperature and reduced saturation of CO_3^{2-} on planktonic calcifiers, meroplanktonic larval life stages and recruitment? Will more subtle effects such as these be a major consideration in the total resulting reef ecosystem and will such effects be widespread or localized?
- What will be the impact of all this on human populations and societies in Melanesia and elsewhere?

A model for projected impacts of coral bleaching with various levels of acclimatization and adaptation to coral bleaching (Figure 14) can also be extrapolated to impacts from acidification. Depending on the frequency of the stress in the case of bleaching and the magnitude of the change for both bleaching and acidification, different capacities to adapt will lead to different outcomes. These could range from short term shifts in dominant coral species from relatively mild levels of stress to worst case conditions of long term "phase shifts" of reef dominance by fleshy macroalgae if acidification levels proceed to where even calcite depositing calcareous algae are disfavored by decreasing carbonate concentrations.

Even with the level of uncertainty that exists for projecting possible outcomes, if the temperature and acidification conditions projected by the Guinotte et al. (2003) and Timmerman models are at all realistic, it is difficult to avoid the conclusion that corals and coral reef will be severely stressed by the end of the century, and that phase shifts to algal dominated reefs are likely throughout Melanesia. What this might mean, at

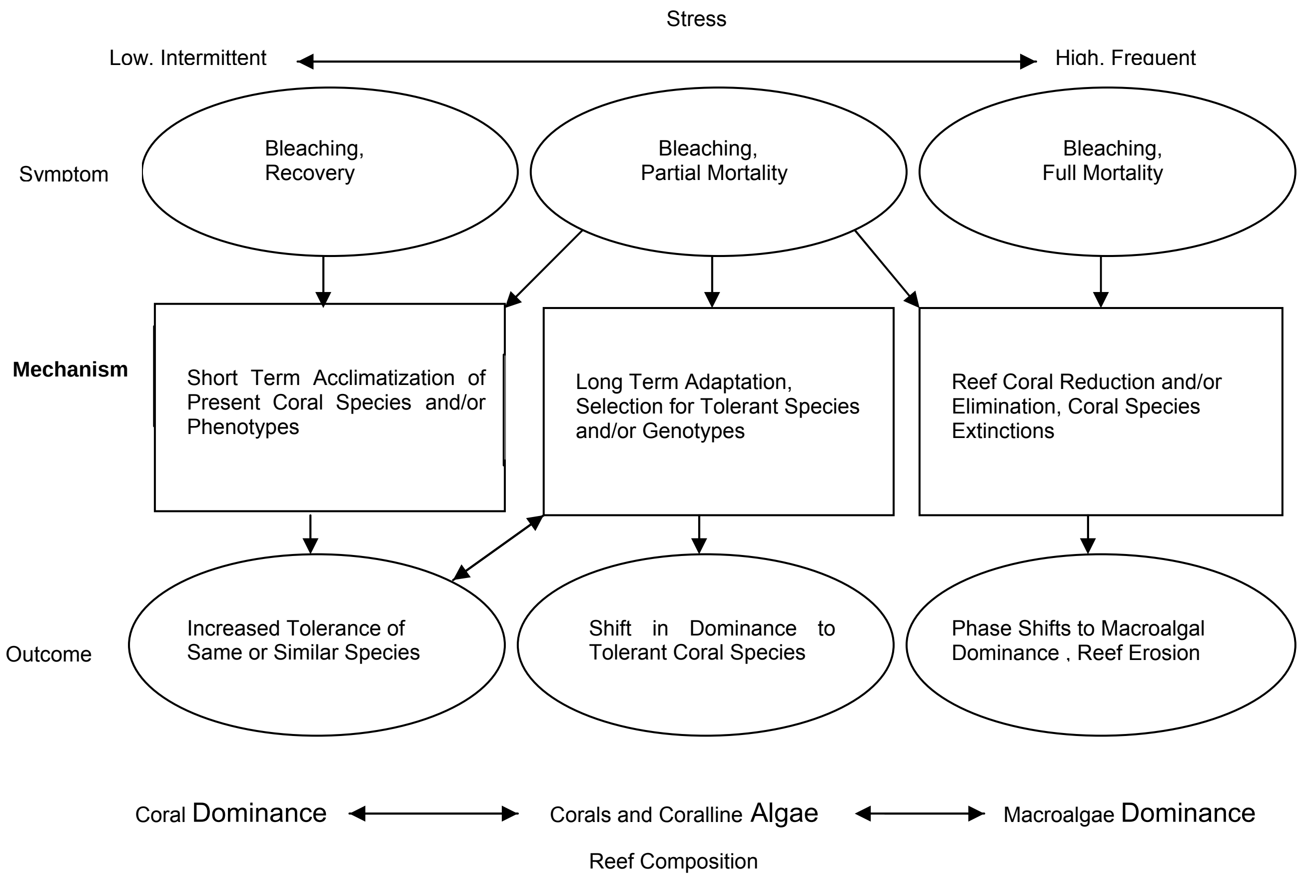

Figure 14. Model summarizing range of responses by reef corals to environmental stresses inducing bleaching and long term changes in composition of the reef community (In Coles and Brown 2003, adapted from Done 1999).

least initially, to practical considerations such as quantity and availability of harvestable fish and invertebrates is uncertain, since studies following El Nino bleaching events have shown no clear pattern of change in reef fish populations (Coles and Brown 2003). However, over the long term, it is likely that erosion of reefs from the combined impacts of coral beaching and acidification would decrease availability of habitat and shelter, leading to decreases in populations of fishes and cryptic invertebrates.

Research Needs

Any model used for projecting future conditions can only be as valid as the empirical data available to formulate and test it. SST data available from satellites has been utilized in developing the NOAA Coral Reef Watch Satellite Bleaching Alert System. First made available in 1997, this service provides a variety of products as well as list server messages sent when SST models indicate that conditions are approaching or exceeding coral bleaching thermal thresholds for a given area. The NOAA system focuses on specific temperature records and alerts for 24 locations around the world, and the only site included from Melanesia is Beqa Lagoon off northern Vitu Levu, Fiji. Given the central location and importance of New Guinea for both Melanesia and the Indo-Pacific, and the inclusion of the Raja Ampat Islands of west New Guinea in the "coral triangle" of maximum species diversity for the world (Fenner 2007), the addition of a New Guinea site to the NOAA bleaching alert system should be requested at http://www.osdpd.noaa.gov/PSB/EPS/CB_indices/indices_form.html. This would provide specific warning information when a bleaching event was imminent, enabling the possibity of evaluating the effects of the stress and tracking SST conditions following the event that could be related to any recovery that might occur.

A prime candidate for the location of this requested site would be Kimbe Bay, PNG where the Nature Conservancy (TNC) has recently completed an extensive evaluation for the establishment of the first Marine Protected Areas (MPAs) to be implemented for the purpose of attempting to provide resistance and resilience to coral bleaching (Salm and McCleod, this workshop). Considerable effort and resources have been directed toward the selection of the Kimbe Bay MPAs, and their implementation should be supported by measurement and monitoring of parameters related to reef condition and biotic communities. Toolkits have been developed by both TNC (http://www.reefresilience.org/r2coral/coral_htm/c_001.htm) and NOAA (http://www.coris.noaa.gov/activities/reef_managers_guide/welcome.html) that offer guidelines for evaluating impacts of coral bleaching and monitoring conditions following an event. A monitoring program should be established for Kimbe Bay and elsewhere in Melanesia where establishment of such programs is feasible. Assessment and monitoring programs related to coral bleaching already underway in Fiji by researchers at the University of the South Pacific and the Reef Explorer Foundation should be encouraged to continue, and researchers in New Caledonia contacted to determine what assessment and monitoring programs are underway or could be established there.

Implications for Natural Resource Management in Melanesia

The indigenous people of the Melanesian area are intimately dependent on the natural services that corals reefs provide to those living on or near the shoreline in tropical island areas. Reefs provide a large portion of their diet, sources of some of the materials needed for making tools and shelter, and recreation opportunities. The culture of these societies is often closely intertwined with reef-related activities. No other populations will be more affected by the climate change-related issues of sea level rise, coral bleaching and ocean acidification that are likely to reduce the protection of shorelines and natural services that have been provided by healthy coral reefs. Given the projections of sea level rise and ocean acidification effect that have been made, it is likely that these will be of major consequence for Melanesian nearshore populations, and that little can be done to counter these effects even if carbon emissions and other greenhouse gases are brought under control in this century (Pittock. 1999). With regard to coral bleaching, the establishment of the Kimbe Bay MPAs will put Melanesia at the forefront of a developing effort to reduce the long term impacts of coral bleaching by selecting for factors within the MPA that could mitigate coral bleaching impact, and optimize conditions for coral reef recovery even if sources of climate change are beyond our control within meaningful timeframes (Salm and Coles 2001). Evaluation of this effort after its implementation and the extension of successful concepts to other protected areas will hopefully provide some amelioration of the most damaging impacts of coral bleaching on coral reef ecosystems in Melanesia and elsewhere.

References

Coles, S. L. 2003. Coral species diversity in the Arabian Gulf and the Gulf of Oman: a comparison to the Indo-Pacific region. Atoll Res. Bull. No. 507.

Coles, S. L and Brown, B.E. 2003. Coral bleaching: capacity for acclimatization and adaptation. Adv. Mar. Biol, 46:183-223.

Coles, S. L. and Jokiel, P. L. 1978. Synergistic effects of temperature, light and salinity on the coral *Montipora verrucosa*. Marine Biology 49:187-195.

Coles, S. L., Jokiel, P. L. and Lewis, C. R. 1976. Thermal tolerance in tropical versus subtropical Pacific corals. Pacific Science 30:159-166.

Cumming, R. L., Toscano, M. A., Lovell, E. R. Carlson, B. A., Dulvy, N. K., Hughes, A., Koven, J. F., Quinn, N. J., Sykes, H. R., Taylor, O. J. S. and D. Vaughan. 2002. Mass bleaching in the Fiji Islands, 2000. Proc. 9th Inter. Coral Reef Sympos. Bali, Vol. 2:1161-1167.

Davies, J. M., Dunne, R. P. and Brown, B. E. 1997. Coral bleaching and elevated sea-water temperature in Milne Bay Province, Papua New Guinea, 1996. Mar. Freshwater Res. 48:513-516.

Fenner, D. 2007. The ecology of Papuan coral reefs. Chap. 5.2, p.771-799, In: Marshall, A. J and Beehler, B. M. (eds.) The Ecology of Papua Vol. 2.

Fine, M. and Tchernov, D. 2007 Scleractinian coral species and survive and recover from decalcification. *Science* 315:1811.

Foale, S. J. 2006. The scale and epistemology of coral bleaching in Papua New Guinea. *Bridging Scales and Epistemologies.* Alexandria: Millennium Ecosystem Assessment.

Guinote, J. M., Buddemeier, R. W. Kleypas, J. A. 2003. Future coral reef habitat marginality: temporal and spatial effects of climate change in the Pacific basin. Coral Reefs 22: 551-558.

Hoegh-Guldberg, O. 1999. Climate change coral bleaching and the future of the world's coral reefs. Mar. Freshwater Res. 50:839-66.

IPCC. 2007. Summary for policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Report of the Intergovernmental Panel on Climate Change (Solomon, S., Qin, D., Manning, M., Chen, Z, Marquis, M., Averyt, K. B., Tignor, M. ans Miller, H. L. (eds.) Cambridge univ. Press, Cambridge, U. K. and New York.

Jokiel, P. L. and Coles, S. L. 1974. Observations on the biotic effects of heated effluent from the Kahe Power Plant, Kahe Point, Oahu. Pacific Science 28:1-18.

Kleypas, J. A., Buddemeier, R.W., Archer, D., Gattuso, J. P, Langdon, C., Opdyke, B. N. 1999a Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. Science 284: 118-120

Kleypas, J. A., McManus, J. W. Lambert, A., Menez, B. 1999b. Environmental limits to coral reef development: where do we draw the line? Amer. Zool. 39: 146-159.
Kleypas, J. A., Buddemeier and Gattuso, J. P, 2001. The future of coral reefs in an age of global change. Int. J. Earth Sci. 90:426-437.
Kleypas, J. A,, Feely, R. A. , Fabry, V. J., Langdon, C. L., Sabine, C. L. and Robbins, L. L. 2006. Impacts of Increasing Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research, report of a workshop held 18–20 April 2005, St. Petersburg, FL. sponsored by NSF, NOAA, and the U.S. Geological Survey.
Peters, E. C. 1997. Diseases of coral-reef organisms. In: Birkeland C. (Ed), Life and Death of Coral Reefs. Chapman and Hall, NY, pp. 114-139.
Pittock, A. B. 1999. Coral reefs an environmental change: adaptation to what? Amer. Zool. 39:10-29.
Richardson, L. L. 1998. Coral diseases: what is really known? Trends in Ecology and Evolution 13:438-443.
Srinivason, M. 2000. Coral bleaching and environmental change. Chap 6 In: The Status of Coral reefs in New Guinea. Global Cpral Reef Monitoring Network, Australian Institute of Marine Science, Townsville, Australia.
Salm, R. V and Coles, S. L. (eds.) Coral Bleaching and Marine Protected Areas. Proceedings of the Workshop on Mitigating Coral Bleaching Impact Through MPA Design. Bishop Museum, Honolulu, 29-31May, 2001. Asia Pacific Coastal Marine Program Report No. 0102, The Nature Conservancy, Honolulu: 118 pp.
Willis, B.L., Page, C. A. and Dinsdale, E. A. 2004 Coral disease on the Great Barrier Reef. In: Rosenberg E, Loya Y (Eds). Springer, Berlin. pp 69-104
Wilkinson, C., Lindon, O., Cesar, H., Hodgson, G., Rubens, J. and Strong, A. E. 1999. Ecological and sociological impacts of 1998 coral mortality in the Indian Ocean: an ENSO impact and warning of future change? Ambio 28: 188-196.