Protection of coral reefs for sustainable livelihoods and development

Input from the IPCC Secretariat based on key findings from the IPCC Fourth Assessment Report (AR4)

The IPCC produces regular multivolume assessment reports on policy-relevant scientific, technical and socio-economic information on climate change. IPCC reports are intended to assist governments and other decision-makers in the public and private sector in formulating and implementing appropriate responses to the threat of human-induced climate change.

The last comprehensive IPCC assessment, the IPCC's Fourth Assessment Report (AR4) was published in 2007. It consists of four volumes – the three Working Group reports and the Synthesis Report. All volumes contain a Summary for Policymakers (SPM), which has been approved by governments IPCC Plenary Sessions line by line.

An assessment of current knowledge on coral reefs in the context of climate change and in particular climate change impacts, adaptation and vulnerability is contained in the Working Group II (WGII) contribution to the AR4 "Climate Change 2007 – Impacts, Adaptation and Vulnerability".

The following quotes and findings are taken from the Working Group II (WGII) contribution to the IPCC Fourth Assessment Report (AR4) and from the AR4 Synthesis Report (SYR) which summarizes and integrates findings from all three Working Groups into a document prepared for the use of policymakers.

This submission introduces relevant key findings through statements taken from the WG II SPM, the SYR and its SPM (SYR SPM). It then provides further details based on the underlying assessment contained in the full WG II report. For this purpose text is taken from the Technical Summary (TS) of the WG II report or directly from chapters as indicated.

Most of the IPCC findings relevant to set the context are in section II of the report outline. The issue of ocean acidification would lend itself to be included in the last bullet of Section IV.A., last bullet on new and emerging challenges. Findings about the importance of multi stresses are relevant for setting the context for protection of coral reefs and related ecosystem as addressed in section VII of the report. References in brackets refer to the reports, their SPM, TS or relevant sections. Underlining has been introduced by the IPCC Secretariat to facilitate tracking of main topics. The highlighting does not reflect special emphasis resulting from the assessment.

Section II:
Importance of protecting coral reefs and related ecosystems for sustainable livelihoods and development (incl. Current status and adverse impacts)

A. Impacts of warming and associated increases in atmospheric CO2

The current knowledge about the vulnerability of coral reefs, in particular to thermal stress, and implications for local resources is summarized in the Summary for Policymakers of the Working Group II contribution (WG II SPM) to the IPCC AR4 as follows:

- In the context of **coastal systems and low-lying areas** the AR4 states: "Corals are vulnerable to thermal stress and have low adaptive capacity. Increases in sea surface temperature of about 1-3°C are projected to result in more frequent coral bleaching events and widespread mortality, unless there is thermal adaptation or acclimatisation by corals." {WG II SPM, page 12}

- In the context of **small islands states** it states: "Deterioration in coastal conditions, for example through erosion of beaches and coral bleaching, is expected to affect local resources, e.g., fisheries, and reduce the value of these destinations for tourism. {WG II SPM, page 15}

Another aspect with will be addressed in more detail in the IPCC 5th Assessment Report (AR5), based on new and emerging science is **ocean acidification** due to increased atmospheric CO2 concentrations. In the following the state of knowledge at the time of the completion of the AR4 is summarized:

> "The uptake of anthropogenic carbon since 1750 has led to the ocean becoming more acidic with an average decrease in pH of 0.1 units. Increasing atmospheric CO2 concentrations lead to further acidification. Projections based on SRES scenarios give a reduction in average global surface ocean pH of between 0.14 and 0.35 units over the 21st century. While the effects of observed ocean acidification on the marine biosphere are as yet undocumented, the progressive acidification of oceans is expected to have negative impacts on marine shell-forming organisms (e.g. corals) and their dependent species." {SYR SPM, page 9, SYR 3.3.4, page 52}

These findings and their implications for delivery of goods and services from ecosystems are further described in the Technical Summary (TS).

> **"Substantial changes in structure and functioning of terrestrial and marine ecosystems are very likely to occur with a global warming of 2 to 3°C above pre-industrial levels and associated increased atmospheric CO2 (high confidence).**
> Major biome changes, including emergence of novel biomes, and changes in species' ecological interactions, with predominantly negative consequences for goods and services, are very likely by, and virtually certain beyond, those temperature increases [4.4]. The previously overlooked progressive acidification of oceans due to increasing atmospheric CO2 is expected to have negative impacts on marine shell-forming organisms (e.g., corals) and their dependent species. "{WG II TS, page 38}

The vulnerability of coral reefs to thermal stress is also noted in the AR4 Synthesis Report (SYR) under "**reasons for concern**". Under the topic "risks to unique and threatened ecosystems" the AR4 Synthesis Report states:

> "There is new and stronger evidence of observed impacts of climate change on unique and vulnerable systems (such as polar and high mountain communities and ecosystems), with increasing levels of adverse impacts as temperatures increase further. An increasing risk of species extinction and coral reef damage is projected with higher confidence than in the TAR as warming proceeds…… Corals are vulnerable to thermal stress and have low adaptive capacity. Increases in sea surface temperature of about 1 to 3°C are projected to result in more frequent coral bleaching events and widespread mortality, unless there is thermal adaptation or acclimatisation by corals. {SYR SPM, page 19}

Further, vulnerability of coral reefs and small islands are included in the list of "robust findings" of the WG II report:

> Some systems, sectors and regions are likely to be especially affected by climate change. The systems and sectors are some ecosystems (tundra, boreal forest, mountain, mediterranean-type, mangroves, salt marshes, coral reefs and the sea-ice biome), low-lying coasts, water resources in some dry regions at mid-latitudes and in the dry topics and in areas dependent on snow and ice melt, agriculture in low-latitude regions, and human health in areas with low adaptive capacity. The regions are the Arctic, Africa, small islands and Asian and African megadeltas. Within other regions, even those with high incomes, some people, areas and activities can be particularly at risk. {SYR 6.2, page 72}

Figure TS.6 from the WG II TS, page 37, and Figure SPM.7 from the AR4 SYR, page 10 illustrate the vulnerability of coral reefs to temperature increases (Annex 1 and Annex 2).
The WG II report contains also a specific case study about coral reefs which is contained in Annex 3.

B. *Importance of multiple stresses and coastal protection*

The importance of multiple stresses is addressed in a number of conclusions as follows:

In the context of observed effects the AR4 concludes:

> "While there is increasing evidence of climate change impacts on coral reefs, separating the impacts of climate-related stresses from other stresses (e.g. overfishing and pollution) is difficult. {WGII report 1.3.4.1 (Chapter 1) page 94}

Perspectives of sustainability and the importance of multiple stresses for coral vulnerability are summarized as follows:

> **"Vulnerability to climate change can be exacerbated by the presence of other stresses.** Non-climate stresses can increase vulnerability to climate change by reducing resilience and can also reduce adaptive capacity because of resource deployment to competing needs. For example, current stresses on some coral reefs include marine pollution and chemical runoff from agriculture as well as increases in water temperature and ocean acidification. …" {WG II TS 5.4, page 75}

Issues of coastal protection due to sea level rise and coral vulnerability are summarized in the WG II TS as follows:

> **"Coasts are experiencing the adverse consequences of hazards related to climate and sea level (very high confidence).** Coasts are highly vulnerable to extreme events, such as storms, which impose substantial costs on coastal societies [6.2.1, 6.2.2, 6.5.2]. Annually, about 120 million people are exposed to tropical cyclone hazards. These killed 250,000 people from 1980 to 2000 [6.5.2]. Throughout the 20th century, the global rise of sea level contributed to increased coastal inundation, erosion and ecosystem losses, but the precise role of sea-level rise is difficult to determine due to considerable regional and local variation due to other factors [6.2.5, 6.4.1]. Late 20th century effects of rising temperature include loss of sea ice, thawing of permafrost and associated coastal retreat at high latitudes, and more frequent coral bleaching and mortality at low latitudes [6.2.5]."
> {Page 40, WG II TS}
>
> "**Coasts are very likely to be exposed to increasing risks in future decades due to many compounding climate-change factors (very high confidence).**
> Anticipated climate-related changes include: an accelerated rise in sea level of 0.2 to 0.6 m or more by 2100; further rise in sea surface temperatures of 1 to 3°C; more intense tropical and extra-tropical cyclones; generally larger extreme wave and storm surges; altered precipitation/runoff; and ocean acidification. [WG1 AR4 Chapter 10; 6.3.2]. These phenomena will vary considerably at regional and local scales, but the impacts are virtually certain to be overwhelmingly negative [6.4, 6.5.3]. Coastal wetland ecosystems, such as salt marshes and mangroves, are very likely threatened where they are sediment starved or constrained on their landward margin [6.4.1].The degradation of coastal ecosystems, especially wetlands and coral reefs, has serious implications for the well-being of societies dependent on coastal ecosystems for goods and services [6.4.2, 6.5.3]."
> {WG II TS, page 40}

C. Regional aspects

While impacts can be very site specific, relevant main impacts on regions are summarized under "main projected impacts on regions". Sections referring to coral reefs and related ecosystems are as follows:

Asia:

"Threats to the ecological stability of wetlands, mangroves and coral reefs around Asia would also increase [10.4.3, 10.6.1]." {WG II TS, page 49}

"Around 30% of Asian coral reefs are expected to be lost in the next 30 years, compared with 18% globally under the IS92a emissions scenario, but this is due to multiple stresses and not to climate change alone." {WG II TS, page 59}

Small Islands:

"Climate change is likely to heavily impact coral reefs, fisheries and other marine-based resources (high confidence). Fisheries make an important contribution to the GDP of many island states. Changes in the occurrence and intensity of El Niño- Southern Oscillation (ENSO) events are likely to have severe impacts on commercial and artisanal fisheries. Increasing sea surface temperature and sea level, increased turbidity, nutrient loading and chemical pollution, damage from tropical cyclones, and decreases in growth rates due to the effects of higher CO2-concentrations on ocean chemistry, are very likely to lead to coral bleaching and mortality [16.4.3]." {WG II TS, pages 57-58}

"New studies confirm previous findings that the effects of climate change on tourism are likely to be direct and indirect, and largely negative (high confidence). Tourism is the major contributor to GDP and employment in many small islands. Sea-level rise and increased sea-water temperature are likely to contribute to accelerated beach erosion, degradation of coral reefs and bleaching (Table TS.2)." {WG II TS, page 58}

"Sea-level rise and increased sea-water temperature are projected to accelerate beach erosion, and cause degradation of natural coastal defenses such as mangroves and coral reefs. …" {WG II TS, page 63}

Africa

"Mangroves and coral reefs are projected to be further degraded, with additional consequences for fisheries and tourism." {WG II TS Box TS.6., page 59}

Latin America

"Sea surface temperature increases due to climate change are projected to have adverse effects on ** N [13.4.4]:
- Mesoamerican coral reefs (e.g., Mexico, Belize, Panama);
- the location of fish stocks in the south-east Pacific (e.g., Peru and Chile)."
  (Box TS.6., page 61)

A specific reference to the **Great Barrier Reef** is made under main projected impacts for systems and sectors as follows:

Loss of corals due to bleaching is very likely to occur over the next 50 years *** C [B4.5, 4.4.9], especially for the Great Barrier Reef, where climate change and direct anthropogenic impacts such as pollution and harvesting are expected to cause annual bleaching (around 2030 to 2050) followed by mass mortality.
{WG II TS, Box TS.5., page 45}

Section II.A
Address new and emerging challenges

The importance of ocean acidification due to an increase of atmospheric CO_2 concentration for shell forming organisms was highlighted already in the AR4. However, limited research results were available at the time of the completion of the report. During the scoping of the IPCC 5th Assessment Report (AR5) particular attention was given to oceans and coastal systems which will be addressed in dedicated chapters in the AR5. Enhanced attention will also be given to aspects of human well being, food security and other aspects of sustainable development.

Special attention and consideration will also be given to the carbon cycle, including ocean acidification, which will be addressed as a cross cutting theme. A dedicated workshop was held in January 2011 in Okinawa to consider, in a multidisciplinary manner, new and emerging science on ocean acidification and its impacts on coral reefs and other ocean ecosystems.

Section VII
The way forward:

As can be seen from the findings of the IPCC quoted under section II, it will be important for an efficient coral protection to address the multiple stresses coral and related ecosystems are exposed to.

Figure TS.6 (page 37 of the Technical Summary of the WGII Report)

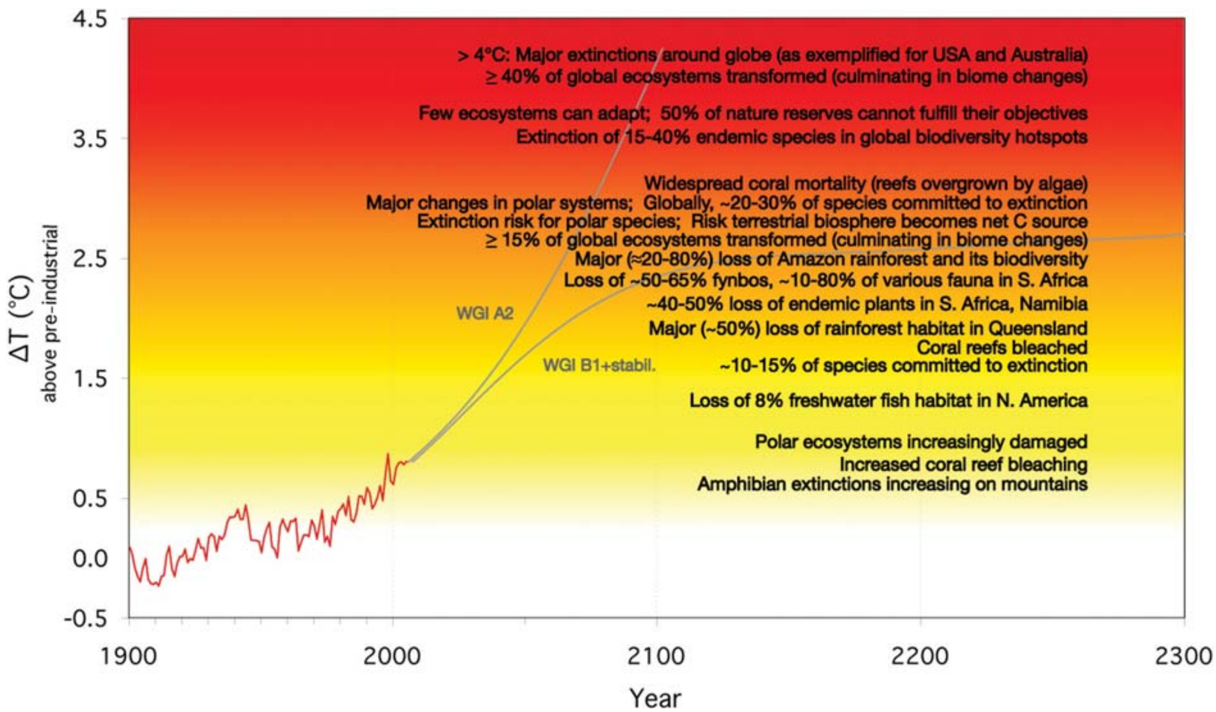
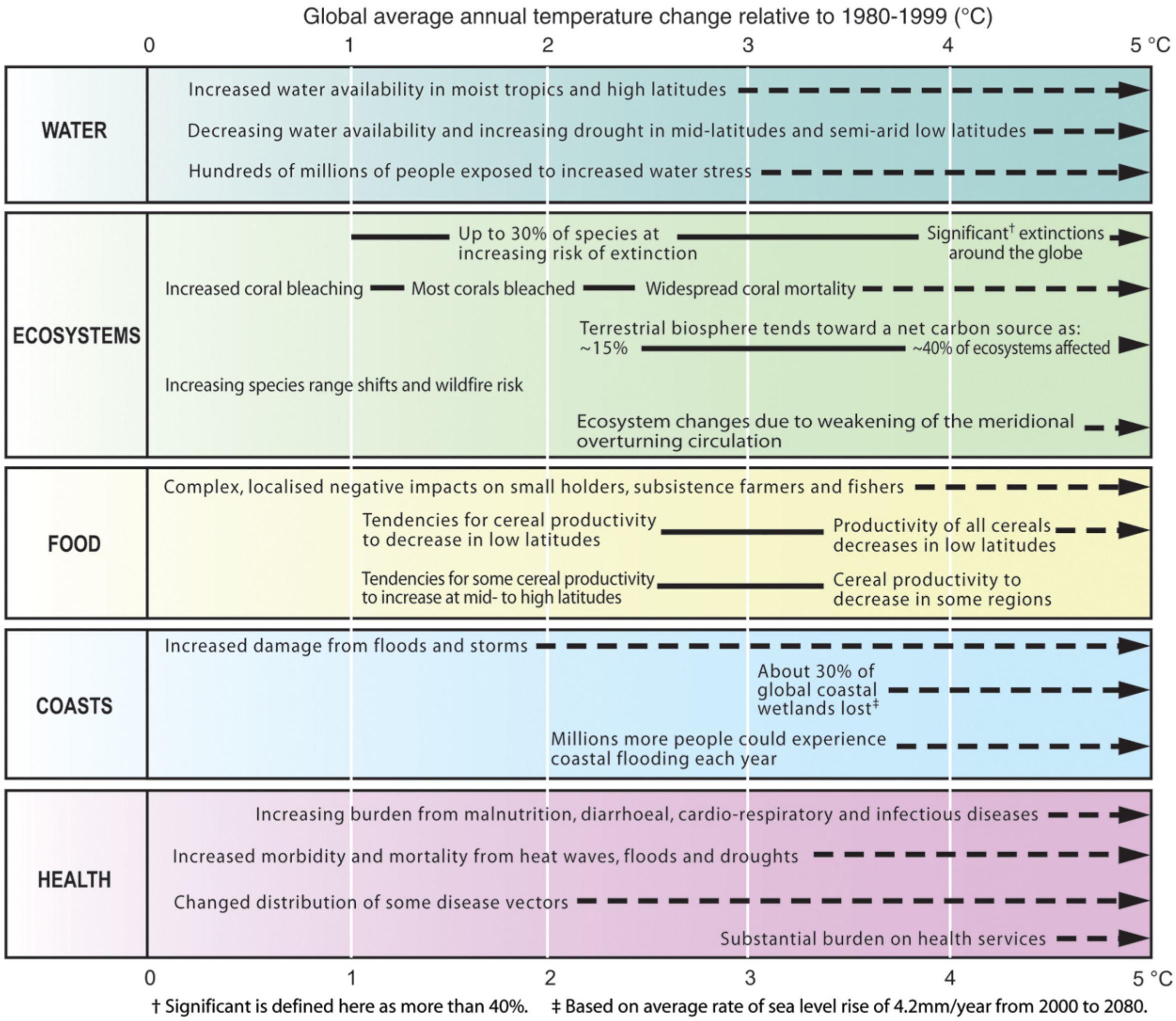


Figure TS.6. *Compendium of projected risks due to critical climate change impacts on ecosystems for different levels of global mean annual temperature rise, ΔT, relative to pre-industrial climate, used as a proxy for climate change. The red curve shows observed temperature anomalies for the period 1900-2005 [WGI AR4 F3.6]. The two grey curves provide examples of the possible future evolution of global average temperature change (ΔT) with time [WGI AR4 F10.4] exemplified by WGI simulated, multi-model mean responses to (i) the A2 radiative forcing scenario (WGI A2) and (ii) an extended B1 scenario (WGI B1+stabil.), where radiative forcing beyond 2100 was kept constant at the 2100 value [WGI AR4 F10.4, 10.7]. White shading indicates neutral, small negative, or positive impacts or risks; yellow indicates negative impacts for some systems or low risks; and red indicates negative impacts or risks that are more widespread and/or greater in magnitude. Illustrated impacts take into account climate change impacts only, and omit effects of land-use change or habitat fragmentation, over-harvesting or pollution (e.g., nitrogen deposition). A few, however, take into account fire regime changes, several account for likely productivity-enhancing effects of rising atmospheric CO2 and some account for migration effects. [F4.4, T4.1]*

SPM.7 (page 10 of the AR4 Synthesis Report SPM)



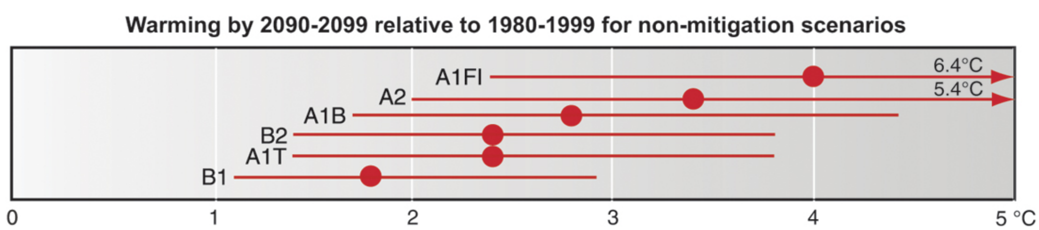


Figure SPM.7. *Examples of impacts associated with projected global average surface warming.* ***Upper panel:*** *Illustrative examples of global impacts projected for climate changes (and sea level and atmospheric CO2 where relevant) associated with different amounts of increase in global average surface temperature in the 21st century. The black lines link impacts; broken-line arrows indicate impacts continuing with increasing temperature. Entries are placed so that the left-hand side of text indicates the approximate level of warming that is associated with the onset of a given impact. Quantitative entries for water scarcity and flooding represent the additional impacts of climate change relative to the conditions projected across the range of SRES scenarios A1FI, A2, B1 and B2. Adaptation to climate change is not included in these estimations. Confidence levels for all statements are high.* ***Lower panel:*** *Dots and bars indicate the best estimate and likely ranges of warming assessed for the six SRES marker scenarios for 2090-2099 relative to 1980-1999. {Figure 3.6}*

C2. Impacts of climate change on coral reefs

C2.1 Present-day changes in coral reefs

C2.1.1 Observed changes in coral reefs (Chapter 1, Section 1.3.4.1)

Concerns about the impacts of climate change on coral reefs centre on the effects of the recent trends in increasing acidity (via increasing CO_2), storm intensity, and sea surface temperatures (see Bindoff et al., 2007, Section 5.4.2.3; Trenberth et al., 2007, Sections 3.8.3 and 3.2.2).

Decreasing pH (see C2.2.1) leads to a decreased aragonite saturation state, one of the main physicochemical determinants of coral calcification (Kleypas et al., 1999). Although laboratory experiments have demonstrated a link between aragonite saturation state and coral growth (Langdon et al., 2000; Ohde and Hossain, 2004), there are currently no data relating altered coral growth *in situ* to increasing acidity.

Storms damage coral directly through wave action and indirectly through light attenuation by suspended sediment and abrasion by sediment and broken corals. Most studies relate to individual storm events, but a meta-analysis of data from 1977 to 2001 showed that coral cover on Caribbean reefs decreased by 17% on average in the year following a hurricane, with no evidence of recovery for at least 8 years post-impact (Gardner et al., 2005). Stronger hurricanes caused more coral loss, but the second of two successive hurricanes caused little additional damage, suggesting a greater future effect from increasing hurricane intensity rather than from increasing frequency (Gardner et al., 2005).

There is now extensive evidence of a link between coral bleaching – a whitening of corals as a result of the expulsion of symbiotic zooxanthellae (see C2.1.2) – and sea surface temperature anomalies (McWilliams et al., 2005). Bleaching usually occurs when temperatures exceed a ‘threshold’ of about 0.8-1°C above mean summer maximum levels for at least 4 weeks (Hoegh-Guldberg, 1999). Regional-scale bleaching events have increased in frequency since the 1980s (Hoegh-Guldberg, 1999). In 1998, the largest bleaching event to date is estimated to have killed 16% of the world’s corals, primarily in the western Pacific and the Indian Ocean (Wilkinson, 2004). On many reefs, this mortality has led to a loss of structural complexity and shifts in reef fish species composition (Bellwood et al., 2006; Garpe et al., 2006; Graham et al., 2006). Corals that recover from bleaching suffer temporary reductions in growth and reproductive capacity (Mendes and Woodley, 2002), while the recovery of reefs following mortality tends to be dominated by fast-growing and bleaching-resistant coral genera (Arthur et al., 2005).

While there is increasing evidence for climate change impacts on coral reefs, disentangling the impacts of climate-related stresses from other stresses (e.g., over-fishing and pollution; Hughes et al., 2003) is difficult. In addition, inter-decadal variation in pH (Pelejero et al., 2005), storm activity (Goldenberg et al., 2001) and sea surface temperatures (Mestas-Nunez and Miller, 2006) linked, for example, to the El Niño-Southern Oscillation and Pacific Decadal Oscillation, make it more complicated to discern the effect of anthropogenic climate change from natural modes of variability. An analysis of bleaching in the Caribbean indicates that 70% of the variance in geographic extent of bleaching between 1983 and 2000 could be attributed to variation in ENSO and atmospheric dust (Gill et al., 2006).

C2.1.2 Environmental thresholds and observed coral bleaching (Chapter 6, Box 6.1)

Coral bleaching, due to the loss of symbiotic algae and/or their pigments, has been observed on many reefs since the early 1980s. It may have previously occurred, but has gone unrecorded. Slight paling occurs naturally in response to seasonal increases in sea surface temperature (SST) and solar radiation. Corals bleach white in response to anomalously high SST (~1°C above average seasonal maxima, often combined with high solar radiation). Whereas some corals recover their natural colour when environmental conditions ameliorate, their growth rate and reproductive ability may be significantly reduced for a substantial period. If bleaching is prolonged, or if SST exceeds 2°C above average seasonal maxima, corals die. Branching species appear more susceptible than massive corals (Douglas, 2003).

Major bleaching events were observed in 1982-1983, 1987-1988 and 1994-1995 (Hoegh-Guldberg, 1999). Particularly severe bleaching occurred in 1998 (Figure C2.1), associated with pronounced El Niño events in one of the hottest years on record (Lough, 2000; Bruno et al., 2001). Since 1998 there have been several extensive bleaching events. For example, in 2002 bleaching occurred on much of the Great Barrier Reef (Berkelmans et al., 2004; see C2.2.3) and elsewhere. Reefs in the eastern Caribbean experienced a massive bleaching event in late 2005, another of the hottest years on record. On many Caribbean reefs, bleaching exceeded that of 1998 in both extent and mortality (Figure C2.1), and reefs are in decline as a result of the synergistic effects of multiple stresses (Gardner et al., 2005; McWilliams et al., 2005; see C2.3.1). There is considerable variability in coral susceptibility and recovery to elevated SST in both time and space, and in the incidence of mortality (Webster et al., 1999; Wilkinson, 2002; Obura, 2005).

Global climate model results imply that thermal thresholds will be exceeded more frequently, with the consequence that bleaching will recur more often than reefs can sustain (Hoegh-Guldberg, 1999, 2004; Donner et al., 2005), perhaps almost annually on some reefs in the next few decades (Sheppard, 2003; Hoegh-Guldberg, 2005). If the threshold remains unchanged, more frequent bleaching and mortality seems inevitable (see

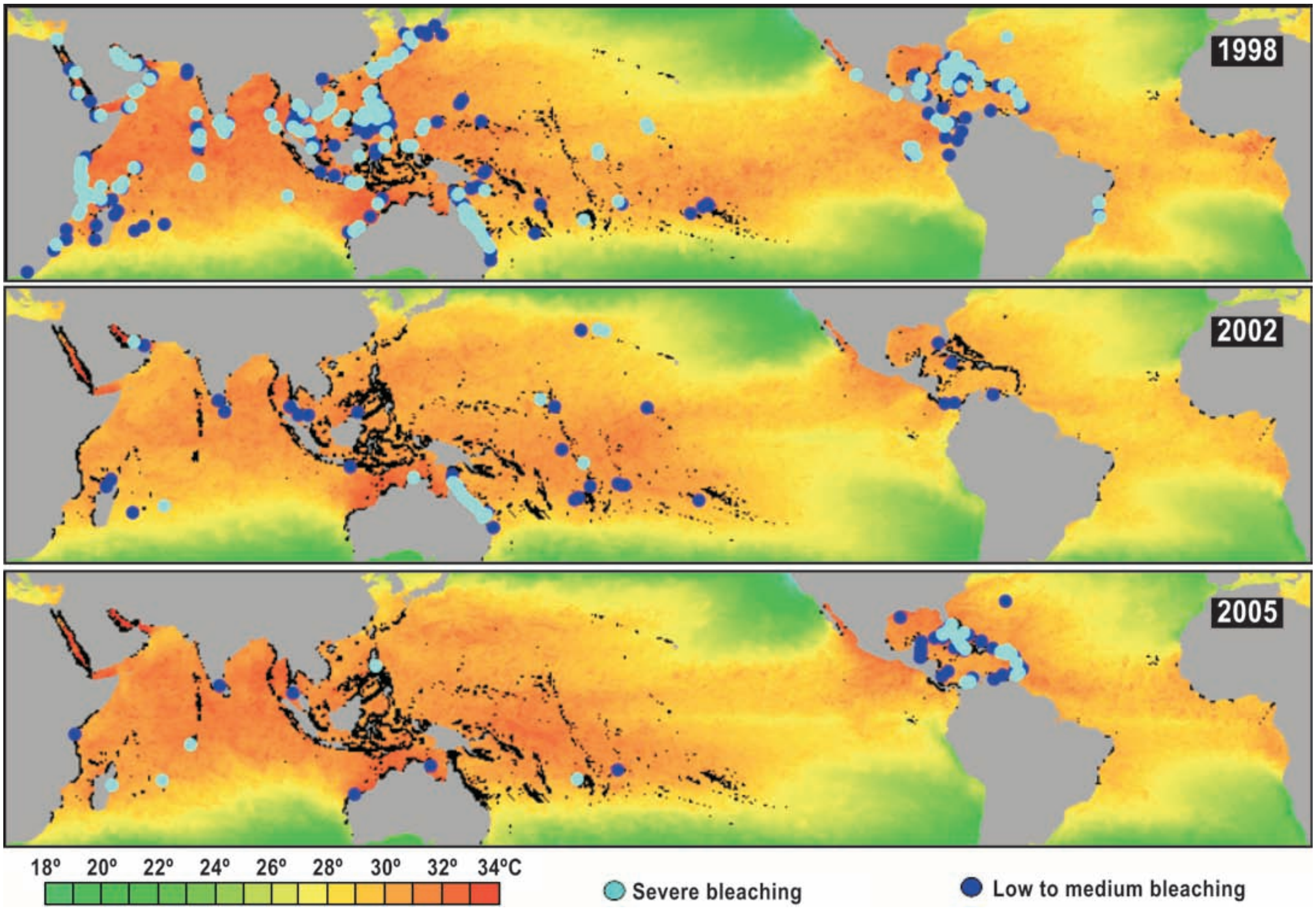


Figure C2.1. *Maximum monthly mean sea surface temperature for 1998, 2002 and 2005, and locations of reported coral bleaching (data sources: NOAA Coral Reef Watch (http://coralreefwatch.noaa.gov/) and Reefbase (http://www.reefbase.org/)).*

Figure C2.2a), but with local variations due to different susceptibilities to factors such as water depth. Recent preliminary studies lend some support to the adaptive bleaching hypothesis, indicating that the coral host may be able to adapt or acclimatise as a result of expelling one clade[1] of symbiotic algae but recovering with a new one (termed 'shuffling', see C2.2.1), creating 'new' ecospecies with different temperature tolerances (Coles and Brown, 2003; Buddemeier et al., 2004; Little et al., 2004; Rowan, 2004; Obura, 2005). Adaptation or acclimatisation might result in an increase in the threshold temperature at which bleaching occurs (Figure C2.2b). The extent to which the thermal threshold could increase with warming of more than a couple of degrees remains very uncertain, as are the effects of additional stresses, such as reduced carbonate supersaturation in surface waters (see C2.2.1) and non-climate stresses (see C2.3.1). Corals and other calcifying organisms (e.g., molluscs, foraminifers) remain extremely susceptible to increases in SST. Bleaching events reported in recent years have already impacted many reefs, and their more frequent recurrence is very likely to further reduce both coral cover and diversity on reefs over the next few decades.

C2.2 Future impacts on coral reefs

C2.2.1 Are coral reefs endangered by climate change? (Chapter 4, Box 4.4)

Reefs are habitat for about a quarter of all marine species and are the most diverse among marine ecosystems (Roberts et al., 2002; Buddemeier et al., 2004). They underpin local shore protection, fisheries, tourism (see Chapter 6; Hoegh-Guldberg et al., 2000; Cesar et al., 2003; Willig et al., 2003; Hoegh-Guldberg, 2004, 2005) and, although supplying only about 2-5% of the global fisheries harvest, comprise a critical subsistence protein and income source in the developing world (Whittingham et al., 2003; Pauly et al., 2005; Sadovy, 2005).

Corals are affected by warming of surface waters (see C2.1.2; Reynaud et al., 2003; McNeil et al., 2004; McWilliams et al., 2005) leading to bleaching (loss of algal symbionts; see C2.1.2). Many studies incontrovertibly link coral bleaching to warmer sea surface temperature (e.g., McWilliams et al., 2005), and mass bleaching and coral mortality often results beyond key temperature thresholds (see C2.1.2). Annual or bi-annual exceedance of

[1] A clade of algae is a group of closely related, but nevertheless different, types.

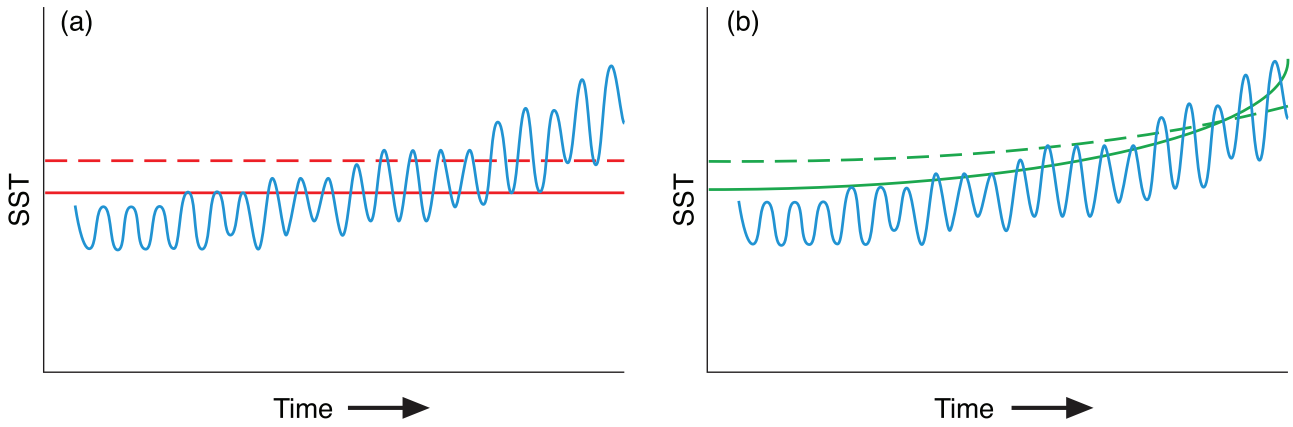


Figure C2.2. *Alternative hypotheses concerning the threshold SST at which coral bleaching occurs: (a) invariant threshold for coral bleaching (red line) which occurs when SST exceeds usual seasonal maximum threshold (by ~1°C) and mortality (dashed red line, threshold of 2°C), with local variation due to different species or water depth; (b) elevated threshold for bleaching (green line) and mortality (dashed green line) where corals adapt or acclimatise to increased SST (based on Hughes et al., 2003).*

bleaching thresholds is projected at the majority of reefs worldwide by 2030 to 2050 (Hoegh-Guldberg, 1999; Sheppard, 2003; Donner et al., 2005). After bleaching, algae quickly colonise dead corals, possibly inhibiting later coral recruitment (e.g., McClanahan et al., 2001; Szmant, 2001; Gardner et al., 2003; Jompa and McCook, 2003). Modelling predicts a phase switch to algal dominance on the Great Barrier Reef and Caribbean reefs in 2030 to 2050 (Wooldridge et al., 2005).

Coral reefs will also be affected by rising atmospheric CO_2 concentrations (Orr et al., 2005; Raven et al., 2005; Denman et al., 2007, Box 7.3) resulting in declining calcification. Experiments at expected aragonite concentrations demonstrated a reduction in coral calcification (Marubini et al., 2001; Langdon et al., 2003; Hallock, 2005), coral skeleton weakening (Marubini et al., 2003) and strong temperature dependence (Reynaud et al., 2003). Oceanic pH projections decrease at a greater rate and to a lower level than experienced over the past 20 million years (Caldeira and Wickett, 2003; Raven et al., 2005; Turley et al., 2006). Doubling CO_2 will reduce calcification in aragonitic corals by 20%-60% (Kleypas et al., 1999; Kleypas and Langdon, 2002; Reynaud et al., 2003; Raven et al., 2005). By 2070 many reefs could reach critical aragonite saturation states (Feely et al., 2004; Orr et al., 2005), resulting in reduced coral cover and greater erosion of reef frameworks (Kleypas et al., 2001; Guinotte et al., 2003).

Adaptation potential (Hughes et al., 2003) by reef organisms requires further experimental and applied study (Coles and Brown, 2003; Hughes et al., 2003). Natural adaptive shifts to symbionts with +2°C resistance may delay the demise of some reefs until roughly 2100 (Sheppard, 2003), rather than mid-century (Hoegh-Guldberg, 2005) although this may vary widely across the globe (Donner et al., 2005). Estimates of warm-water coral cover reduction in the last 20-25 years are 30% or higher (Wilkinson, 2004; Hoegh-Guldberg, 2005) due largely to increasing higher SST frequency (Hoegh-Guldberg, 1999). In some regions, such as the Caribbean, coral losses have been estimated at 80% (Gardner et al., 2003). Coral migration to higher latitudes with more optimal SST is unlikely, due both to latitudinally decreasing aragonite concentrations and projected atmospheric CO_2 increases (Kleypas et al., 2001; Guinotte et al., 2003; Orr et al., 2005; Raven et al., 2005). Coral migration is also limited by lack of available substrate (see C2.2.2). Elevated SST and decreasing aragonite have a complex synergy (Harvell et al., 2002; Reynaud et al., 2003; McNeil et al., 2004; Kleypas et al., 2005) but could produce major coral reef changes (Guinotte et al., 2003; Hoegh-Guldberg, 2005). Corals could become rare on tropical and sub-tropical reefs by 2050 due to the combined effects of increasing CO_2 and increasing frequency of bleaching events (at 2-3 × CO_2) (Kleypas and Langdon, 2002; Hoegh-Guldberg, 2005; Raven et al., 2005). Other climate change factors (such as sea-level rise, storm impact and aerosols) and non-climate factors (such as over-fishing, invasion of non-native species, pollution, nutrient and sediment load (although this could also be related to climate change through changes to precipitation and river flow; see C2.1.2 and C2.2.3; Chapter 16)) add multiple impacts on coral reefs (see C2.3.1), increasing their vulnerability and reducing resilience to climate change (Koop et al., 2001; Kleypas and Langdon, 2002; Cole, 2003; Buddemeier et al., 2004; Hallock, 2005).

C2.2.2 Impacts on coral reefs (Chapter 6, Section 6.4.1.5)

Reef-building corals are under stress on many coastlines (see C2.1.1). Reefs have deteriorated as a result of a combination of anthropogenic impacts such as over-fishing and pollution from adjacent land masses (Pandolfi et al., 2003; Graham et al., 2006), together with an increased frequency and severity of bleaching associated with climate change (see C2.1.2). The relative significance of these stresses varies from site to site. Coral mortality on Caribbean reefs is generally related to recent disease outbreaks, variations in herbivory,[2] and hurricanes (Gardner et al., 2003; McWilliams et al., 2005), whereas Pacific reefs have been particularly impacted by episodes of coral

[2] Herbivory: the consumption of plants by animals.

bleaching caused by thermal stress anomalies, especially during recent El Niño events (Hughes et al., 2003), as well as non-climate stresses.

Mass coral-bleaching events are clearly correlated with rises of SST of short duration above summer maxima (Douglas, 2003; Lesser, 2004; McWilliams et al., 2005). Particularly extensive bleaching was recorded across the Indian Ocean region associated with extreme El Niño conditions in 1998 (see C2.1.2 and C2.2.3). Many reefs appear to have experienced similar SST conditions earlier in the 20th century and it is unclear how extensive bleaching was before widespread reporting post-1980 (Barton and Casey, 2005). There is limited ecological and genetic evidence for adaptation of corals to warmer conditions (see C2.1.2 and C2.2.1). It is very likely that projected future increases in SST of about 1 to 3°C (Section 6.3.2) will result in more frequent bleaching events and widespread mortality if there is no thermal adaptation or acclimatisation by corals and their symbionts (Sheppard, 2003; Hoegh-Guldberg, 2004). The ability of coral reef ecosystems to withstand the impacts of climate change will depend on the extent of degradation from other anthropogenic pressures and the frequency of future bleaching events (Donner et al., 2005).

In addition to coral bleaching, there are other threats to reefs associated with climate change (Kleypas and Langdon, 2002). Increased concentrations of CO_2 in seawater will lead to ocean acidification (Section 6.3.2), affecting aragonite saturation state (Meehl et al., 2007) and reducing calcification rates of calcifying organisms such as corals (LeClerq et al., 2002; Guinotte et al., 2003; see C2.2.1). Cores from long-lived massive corals indicate past minor variations in calcification (Lough and Barnes, 2000), but disintegration of degraded reefs following bleaching or reduced calcification may result in increased wave energy across reef flats with potential for shoreline erosion (Sheppard et al., 2005). Relative sea-level rise appears unlikely to threaten reefs in the next few decades; coral reefs have been shown to keep pace with rapid postglacial sea-level rise when not subjected to environmental or anthropogenic stresses (Hallock, 2005). A slight rise in sea level is likely to result in the submergence of some Indo-Pacific reef flats and recolonisation by corals, as these intertidal surfaces, presently emerged at low tide, become suitable for coral growth (Buddemeier et al., 2004).

Many reefs are affected by tropical cyclones (hurricanes, typhoons); impacts range from minor breakage of fragile corals to destruction of the majority of corals on a reef and deposition of debris as coarse storm ridges. Such storms represent major perturbations, affecting species composition and abundance, from which reef ecosystems require time to recover. The sequence of ridges deposited on the reef top can provide a record of past storm history (Hayne and Chappell, 2001); for the northern Great Barrier Reef no change in frequency of extremely large cyclones has been detected over the past 5,000 years (Nott and Hayne, 2001). An intensification of tropical storms (Section 6.3.2) could have devastating consequences on the reefs themselves, as well as for the inhabitants of many low-lying islands (Sections 6.4.2 and 16.3.1.3). There is limited evidence that global warming may result in an increase of coral range; for example, the extension of branching Acropora polewards has been recorded in Florida, despite an almost Caribbean-wide trend for reef deterioration (Precht and Aronson, 2004), but there are several constraints, including low genetic diversity and the limited suitable substrate at the latitudinal limits to reef growth (Riegl, 2003; Ayre and Hughes, 2004; Woodroffe et al., 2005).

The fate of the small reef islands on the rim of atolls is of special concern. Small reef islands in the Indo-Pacific formed over recent millennia during a period when regional sea level fell (Dickinson, 2004; Woodroffe and Morrison, 2001). However, the response of these islands to future sea-level rise remains uncertain, and is addressed in greater detail in Chapter 16, Section 16.4.2. It will be important to identify critical thresholds of change beyond which there may be collapse of ecological and social systems on atolls. There are limited data, little local expertise to assess the dangers, and a low level of economic activity to cover the costs of adaptation for atolls in countries such as the Maldives, Kiribati and Tuvalu (Barnett and Adger, 2003; Chapter 16, Box 16.6).

C2.2.3 Climate change and the Great Barrier Reef (Chapter 11, Box 11.3)

The Great Barrier Reef (GBR) is the world's largest continuous reef system (2,100 km long) and is a critical storehouse of Australian marine biodiversity and a breeding ground for seabirds and other marine vertebrates such as the humpback whale. Tourism associated with the GBR generated over US$4.48 billion in the 12-month period 2004/5 and provided employment for about 63,000 full-time equivalent persons (Access Economics, 2005). The two greatest threats from climate change to the GBR are (i) rising sea temperatures, which are almost certain to increase the frequency and intensity of mass coral bleaching events, and (ii) ocean acidification, which is likely to reduce the calcifying ability of key organisms such as corals. Other factors, such as droughts and more intense storms, are likely to influence reefs through physical damage and extended flood plumes (Puotinen, 2006).

Sea temperatures on the GBR have warmed by about 0.4°C over the past century (Lough, 2000). Temperatures currently typical of the northern tip of the GBR are very likely to extend to its southern end by 2040 to 2050 (SRES scenarios A1, A2) and 2070 to 2090 (SRES scenarios B1, B2) (Done et al., 2003). Temperatures only 1°C above the long-term summer maxima already cause mass coral bleaching (loss of symbiotic algae). Corals may recover but will die under high or prolonged temperatures (2 to 3°C above long-term maxima for at least 4 weeks). The GBR has experienced eight mass bleaching events since 1979 (1980, 1982, 1987, 1992, 1994, 1998, 2002 and 2006); there are no records of events prior to 1979 (Hoegh-Guldberg, 1999). The most widespread and intense events occurred in the summers of 1998 and 2002, with about 42% and 54% of reefs affected, respectively (Done et al., 2003; Berkelmans et al., 2004). Mortality was distributed patchily, with the greatest effects on near-shore reefs, possibly exacerbated by osmotic stress caused by floodwaters in some areas (Berkelmans and Oliver, 1999). The 2002 event was followed by localised outbreaks of coral disease, with incidence of some disease-like syndromes increasing by as much as 500% over the past decade at a few sites (Willis et al., 2004). While the impacts of coral disease on the GBR are currently minor, experiences in other parts of the world suggest that disease has the potential to be a threat to GBR reefs. Effects from thermal stress are likely to be exacerbated under future scenarios by the gradual acidification of the world's oceans, which have absorbed about 30% of the excess CO_2 released to the atmosphere (Orr et al., 2005; Raven et al., 2005). Calcification declines with decreasing carbonate ion concentrations, becoming zero at carbonate ion concentrations of approximately 200 μmol/kg (Langdon et al., 2000; Langdon, 2002). These occur at atmospheric CO_2 concentrations of approximately 500 ppm. Reduced growth due to acidic conditions is very likely to hinder reef recovery after bleaching events and will reduce the resilience of reefs to other stressors (e.g., sediment, eutrophication).

Even under a moderate warming scenario (A1T, 2°C by 2100), corals on the GBR are very likely to be exposed to regular summer temperatures that exceed the thermal thresholds observed over the past 20 years (Done et al., 2003). Annual bleaching is projected under the A1FI scenario by 2030, and under A1T by 2050 (Done et al., 2003; Wooldridge et al., 2005). Given that the recovery time from a severe bleaching-induced mortality event is at least 10 years (and may exceed 50 years for full recovery), these models suggest that reefs are likely to be dominated by non-coral organisms such as macroalgae by 2050 (Hoegh-Guldberg, 1999; Done et al., 2003). Substantial impacts on biodiversity, fishing and tourism are likely. Maintenance of hard coral cover on the GBR will require corals to increase their upper thermal tolerance limits at the same pace as the change in sea temperatures driven by climate change, i.e., about 0.1-0.5°C/decade (Donner et al., 2005). There is currently little evidence that corals have the capacity for such rapid genetic change; most of the evidence is to the contrary (Hoegh-Guldberg, 1999, 2004). Given that recovery from mortality can be potentially enhanced by reducing local stresses (water quality, fishing pressure), management initiatives such as the Reef Water Quality Protection Plan and the Representative Areas Programme (which expanded totally protected areas on the GBR from 4.6% to over 33%) represent planned adaptation options to enhance the ability of coral reefs to endure the rising pressure from rapid climate change.

C2.2.4 Impact of coral mortality on reef fisheries (Chapter 5, Box 5.4)

Coral reefs and their fisheries are subject to many stresses in addition to climate change (see Chapter 4). So far, events such as the 1998 mass coral bleaching in the Indian Ocean have not provided evidence of negative short-term bio-economic impacts for coastal reef fisheries (Spalding and Jarvis, 2002; Grandcourt and Cesar, 2003). In the longer term, there may be serious consequences for fisheries production that result from loss of coral communities and reduced structural complexity, which result in reduced fish species richness, local extinctions and loss of species within key functional groups of reef fish (Sano, 2004; Graham et al., 2006).

C2.3 Multiple stresses on coral reefs

C2.3.1 Non-climate-change threats to coral reefs of small islands (Chapter 16, Box 16.2)

A large number of non-climate-change stresses and disturbances, mainly driven by human activities, can impact coral reefs (Nyström et al., 2000; Hughes et al., 2003). It has been suggested that the 'coral reef crisis' is almost certainly the result of complex and synergistic interactions among global-scale climatic stresses and local-scale, human-imposed stresses (Buddemeier et al., 2004).

In a study by Bryant et al. (1998), four human-threat factors – coastal development, marine pollution, over-exploitation and destructive fishing, and sediment and nutrients from inland – provide a composite indicator of the potential risk to coral reefs associated with human activity for 800 reef sites. Their map (Figure C2.3) identifies low-risk (blue), medium-risk (yellow) and high-risk (red) sites, the first being common in the insular central Indian and Pacific Oceans, the last in maritime South-East Asia and the Caribbean archipelago. Details of reefs at risk in the two highest-risk areas have been documented by Burke et al. (2002) and Burke and Maidens (2004), who indicate that about 50% of the reefs in South-East Asia and 45% in the Caribbean are classed in the high- to very-high-risk category. There are, however, significant local and regional differences in

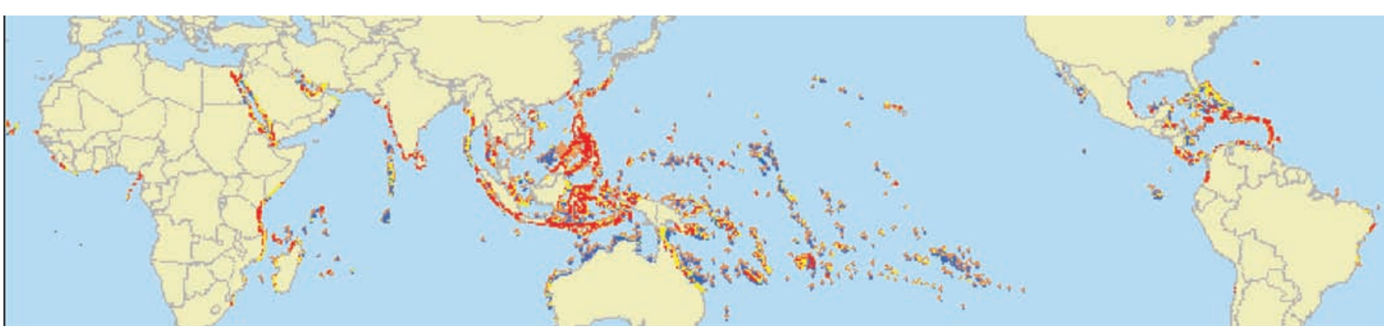


Figure C2.3. *The potential risk to coral reefs from human-threat factors. Low risk (blue), medium risk (yellow) and high risk (red). Source: Bryant et al. (1998)*

the scale and type of threats to coral reefs in both continental and small-island situations.

Recognising that coral reefs are especially important for many Small Island states, Wilkinson (2004) notes that reefs on small islands are often subject to a range of non-climate impacts. Some common types of reef disturbance are listed below, with examples from several island regions and specific islands.

1. Impact of coastal developments and modification of shorelines:
   - coastal development on fringing reefs, Langawi Island, Malaysia (Abdullah et al., 2002);
   - coastal resort development and tourism impacts in Mauritius (Ramessur, 2002).
2. Mining and harvesting of corals and reef organisms:
   - coral harvesting in Fiji for the aquarium trade (Vunisea, 2003).
3. Sedimentation and nutrient pollution from the land:
   - sediment smothering reefs in Aria Bay, Palau (Golbuua et al., 2003) and southern islands of Singapore (Dikou and van Woesik, 2006);
   - non-point source pollution, Tutuila Island, American Samoa (Houk et al., 2005);
   - nutrient pollution and eutrophication, fringing reef, Réunion (Chazottes et al., 2002) and Cocos Lagoon, Guam (Kuffner and Paul, 2001).
4. Over-exploitation and damaging fishing practices:
   - blast fishing in the islands of Indonesia (Fox and Caldwell, 2006);
   - intensive fish-farming effluent in Philippines (Villanueva et al., 2006);
   - subsistence exploitation of reef fish in Fiji (Dulvy et al., 2004);
   - giant clam harvesting on reefs, Milne Bay, Papua New Guinea (Kinch, 2002).
5. Introduced and invasive species:
   - non-indigenous species invasion of coral habitats in Guam (Paulay et al., 2002).

There is another category of 'stress' that may inadvertently result in damage to coral reefs – the human component of poor governance (Goldberg and Wilkinson, 2004). This can accompany political instability; one example being problems with contemporary coastal management in the Solomon Islands (Lane, 2006).

References

Abdullah, A., Z. Yasin, W. Ismail, B. Shutes and M. Fitzsimons, 2002: The effect of early coastal development on the fringing coral reefs of Langkawi: a study in small-scale changes. *Malaysian Journal of Remote Sensing and GIS*, **3**, 1-10.

Access Economics, 2005: *Measuring the Economic and Financial Value of the Great Barrier Reef Marine Park*. Report by Access Economics for Great Barrier Reef Marine Park Authority, June 2005, 61 pp. http://www.accesseconomics.com.au/publicationsreports/showreport.php?id=10&searchfor=Economic%20Consulting&searchby=area.

Arthur, R., T.J. Done and H. Marsh, 2005: Benthic recovery four years after an El Niño-induced coral mass mortality in the Lakshadweep atolls. *Curr. Sci. India*, **89**, 694-699.

Ayre, D.J. and T.P. Hughes, 2004: Climate change, genotypic diversity and gene flow in reef-building corals. *Ecol. Lett.*, **7**, 273-278.

Barnett, J. and W.N. Adger, 2003: Climate dangers and atoll countries. *Climatic Change*, **61**, 321-337.

Barton, A.D. and K.S. Casey, 2005: Climatological context for large-scale coral bleaching. *Coral Reefs*, **24**, 536-554.

Bellwood, D.R., A.S. Hoey, J.L. Ackerman and M. Depczynski, 2006: Coral bleaching, reef fish community phase shifts and the resilience of coral reefs. *Glob. Change Biol.*, **12**, 1587-1594.

Berkelmans, R. and J.K. Oliver, 1999: Large-scale bleaching of corals on the Great Barrier Reef. *Coral Reefs*, **18**, 55-60.

Berkelmans, R., G. De'ath, S. Kininmonth and W.J. Skirving, 2004: A comparison of the 1998 and 2002 coral bleaching events of the Great Barrier Reef: spatial correlation, patterns and predictions. *Coral Reefs*, **23**, 74-83.

Bindoff, N., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, C.K. Shum, L. Talley and A. Unnikrishnan, 2007: Observations: oceanic climate change and sea level. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, Eds., Cambridge University Press, Cambridge, 385-432.

Bruno, J.F., C.E. Siddon, J.D. Witman, P.L. Colin and M.A. Toscano, 2001: El Niño related coral bleaching in Palau, Western Caroline Islands. *Coral Reefs*, **20**, 127-136.

Bryant, D., L. Burke, J. McManus and M. Spalding, 1998: *Reefs at Risk: A Map-Based Indicator of Threats to the World's Coral Reefs*. World Resources Institute, Washington, DC, 56 pp.

Buddemeier, R.W., J.A. Kleypas and B. Aronson, 2004: *Coral Reefs and Global Climate Change: Potential Contributions of Climate Change to Stresses on Coral Reef Ecosystems*. Report prepared for the Pew Centre on Global Climate Change, Arlington, Virginia, 56 pp.

Burke, L. and J. Maidens, 2004: *Reefs at Risk in the Caribbean*. World Resources Institute, Washington, District of Columbia, 81 pp.

Burke, L., E. Selig and M. Spalding, 2002: *Reefs at Risk in Southeast Asia*. World Resources Institute, Washington, District of Columbia, 72 pp.

Caldeira, K. and M.E. Wickett, 2003: Anthropogenic carbon and ocean pH. *Nature*, **425**, 365-365.

Cesar, H., L. Burke and L. Pet-Soede, 2003: *The Economics of Worldwide Coral Reef Degradation*. Cesar Environmental Economics Consulting (CEEC), Arnhem, 23 pp.

Chazottes, V., T. Le Campion-Alsumard, M. Peyrot-Clausade and P. Cuet, 2002: The effects of eutrophication-related alterations to coral reef communities on agents and rates of bioerosion (Reunion Island, Indian Ocean). *Coral Reefs*, **21**, 375-390.

Cole, J., 2003: Global change: dishing the dirt on coral reefs. *Nature*, **421**, 705-706.

Coles, S.L.and B.E. Brown, 2003: Coral bleaching: capacity for acclimatization and adaptation. *Adv. Mar. Biol.*, **46**, 183-224.

Denman, K.L., G. Brasseur, A. Chidthaisong, P. Ciais, P. Cox, R.E. Dickinson, D. Hauglustaine, C. Heinze, E. Holland, D. Jacob, U. Lohmann, S. Ramachandran, P.L. da Silva Dias, S.C. Wofsy and X. Zhang, 2007: Couplings between changes in the climate system and biogeochemistry. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, Eds., Cambridge University Press, Cambridge, 499-587.

Dickinson, W.R., 2004: Impacts of eustasy and hydro-isostasy on the evolution and landforms of Pacific atolls. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **213**, 251-269.

Dikou, A. and R. van Woesik, 2006: Survival under chronic stress from sediment load: spatial patterns of hard coral communities in the southern islands of Singapore. *Mar. Pollut. Bull.*, **52**, 7-21.

Done, T., P. Whetton, R. Jones, R. Berkelmans, J. Lough, W. Skirving and S. Wooldridge, 2003: Global climate change and coral bleaching on the Great Barrier Reef. Final Report to the State of Queensland Greenhouse Taskforce through the Department of Natural Resources and Mining, Townsville, 49 pp. http://www.longpaddock.qld.gov.au/ClimateChanges/pub/CoralBleaching.pdf.

Donner, S.D., W.J. Skirving, C.M. Little, M. Oppenheimer and O. Hoegh-Guldberg, 2005: Global assessment of coral bleaching and required rates of adaptation under climate change. *Glob. Change Biol.*, **11**, 2251-2265.

Douglas, A.E., 2003: Coral bleaching: how and why? *Mar. Pollut. Bull.*, **46**, 385-392.

Dulvy, N., R. Freckleton and N. Polunin, 2004: Coral reef cascades and the indirect effects of predator removal by exploitation. *Ecol. Lett.*, **7**, 410-416.

Feely, R.A., C.L. Sabine, K. Lee, W. Berelson, J. Kleypas, V.J. Fabry and F.J. Millero, 2004: Impact of anthropogenic CO_2 on the $CaCO_3$ system in the oceans. *Science*, **305**, 362-366.

Fox, H. and R. Caldwell, 2006: Recovery from blast fishing on coral reefs: a tale of two scales. *Ecol. Appl.*, **16**, 1631-1635.

Gardner, T.A., I.M. Cote, J.A. Gill, A. Grant and A.R. Watkinson, 2003: Long-term region-wide declines in Caribbean corals. *Science*, **301**, 958-960.

Gardner, T.A., I.M. Côté, J.A. Gill, A. Grant and A.R. Watkinson, 2005: Hurricanes and Caribbean coral reefs: impacts, recovery patterns and role in long-term decline. *Ecology*, **86**, 174-184.

Garpe, K.C., S.A.S. Yahya, U. Lindahl and M.C. Ohman, 2006: Long-term effects of the 1998 coral bleaching event on reef fish assemblages. *Mar. Ecol.–Prog. Ser.*, **315**, 237-247.

Gill, J.A., J.P. McWilliams, A.R. Watkinson and I.M. Côté, 2006: Opposing forces of aerosol cooling and El Niño drive coral bleaching on Caribbean reefs. *P. Natl. Acad. Sci. USA*, **103**, 18870-18873.

Golbuua, Y., S. Victora, E. Wolanski and R.H. Richmond, 2003: Trapping of fine sediment in a semi-enclosed bay, Palau, Micronesia. *Estuar. Coast. Shelf S.*, **57**, 1-9.

Goldberg, J. and C. Wilkinson, 2004: Global threats to coral reefs: coral bleaching, global climate change, disease, predator plagues, and invasive species. *Status of Coral Reefs of the World: 2004*, C. Wilkinson, Ed., Australian Institute of Marine Science, Townsville, 67-92.

Goldenberg, S.B., C.W. Landsea, A.M. Mestas-Nunez and W.M. Gray, 2001: The recent increase in Atlantic hurricane activity: causes and implications. *Science*, **293**, 474-479.

Grandcourt, E.M. and H.S.J. Cesar, 2003: The bio-economic impact of mass coral mortality on the coastal reef fisheries of the Seychelles. *Fish. Res.*, **60**, 539-550.

Graham, N.A.J., S.K. Wilson, S. Jennings, N.V.C. Polunin, J.P. Bijoux and J. Robinson, 2006: Dynamic fragility of oceanic coral reef ecosystems. *P. Natl. Acad. Sci. USA*, **103**, 8425-8429.

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

Hallock, P., 2005: Global change and modern coral reefs: new opportunities to understand shallow-water carbonate depositional processes. *Sediment. Geol.*, **175**, 19-33.

Harvell, C.D., C.E. Mitchell, J.R. Ward, S. Altizer, A.P. Dobson, R.S. Ostfeld and M.D. Samuel, 2002: Climate warming and disease risks for terrestrial and marine biota. *Science*, **296**, 2158-2162.

Hayne, M. and J. Chappell, 2001: Cyclone frequency during the last 5000 years at Curacao Island, north Queensland, Australia. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **168**, 207-219.

Hoegh-Guldberg, O., 1999: Climate change, coral bleaching and the future of the world's coral reefs. *Mar. Freshwater Res.*, **50**, 839-866.

Hoegh-Guldberg, O., 2004: Coral reefs in a century of rapid environmental change. *Symbiosis*, **37**, 1-31.

Hoegh-Guldberg, O., 2005: Low coral cover in a high-CO_2 world. *J. Geophys. Res. C*, **110**, C09S06, doi:10.1029/2004JC002528.

Hoegh-Guldberg, O., H. Hoegh-Guldberg, D.K. Stout, H. Cesar and A. Timmerman, 2000: *Pacific in Peril: Biological, Economic and Social Impacts of Climate Change on Pacific Coral Reefs*. Greenpeace, Sidney, 72 pp.

Houk, P., G. Didonato, J. Iguel and R. van Woesik, 2005: Assessing the effects of non-point source pollution on American Samoa's coral reef communities. *Environ. Monit. Assess.*, **107**, 11-27.

Hughes, T.P., A.H. Baird, D.R. Bellwood, M. Card, S.R. Connolly, C. Folke, R. Grosberg, O. Hoegh-Guldberg, J.B.C. Jackson, J. Kleypas, J.M. Lough, P. Marshall, M. Nystrom, S.R. Palumbi, J.M. Pandolfi, B. Rosen and J. Roughgarden, 2003: Climate change, human impacts, and the resilience of coral reefs. *Science*, **301**, 929-933.

Jompa, J. and L.J. McCook, 2003: Coral-algal competition: macroalgae with different properties have different effects on corals. *Mar. Ecol.–Prog. Ser.*, **258**, 87-95.

Kinch, J., 2002: Giant clams: their status and trade in Milne Bay Province, Papua New Guinea. *TRAFFIC Bulletin*, **19**, 1-9.

Kleypas, J.A. and C. Langdon, 2002: Overview of CO_2-induced changes in seawater chemistry. *World Coral Reefs in the New Millenium: Bridging Research and Management for Sustainable Development*, M.K. Moosa, S. Soemodihardjo, A. Soegiarto, K. Romimohtarto, A. Nontji and S. Suharsono, Eds., Proceedings of the 9th International Coral Reef Symposium, 2, Bali, Indonesia. Ministry of Environment, Indonesian Institute of Sciences, International Society for Reef Studies, 1085-1089.

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

Kleypas, J.A., R.W. Buddemeier and J.P. Gattuso, 2001: The future of coral reefs in an age of global change. *Int. J. Earth Sci.*, **90**, 426-437.

Kleypas, J.A., R.W. Buddemeier, C.M. Eakin, J.P. Gattuso, J. Guinotte, O. Hoegh-Guldberg, R. Iglesias-Prieto, P.L. Jokiel, C. Langdon, W. Skirving and A.E. Strong, 2005: Comment on "Coral reef calcification and climate change: the effect of ocean warming". *Geophys. Res. Lett.*, **32**, L08601, doi:10.1029/2004GL022329.

Koop, K., D. Booth, A. Broadbent, J. Brodie, D. Bucher, D. Capone, J. Coll, W. Dennison, M. Erdmann, P. Harrison, O. Hoegh-Guldberg, P. Hutchings, G.B. Jones, A.W.D. Larkum, J. O'Neil, A. Steven, E. Tentori, S. Ward, J. Williamson and D. Yellowlees, 2001: ENCORE: The effect of nutrient enrichment on coral reefs: synthesis of results and conclusions. *Mar. Pollut. Bull.*, **42**, 91-120.

Kuffner, I. and V. Paul, 2001: Effects of nitrate, phosphate and iron on the growth of macroalgae and benthic cyanobacteria from Cocos Lagoon, Guam. *Mar. Ecol.–Prog. Ser.*, **222**, 63-72.

Lane, M., 2006: Towards integrated coastal management in the Solomon Islands: identifying strategic issues for governance reform. *Ocean Coast. Manage.*, **49**, 421-441.

Langdon, C., 2002: Review of experimental evidence for effects of CO_2 on calcification of reef builders. *Proc. of the 9th International Coral Reef Symposium*, Ministry of Environment, Indonesian Institute of Science, International Society for Reef Studies, Bali 23–27 October, 1091-1098.

Langdon, C., T. Takahashi, C. Sweeney, D. Chipman, J. Goddard, F. Marubini, H. Aceves, H. Barnett and M.J. Atkinson, 2000: Effect of calcium carbonate saturation state on the calcification rate of an experimental coral reef. *Global Biogeochem. Cy.*, **14**, 639-654.

Langdon, C., W.S. Broecker, D.E. Hammond, E. Glenn, K. Fitzsimmons, S.G. Nelson, T.H. Peng, I. Hajdas and G. Bonani, 2003: Effect of elevated CO_2 on the community metabolism of an experimental coral reef. *Global Biogeochem. Cy.*, **17**, 1011, doi:10.1029/2002GB001941.

LeClerq, N., J.-P. Gattuso and J. Jaubert, 2002: Primary production, respiration, and calcification of a coral reef mesocosm under increased CO_2 pressure. *Limnol. Oceanogr.*, **47**, 558-564.

Lesser, M.P., 2004: Experimental biology of coral reef ecosystems. *J. Exp. Mar. Biol. Ecol.*, **300**, 217-252.

Little, A.F., M.J.H. van Oppen and B.L. Willis, 2004: Flexibility in algal endosymbioses shapes growth in reef corals. *Science*, **304**, 1492-1494.

Lough, J.M., 2000: 1997-98: unprecedented thermal stress to coral reefs? *Geophys. Res. Lett.*, **27**, 3901-3904.

Lough, J.M. and D.J. Barnes, 2000: Environmental controls on growth of the massive coral *Porites*. *J. Exp. Mar. Biol. Ecol.*, **245**, 225-243.

Marubini, F., H. Barnett, C. Langdon and M.J. Atkinson, 2001: Dependence of calcification on light and carbonate ion concentration for the hermatypic coral *Porites compressa*. *Mar. Ecol.–Prog. Ser.*, **220**, 153-162.

Marubini, F., C. Ferrier-Pages and J.P. Cuif, 2003: Suppression of skeletal growth in scleractinian corals by decreasing ambient carbonate-ion concentration: a cross-family comparison. *P. Roy. Soc. Lond. B*, **270**, 179-184.

McClanahan, T.R., N.A. Muthiga and S. Mangi, 2001: Coral and algal changes after the 1998 coral bleaching: interaction with reef management and herbivores on Kenyan reefs. *Coral Reefs*, **19**, 380-391.

McNeil, B.I., R.J. Matear and D.J. Barnes, 2004: Coral reef calcification and climate change: the effect of ocean warming. *Geophys. Res. Lett.*, **31**, L22309, doi:10.1029/2004GL021541.

McWilliams, J.P., I.M. Côté, J.A. Gill, W.J. Sutherland and A.R. Watkinson, 2005: Accelerating impacts of temperature-induced coral bleaching in the Caribbean. *Ecology*, **86**, 2055-2060.

Meehl, G.A., T.F. Stocker, W. Collins, P. Friedlingstein, A. Gaye, J. Gregory, A. Kitoh, R. Knutti and co-authors, 2007: Global climate projections. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt,

M. Tignor and H.L. Miller, Eds., Cambridge University Press, Cambridge, 747-846.

Mendes, J.M. and J.D. Woodley, 2002: Effect of the 1995-1996 bleaching event on polyp tissue depth, growth, reproduction and skeletal band formation in *Montastraea annularis*. *Mar. Ecol.–Prog. Ser.*, **235**, 93-102.

Mestas-Nunez, A.M. and A.J. Miller, 2006: Interdecadal variability and climate change in the eastern tropical Pacific: a review. *Prog. Oceanogr.*, **69**, 267-284.

Nott, J. and M. Hayne, 2001: High frequency of 'super-cyclones' along the Great Barrier Reef over the past 5,000 years. *Nature*, **413**, 508-512.

Nyström, M., C. Folke and F. Moberg, 2000: Coral reef disturbance and resilience in a human-dominated environment. *Trends Ecol. Evol.*, **15**, 413-417.

Obura, D.O., 2005: Resilience and climate change: lessons from coral reefs and bleaching in the western Indian Ocean. *Estuar. Coast. Shelf Sci.*, **63**, 353-372.

Ohde, S. and M.M.M. Hossain, 2004: Effect of $CaCO_3$ (aragonite) saturation state of seawater on calcification of *Porites* coral. *Geochem. J.*, **38**, 613-621.

Orr, J.C., V.J. Fabry, O. Aumont, L. Bopp, S.C. Doney, R.A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, R.M. Key, K. Lindsay, E. Maier-Reimer, R. Matear, P. Monfray, A. Mouchet, R.G. Najjar, G.K. Plattner, K.B. Rodgers, C.L. Sabine, J.L. Sarmiento, R. Schlitzer, R.D. Slater, I.J. Totterdell, M.F. Weirig, Y. Yamanaka and A. Yool, 2005: Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, **437**, 681-686.

Pandolfi, J.M., R.H. Bradbury, E. Sala, T.P. Hughes, K.A. Bjorndal, R.G. Cooke, D. McArdle, L. McClenachan and co-authors, 2003: Global trajectories of the long-term decline of coral reef ecosystems. *Science*, **301**, 955-958.

Pauly, D., J. Alder, A. Bakun, S. Heileman, K.H. Kock, P. Mace, W. Perrin, K. Stergiou, U.R. Sumaila, M. Vierros, K. Freire and Y. Sadovy, 2005: Marine fisheries systems. *Ecosystems and Human Well-being. Volume 1: Current State and Trends*, R. Hassan, R. Scholes and N. Ash, Eds., Island Press, Washington, District of Columbia, 477-511.

Paulay, G., L. Kirkendale, G. Lambert and C. Meyer, 2002: Anthropogenic biotic interchange in a coral reef ecosystem: a case study from Guam. *Pac. Sci.*, **56**, 403-422.

Pelejero, C., E. Calvo, M.T. McCulloch, J.F. Marshall, M.K. Gagan, J.M. Lough and B.N. Opdyke, 2005: Preindustrial to modern interdecadal variability in coral reef pH. *Science*, **309**, 2204-2207.

Puotinen, M.L., 2006: Modelling the risk of cyclone wave damage to coral reefs using GIS: a case study of the Great Barrier Reef, 1969-2003. *Int. J. Geogr. Inf. Sci.*, **21**, 97-120.

Precht, W.F. and R.B. Aronson, 2004: Climate flickers and range shifts of coral reefs. *Front. Ecol. Environ.*, **2**, 307-314.

Ramessur, R., 2002: Anthropogenic-driven changes with focus on the coastal zone of Mauritius, south-western Indian Ocean. *Reg. Environ. Change*, **3**, 99-106.

Raven, J., K. Caldeira, H. Elderfield, O. Hoegh-Guldberg, P. Liss, U. Riebesell, J. Shepherd, C. Turley and A. Watson, 2005: Ocean acidification due to increasing atmospheric carbon dioxide. Policy Document 12/05, The Royal Society, The Clyvedon Press Ltd, Cardiff, 68 pp.

Riegl, B., 2003: Climate change and coral reefs: different effects in two high-latitude areas (Arabian Gulf, South Africa). *Coral Reefs*, **22**, 433-446.

Reynaud, S., N. Leclercq, S. Romaine-Lioud, C. Ferrier-Pages, J. Jaubert and J.P. Gattuso, 2003: Interacting effects of CO_2 partial pressure and temperature on photosynthesis and calcification in a scleractinian coral. *Global Change Biol.*, **9**, 1660-1668.

Roberts, C.M., C.J. McClean, J.E.N. Veron, J.P. Hawkins, G.R. Allen, D.E. McAllister, C.G. Mittermeier, F.W. Schueler, M. Spalding, F. Wells, C. Vynne and T.B. Werner, 2002: Marine biodiversity hotspots and conservation priorities for tropical reefs. *Science*, **295**, 1280-1284.

Rowan, R., 2004: Coral bleaching: thermal adaptation in reef coral symbionts. *Nature*, **430**, 742.

Sadovy, Y., 2005: Trouble on the reef: the imperative for managing vulnerable and valuable fisheries. *Fish Fish.*, **6**, 167-185.

Sano, M., 2004: Short-term effects of a mass coral bleaching event on a reef fish assemblage at Iriomote Island, Japan. *Fish. Sci.*, **70**, 41-46.

Sheppard, C.R.C., 2003: Predicted recurrences of mass coral mortality in the Indian Ocean. *Nature*, **425**, 294-297.

Sheppard, C.R.C., D.J. Dixon, M. Gourlay, A. Sheppard and R. Payet, 2005: Coral mortality increases wave energy reaching shores protected by reef flats: examples from the Seychelles. *Estuar. Coast. Shelf S.*, **64**, 223-234.

Spalding, M.D. and G.E. Jarvis, 2002: The impact of the 1998 coral mortality on reef fish communities in the Seychelles. *Mar. Pollut. Bull.*, **44**, 309-321.

Szmant, A.M., 2001: Why are coral reefs world-wide becoming overgrown by algae? 'Algae, algae everywhere, and nowhere a bite to eat!' *Coral Reefs*, **19**, 299-302.

Trenberth, K.E., P.D. Jones, P.G. Ambenje, R. Bojariu, D.R. Easterling, A.M.G. Klein Tank, D.E. Parker, J.A. Renwick, F. Rahimzadeh, M.M. Rusticucci, B.J. Soden and P.-M. Zhai, 2007: Observations: surface and atmospheric climate change. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, Eds., Cambridge University Press, Cambridge, 235-336.

Turley, C., J. Blackford, S. Widdicombe, D. Lowe and P. Nightingale, 2006: Reviewing the impact of increased atmospheric CO_2 on oceanic pH and the marine ecosystem. *Avoiding Dangerous Climate Change*, H.J. Schellnhuber, W. Cramer, N. Nakićenović, T.M.L. Wigley and G. Yohe, Eds., Cambridge University Press, Cambridge, 65-70.

Villanueva, R., H. Yap and N. Montaño, 2006: Intensive fish farming in the Philippines is detrimental to the reef-building coral *Pocillopora damicornis*. *Mar. Ecol.–Prog. Ser.*, **316**, 165-174.

Vunisea, A., 2003: Coral harvesting and its impact on local fisheries in Fiji. *SPC Women in Fisheries Information Bulletin*, **12**, 17-20.

Webster, P.J., A.M. Moore, J.P. Loschnigg and R.R. Leben, 1999: Coupled ocean–temperature dynamics in the Indian Ocean during 1997-98. *Nature*, **401**, 356-360.

Whittingham, E., J. Campbell and P. Townsley, 2003: *Poverty and Reefs*. DFID-IMM-IOC/UNESCO, Exeter, 260 pp.

Wilkinson, C.R., 2002: *Status of Coral Reefs of the World*. Australian Institute of Marine Science, Townsville, 388 pp.

Wilkinson, J.W., 2004. *Status of Coral Reefs of the World*. Australian Institute of Marine Science, Townsville, 580 pp.

Willig, M.R., D.M. Kaufman and R.D. Stevens, 2003: Latitudinal gradients of biodiversity: pattern, process, scale, and synthesis. *Annu. Rev. Ecol. Evol. Syst.*, **34**, 273-309.

Willis, B.L., C.A. Page and E.A. Dinsdale, 2004: Coral disease on the Great Barrier Reef. *Coral Health and Disease*, E. Rosenberg and Y. Loya, Eds., Springer, Berlin, 69-104.

Woodroffe, C.D. and R.J. Morrison, 2001: Reef-island accretion and soil development, Makin Island, Kiribati, central Pacific. *Catena*, **44**, 245-261.

Woodroffe, C.D., M. Dickson, B.P. Brooke and D.M. Kennedy, 2005: Episodes of reef growth at Lord Howe Island, the southernmost reef in the southwest Pacific. *Global Planet. Change*, **49**, 222-237.

Wooldridge, S., T. Done, R. Berkelmans, R. Jones and P. Marshall, 2005: Precursors for resilience in coral communities in a warming climate: a belief network approach. *Mar. Ecol.–Prog. Ser.*, **295**, 157-169.