Topic 5: Climate change

This short session centred on the effects of global warming and sea-level rise on coral systems, in Bermuda, the Caribbean and the Indian Ocean, with a contribution on the effects of sea-level rise, storm increase and erosion on breeding seabirds in Bermuda.

It had originally been planned to include also contributions from the Antarctic, high temperate latitudes and a global overview, but these latter were not available in the event. Nevertheless, the presentations given cover large topics of major importance.

Chaired by: Martin Drury, UKOTCF (right); and Lynda Varlack, BVI Government Conservation & Fisheries Department (left)

Scientific overview of climate change implications as it relates to small islands

Nicholas R. Bates, Craig Carlson, Dennis Hansell, Rod Johnson, Debbie Steinberg & Tony Knap, Bermuda Biological Station for Research

The presentation addresses physical and biogeochemical variability in the North Atlantic Ocean, using perspectives from two long-term oceanographic time-series, Hydrostation S (1954-present) and the U.S. JGOFS Bermuda Atlantic Time-series (BATS) site (1988-present). It focuses on linkages between modes of climate variability (e.g., NAO/ENSO and ocean biogeochemistry). Effects on coral reef ecosystems addressed include coral bleaching and changes in ocean chemistry.

Dr Nick Bates, Bermuda Biological Station for Research
nick@bbsr.edu

Acknowledgements

Background

Ecosystems in the recent past are effectively in the geological period of the Anthropocene
- domination of ecosystems by *Homo sapiens.* This species is prolific at biogeochemical (BGC) recycling. This too can lead to ecosystem shifts.

H. sapiens traits:
- top competitor for space (urbanization)
- effective predator (overfishing)
- prolific biogeochemical (BGC) recycler (C, N, P, H20 cycles)
- symbiotic relationships with other species (ranching, habitat protection)

Ecosystem responses:
- habitat loss
- food web adjustment to ecosystem shift
- ecosystem shift: atmospheric CO_2 higher than past 105–106 years
- habitat gain/loss

Importance of Coral Reefs

Although interested in the response of ecosystems in general to climate change, we focus on coral reefs, because:
1. Reefs are important marine ecosystems
2. Important for fisheries; in developing countries, they contribute about 25 percent of the food catch, providing food to one billion people in Asia alone
3. Marine biodiversity; they offer great promise for pharmaceuticals now being developed as possible cures for cancer, arthritis, human bacterial infections, viruses and other diseases
4. Buffer adjacent shorelines from wave action
5. They represent an ecosystem that is in rapid decline
   - 25% of all reefs are considered gone
   - about half of these were lost due to climate change

Many ecosystems, particularly coastal ecosystems, are facing problems similar to those that reefs are facing

Coral reefs are in crisis because of:

1. Pollution from poor land use, chemical loading, marine debris, and invasive alien species.

Reef Ecosystem Shifts in Jamaica

Slide modified from: J. Kleypas, NCAR

drastic reductions of the herbivores – the animals that grazed down the fleshy algae. High biodiversity on reefs usually means that when one functional species is removed – here, the herbivorous fish – another species can fill that position. Once the fish were removed, the task of keeping the algae grazed down fell on the backs of the sea urchin, and they grew in numbers and managed the job. However, a mysterious disease wiped out this species throughout the Caribbean, which left the reef without any grazers, and the Jamaican reef shifted from being coral-dominated to being algal-dominated

2. Over-fishing and related harm to habitats by fishing gear and marine debris.
3. Destructive fishing practices (such as cyanide and dynamite fishing).
4. Dredging and shoreline modification.
5. Disease outbreaks that are increasingly prevalent in reef ecosystems.
6. Global climate change and associated impacts (such as coral bleaching, more frequent storms and rise in sea level).

The illustration above shows the sequence of events on Jamaican reefs. The Jamaican reefs in the 1960s probably looked something like this – high coral cover. Overfishing on these reefs resulted in

This diagram (below) illustrates potential effects of increased atmospheric CO_2 on reefs. Solid lines show the most direct effects (e.g. changes in seawater chemistry are irrefutable). Dashed lines show less certain (albeit not necessarily less important) effects (e.g. increases in temperature). Dotted lines show effects which could happen, but are less directly caused by atmospheric CO_2. This talk focuses on seawater chemistry effects. Here, unlike arguments about whether increased CO_2 will lead to increases in temperature, one does not have to argue over whether seawater chemistry will change.
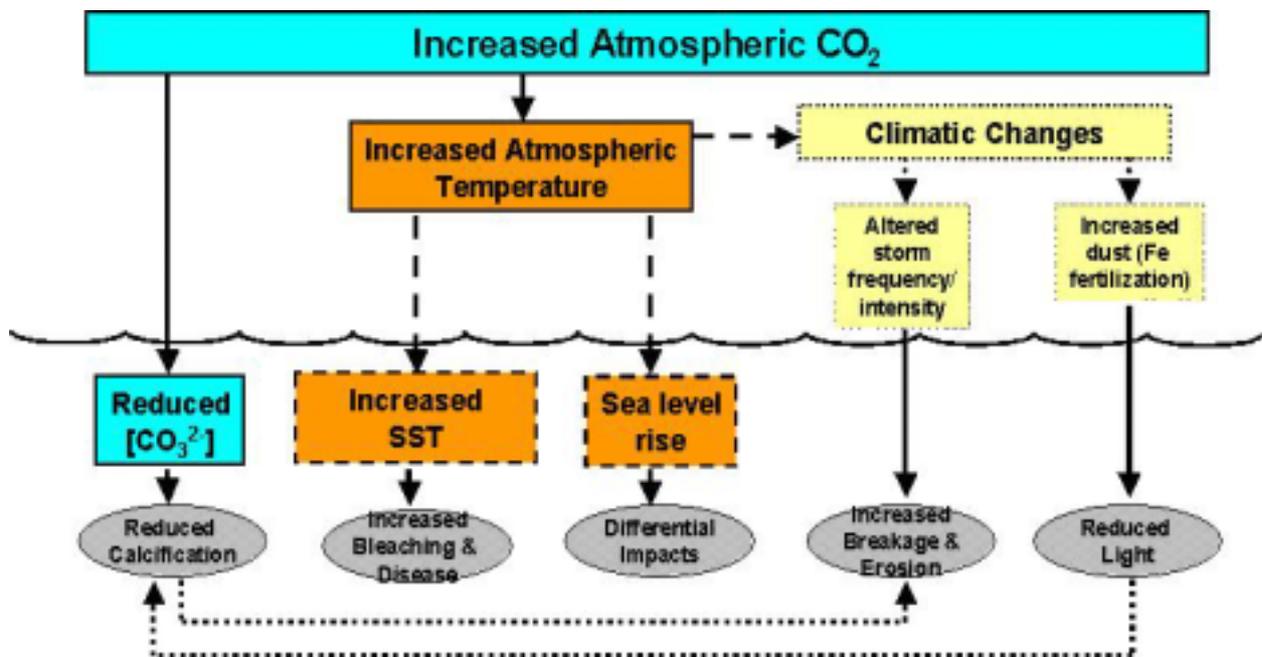
Coral Bleaching

There has been a dramatic increase in coral bleaching since the 1980s; 15% were destroyed in 1997-98. There is a lack of historical data:
- No written or folklore records of 'white reefs'

And a lack of paleontological data:
- No bleaching signal in coral skeletons
- Large scale die-offs not evident in geological records

To monitoring coral-bleaching:
- NOAA-NESDIS monitoring 24 reef sites at present.
- NOAA-NESDIS monitoring global SST for hot-spots, and early warming.

The diagrams below show in blue the surface sea temperatures throughout 2002 and early 2003 in Bermuda (above) and the Virgin Islands (below). The red line shows the threshold for coral-bleaching. The potential was high in Bermuda in 2002. In the Virgin Islands, there was no potential from SST for bleaching in 2002, although there was not much leeway.

Future Coral Bleaching

Climate questions:
1. How much will SST rise?
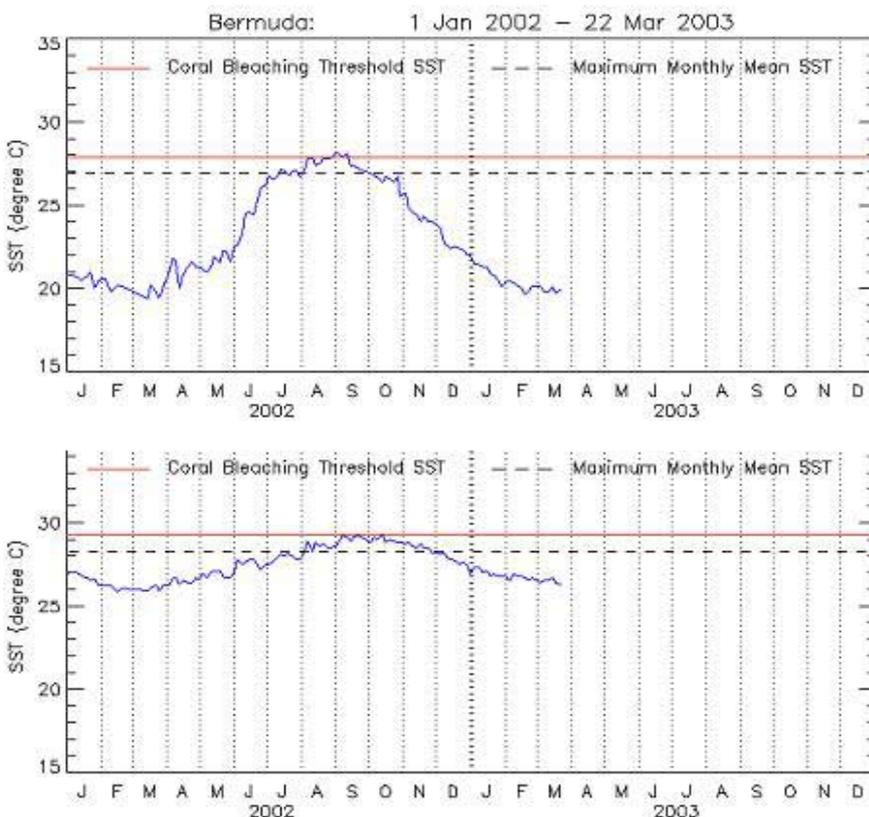
- future CO_2 rise
- accuracy of models
- future variability
- thermostat hypothesis
- future El Niño intensity/frequency

2. How fast will SST rise?

Biology Questions
1. What is the thermal tolerance of corals?
- geographical variation
- species - species variation
- within-species variation

2. How fast can species adapt?
- acclimatization
- "adaptive bleaching"
- Darwinian adaptation

3. Ecosystem effects

Mass bleaching events occur in El Niño years, so that important points are:
1. Rate of temperature rise versus rate of adaptation
2. Role of temperature variability - are corals from more variable environments better adapted?
3. Role of steady rise in average temperature.

Effects of CO_2 on Coral Reefs

First, we address some of the science about how CO_2 levels are affecting seawater chemistry, and particularly how altered carbonate ion concentration will affect calcification in reef organisms

Atmospheric CO_2 will almost certainly reach twice pre-industrial levels, even if we manage to halt any further emission increases (illustratation at top of next page). Timing of when we will reach double CO_2 varies, but most models point to around 2065. Some researchers carry this further to show that we could indeed reach 3 x CO_2 by the end of

From IPCC, 2000

From Wigley, 2000
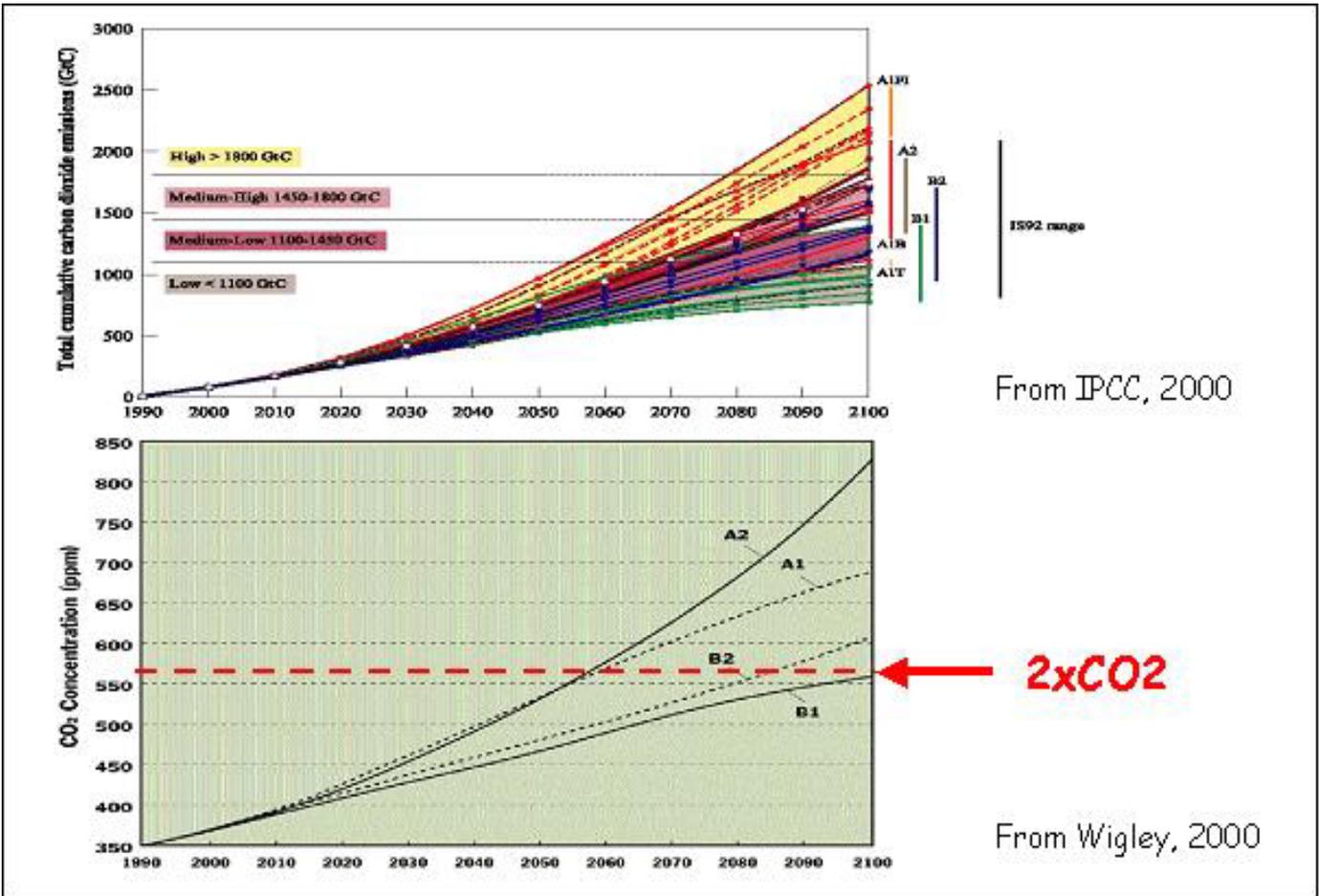
the century.

The main issue that we will address in this talk has to do with more or less direct effects of atmospheric CO_2 on reefs, starting with some background on the historical records of CO_2 concentrations. The top diagram low on the page is the CO_2 record from the Vostok ice core. This record is considered very accurate since it measures CO_2 concentrations fairly directly. The value over the last 420 thousand years has fluctuated between 180 and 300 ppmv. The middle panel is the CO_2 records as derived from boron isotopes in foraminifera. This is a less robust record, still it indicates that CO_2 levels have remained below 500 ppmv for the last 24 million years. The lower panel represents CO_2 concentrations estimated by the model GEOCARB III, which is based
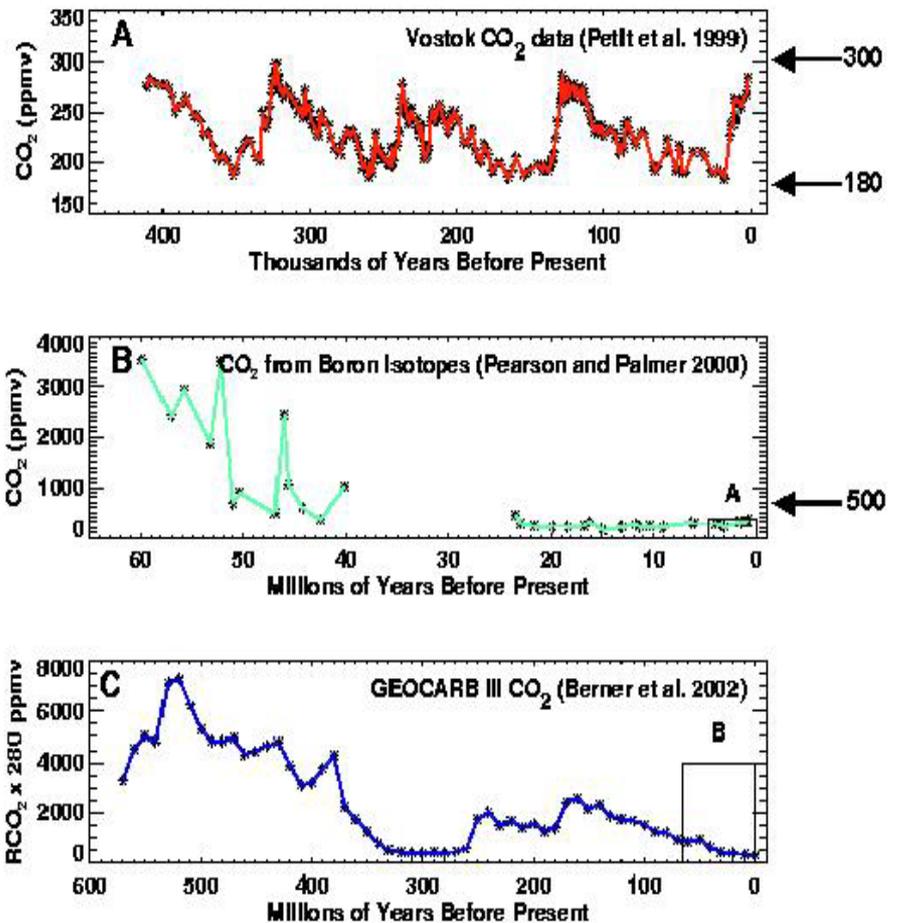
on a suite of inputs. The point of this illustration is that ecosystems of today evolved under relatively low CO_2 levels for at least 1/2 million years and probably for many millions of years.

This increase is unprecedented on human time-scales. "Present-day atmospheric burdens of these two important greenhouse gases [CO_2 CH_4) seem to have been unprecedented during the past 420,000 years" (Petit *et al.* 1999). Pearson & Palmer (2000) used boron-isotope ratios in forams to estimate pH of surface seawater, and reconstructed atmospheric CO_2 over the last 60 million years: "Since the early Miocene (about 24 my ago, atmospheric CO_2 concentrations appear to have remained below 500 ppm and were more stable than before, although transient intervals of CO_2 reduction may have occurred during periods of rapid cooling approximately 15 and 13 my ago."

It is certainly difficult to assert here that there is a relationship between past CO_2 levels and reef development (although some have proposed this in the past). However, this fact is interesting to note.

This diagram illustrates how increases in atmospheric CO_2 alter seawater chemistry.
As CO_2 is driven into the ocean, it quickly forms carbonic acid, which is a weak acid. Most of this rapidly dissociates to either HCO_3^- or CO_3^{2-}.

Alkalinity is the excess of positive ions in seawater.

This excess positive charge is balanced by the proportion of HCO_3^- to CO_3^{2-}. If more negative charge is needed, then some of the HCO_3^- is converted to CO_3^{2-}, and if less is needed, then some of the CO_3^{2-} is converted to HCO_3^-. As a first approximation, the carbonate ion concentration can be estimated as the alkalinity - total CO_2 concentration. In terms of how adding CO_2 changes the equation, one can easily see that by adding CO_2, the total CO_2 increases (note that this does not alter the alkalinity), and hence the carbonate ion concentration will go down. Also shown in this picture are the processes of photosynthesis/respiration and calcification. Photosynthesis/respiration alters the total CO_2 concentration, while calcification alters both the total CO_2 concentration and the alkalinity

This illustrates the kind of changes one might expect under double CO_2 conditions. Note that although the total CO_2 increases, the carbonate ion concentration goes down. Note also the decrease in aragonite saturation state. This calculation does not take into account any increase in temperature (this will be covered later)

The illustration at the top of the next page shows how the ratios of the various ions change in

CO_2 Chemistry in Seawater

	1xCO_2	2xCO_2	
CO_2	280	560	
CO_2 aq ($CO_2 + H_2O$) / H_2CO_3 Carbonic acid	8	16	
bicarbonate $HCO_3^- + H^+$	1635	1867	
carbonate $CO_3^{2-} + H^+$	272	177	
	1915	2061	TCO_2
	8.17	7.93	pH
	4.3	2.8	Ω-arag

$$\Omega = [Ca^{2+}][CO_3^{2-}]/K_{sp}$$
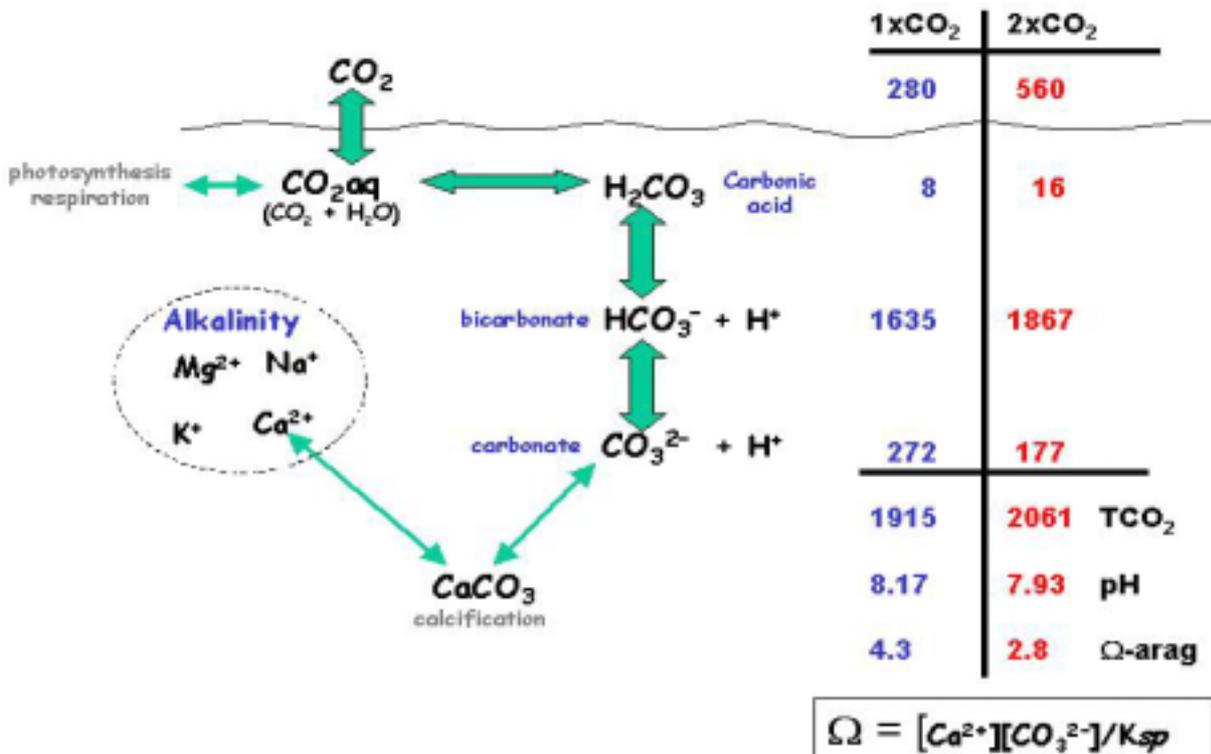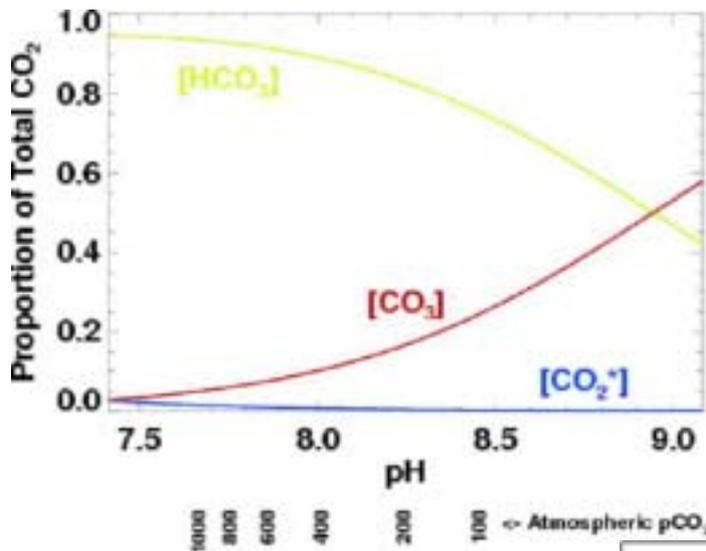
of sea surface temperature (SST) (below), are indeed remarkable similar. This confounds the issue of what controls the distribution of reefs (black dots on temperature map) - could aragonite saturation state have anything to do with where reefs occur?

By the middle of this century, we might be looking at a 20-30% reduction in calcification on reefs. Carbonate ion concentration is expected to decrease by about 30% as atmospheric CO_2 concentration doubles that of the pre-industrial. This takes into account both increases in CO_2 and 2°C warming

response to increases in atmospheric CO_2. As atmospheric CO_2 increases, more CO_2 is driven into seawater and pH is lowered. Also, the relative concentrations of carbonate and bicarbonate ions shift.

Temperature has an additional effect on carbonate equilibria. Warm water holds less CO_2 than cold water, and so the CO_3^{2-} concentration in warm waters is higher than it is in cold waters. So colder water has lower carbonate ion concentration than warmer water. The net effect is that a 2°C warming lessens the effect by about 10%

To stress the importance of temperature, two plots, one of saturation state (right) and the other
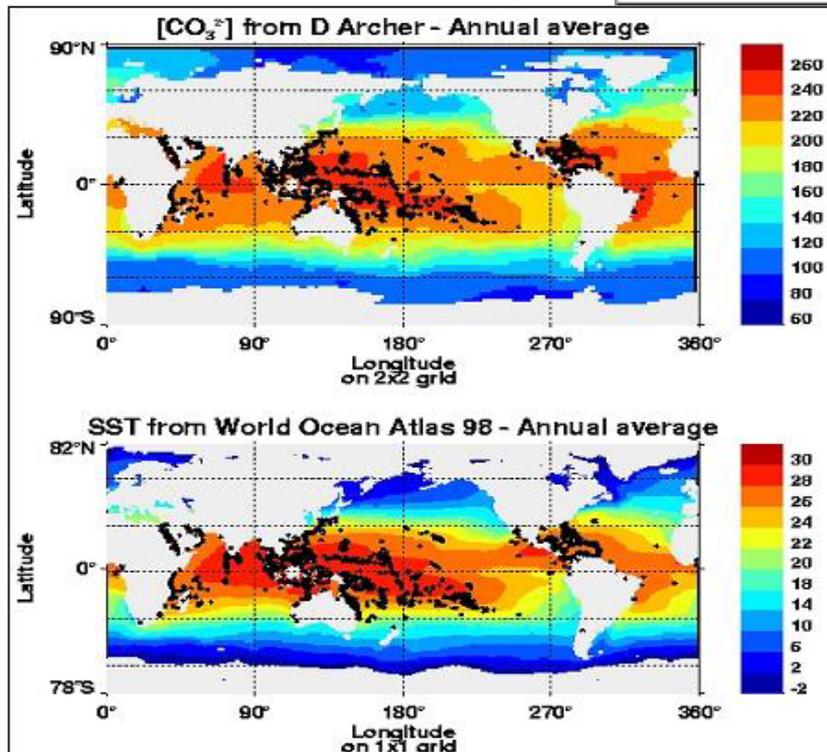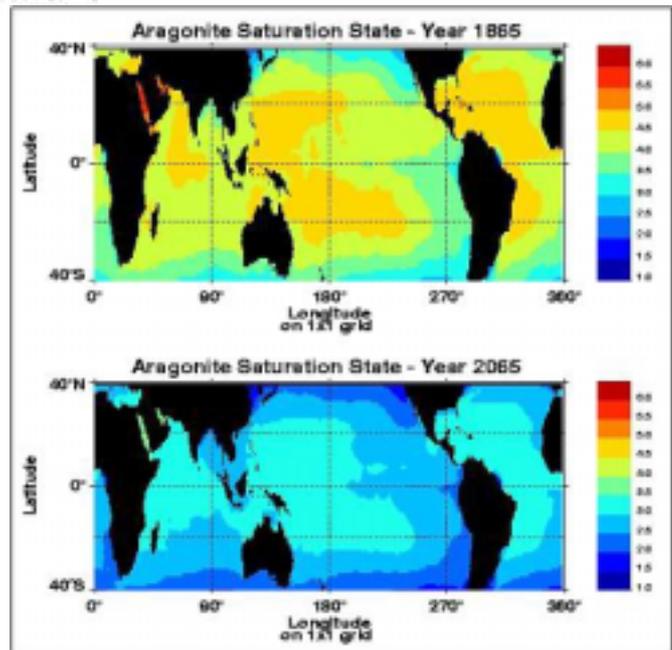
(assuming a uniform 2°C warming). Experiments performed by Chris Langdon and others demonstrate that calcification in corals and coralline algae is likely to decrease by about 15-30% over this same time period.

Hypothesis: reef $CaCO_3$ production will decrease by 15–30% under doubled pCO_2 conditions.

Supporting/refuting evidence:
• Aquarium/mesocosm experiments
• Coral cores - Lough & Barnes (1997) did not detect long-term decrease in calcifica-

tion in GBR *Porites* cores
- Current reef distribution (saturation state strongly correlated with temperature)
- Field evidence? (difficult to obtain)
  - Geologic record (corals existed during periods thought to have high pCO_2, but did not build reefs)
  - Distribution of inorganic $CaCO_3$ - marine cements/ooids.

Effects of doubled CO_2 on calcification

Organism/ System	Manipulation	% Calc. Decrease	Reference
Corallina	1	-44	Gao 1993
Porolithon	2	-25	Agegian 1985
Amphiroa	3	-36	Borowitzka 1981
Turbinaria	2	-15	Marubini *et al.* (in press)
Stylophora	2	-15	"
Goniastrea	2	-16	"
Acropora	2	-18	"
Porites	2	-18	"
	1	-19	Marubini *et al.* 2001
Acropora	2	-37	Schneider & Erez 2000
Porites	2	-27	Marubini & Atkinson 1999
Porites/Montipora	2	-51	Langdon & Atkinson (in prep)
Montipora	3	-22	Langdon (in press)
Gr. Bahama Banks*	4	-82	Broecker & Takahashi 1964 Broecker *et al.* 2001
B2 mesocosm*	1,3,4	-54	Langdon *et al.* 2000
Monaco mesocosm	1	-21	Leclercq *et al.* 2000

* dominated by coralline algae
Modified from: J. Kleypas, NCAR

The third column represents the percentage change in calcification rate by doubling the pre-industrial CO_2 concentration. Regardless of how the system is manipulated, all experiments have shown a decrease in calcification rate. The first thing to notice is that the algae (HMC) seem to show a stronger response to changes in carbonate chemistry. The corals tend to show a somewhat lower response

Hypothesis: dissolution of sedimentary $CaCO_3$, in response to increased pCO_2 and lowered pH, will adequately buffer water column chemistry

Evidence:
- Demonstrated (used) in marine aquaria. Flow of water through system enhances dissolution of carbonates and maintains equilibrium
- Over time-scales of deep ocean circulation, dissolution of deep-sea carbonates does buffer ocean system, although equilibrium would not be reached for 5000-6000 years (Archer *et al.* 1998)

Question: How rapidly can sediment dissolution buffer surrounding water column?
- effects of water residence time
- effects of sediment porosity, grain size, etc

Hypothesis: increasing pCO_2 in ocean will fertilize zooxanthellae, thus increasing coral growth rates

Reasoning:
- Zooxanthellae known to increase coral calcification/production ("super-corals" *sensu* Benson 1984)
- Anything that enhances zooxanthellae growth should also enhance calcification

Evidence:
- Zooxanthellae in corals use HCO_3^- rather than CO_2
- Increase in zooxanthellae growth does not necessarily enhance coral growth (e.g. increased nutrients enhances zooxanthellae growth and compete with corals for carbon - Marubini *et al.* 1999)

Future strategies

- Better determination of reef carbonate budgets
  - how much $CaCO_3$ corals precipitate
  - how much dissolves
  - how much exported, etc
- Better determination of light/temperature/ CO_3^{2-} controls on coral calcification
- Resolving coral biochemistry questions (ion transport mechanisms ?)
- Field experiments (e.g. need marine equivalent of terrestrial FACE program ?)

Table   Factors in the Rise and Fall of Sea Level in the Twentieth Century (in centimeters)

	Best estimate	Possible range
Thermal expansion		
Surface water	+5	+1.5 to +7
Deep water	?	?
Melting of land ice		
Mountain glaciers	+3	+2 to +4.6
Antarctic ice	?	−10 to +13
Greenland ice	+2.5	+2.3 to +2.5
All factors	+10.5	−4 to +27
Observed sea level rise	+15	+12 to +20

Major question:
Increased sea level rise. Will coral growth keep up?

Other effects

Increasing Frequency of Hurricanes?
Greenhouse Effects?

Conclusions

- changes in ocean chemistry <u>will</u> significantly impact coral reefs.
- calcification will decrease in the future.
- there may be more bleaching events associated with global warming.

References

IPCC *Emissions Scenarios. Summary for Policymakers.* A special report of IPCC Working Group III. IPCC, 20pp (based on SRES report below).

Pearson & Palmer 2000. Atmospheric carbon dioxide concentrations over the past 60 million years. *Nature*

Petit *et al.* 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature*

SRES - *Special Report on Emissions Scenarios*, SRES, IPCC, 2000.

Wigley, T.M.L. 2000. *The science of climate change: global and U.S. perspectives.* Pew Center on Global Climate Change. 48pp.

British Indian Ocean Territory – the Fate of Small Coral Islands: trends of temperature and sea-level rise

Charles Sheppard, Friends of the Chagos & Warwick University

Four years after most corals died on the central Indian Ocean reefs of Chagos, the erosion of dead corals that followed has removed most branching forms and has eroded the surfaces of most others. Some reef surfaces just below low sea level have 'dropped' 1.5 m. Juvenile corals are abundant, though most settlement is occurring on eroding table corals or other unstable substrates, and are of less robust species.

Rising temperature will result in recurring mortality events, and the probability of this will increase very rapidly from about 2015. Sea levels are predicted to rise by 5-20 cm in this region by 2020. Erosion of some sections of rim, normally usually rising to only about 1-2 metres above high sea level, is already taking place.

It is concluded that at present erosion is 'winning' over new growth. Increased recruitment could reverse this, although only if no further mortality occurs caused by repeat warming episodes. Although the islands have high rainfall, their vegetation depends on the continued existence of their fresh water lenses, which will increasing become threatened as sea level rises and as rising temperature continues to kill the corals of these reefs.

Dr Charles Sheppard, Department of Biological Sciences, University of Warwick, Coventry CV4 7AL, UK. csheppard@bio.warwick.ac.uk

This focuses on the islands and reefs of British Indian Ocean Territory (Chagos), though it applies to most low coral islands in this region.

Four years after most corals died on the central Indian Ocean reefs of Chagos (Fig 1), erosion and recovery have been studied to 30 m depth. Mortality from the warming event was very high to 15 m deep in northern atolls, and was very high to >35 m deep in central and southern atolls; coral cover fell from an average of 50-70% to less than 5% in most places. Some lagoonal areas lost only half of their corals. The erosion of dead corals that followed has removed most branching forms and has eroded the surfaces of most others (Fig 2); bioerosion is high, and sandy and rubble chutes are visible, carrying volumes of

Figure 1. The seaward reef slopes in Chagos, before and after the 1998 warming.
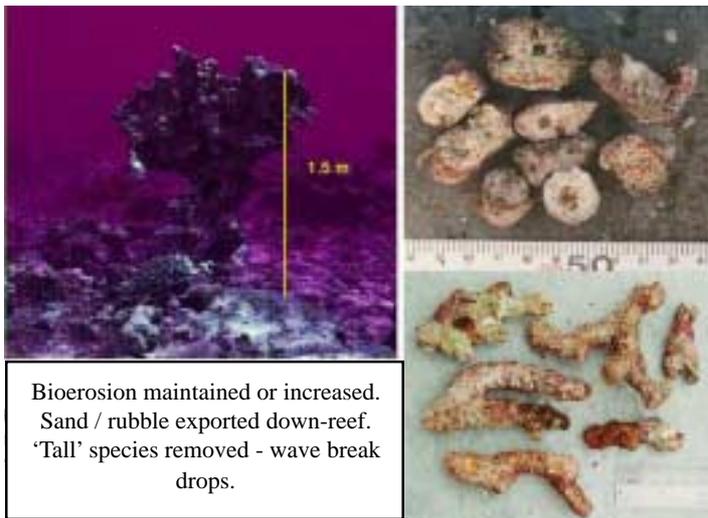
Bioerosion maintained or increased. Sand / rubble exported down-reef. 'Tall' species removed - wave break drops.

Figure 2. Erosion of the protective seaward corals. The 'stump' shows how tall these corals were (left). Right: erosion and 'hollowing out' of fragments of corals killed in 1998.

unconsolidated rubble may provide a difficult place for coral settlement. Juvenile corals are abundant, though most settlement is occurring on eroding table corals or other unstable substrates, and are of less robust species.

New temperature (SST) data sets have blended historical and forecast temperatures, producing a series of monthly SST data from 1871 to 2099 (Fig 4). The critical SST in Chagos causing the mortality was 29.9°C, and mean SST has risen 0.65°C since 1950. Rising temperature will result in recurring mortality events, and the probability of this will increase very rapidly from about 2015 (Fig 5). Corals need about 5 years from settlement to reach reproductive age, and

coral debris off the reef and into deep water. Some reef surfaces just below low sea level have 'dropped' 1.5 m due to the loss of their dense thickets of branching coral *Acropora palifera*.

The islands are protected from erosion by three main features: the seaward shallow corals, the algal ridge, and the broad shallow reef flat (Fig 3). Coral bioerosion is substantial, reducing 3-D reef 'structure' and making a habitat which is less conducive to maintaining a high biodiversity, and the
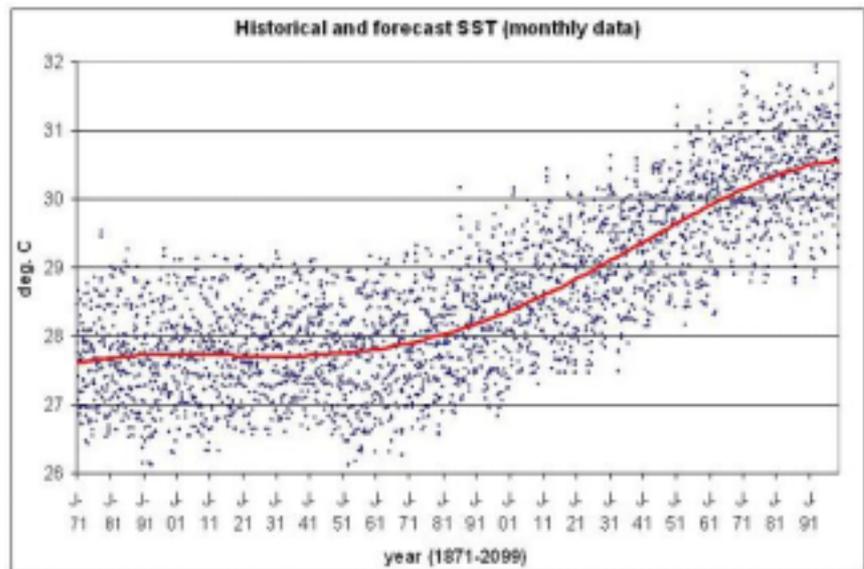
Figure 4. SST curve for Chagos from 1871 to 2099.

most grow very slowly, so with recurring mortality events from rising SST recovery is questionable and increasingly unlikely.

Sea levels are predicted to rise by 5-20 cm in this region by 2020 (Fig 6). The short data set that exists shows that in the 1980s sea level rose

Figure 3. Aerial view of Salomon atoll showing the three wave-protecting 'protective barriers' to erosion:
1. Shallow, 'rough water' corals; 2. Reef crest;
3. Extensive reef flat at low water level.
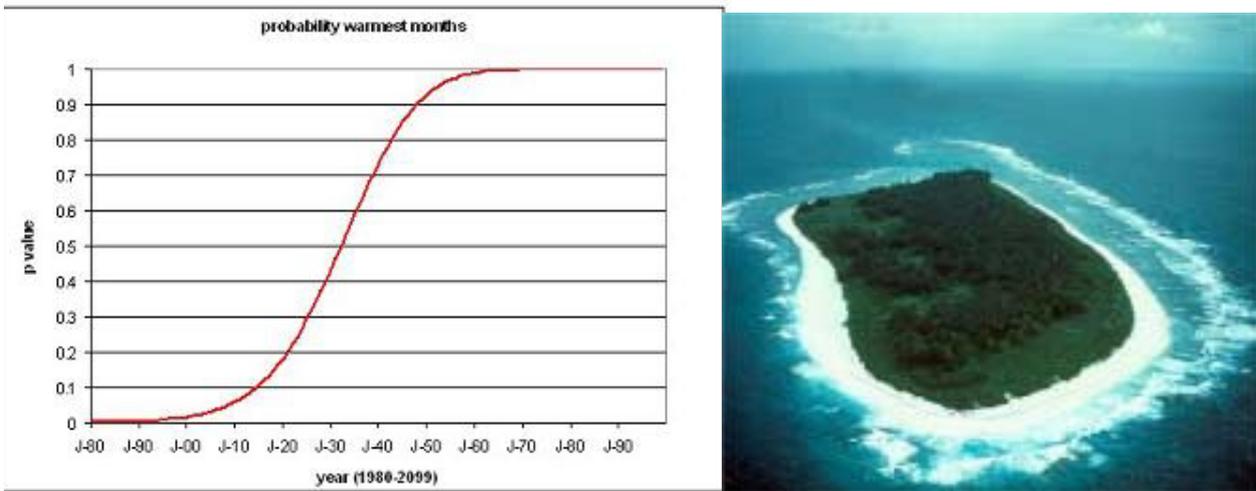
Figure 5. Probability of recurrence of a 1998 SST temperature in Chagos.

about 5.5 mm per year. Although this is a short series, it matches closely those of adjacent areas, such as the Maldives.

Profiles across several coral islands shows that most islands have a depression in their middle, which dips to present sea level or below. A higher 'rim' surrounds most, and this rim extends usually to about 1-2 metres above high sea level (Fig 7). Erosion of some sections of rim is already taking place.

Figure 6. Sea level trace for the Chagos archipelago.

It is concluded that at present erosion is 'winning' over new growth. Increased recruitment could reverse this, although only if no further mortality occurs caused by repeat warming episodes. Given the general 'Brunn rule' for sandy beaches (which says that horizontal erosion proceeds at about 150 times the vertical rise in sea level), at least 1 metre of horizontal beach erosion may be lost to erosion each year. As sea level rises, the possibility of sea water intrusion, and of island rim breaching, are clearly significant. Although the islands have high rainfall, their vegetation depends on the continued existence of their fresh water lenses, which will increasing become threatened as sea level rises and as rising SST continues to kill the corals of these reefs.
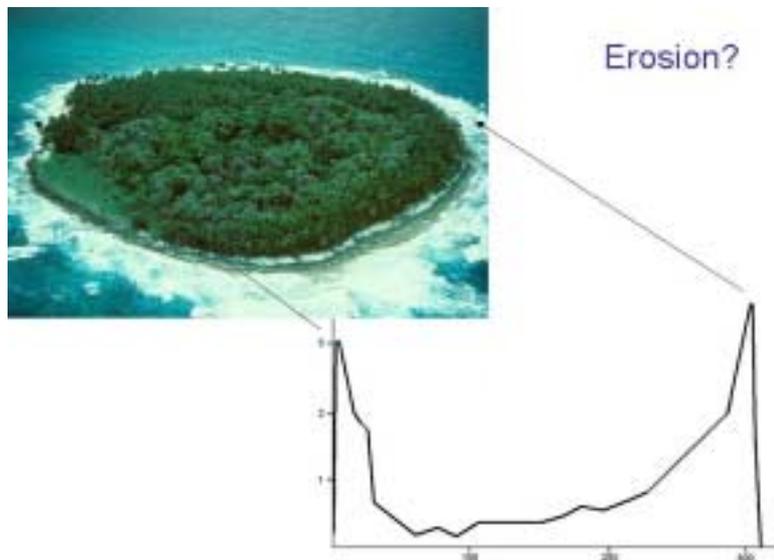
Figure 7. Profile across one island (North Brother, Great Chagos Bank) with photo of the island.

Implications of global warming and sea-level rise for coastal nesting birds in Bermuda

David B Wingate and Patrick Talbot

Evidence from tide gauge and tectonic measurements world wide suggests that absolute sea level rose by approximately 20cm during the 20th century, but the rate of rise is accelerating and may attain 5mm/yr in the 21st century. This may be the highest rate recorded since the advent of human civilization. Bermuda has long been recognized as a tectonically stable platform and has been used as a benchmark for measuring glacial eustasy. Our own tide gauge measurements since 1930 support the global estimate.

This paper summarizes 50 years of subjective observations by the senior author on the effect of this sea level rise on mangrove, beach/dune and rocky coastal habitats and reviews additional objective research on mangroves. It also provides objective data on the impact of this rise on three species of seabirds which nest in the rocky coastal habitat - the habitat that comprises > 90% of Bermuda's coastline.

Two of the three species, the Bermuda petrel (Cahow) *Pterodroma cahow* and the white tailed tropicbird (Longtail*) Phaethon lepturus catesbyi* have suffered very significant effects, mostly within the last decade, and because both are highly philopatric, they are unlikely to relocate their breeding sites in time to avoid further harm.

The slowly increasing Cahow, is presently restricted to 4 tiny islets totalling < 1 ha. which are protected only partly from the open ocean by Bermuda's unique south shore boiler reefs. Between 1951 and 1995 the worst damage caused by storm waves or hurricane storm surge never affected more than two nesting sites at a time. Then in 1995 and again in 1999 storm surge from two major near-miss hurricanes completely over-washed two of the islets and caused severe erosion and cliff falls on the other two, trashing 40% of the nest-sites on both occasions The Cahow recovery team barely had time to repair the damage before the birds returned for their winter nesting season. Clearly, a direct hit category 3 or a late season hurricane at the beginning of the winter nesting season could be catastrophic. This rapidly growing threat results not only from sea level rise, but also from the predicted increase in frequency and severity of storms with global warming.

The tropicbird is Bermuda's most common coastally nesting seabird, with a breeding population estimated between 1500-2000 nesting pairs. Data from a survey of >200 marked nest sites in the Castle harbour island nature reserve, monitored by Wingate from 1973-1980 and resurveyed by Talbot beginning in 2001, has provided the greatest insight into the process and scale of nest site destruction/ creation, and the relative contribution of sea level rise, normal weathering and catastrophe events to this process.

From a global perspective, the threat to coastal nesting birds from sea level rise results indirectly from the sheer scale of anthropogenic development in coastal areas and our inevitable tendency to try and defend that development against sea level rise by the construction of coastal defences such as seawalls, sand replacement and landfill, rather than dismantling and retreating. By interposing our built environment and trying to hold the line against the natural landward pro-gradation of coastal

habitats that would otherwise occur, we are ultimately dooming both. This problem is already apparent along Bermuda's main island coastline where significant anthropogenic development has already occurred. In our attempts to defend this development from erosional encroachment, an increasing number of property owners are applying for planning permission to build concrete seawalls and other defences, which inevitably destroy the natural erosion cavities and cliff talus in which tropicbirds nest, not to mention the effects on the aesthetic beauty of our coastline. The Tropicbirds' nesting options are becoming increasingly constrained from above by human development and from below by sea level rise.

The only near-term option for helping both the Cahow and the Tropicbird has been to design and build *artificial* nesting cavities on the highest points of the islets and cliff tops in a manner that is safe both from sea-flooding and mammal predators. A longer-term project is being undertaken to attract the Cahow to nest on the much larger and higher predator-free Nonsuch Island.

Dr David Wingate, Bermuda Audubon Society, PO BoxCR86, Crawl, Bermuda CRBX. pennyhill@northrock.bm

Introduction: The Case For Global Sea-Level Rise

Data from tide gauges, satellite altimetry and measurements of tectonic uplift and subsidence taken worldwide suggest that, after a long period of near stasis in the late Holocene, global sea-level rise began accelerating again in the 19th century and rose by approximately 20 cm during the 20th century. The rate of rise is expected to at least double again during the 21st century. The most recent estimates from climate modelling range from 19 to 71cm with a central value of 49cm (Sterr 1998). This would be the highest sustained rate of rise since the advent of human civilization and, whether or not the cause is primarily anthropogenic as most scientists now believe, it will have profound implications for both wildlife and human populations that live on our coastlines.

Bermuda is one of the smallest and most remote oceanic islands in the world, located at 32°45'N and 64°17'W and with a land area of 57 km². It has long been recognized as a tectonically stable benchmark for measuring glacial eustasy as recorded in its Pleistocene carbonate sediments (Vacher & Hearty 1989). Bermuda's tide gauge measurements, recorded since 1932 (Barnett 1984, Pirazzoli 1986) are not surprisingly, therefore, consistent with the global estimate of sea-level rise.

Due to the even more rapid sea-level rise of the early Holocene, >4000 years ago, most of Bermuda's coastline is already erosional, comprised mainly of sea-cliffed aeolianite dunes of marine carbonate sediment in various stages of cementation and diagenesis. Coastal cliffs, or low rocky shores and islets, presently make up 93% of the coastline, beaches comprise approximately 6% and mangroves only about 1%.

This paper summarizes fifty years of subjective observations by the senior author on the effect of the recent accelerating sea-level rise on Bermuda's mangrove, beach/dune and rocky coastal habitats and reviews additional objective research on mangroves. It also provides specific information on the impact of this rise on three species of coastally nesting seabirds, all of which nest in the rocky coastal habitat.

Effects of Sea-Level Rise on Bermuda's Coastal Habitats

1) Mangrove Habitat
In a classic study of the effect of sea-level rise on the rate of formation or destruction of mangroves,

carried out at Hungry Bay mangrove swamp, Bermuda (Ellison 1993), it was demonstrated that "low island" mangroves, i.e. those without any input of estuarine sediment, build at a rate of only 7-9 cm per 100 years and that any sea-level rise in excess of this rate results in erosion and destruction.

Ellison measured and dated the mangrove peat profiles of Hungry Bay in relation to ordinance datum (mean present day sea-level). Mangrove peat forms between mean sea-level and high water mark and has been shown to be a definitive sea-level indicator (Ellison 1989). Hence the dated stratigraphy in Hungry Bay provides several points for sea-level reconstruction.

Her data show that sea-level was rising at 25cm/100yr before 4000BP, 6cm/100yr between 4000BP and 1200BP and up again to 14.3cm/100yr between 1200BP and the present. As the rate of mangrove peat formation only exceeded sea-level rise in the period between 4000BP and 1200BP the mangrove swamp has probably been retreating for the last 1200 years. The stratigraphy near the mouth of the swamp not only confirms this, but provides an actual measure of the loss, which is 2.24 acres, nearly one quarter of the original area of 8.5 acres. Moreover, there has been direct visual confirmation of this process occurring at an accelerating rate over the past four decades.

The situation with continental mangrove swamps, or their salt marsh equivalent, where estuarine sediment input permits a more rapid build up of peat (up to 18.8cm/100yr) is somewhat better, but nevertheless now below the present rate of sea-level rise. As the land gradients in these two habitats are extremely shallow, just a few centimetres of sea-level rise can result in many metres of landward erosion and inundation following the Bruun rule (Bruun 1962), which states that increased wave erosion with higher sea-level removes sediment from shore faces in the upper part of the tide range and re-deposits it in the lower part, typically resulting in low cliffing of the peat along the seaward margin of mangroves or salt marshes.

There have already been huge losses of marshland important to nesting and wintering water birds in Louisiana from this process (Gosselink & Baumann 1980, Childers & Day 1990). Bermuda's mangroves are very diminutive, however, and do not in any case provide exclusive nesting or feed-

ing habitat for any locally breeding species.

2) Beach/Dune Habitat

Bermuda's beach/dune habitat is more extensive than the mangrove habitat, primarily because the source material - carbonate sediments derived from the growth, respiration and decomposition of shallow water coral-reef and sea-grass communities and from re-cycled rubble and sand from coastal cliff erosion - has a much higher, and larger scale, depositional rate than mangrove peat in the tropical marine environment.

Although some sediment is lost through down-slope erosion off the edge of the Bermuda platform in storms and hurricanes, the generally high rate of sediment generation probably accounts for the fact that long-shore current derived beaches often front coastlines that are otherwise erosional, being backed by cliffs rather than beach dunes.

A high proportion of Bermuda's South Shore beaches are of this type and regularly wash away temporarily when major storms or hurricanes re-assert the long term erosional trend. As with mangrove swamps and salt marshes, erosion of beaches with sea-level rise follows the Bruun rule of landward pro-gradation, hence those beaches presently backed by cliffs will ultimately be lost.

This is not a good scenario for an island whose economy depends largely on tourism! Although beaches elsewhere are important as nesting habitat for certain shorebirds and terns, there are no present day beach nesting species in Bermuda.

3) Rocky Coastal Habitat

As indicated in the introduction, the rocky coastal habitat makes up more than 90% of Bermuda's coastline. Its ruggedly beautiful aspect is shaped by two fundamentally different erosional processes.

One is on-going and almost imperceptibly subtle and slow in its effect and includes wind abrasion, freshwater solution and bio-erosion under the general heading of "weathering". (The dark grey surface colour that develops on our otherwise white aeolianite is caused by a blue-green algae (cyanobacteria) that colonizes the surface.)

The other process is stochastic but catastrophic in scale and caused entirely by hurricane waves. Fifty years of personal observation has convinced the senior author that the macro features of our coastline - those jagged ledges, stacks and gullies and huge blocks of fallen cliff and rock talus - have been shaped by major catastrophe events occurring at rare intervals on the order of a century, or even several centuries apart. Weathering provides only an aesthetic veneer to those features.

Effects of Sea-Level Rise on the Coastal Nesting Seabirds

Common tern

The common tern *Sterna hirundo* with a current breeding population of only 25 pairs, (Wingate, unpublished data) nests only on small rocky islets

located within Bermuda's larger enclosed sounds and harbours where their sheltered location from ocean waves makes them safe from all but hurricanes. Interestingly, a unique bio-erosional notch threatens to topple a few of the smallest islets in Harrington Sound, but if sea-level rise accelerates as predicted, these and some others will be submerged during the 21st century. This need not necessarily be a problem for this non-philopatric species, which can readily move to new locations. However, because the Bermuda tern population tends to nest territorially, one pair per islet, the population might decline further if the number of nesting islets declines.

Bermuda petrel or Cahow

Of far greater concern is the endangered endemic Bermuda petrel or Cahow *Pterodroma cahow.* Pre-colonially this then super abundant seabird was an inland nester, excavating its burrows in soil under the forest. However, introduced mammal predators and human harvesting for food rapidly reduced it to the verge of extinction (Lefroy 1877). At the

time of its rediscovery in 1951 (Murphy & Mowbray 1951), it survived only on a few tiny predator-free off-shore islets totalling less than one hectare in area and comprised exclusively of rocky

coastal habitat. Lacking soil for burrowing, the Cahow was forced to occupy erosional crevices in the coastal cliffs where it came into nest-site competition with the much more common White-tailed Tropicbird (Wingate 1978). Despite these limitations, an intensive conservation effort employing defences against tropicbirds and the

open ocean by Bermuda's unique algal-vermetid "boiler" reefs (Ginsberg & Schroeder 1973).

construction of artificial burrows has enabled it to increase from 18 pairs in 1961 (when the *entire* breeding population first began to be monitored), to 65 pairs in 2003 (Wingate 1985 and unpublished data).

The Cahow's nesting islets at the mouth of Castle Harbour are protected only marginally from the

Consequently they are extremely vulnerable to over-wash and wave erosion in major storms and

hurricanes. Between their rediscovery in 1951 and 1989, however, the worst damage experienced never affected more than two nesting sites at a time. Hurricanes Dean and Gabrielle in 1989

caused damage to six of the nest sites. Then in 1995 and again in 1999, storm surge and ground swell from two major near-miss hurricanes, Felix and Gert, completely over-washed

two of the islets and caused major erosional damage to two others, trashing 40% of the nest sites on both occasions! The Cahow recovery team barely had time to repair the damage before the birds returned for their winter nesting season (Wingate 1995). These were category 2 and 3 hurricanes, which missed Bermuda by 40 miles and 125 miles respectively. Quite clearly a direct hit category 3 or 4, or a late season hurricane overlapping the beginning of the nesting season in late October or November, could be catastrophic. This rapidly growing problem results not only from sea-level rise but also from the predicted increase in the frequency and intensity of storms with global warming.

The Cahow is a very long-lived species with some breeding pairs occupying nest sites for 15 to 20 years before mortality disrupts them. They are also highly philopatric, with new pairs establishing closely adjacent to the pre-established pairs. Thus all of the population increase so far has been confined to the relic breeding islets. There is an urgent need to attract new pairs of Cahows to nest

on larger and higher predator-free islands and the Nonsuch "Living Museum" nature reserve was established in 1961 with this ultimate goal in mind (Wingate 1978, B. Cartwright, L. Nash and D. B. Wingate 2001). Techniques have already been developed elsewhere for attracting petrels to new islands (Bell 1996, Podolsky & Kress 1989) and we hope to begin implementing these for the Cahow as soon as possible.

White-tailed tropicbird or "Longtail"

The White-tailed tropicbird or "Longtail" *Phaethon lepturus catesbyi* is the only pre-colonial nesting seabird of Bermuda which has survived in substantial numbers, owing primarily to its

obligate cliff hole nesting niche which makes most of the nest sites inaccessible to the introduced mammal predators (Gross 1912). Like the Cahow,

it is a long-lived and highly philopatric species with some breeding pairs occupying nest sites for ten or more years before mortality disrupts them. An estimated 2000 breeding pairs still breed along most of the main island coastline and adjacent islets, but they are declining gradually for a number of anthropogenic reasons apart from the effects of sea-level rise. These include dog, cat, rat and American crow predation; competition from cliff nesting feral pigeons; coastal development by man; and block-age of nest sites by dumped vegetation and trash, or overgrowth by invasive alien plants (Wingate unpublished data).

The Castle Harbour national park islands are free of the foregoing problems but subject, like the Cahow islets, to ocean swells. This paper reviews data from a 200+ nest site study there; this was carried out by Wingate from 1970 to 1983, and revisited 20 years later by Talbot, beginning in 2001.

As the emphasis of this survey was on nest site parameters and breeding success, rather than biometrics, and tropicbirds tend to be more sensi-tive to human disturbance than Cahows or terns, the methodology was designed to be as non-invasive as possible. Birds were not handled or ringed and nests were checked only in late after-noon or at night when the birds were less active or sleeping.

As incubation lasts 43 days and fledging approxi-mately 60, once monthly checks were determined to be adequate for confirming success or failure in more than 95% of cases. Birds remaining on nests overnight were assumed to be brooding an egg or chick even if the latter were not visible (chicks are brooded for about 20 days). The final nest check was timed to be as close to fledging stage as possible. Nest failures were usually confirmable by the presence of broken eggshell or a dead chick or by their disappearance well before hatching or fledging time. Nests which still contained healthy looking chicks close to fledging age were assumed

to be successful if vacant on a subsequent check.

This survey has so far provided the clearest insight into the process, and scale, of nest-site destruction and creation resulting from normal weathering, catastrophe events, and sea-level rise, respectively.

Tropicbirds are able to play only a minor role in the excavation of nest sites because they nest primarily in a rocky environment. The basic requirements for a viable tropicbird nest site are: a sandy or soily substrate (they do not use nest material); protection from direct sunlight, at least in the hotter hours of the day; and shelter from the rain. Four types of cavities provide these condi-tions:

1. Eroded pocket holes in cliffs, generally formed where un-cemented sand replaced decomposed tree stems, roots or branches following burial by a dune in the younger aeolianites, but also formed by solution pipes and caves in the older and more modified aeolianites.

2. Deep erosional crevices where certain dune strata or accretionary soils have a lesser degree of cementation.

3. Cliff-fall rock talus, which provides natural cavities between rock slabs that gradually accumulate enough sand in them to become useable.

4. Sandy areas under dense vegetation. This last type of nest site is now very rare on Bermuda, and no longer viable on the main islands, because of greater exposure to rain and predators.

Our surveys revealed that weathering plays the major role in nest-site creation, with new nest-sites being created only gradually by differential erosion of the cliff faces and accumulation of sand or soil

in the cliff holes or under cliff-fall talus. Hurricane catastrophe events, on the other hand, play the major role in nest site destruction by causing cliff falls and re-working cliff-base talus, or by washing sand and soil out of the nesting crevices and back-filling or blocking them with rocks. These events are stochastic, resulting in immediate episodic losses of nest sites, which then requires many years or decades of normal weathering before new ones are created.

In the long term, rising sea-level should not cause an overall reduction of nest-sites except on the low relief islets where there are no higher options to escape sea flooding. On Bermuda's mainland, however, where interposing anthropogenic development along the coastline constrains the ability of the tropicbirds to find safe new nest sites higher up on the cliffs, this has become a major cause of decline. An effort is now being made to mitigate this problem by developing specifications and designs for mass producible artificial nest sites safe from mammal predators, and requiring that they be included in any planning approval for coastal development

(Wingate 1988, Dobson 2002). There is an extraordinary opportunity here because tropicbirds have no aversion to nesting in close proximity to people; require only 0.5 cubic metre of nest cavity on land; and always land and depart directly from that nest cavity.

The approximately 25-year hiatus between the mid-point of our two tropicbird surveys has additionally provided a sobering indication of the scale of nest site disruption and breeding failure that has resulted from accelerating sea-level rise and increased intensity of storms (Table 1).

Over this quarter century period, an extraordinary 90 (45.7%) of the 197 nests in the original survey were destroyed, mainly by the hurricane events of 1995 and 1999. While 50 (24.5%) new natural nest sites out of 204 nests have gradually been created and colonized since the original survey, the

Table 1 Comparison of breeding success* in a predator-free population of white-tailed tropicbirds *Phaethon lepturus* nesting on the Castle Harbour Islands Nature Reserve, Bermuda, monitored from 1970 to 1983 and again in 2001-2002.
 * % breeding success is defined here as the percentage of nests regularly visited by adults that fledged a chick, whether or not an egg was confirmed.

Original Survey (All natural nests)

Year	Occupied Nests	Fledglings	% Success
1970	118	87	73.7
1971	129	64	49.6
1972	128	90	70.3
1973	143	89	62.2
1974	166	121	72.9
1975	168	103	61.3
1976	169	121	71.6
1977	178	125	70.2
1978	179	119	66.5
1979	197	139	70.6
1980	191	134	70.2
1981	171	103	60.2
1982	No survey conducted		
1983	192	127	66.1
		Mean	66.6

Repeat Survey (Natural nests only *)

Year	Occupied Nests	Fledglings	% Success
2001	132	63	47.7
2002	130	65	50.0
		Mean	48.8

* The repeat survey includes a number of man-made or radically repaired natural nests which would not otherwise have existed or been useable following hurricane destruction. These have deliberately been excluded from this table in order to compare results as they would have been without human intervention.

majority are still so marginal that they are experiencing very low breeding success due mainly to crow predation and exposure to sun and rain.

This, plus increased short-term competition for the reduced number of optimal nests (which often results in vicious fights to the death), has lowered the breeding success in occupied natural nest sites from 66.6% in 1970-83 to 48.8% in 2001-2. This comparison is preliminary, of course, and may not be as statistically significant in the longer run, because the repeat survey has been under way for

only two years, and one of the ten years of the original survey *did* have a breeding success rate that matches the current mean of the repeat survey.

It is worth mentioning here that the repeat survey additionally includes a number of man-made nest-sites that were rebuilt after the hurricanes or added to the survey islands after the initial survey. These were deliberately excluded from the foregoing breeding success comparison because they would not otherwise have existed. However, if we consider what percentage of the new survey they represent, particularly in regard to breeding success (Table 2), it becomes possible to get some idea of how many additional man-made nests might have to be provided in order to restore the breeding success to the level of the original survey.

Table 2 **The results of the 2001-2002 survey with the data from the additional man-made nests included**.

Year	Occupied Nests	Fledglings	%Success
2001	149	75	50.3
2002	155	79	51.0
		Mean	50.7

Conclusions

The evidence provided from these studies on Bermuda suggests that, on the global scale, we can expect an increasing trend towards erosional coastlines, resulting in an increasing proportion of rocky or cliffed coastlines and a proportionate loss of mangrove, salt marsh and beach/dune habitat. Provided that there is space for these habitats to pro-grade naturally inland, however, they can keep pace with sea-level rise to a varying degree.

The main problem arises from the sheer scale of anthropogenic development along coastlines and our obvious reluctance to abandon this built environment in the face of sea-level rise. In our efforts to protect, rather than abandon and retreat, we construct coastal defences such as sea-walls, sand-replacement and landfill and thus either destroy or block the natural landward pro-gradation of the coastal habitats. Taking a longer-term view, this approach can result only in the destruction of both the habitats and the species that breed or feed in them. Ultimately, of course, our built environment becomes doomed as well, when the rising costs of defending it can no longer be justified economically.

Acknowledgements

Literature Cited

Barnett, T. P., 1984. The estimation of global sea-level change: A problem of uniqueness. *Journal of Geophysical Research* 89:7980-7988

Bruun, P., 1962. Sea-level rise as a cause of shore erosion. *Journal of the Waterways and Harbours Division, Proceedings of the American Society of Engineers* 88: 117-130

Bell, B., 1992. Translocation of fluttering shearwater: developing a method to re-establish seabird populations. In: *Re-introduction Biology of Australian and New Zealand Fauna.* M. Serena (ed.), Surrey Beatty and Sons, Chipping Norton.

Cartwright B., L. Nash & D. B. Wingate, 2001. *Guide to Nonsuch Island "Living Museum" Nature Reserve.* Bermuda Zoological Society.

Childers, D. L. & J. W. Day, 1990. The dilution and loss of wetland function with conversion to open water. *Wetlands Ecology and Management* 1. 1-9.

Dobson, A., 2002. *A Birdwatching Guide to Bermuda.* Arlequin Press.

Ellison J. C., 1989. Pollen analysis of mangrove sediments as a sea-level indicator: Assessment from Tongatapu, Tonga. *Palaeogeography, Palaeoclimatology, Palaeoecology* 74: 327-341.

Ellison, J. C., 1993. Mangrove retreat with rising sea-level, Bermuda. *Estuarine, Coastal and Shelf Science* 37:75-87

Ginsburg, R. N. & J. H. Schroeder, 1973 Growth and submarine fossilization of algal cup reefs, Bermuda. *Sedimentology* 20:575-614.

Gosselink, J. G. & R. H. Baumann, 1980. Wetland inventories: Wetland loss along the United States coast. *Zeitschrift fur Geomorphologie, N.F.* Supplement Band 34: 173-187.

Gross, A. O., 1912. Observations on the yellow-billed Tropic-bird *Phaethon americana* Grant at the Bermuda islands. *Auk* 29:49-71

Lefroy J. H., 1877. *Memorials of the Discovery and Early Settlement of the Bermudas or Somers islands 1511-1687. Compiled from colonial records and other original sources.* 2 vol. Longmans, Green and Company, London.

Murphy, R. C. & L. S. Mowbray, 1951. New light on the Cahow *Pterodroma cahow. Auk* 68: 266-280

Pirazzoli, P. A., 1986. Secular trends of relative sea-level (RSL) changes indicated by tide gauge records. *Journal of Coastal Research* 1: 1-126.

Podolsky, R. H. and S. W. Kress, 1989. Attraction and colonization of Dark-rumped petrels *Pterodroma phaeopygia* to Santa Cruz Island, Galapagos. In *Annual Report National Audubon Society*: Ithaca, N.Y.

Sterr, Horst, 2001. Implications of climate change on sea-level. In: *Climate of the 21st Century: Changes and Risks.* Jose L. Lozan, Hartmut Grabl & Peter Hupfer (eds.), Wissenschaftliche Auswertungen.

Vacher, H. L. & P. Hearty, 1989. History of stage 5 sea-level in Bermuda: Review with new evidence of a brief rise to present sea-level during substage 5a. *Quaternary Science Reviews* 8: 159-168.

Wingate, D. B., 1978. Excluding competitors from Bermuda petrel nesting burrows. In: *Endangered Birds: Management Techniques for Preserving Threatened Species.* Temple, S. A. (ed.), University of Wisconsin Press, Madison.

Wingate, D. B., 1985. The restoration of Nonsuch Island as a living museum of Bermuda's pre-colonial terrestrial biome. *ICBP Technical Publication No. 3.* 225-238

Wingate, D. B., 1988. Making safe artificial nesting sites for Longtails as a practical measure to reverse the present chronic trend of decline. *Monthly Bulletin, Department of Agriculture and Fisheries, Bermuda,* 59:61-65

Wingate, D. B., 1995. Cahow up-date. Monthly *Bulletin, Department of Agriculture and Fisheries, Bermuda,* 66:101-105