# The Impact of Climate Change on Bermuda

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# Executive Summary

There is unequivocal evidence that the earth's climate is warming at an alarming rate. There is also general global consensus that this is as a result of greenhouse gases resulting largely from human industrial and farming activities. The effects of climate change are not geographically equitable, nor are they consistent or easily predictable. However, there is little doubt that they may have catastrophic elements. There is also increasing concern that climate change may present a huge global security threat. However, if we act promptly we may be able to make the necessary changes to counter this trend, bring economic benefits and avoid social disruption by anticipating potential damage and minimising threats to our ecosystems, human health, property and infrastructure.

This report, which has been commissioned by the Bermuda National Trust, sets out to explore how climate change may affect Bermuda, with the intent of stimulating more informed discussion throughout the community. The introductory section considers the economic, social and physical vulnerability of all small islands and how these relate to Bermuda. Particular emphasis is placed on the issue of global food security and the fact that the two main sectors underpinning the island's economy, international business and tourism, may be significantly affected by climate change on both a global and local scale. However, Bermuda also has some inherent characteristics that give it resilience. It also has an opportunity to take a lead in setting an example for small oceanic islands by developing strategies and proactive measures towards sustainable development which at the same time will mitigate the processes of global climate change. The basic framework is already in place with the island's Sustainable Development Plan.

Chapter 2 explores the causes behind climate change. It considers why current changes differ from those in the past history of the earth, the impact of greenhouse gases (GHG) and how human activities contribute to accumulation of these gases. The resulting impacts on global temperatures, rainfall patterns, storm activity, flash floods, drought and sea level are then outlined. This chapter concludes with a consideration of future scenarios and predicted changes.

Chapter 3 explores what we know about Bermuda's climate in the context of our geographical location and regional oceanographic influences, and gives consideration to how projected global changes may affect us regionally and locally. It questions the extent to which we can rely on the general predictions made by the International Panel for Climate Change (IPCC) for our region, but acknowledges that even the absence of more locally relevant data should not prevent us from taking immediate action. Chapter 4 gives a brief history of sea level change in Bermuda and presents the most current observations of the present day rate of rise. It explains why sea level rise projections of 0.59 m and 2.0 m rise are made for the island. 0.59 m represents the highest predicted rise by the IPCC for this century (excluding the impact of the ice sheets melting); 2.0 m has been calculated to be the highest likely rise possible if ice sheet melt is taken into consideration.

Chapter 5 looks at Bermuda's infrastructure, cautioning that infrastructural design is currently maintained on the premise that the future climate will remain constant. Buildings, transport, waste disposal, waste water and sewage and telecommunications are discussed in the context of predicted sea level rise, rising temperatures, heavier flooding and more intense storm activity. The impacts of these on the structural integrity of our infrastructure are considered, as well as the economic impacts in terms of increased maintenance costs and disruption to our tourist and international business resulting from closure of the airport. The impact of maintaining this infrastructure on our GHG emissions is also noted.

Despite the fact that Bermuda has no surface freshwater resources, chapter 6 notes the intelligent design of the island's roof catchment and underground storage system for individual households, which has historically served our basic freshwater needs. Less conservative water usage but higher population density is stretching these resources nowadays and forcing us to become increasingly dependent on groundwater extraction and desalination plants. Whilst sea level rise may have little impact on these resources, higher temperatures and more intense storm activity may increase bacterial and saltwater contamination of stored water causing health issues.

Bermuda's electricity costs are amongst the highest in the world and demand is growing faster than the current power plant will be able to support. Moreover, sea level rise poses a serious threat to the existing plant. There is a growing interest in alternative renewable energy, both to reduce our dependence on the importation of fossil-based fuels, reduce costs and also to meet our global responsibility to reduce our carbon footprint. This is discussed in chapter 7.

Good health is an essential gauge of our quality of life and a fundamental component of sustainable development and the future social and economic integrity of the island. Chapter 8 discusses the socio-economic impacts of climate change on community health and well-being, including loss of income and productivity, population displacement and social disruption, diminished quality of life, psychological stress and increased costs to health care. Additionally, the effect of changes in weather and climatic conditions on respiratory infections, heat related diseases, contamination of water supplies and the increased incidence of infectious, and food and water-borne diseases is presented. Progressive development and implementation of biological and health surveillance measures as already practiced by the Ministry of Health are essential to adaptation to climate change.

Chapter 9 looks at the considerable impact of climate change on our tourist industry. The most serious will result from the effects of any possible greenhouse gas reduction policies (eg. introduction of carbon quotas) which could impact tourist mobility in the future, and from more intense hurricane activity and sea level rise. Tourism is a major contributor to our GHG emissions so it will be incumbent on us to develop an innovative, coherent policy strategy that decouples tourism from increased energy use and GHG emissions, so as to allow tourism growth.

Bermuda has a rich built heritage, much of which still stands, and much of which is preserved in the ground. Our reefs are also adorned with a diverse array of historic ship wrecks. The possible physical and chemical impact on these of rising seas, more intense storms, increasing temperatures and more flooding is discussed in chapter 10.

The effect of climate change on local agriculture and fisheries is discussed in chapters 11 and 12 respectively. Both industries have seen declines at a time when there is growing concern over global food security. Climate change promises to add further challenges to the struggling agricultural sector, requiring innovative solutions; predicted rising temperatures may however benefit local fisheries by extending breeding seasons and species ranges. The potential for the proliferation of invasive species may negatively affect both sectors.

Whilst warmer temperatures and rising $CO_2$ levels might benefit Bermuda's mangrove and seagrass communities, rising sea levels may have serious consequences, particularly as coastal squeeze prevents upwards retreat. Adaptive management needs to focus on relieving existing pressure and undertaking restoration efforts. This is discussed in chapters 13 and 14.

Extensive global research has focused on the possible impacts of climate change on reefs and this is referenced in chapter 15. The northerly extension of Bermuda's reef system and accompanying colder temperatures suggest higher absorption of $CO_2$ into the oceans, increasing ocean acidification and threatening to negatively impact reef growth. At the same time, the potential positive benefits of generally cooler temperatures are considered in the context of Bermuda's protective reef system.

Most of Bermuda's 290 km of shoreline comprises rocky shore, beach or dune. These will bear the full force of increased storm intensity as well as sea level rise, and decreases in the area of these habitats is discussed in chapter 16 along with the implications for their flora and fauna. The impact of rising temperatures on physiology, reproductive behaviour and availability of food for these organisms is also considered, as well as its impact on invasive species and increasing ocean acidity.

Finally, chapters 17, 18 and 19 consider the specific impacts of climate change on three of the most visible taxonomic groups in Bermuda; plants, birds and reptiles. Appropriate management action for all three groups is discussed and the need for making sure that climate change is not considered in isolation of the other threats they face, is stressed. The need to increase the available habitat either through dedicated nature reserves, land corridors, backyard plantings, or artificial nests, as well as programmes to cull invasive or predatory species and the expansion of programmes to educate the community are emphasised.

# Introduction

Climate change is an issue that is now firmly on the world stage, and is believed by many to be one of the greatest challenges humans will face this century and beyond. “Climate change threatens the basic elements of life for people around the world – access to water, food availability, health, and use of the land and environment” (Stern, 2006). It will affect jobs and livelihoods, food security and recreation. If current predictions are on target it is possible that climate change-induced famine may displace more than 250 million people worldwide by 2050. By the end of the century 1-3 billion people could experience acute water shortage and climate-driven diseases could kill nearly 200 million people in sub-Saharan Africa alone. A secret Pentagon report published by The Observer in 2004 predicted that ”abrupt climate change could bring the planet to the edge of anarchy as countries develop a nuclear threat to defend and secure dwindling food, water and energy supplies” and concluded that ‘the threat to global stability vastly eclipses that of terrorism” (Townsend and Harris, 2004).

> ***“Climate change threatens the basic elements of life for people around the world – access to water, food availability, health, and use of the land and environment”. (Stern Review, 2006).***

Whilst we know that throughout the earth’s history the climate has changed dramatically, it is the current rate of change that presents such an alarming picture. The latest report of the Intergovernmental Panel on Climate Change (IPCC, 2007) is clear that the average increase in global warming is nearly 1°C above the pre-industrial era. Due to lags in the impact of greenhouse gases on the climate system, a warming up to 1.5–2°C is practically unavoidable.

One of the challenges we face in addressing this change is the often conflicting information with which we are presented. The fact is that climate change is hard to predict and current models often disagree about the extent of the threat. However, most significantly the fourth assessment of the IPCC (2007) now claims that “most of the observed increase in global average temperatures since the mid 20th century is ***very likely*** due to the observed increase in anthropogenic greenhouse gas emissions”. Equally significant is the current scientific evidence suggesting that whilst human activity has been the significant factor in accelerating this change, we are in a position if we act immediately to change our behaviour and help slow this trend.

In 2006, the Stern Review acknowledged that we know enough about climate change to understand the risks and it advocates immediate action as a long term investment, which will considerably outweigh the costs of not addressing the issue and facing more serious consequences in the future. It stresses that climate change will undoubtedly increase global economic and political instability, noting that “volatile weather exacerbates competition and conflict over natural resources”.

**_Box 1. IPCC_**

*In 1988 the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) established the Intergovernmental Panel on Climate Change (IPCC) to assess, compile and synthesize scientific, technical and socio-economic information relevant to climate change, and its potential impacts. The IPCC also proposes options for adaptation and mitigation and produces periodic Assessment Reports. These are globally considered the primary reference regarding our knowledge of climate change.*

The global community is working to address the climate change issue. In 1992, the United Nations Framework Convention on Climate Change (UNFCC) was signed by 154 countries agreeing to stabilize the amount of greenhouse gases in the atmosphere. In December 1997, 161 industrialised nations committed to reduce their emissions by 2012 as a percentage of 1990 levels under the Kyoto Protocol. Under Article 4.1 of the Convention, all Parties have certain general commitments to:

- prepare national inventories of greenhouse gas emissions,
- implement measures to mitigate climate change,
- promote and cooperate in the development, application and diffusion, including transfer, of technologies, practices and processes that reduce greenhouse gas emissions,
- preserve sinks and reservoirs of greenhouse gases,
- cooperate in preparing for adaptation to the impacts of climate change,
- promote and cooperate in research on climate change,
- exchange information related to climate change,
- promote and cooperate in education, training and public awareness related to climate change, and
- report information related to the above in “national communications”.

In 2008, the Kyoto Protocol was extended to Bermuda under the UK’s ratification (Government of Bermuda, 2008). In 2008, the Bali Roadmap set out a process for negotiations of emissions targets to further the implementation of the Kyoto Protocol by the end of 2009.

The UNFCCC lists specific areas in particular need of adaptation, including coastal zones, water resources, agriculture, and areas affected by drought and desertification, as well as floods. Article 4.8 complements this list by adding small island countries, countries with forest areas liable to forest decay, countries prone to natural disasters and countries with fragile ecosystems, including mountain ecosystems.

Global assessments suggest that the inherently vulnerable nature of all small islands economically, socially and physically will place them at high risk from the negative impacts of climate change (Tompkins *et al*., 2005; IPCC, 2007; Brown, 2008). Bermuda is no exception, although better placed than some. Factors which likely contribute to our vulnerability include:

- the small size of the island which limits the options available to us in adapting to climate

change and sea level rise,
- increasing urbanization and our high population density,
- the close proximity of much housing and infrastructure to the coastline,
- intense competition for land use,
- the relatively low-lying nature of the land and our geographical position which makes us vulnerable to tropical storm activity and associated storm surge,
- limited natural resources and fresh water supplies,
- depletion of our non-renewable resources and fragile, already stressed, ecosystems,
- our geographic isolation, the distance to major markets and our dependence on imports including food and oil, and
- our small internal markets and high sensitivity to external market shocks.

These factors are all inter-related and combine to heighten our social and ecological vulnerability to climate change.

Perhaps one of the least appreciated aspects of our exposure to the impacts of climate change is that of global food security. Food crop production around the globe is being negatively affected by climate change and food commodity prices have soared. Countries including Egypt, India and Vietnam, have cut off their rice exports in response to soaring prices at home, thereby exacerbating the effects on rice-importing countries. Bermuda has enough fresh food to supply the resident population for about a week, and enough food in the supermarkets for approximately 3 weeks, so with limited ability to feed ourselves, it is imperative that we prepare ourselves for changing circumstances. These changes may simply be reflected in rising costs, but we cannot ignore the possibility of more limited global supplies in the future.

We must also remember that Bermuda's economy is underpinned by two main sectors, international business (specifically insurance and reinsurance) and tourism. Both have the potential to be significantly impacted by climate change, especially if, in the future, carbon quotas are introduced as these may well affect consumer choice over holiday destinations as well as travel in general. Meanwhile climate change, recently quoted as "an underwriter's worst nightmare" due to the challenges related to assessing risk from such unpredictable effects, is likely to have a broad impact across all forms of insurance.

However, despite our apparent vulnerability, Bermuda also has some inherent characteristics that give it resilience. As a relatively affluent community, the island has a solid infrastructure including island wide accessibility to transport, electricity, clean water and telephone and/or Internet communication, good health care, an educated population, high building standards and long experience of dealing with climate variability and extreme weather events such as hurricanes.

It would also be easy to take the view that Bermuda's contribution to climate change is insignificant. Certainly, the island as a whole does not emit vast quantities of greenhouse gases. However, if we consider each global citizen as an equal, then the residents of Bermuda have an appalling track record, emitting an average of just over 10 tonnes of carbon each year each (Manson and Hasselbring, 2005). In 2003, this placed us as the 10$^{th}$ highest global per capita contributors of $CO_2$ emissions. Each time we drive our car, switch on the air-conditioning or heating, lights, water heaters, or driers, fly overseas or buy goods imported from abroad, we are adding to our carbon footprint. In order to meet projected targets for emissions reductions under the Kyoto Protocol, per capita emissions need to be reduced to just 3.3 tonnes per year by 2050 based on the current global population. However, with projected expansion in the population, this would result in an adjustment to 2.0 tonnes/year (Byrne, 2008).

## *The Aim of this Report*

As the second largest landowner in Bermuda, the Bermuda National Trust is concerned about the impact of a changing climate on the Bermudian community and on its natural and built heritage. The aim of the current initiative by the Trust is to document what we know about the likely impacts of climate change on Bermuda. Where local data is absent, information has been drawn from other jurisdictions where relevant parallels exist. Climate change will have social and economic impacts on all sectors in our community so this review also gives consideration to these with the intent of providing an opportunity for informed discussion throughout the community. It is hoped that it might also serve as a framework for developing a coordinated approach to climate change which broadens the range of solutions and increases our capacity for mitigation and adaptation.

Only by addressing climate change head-on will we have an opportunity to build resilience and improve management of our natural resources and protect the well-being of our community. Building resilience, which involves increasing the ability of a system (social and ecological) to withstand shocks and surprises and to revitalise itself if damaged, offers the prospect of a sustainable response. The White Paper on Bermuda's Marine Resources and the Fishing Industry (Government of Bermuda, 2005a), the Bermuda Biodiversity Country Study (Anderson *et al*., 2001) and the State of the Environment Report (Government of Bermuda, 2005b) have shown that as a direct consequence of continuing human activities, many of our natural systems are already under severe stress. Building resilience into management of our natural and built heritage first requires an understanding of how these will likely respond to the additional stress of a changing climate and what factors may promote their survival.

In the following chapters Bermuda's vulnerability to the existing and future impacts from climate change are considered under the following framework: climate and sea level rise, infrastructure, freshwater and energy resources, human health, tourism and built heritage; agriculture and fisheries; and biodiversity including coastal habitats, mangroves, seagrasses and coral reefs, plants, birds and reptiles. Each chapter concludes with a short section highlighting some general recommendations about strategies that could be implemented to enhance Bermuda's resilience to the threats of climate change. This is by no means an exhaustive assessment. It is merely a seed for further discussion and development. The information put forward has been collated from a thorough review of the scientific literature specific to Bermuda, as well as from studies conducted in other jurisdictions that may have local significance. Further information was also gathered through a consultative process with a local network of experts representing diverse community stakeholder interests.

It is widely accepted that early action to adapt to climate change could bring economic benefits and avoid social disruption by anticipating potential damage and minimising threats to our ecosystems, human health, property and infrastructure. Indeed new economic opportunities such as new markets for innovative products and services may emerge through the process of adaptation. Mainstreaming climate change into national policies and planning processes does not require a dramatic departure from all that has gone before. It can be done by adjusting existing policies, programmes and structures. What is required is a commitment to dealing with climate, environmental, social and economic needs and vulnerabilities in a holistic manner.

With its prosperous economy Bermuda also has the opportunity to set an example for small oceanic territories in developing strategies and proactive measures towards sustainable development which at the same time will mitigate the processes of global climate change. Integrated conservation and development approaches that include collaborative resource management will be central to reducing our vulnerability and increasing resilience; successful adaptation can only be achieved through cross-sector integration with other policies such as disaster preparedness, land-use planning, environmental conservation and coastal planning. The basic framework is already in place with the island's Sustainable Development Plan which was formally adopted by the Government in early 2008. Choosing how we respond to the threats from climate change is in many ways another version of the larger sustainable development question. We need to assess what development options are available that enable us to become more resilient to environmental change whilst at the same time promoting the resilience of future generations.

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# 2. What is Global Climate Change?


**SUMMARY**

- Over its 4.5 billion year life, the earth's climate has continually changed and the planet has in turn responded. However, we are now going through a period of change on a scale and at a rate that has not been experienced for hundreds of thousands of years.

- Warming of the climate system is unequivocally the result of escalating greenhouse gas emissions produced primarily through human industrial and farming activities.

- Rising temperatures are affecting rainfall patterns, triggering more intensive tropical storm activity, hotter days, hotter nights and droughts, storm surges and flash floods. They are also causing global sea levels to rise at a current rate of 0.31 mm/year. Species are being driven to extinction, habitats are changing and millions of people may ultimately be displaced from their homes and face severe food and water shortages.

- Future predictions are tied to a series of scenarios based on the extent and speed with which the global community acts to reduce its $CO_2$ emissions. Under the United Nations Framework Convention on Climate Change (Kyoto Protocol), global reductions must be reduced by 60% by 2050. This means the average Bermuda resident must reduce their emissions from 10 tonnes of carbon per person, per year to 3.3 tonnes.

- Global temperature will continue to increase depending on how quickly greenhouse emissions are reduced, with an average range of 1.8 to 4.0 °C by the year 2100; a future 0.2°C decadal temperature rise would equate to a sea level rise of 0.18 – 0.59 mm/year but sea level rise up to 2 m is not out of the question if melting of the ice sheets accelerates. Rainfall is also expected to become much more erratic across the globe.

## 2.1 Introduction

Over its 4.5 billion year life, the earth's climate has continually changed and the planet has in turn responded to these changes. However, we are now going through a period of change at a rate that has not been experienced for millions of years (IPCC, 2007). This has triggered widespread global concern particularly regarding the impacts of these changes and raised challenging questions as to how we respond both as a global community and as individual citizens, particularly given growing consensus that human activities have been the primary driving force behind these accelerated changes.

The most significant and immediate of these changes are:

- **Increasing air and sea temperatures**
- **Rising sea level**
- **Changes in rainfall patterns**
- **More extreme weather conditions**

All these changes are inter-linked. Warming temperatures are causing the sea level to rise as well as affecting rainfall patterns, triggering more intensive tropical storm activity, hotter days, hotter nights and droughts, storm surges and flash floods. Whilst there are regional differences in how these changes are occurring, every part of the globe is being affected to some extent.

> ***Box 2. Climate and Weather***
>
> It is important to make the distinction between climate and weather. Climate is defined as the average 30-year weather pattern of a region. Weather on the other hand is a much more localized phenomenon, and something we experience from day to day. Making this distinction is important because our weather can be highly variable from one year to the next, but when we refer to climate change we are looking at the longer term trends.

## 2.2 What is Causing Global Climate Change?

So, why are global temperatures rising? The seriousness of this issue prompted the World Meteorological Organisation and the United Nations Environment Program to establish the International Panel on Climate Change (IPCC) in 1988. The IPCC's mandate is to provide an objective assessment and summary of all the scientific, technical and socio-economic information relating to human-driven climate change. Drawing on the expertise of thousands of scientists, the IPCC has produced a series of reports, most recently its Fourth Synthesis Report published in 2007 (IPCC, 2007a). This latest report builds on its previous findings with new and more comprehensive data gathered over the previous six years, more sophisticated data analyses, and a better understanding of the processes involved and their simulation in models.

Most significantly, the 2007 report recognises that "warming of the climate system is unequivocal" and it now acknowledges that since the mid-20th century, most of the ongoing global temperature increase can be accounted for by an increase in concentrations of greenhouse gases, caused through human activities. Figure 1 below illustrates the earth's natural greenhouse effect.

*Acknowledging that human activities are contributing to climate change is significant because it means that we have both a responsibility, and an opportunity to take action to try to reverse this potentially catastrophic trend.*

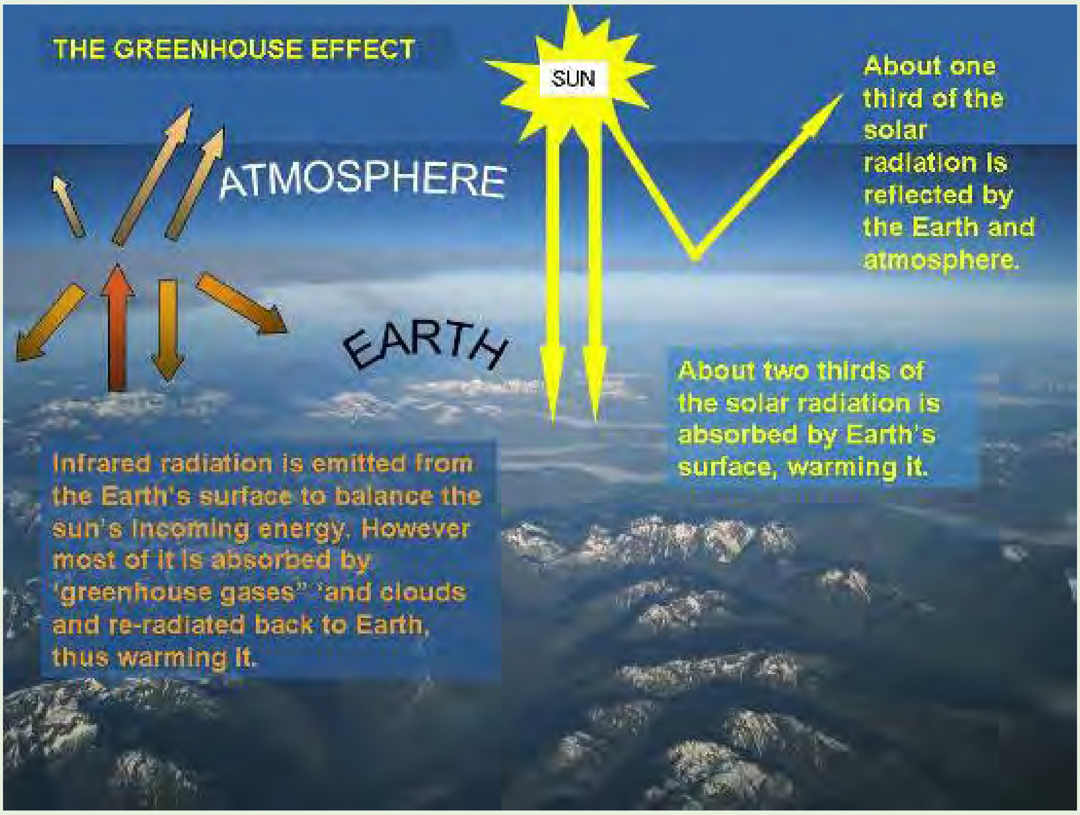


*Figure 1. Diagram to illustrate the natural 'Greenhouse Effect'.*

## *2.3 Global Climate Trends*

If we look at the most significant and immediate impacts of climate change, we can get a better gauge of the overall problem. However, one of the key things to note is that our climate will not necessarily change smoothly over time; rather there may be abrupt, non-linear changes, making planning and adaptation a critical factor.

### *Box 3. Greenhouse gases*

- The earth's atmosphere naturally functions much like a greenhouse, trapping about 70% of the solar and infrared radiation from space in gases such as carbon dioxide and methane, nitrous oxide, fluorinated gases as well as water vapour. If this did not happen, the average temperature of the earth would be about - 19 °C.

- However, human activities involving the burning of fossil fuels like coal and oil as well as deforestation through which massive amounts of stored carbon are released, and agriculture have dramatically increased these heat–trapping gases increasing this "greenhouse" effect.

- As more heat is trapped, global temperatures rise. In 2008, carbon dioxide ($CO_2$) levels were 387 parts per million (ppm), up from 280 ppm in pre-industrial times (1880)). As far back as 1896 the Swedish chemist Svante Arrhenius predicted that a doubling of atmospheric $CO_2$ would increase global temperatures by 3-6 °C.

- Recent data reveal that the levels of $CO_2$ are continuing to rise at an accelerated rate. From 1970 to 2000, the concentration rose by 1.5ppm each year, but since 2000 the annual rise has leapt to an average 2.1ppm (http://www.esrl.noaa.gov/gmd/ccgg/trends). This is higher than at any time during the past 650,000 years. Coupled with the fact that greenhouse gases can take decades or longer to be removed from the atmosphere, we clearly face a huge challenge.

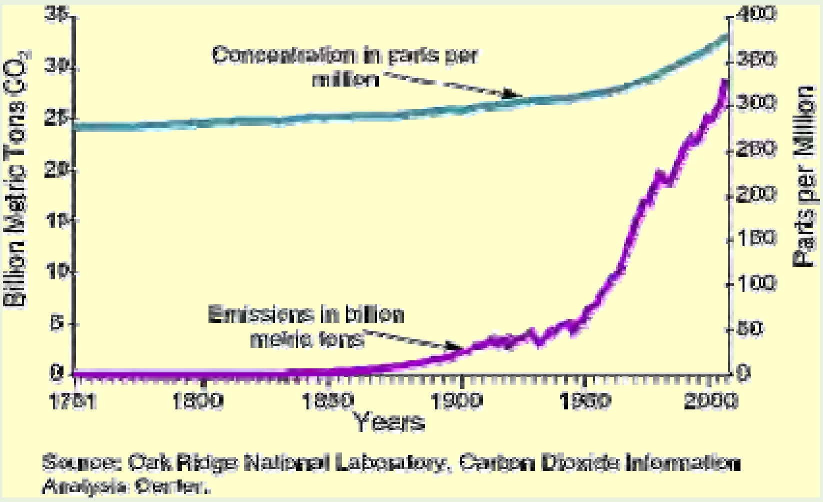


*Figure 2. Carbon Dioxide Emissions and Carbon Dioxide Concentrations (1751-2004)*

## 2.3.1 Our warming planet

- Temperature records dating back to 1850 reveal that the average global temperature has risen by 0.74 °C over the past hundred years.

- 11 of the 12 warmest years (since records began in 1850) have occurred since 1995 (IPCC, 2007).

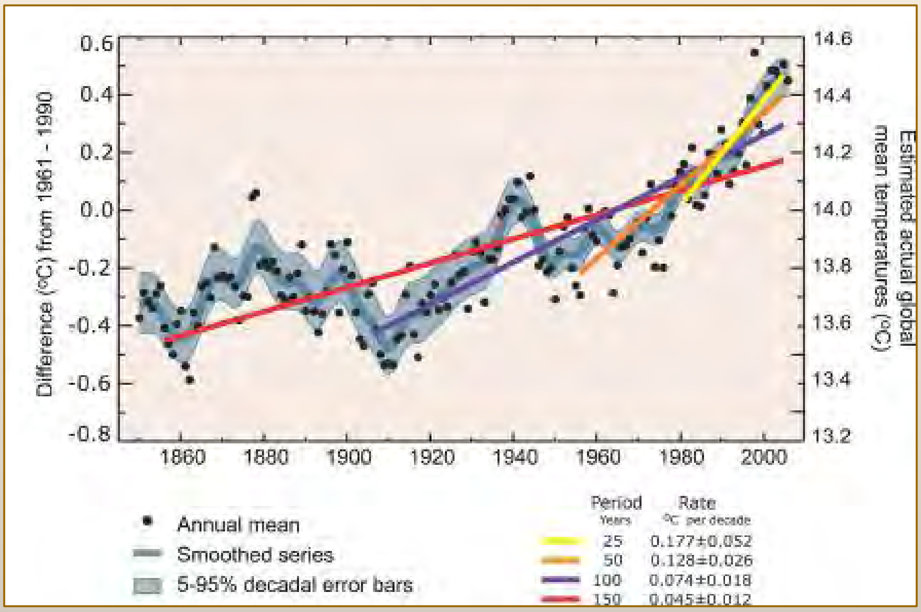


*Figure 3. Annual global mean temperatures with linear fits to the data. (Source IPCC 2007: WG1-AR4).*

- This increase has not been consistent either through time, or across the globe. Significant regional differences reveal that in the Caribbean, Indian Ocean and Mediterranean regions, warming ranged from 0 to 0.5 °C per decade from 1971 to 2004 (Trenberth *et al*., 2007). Meanwhile, some high latitude regions, including the western Canadian Arctic Archipelago and the interiors of Asia, have experienced more rapid warming than the global mean (McBean *et al*., 2005). Projected temperature changes are also greatest over land and increase from the coast to the interior of the continents.

- The average rate of global warming has also accelerated, rising almost twice as quickly over the past 50 years, when compared to the past 100 years.

- Over the last 50 years, cold days and cold nights appear to have become less frequent, hot days, hot nights and heat waves have been more frequent, and the average temperature difference between day and night has decreased (IPCC, 2007).

- The ocean absorbs most of the heat added to the system (over 80%) and ocean temperatures up to depths of 3,000 m have also risen over the past four decades, although not as quickly as for the land masses (IPCC, 2007).

## 2.3.2 The effects of rising temperatures

### *Sea Level Rise*

One of the consequences of rising temperatures is that of sea level rise. There are two main reasons for this. Firstly, the water in the ocean expands as the temperature rises and secondly, the world's glaciers and ice caps are melting.

- Studies of ancient climates have revealed a repeated positive relationship between surface temperature and sea level rise. We know that over the past million years, cold ice ages have alternated with warm interglacial periods, with sea levels rising (warm periods) and falling (ice ages) over a 120 m range. For example, global temperatures during the last interglacial period, which occurred about 125,000 years ago, were 3–5 °C higher and sea level was correspondingly 4-6 m higher. However, unlike the present day scenario, it was changes in the earth's orbit rather than human-driven greenhouse gas emissions that caused the higher temperatures and subsequent retreat of polar ice during that period (IPCC, 2007).

- In another example from the past, Rahmstorf (2007) and Dowsett *et al*. (1994) suggest that even further back about three million years ago (the Middle Pliocene), global temperature was 1.95-3.0°C warmer than today and sea level was as much as 24–35 m higher.

- Studies have revealed that the average global rise in sea level since 1961 has been 1.8mm/year, but that since 1995, sea level rise has accelerated and the average rate has risen to 3.1 mm/year (IPCC, 2007).

- Sea level rise is not uniform across the globe. Geographical variation occurs as a result of differences in salinity, temperature changes, wind and ocean circulation. Also, regional sea level is affected on shorter time scales by variability in the climate such as that caused by El Nino and the North Atlantic Oscillation.

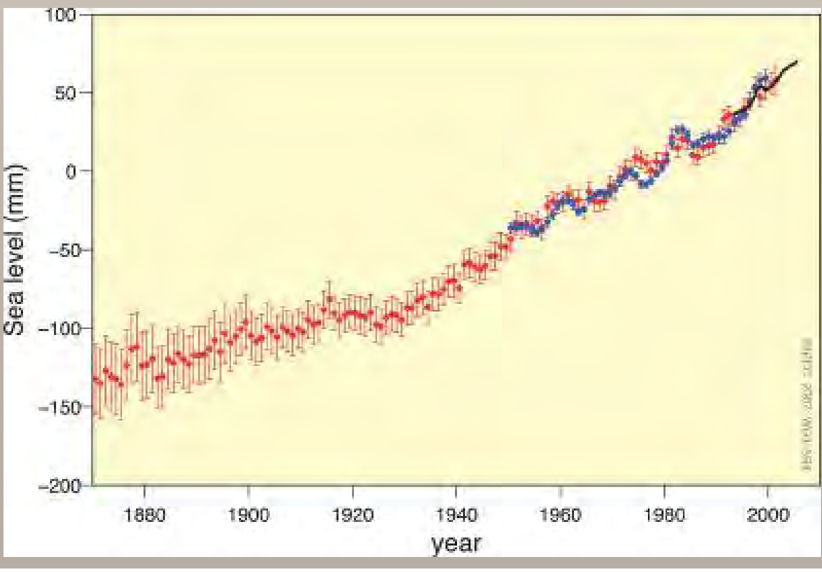


*Figure 4. Annual averages of the global mean sea level based on reconstructed sea level fields since 1870 (red), tide gauge measurements since 1950 (blue) and satellite altimetry since 1992 (black). Error bars are 90% confidence intervals (Source IPCC 2007: WG1-AR4).*

### *Glacial Melting*

*Photograph 1. Shoup Glacier, Alaska is typical of glaciers across the globe, which are retreating due to a warming climate.*

- Global warming has hit the polar regions hardest. Greenland has warmed by 4°C since 1991, far more than the rest of the globe.

- A few years ago, scientists were predicting that the Arctic Ocean would be free of ice in the summertime by 2030-2040, a condition that has not existed for at least a million years. Recent research has revised these predictions suggesting that ice-free conditions could occur by 2013. Between 2005 and 2007, summertime ice in the Arctic dropped 23% (National Geographic, 2008).

- The shrinking sea ice and snow cover drive what is known as a positive feedback loop. As more ice and snow melts, there is less white surface available to reflect solar energy, whilst larger regions of dark, sunlight absorbing seawater and forests open up, which together cause more ice to melt. It is estimated that 90% of incident solar radiation is reflected by snow and ice; in contrast only about 10% is reflected by open oceans or forested lands.

- In addition to snow and glacial melt, reports of the permafrost melting are also causing concern. Vast amounts of the greenhouse gas methane are trapped in the permafrost, which will be released as melting occurs. 20 years after its release, methane is 72 times more potent than $CO_2$.

### *Changes in Precipitation*

In addition to triggering rising sea levels, higher temperatures put more energy and water vapour into the atmosphere. As well as intensifying the greenhouse effect, increasing water vapour fuels heavier rainfall. However there are numerous factors at play which ensure global variations.

- The Mediterranean and southern parts of Africa and Asia are experiencing less rainfall, as are the Mediterranean Basin and the Sahel.

- Conversely, atmospheric water content is increasing and mid to high latitudes are becoming wetter. More frequent heavy precipitation events have been experienced in North and South America, northern Europe and northern Asia (IPCC, 2007).

- Even in areas where there is less total rainfall, heavy rain events have increased. 40 million people were displaced by floods in South Asia in 2007 (Nat. Geographic, 2008).

### *More Extreme Storm Activity*

- The higher levels of water vapour in the atmosphere caused by rising temperatures help fuel more powerful hurricane activity. The IPCC (2007) reports that since 1970 there has been a 75% increase in the number of category 4 and 5 hurricanes. However, longer records for the North Atlantic suggest that the recent extreme period may be similar in level to that of the late 19th century (Trenberth *et al*., 2007). In the Caribbean, hurricane activity was greater from the 1930s to the 1960s, in comparison with the 1970s and 1980s and the first half of the 1990s. Beginning with 1995, though, all but two Atlantic hurricane seasons have been above normal (relative to the 1981-2000 baseline). The exceptions are the two El Niño years of 1997 and 2002. El Niño acts to reduce activity and La Niña acts to increase activity in the North Atlantic.

#### *Box 4. ENSO (El Nino –Southern Oscillation)*

- ENSO is a global phenomenon involving sustained temperature fluctuations of more than 0.5°C in the surface waters of the tropical eastern Pacific Ocean (referred to as El Niño and La Niña) and monthly or seasonal fluctuations in the air pressure difference between Tahiti and Darwin (known as the Southern Oscillation).
- La Niña is characterized by unusually cold ocean temperatures in the eastern equatorial Pacific, whilst El Niño is characterized by unusually warm temperatures.
- ENSO is the best known source of year-to-year variability in weather and climate around the world, showing 2–7year cycles.
- The effects of ENSO in the Atlantic Ocean lag behind those in the Pacific and Indian Oceans by 12 to 18 months.
- ENSO is typically associated with major floods and droughts, but the impact of global warming on its intensity or frequency is unknown.

### *Box 5. Summary of Known Global Climate Changes*

***Rising air and sea surface temperature:***

- Average global air surface temperature has increased by 0.74°C (0.56°C to 0.92°C) over the last 100 years.
- 11 of the 12 warmest years on record (since 1850) have occurred since 1995.
- The average temperature of the oceans, which absorbs more than 80% of the heat added to the climate system, has increased to depths of 3,000 m.
- Glaciers and snow cover have declined in both northern and southern hemispheres; the northern polar ice cap has decreased in thickness by 40%.
- The maximum area covered by seasonally frozen ground has decreased by 7% in the northern hemisphere.
- Since 1978 satellite data has shown that the annual average extent of Arctic sea ice has decreased by 2.7% per decade with greater decadal decreases (7.4%) in summer.
- El Niño events have become more frequent, persistent and intense during the last 20 years compared to the previous 100.

***Sea level rise:***

- Global average sea level has risen by an average of 1.8 mm annually over the last 100 years. This rate has increased to 3.1mm since 1993.

***Changes in precipitation:***

- The frequency of heavy precipitation events has increased over most land areas and increased precipitation has been observed in eastern parts of North and South America, northern Europe and north and central Asia, and decreased in North and West Africa and parts of the Mediterranean.
- The length and severity of droughts has increased since the 1970s especially in the tropics and subtopics: drying has been documented in the Sahel, Mediterranean, and southern Africa and Asia.

***Changes in storm activity:***

- There is evidence that intense tropical cyclone activity in the North Atlantic has increased since 1970, however the absence of routine satellite observations before 1970 do not allow for accurate analysis of longer term trends.

*Source: IPCC (2007)*

## *2.4 The Impacts of Climate Change*

“Climate shapes ecosystems and species, determines the types of engineering structures we build (from houses to bridges), and affects our culture, our moods, our leisure pursuits” (Hulme, 2006).

- The signs of climate change are already here; glaciers are melting, seas are rising, lakes are freezing later, heat waves and floods are more frequent. Of more than 29,000 observational data series from 75 studies that show significant change in physical and biological systems, more than 89% are consistent with the direction of change expected in response to global warming (IPCC, 2007).

- Plants and animals, whose biological clocks depend on natural cues such as the timing of spring, are also providing signs of change; it is estimated that up to 40% of all species have shifted their ranges towards the poles or up mountainsides in order to survive these changes. 60% of species show changes in the timing of breeding or flowering or migration. Growth, physiology, reproduction and behaviour are all being affected. It is projected that 20-30% of known species will be at greater risk of extinction if warming exceeds 1.5-2.5$^{o}$C in relation to 1999 levels. If it exceeds 3.5$^{o}$C, all models suggest large number of species extinctions in the range of 40-70%.

- Meanwhile habitats are changing and in some cases shrinking, either through physical destruction from storms or from sea level rise. Invasive species are thriving as changing habitats become more hospitable to them and physical barriers that have historically prevented their spread are destroyed.

- In the oceans, coral reefs have been severely impacted by rising temperatures, which cause bleaching and death if temperatures remain elevated for too long. Such an event in 1997-1998 caused the death of 16% of the world's coral reefs. Coral reefs may also be impacted by rising $CO_2$ levels absorbed by the oceans to form carbonic acid, and causing the acidity of the water to rise. This in turn is believed to slow down the ability of corals to build their skeletons and other marine organisms to grow their shells.

- On the other hand, some species may be thriving. Increased concentrations of atmospheric carbon dioxide cause rates of photosynthesis to increase which in turn improves water use efficiency in some plant species allowing them to be more drought-tolerant.

- Diseases such as malaria are spreading and have migrated to higher altitudes. For example, malaria is now present over 2,000 m above sea level in the Columbian Andes (Hawkins *et al*., 2008).

- Loss of human life from heat waves like the one that hit Europe in 2003, flooding and tropical storms has been increasing. It is estimated that climate change doubled the likelihood of the 2003 heat wave. Arid regions have also become drier as a result of climate change with devastating effects on the agriculture and hence survival of populations especially in Africa. Property loss and damage to the infrastructure from many of these events has been severe. 11% of Bangladesh would be submerged with a further 40 cm sea level rise, displacing 7-10 million people.

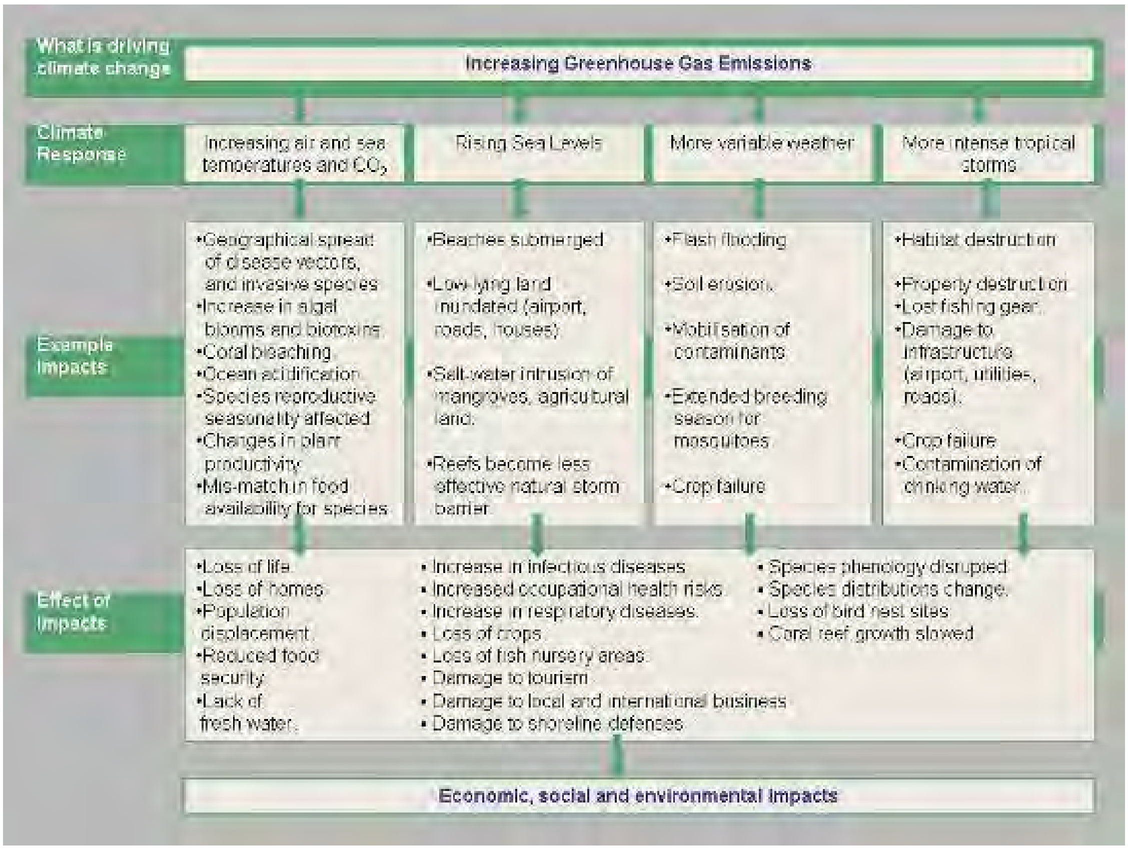


*Figure 5. Some of the main impacts of climate change to be expected in Bermuda. (Adapted from Tomkins, (2005) for Bermuda)*

## 2.5 Global Climate Projections

So just how hot will it get? Whilst there will always be an inherent uncertainty in trying to predict the future climate, significant advances in information gathering and modelling are allowing scientists to make increasingly accurate forecasts. As we look to the future, the IPCC have presented a series of possible projections based on different $CO_2$ emissions scenarios (Nakicenovic, *et al*., 2000), which in turn will depend on how quickly the global community acts to tackle the issue. Key factors that will determine future levels of greenhouse gases in the atmosphere are population growth, economic development, technical innovation, energy consumption, land use, agricultural development and environmental policy.

| | SRES B1 | SRES A1B | SRES A2 |
|---|---|---|---|
| PPM $CO_2$ in 2100 | 550 | 720 | 850 |
| Population Growth | Low | Low | High |
| GDP Growth | High | Very high | Medium |
| Energy Use | Low | Very high | High |
| Land-Use Changes | High | Low | Medium/high |
| Resource Availability | Low | Medium | Low |
| Rate of Technological Change | Medium | Rapid | Slow |

*Table 1. Characteristics of IPCC SRES Emissions Scenarios (Source: Columbia University Center for Climate Systems Research, 2006)*

There are 7 SRES emissions scenarios, but the International Energy Agency (IEA) has endorsed Scenario A1B as the most likely, and various international reviews are using this as their guidance (IUCN). B1 (producing the least amount of GHG over the course of this century) and A2 (producing the most by 2100) largely span the range of possible futures and are also included in most modeling. A1B produces an intermediate GHG increase by 2100 although during the near term it actually produces more than A2, initially allowing GHG to increase by 1% each year (which is what the current rate of increase appears to be).

### *Increasing $CO_2$*

The most recent figures published by the US National Oceanic and Atmospheric Administration (http://www.esrl.noaa.gov/gmd/ccgg/trends) confirm that $CO_2$ is accumulating in the atmosphere faster than expected. From 1970 to 2000, the concentration rose by about 1.5ppm each year, but since 2000 the annual rise has increased to an average 2.1ppm. Some scientists fear that the shift could indicate that the earth is losing its natural ability to soak up billions of tonnes of $CO_2$ each year. Climate models assume that about half our future emissions will be reabsorbed by forests and oceans, but the new figures confirm this may be too optimistic. Under the United Nations Framework Convention on Climate Change (UNFCCC), global reductions in emissions of the order of 60% are being called for by 2050. What does this mean for Bermuda? The lifestyle of the average Bermuda resident results in 10 tonnes of carbon per person, per year (Manson and Hasselbring, 2005). This places us as one of the highest per capita carbon emitters in the world (see Figure 6 below). To meet reductions being called for by the UNFCCC, we need to reduce our emissions to 3.3 tonnes per year (Byrne, 2008). However, these projections are based on the current global population; allowing for population growth, this would translate in a reduction to 2.2 tonnes/year by 2020, and 2.0 tonnes/year by 2050 (Byrne, 2008).

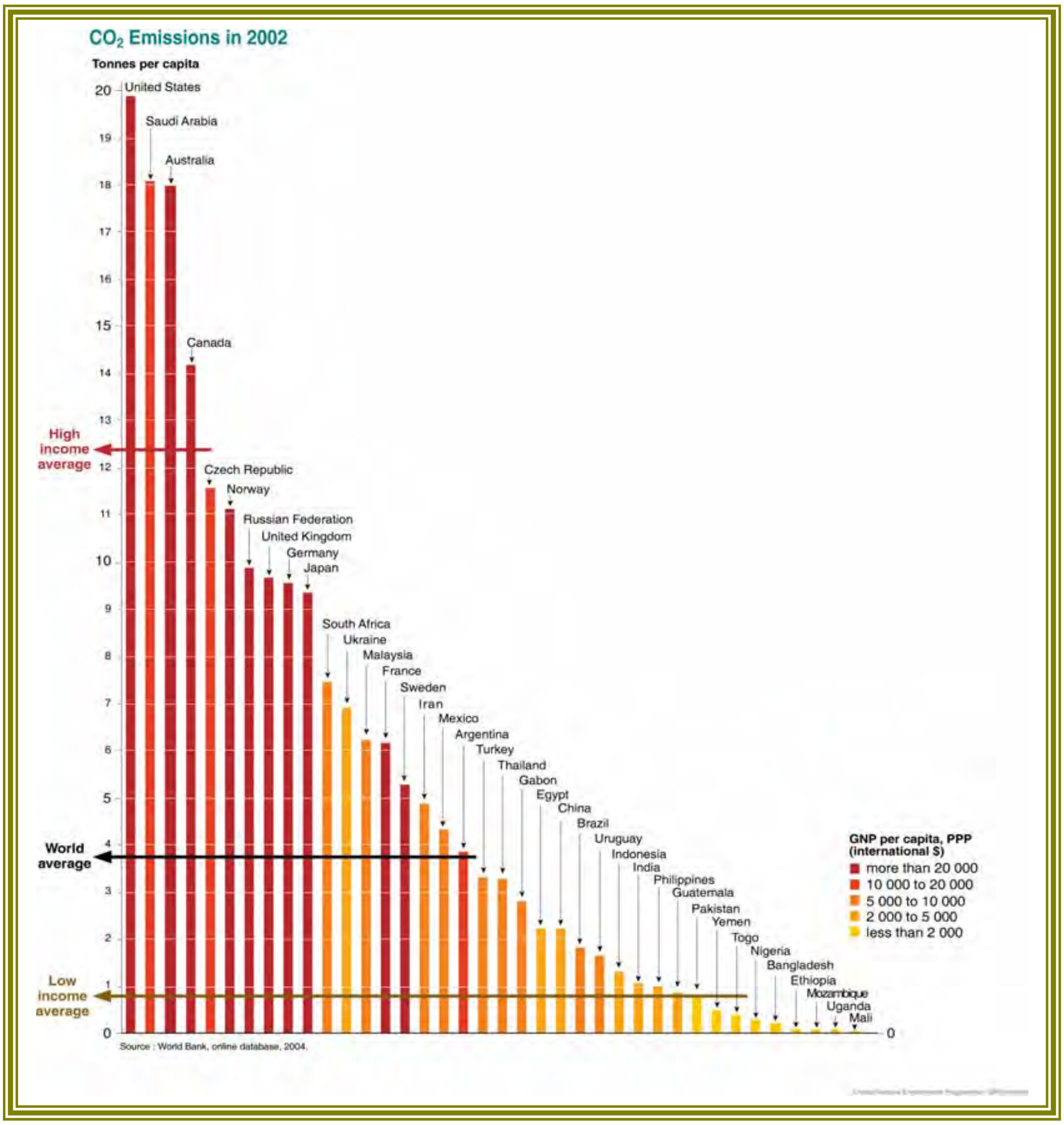


*Figure 6. National per capita $CO_2$ emissions (Source: UNEP/GRID-Arendal) http://maps.grida.no/go/graphic/national_carbon_dioxide_co2_emissions_per_capita)*

### *Increasing Temperature*

IPCC (2007) predictions suggest that the average global temperature will continue to increase depending on how quickly greenhouse emissions are reduced, with an average range of 1.8 to 4.0 °C by the year 2100. A rise of 2 °C would be at least equivalent to the warmest global climate conditions of the last 2 million years.

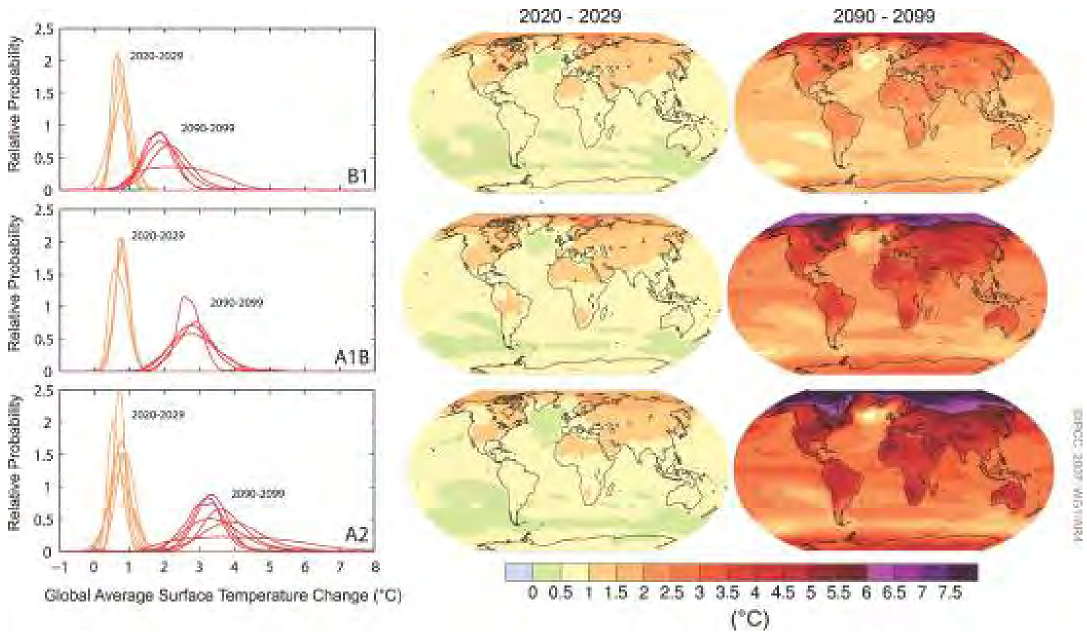


*Figure 7. Projected surface temperature changes for the early and late 21st century relative to the period 1980-1999. (Source IPCC 2007: WG1-AR4 Figure SPM.6).*

### Changing Precipitation

Precipitation is forecast to become much more erratic with longer periods of drought and more intense periods of flooding which will be geographically distorted.

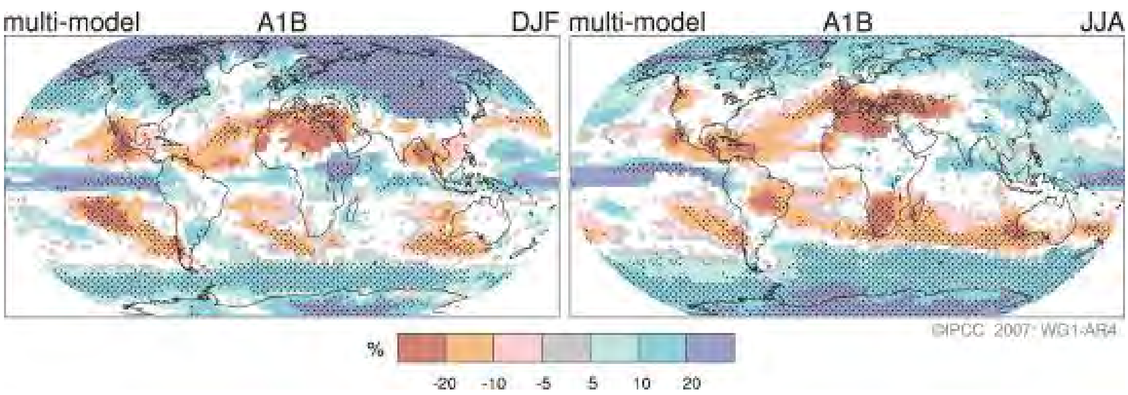


*Figure 8. Projected Patterns of Precipitation Changes. Relative Changes in precipitation (in %) for 2090-2099, relative to 1980-1999. Values are based on the SRES A1B scenario for December to February (left) and June to August (right). White areas are where less than 66% of the models agree. (Source IPCC, 2007: WG1-AR4 Figure SPM.7.)*

### Sea Level Rise

The IPCC (2007) predicts that a future 0.2°C decadal temperature rise would equate to a sea level rise of 0.18 – 0.59 mm/year, depending on how quickly the global community acts to reduce its greenhouse gas emissions. Table 2 below reflects the sea level rise anticipated under the IPCC's three most likely future emissions scenarios (B1, A1B and A2) endorsed by the International Energy Agency. However, the worst case scenario (A1F1 below) presented by the IPCC calls for an upper limit of 0.59 m sea level rise (IPCC, 2007).

| | Temperature Change (°C at 2099 relative to 1980-1999) | | Sea Level Rise (m at 2090-2099 relative to 1980-1999) |
|---|---|---|---|
| | Best Estimate | Likely Range | Model-based Range |
| Year 2000 constant | 0.6 | 0.3-0.9 | N/A |
| B1 Scenario | 1.8 | 1.1-2.9 | 0.18-0.38 |
| A1B Scenario | 2.8 | 1.7-4.4 | 0.21-0.48 |
| A2 Scenario | 3.4 | 2.0-5.4 | 0.23-0.51 |
| A1F1 Scenario | 4.0 | 2.4-6.4 | 0.26-0.59 |

*Table 2. Projected global average surface warming and sea level rise by the end of the 21st century (Extracted from IPCC, 2007: WG1-AR4 Table SPM.3.)*

Alarmingly, since the latest IPCC (2007) report scientists have been observing accelerated rates of change that is spurring a new sense of urgency. This urgency stems from findings suggesting that the polar ice sheets appear to be much more susceptible to warming than previously realised. The IPCC (2007) stresses that their current predictions may not accurately capture changes in the ice sheets. Although scientists generally believe that it would take centuries before the large ice sheets melt completely, several scientists caution that warming could reach a threshold within this century beyond which destabilization of the large ice sheets would be irreversible (Overpeck *et al*., 2006; Gregory and Huybrechts 2006). This would cause sea level rise to significantly exceed current IPCC projections.

In a more recent study (Rohling *et al*., 2007), researchers have looked at the interglacial period 124,000 to 119,000 years ago, when earth's climate was warmer than it is now due to a different configuration of the planet's orbit around the sun. Sea levels during that time reached up to 6m above where they are now, rising 1.6m per century and fuelled by the melting of ice sheets that covered Greenland and Antarctica. Greenland at that time was 3°C to 5°C warmer than now, which is similar to the warming expected in this region in the next 50 to 100 years.

In another study, Pfeffer *et al.* (2008) have performed gross calculations to assess the maximum rise that can reasonably be expected taking into consideration the dynamic effect of ice not just melting but of being pushed straight into the ocean. In Greenland, ice streams flow down steep valleys that end beneath the current sea level, so they searched for rocky bottlenecks in ice stream beds which physically prevent Greenland's ice from sliding into the Atlantic. Pfeffer and his team believe that these bottlenecks must limit the rate of sea level rise from Greenland. They also collected information on the fastest speeds at which ice sheets have ever been seen to move over rock and into the sea, both in Antarctica and in Greenland, and then calculated how much ice would have to be released into the oceans to accommodate a sea level rise of 2 m-5 m by 2100. They conclude that a rise of 0.8 m to 2 m is physically possible.

Despite often confusing data and various levels of uncertainty surrounding future projections, the fact remains that we do know enough about the general trend in sea level rise, as well as more variable climate conditions and a general warming trend to be concentrating on developing a wide range of possible policy responses, especially adaptive responses that we may implement.

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# Bermuda's Climate

**SUMMARY**

- Bermuda's climate is sub-tropical due to the transport of warm water from the Caribbean by the Gulf Stream as well as the semi-permanent Bermuda-Azores high-pressure system.

- Bermuda is far enough north to be influenced by the westerlies in winter, which bring strong northerly gales and cooler weather atypical of the truly sub-tropical regions to the south. In summer, on average one hurricane approaches Bermuda every year, and a severe hurricane is expected every 4-5 years. Storm and hurricane activity is under the influence of the North Atlantic Oscillation (NAO), and the El Nino Southern Oscillation (ENSO).

- Under the IPCC projections, Bermuda falls under the North American region with temperatures expected to rise between on average by 3.6°C over the next century (2.8°C-4.3°C). Annual rainfall precipitation is expected to increase on average 7% (5%-10%), however downfalls may be expected to be less frequent but heavier.

- Higher sea surface temperatures may result in a more permanent El Nino-like state, reducing the frequency of hurricane formation, but may also cause more intense hurricanes when they do form. Increasing desertification in Africa may also reduce hurricane formation. Less frequent storm activity may increase winter storm activity in order to ensure transfer of tropical heat poleward.

- Given our geographic isolation, our small size and the fact that the Island's climate is significantly moderated by the surrounding ocean, more locally-relevant data collection and forecasting is needed to make more realistic projections.

## 3.1 Introduction

Bermuda is located latitude 32’ 19” N and longitude 64’ 46” W, 960 km from the nearest continental land mass (Cape Hatteras), at the northern fringe of the tropics in the western North Atlantic and on the northern edge of the Sargasso Sea. Bermuda’s climate is sub-tropical, despite its northerly latitude (although there is generally more seasonal variability than in the truly sub-tropical islands to our south). This is largely explained by the transport of warm waters in the Gulf Stream current from the Caribbean (Anderson *et al*., 2001). Although Bermuda lies to the east of this northerly flowing current, spin-offs, or eddies bring warm water to the island. The other underlying factor of the sub-tropical climate is a semi-permanent area of high atmospheric pressure known as the Bermuda-Azores high-pressure system. Whilst the prevailing winds are south-westerly, from May - October the ‘high’ sets up and deflects summer storms west of the island to the north giving us predominantly light south-easterly summer breezes. However, Bermuda is far enough north to be influenced by the westerlies in winter, which bring strong northerly gales and cooler weather atypical of the truly sub-tropical regions to the south.

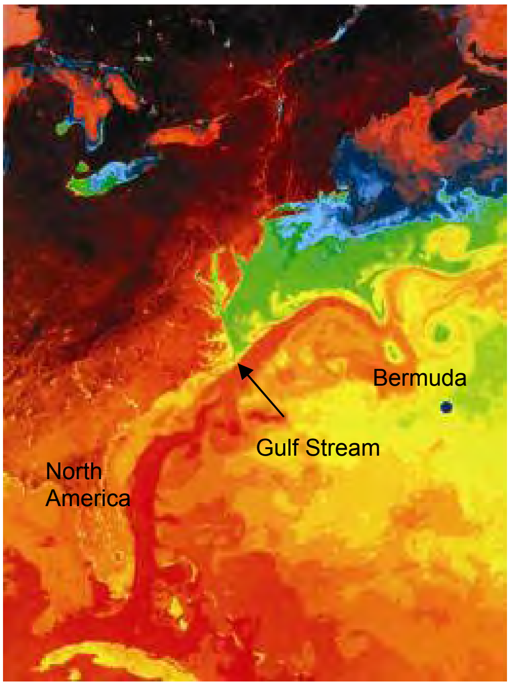


*Figure 9. Infrared image showing path of Gulf Stream (NASA).*

Coinciding with the seasonality of the Bermuda-Azores high is the tropical storm season, which runs from May to November. On average, one hurricane approaches Bermuda every year, and a severe hurricane is expected every 4-5 years. Most of the cyclones that impact Bermuda originate off the coast of Africa and migrate westwards, driven by the prevailing winds. Some head into the Gulf of Mexico; others curve eastwards and may threaten Bermuda. Storm formation requires certain prevailing conditions. These are; 1) sea surface temperature at or above 26.5 °C and extending down to a depth of 50 m in order to make the atmosphere unstable enough to allow the storm’s formation, 2) storms at least 500 km from the equator for the Coriolis force to take effect, 3) a moist mid-troposphere to prevent developing thunderstorms from dissipating, 4) rapid cooling of the water as it ascends, adding further instability, and 5) low vertical wind shear so that storm formation is not disrupted (Gray, 1968, 1979).

The direction that a hurricane takes appears to be somewhat dependent on the North Atlantic Oscillation (NAO). The NAO is the result of the sea level pressure differences caused by a permanent low pressure system over Iceland (Icelandic low) and the Bermuda-Azores high

(Barnston and Livezey 1987).The NAO controls the strength and direction of westerly winds and storms across the North Atlantic. There appears to be a greater threat of hurricanes to Bermuda if the NAO is in a positive state (ie. when there is a higher pressure gradient between the Icelandic Low and the Bermuda-Azores High), as more storms curve eastwards (Elsner and Jagger 2004). It can also cause more frequent and stronger winter storms across the Atlantic. Over the past half a century, the NAO has tended to switch between a positive and negative state approximately every 8 years. ENSO (El Nino Southern Oscillation) impacts the formation of storms in the Atlantic as well. Fewer storms occur when ENSO is in an El Nino state because there is greater vertical wind shear (caused by increased surface evaporation and convection) disrupting tropical storm formation. In a La Nina year, less wind shear leads to greater storm formation over the Atlantic. La Nina years typically see more named storms in the Atlantic basin than normal ENSO or El Nino years (NOAA, 1998; Guishard, pers.comm.).

With the moderating influence of the surrounding ocean, Bermuda's mean monthly air temperatures range from 18.5°C in February to 29.6°C in August. The annual total rainfall of 150 cm is irregularly distributed through the year, and humidity is uniformly high (70-82%). On average, October is the wettest month and April the driest, but this varies tremendously from year to year. Droughts lasting up to three months are not uncommon. Rainfall patterns reveal a definite "island effect". The prevailing westerly winds coupled with convection over the land mass bring greater rainfall over the eastern end of Bermuda. Humidity is uniformly high at 70-82% year round, whilst the solar energy reaching the surface of Bermuda has a marked seasonality averaging 640 gcal/cm$^2$/day in July, and 240 gcal/cm$^2$/day in December (Anderson *et al*., 2001).

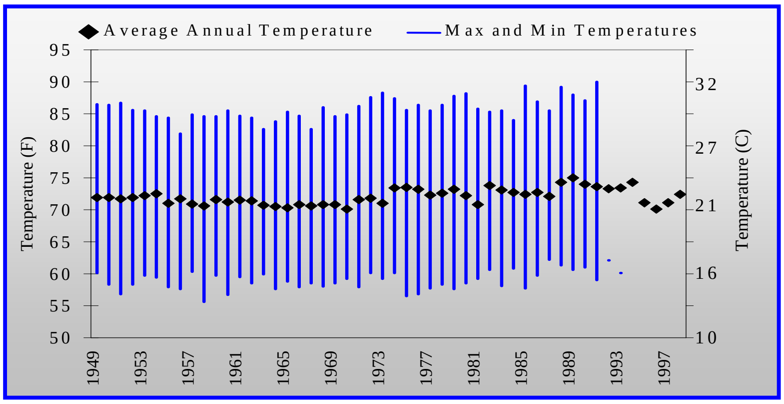


*Figure 10. Average annual temperature with average minimum and maximum air temperatures recorded in Bermuda between 1949 and 1998 (Anderson et al., 2001).*

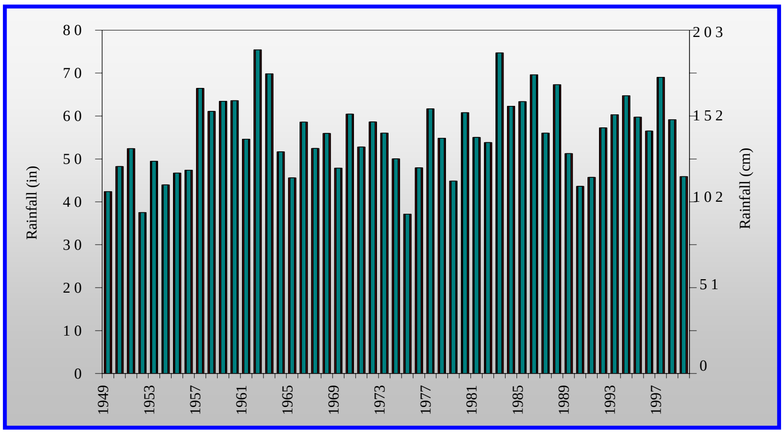


*Figure 11. Annual rainfall recorded in Bermuda between 1949 and 1998 (Anderson et al., 2001).*

The temperature of the seawater surrounding Bermuda is much more stable than the air, ranging from a low of about 18°C in January to a high of 29°C in August. In the shallower inshore waters the range of temperatures is greater, from about 14°C to 30°C. In deeper waters (deeper than 65 m), the temperature is a constant 18°C. The salinity of the waters around Bermuda is 36-37 ‰.

## *3.2 Impact of Climate Change on Bermuda's Climate*

There is considerable uncertainty regarding the extent to which climate change will take place at regional and sub-regional levels, however it is likely that climate change will have some affect on local weather patterns. Any true long term change is likely to be obscured initially by short term changes driven for instance by the decadal but irregular cycle of the North Atlantic Oscillation. There is the further possibility that melting ice may result in the initial 'switching-off' or at least slowing of the 'Atlantic conveyor belt', which is part of the global Thermohaline Circulation (THC) shown below in Figure 12. The THC is driven by differences in the temperature and salinity of oceanic water masses which determines their density. Cooler and more saline water sinks; warmer, less saline water floats above the denser water masses. Some scientists suggest that if the Atlantic belt was to slow or switch off, there would be a significant cooling effect in the Atlantic. However, there is currently insufficient data to support this so no further consideration is given to the subject in this report.

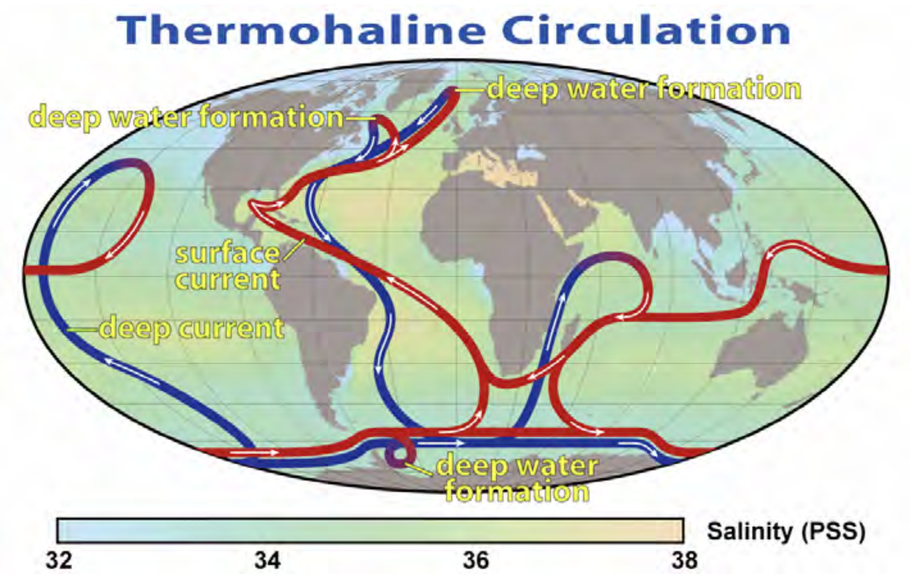


*Figure 12. The global Thermohaline Circulation. (NASA).*

Bermuda is included in the “North East America” zone for the purposes of the IPCC projections on climate change. Whilst it might seem unreasonable to conclude that as an isolated oceanic island, we will experience changes similar to those occurring in the continental USA, with no other projections to rely on at present we should at least give consideration to these models.

### *Increasing temperature*

Under the North East America regional model, temperatures are projected to rise 3.6°C by 2100 (with a margin of uncertainty of 2.8 °C to 4.3 °C for the 25$^{th}$ and 75$^{th}$ percentiles) (IPCC, 2007).

### *Changes in precipitation*

Current global precipitation trends point to greater precipitation in the mid-latitudes, with less in the tropics (IPCC, 2007). Higher air and ocean temperatures in the tropics tend to result in greater evaporation, increasing atmospheric water vapour and consequently precipitation in the northern hemisphere. Annual precipitation rates for the North East America zone are projected to rise 7% (5% and 10% for the 25$^{th}$ and 75$^{th}$ percentiles). An increase in rainfall variability is also to be expected, possibly with more intense rainstorms interspersed with longer periods of drought. Figure 11 shows the irregularity of annual rainfall already experienced in Bermuda.

Increasing sea surface temperature also increases the amount of precipitation that can fall during a storm event. According to Trenberth *et al.* (2007) for every 1°C increase of sea surface temperature, storm precipitation increases by 8%.

Meanwhile, increasing water vapour in the atmosphere exacerbates the greenhouse effect. The amount of water vapour in the atmosphere has in fact increased from 1% to 4% since the Industrial Revolution (Groisman *et al*., 2004).

### *More intense tropical storms*

Predicted global increases in sea surface temperatures may lead to the creation of a more permanent ‘El Nino-like’ state, giving rise to greater wind shear and reduced frequency of hurricane formation. However, an increase in sea surface temperature and therefore greater convection in the Atlantic would result in a greater intensity in the cyclones that are able to form, as evaporating water tends to fuel storm formation. The end result could be fewer hurricanes formed, but greater intensity of those that do (Emanuel, 1987, 2006). Higher sea surface temperatures have also been shown to help in the formation of storms of greater diameter.

However, another factor that must be taken into account regarding storm formation is that global precipitation changes suggest increasing desertification over Saharan and sub-Saharan Africa (Zhang *et al*., 2007), which would impede tropical cyclone formation. Meanwhile, Jiang and Perrie (2008) suggest that when $CO_2$ is elevated in the atmosphere, hurricanes tend to move closer to North America, possibly also placing Bermuda at greater risk (Baltimore, 2008).

Fewer tropical storms may however result in more winter storms (Baltimore, 2008).Tropical storms serve to transfer heat from the tropics to the poles. Less frequent hurricane activity may upset this transfer, resulting in more winter storms forming to complete the movement of heat from the equator. Hart (2008) showed that in years with 12 or more recurving tropical cyclones in the Atlantic, snow cover on the North American continent is reduced and winter storms are not as frequent. Conversely, years with five or less tropical cyclones show greater snow cover over North America, and an increased number of winter storms.

### *Increasing carbon dioxide*

Increasing $CO_2$ is of course the underlying cause of all global climate change variables likely to impact Bermuda's own climate.

***Table 3. Summary of impacts of climate change on Bermuda's climate.***

| CLIMATE CHANGE | EXPECTED IMPACTS |
|---|---|
| Rising temperatures | • Projected to cause temperatures to rise 3.6°C by 2100 (with a margin of uncertainty of 2.8 °C to 4.3 °C for the 25$^{th}$ and 75$^{th}$ percentiles).<br>• Increases the amount of precipitation that can fall during a storm event.<br>• May lead to the creation of a more permanent 'El Nino-like' state, giving rise to greater wind shear and reduced frequency of hurricane formation.<br>• May result in hurricanes of greater intensity.<br>• May help in the formation of storms of greater diameter. |
| Greater variability in global rainfall | • Annual precipitation rates are projected to rise 7% (5% and 10% for the 25$^{th}$ and 75$^{th}$ percentiles).<br>• Will likely result in an increase in rainfall variability with more intense rainstorms interspersed with longer periods of drought.<br>• Increasing desertification over Saharan and sub-Saharan Africa may impede tropical cyclone formation. |
| Increasing $CO_2$ | • Underlying cause of climate change.<br>• May drive hurricanes closer to North America, possibly also placing Bermuda at greater risk. |
| More intense, but less frequent tropical storms | • May result in more winter storms to transfer tropical heat polewards. |

## 3.3 Mitigation and Adaptation

Bermuda has no official public weather service. The Bermuda Weather Service operates under SERCO strictly to serve airport operations. It makes basic weather information collected at the Bermuda Airport available to the public as a community service. Forecasting data is derived from US sources. Weather data does exist for Bermuda back to the mid-1800s but the Bermuda Weather Service does not have the resources to analyse this, nor does it currently have the resources to conduct research on possible future trends. There is clearly a need to provide these resources in order to improve local forecasting in light of escalating global changes.

Any future forecasting efforts should also place Bermuda in the oceanic context in which it lies. The Bermuda Atlantic Time-series Study (BATS) conducted by the Bermuda Institute of Ocean Sciences (BIOS) is a significant resource which could perhaps be used as a platform for providing locally relevant climate data. The interdisciplinary BATS sampling station located off Bermuda includes physical, chemical and biological observations and is producing data to better understand global climate change and the oceans' responses to variations in the atmosphere. Documenting increasing levels of $CO_2$ and understanding of how low frequency physical forces such as the North Atlantic Oscillation impact biogeochemical cycling are already essential components of the research programme but there is also perhaps an opportunity for a more integrated approach between BIOS and the Bermuda Weather Service to allow more accurate weather forecasting and climate projections for Bermuda.

## 3.4 Acknowledgements

The author is especially grateful to Dr. Mark Guishard, Director, Bermuda Weather Service for his input.

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# 4. Sea Level Rise in Bermuda


**SUMMARY**

- Sea levels in Bermuda have fluctuated widely over the past million years. The highest stand recorded was +22 m above present; the lowest -120 m below.

- Sea level has been rising again since the last ice age approximately 18,000 years ago, but the rate of rise has been staggered.

- Sea level changes are not consistent across the globe; there is variation between regions as a result of regional differences in temperature, salinity, winds and ocean circulation.

- Examination of local data reveals disparity; data collated from 10 authors suggest an average rate of sea level rise over the past 2000 years of 2 mm/year. Tide data collected in Ferry Reach since 1932 suggest that in the last 74 years sea level has risen at a rate of 2.04 mm +/- 0.47 mm/year. However, separate analysis from historic photographs indicates that sea level has risen 40.6 cm over the past 131 years, or about 3.1 mm/year.

- There is considerable annual background variation in sea level attributed to lunar affects on tides, the local steric anomaly and occasional meso-scale eddies. The first two of these add 0.865 m to ordnance datum. Warm water meso-scale eddies may add a further 0.25 m.

- A rise of 0.59 m as predicted by IPCC (2007) means that 186.6 ha of land will be inundated with sea water. A 2 m rise, believed to be the upper limit attainable this century, would result in 819.3 ha of inundated land.

## 4.1 Introduction

Present day Bermuda is a low-lying oceanic archipelago comprising a fishhook-shaped chain of four main islands which are surrounded by hundreds of islets, giving a total land mass of 5,370 hectares. Gently rolling hills rise to a maximum elevation of 79 m. Bermuda lines the southeastern edge of a large lagoon formed by the truncated top of one of three extinct volcanic peaks forming the Bermuda Seamount which rises about 4,000 m from the seabed. Presenting a total shoreline of 290 km, the islands also enclose several large inshore basins. Surrounding the whole archipelago, and covering an area of about 750 $km^2$ is the world's most northerly coral reef platform.

Recent re-examination of the island's tectonic history (Blasco *et al.,* 2008) suggests that the Bermuda Seamount is about 45-60 million years old. Over the last million years Bermuda developed a limestone cap on top of this seamount, formed from wind blown sand dunes up to 140 m thick whose carbonate sediments were derived from coral reef organisms. The sand dunes eventually stabilised into today's low-lying landscape.

*Photograph 2. Sand dune bedding on South Shore*

Bermuda has experienced a yo-yo effect of rising and falling sea levels over its geological history. Scientific evidence has shown that during just the past 1 million years sea level fluctuations varied enormously, alternately flooding and exposing the platform every 100,000 years or so and significantly changing the size of the land mass (Sterrer *et al.,* 2004). High sea levels would have left just a string of a few islets surrounded by an extensive shallow water lagoon, whilst low sea level stands would have exposed a contiguous area of nearly 100,000 hectares. Figure 13 below shows these trends but disguises the fact that each sea level rise has not been smooth. Instead it has occurred in staggered episodes with periods of accelerated rise followed by periods of little change.

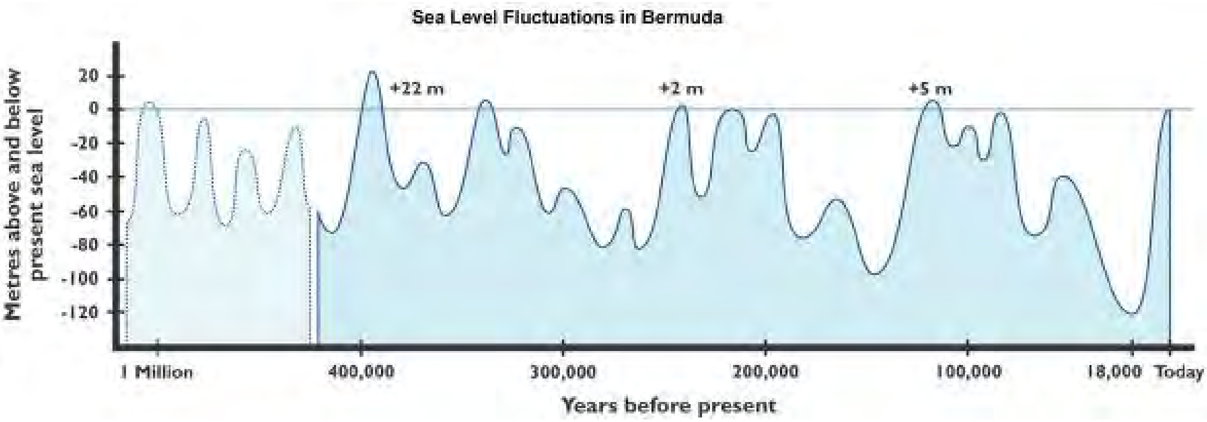



*Figure 13. Sea level rise during the Pleistocene showing highest sea level stand recorded at +22m, approximately 400,000 years ago. (Modified from BAMZ collection).*

Evidence of a high sea level stand 20 ± 3m above present (Hearty *et al.,* 1999) which occurred about 400,000 years ago has been recorded from marine conglomerates. Hearty *et al*. (1999) conclude that such a high stand must have been supported by melting of the Greenland and the Western Antarctic ice sheets, as well as a portion of the East Antarctic ice sheet. Low sea level stands are evidenced at 120 m below present sea level (approximately 18,000 years ago). These low sea levels were most likely accompanied by lower air and water temperatures (Beck *et al*., 1997).

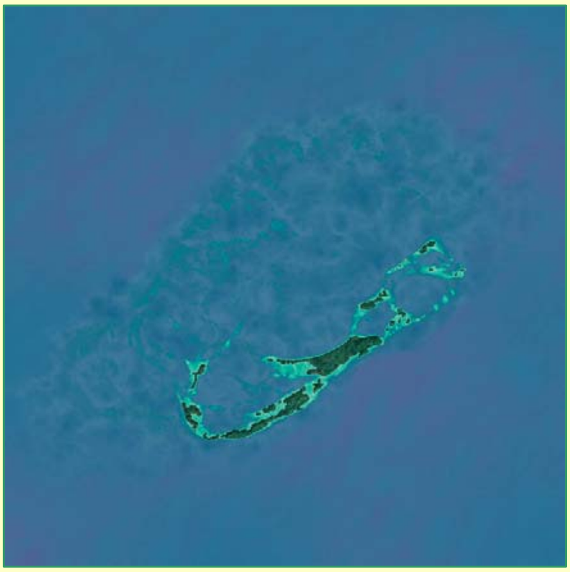


*Figure 14 (top) showing Bermuda during the highest sea level stand +22 m and Figure 15 (below), during the lowest recorded sea level stand (-120 m). (Source: Computer simulation by Frank Vitz and Associates, courtesy of BAMZ Collection).*

## 4.2 Impact of Climate Change on Sea Level

Global sea levels have risen around 130 meters since the depths of the last ice age about 18,000 years ago. Most of the rise occurred at a remarkable rate of 15 - 20 mm/yr for the first 6,000 years. Then, according to the IPCC (2007) from 3,000 years ago to the start of the 19th century the rate of sea level rise was almost constant, at 0.1 to 0.2 mm/yr.

In the 1900s the rate of rise increased to 1 to 2 mm/yr, and from 1993 to the present satellite altimetry has indicated a rate of rise of about 3 mm/yr. Most of this (1.6 mm/yr) is due to thermal expansion of the water followed by glacial and ice cap melting (0.77 mm/yr). The remainder has largely been attributed to melting of the Greenland and Antarctic Ice Sheets according to the IPCC (2007).

Sea level changes are not consistent across the globe. Variation results from regional differences in temperature, salinity, winds and ocean circulation, all of which influence sea level as well as climate-driving factors such as El Nino and the North Atlantic Oscillation.

In an ongoing study in Bermuda being conducted by the Geological Survey of Canada, the Bermuda Underwater Exploration Institute and the Department of Conservation Services, Blasco *et al.* (2008) have been analysing data published by 10 authors between 1965 and 1996 relating to sea level rise in Bermuda over the past 8000 years. The data show considerable variation in rates from one study to the next. By focusing on the past 2000 years, Blasco and his team have integrated these data and plotted them to reveal an average rate of sea level rise over this period of 2 mm/year (which is consistent with the IPCC (2007) data for regional sea level rise in Bermuda. Meanwhile, tide data collected in Ferry Reach since 1932 suggest that in the last 74 years sea level has risen at a rate of 2.04 mm +/- 0.47 mm/year. However, separate analysis by this team reveals that historic data from the seawall built at the British Naval Dockyard in 1835 and photographed in 1876 indicates that sea level has risen 40.6 cm over the past 131 years, or about 3.1 mm/year.


*Photograph 3. Steve Blasco measures the Naval Dockyard wall to calculate current sea level from the scum line for comparison with archived photographs from 1876. (Source: P. Rouja).*

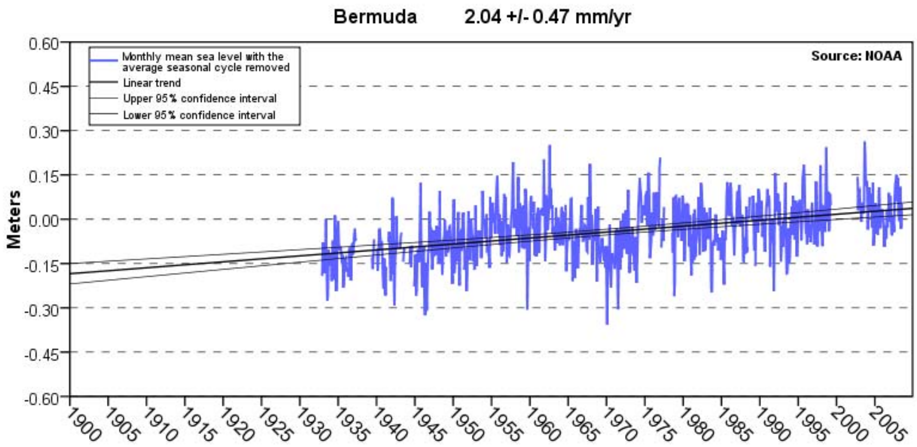



*Figure 16. Showing NOAA sea level data for Bermuda, and a mean sea level rise trend of 2.04 mm/year +/- 0.47 mm/year based on monthly data collected from 1932 to 2006. (Source: NOAA http://tidesandcurrents.noaa.gov).*

Clearly the issue is not entirely straightforward, and coupled to the actual rate of sea level rise is the issue of subsidence. Satellite GPS vertical motion velocity data published by the Jet Propulsion Laboratory in the US indicates that the island has been subsiding at the rate of 0.9 mm/year since 1993. These data have been derived from the vertical motion sensor positioned at the Bermuda Institute of Ocean Sciences.

In trying to determine the future impact of sea level rise in Bermuda, it is important to remember that there is considerable annual background variation about the mean. Lunar affects on tides and a local steric anomaly affect the actual sea level on an annual basis. These must be factored in if full consideration is to be given to the impact of rising sea level.

Local tides give us a tidal range of 0.8 – 1.2 m depending on the moon. Additionally, there are semi-annual fluctuations related to water temperatures that need to be superimposed. In the early summer, an upper "mixed layer" of warm water develops in the ocean around Bermuda, with temperatures often exceeding 25°C by late summer and extending down to 100 m depth or more. Therefore from April to November the surface ocean waters around Bermuda undergo thermal expansion with a related sea level rise of about 0.25 m. It is this “steric anomaly” which is responsible for the very high tides typically observed towards the end of the calendar year (see Figure 17 below). Cooler air temperatures and storm activity in the autumn mean that from November onwards the warmer surface layer and the associated thermocline below dissipate. By January, a deeper mixed layer has formed with near constant temperatures of approximately 18°C extending from the surface down to 450 m.

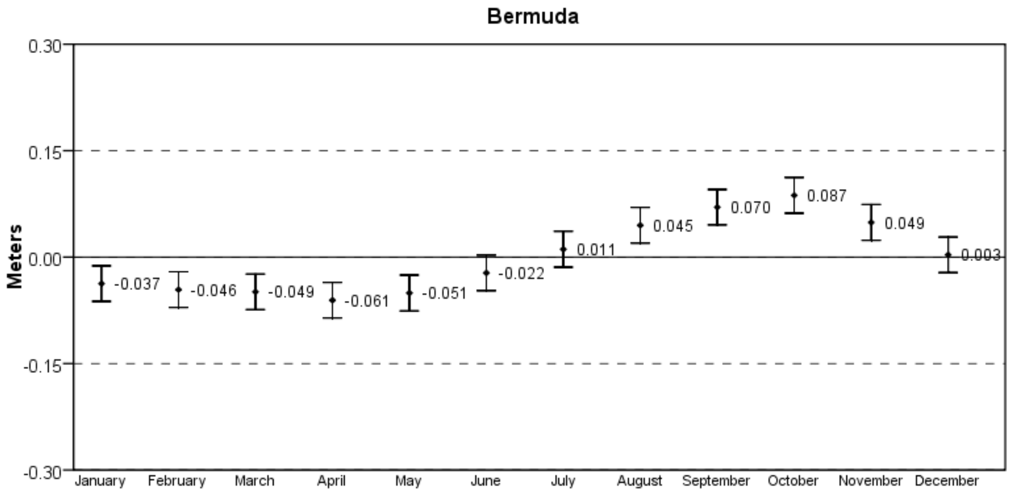



*Figure 17. Average seasonal cycle of mean sea level, caused by regular fluctuations in coastal temperature, winds, atmospheric pressures and ocean currents. (Source: NOAA http://tidesandcurrents.noaa.gov)*

Finally, an additional factor that needs to be assessed in Bermuda is the impact of meso-scale eddies of warm and cold water. Generated in deep water, these can either depress sea level (cold eddies) or increase it (warm eddies). They may persist in the local area for many months. In 2003, there were three such anomalies (*http://tidesandcurrents.noaa.gov*) with one in November that raised sea level by about 25 cm (Government of Bermuda, 2005).

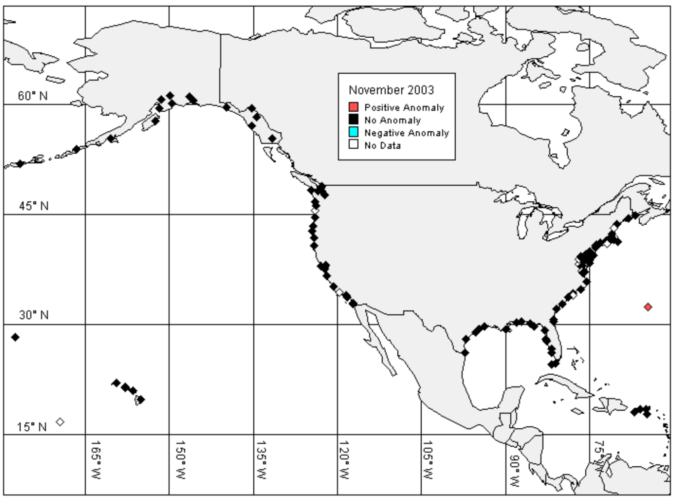



*Figure 18. Showing NOAA record of steric anomaly that affected Bermuda in 2003 (Source NOAA http://tidesandcurrents.noaa.gov).*

## *Box 6. Methodology for Sea Level Projections*

In calculating projections for future lea level rise in this report, the Digital Terrain Model (DTM) (© Government of Bermuda) has been used as the basis for the GIS shape files. The DTM works from ordnance datum as 0 m elevation. Current Mean Sea Level is calculated as being 0.21 m above ordnance datum. An additional 0.125 m has been allowed for the steric anomaly (the amplitude of the steric anomaly is about 0.25 m on a monthly average basis so half of this (0.125 m) gives the approximate value for the maximum steric level above the mean because the curve is approximately "symmetrical" (Rowe, pers. comm.). Finally, allowing for the spring tide amplitude (0.6 m) a total of 0.935 m has been added to the DTM. (It was decided that the addition of chance meso-scale eddies would not be included in these projections).

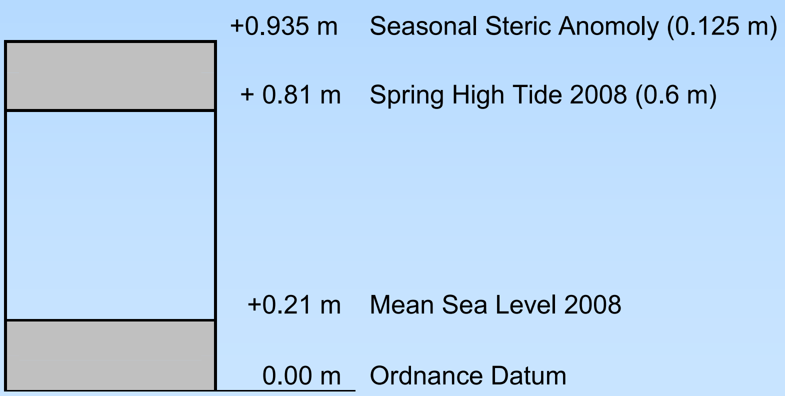
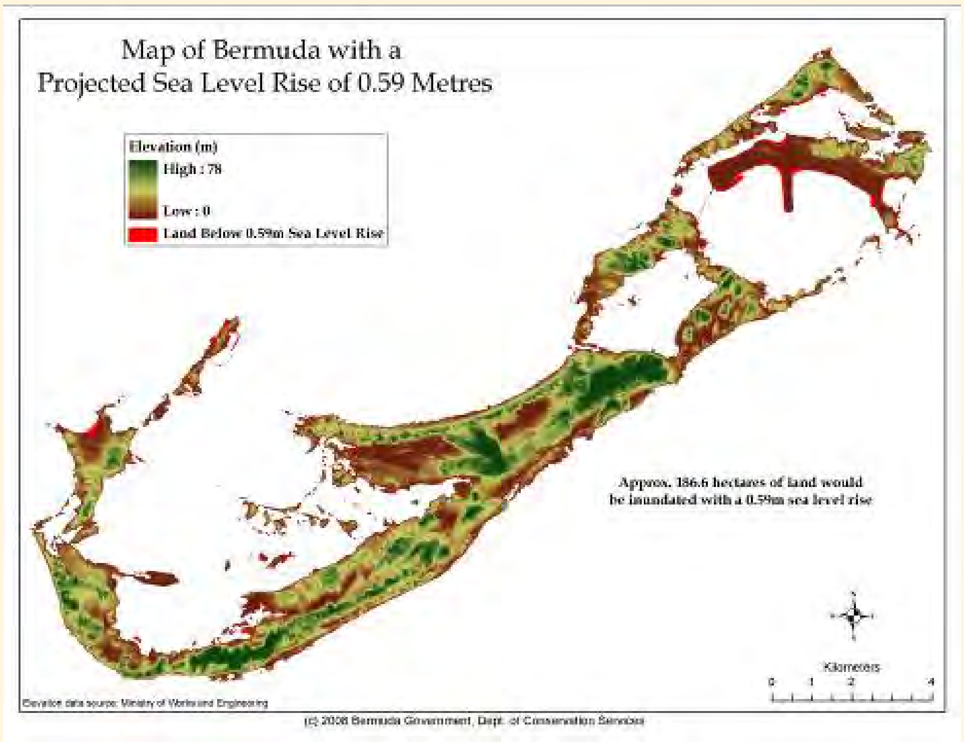
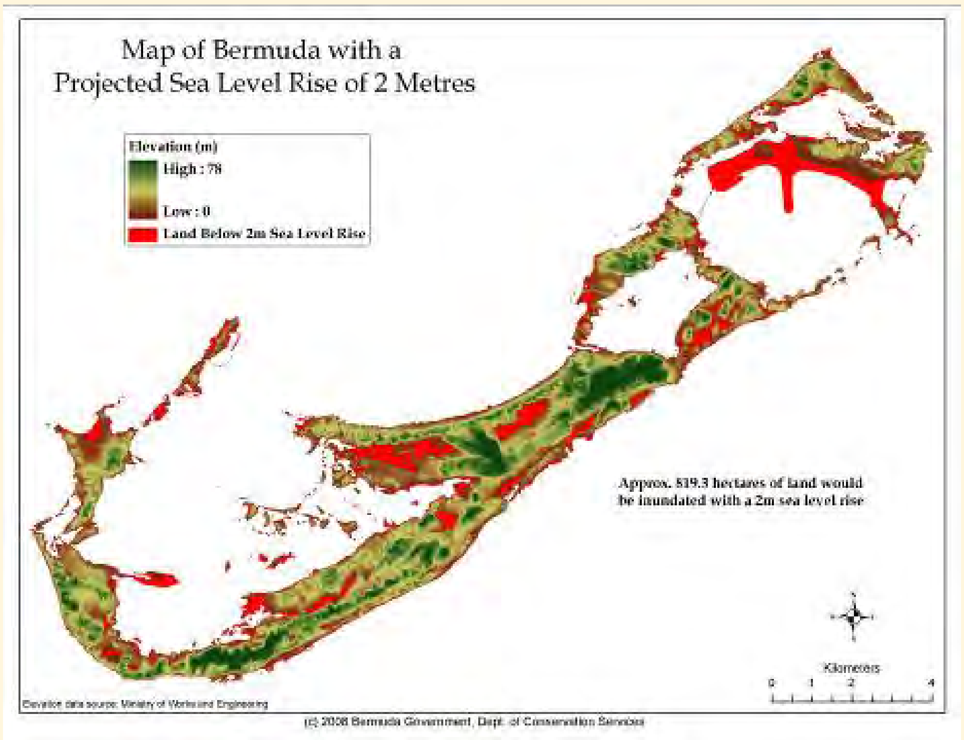



*Figure 19. Showing local benchmarks for tidal height in Bermuda.*

Using this baseline, the following figures show sea level rise projections across Bermuda for two scenarios. The first of these is for 0.59 m (the upper end of the IPCC (2007) sea level projections for the 21st century. This shows that approximately 186.6 ha of land would be inundated during high tides. However, the IPCC (2007) underlined that this estimate only included rises caused by the expansion of sea water in a warmer climate, not the water contributed by the decline of Greenland and Antarctica ice sheets. Whilst further modeling is required to determine more accurate predictions, gross calculations to assess the maximum possible rise that can be expected this century suggest that 2 m is physically possible (Pfeffer *et al.*, 2008), so the second projection accounts for a 2 m rise and reveals more alarmingly that 819.3 ha would be lost to the sea. This is 14% of Bermuda's land area.




*Map 1. Showing a projected sea level rise of 0.59 m (the IPCC 2007 upper limit) on the Bermuda elevation model.*




*Map 2. Showing a projected sea level rise of 2.0 m (Pfeffer et al., 2008) upper limit) on the Bermuda elevation model.*

As a final note, storm surge during hurricanes will also cause elevated sea levels. With storm intensity predicted to increase in the Atlantic as a result of climate change, Category 1 hurricanes might be expected to produce a surge of 1.2 – 1.5 m on top of the above projections. A Category 3 storm may add an additional 2.7 – 3.6 m whilst a Category 5 storm may produce a 5.5 m or greater storm surge (National Hurricane Center, 2007).

It is perhaps worth noting that compared with many islands, Bermuda is fortunate to have a shoreline that for the most part rises quite steeply, sparing us the impacts from sea level rise that may be felt more dramatically in other jurisdictions.

## 4.3 Acknowledgements

The author gratefully acknowledges input from Dr. Steve Blasco of the US Canadian Geological Survey and Dr. Philippe Rouja (Custodian of Historic Wrecks) and Ms. Mandy Shailer (GIS Coordinator), Department of Conservation Services.

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# 5. Impact of Climate Change on our Infrastructure


**SUMMARY**

- Bermuda's infrastructural base (including ports, airports, telecommunications, settlements and businesses) which supports the island's vital socio-economic sectors is clearly vulnerable to the impacts of climate change.

- Most, if not all of our infrastructure is typically designed, built and maintained on the premise that the future climate will be similar to that experienced in the past. We now know that this is an unrealistic assumption and to continue along this path is to present significant risk to this infrastructure and the owners, managers, and community that rely on it.

- With land resources totaling just 5,370 ha, land is a precious commodity and there is strong competition for it amongst different sectors. Climate change will only add stress and increase competition for these resources.

- Saltwater inundation will lead to corrosion of steel and concrete as well as degradations to road and runway foundations, bridges and ports. Rising temperatures increase expansion and materials degradation of concrete joints, steel, asphalt, protective cladding, coatings, sealants, timber and masonry. In addition to reducing life expectancy, there will be increased maintenance costs and potential structural failure during extreme events.

- Increased storm intensity will cause material fatigue, flooding from storm surge, wind damage to telecommunications' infrastructure and disruption to service, increased costs of maintenance and replacement of transport infrastructure, and disruption of transport service all leading to economic impacts.

- A comprehensive coastal zone management plan is needed building on the Draft Planning Statement (2008) which deals with both sea level rise and the other impacts of global climate change. Such a plan should ensure that risks to people are minimized, while recognizing the need to protect and maintain important coastal ecosystems.

## 5.1 Introduction

Like most small islands, Bermuda's infrastructural base (including ports, airports, telecommunications, settlements and businesses) which supports the island's vital socio-economic sectors occupies coastal locations, which are clearly most vulnerable to the impacts of climate change. In fact, by globally accepted definitions 100% of Bermuda's population resides in a coastal location.

Most, if not all of our infrastructure is typically designed, built and maintained on the premise that the future climate will be similar to that experienced in the past. We now know that this is an unrealistic assumption and to continue along this path is to present significant risk to this infrastructure, the owners, managers, and community that relies on it.

Turnover of infrastructure is a gradual process, with replacement and upgrade typically occurring on a needs basis, often dictated by differences in the life span and need for different infrastructure items. Advances in technology may also render some forms of infrastructure obsolete although changes need to be balanced with a desire to maintain our archaeological heritage and identity.

With land resources totaling just 5,370 ha, land is a precious commodity (Government of Bermuda, 2005). Economic growth has resulted in increasing pressure to develop these limited resources. This is set against a need to preserve open spaces for social, environmental and aesthetic needs. Climate change will only add stress and increase competition for these resources.

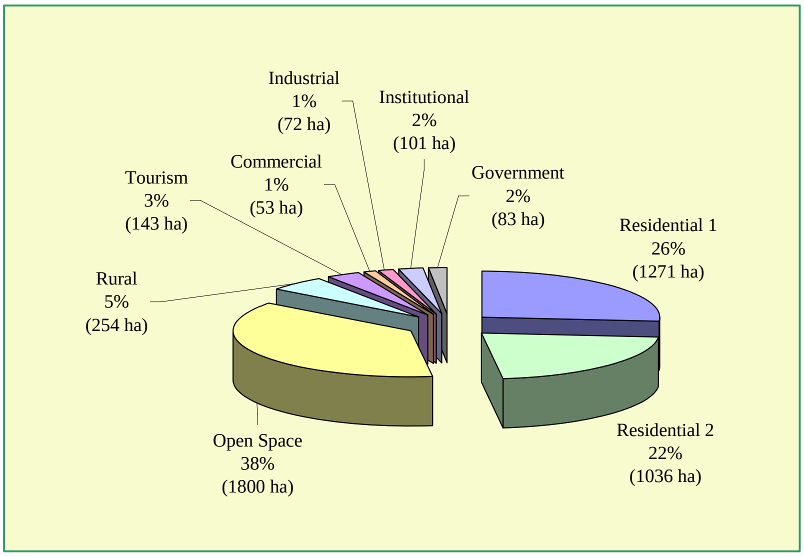



*Figure 20. Land use according to the Bermuda Plan 1992 (excluding City of Hamilton. (Source, Anderson et al., 2001)*

In 2004, there were over 28,000 households (Government of Bermuda, 2008) and the following figure illustrates the population density across the island.

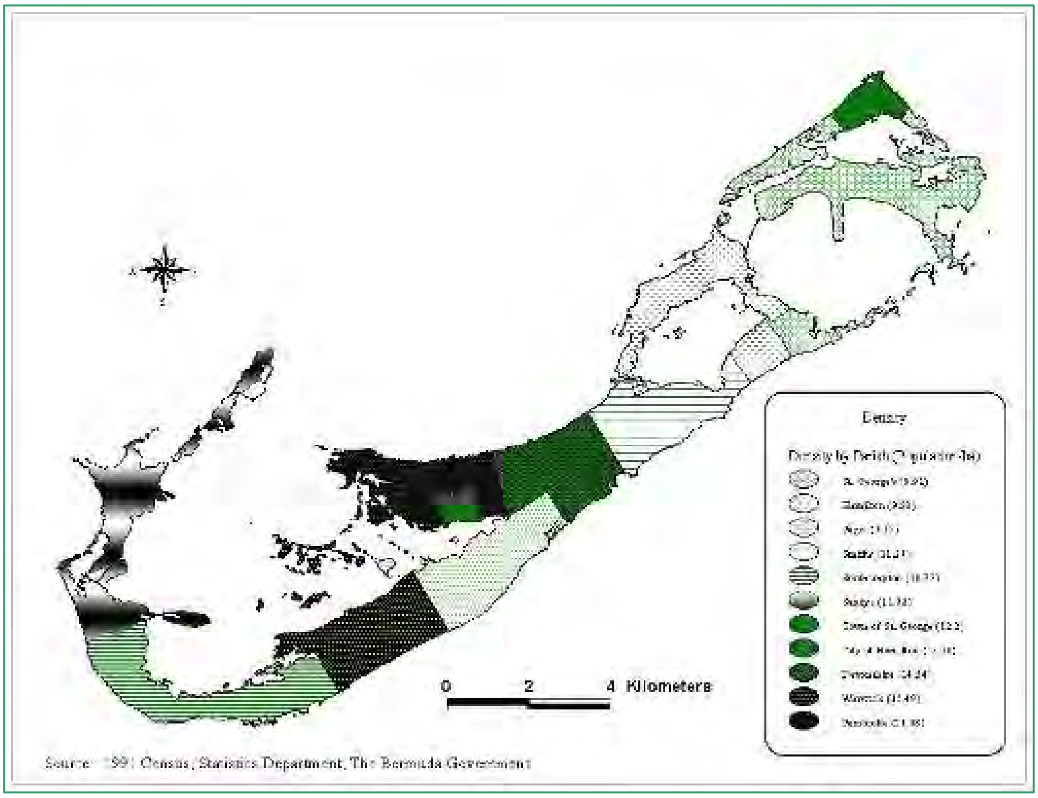



*Figure 21. Population distribution across Bermuda in 1991 (Source: Anderson et al., 2001).*

We can divide Bermuda's infrastructure into several components: buildings, transport (land, air, sea), solid waste disposal, wastewater, and telecommunications.

<u>Buildings</u>

In Bermuda, the design, siting and construction standards for new infrastructure are controlled by the Development and Planning Act 1974 administered through the Department of Planning. This Act establishes a broad framework of control. Planning permission is required for any development of land, and each application is assessed against the Bermuda Plan (currently the Bermuda Plan 1992, but the draft Bermuda Plan 2008 Plan is under review (Government of Bermuda, 2008b). Once approval in principle is granted, a building permit is required for almost all building. Infrastructure and inspections need to be made at certain stages of the building process, so as to ensure compliance with relevant standards.

For major infrastructure or controlled buildings or equipment, additional approvals are required under relevant environmental impact assessment legislation (i.e. Environmental Authority (Department of Environmental Protection and the Department of Environmental Health). The design and construction of most infrastructure typically involves individuals from different professions, including architects, town planners, engineers, lawyers and surveyors. The services they provide are to some extent reliant on each other, and all are subject to professional responsibilities particular to their discipline. Many of these professional responsibilities are supported by legislation that regulates conduct of the members of the profession in question.

This framework ensures that Bermuda does have a very effective planning and building control system.

## Transport

### *Land*

Transport infrastructure includes roads, bridges, ports and the airport. Bermuda has approximately 209 km of public roadway and 248 km of private roads (Government of Bermuda, 2005). The network is well developed with little room for further development. The public road system is maintained by the Ministry of Works and Engineering. Private roads are maintained by the landowners, but are regulated under the Development and Planning Act, 1974. There were 48,054 registered road vehicles in 2007 (Government of Bermuda, 2008).

Several bridges link the main islands. The vulnerability of the longest, the Causeway was apparent during Hurricane Fabian which breached the bridge and left the east end of the island stranded, and the airport inaccessible to residents west of the Causeway. Major construction works have been completed in the past decade on Somerset Bridge and the Causeway.

### *Air*

The F. L. Wade International Airport is a civil airport owned and operated by the Department of Airport Operations. It provides a critical link for Bermuda, isolated as it is from other land masses. Operating standards are consistent with the recommended practices and standards of the International Civil Aviation Organisation (ICAO), as well as the US. Federal Aviation Administration and the U. K. Civil Aviation Authority. Occupying 227 ha of land (excluding the disused runway extending into Castle Harbour) the airport has one operational runway, 2,961 m long and 46 m wide and several taxiways (Government of Bermuda, 2005). In 2002, there were nearly 14,000 aircraft arrivals and departures, almost 850,000 passengers and 7 million kg of mail and cargo (Government of Bermuda, 2005).

Airport storm water drains into Castle Harbour through drains running under the runway; these drains were upgraded in 1996, when plastic pipes were installed within the existing pipes. The runway has recently been re-surfaced. There is an active ongoing land reclamation scheme at the airport site utilising ash block from the waste incinerator and waste metal.

### *Sea*

Bermuda has three ports in Hamilton, St. George’s and Dockyard. In 2001, 1,566 boats from overseas docked in Bermuda; 69% of these were yachts, the rest were ships, of which 71% were passenger and cargo (Government of Bermuda, 2005). Current plans include the re-designation and construction of Dockyard as the sole port for cruise ship arrivals supporting a move towards newer, larger ships capable of accommodating up to 2,500 passengers and 800 crew. Cruise ship passengers currently account for just over 50% of Bermuda's tourist visitors.

Ferry transport also has quite strong public support from residents (particularly between Hamilton and Somerset/Dockyard and Hamilton and St. George's), as well as being popular with tourists. Recent upgrades to the ferry system have improved the service and currently there are 7 ferries in operation. Better utilization of Bermuda's waterways to alleviate land transport problems and to encourage larger cruise ships also requires upgrades to the infrastructure.

Solid Waste Disposal

70,000 tonnes of domestic and commercial non-bulk waste is burnt at the mass burn Tynes Bay incinerator annually. Ash residue is mixed with cement to form blocks placed in Castle Harbour. Inert waste is handled at the Airport Waste and Land Reclamation Facility. About 40 container loads of hazardous waste are currently shipped off the island but this may not be possible in the future (Government of Bermuda, 2005). Approximately 25,000 tonnes of horticultural and food waste is handled at the Marsh Folly Compost Facility each year (http://www.gov.bm).

Waste water and sewage

Of Bermuda's annual rainfall, it is estimated that 75% evaporates (Government of Bermuda, 2008). The rest may pick up contaminants before entering the groundwater and then the ocean. Water running off artificial surfaces such as roads, parking lots and industrial lots, picks up pollutants from traffic, tyres, paints, solvents and oil as well as silt and soil. All public roads are maintained to ensure efficient storm water run-off, however during heavy rainfall, flooding can be a significant problem. Parts of Bermuda are already subject to regular flooding, particularly in the designated industrial sections of Pembroke around Mills Creek. These areas are undergoing renovations to the drainage system to try and manage problematic flood waters. Pembroke Canal runs through the main industrial area including the Bermuda Electric Light Company. High tides plus freshwater run-off cause frequent overflows. Infrastructure provision for drainage is managed by the Ministry of Works and Engineering which is responsible for ongoing drainage management, operations and maintenance.

Sewage disposal in Bermuda is accomplished mainly by discharge into household cesspits. The Town of St. George's and City of Hamilton both have a public sewerage system. Most sewage is benign domestic in nature rather than toxic industrial. Sewerage from the City receives primary treatment before being pumped offshore. Deep-sealed boreholes are installed for effluent disposal in high density developments.

Telecommunications

Bermuda has excellent cable and satellite communications and service links. The telecommunications infrastructure services include the fixed line network (trunk lines to exchange stations), and the mobile network (transmission towers). Most of the fixed lines have now been buried, making them less vulnerable to tropical storms.

## 5.2 Impact of Climate Change on Infrastructure

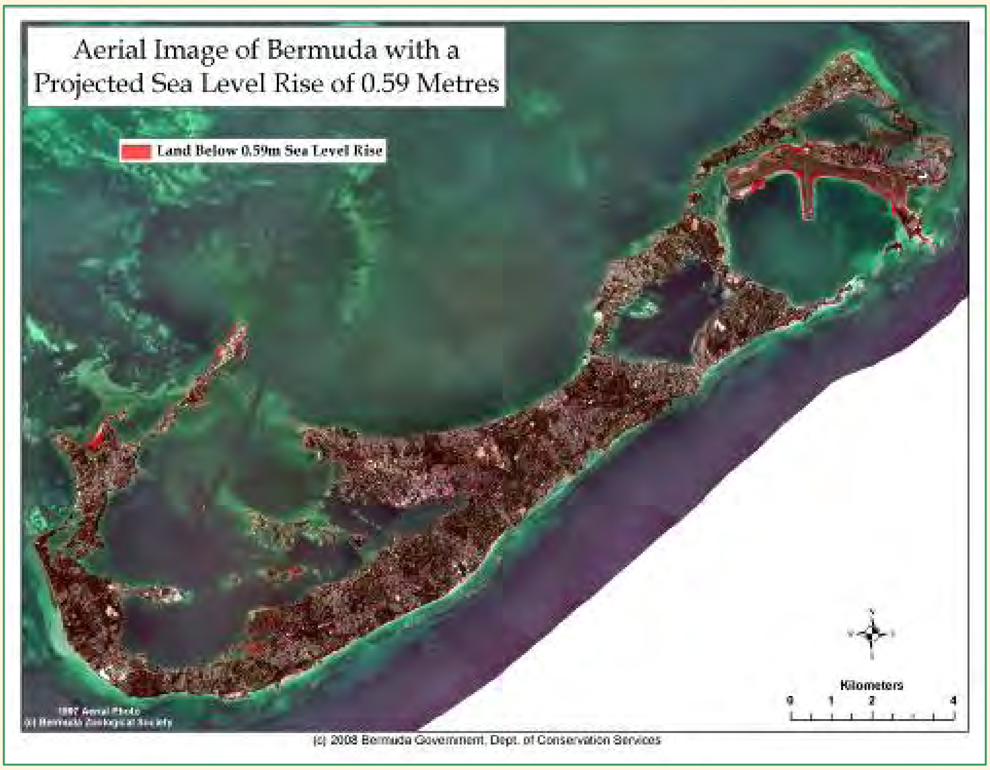
Climate change poses a significant risk to infrastructure and its owners, managers and longterm operators. There will be direct impacts on the human-made physical infrastructure and the intended service it provides to the community, industry, government and the natural environment. These may then result in secondary impacts on human health and amenities as well as presenting significant financial costs in the form of ancillary plant/equipment to maintain, repair and replace it. Governance may also be affected.

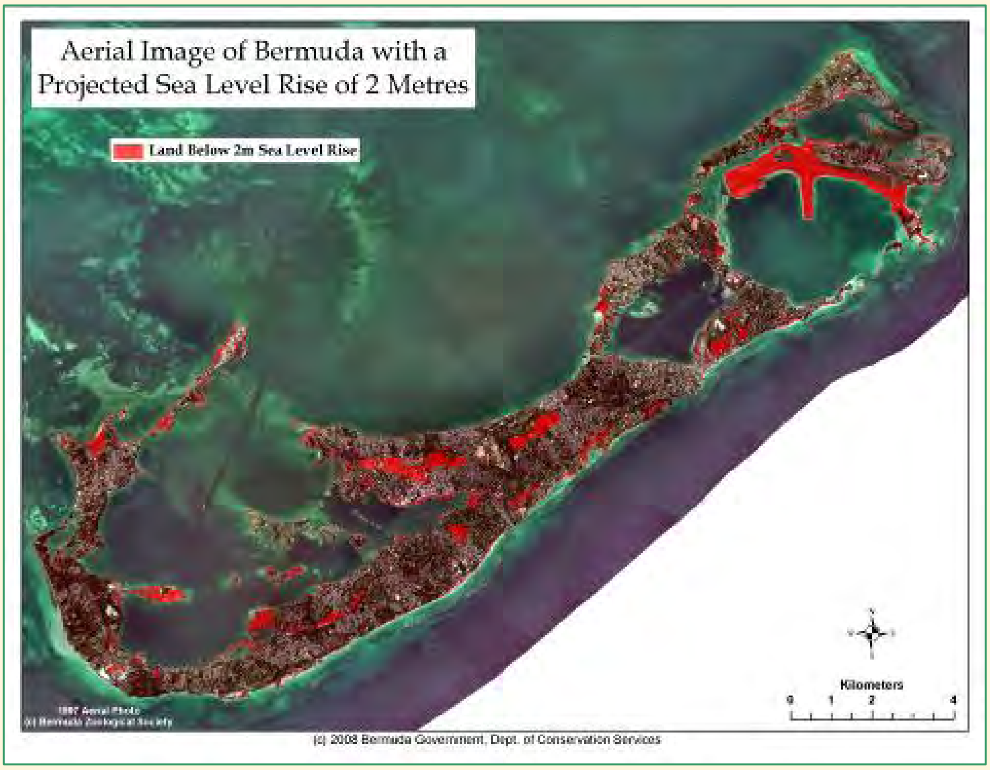
### *Sea level rise*

Sea level rise will affect all aspects of our infrastructure. Saltwater inundation will lead to corrosion of steel and concrete in buildings thereby reducing the life expectancy of buildings, structures and facilities, increasing maintenance costs and leading to potential structural failure during extreme events. There will be degradations to road and runway foundations as well as the bridges. Ports and residences will also be affected. All these impacts will be compounded when storm surge and related flooding are added to the rising sea levels. The following series of maps shows the impact of a sea level rise of 0.59 m (the upper end of the IPCC (2007) predictions) and 2 m, the predicted upper limit possible by the end of the century (Pfeffer *et al*., 2008).

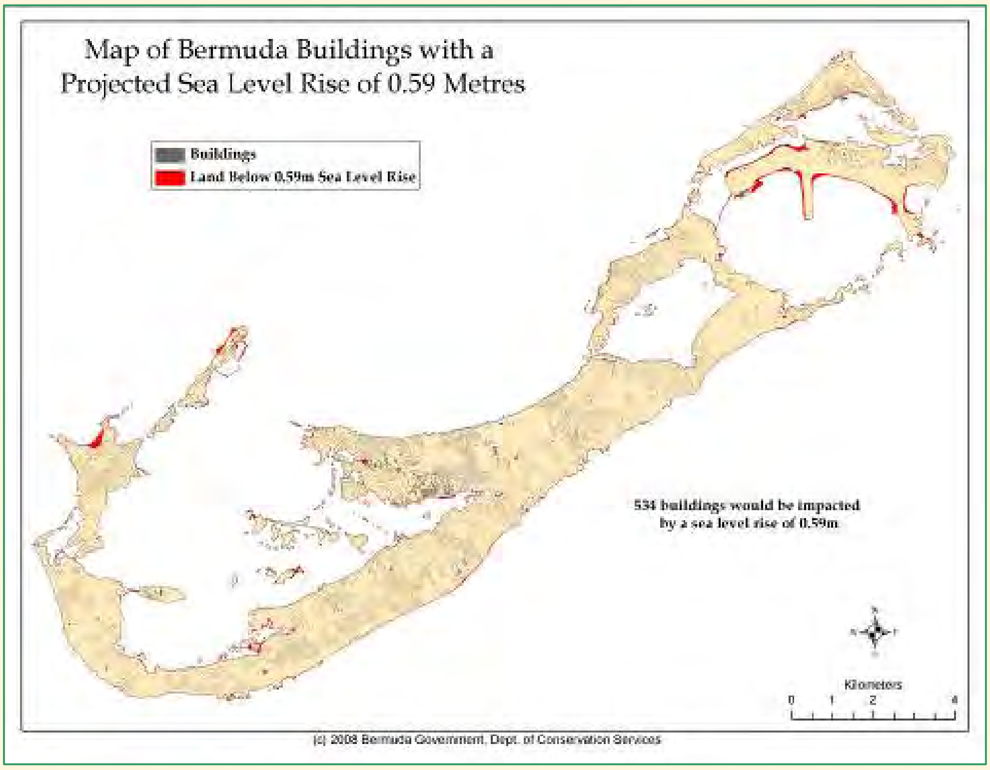
Maps 3 and 4 give an overall impression of how Bermuda would be affected. Maps 5 and 6 reveal that with a 0.59 m sea level rise, 534 buildings would be affected, whilst 1,977 would be impacted by a 2 m rise. These are followed by Maps 7, 8, 9 and 10, which show projections of sea level in Hamilton and St. George's. In all cases, both with a 0.59 m rise and particularly a 2 m rise, it is apparent that the waterfront and port in both towns is significantly inundated, at least during high tides.

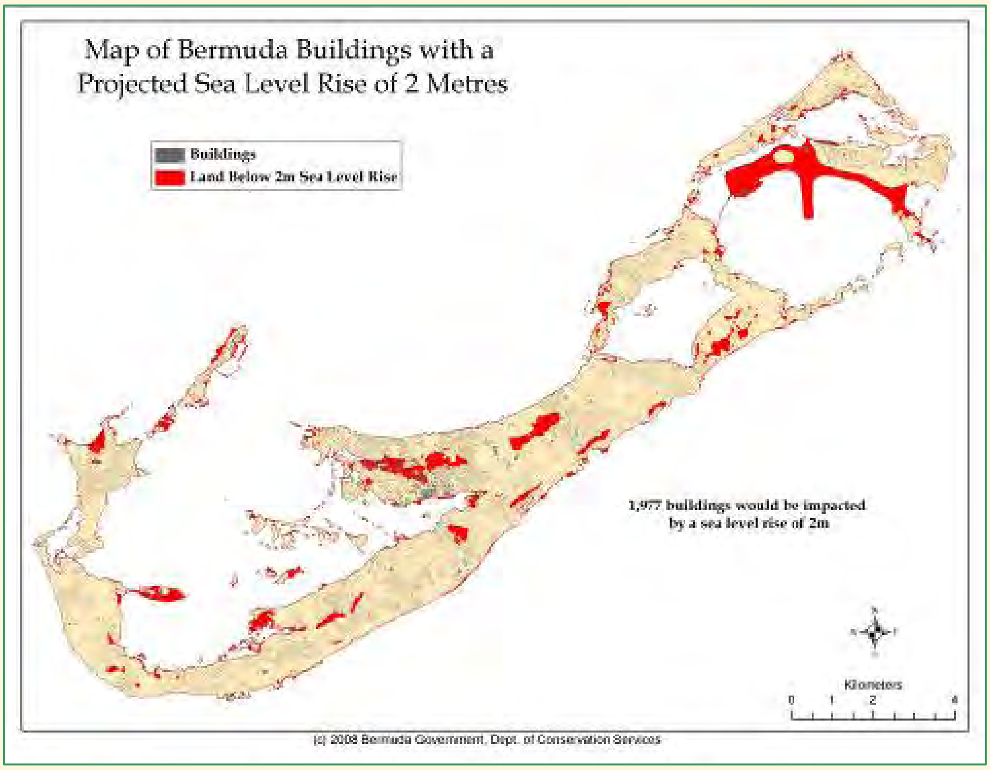
The situation at the F. L. Wade International Airport is similarly alarming, as seen in Maps 11 and 12. ICAO regulations stipulate that runways must be setback a specific distance from the shoreline, and even with a 0.59 m sea level rise, there is significant loss of land adjacent to the main runway; with a 2 m sea level rise, the whole airport will be underwater. Even a 0.59 m rise would eliminate the Airport Waste and Land Reclamation Facility.



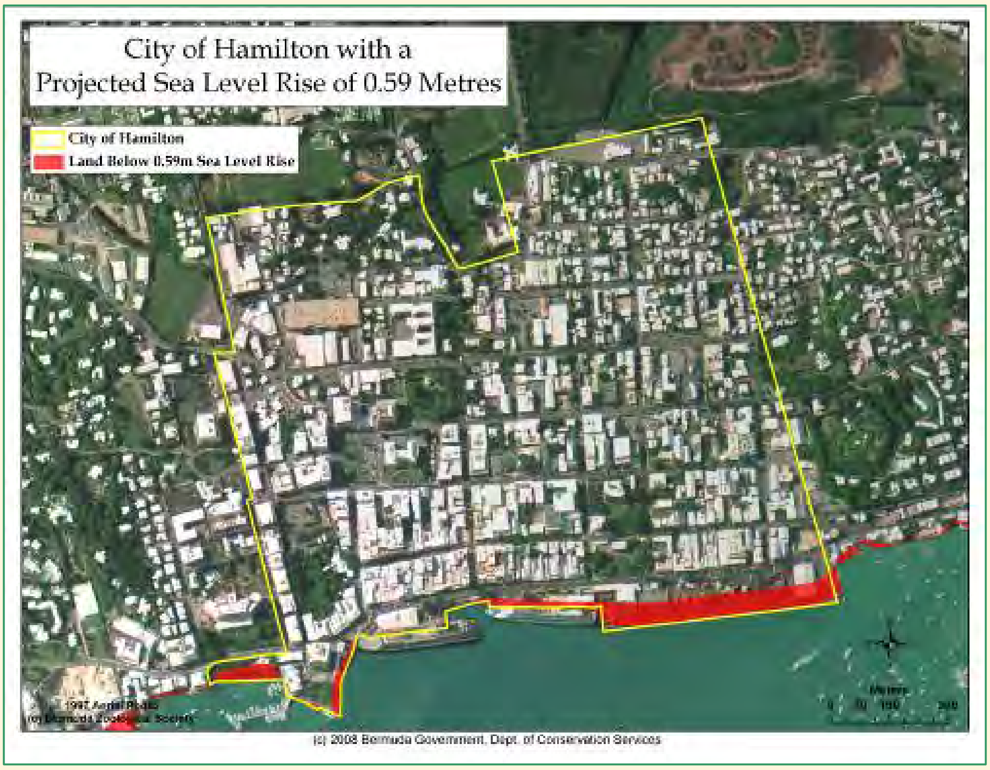




*Map 3 (above) showing the overall impact of a 0.59 m sea level rise and Map 4 (below) of a 2.0 m sea level rise*




*Map 5 (above) showing the impact of a 0.59 m sea level rise on Bermuda's buildings and Map 6 (below) of a 2.0 m sea level rise.*





*Map 7 (above) showing the impact of a 0.59 m sea level rise on the City of Hamilton and Map 8 (below) of a 2.0 m sea level rise.*



*Map 9 (above) showing the impact of a 0.59 m sea level rise on the Town of St. George's and Map 10 (below) of a 2.0 m sea level rise.*



*Map 11 (above) showing the impact of a 0.59 m sea level rise on the F.L. Wade International Airport and Map 12 (below) of a 2.0 m sea level rise.*

### *Increasing temperature*

Temperature and solar radiation increases forecast to occur with climate change could reduce the life of building and facility elements due to increased expansion and materials degradation of concrete joints, steel, asphalt, protective cladding, coatings, sealants, timber and masonry. In addition to reducing life expectancy, there will be increased maintenance costs and potential structural failure during extreme events. Rising temperatures may also lead to asphalt degradation of road surfaces and airport tarmacs, structural material degradation of bridges and may also accelerate the degradation of telecommunication transmission cables.

### *Changes in precipitation*

An increase in the intensity of extreme rainfall may accelerate the rate of damage to buildings and our urban facilities. There will be increased risk from flooding if existing drainage issues are not resolved; electrical substations, telecommunication exchanges, manholes and underground pits will be more susceptible, as will roads and the airport tarmacs, which may degrade more quickly.

### *More intense tropical storms*

Our airport and ports, as well as bridges, roads and buildings are all susceptible to tropical storms; all are particularly at risk when storm surges combine with sea level rise, as was witnessed in Hurricanes Emily and Fabian. Extreme storm events all cause fatigue of materials, structures and foundations of buildings and facilities. Increased storm surges have the potential to lead to the flooding of telecommunications exchange stations whilst the predicted increased intensity of storms will also affect the above ground fixed line telecommunications transmission infrastructure and therefore reductions in the level of service that they provide. Increased frequency and length of network outages would cause a disruption to communication services provided to the community, business and government, while potentially affecting emergency response and coordination efforts. Costs of supply may increase due to an intensified maintenance regime. Mobile telecommunications towers may be adversely affected by stronger winds. The projected increase in storm activity may also increase the cost of transport infrastructure maintenance and replacement, and the disruption of transport services which could have

*Photograph 4. Showing structural damage to South Shore Road caused by Hurricane Fabian.*

significant economic impacts. Hurricane Fabian left the F.L. Wade International Airport flooded (and fish stranded on the runway, Guishard (pers. comm.)) resulting in its closure; a number of the major international businesses had to relocate their board meetings. If this becomes a more frequent occurrence, Bermuda may become a less desirable location from which to do business.

***Table 4. Summary of impacts of climate change on Bermuda's infrastructure***

| CLIMATE CHANGE | EXPECTED IMPACTS |
|---|---|
| Sea level rise | • Saltwater inundation of airport (a 2 m rise would drown it).<br>• Flooding and structural integrity of residential and commercial buildings affected (1,977 buildings with 2 m rise).<br>• Structural integrity of Ports of City of Hamilton and St. George's compromised.<br>• Structural integrity of roads and airport tarmac affected.<br>• Increased maintenance costs of Bermuda's infrastructure. |
| Increasing temperature | • Degradation of concrete joints, steel, protective cladding, coatings, sealants, timber and masonry leading to potential structural failure during extreme events.<br>• Increased maintenance costs.<br>• Degradation of asphalt road surfaces and airport tarmacs.<br>• Degradation of telecommunications cables. |
| More intense tropical storms | • Fatigue of materials, structures and foundations of buildings and facilities.<br>• Increased storm surges have the potential to lead to flooding.<br>• Damage to above ground fixed line telecommunications transmission infrastructure and therefore reductions in the level of service that they provide.<br>• Costs of telecommunications supply may increase due to an intensified maintenance regime.<br>• Increased cost of transport infrastructure due to maintenance and replacement.<br>• Disruption of transport services which could have significant economic impacts. |
| Heavier, less frequent rainfall events | • Increased risk of flooding of buildings, electrical substations, telecommunications exchanges, manholes and underground pits, as well as roads and the airport runway. |

## 5.3 Impact of Infrastructure on GHG Emissions

Ongoing maintenance of our infrastructure results in GHG emissions. Manson and Hasselbring (2005) reported on 2000 annual emissions for Bermuda. By far the most significant emissions are from our transportation system, primarily 164.5 Gg of $CO_2$ and 15.57Gg of CO (carbon monoxide), compared with 14.27 Gg of $CO_2$ from residential emissions. Handling of waste water only produces small amounts of methane and nitrous oxide. They suggest that advances in the efficiency of vehicle engines, has tended to counter the increase in traffic since 1990 so the emissions remained relatively stable between 1990 and 2000.

***Table 5. Summary of impacts of Bermuda's infrastructure on GHG emissions.***

| GHG | IMPACTS |
|---|---|
| Greenhouse gas (GHG) emissions | • All transport on the island results in emissions of various GHGs.<br>• Road and airport tarmac maintenance will contribute to emissions.<br>• Importation of replacement building materials also contributes to carbon emissions.<br>• Waste management and wastewater handling contribute to GHG production. |

## 5.4 Mitigation and Adaptation Measures

By its very nature as an isolated island, Bermuda with a strong economy has some inherent characteristics that will give it resilience in the face of climate change. The island has a solid infrastructure including island wide accessibility to transport, electricity and telephone and/or Internet communication, high building standards and long experience of dealing with climate variability and extreme weather events such as hurricanes. However, some of the risks identified in this summary represent a significant challenge for our community whether we are infrastructure owners, managers or decision makers. It is apparent that all sectors will be affected, and that current assumptions about the likely range of future climate conditions require review.

There are three general categories of response with regards to the impact of climate change on our infrastructure:

1) Retreat, which involves no effort to protect the land from the sea and ultimately results in the abandonment of the impacted areas;

2) Accommodation, whereby we continue to use the land at risk but do not attempt to prevent it from being flooded; and

3) Protection, which involves hard structures such as sea walls and dikes, as well as soft solutions such as dunes and vegetation, to protect the land from the sea so that existing land uses can continue.

As part of an overall response strategy we might consider the gradual replacement of infrastructure in non-threatened locations, where this proves feasible. Adoption of increasingly rigorous building codes and other design and construction standards, mandatory building setbacks in coastal areas, and diversification of economic activities might also be appropriate adaptations. There may be a need for developers to build higher, ensure drainage and employ coast care mechanisms such as planting and other land management measures. At the very least, there is a need for a comprehensive coastal zone management plan which deals with both sea level rise and the other impacts of global climate change. Such a plan should ensure that risks to people are minimized, while recognizing the need to protect and maintain important coastal ecosystems.

A step towards this has been made by the Planning Department, which is adopting a more precautionary approach to coastal development and taking increased vulnerability of coastal properties into account in their Draft Planning Statement 2008 (Government of Bermuda, 2008b). Following a coastal erosion study conducted in 2004 (Government of Bermuda, 2004) a new “Coastal Reserve” zone (COR) has been included. The stated objectives of the COR are to protect and conserve the ecological, natural scenic qualities of coastal areas and islands and to protect the coastal areas and islands from storm surge and erosion. It provides a ‘buffer or setback between the shoreline and development areas’ …and its boundaries ‘take into account the wave energy, storm surge and erosion risk at particular locations around the island, the mean low and high watermark, elevation, topography and shoreline type’. Islands, headlands and other areas of high visual and habit are usually all within the COR zone but COR areas adjacent to developed areas may be more limited.

Improving scientific and public understanding of the problem is also a critical component of any response strategy. The highest priorities for basic research are better projections of changes in the rate of sea level rise, precipitation and the frequency and intensity of storms. However, it is important to remember that we know enough about the general trend in sea level rise and the possibility of a large increase to begin thinking about a wide range of possible policy responses.

Of all the infrastructure sectors discussed, it is the building sector which has the most diversity of ownership and number of individual owners. Communicating the risks of climate change to owners must be undertaken in a responsible fashion, and by ensuring that the risks are appropriately incorporated into decision making. It must be remembered that property insurance costs are sensitive to the effects of catastrophic events such as hurricanes and floods.

## 5.5 Acknowledgements

The author is extremely grateful to Ms. Mandy Shailer, GIS Coordinator, Department of Conservation Services, for all the GIS projections and to Mr. Jack Ward, Director and Mr. Peter Drew, Planning Consultant, Department of Conservation Services for their input.

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# 6. Impact of Climate Change on Fresh Water


**SUMMARY**

- Water resource issues concern a wide range of socio-economic and environmental sectors including health, agriculture, biodiversity, public safety and industry.

- Most Bermudians rely on rainwater roof catchments from which falling rain is directed to mandated underground storage tanks. Hotel developments, the hospital and businesses depend on supplemental groundwater and treated sea water distributed by pipelines and water “truckers”.

- Additionally, 4 fresh groundwater lenses located in the younger limestones provide up to 9.1 million litres/day, whilst there is capacity for about 5 million litres/day through reverse osmosis of seawater.

- Bermuda’s relatively steeply inclined shoreline minimises the impact of sea level rise on the freshwater lenses up to 0.59 m above present. However a sea level rise of 2 m, the maximum predicted rise for this century, would affect 143.6 ha of the land area of freshwater collection and drainage. High winds experienced during more intense storms will drive salt, debris and potential contaminants into our tanks.

- Increasing temperatures will result in higher evaporation more water usage and higher levels of bacterial contamination. Heavier downpours may also cause more severe flooding and mobilization of surface contaminants, offsetting the benefits of more rain.

- Adaptation and mitigation measures will include more stringent water conservation practices, maintenance of healthy natural ecosystems which ultimately influence groundwater resources, more environmentally-sound desalination operations and better weather forecasting.

## 6.1 Introduction

Water is one of our most valuable commodities and an adequate and clean supply of fresh water is essential to our continued well-being. Water resource issues concern a wide range of socio-economic and environmental sectors including health, agriculture, biodiversity, public safety and industry. Indeed, there are few activities that do not in some way depend on or interact with water resources.

Like most limestone islands with no natural surface water or streams, Bermuda's main freshwater source is rainfall and Bermudians have traditionally relied on rainwater roof catchments from which falling rain is directed to underground storage tanks. By law (Water Storage Regulations, 1951), each house must have 80% of its roof area guttered to collect this water and a storage tank with a capacity of at least 454.6 litres/per $m^2$ collection area (Government of Bermuda, 2005). Calculations for the required tank size for a dwelling are based on an average total rainfall of 141 cm/year (Government of Bermuda, 2005). As rainfall is relatively evenly distributed throughout the year this approach has generally worked for the individual homeowner but larger, sub-divided houses, hotel developments, the hospital and businesses must depend on groundwater and treated sea water distributed by pipelines and water "truckers" to supplement their rainwater roof catchment systems. 10% of the population is supplied by the water industry (Government of Bermuda, 2008). There have been two occasions in the past 20 years, when the Bermuda Government had to ship fresh water to Bermuda to augment an insufficient local supply. According to 2007 data, 6.94 million $m^3$/year of fresh water were available 95% of the time (Government of Bermuda, 2008).

There are four fresh groundwater lenses located in the younger limestones with as much as 10 m of freshwater floating on top of the sea water. The lenses are those at Somerset, Port Royal and St. George's, and the larger central lens in Pembroke and Devonshire. Combined these provide up to 9.1 million litres/day. The rates of abstraction by the commercial water producers and by the Ministry of Works and Engineering are carefully monitored and restricted by the Environmental Authority of the Ministry of the Environment to ensure these rates do not exceed replenishment rates from rainfall (Government of Bermuda, 2005). Rainwater is naturally filtered though the limestone bedrock before reaching the lenses. However, since disposal of most domestic wastewater and sewage occurs through cesspits, testing of well water by the Health Department is carried out before it can be approved for drinking. Groundwater abstracted from the more than 3500 private household wells in Bermuda makes a significant contribution to Bermuda's water supply. However due to the lack of suitable treatment, use of this water is, for the most part, restricted to toilet flushing and laundering.

A sea water reverse osmosis plant, operated by Bermuda Water Works, produces 2.275 million litres of fresh water per day from sea water. A desalination plant is also being commissioned by the Bermuda Government adjacent to the Tynes Bay incinerator, with a capacity of a further 2.275 million litres/day. A number of homes also have their own reverse osmosis plants.

## 6.2 Impact of Climate Change on Fresh Water

As our freshwater supply is still largely dependent on adequate rainfall, the possible impacts of climate change are significant. Whilst Bermudians have traditionally evolved very conservative water usage habits (136.38 litres/day), by catering to the tourism and international business sectors we have to allow for considerably higher per capita usage (Government of Bermuda, 2005).

### *Sea level rise*

At some point, sea level rise will reduce the land area and therefore the surface area available for rainwater to drain into the freshwater lenses, although as Rowe (pers. comm.) explains, because of Bermuda's relatively steeply inclined shorelines there would not be any momentous change in the land area of Bermuda for sea level rises up to 0.59 m (current IPCC upper limit prediction) above present. However a sea level rise of 2 m, the maximum predicted rise for this century, would affect 138 ha of the land area of freshwater collection and drainage. With a mean tidal range of 75 cm, and a seasonal steric anomaly of 0-25 cm above ordnance datum, Rowe (pers. comm.) notes that Bermuda's fresh water lenses already demonstrate an ability to adjust to changing sea levels. Further explaining that longer term trends of sea level rise up to 60 cm would simply cause the lens to float upwards he adds that the geology of the saturated zone in which the lenses reside would not change significantly either.

### *Increasing temperature*

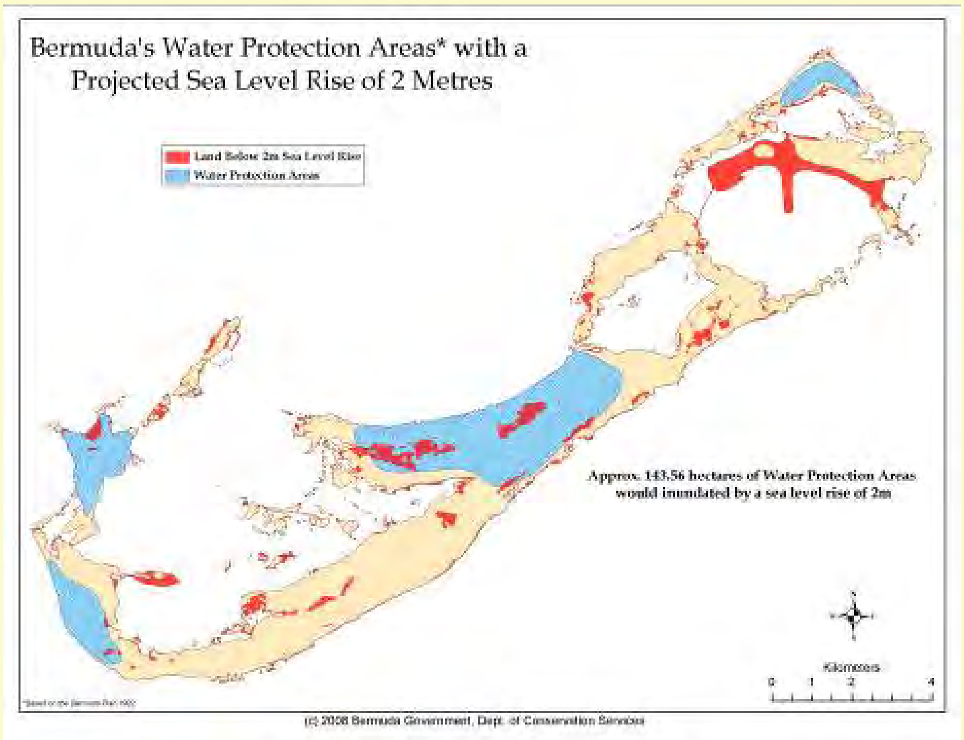
Increasing temperatures will result in higher evaporation and will drive water usage up. As temperatures increase, bacterial populations that control nitrification processes in the soils may also increase, possibly leading to increased bacterial contamination of the groundwater.

### *Changes in precipitation*

Under IPCC (2007) models it is predicted that rainfall levels in Bermuda may increase slightly (up to 5%). This may appear to be good news, but this will depend on the intensity and seasonal distribution of the rainfall, and will be countered by higher predicted temperatures. The IPCC predictions for elevated rainfall also suggest that Bermuda may be subject to heavier downpours, which could possibly cause more severe flooding and thus a greater risk of freshwater pollution from mobilization of surface contaminants.

### *More intense tropical storms*

Increased intensity of storms threatens the quality of our household water supplies as high winds drive salt onto our roofs and into our tanks. They also drive debris and potential contaminants into the tanks.




*Map 13. Showing extent of saltwater inundation of the freshwater lenses with a 2 m sea level rise.*

***Table 6. Summary of impacts of climate change on freshwater resources in Bermuda.***

| CLIMATE CHANGE | EXPECTED IMPACTS |
|---|---|
| Sea Level Rise | • A 2 m rise will intrude on the central freshwater lens supply.<br>• Will cause saltwater contamination of household tanks. |
| Rising temperatures | • Will cause greater evaporation and may drive water usage up.<br>• Will promote conditions for multiplication of bacteria and will therefore increase frequency of contamination of water supplies. |
| More intense tropical storms | • Will cause saltwater contamination of household tanks. |
| Heavier, less frequent rainfall events | • Will keep tanks topped up, but may cause flooding and potential mobilization of contaminants into groundwater. |

## 6.3 Impact of Fresh Water on GHG Emissions

Local freshwater usage impacts climate change through the use of freshwater pumps which are currently dependent on a fossil fuel-based electricity supply. The desalination plants are also currently driven through generators running on fossil fuels, whilst local water truckers rely on diesel for their trucks.

Despite a ready supply of fresh drinking water, many of Bermuda's residents also resort to drinking imported bottled water. Between the transportation costs of shipping to Bermuda and the greenhouse gas emissions generated in manufacturing the plastic bottles, this adds quite unnecessarily to our impact on climate change, given that our household tanks are able to deliver good quality drinking water. Furthermore, whilst we often boast of the island's conservative and well managed approach to freshwater collection and use in Bermuda, it is important that we remember that this only applies to personal water usage. With our dependence on the importation of goods from overseas, we often fail to acknowledge the water required in the manufacturing of all these products. To put this in context it is worth noting that the production of just 0.5 kg of ground beef requires 2,500 litres of water.

***Table 7. Summary of impacts of freshwater use in Bermuda on GHG emissions.***

| GHG | IMPACTS |
|---|---|
| Greenhouse gas (GHG) emissions | • Increased by use of fossil-fuel based electricity for pumping water throughout household and for desalination efforts.<br>• Increased by use of diesel powered trucks for water distribution.<br>• Increased due to importation of bottled drinking water used when tank water supply drained or contaminated. |

## 6.4 Mitigation and Adaptation Measures

The top priority for adaptation in the water sector must be to ensure that water demand does not exceed supply by promoting actions which reduce our usage. We also need to reduce our vulnerability to increases in climate variability and extreme events. Another priority should be to promote sound environmental practices to ensure the health of our natural ecosystems and the services they provide which ultimately influence our groundwater resources.

A wide range of strategies are available to address these priorities. These include ongoing education of both residents and visitors about more efficient water usage (turning off running taps, only running washing machines for full loads, using washing up water for watering plants etc.) and the importance of maintaining clean roofs and tanks. Current regulations governing the size of the tank required relative to the catchment area do not take into account the number of occupants, and may need to be revised given the increasing number of multiple occupancy condominium complexes being built (Government of Bermuda, 2005). The installation of water meters to monitor usage, and the use of well water to supply flushing water are also options that have been employed.

In terms of reducing our vulnerability to changing rainfall patterns and storms, we could invest more in forecasting systems to give advance warning of climate hazards and impacts. Contingency and disaster plans have already been developed for Bermuda through the Emergency Measures Organisation and a preliminary flood risk assessment inclusive of detailed flood maps has been undertaken and shared with residents (Ward, pers. comm.).

In terms of our carbon emissions, we can help reduce them by minimizing our water usage, and by seeking alternative renewable energy sources for meeting the electricity demands required to pump the water. We could also minimize our dependence on trucking for distributing supply and install a more widespread piping system for fresh water.

## 6.5 Acknowledgements

The author is especially grateful to Mr. Mark Rowe, Government Hydrologist, Department of Environmental Protection and Mr. Jack Ward, Director and Ms. Mandy Shailer, GIS Coordinator of the Department of Conservation Services for their input and critique.

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# 7. Impact of Climate Change on Energy


**SUMMARY**

- Bermuda is entirely dependent on the importation of fossil fuels to support its energy demands, requiring 800,000 barrels of heavy fuel oil and 200,000 barrels of diesel oil yearly.

- With a current maximum capacity of 169 MW, BELCO generated 118 MW of power in 2007. It is projected that by 2020, local demand will be as high as 145 MW. Current costs for the consumer in Bermuda are 39 cents/KWh (December, 2008).

- BELCO's transmission system comprises 34 substations, 217 km of underground transmission cable, 193 km of high voltage underground distribution cable, 877 km miles of high overhead distribution lines and 595 km of low voltage overhead service lines.

- Rising sea levels pose a very serious threat to parts of the main BELCO Power Plant. Warmer temperatures may result in an increase in the peak demand for electricity, as well as affecting transmission by reducing efficiency of conductivity.

- Escalating $CO_2$ levels are the driving force behind global climate change. Under the Kyoto Protocol, abiding parties are expected to reduce their emissions and to do this it will be necessary to adopt more conservative energy use. Current annual per capita emissions for Bermuda are 10 tonnes carbon over half of which is from energy use. To meet Kyoto targets, we will need to reduce this to at most 3.3 tonnes/year per global citizen by 2050.

- More extreme rainfall events may flood the main power plant as well as the power substations, and potentially underground cabling, whilst more intense storms will damage the electrical transmission infrastructure and service and possibly supply.

- Mitigation of climate change must be achieved firstly through energy conservation measures and secondly, through the use of alternative, renewable energy sources. These may include solar, wind, ocean, biomass, biogas and fuel cells.

## 7.1 Introduction

In most small islands, energy is primarily derived from non-renewable sources, mainly from imported fossil fuels. In the context of climate change, the main contribution to greenhouse gas emissions is from energy use. The need to introduce and expand renewable energy technologies in small islands has been recognised for many years although progress in implementation has been slow.

With no petroleum, natural gas or coal resources, Bermuda is almost entirely dependent on the importation of fossil fuels to support its energy demands. Despite the island's small size, an affluent population with a high standard of living demands relatively high energy usage for residential, commercial and institutional usage. Approximately 800,000 barrels of heavy fuel oil and about 200,000 barrels of No. 2 diesel oil were imported in 2007 for this purpose and 97% of the island's energy is provided and distributed from this by BELCO at their 9.3 hectare Cemetery Road plant in Pembroke (BELCO, 2008). The remaining 3% is generated through the Bermuda Government's mass burn incinerator at the Tynes Bay Waste Treatment Facility.

With a current maximum capacity of 169 MW, BELCO generated a total of 118 MW of power in 2007, and the total energy supplied to the system was 718 GWh (BELCO, 2008). A further 1.2 MW is provided from the Tynes Bay Waste Incinerator. It is projected that by 2020, total local demand will be as high as 145 MW. BELCO currently recognizes an urgent need to either redevelop its central Pembroke Power Station to meet these increased demands and replace the existing old and inefficient plant, or incorporate renewable energy alternatives into their distribution grid, or a combination of both. Their transmission system comprises 34 substations, 217 km of underground transmission cable, 193 km of high voltage underground distribution cable, 877 km miles of high overhead distribution lines and 595 km of low voltage overhead service lines (BELCO, 2008).

Current costs for the consumer in Bermuda are 39 cents/KWh (December 2008) by the time fuel adjustment costs are included. An expanding global population coupled with a finite petroleum supply will continue to drive up the costs of petroleum-based energy production in the long term.

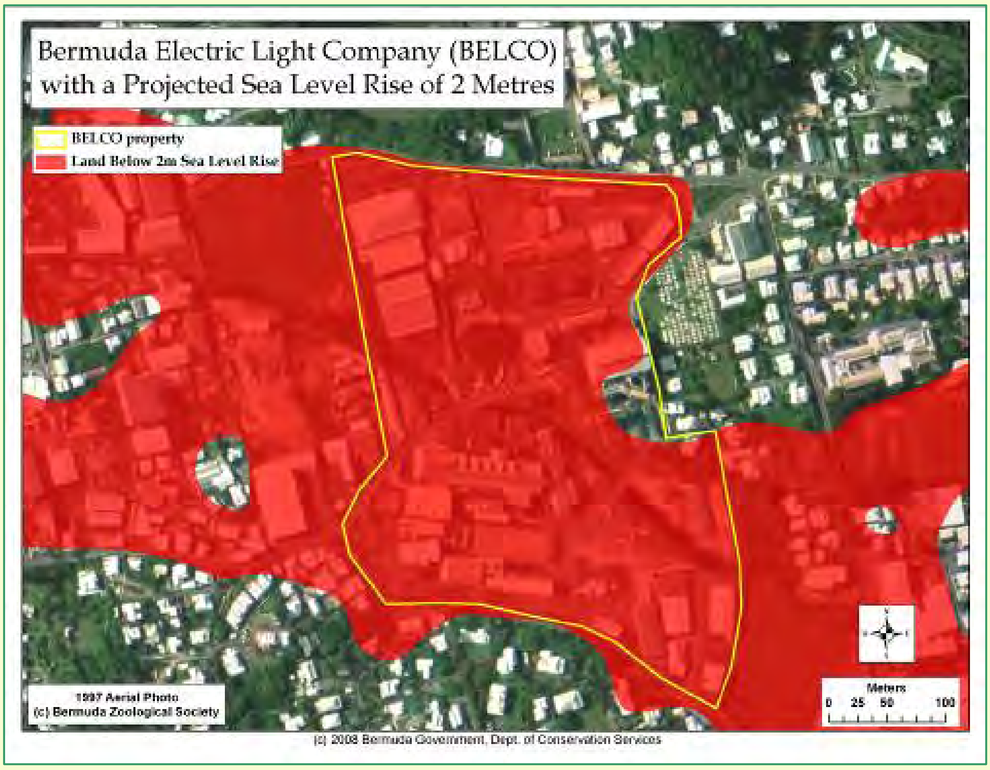
## 7.2 Impact of Climate Change on Energy Resources

There are a number of significant threats posed by climate change to Bermuda's energy sectors.

### *Increasing sea level*

BELCO's main power plant is located in Pembroke along the Pembroke Canal, which is noted for its drainage issues. Current efforts are under way by the Ministry of Works and Engineering to try and relieve these problems but rising sea levels pose a very serious threat to parts of the BELCO

Plant. Map 14 below shows the impact of a 2 m sea level rise (the maximum predicted upper limit possible by the end of the century (Pfeffer *et al*., 2008)). In addition to the main power plant BELCO has 34 substations across the island; some of which are on low-lying land.




*Map 14. Red area shows projected 2 m sea level rise; BELCO is delineated by the yellow border.*

### *Increasing temperature*

Hotter temperatures are likely to result in an increase in the peak demand for electricity for air conditioning. At the same time, efficiency of the transmission may be reduced because conductivity in the lines is affected. The strain on the system as demand grows could result in brownouts or blackouts and system failures. BELCO is addressing this by seeking permission to expand and also by actively seeking to accommodate renewable energy sources.

### *Increasing carbon dioxide*

Escalating $CO_2$ levels are the driving force behind global climate change. Under the Kyoto Protocol, abiding parties are expected to reduce their emissions and to do this it will be necessary to adopt more conservative energy use. There is a possibility that carbon quotas may eventually be imposed on countries to try and force emissions reductions.

### *Changes in precipitation*

More extreme rainfall events may flood the main BELCO power plant as well as the power substations, and potentially underground cabling.

### *Increasing storm activity*

The potential for increased intensity of extreme storm events may cause significant damage to electricity transmission infrastructure and services as well as the acceleration of the degradation of materials and structural integrity of power generation equipment. Increased wind and lightning, storm surges and flooding could damage transmission lines and structures, resulting in a knock-on increase in the cost of power supply and infrastructure maintenance. Bermuda is also totally dependent at present on imported oil, so tropical storms which damage the coastal or offshore oil infrastructure (such as offshore oil platforms, pipelines, refineries, oil tanker wharves) which supply us, will also have an impact.

***Table 8. Summary of impacts of climate change on Bermuda's energy resources***

| CLIMATE CHANGE | EXPECTED IMPACTS |
|---|---|
| Sea level rise | • May cause flooding of main power plant and substations and possibly underground cabling.<br>• Increasing cost to consumer. |
| Increasing temperature | • Increase in peak demand and potential blackouts.<br>• Reduction in efficiency of transmission.<br>• Increasing cost to consumer. |
| Increasing $CO_2$ | • Will drive energy conservation and a reduction in usage of fossil fuels. |
| Heavier, less frequent rainfall events | • Possible flooding of power plant, substations and cabling.<br>• Increasing cost to consumer. |
| More intense tropical storms | • Damage to infrastructure and service.<br>• Degradation of materials and structural integrity of power generation equipment.<br>• Increasing cost to customer.<br>• Threat to Bermuda's overseas oil supplies. |

## 7.3 Impact of Energy Resources on GHG Emissions

Almost everyone in Bermuda contributes to the climate change problem through the use of cars, air-conditioning or heating, lights and televisions, flying overseas and buying imported goods flown in from overseas. We rely on non-renewable fossil fuels (oil, gas, and petroleum) extracted from the ground to provide us with the energy that we consume to live our lives as we choose. In burning these fossil fuels we are creating the GHGs that contribute to climate change.

Historically, most island states have not been responsible for the build-up of greenhouse gases in the atmosphere and currently account for less than 1% of greenhouse gas emissions. With a population of just 65,000 and a land mass of 53 $km^2$, it might be reasonable to make the assumption that Bermuda has also not contributed significantly to GHGs. In 2003, the Bermuda Government conducted a preliminary investigation into its contribution to climate change through a review of anthropogenic greenhouse gas emissions produced on the island (Manson and Hasselbring, 2003). The results of this research indicated that on a per citizen basis, Bermuda's residents contribute approximately 10 tonnes of carbon/year. In 2003, this placed us as the $10^{th}$ highest global per capita contributors of $CO_2$ emissions. Nearly 100% of these total emissions come from the energy sector. Of these, about two thirds are from electricity generation and one third from transportation, as detailed in the table below.

| Bermuda's Greenhouse Gas inventory for 2000 (Gg) | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Greenhouse Gas Source and Sink categories** | **$CO_2$** | **$CH_4$** | **$N_2O$** | **$NO_X$** | **CO** | **NMVOC** | **$SO_2$** |
| **Total Energy** | 610.07 | 0.056 | 0.004 | 2.25 | 15.66 | 2.95 | 5.27 |
| ***A) Fuel Combustion Activities*** | 610.07 | 0.056 | 0.004 | 2.25 | 15.66 | 2.95 | 5.27 |
| **1 Energy Industries** | 431.30 | 0.016 | 0.003 | 1.06 | 0.08 | 0.03 | 5.06 |
| Public electricity and heat production | 431.30 | 0.016 | 0.003 | 1.06 | 0.08 | 0.03 | 5.06 |
| **2 Manufacturing Industries and Construction** | 0.00 | 0.000 | 0.000 | 0.00 | 0.00 | 0.00 | 0.00 |
| **3.Transport** | 164.50 | 0.039 | 0.001 | 1.17 | 15.57 | 2.92 | 0.14 |
| Road Transportation | 164.50 | 0.039 | 0.001 | 1.17 | 15.57 | 2.92 | 0.14 |
| **4. Other Sectors** | 14.27 | 0.001 | 0.000 | 0.01 | 0.01 | 0.00 | 0.00 |
| Residential | 14.27 | 0.001 | 0.000 | 0.01 | 0.01 | 0.00 | 0.00 |
| ***B) Fugitive Emissions from Fuels*** | 0.00 | 0.000 | 0.000 | 0.00 | 0.00 | 0.00 | 0.00 |
| **1 Solid Fuels** | 0.00 | 0.000 | 0.000 | 0.00 | 0.00 | 0.00 | 0.00 |
| **2 Oil and Natural Gas** | 0.00 | 0.000 | 0.000 | 0.00 | 0.00 | 0.00 | 0.00 |
| **International bunkers** | 87.97 | 0.001 | 0.002 | 0.37 | 0.12 | 0.06 | 0.03 |
| Aviation | 87.97 | 0.001 | 0.002 | 0.37 | 0.12 | 0.06 | 0.03 |

*Table 9. National Greenhouse Gas Inventory for Energy (Taken from Manson and Hasselbring, 2005).*

## 7.4 Mitigation and Adaptation Measures

Bermuda has the opportunity to set an example for small island territories in developing strategies and proactive measures towards sustainable development which at the same time will help mitigate global climate change by reducing our GHG emissions. Contributing to the reduction of greenhouse gas emissions is an important step for us to take both through our responsibility as global citizens (and through our responsibility under the Kyoto Protocol) and because the island will benefit from reducing our fossil fuel dependency, as well as our dependency on imported goods by encouraging local production. In order to meet Kyoto limits, every global citizen at current population levels will need to reduce their carbon emissions to 3.3 tonnes/year by 2050 (Byrne, 2008). However, allowing for population growth this will equate to 2.2 tonnes by 2020 and 2.0 tonnes by 2050 (Byrne, 2008).

The Stern Review (Stern, 2006) suggests that in order to mitigate against climate change, three policy elements are required. These are: 1) putting a price on carbon; 2) implementing a technology policy; and 3) removing barriers to international change. Stern continues: "Those who produce greenhouse gas emissions are bringing about climate change, thereby imposing costs on the world and on future generations, but they do not face the full consequences of their actions themselves." He suggests that an appropriate price for carbon could be achieved by raising taxes, by tougher regulation or by carbon-trading; a mechanism whereby companies or countries would pay for the right to pollute. The incentive is that, faced with the full social cost of our actions, we would convert from using goods and services with high carbon costs, to investing in low carbon alternatives. The latter are currently more expensive than the fossil-fuel alternatives, but presumably as this sector grows, costs will drop.

There is growing interest in developing renewable and alternative energy sources for Bermuda. The Government of Bermuda is in the process of preparing a Green Paper on Energy. Potential future energy sources include solar, biomass, biogas, ocean energy, wind and fuel cells. This will be a significant adaptation, but in developing these alternatives the impacts of future climate change must be taken into consideration, particularly with regards to their location. Alternatives will need particularly to be robust enough to withstand more intense hurricanes and a rising sea level. A more immediate adaptation will be behavioural modifications in how we use energy in our daily lives. Energy conservation must be the first step in reducing our emissions.

## 7.5 Acknowledgements

The author is especially grateful to Ms. Mandy Shailer, GIS Coordinator of the Department of Conservation Services for her GIS map projections.

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# 8. Impact of Climate Change on Human Health


**SUMMARY**

- Good health is an essential gauge of our quality of life and a fundamental component of sustainable development and the future social and economic integrity of the Island. Bermuda enjoys a high standard of health but recent trends suggest the picture is changing. Chronic, non-communicable diseases have replaced infectious diseases as a major cause of mortality, but a major concern of climate change is the threat of a resurgence of infectious diseases.

- Changes in weather and climatic conditions influence respiratory infections and heat related diseases whilst flooding, storm surges and topical cyclones lead to an increased risk of injury and increase the risk of contamination of water with hazardous substances. We can also expect changed patterns of diseases and hence increased water and food borne disease (diarrhoea, food poisoning and salmonellosis).

- There may be significant socio-economic impacts on community health and well-being, which include loss of income and productivity, population displacement and social disruption, diminished quality of life, psychological stress and increased costs to health care.

- The linkage between climate change mitigation and adaptation actions is particularly strong in the health sector because of the health benefits derived from reducing greenhouse gas emissions. We can avoid many climate-related extremes by adopting a wide range of physical and social adaptation measures and by promoting healthy lifestyles.

- Well practiced emergency management plans are already in place in Bermuda to deal with weather-related hazards.

- Progressive development and implementation of biological and health surveillance measures as already practiced by the Ministry of Health are essential to adaptation to climate change.

## 8.1 Introduction

One of the most pressing concerns regarding climate change is the impact it may have on our physical, social and psychological well-being. Certainly, the IPCC predicts significant, often complex adverse impacts (IPCC, 2007), which may have consequences for health and the health care sector in Bermuda. However, with high standards of local health care and emergency preparedness and response, Bermuda has the adaptive capacity to tackle these.

Good health is not only an essential gauge of our quality of life but is also a fundamental component of sustainable development and the future social and economic integrity of the island. Bermuda enjoys a high standard of health, ranking 25th in the world on life expectancy but recent trends suggest the picture is changing. As is typical of most wealthy communities, chronic, non-communicable diseases have replaced infectious diseases as a major cause of mortality for Bermuda's residents (Attride-Stirling, 2006). Circulatory diseases accounted for 36% of all deaths in 2005, and cancers 25%. Accidents and violence ranked third with 7% and diabetes and respiratory diseases factored in fourth and fifth, with about 3.5% of deaths attributed to each.

Despite this shift from infectious to chronic diseases, one of the major concerns of climate change must be threat of a resurgence of infectious diseases. Throughout Bermuda's history, mosquitoes have presented one of the most significant and deadly human health problems, transmitting yellow fever and dengue fever in epidemic outbreaks. The 1940s dengue fever outbreak affected thousands of residents and resulted in an island wide mosquito eradication problem that saw the mosquito primarily responsible (*Aedes aegypti*) declared eradicated by the 1960s (Government of Bermuda, 2005). Unfortunately, the mosquito was re-introduced in 1998 and has now re-established itself. The Asian Tiger mosquito, (*Aedes albopictus)* which was first reported in Bermuda in 2000 also carries dengue fever, as well as West Nile Virus in the USA and like the dengue mosquito, is now found island wide. The common mosquito, (*Culex pipiens*) which is the main vector for West Nile Virus in the USA is also prevalent locally, whilst the fourth locally found mosquito species the salt marsh mosquito (*Ocleritatus sollicitans*) is a vector of encephalitis and dog heartworm.

## 8.2 Impact of Climate Change on Human Health

The relationship between health and climate has long been apparent in Bermuda. Changes in weather and climatic conditions influence respiratory infections and heat exhaustion whilst the impacts of extreme weather disasters including flooding, drought, storm surges and tropical cyclones lead to an increased risk of injury, vector, food and water-borne diseases, stress-related disorders and death. There may also be significant socio-economic impacts on community health and well-being, which include loss of income and productivity, social disruption, diminished quality of life and increased costs to health care.

### *Sea level rise*

Sea level rise will primarily affect residents through property damage and loss and impacts on our infrastructure. The most likely health ramifications from this will be psychological stress, possibly with longlasting effects on anxiety levels and depression. There may also be social disruptions.

Unusually high sea levels such as the high stand experienced locally in November 2003, also promote reproduction of the salt marsh mosquito. This species, which is saltwater tolerant, lays its eggs in pools and puddles produced either by high tides or heavy rains (Government of Bermuda, 2005).

### *Increasing temperature*

Projected increases in temperature have implications for occupational health and safety, and will influence a range of heat-related illnesses including heat exhaustion, heat rash, cramps and oedema, as well as potentially heatstroke. These may lead to death or chronic illness, or impaired ability to carry out physical and mental tasks with increased likelihood of accidents. It is anticipated that Bermuda's residents will largely be able to adapt to gradual changes in average temperatures through normal acclimatization. Heatstroke is extremely rare in Bermuda however heat exhaustion is more common especially amongst non-acclimated visitors and residents in the summer months (Schultz, pers. comm.). Fortunately the moderating affects of the ocean on temperatures over the island mean that we are not subject to the extreme highs or heat waves observed on continental landmasses. Inevitably, those most affected will be vulnerable groups, such as infants (with a higher surface area to body mass), the elderly whose natural thermoregulatory abilities are not as efficient, as well as those with pre-existing health conditions. Current global warming trends show that night-time minimum temperatures are increasing more rapidly than daytime maximum temperatures, so there would be less relief due to night-time cooling than there is at present, further increasing temperature stress.

Higher temperatures may also increase the incidence of water, food and vector borne diseases by changing the geographic distribution of disease vectors and shortening their incubation periods (IPCC, 2007b). Warmer temperatures are known to accelerate the larval stage of mosquitoes, causing them to be smaller and to feed more frequently. Higher temperatures also reduce the incubation period for the parasite that causes dengue. At 30°C, dengue type 2 has an incubation period of 12 days, but only seven days at 32°C - 35°C. It has been projected that a 2°C increase in average temperature could lead to a three-fold increase in the rate of transmission of dengue fever in the Caribbean (Chen *et al*., 2006). Mosquitoes would also benefit from warmer winters, as cold temperatures currently reduce mosquito populations by killing mosquito eggs, larvae and adults.

Rising temperatures cause flies, cockroaches and rodents to become more active, thereby increasing the chance of contact between food and pest species. Therefore, foodborne diseases such as diarrhoea, food poisoning, salmonellosis and typhoid may also rise. The Department of Health notes that salmonellosis episodes tend to increase after hurricanes where there may be extended power outage and poor storage of food. In 2007, there were 81 reported cases of diarrhoea and gastroenteritis. Rising temperatures will also cause our fresh water supplies to stagnate more quickly leading to higher incidence of gastroenteritis unless addressed.

Birds can act also as biological or mechanical carriers of human pathogens. Climate change has been implicated in changes in the migratory and reproductive timing of several bird species, possibly leading to shifts in the geographical distribution of vectors and pathogens.

Changing climactic conditions are also increasing the incidence of ciguatera poisoning in some regions of the world. Although ciguatera is extremely rare in Bermuda, the algal blooms that produce ciguatoxins, which are ingested by fish and then consumed by humans are becoming more frequent across the globe. It is believed that the cause of this is a combination of factors including habitat disturbance from extreme weather, warmer waters, as well as increased transmission of iron-enriched dust particles from the Sahara (http://visibleearth.nasa.gov/view_rec.php?id=6199).

It is also important to point out that climate change may have some health benefits, by possibly restricting distribution of diseases where temperatures or rainfall exceed upper thresholds of the vectors.

### *Increasing UV Radiation*

Climate change may be expected to change human exposure to ultraviolet radiation (UVR) exposure by extending the summer season. This could result in an increase in eye damage (cortical cataracts), skin cancer and sunburn. Skin cancer is the largest growing cause of cancer, however warmer temperatures might actually drive people to spend more time in the shade or indoors, so this may not be such a significant impact in the local context.

### *Increasing Carbon Dioxide*

Studies in the USA on the poison ivy (*Toxicodendron radicans*) have shown that under higher $CO_2$ levels, the plants produced a more allergenic form of urushiol, suggesting that it will become more toxic (and more abundant) in the future (Mohan *et al.,* 2006).

### *Increasing Ozone*

Climate change could affect both average and peak air pollution levels associated with pneumonia, chronic obstructive pulmonary diseases, asthma, allergic rhinitis and other respiratory diseases. For example, background concentrations of ground-level ozone are expected to increase. Ozone occurs naturally, and as a secondary pollutant formed in the presence of sunlight and high temperatures through photochemical reactions with emissions for example from vehicles. Ozone production is affected by temperature, wind, solar radiation and atmospheric moisture. Whilst not typically a problem in Bermuda, local meterological conditions may prevail (stationary or slowly migrating anticyclonic or high pressure systems) which reduce pollution dispersion and diffusion and cause elevated levels, particularly during morning and evening rush hour.

### *Changes in precipitation*

Heavier rainfalls leading to flooding may increase the risk of contamination of waters with dangerous chemicals, heavy metals or other hazardous substances, either from storage containers or through mobilization of chemicals already present in the environment. There may also be health risks associated with longterm contamination of soil and sediment and flooding can also cause injuries and drowning.

Increased levels of standing water associated with more intense flooding events may also encourage breeding of the *Aedes aegypti* mosquito that transmits dengue fever.

### *More intense tropical storms*

Changes in the climate are affecting the distribution and seasonality of some allergenic pollen species. Wind blown dust originating in the desert regions of Africa can affect air quality, carrying large concentrations of respirable particles and trace elements, fungal spores and bacteria that can all affect human health (http://visibleearth.nasa.gov/view_rec.php?id=6199). Respiratory diseases, such as asthma, bronchitis and respiratory allergies and infections may therefore become more prevalent with more intense storms. Department of Environmental Health data from 2007 indicates respiratory diseases affected a total of 494 of Bermuda's residents but there appears to be no appreciable increase in numbers of people affected over the past 10 years (Government of Bermuda, 2008).

Intense storms and hurricanes may also increase the incidence of gastroenteritis through contamination of our fresh water with salt water and debris, washed off our roofs and down the drains into our storage tanks.

There is also increasing evidence of important mental disorders arising as a result of natural disasters and studies have also revealed that men and women are affected differently in all phases of a disaster. Natural disasters have been shown to result in increased domestic violence against, and post-traumatic stress disorders in women (IPCC, 2007b).

***Table 10. Summary of impacts of climate change on human health in Bermuda.***

| CLIMATE CHANGE | EXPECTED IMPACTS |
|---|---|
| Sea level rise | • Increasing psychological stress (anxiety, depression).<br>• Increased breeding of salt marsh mosquito.<br>• Population displacement/social disruption. |
| Increasing temperature | • Increased occupational health and safety risks.<br>• Heat-related illnesses.<br>• Increased respiratory and cardiovascular illnesses.<br>• Changed patterns of diseases caused by bacteria, viruses and other pathogens carried by mosquitoes, and other vectors, and shortening of their incubation periods.<br>• Increased water and food borne disease (diarrhoea, food poisoning, salmonellosis and typhoid).<br>• Increased incidence of ciguatera poisoning. |
| Increasing UV Radiation | • Increased threat from UV radiation (eye damage, skin cancer, sunburn, disturbed immune function). |
| Increasing GHG emissions | • Increased toxicity of poison ivy.<br>• Increase in average and peak air pollution levels associated with pneumonia, chronic obstructive pulmonary diseases, asthma, allergic rhinitis and other respiratory diseases. |
| Heavier, less frequent rainfall events | • Increased risk of contamination of waters with hazardous substances.<br>• Flooding leading to injuries and drowning.<br>• Increased breeding activity of dengue fever mosquito. |
| More intense tropical storms | • Damaged public health infrastructure.<br>• Injuries and illnesses.<br>• Increasing prevalence of respiratory diseases, such as asthma, bronchitis and respiratory allergies.<br>• Social and mental health stress due to disasters.<br>• Population displacement. |

## 8.3 Impact of Human Health on GHG Emissions

Higher summer temperatures are likely to increase energy consumption for cooling, thereby adding to pollution emissions.

## 8.4 Mitigation and Adaptation Measures

The linkage between climate change mitigation and adaptation actions is particularly strong in the health sector because of the health benefits derived from reducing greenhouse gas emissions. Certainly, shifts to cleaner energy sources and other reductions in greenhouse gas emissions, including more emphasis on walking and using public transport, will yield positive health benefits. The Ministry of Health is already promoting this.

We can also avoid many climate-related extremes by adopting a wide range of physical and social adaptation measures. Clothing and lifestyles can be varied with the season. The design of our buildings and other structures can be modified to provide more shade, withstand hurricane-force winds (with strict building codes in place and land-use regulations including a new coastal conservation zone which restricts building too close to the shoreline), and incorporate air-conditioning. Behavioural, social and economic adaptations allow us to remain generally healthy and comfortable except under the most extreme weather and climate conditions. Longer term measures aimed at reducing heat across the island might consider large-scale use of light-coloured, reflective 'cool' surfaces or the strategic placement of vegetation to provide shade which would also serve to reduce energy usage.

However, we must acknowledge that in the future we may experience climate driven changes beyond our historical experience, placing new stresses on our society and the health sector. Examination of the factors that affect our current capacity to adapt, including physiological factors, psychological factors (e.g., knowledge, beliefs, attitudes), socio-economic factors, and the characteristics of health care systems is essential. Particular focus must be given to the more vulnerable sectors of the community, including seniors, children, chronically ill and disabled people and those of low-income or homeless. The threat of climate change can however be integrated into existing frameworks, rather than being addressed as a separate issue.

Well practiced emergency management plans are already in place in Bermuda to deal with weather-related hazards as a consequence of our isolated geographical location and susceptibility to hurricanes. The small size of the land and the ability to reach all sectors of the community with information and updates via radio, Internet, televisions or telephone is an essential component in these plans. The construction of new satellite clinics at each end of the island is further strengthening the island’s ability to deal with such events. The strengthening of local weather forecasting capabilities would be helpful.

Progressive development and implementation of biological and health surveillance measures as adaptations to climate change are also essential. Ongoing monitoring for emerging diseases as well as public education programmes that provide information on reducing the risk of exposure and transmission serve to limit the threat of infectious diseases. Rigorous ongoing mosquito ('House Index' and 'Fight the bite') and vermin control by the Health Department are critical to this, whilst the Government of Bermuda's "Well Bermuda" programme (Attride-Stirling, 2006) is a strategic initiative to promote island wide health that in itself will ensure greater resilience to the impacts of climate change.

## 8.5 Acknowledgements

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# 9. Impact of Climate Change on Tourism


**SUMMARY**

- Tourism has for the better part of a century constituted one of the pillars of Bermuda’s economy. In 2007, the total number of tourists to Bermuda was 659,572. Of these, 305,548 were air arrivals (primarily from the US, Europe and Canada) and 354,024 were cruise ship passengers. Tourist spending was just over $500 million in 2007, or 10.5% of Bermuda’s GDP which totalled $4.9 billion.

- In terms of climate change, tourism is a double-edged sword; economically we depend on it, yet as an island we will be particularly vulnerable to the affects of climate change resulting from greenhouse gas emissions (to which tourism is a major contributor), especially through sea level rise and an increase in the intensity of tropical storms.

- The effects of any possible greenhouse gas reduction policies (eg. introduction of carbon quotas) could seriously impact tourist mobility in the future. Per passenger emissions per cruise ship mile are higher than from air miles.

- More intense hurricane activity and sea level rise will affect local tourism. Beach erosion, saltwater inundation of beach structures, amenities, hotels and restaurants, damage to infrastructure (eg. airport), and the coral reef may all cause lost revenue from tourism.

- Bermuda may benefit from degradation of the Caribbean reefs due to elevated temperatures whilst our reefs remain healthy if temperatures do not exceed tolerance limits.

- An integrated coastal zone management approach building upon existing policy and legislation may be the best adaptation strategy to inject resilience into our tourist industry.

## 9.1 Introduction

International tourism is one of the most important and rapidly growing service industries in the world. Its continued success is closely related to the preservation and enhancement of environmental resources, as well as local climatic conditions; these factors combined are probably the major drivers in determining the attractiveness of a region as a holiday destination.

Tourism has for the better part of a century constituted one of the pillars of Bermuda's economy, and especially since the mass tourism boom of the 1960s. In 2007, the total number of tourists to Bermuda was 659,572 (Government of Bermuda, 2008), or over 10 times the population of the island. Of these, 305,548 were air arrivals (75% from the US, and the remainder split fairly equally between the UK, Canada and 'other' destinations eg. Europe and Latin America), and 354,024 were cruise ship passengers. Tourist spending was just over $500 million in 2007, or 10.5% of Bermuda's GDP which totals almost $4.9 billion.

The total number of people directly employed in tourism was 4,810 in 1997 but clearly tourism-stimulated employment and income filter into the economy through wholesale and retail businesses, transportation and many trades and professions (Murphy and Gomez, 1981). The tourist industry has a significant impact on our resources, employing local and foreign manpower, land for hotels, restaurants and recreation, as well as transport, sewage, and waste disposal facilities, and consumption of local and imported goods. In 2007, the number of tourists on the island on any day per 1,000 residents was 81, or 5,197 tourists per day per total resident population (Government of Bermuda, 2008).

The potential impacts of climate change have significant considerations for planning in the tourist industry. As climate related trends in tourist volumes start to manifest themselves globally, we need be better prepared and equipped to manage our own infrastructure to adapt accordingly.

## 9.2 Impact of Climate Change on Tourism

It is thought that the direct effect of climate change may affect major intraregional tourism flows where climate is significant, including Northern Europe to the Mediterranean and the Caribbean, North America to the Caribbean, and to a lesser extent North East Asia to Southeast Asia. However, there is no evidence to suggest that a change in climate will directly lead to a significant reduction in the volume of global tourism.

We must anticipate though that the impact of climate change on tourism will steadily intensify. Climate defines the length and quality of tourism seasons and plays a major role in destination choice and tourist spending. New studies confirm previous findings that the effects of climate change on tourism are likely to be direct and indirect (eg. through increased stresses placed on environmental systems) and largely negative. For example, sea level rise and increased sea water temperature will cause accelerated beach erosion, degradation of coral reefs, and coral bleaching in many locations. The importance of environmental attributes in determining the choice and enjoyment of tourists visiting Bonaire and Barbados and possible changes resulting from climate change (coral bleaching and beach erosion) have been investigated by Uyarra *et al*. (2005). Despite having a different infrastructure and catering to two very different tourism markets, the study concluded that such changes on these two Caribbean islands would have significant impacts on destination selection by visitors. Changes in water availability, biodiversity loss, reduced landscape aesthetic, altered agricultural production, increased natural hazards, damage to infrastructure and the increasing incidence of vector borne diseases will all impact tourism to varying degrees. Additional impacts from climate change may include a loss of cultural heritage from inundation and flooding which will reduce the amenity value for coastal users.

The most serious impacts for Bermuda will likely result from the effects of any possible greenhouse gas reduction policies (eg. introduction of carbon quotas) which could impact tourist mobility in the future, from more intense hurricane activity and sea level rise. Tourism would be particularly affected by the former given our geographic isolation and the travel distance required to get here. Hurricane activity and sea level rise will both stress the critical infrastructure required to support tourism particularly given that our tourist industry is heavily based on coastal and marine resources. This in time would have a knock-on effect to small retail businesses, entertainment, restaurants and the wider local economy.

We must bear in mind also that climate change is thought to pose a risk to future economic growth and to the political stability of some nations. Any reduction of global GDP due to climate change would reduce the discretionary wealth available to consumers for tourism and have negative implications for future tourism.

### *Sea level rise*

Sea level rise presents one of our greatest challenges. With a concentration of tourist resorts on the more exposed South Shore, coupled with the fact that the favourite tourist beaches are located along this shore line, any rise in sea level will have a negative impact. With a 0.59m rise (the upper limit of the IPCC (2007) predictions it has been calculated that at least 31% of Bermuda's beach and dune habitat would be inundated (Shailer, 2008). A 2m rise (the maximum predicted possible rise in the next century (Pfeffer *et al*., 2008)) would result in 54% loss of our beaches and dunes. Beach structures and amenities, hotels and restaurants may also lose real estate through climate change. This will be compounded by the more intense hurricanes that are predicted.

### *Increasing temperature*

Increasing air temperatures are not likely to deter tourists from travelling to Bermuda although there will be a resulting drain on our energy resources as the need for air conditioning increases. Increasing sea surface temperatures may however affect one of our most valuable natural assets; our coral reef. The main concern as discussed later is that rising temperatures may lead to bleaching of our corals; bleaching can lead to the death of the reef. Bermuda may benefit from being significantly further north than our neighbouring Caribbean islands in that our annual maximum temperatures are lower than in these tropical destinations; so whilst bleaching has been a significant problem further south, there have been relatively few bleaching events here. Bermuda may in fact be able to boast one of the healthiest coral reef systems, providing that other pressures to the marine environment are kept in check.

### *Increasing carbon dioxide*

This may be the most significant threat to our tourism industry as greenhouse gas emissions policies become more widely adopted and stringently imposed. They will lead to an increase in transport costs and may foster environmental attitudes that lead tourists to change their travel patterns (e.g., shift transport mode or destination choices). There has been substantial recent media coverage on this topic, specifically as it relates to air travel. A return flight from London to Bermuda for example results in 1.53 tonnes of carbon emissions. New York to Bermuda produces 0.28 tonnes (http://www.climatecare.org). In order to meet current emissions reductions, emissions per global citizen need to be reduced to 3.3 tonnes per year by 2050 (Byrne, 2008). This would just about allow for two return flights to the UK per year, not taking into account the rest of our carbon budget needed for daily living.

Furthermore, whilst it is a commonly held belief that carbon emissions from flying are higher than from cruising, it is now increasingly acknowledged that this is untrue. In an article by the UK Guardian in 2006 (http://www.guardian.co.uk/travel/2006/dec/20/cruises.green) one carbon offsetting company (Climate Care, http://www.climatecare.org), stated that "According to our calculations, a cruiseliner such as Queen Mary 2 emits 0.43kg of $CO_2$ per passenger mile, compared with 0.257kg for a long haul flight (even allowing for the further damage of emissions being produced in the upper atmosphere). The article goes on to report that "George Marshall of the Climate Outreach Information Network has conducted a rough initial calculation for the Queen Elizabeth II. Cunard says the ship burns 433 tonnes of fuel a day, and takes six days to travel from Southampton to New York. If the ship is full, every passenger with a return ticket consumes 2.9 tonnes of fuel. A tonne of shipping fuel contains 0.85 tonnes of carbon, which produces 3.1 tonnes of carbon dioxide when it is burnt. Every passenger is responsible for 9.1 tonnes of emissions. Travelling to New York and back on the QEII, in other words, uses almost 7.6 times as much carbon as making the same journey by plane."

### *Changes in precipitation*

Whilst heavy downpours may be an inconvenience to tourists to Bermuda, this impact is unlikely to act as a significant deterrent. However, localised flooding may temporarily impact the local infrastructure such as the transport network.

### *More intense tropical storms*

More intense hurricane activity may well become a deterrent to tourists, although this may result in cancelled holidays rather than an overall downturn in bookings. However, stronger storms will accelerate beach erosion which will negatively impact the tourist industry. More storm activity may also increase damage to the coral reef, which is a key asset to the industry. The local infrastructure may also be affected by storm damage; closure of the airport for example for any length of time, could seriously affect revenue from tourism.

*Table 11. Summary of impacts of climate change on tourism in Bermuda.*

| CLIMATE CHANGE | EXPECTED IMPACTS |
|---|---|
| Sea level rise | • Saltwater inundation of beach structures, amenities, hotels and restaurants.<br>• Significant loss of beach and dune, negatively affecting visitor experience. |
| Increasing temperature | • May drain energy resources as more tourists run air conditioning and spend more time inside.<br>• Possible threat of coral bleaching although Bermuda may benefit from degradation of Caribbean reefs whilst our reefs remain healthy. |
| Increasing $CO_2$ | • May become a limiting factor if GHG policies become more widely adopted.<br>• Per passenger emissions per cruise ship mile are higher than from air miles. |
| More intense tropical storms | • Damage to infrastructure (eg. airport) causing lost revenue from tourism.<br>• Acceleration of beach erosion.<br>• A deterrent resulting in cancelled holidays.<br>• Damage to coral reef, an important asset to the industry. |
| Heavier, less frequent rainfall events | • Localised flooding may be a temporary inconvenience. |

## *9.3 Impact of Tourism on GHG Emissions*

As an isolated island destination, there is no question that tourism has a huge negative impact on GHG emissions. Travel to Bermuda involves a minimum distance of 2,500 km for a return trip from the US. This equates to 0.28 tonnes of carbon emissions. Additionally, annual electricity consumption directly attributed to tourists is 574,726 kWh, or just under 1% of Bermuda's total electricity consumption (Government of Bermuda, 2008). There were also 600 licensed taxis on the island in 2005 (Government of Bermuda, 2005), many catering to tourists. Additionally, the National Transportation Management Report calculated that approximately 30-40% of hotel visitors and 10-15% of cruise ship visitors rent motor cycles (Government of Bermuda, 2002), all adding to our emissions profile. This is thus a double-edged sword; we depend on tourism which contributes to greenhouse gas emissions, yet as an island we will be particularly vulnerable to the affects of climate change resulting from these emissions, especially through sea level rise and an increase in the intensity of tropical storms.

## *9.4 Mitigation and Adaptation Measures*

Despite declining tourism, it remains a key sector of our economy so it will be imperative for us to try and assess the risks accurately, mitigate where possible, and adapt where not. The critical challenge before us will be to develop an innovative, coherent policy strategy that tries to decouple tourism from increased energy use and GHG emissions, so as to allow tourism growth. Tourism-related emissions are projected to continue to grow rapidly under 'business as usual' conditions. We will need to adapt to climate change in order to minimize associated risks and capitalize upon new opportunities, in an economically, socially and environmentally sustainable manner. Specific strategies which focus our efforts on protecting the key tourist assets may provide a means of reducing the environmental impacts and economic costs of climate change. This must be undertaken within the context of the broader Sustainable Development Plan, the Draft Development Plan 2008, the Fisheries Act 1972 and the Protected Species Act 2003. The development of an integrated coastal zone management approach may be a valuable approach, building on the Bermuda Coastal Erosion Vulnerability Assessment undertaken in 2004 (Government of Bermuda, 2004). As part of an overall response strategy we might consider the adoption of increasingly rigorous building codes and other design and construction standards and mandatory building setbacks in coastal areas.

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# 10. Impact of Climate Change on our Built Heritage


**SUMMARY**

- Bermuda's traditional architectural style is one of the Island's most distinguishing aspects. In order to preserve the Island's traditional architectural heritage, the Development and Planning Act 1974 'lists' 785 individual buildings of special architectural or historical interest, affording them special protection.

- 58 historic areas have also been designated; most surround historic fortifications, encompass sites of significant archaeological value or comprise districts with heavy concentrations of buildings and structures of special historical and architectural value, including Naval Dockyard and The Town of St. George, which is a designated World Heritage Site. Bermuda also has quite a rich archaeological heritage, with over 4,000 structures and ruins identified as far back as the 1898 Savage Map. There are also over 150 known shipwrecks.

- Climate change is expected to have a number of direct physical impacts on our built heritage. Historic buildings typically have a greater intimacy with the ground than modern ones and as a result are more porous, tending to draw water up into their structures and then lose it to the environment by surface evaporation.

- Rising sea level will lead to saltwater inundation of low-lying historic buildings through flooding, and may result in increased salt crystallisation on built surfaces, as well as leading to changes in soil chemistry which may affect archaeological sites. More intense storms will cause structural damage.

- Rising temperatures may affect soil stability, activation of ground contaminants which impact foundations and infestation of timbers by new pests. Flooding from heavier rainfalls will damage building materials not designed to withstand prolonged immersion, as well as promote the growth of damaging micro-organisms such as moulds and fungi in post-flooding drying.

## 10.1 Introduction

Bermuda's traditional architectural style is one of the island's most distinguishing aspects. Designed for functionality at the time, incremental changes have crept in over the decades as more modern construction materials have become available, and construction methods themselves have changed. In order to preserve the island's traditional architectural heritage, the Development and Planning Act 1974 'lists' individual buildings of special architectural or historical interest, affording them special protection. There are 785 listed buildings, which include forts (85), churches, houses and gate-posts (Government of Bermuda, 2005).

Buildings are graded according to their condition and the alterations that may be made to them (Government of Bermuda, 2005). Grade 1 listed buildings, of which there are 122, are those that have essentially survived in their original condition and cannot be altered in structure or decoration. Grade 2 listed buildings (244 in total) are allowed alterations as long as they do not impinge on the protected parts of the building. Grade 3 buildings (370 in total) may have alterations only in keeping with the dominant structural and decorative style of the building. Grade HM buildings (of which there are 49) include other buildings such as defensive structures, monuments, outbuildings and ruins. 58 historic areas have also been designated. Most either surround historic fortifications, encompass sites of significant archaeological value or comprise districts with heavy concentrations of buildings and structures of special historical and architectural value, including Naval Dockyard and The Town of St. George, the oldest town in the New World and a designated World Heritage Site since 2000 (Government of Bermuda, 2005). As a World Heritage Site, St. George's is protected under the Convention Concerning the Protection of the World Cultural and Natural Heritage which was adopted by UNESCO in 1972 in order to "encourage the identification, protection and preservation of cultural and natural heritage considered to be of outstanding value to humanity".

Bermuda also has quite a rich archaeological heritage, with over 4,000 structures and ruins identified as far back as the 1898 Savage Map (Government of Bermuda, 2005). There is however little statutory protection for these archaeological resources (Government of Bermuda, 2005). The Bermuda National Trust along with its partners is actively involved in promoting archaeological research as part of its 'Old House Survey' of buildings constructed before 1898. The Bermuda Maritime Museum also conducts archaeological digs on Bermuda's forts.

Beneath the sea the island guards the secrets of over 150 known, and likely many more still unknown, shipwrecks (Rouja, pers. comm.). Many of these have lain for centuries, covered or partially covered by sand which protects them from mechanical erosion. This protective cover also creates an anaerobic microenvironment which helps preserve many organic substances associated with the wrecks (Gillies, 2007).

## 10.2 Impact of Climate Change on our Built Heritage

Climate change is expected to have a number of direct physical impacts on built heritage: Historic buildings typically have a greater intimacy with the ground than modern ones. As a result, they are more porous, tending to draw water up into their structures and then lose it to the environment by surface evaporation (Cassar, 2006). The secondary effect is increasing erosion and salt weathering, and their walls and floors are the main surfaces through which these reactions occur. Extreme or sudden changes in diurnal or seasonal variation of temperature and humidity can cause the cracking, splitting and flaking of materials and surfaces.

Archaeological evidences may be especially affected by climate change. These evidences are preserved in the ground because they have attained a balance with the hydrological, chemical and biological processes of the soil (Cassar, 2006). No matter whether the trend is toward an increased frequency of droughts or floods, the changes in water table levels, in humidity cycles in time of wetness, in groundwater, and in soil chemistry will impact on the conservation of archaeological remains, potentially exacerbating decay mechanisms. Thus climate change may jeopardize the conservation of precious evidences whose existence is not even known today.

### *Sea level rise*

Sea level rise threatens our coastal areas as well as low-lying inland basins. In addition to direct salt water inundation of low-lying historic buildings through flooding, it may result in increased salt crystallisation on built surfaces, and will lead to changes in soil chemistry which may affect archaeological sites.

### *Increasing temperature*

Increased soil temperature resulting from increased atmospheric temperature may also affect soil stability. For example, ground contaminants may become more active and potentially attack foundations. Timber materials may also be subject to increased biological infestation as a result of temperature-driven range extensions of previously absent pests.

### *Changes in precipitation*

With heavier rainfall events predicted, increased flooding will damage building materials not designed to withstand prolonged immersion. In addition, post-flooding drying may encourage the growth of damaging micro-organisms such as moulds and fungi and cause staining. There may be greater humidity in the lower parts of the buildings and consequently an increase in salt contamination of the structures. Changes in sediment moisture can be expected to affect archaeological data preserved in waterlogged, anaerobic, or anoxic conditions. It will also lead to the loss of stratification integrity due to cracking and heaving.

***More intense tropical storms***

Coastal erosion, leading to a significant retreat of the shoreline may threaten a number of our historic buildings. More intense storms, with higher wind gusts can result in significant structural damage of either the whole structure, or specific, more vulnerable elements. Hurricane Fabian in 2003 toppled one of the remnant walls of Southampton Island Fort in Castle Harbour, as pictured below. Meanwhile, the Department of Planning documented some damage sustained in 56 of 153 listed buildings in the St. George's World Heritage Site after Hurricane Fabian. In contrast, only 25 non-listed buildings were damaged (Government of Bermuda, 2005).

*Photograph 5 showing the collapsed wall of Southampton Island Fort after Hurricane Fabian in 2003.*

Bermuda's shipwrecks, particularly those in shallow waters may also impacted by tropical storms, however the impact is typically much less than to buildings on land. Through their scouring action, heavy storms may also serve to uncover and reveal new shipwrecks, thereby adding to our local heritage.

***Table 12. Summary of impacts of climate change on Bermuda's built heritage***

| CLIMATE CHANGE | EXPECTED IMPACTS |
|---|---|
| Sea Level Rise | • Direct flooding and saltwater inundation of buildings.<br>• Changes in soil chemistry which may affect archaeological sites.<br>• Increased salt crystallisation on built surfaces. |
| Increasing temperatures | • May affect soil stability<br>• Higher ground temperatures might lead to ground contaminants becoming more active and potentially |

| | |
|---|---|
| | attacking foundations.<br>• May increase the geographic range of pest species which affect timber structures. |
| Heavier, less frequent rainfall events | • Will damage building materials not designed to withstand prolonged immersion.<br>• Post-flooding drying may encourage the growth of damaging micro-organisms such as moulds and fungi and staining.<br>• Will cause greater humidity in the lower parts of the buildings and, consequently, an increase in salt contamination of the structures.<br>• Changes in sediment moisture can be expected to affect archaeological data preserved in waterlogged, anaerobic, or anoxic conditions.<br>• Increasing soil moisture will also lead to the loss of stratification integrity due to cracking and heaving. |
| More intense tropical storms | • Will cause significant structural damage of either the whole structure, or specific, more vulnerable elements.<br>• May cause damage to shipwrecks.<br>• May also uncover and reveal new wrecks. |

## *10.3 Mitigation and Adaptation Measures*

Maintenance, monitoring and vulnerability assessments are a necessary part of developing adaptation measures to protect our built heritage. It is also essential that we first have a baseline of the condition of this heritage from which to gauge the impacts of climate change. Relieving existing pressure on our historic buildings will also help reinforce their resilience; this includes the removal of invasive species such as the casuarina, Indian laurel and Mexican pepper trees, all of which have root structures that can undermine the foundations of these buildings, as well as grow through roofs and walls. Ensuring adequate enforcement of existing protection on these buildings in the face of rampant development is also essential.

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# 11. Impact of Climate Change on Agriculture


**SUMMARY**

- In addition to improving the balance of trade, contributing immeasurably to our quality of life by maintaining visual open spaces, reducing our contribution to GHG emissions, and representing an important part of our cultural heritage, local agriculture may become increasingly significant by enhancing our food security. This is a growing global concern that will impact Bermuda.

- 20% of our fresh produce is locally produced, with about 120 types of vegetables and herbs grown. 6 dairy, 1 poultry, 1 piggery, 1 slaughterhouse and more recently 1 free-range chicken farm provide 100% of the Island's fresh milk requirement, 15% of the Island's local fresh egg requirement and some fresh meat.

- High summer temperatures and unpredictable rainfall patterns already dictate a lull in crop production through the summer months, whilst milk production drops from June to September because of heat stress. Further temperature rise will only exacerbate this whilst range extensions of harmful invasive pests is likely to increase leading to more crop damage.

- Salt water intrusion from sea level rise is already eliminating arable land, whilst heavy rainfall threatens soil stability and affects the production of honey on the Island. Tropical storms are one of the main threats facing local farmers causing direct destruction of crops, interference with planting seasons and crop and milk output.

- Adaptation and mitigation measures will require a proactive approach that builds resilience into our agricultural systems including more focus on organic farming, backyard gardens and community farms, experimentation with different crops, ongoing vigilance against pest species and more infrastructural support in the event of storms.

## 11.1 Introduction

The global community is quickly realizing that the issue of food security in the face of climate change may present one of the most significant challenges facing society. For an island as isolated as Bermuda, there is little doubt that our current reliance on international imports and lack of a truly sustainable food source makes us vulnerable. Increasing local food production may become an important adaptation to the threats posed by climate change so it will be essential to manage the risks to the agriculture sector and encourage innovative solutions.

Bermuda has a long history of agricultural production and farming was once the mainstay of the local economy. However, with increasing costs of production, loss of farmland to development and improved refrigerated transport systems the sector has been in decline in recent years. At the time of the first reliable estimate in 1829, about 200 ha were cultivated. The 19th century saw a rapid increase in land under cultivation, with Bermuda's famous onions and lilies being the major crops. By 1912, 1,214 ha were under cultivation and until the 1930s the island was a major exporter of vegetables to the USA (Government of Bermuda, 2005).

Nowadays, about 20% of our fresh produce is locally produced (Bermuda Board of Agriculture, 2004) and Bermuda's agricultural industry, which comprises horticultural crops, dairy, honey and egg production contributes about 1% to GNP (Spreen *et al*., 2002) and provides employment for over 200 people either directly or through related services (Government of Bermuda, 2005). In addition to improving the balance of trade and helping to enhance food security, agricultural production contributes immeasurably to our quality of life by maintaining visual open spaces, and is an important part of our cultural heritage.

154 hectares of actively farmed agricultural land are distributed across the island, primarily in lowland depressions where the rich soil is deepest. A further 128 hectares are designated for agricultural protection under the Bermuda Plan (Government of Bermuda, 2008) but are not in active production. About 120 types of vegetables and herbs are grown, and most of the farmers are "full-service" providing a wide variety of seasonal produce, which necessitates an extremely challenging task of juggling overlapping crop cycles, farming of widely separated plots and individual packaging and marketing (Spreen *et al*., 2002). Embargoes are established on foreign imports of some crops to try and protect the market for the local farmers, and the local crops from introduced pest species, but about 15-50% of wastage is still reported from unsold produce amongst the farms.

For farming purposes, Bermuda's weather can be unpredictable and farmers often risk losing whole stands of crops planted either too early or late in the season. Most crops are 'cool-weather' crops unavailable in midsummer and include green snap beans, broccoli, cabbage, cauliflower, carrots (13% of total crop acreage and the most profitable crop per hectare) and potatoes (18% of total crop acreage). Summer crops include corn (10% of total crop acreage), cucumbers, peppers, summer squash and Bermuda pumpkin. The main fruit crops are bananas and tomatoes, but current conditions could support more than 100 different fruits (Spreen *et al*, 2002).

Most farmers follow a rotation of crops that includes consideration of soil type and cross-crop susceptibility to diseases and insects, as well as compatibility with left-over herbicides from previous crops. Some farms use an irrigation system; using water from reverse osmosis or extracted from wells, although generally the groundwater is too saline.

In addition to the commercial production of crops, it is estimated that about 56 hectares of land are farmed by home owners, of which perhaps half are dedicated to fruit trees (Spreen *et al.*, 2002). Backyard gardening therefore represents about 27% of the land currently used for the production of fruit and vegetables and an estimated 39% of the population engages in some form of vegetable gardening (Bermuda Board of Agriculture, 2004). Plant nurseries and garden supply stores report that seeds and seedling sales are growing at 10% per annum.

Animal-based agriculture has also been on the decline, with the 11 dairy and 13 commercially operated poultry farms plus piggery farms reported in 1970, reduced to 6 dairy, 1 poultry and 1 piggery in 2000, plus 1 slaughterhouse and more recently 1 free-range chicken farm (Government of Bermuda, 2005). The dairy farms, with 202 milking cows provide 100% of the island's fresh milk requirement, whilst the 7,000 laying hens provide just 15% of the island's local fresh egg requirement, down from 95% in 1971.

Current legislation concerning agriculture includes the Bermuda Plan 2008 which provides for the protection of agricultural land and soil conservation through a dedicated conservation zone, as well as the Agriculture Act 1930, under which a suite of regulations establish a support system for local agriculture, including mandating a system to ensure rigorous protection from potentially invasive pest species and diseases, as well as establishing standards for animal care and welfare. Protection of the local market for farmers through embargoes is effected under the Importation of Fruits, Vegetables and Flowers Act 1961. Further standards for animal care are laid out under the Care and Protection of Animals Act 1975.

## 11.2 Impact of Climate Change on Agriculture

The global consensus is that subsistence and commercial agriculture on small islands will be adversely affected by climate change (IPCC, 2007). Local agricultural production is likely to be impacted by a variety of factors including sea level rise, temperature changes, $CO_2$ levels, storm inundation, seawater intrusion into freshwater lenses, soil salinisation, temperature changes and changes in water supply. Perhaps the most significant impact will be the increasingly unpredictable nature of our weather patterns; a variable that already challenges Bermuda's farming community.

### *Sea level rise*

In Bermuda, the impact of saltwater intrusion is already being seen across some agricultural plots in Bermuda and future predictions only suggest further impact and loss of arable production. Maps 15 and 16 show the amount of arable land lost with projected rising sea levels. The first projects a rise of 0.59 m which is the upper end of the IPCC (2007) projections and shows 16 agricultural plots being affected. However, the Panel underlined that this estimate only included rises caused by the expansion of sea water in a warmer climate, not the water contributed by the decline of the Greenland and Antarctica ice sheets. Whilst further modeling is required to determine more accurate predictions, gross calculations to assess the maximum possible rise that can be expected this century suggest that 2 m is physically possible, so the second projection accounts for a 2 m rise and reveals that 133 plots and 29.157 ha would be impacted by the resulting salt water intrusion.

### *Increasing temperature*

High summer temperatures and unpredictable rainfall patterns already dictate a lull in crop production through the summer months, whilst milk production tends to be lower from June to September as a result of the higher temperatures and likely heat stress. Future climate predictions for Bermuda suggest conditions that may only exaggerate this. Consideration must also be given to the fact that potential and currently invasive weeds, pests and diseases may be stimulated with changing climates. Crop damage through invasive pests already costs the industry upwards of $100,000 per annum (Sinclair, pers. comm.) and higher temperatures may promote pestilent species.

### *Increasing carbon dioxide*

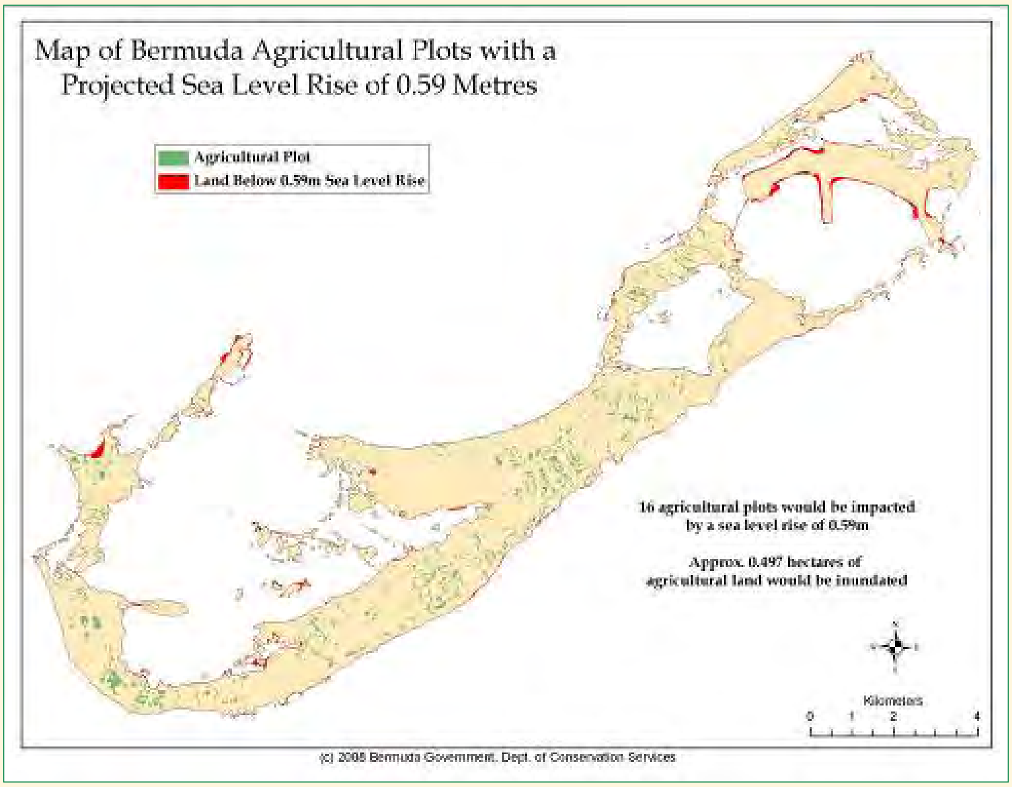
Increasing $CO_2$ in the atmosphere may increase crop productivity however it is believed that this well be a temporary effect, as plants acclimate to change.

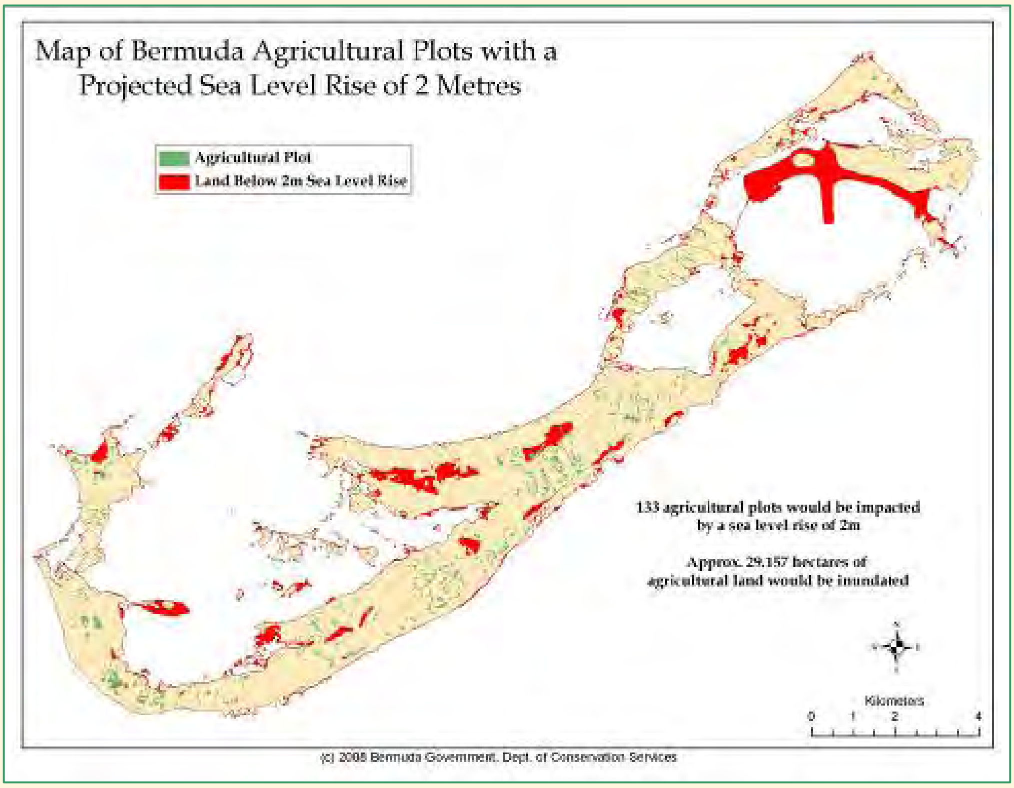
### *Changes in precipitation*

Heavy rainfall threatens soil stability, especially on the sides of the valleys supporting crop production. Excessive rain will also affect the production of honey on the island. The exportation of honey and beeswax has long featured in the island's history and today about 30 beekeepers (only one of which is commercial) maintain 319 hives, with each hive containing 60,000 – 80,000 bees. Each hive averages 56.7 – 68 kg of honey per year which is consumed locally. The quality and duration of nectar flows is affected by weather including heavy rain, hurricanes and high winds.

### *More intense tropical storms*

Extreme weather conditions are also considered to be one of the main threats facing local farmers and the direct destruction of crops caused by hurricanes has been evidenced in recent years. Hurricane Fabian for example, put several local farmers out of business (Government of Bermuda, 2003). However, tropical storms do not just cause the destruction of crops, but also




*Map 15 (above) showing the impact of a 0.59 m sea level rise on Bermuda's agricultural plots and Map 16 (below) of a 2.0 m sea level rise.*

affect planting. September and October is the main planting season and this coincides with the period of greatest tropical storm activity. This also coincides with one of the year's major nectar flows, so honey production can be affected. Meanwhile, the loss of electrical power in some storms has seriously impacted the local dairy farmers who have suffered substantive and protracted losses in productivity as a result of not being able to milk their herds when mechanized milking equipment was inoperable.

Finally, energy and food security will also become a more important consideration in the future. Globally, agricultural land is being used to grow crops for the production of biofuels and this is already leading to higher food prices and predictions that the era of 'cheap food' has come to an end. This includes feed for animals and the price of cattle feed has tripled in Bermuda in the past year. It is clear that with ongoing growth of the world's human population compounded by the widespread loss of valuable farmland, increasing scarcity of fresh water, and global challenges to pollinating species, food security and availability will become a critical motivating factor driving local and international policies once again. Safeguarding agricultural land for future food production could be critical to securing Bermuda's future.

***Table 13. Summary of impacts of climate change on agriculture in Bermuda.***

| CLIMATE CHANGE | EXPECTED IMPACTS |
|---|---|
| Sea level rise | • Saltwater intrusion leading to loss of arable land. |
| Increasing temperature | • Heat stress in cattle.<br>• Unsuitable climate for certain crops.<br>• Stimulation of potentially invasive species. |
| Increasing $CO_2$ | • May increase crop productivity however likely to be a temporary benefit as plants acclimate to change. |
| More intense tropical storms | • Destruction of crops and loss of power leading to long-term loss of productivity of dairy animals.<br>• Honey production affected.<br>• Planting season disrupted. |
| Heavier, less frequent rainfall events | • Increasing soil erosion.<br>• Honey production affected. |

## *11.3 Impact of Agriculture on GHG Emissions*

Although almost negligible in terms of the island's overall emissions, it should be remembered that conventional farming does contribute to the production of greenhouse gases. Methane is produced by herbivores during digestion of carbohydrates (enteric fermentation). Cattle and sheep produce more than horses and pigs because they can digest cellulose, a complex carbohydrate which results in the release of more methane. Methane is also produced from the decomposition of livestock manure. 0.087 Gg of methane are produced annually in Bermuda (Manson and Hasselbring, 2005). Meanwhile nitrous oxide is emitted through nitrification and denitrification of agricultural soils. 0.000005 Gg are produced annually in Bermuda (Manson and Hasselbring, 2005). $CO_2$ emissions from burning fossil fuels for farm power and transport and land clearing are another consideration. Whilst carbon quotas may eventually be applied, in the interim it is incumbent upon us as a community to find ways to reduce our emissions.

Significantly, recent evidence about organic farming suggests that it might have "profound implications in the battle against global warming" (www.strauscom.com/rodale-release). The world's longest running study of organic farming, the Rodale Institute's groundbreaking Farming Systems Trial®, has documented that organic soils actually capture atmospheric carbon dioxide and convert it into soil material, serving as carbon sinks.

***Table 14. Summary of impacts of agriculture in Bermuda on GHG emissions.***

| GHG | IMPACTS |
|---|---|
| Greenhouse gas (GHG) emissions | • Local farming reduces GHG by eliminating 20% of need for imported fresh produce.<br>• Conventional farming produces methane and nitrous oxide thereby increasing emissions.<br>• Organic farming decreases energy, fuel and irrigation costs and serves as a carbon sink so reducing emissions. |

## 11.4 Mitigation and Adaptation Measures

With the very real threat that climate change presents to us, there are some key areas in which measures can be taken to manage the risks to sustainable agriculture and indeed enhance the opportunities for innovative solutions. These include; 1) development of adaptation strategies that could enable us to be proactive and build resilience into our agricultural systems, 2) adoption of mitigation strategies to reduce our greenhouse gas emissions, 3) research and development to enhance the sectors' capacity to respond, and 4) improved awareness and information sharing to inform decision-making within the sector. Bermuda's unique, geographically isolated position may reveal some new opportunities upon which the agricultural sector could capitalise. Existing policies and strategies will provide an important framework for developing these measures.

In 2003, the Minister of the Environment (Bermuda Board of Agriculture, 2004) presented a vision statement for agriculture in Bermuda which reads: "The Bermuda Government recognizes that it is unwise to become fully dependent upon imports to satisfy the food needs of the island, and that agriculture contributes to the preservation of our quality of life and the maintenance of the rural character of the islands. In light of these truths, Government is committed to preserving the viability of local agriculture through:

- Protecting arable land for the benefit of present and future generations,
- Encouraging the advancement of agricultural techniques,
- Providing incentives to promote the profitability of agriculture,
- Continuing to use the embargo system to promote stability in the local market for fresh produce".

In 2004, the Bermuda Board of Agriculture highlighted a number of challenges to the industry that would need to be overcome to further these goals (Board of Agriculture, 2004). These challenges included extreme weather, an aging community of farmers, a lack of sustainable arable land and poor land husbandry for land not in production, pest species, a lack of support services and an inconsistent land tendering system. As a consequence they prepared a number of specific recommendations. These included disaster relief measures such as; 1) negotiating a crop insurance facility for disaster relief, 2) duty relief on imports of farm equipment and supplies (in place now), 3) payroll tax relief for recovery period, 4) access to interest free loans for rebuilding of the industry, 5) Emergency Measures Organisation priority listing to facilitate problems with electricity supply for irrigation and animal husbandry, and 6) temporary fast track for immigration where needed for recovery efforts. Other recommendations included strengthening government veterinary support and ongoing duty relief on imported machinery, and upgrading the Marketing Centre to increase chill storage. They further advocated for; the establishment of a farming apprenticeship programme to introduce and train future generations, including a work release programme for suitable individuals needing rehabilitation or leaving the correctional system; a hands-on programme be developed to specifically target backyard farmers and their families to develop community farming; promoting farming within cultural tourism and based upon the culinary arts festival.

Reinforcing the foundation of the industry in this way will be an essential part of adapting to the impacts of climate change on local agriculture and global food security. In addition though, research and development is needed to improve the forecasting capacity of models at local scales to predict climate impacts on agriculture, and to give consideration to new crops that might be better suited to the changing conditions, or new technologies that can overcome the issues posed by more variable climate patterns on our current suite of crops.

It will also be imperative for the Department of Environmental Protection to continue to network with neighbouring jurisdictions to keep track of disease or pest threats, and to ensure that local legislation controlling imports is rigorously enforced to minimise the threat of invasive species. Our isolation from agricultural diseases already threatening the US continent and neighbouring Caribbean islands could in fact work to our advantage and inspire innovative farming initiatives that see Bermuda exporting healthy strains of crops of animals. As Ward (pers. comm.) points out, the honeybee population in the US is currently in crisis due to disease coupled with the negative impacts of pesticides on the bee population. However Bermuda's bees have a clean bill of health and through a programme of queen bee production, could perhaps be used to 'restock' the US populations.

The impacts of climate change will likely also dictate a need for higher resilience against both excess of water (due to high intensity rainfall) and lack of water (due to extended drought periods). In either case, the amount of organic matter in the soil may prove critical as it improves and stabilizes the soil structure so that the soils can absorb higher amounts of water without causing surface run-off, which could result in soil erosion and flooding. Organic matter in the soil also improves the water absorption capacity of the soil during periods of extended drought. Organic agriculture, combining zero or low tillage and permanent soil cover may increase the soil's organic carbon, reduce mineral fertilizers use and reduce on-farm energy costs.

As stewards of natural resources, the farming community also needs to strive for mitigation strategies to reduce greenhouse gas emissions. These might include promoting cost-effective alternatives to fossil fuel in agriculture, including bioenergy, exploring opportunities to reduce energy use in agriculture through improved efficiency, developing best management practices for methane and nitrogen and developing tools to encourage soil management practices that improve carbon storage. With clear evidence that organic farming decreases energy, fuel and irrigation costs and serves as a carbon sink, organic agricultural production could in fact take on a lead role in regenerating the environment.

Finally, it is also essential that the issues that climate change presents are effectively communicated through incorporation into education and training packages, as well as incorporation of climate change into policy communications. Agricultural camps, the Annual Exhibition, the Farmers' Market and the Paget Community Garden are all vehicles for information dissemination.

## 11.5 Acknowledgements

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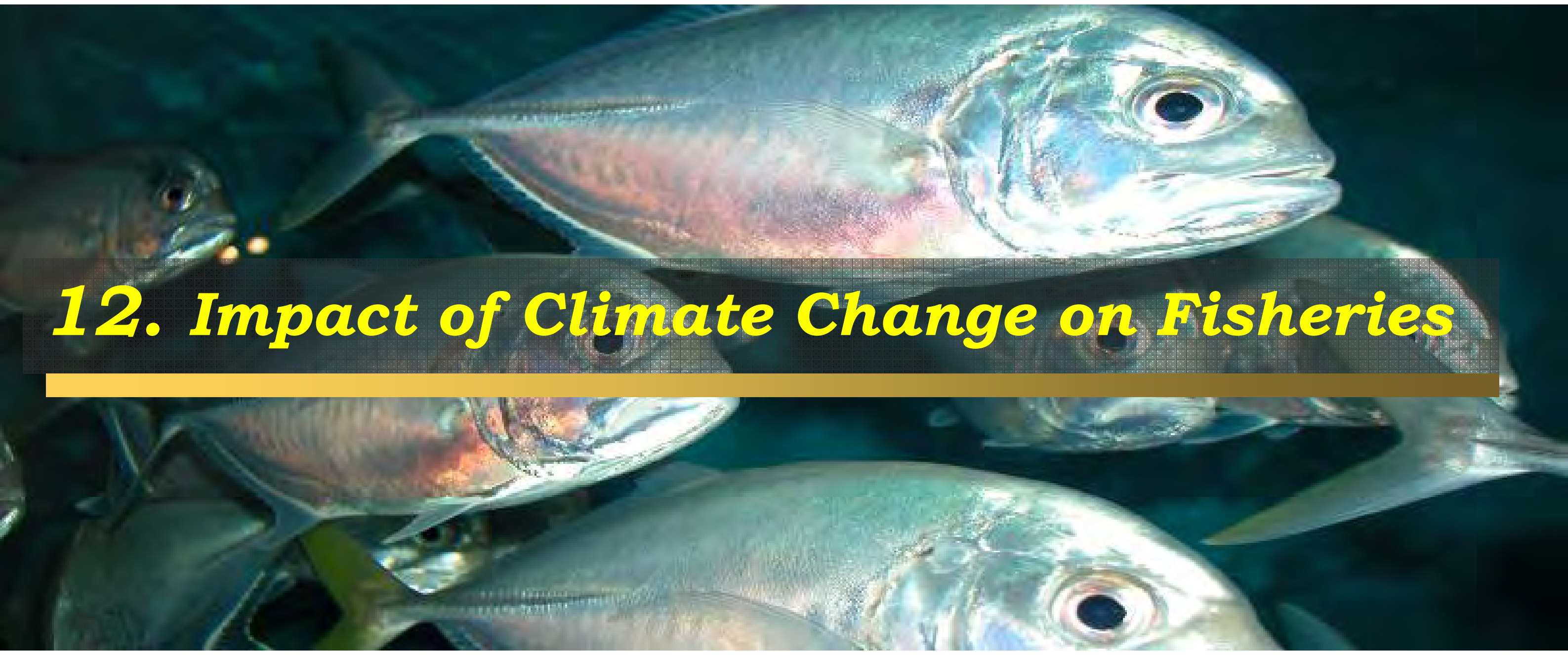

# 12. Impact of Climate Change on Fisheries


**SUMMARY**

- Fish is one of the last remaining "wild foods" in the diets of Bermuda residents and represents not only a rich source of several unique dietary nutrients, but also forms an important part of Bermuda's cultural identity. It may also become increasingly significant by enhancing our food security. The threat to fisheries is a growing global concern that will impact Bermuda.

- The mainstays of the fishery are the offshore pelagic species, yellowfin tuna, blackfin tuna, wahoo and to a lesser extent dolphinfish, as well as lobsters, groupers, snappers and reef fish like grunts and coneys. There are currently 331 licensed fishermen and commercial landings total 418 metric tones per year.

- Sea level rise will impact the fishery mainly through loss of nursery habitat. More intense storm activity will also affect nursery habitat as well as larval retention, fish behaviour and fishing effort.

- Changing ocean temperature will have a significant direct affect on fish metabolism, growth rate, productivity, seasonal reproduction, distribution, susceptibility to diseases, toxins (algal blooms) and mortality as well as invasive species. It may also cause mis-match in food availability with plankton. However, as many species found in Bermuda are at their northern limits, warming oceans may have a favourable impact, extending the fishery for migratory species and increasing species diversity on the reef.

- Natural variability in recruitment and productivity is typical of any fishery so management practices have already developed an adaptive approach. However, Bermuda's marine resources will be more resilient to climate change impacts if additional pressures (harvesting, loss of habitat, pollution, disturbance, invasive species) can be minimized.

## 12.1 Introduction

With steady harvesting pressure over its 500-year history, Bermuda's fish stocks have been severely depleted (Lefroy, 1876). Certain species are economically extinct, whilst others have become locally extinct (extirpated) (Butler *et al.,* 1993). In 1990, after it had become apparent that groupers could not support the heavy fishing pressure being exerted on them (despite a series of increasingly restrictive management tactics), and with fears that the health of the entire coral community was being jeopardized as landings of previously ignored reef grazers increased, the trap fishery was closed.

Despite this, Dewailly and Rouja (2008) note that fish is one of the last remaining "wild foods" in the diets of Bermuda residents and represents not only a rich source of several unique dietary nutrients but also forms an important part of Bermuda's cultural identity. With rigorous legislation in place including two seasonally protected areas to safeguard the grouper spawning grounds and a highly regulated commercial fishery, fishing for finfish continues mainly by hook and line/trolling. The mainstays of the fishery today are the offshore pelagic species, yellowfin tuna (*Thunnus albacares*) and blackfin tuna (*Thunnus atlanticus*) (Luckhurst *et al*., 2001) wahoo (*Acanthocybium solandri*), and to a lesser extent dolphinfish (*Coryphaena hippurus*) (Luckhurst and Trott, 1998). These authors reported increasing commercial landings of yellowfin tuna and wahoo between 1975 and 1998 concurrent with the demise of the reef fishery. There are currently 331 licensed fishermen and commercial landings total 418 metric tones (Government of Bermuda, 2008).

Bait, jacks and little tunny are caught in seine nets, and a commercial lobster fishery deploying specially designed traps which exclude most finfish is ongoing. Landings for reef fish (primarily groupers, snappers and miscellaneous species (grunts, coneys etc) caught by hand line total approximately 100 metric tonnes. Sportfishing, focusing on offshore pelagics rather than vulnerable reef species is popular with both Bermudians and tourists alike. There are 26 licensed charter fishing vessels. A study conducted in 1999 estimated that recreational pelagic fisheries accounted for 17% of the overall extraction of pelagic stocks, although this varied significantly by species, with up to 42% for yellowfin tuna (Hellin, 1999).

The global community is fast realizing that the issue of food security in the face of climate change may present one of the most significant challenges facing society. Bermuda's current reliance on international imports makes us extremely vulnerable. Increasing local food availability through fishing may become an essential adaptation to the threats posed by climate change, but given the historical pressure the fishery has faced, it will be particularly critical that sound management practices prepare for heavier fishing practices in concert with any risks from climate change.

## 12.2 Impact of Climate Change on Fisheries

Climate change may have both direct and indirect impacts on our fish stocks, including impacts on habitats, the resources, harvesting patterns, shore facilities and fishing communities.

### *Sea Level Rise*

Sea level rise will impact Bermuda's fish populations in so far as it impacts their nursery seagrass and mangrove habitats. Further, if corals cannot keep pace with rising seas and start dying off, then clearly the island's reef fish stocks will be negatively affected.

### *Increasing Temperature*

Changes in Species Distribution

Fish are poikilothermic, meaning that their body temperatures vary according to the ambient temperatures. Therefore, any change in the temperature of the ocean will have a significant effect on their metabolism, growth rate, productivity, seasonal reproduction, distribution, susceptibility to diseases and toxins and mortality. It is also reasonable to assume that migratory species are likely to be able to compensate for climate change by adjusting their migratory routes and distribution patterns. In Bermuda, the highest landings for yellowfin coincide with the warmest water temperatures (30 $^{o}$C) and the lowest when the temperature is at the low end of the preferred thermal range for the species (18 $^{o}$C) (Luckhurst *et al*., 2001). Studies of yellowfin tuna in the Caribbean, suggest that they would not survive a 1°C rise in the temperature of the Caribbean Sea and would migrate further north as formerly cold waters become milder (Moxam, 2008). This could benefit Bermuda's fishery.

Local landings for blackfin tuna are considerably lower and the seasonal trends suggest that perhaps they prefer temperatures above 20 $^{o}$C and so are only present in Bermuda's fishing grounds during the warmer months (Luckhurst *et al*., 2001). If temperatures rise according to climate change predictions, this may promote an extended local blackfin tuna fishing season. However, it is unclear whether the high recapture rates reported for both yellowfin (17.3%) and blackfin (10.8%) as part of a long term tagging programme reflect a stable migratory route or a resident population (Luckhurst *et al*., 2001). Bermuda's dolphinfish however, are believed to be part of a 'northern' stock which occurs near Puerto Rico in January/February, travels north to North Carolina in June/July, and then returns south via Bermuda in July/August (Oxenford and Hunte, 1986). Again, warming oceans in the Caribbean Sea could drive the stock north, possibly favouring Bermuda with an extended season.

Climate change is expected to cause shifts in distribution of species at the extremes of their ranges. The majority of reef fish species in Bermuda are at their northernmost extremes (Glasspool, 1994), and this has been used to explain why our coral reefs only support about 55% of the reef fish species found further to our south in the Caribbean. Any local warming therefore might encourage the recruitment and success of more species, thereby enhancing our local marine biodiversity and fish stocks.

Changes in food availability

Possible changes in the Atlantic conveyer belt may affect fish populations and the aquatic food web as species seek conditions suitable for their lifecycle. Most marine fish produce a planktonic larval phase whose survival is believed to be strongly dependent on primary productivity and therefore the availability of sufficient phytoplankton at the base of the foodweb. Studies also show that in some areas, phytoplankton has decreased by up to 30% over the past decade. A study based on over 100,000 plankton samples collected between 1958 and 2002 with the Continuous Plankton Recorder (CPR) (Richardson and Schoeman, 2004), revealed an increase in phytoplankton abundance in the cooler regions of the NE Atlantic (north of $55^{o}$N) and a decrease in warmer regions (south of $50^{o}$N). This has been explained by the fact that although warming has caused a reduction of vertical mixing in both regions, the water is sufficiently cold and turbulent in the north for the increased temperatures to benefit planktonic productivity. This benefit is not realised further south.

As spawning activity in some fish has been linked to water temperature, increasing temperatures may trigger earlier spawning which could result in a temporal ‘mismatch’ with the availability of the food source. Complicating this is the fact that these planktonic communities (both food and larvae) are dependent on the properties and movement of the water and are therefore intrinsically mobile. The potential for rapid changes in distribution is therefore inherent and such a “match-mismatch” hypothesis is used to explain variability in survival and consequent recruitment to fishable stocks.

In Bermuda, Burnett-Herkes (1975) documented the spawning season of the red hind (*Epinephalus guttatus*) and observed not only that their sexual activity appeared to be defined by the minimum and maximum seasonal temperatures, but that peak spawning occurred 3 months after peak primary productivity from February-April. Trott (pers. comm.) observed that reproductive activity in coneys (*Epinephalus vulva*) only commences when the water temperatures rises above $20^{o}$C, typically in April, and that peak spawning occurs when temperatures reach 23.5 $^{o}$C – 25 $^{o}$C in June. She noted little activity in the hottest months, August and September. Meanwhile, Glasspool (1994) observed the abundance of larval reef fish to be greatest from late May to October. She proposed that for some species there appeared to be a correlation between distribution and a seasonal convergence zone which possibly retains the larvae within the northern lagoon, enabling them to complete their development in the vicinity of suitable settlement habitat. Temperature and salinity changes and more intense tropical storm activity brought about by climate change could disrupt this retention mechanism. Peak larval settlement of lobsters takes place during the hurricane season and it is therefore possible that the impact of these storms on water masses carrying recruits could affect the settlement of lobster larvae and subsequent recruitment. Further, although Bermuda is managed for the purposes of most of its marine resources as if it was self-replenishing, Gulf Stream eddies serve to maintain some genetic homogeneity with Caribbean stocks and disruptions to larval input from this ‘upstream’ supply would inevitably have some bearing on our reef fish stocks.

Changes in distribution of disease vectors and invasive alien species

Warmer waters have also been linked to mass mortalities of many aquatic species. For example, the northward spread of two protozoan parasites (*Perkinsus marinus* and *Haplosporidium nelsoni*) from the Gulf of Mexico to Delaware Bay has caused mass mortalities of eastern oysters (*Crassostrea virginica*). Winter temperatures consistently lower than 3 $^{o}$C limit the development of the MSX disease caused by *Perkinsus* (Hofmann *et al.,* 2001) so if winter temperatures remain higher, the northerly spread of this and other pathogens can be expected to continue.

In Bermuda's waters, recent and growing concern has focused on the invasive lionfish (*Pterois volitans*). Believed to have been released accidentally and/or intentionally from saltwater aquaria in the USA (Hare and Whitfield, 2003) or the Bahamas (Flook, pers. comm.), this native of the Pacific Ocean has found its way to Bermuda where it has become an unwelcome invasive species. Whilst our terrestrial habitats have been inundated by invasive alien species, until now, the marine environment has remained relatively free from such threats. The introduction of the lionfish has changed this and exerted a new pressure on our marine ecosystem. Anecdotal evidence suggests that breeding populations of this voracious predator have now become established in local waters (Flook, pers. comm.). Cursory observations suggest that the lionfish can be found in both deepwater and nearshore locations but that this distribution maybe seasonally driven, with the fish moving offshore in the winter months when the inshore water temperatures drop, and only moving inshore when the waters warm in the summer. If this is the case, it may provide a temporary reprieve from predation for our juvenile fish developing in the nearshore nursery habitats.  However, if climate change promotes elevated temperatures around Bermuda as predicted, the apparent seasonal migration of the lionfish into deeper waters may not occur with the result that our vulnerable reef fish could be subject to year round predation. Warmer waters could also extend their reproductive season facilitating their population growth. We only have to look to the Bahamas to assess the seriousness of the threat presented to our fish stocks by this invasive species.

Increasing seawater temperatures may also lead to the increased incidence of toxic red tides. This includes ciguatera, which proliferates on dead corals and certain macroalgae leading to public health problems caused by ingestion of sea food as well as high rates of mortality among fish and marine birds. There have been three fairly recent, documented incidents of sudden mass mortality in scallop species (*Euvola ziczac* and *Arcopecten gibbus*) and in the pinfish (*Lagodon rhomboides*) which coincided with maximum sea surface temperatures and the breakdown of the thermocline in Harrington Sound (Sarkis, pers. comm.). Sarkis explains that a range of recognized 'harmful' algal species were identified in the plankton at the time, and whilst the factors favouring harmful algal blooms (HAB) are still under global discussion, their presence in Bermuda and known proliferation with elevated sea surface temperatures is a matter of concern.

### *Change in Precipitation*

Flooding may also increase the organic input from land run-off into nearshore habitats resulting in fish die-offs through oxygen depletion. Oxygen levels are generally low in our inshore waters during the summer months due to elevated temperatures placing many species near their tolerance limits (Sarkis, pers. comm.)

### ***More intense tropical storms***

Impact on fishery habitat

Coral reefs provide the habitat for a variety of reef fishes and spiny lobsters that are locally exploited. Storm damage that breaks up the three dimensional structure of the reef may be expected to affect reef fish and abundance and diversity which is related to the complexity of the reef structure. Hurricanes also appear to cause direct mortality of adult fishes by stranding them. Hurricane Fabian caused reef fish to be deposited on the airport runway (Guishard, pers. comm.) and on the trail at Spittal Pond (pers. obs.). Hurricanes also appear to affect the distribution of adults, which move into the least damaged areas, and juveniles, which may not settle in damaged areas (Lassig, 1983; Bouchon *et al*., 1981; Letoureur *et al*., 1993).

The larvae of most reef fish settle out of the plankton directly onto the coral reef, but in certain species (mainly from the Haemulidae (grunts), Lutjanidae (snappers) and Scaridae (parrotfish)), the larvae first settle into a nursery habitat, typically mangroves or seagrasses (Nagelkerken *et al*., 2000). These nurseries are believed to enhance the density, growth and survival of these fish. Huijbers *et al.* (2008) determined that in parts of Bermuda where these nursery habitats are sparse, some typical 'nursery' species can adapt and settle onto shallow patch reefs instead. However, two species important to the local reef fishery, *Haemulon sciurus* (bluestriped grunt) and *Lutjanus griseus* (grey snapper) are not so flexible and depend on the nursery mangrove and seagrass habitats. As we have seen, mangroves are particularly prone to the impacts of climate change, which may in turn affect the numbers and size of recruits that survive to enter the fishery.

Impact on fishing revenue

Storms also affect fish availability by affecting the distribution of the resource, or the way they interact with the fishing gear (Mahon, 2002b). In the eastern Caribbean, from November through May, and particularly in February to April the sea is reported to "roll" or "surge" intermittently. The effect of these surges is to stir up the sea in shallow areas down to depths of 20-30 m. At these times, lobsters leave their hiding places and move about, thus increasing their vulnerability to traps. (Outerbridge (pers. comm.) confirms that this is true also in Bermuda). In Antigua, Hurricane Luis was followed by a large increase in lobster catches. Increased vulnerability of lobsters to fishing due to storms could result in stock depletion leading to recruitment overfishing and stock decline (Mahon and Joseph, 1997). Reef fishes also reportedly show a response in availability due to storms. Immediately before storms their availability is low, but when fishermen are able to return to fishing after storms, there can be short periods in which catches are higher than usual.

Revenue from fishing is affected by the amount of catch per unit effort extended, and changes in stock abundance and availability will affect this. Climate-related changes that reduce the number of days on which vessels can fish will also bring about a short term reduction in catch per vessel and overall catch. More intense storms therefore will increase costs by; increasing travelling times to fishing grounds, increasing fuel costs in rough seas, increasing labour costs due to the working conditions, increasing maintenance costs due to damage of the vessel, equipment and fishing gear (Mahon, 2002). Destruction of lobster traps during the windy season is one of the main costs caused by inclement weather. This reduction in fishing effort however, may lead favourably to stock recovery in over-exploited stocks in the longer term, and thereafter to increased catch per unit effort and increased total landings.

***Table 15. Summary of impacts of climate change on Bermuda's Fishery***

| CLIMATE CHANGE | EXPECTED IMPACTS |
|---|---|
| Sea Level Rise | • Negatively affects juvenile nursery habitats including mangroves and seagrasses.<br>• Potential threat to survival of coral reefs and reef fish. |
| Increasing temperatures | • Affect duration of breeding season.<br>• Will affect food availability by causing mismatch between timing of primary production and spawning events.<br>• Result in more toxic red tides.<br>• Will favour invasive species and spread of fish diseases vectors as well as harmful algal blooms (HAB).<br>• May cause northward movement of Caribbean/Atlantic migratory fish stocks, favouring Bermuda with an extended fishing season.<br>• May also favour successful recruitment of a more diverse suite of Caribbean reef species.<br>• Decreasing $O_2$ as a result of increasing temperature may stress marine species. |
| Increasing $CO_2$ | • May benefit the algae attached to seagrasses leading to seagrass decline through shading and hence loss of juvenile fish habitat.<br>• May cause decreased calcification of reefs, impacting the whole reef ecosystem. |
| More intense tropical storms | • Disrupt local larval retention mechanisms during summer months.<br>• Physically destroy nursery and adult habitats.<br>• Result in fish strandings on land.<br>• May result in re-distribution of fish away from damaged areas changing the dynamics on a particular reef.<br>• Cause loss in revenue from fishing through lost effort (damage to gear, conditions too rough to fish). |
| Heavier, less frequent rainfall events | • May result in increase of organic matter into nearshore habitats leading to fish kills from oxygen depletion. |

## 12.3 Impact of Fisheries on GHG Emissions

The only significant impact Bermuda's fisheries have on climate change is the emission of greenhouse gases through fuel consumption in fishing boats.

## 12.4 Mitigation and Adaptation Measures

Natural year to year variability and decadal scale variability in recruitment and productivity is typical in most fisheries (Mahon, 2002b). With effective management therefore involving monitoring and feedback, fisheries have already developed adaptive strategies with catches varying according to the state of the stock and fisherman having to adapt accordingly. However, climate change presents an additional pressure on top of the many (fishing pressure, loss of habitat, pollution, disturbance, invasive species) which fish stocks already experience. Bermuda's marine resources will be more resilient to climate change impacts if these stresses can be minimised.

Effective adaptation of Bermuda's fisheries to the impacts of climate change will therefore be closely tied to existing efforts to improve fisheries management of our resources. With an already well-regulated fishery the most appropriate response may be to ensure that our current monitoring efforts are capturing gross trends in the fisheries, and hence departures from these that may be attributable to climatic change. If detected, adaptive measures to changes in stock distribution, recruitment levels and variability and adult biomass and production may be achieved through conventional assessment and management approaches by adjusting fishing effort to levels appropriate with the yield levels that can be sustained by the fish populations. This may require investment in gear development, greater flexibility within the fishing community to switch between bottom-dwelling reef fish and pelagic species, as well as increased seaworthiness of and safety aboard fishing vessels and greater security of vessels during tropical storms.

The significance of certain nursery habitats to the fishery would also suggest that efforts to minimise their destruction and where possible actively restore them in terms of quantity and quality would be an appropriate precautionary adaptation to the effects of climate change. A Coastal Zone Management Plan that includes the measures needed to adequately deal with the effects of climate change on coastal habitats would be helpful, and could plan for shoreward retreat of habitats. The new Coastal Conservation Zone introduced into the Bermuda Plan 2008 (Government of Bermuda, 2008b) is an important step towards this, but only allows for protection of terrestrial habitats; provision for coastal marine habitats is urgently needed.

There may also be a need to implement more rigorous monitoring of fish products and toxin levels, whilst consideration should also be given to the fact that climate change may cause the dislocation of workers from other sectors; possible benefits from stock recovery due to reduction in effort from to climate change impacts, may be negated by this (Mahon, 2002b).

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# 13. Impact of Climate Change on Mangroves


**SUMMARY**

- Bermuda's mangroves are highly productive and serve as an important habitat for many species, including as a nursery for exploited fish species. There are three distinct mangrove communities found locally; coastal, fringing and pond mangroves.

- Mangroves play a critical role in stabilizing coastal areas and serve as a 'bioshield' against storms. They also serve as a carbon sink.

- Bermuda's 2 mangrove species are at the most northerly limit of their geographical range. Evidence suggests that poleward mangroves are more resilient to the impacts of climate change and rising temperatures and $CO_2$ levels may in fact lead to increased productivity and diversity.

- Sea level rise presents the biggest threat to Bermuda's mangroves, eroding their seaward edges and occurring faster than they are able to retreat. Intense storms can also have a destructive impact. Exposed coastal and fringing mangroves will be more significantly impacted than pond mangroves.

- Adaptive management that seeks to maintain the health of existing mangroves as well as restoring swamps in suitable areas, preventing further erosion and providing buffer zones will be most effective in promoting resilience or recovery.

## 13.1 Introduction

Mangrove trees have adapted special aerial roots, support roots, and buttresses to live in muddy, shifting, and saline conditions. Mangroves provide an important habitat for a diverse suite of fish, crustaceans, molluscs, insects and birds. They are an important nursery area for some of Bermuda's commercially exploited reef fish (Huijbers *et al*., 2008). They also play a critical role in filtering and stabilizing coastal areas by trapping sediment and protecting the shoreline against storm damage, serving as a 'bio-shield'. Large quantities of peat are produced within the mangrove habitat from decaying litter fall and root growth, forming the base of an extensive food web. Thus their presence also enriches neighbouring habitats such as seagrasses and coral reefs, increasing their productivity in turn.

Bermuda's mangrove swamps are the most northerly in the world. Unusually co-existing with salt marshes (Thomas, 2004) and occupying a total of just 17.5 hectares (Anderson *et al*., 2001), they are much reduced from their original extent. Only two species of mangrove tree are found locally: the red mangrove (*Rhizophora mangle*), which is commonly found in the seaward part of coastal swamps and the black mangrove (*Avicennia nitida*), which inhabits a more landward position. Behind it the buttonwood (*Conocarpus erectus*), which is not a true mangrove and cannot root in salt water, often appears as a narrow strip. Unfortunately the invasive Mexican pepper (*Schinus terebinthifolia*) is actively displacing the buttonwood, although it cannot compete with the true mangroves. Thomas (2004) describes three distinct types of mangrove swamps in Bermuda, each with a different structure: coastal or bay mangrove swamps (eg. Hungry Bay); fringing mangrove swamps (eg. Mullet Bay); and the marine pond mangrove swamps such as those in Lovers Lake which typically only have one of the mangrove species present. The mangroves which are most significant as nursery areas include the coastal and fringing, and those ponds in which there is significant tidal exchange with the ocean (eg. Walsingham and Evans Ponds).

## 13.2 Impacts of Climate Change on Mangroves

Mangrove communities like those in Bermuda, with small tidal ranges and limited sediment supply, are considered extremely vulnerable to sea level rise (UNEP 1994). Mangrove species vary greatly with response to environmental factors. Temperature, (atmospheric and/or sea surface) is reported to be the limiting factor for high latitude mangroves (like Bermuda's) (Saenger *et al*., 1977). It might be expected therefore that Bermuda's mangroves will be affected by climate change however the type of mangrove (coastal, fringing or marine pond) will be a significant determinant in the extent of the impact.

### *Sea level rise*

Sea level rise has long been considered the greatest climate change challenge that mangrove ecosystems will face (Field, 1995), particularly for low-lying island mangrove systems where the only sediment available is from the mangroves themselves (Ellison and Stoddart, 1991). Individual mangrove species apparently show varying tolerances to the period, frequency, and depth of saltwater inundation (Semeniuk, 1994), but geological records indicate that they can adapt to sea level rise if, a) it occurs slowly enough (Ellison and Stoddart, 1991), b) adequate space exists either seaward or landward for expansion (roads, agricultural fields, urbanization, sea walls all hinder this), and c) if other environmental conditions are met (eg. orientation to wave fetch and local currents, steepness of slope, the areal distribution of wetlands and the geology of the neighbouring watersheds).

Tidal range and sediment supply are two critical indicators of mangrove response to sea level rise. Hendry and Digerfeldt (1989) discovered that in mangrove communities in western Jamaica the rate of sedimentation (peat production) exceeded the rate of the mid-Holocene sea level rise (about 3.8 mm/yr) presumably enabling the mangrove to keep pace with rising seas. However, Ellison and Stoddart (1991) showed that on low islands, mangroves could only keep pace with a sea level rise of up to 8 cm/100 years, but not at rates over 12 cm/100 years.

Hungry Bay represents Bermuda's most extensive mangrove swamp and dates back about 6,000 years to the mid-Holocene when sea level rise slowed from the rapid rates of the previous 5,000 years. Yet there is clear evidence that it is now threatened. Ellison (1991) suggests that the mangrove system appeared to be at equilibrium with sea level around the 1930s. Since then she notes that it has failed to maintain sedimentation rates relative to the sea level rise and the peat levels at the seaward edge were - 0.2 m below Bermuda's 1964 ordnance datum in the late 1980s. Further, she suggests that the more alkaline conditions recorded in the mangrove are indicative of a system dominated by sea water and the rapid removal of decaying material, which would normally be allowed to accumulate in a healthy system. There is also evidence of freshwater outflow into the swamp at low tide from the freshwater lens adjacent to the Bay (Rowe, 1984), and the ebb tides flow twice as fast as flood tides. The result is that leaf litter is not accumulating sufficiently to enable the mangrove to keep up with rising seas. Further, evidence suggests that the seaward edge of the swamp has retreated about 80 m in recent years, exacerbated by the gradual opening of the gap to the ocean at the southern corner of the swamp, as well as by the mangrove creek that was intentionally dug in the 1950s/ 1960s to allow access to boats. Maps 17 and 18 show the area of Hungry Bay mangrove lost with projected rising sea levels. The first projects a rise of 0.59 m which is the upper end of the IPCC (2007) projections the second projection accounts for a 2 m rise which may be more realistic when melting of the ice sheets is taken into consideration. The percentage of mangroves inundated by sea water in the first projection is 18.8%; under a 2 m sea level rise, this increases to 61.4% (M. Shailer, pers. comm.)

Sea level rise is also likely to affect the fringing mangroves along Ferry Reach and Mullet Bay, but its impact on the pond mangroves is less certain. In ponds with a very limited tidal range, there may be very little impact. The extent of the impact will also depend on the extent to which the mangroves can retreat. In ponds formed in sink holes (such as Walsingham Pond), the ability of the mangroves to retreat is limited by the hard karst surround. However, in ponds formed in shallow depressions there may be much greater capacity for upwards retreat.

### *Increasing temperature*

Given the fact that the mangroves in Bermuda are at their most northerly extension, it is likely that they will be more resilient to temperature rises than elsewhere. Edwards (1995) argues that increasing sea-surface and air temperatures would likely benefit mangroves living near the poleward limits of current distributions, leading to increased species diversity, greater litter production, and larger trees in these mangrove systems. However, temperature increases may impact mangroves by changing the seasonal patterns of reproduction and the length of time between flowering and the fall of mature propagules (UNEP, 1994; Ellison, 2000). Most mangroves produce maximal shoot density when mean air temperature rises to 25°C. At temperatures above 25°C, some species show a declining leaf formation rate (Saenger and Moverly, 1985). Temperatures above 35°C have led to thermal stress affecting mangrove root structures and establishment of mangrove seedlings (UNESCO, 1992). At leaf temperatures of 38-40°C, almost no photosynthesis occurs (Clough *et al*., 1982; Andrews *et al.,* 1984).

### *Increasing carbon dioxide*

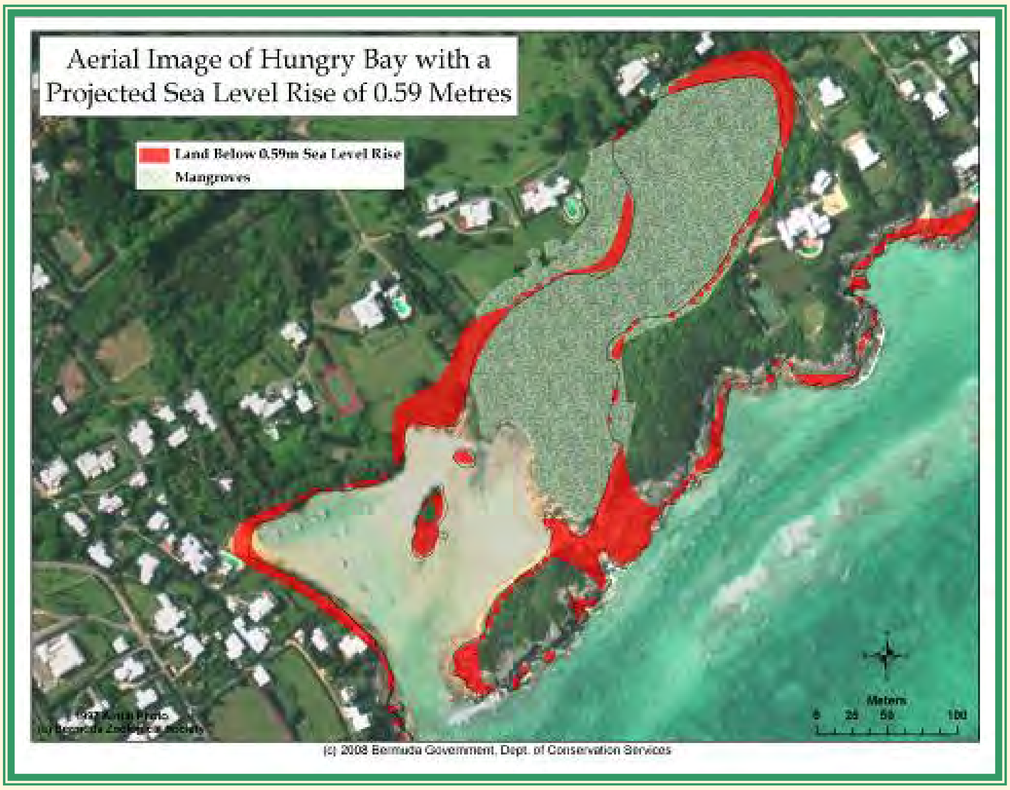
Increased levels of $CO_2$ are expected to enhance photosynthesis and mangrove growth rates (UNEP, 1994). There may be a knock-on effect to mangroves of possible damage to coral reefs from acidification due to increased $CO_2$ levels because mangrove systems depend on the reefs to provide shelter from wave action (Trenberth, 2005).

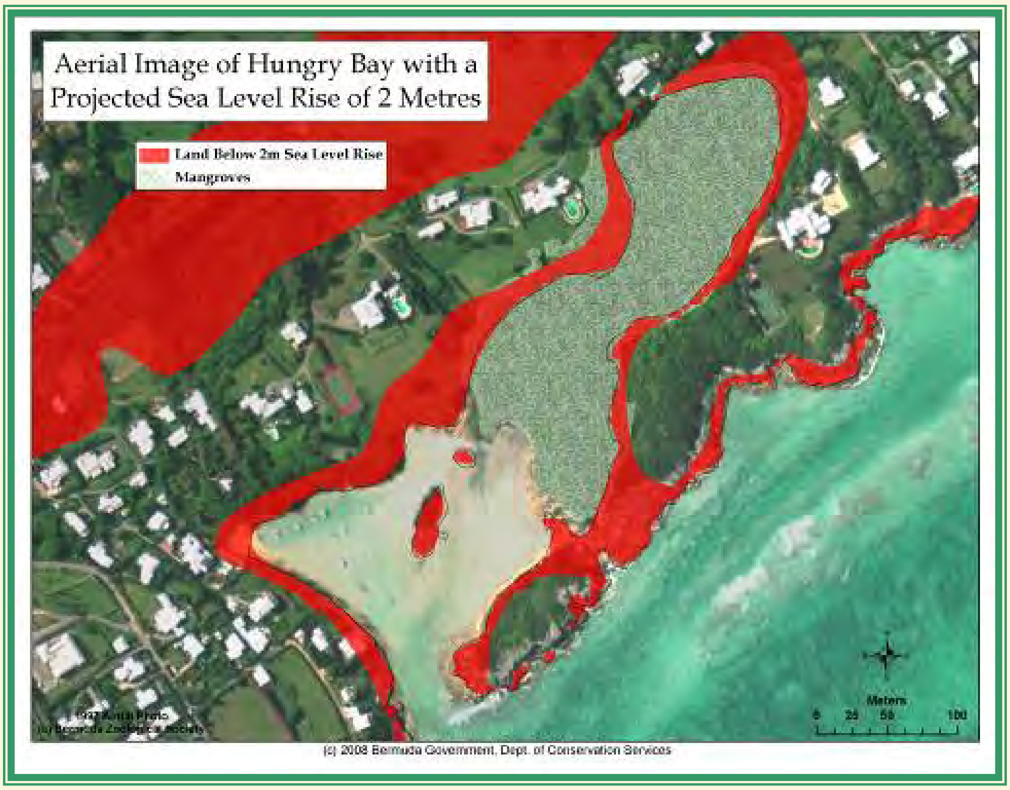
### *Changes in precipitation*

Changes in precipitation patterns caused by climate change may have a profound effect on both the growth of mangroves and their areal extent (Field, 1995; Snedaker, 1995). Increased precipitation may increase mangrove area, diversity of mangrove zones, and mangrove growth rates in some species (Field, 1995). However, too much water may 'suffocate' the mangroves; Ellison (2000) suggests that flooding, whether caused by increased precipitation, storms, or relative sea level rise may actually result in decreased productivity, photosynthesis, and survival.

### *More intense tropical storms*

Studies in the Caribbean have shown that large storms have resulted in mass mortality in 10 mangrove forests in the past 50 years (Jimenez *et al*., 1985; Armentano *et al*., 1995). The mangroves in Anguilla showed between 68% and 99% mortality as a result of a category 4 hurricane (Bythell *et al*., 1996) and Hurricane Mitch, a category 5 storm destroyed 97% of the mangroves in Guanaja, Honduras (Cahoon and Hensel, 2002). Ellison (1991) reports that Wingate estimated that Hurricanes Emily and Dean in 1987 and 1989 respectively caused a 35-40% destruction of biomass of the Hungry Bay mangrove. Thomas (2003) conducted a survey of the island's mangrove swamps after Hurricane Fabian and reported that "hundreds of $m^2$ of mangrove swamp were torn up and hurled back into the swamp breaking off other trees as they went". He noted that the debris penetrated 20-30 m back coming to rest against an impenetrable wall, which he suggests may act as a barrier to storms, protecting the interior of the swamp which is in "amazingly good condition". Thomas (2003) also observed that the fringing mangrove swamp




*Map 17 (above) showing the impact of a 0.59 m sea level rise on the Hungry Bay mangrove and Map 18 (below) of a 2.0 m sea level rise.*

Blue Hole was very badly impacted by the hurricane, with many of the trees broken or uprooted and the Bermuda bean and other 'swamp-back' herbs were annihilated. In contrast in Walsingham Pond, he reported that the mangroves were "almost unscathed" with only a few trees toppled and this was the same for the mangroves in Evans, Lovers, Trotts and Mangrove ponds.

***Table 16. Summary of impacts of climate change on Bermuda's mangroves***

| CLIMATE CHANGE | EXPECTED IMPACTS |
|---|---|
| Sea level rise | • Impacts mangroves if sediment build-up cannot keep pace with rising seas.<br>• Causes erosion of the seaward edges. |
| Increasing temperature | • Positively increases litter production and may result in larger trees.<br>• May affect seasonality of reproduction and temperatures above 25 $^{o}$C may impact leaf formation.<br>• May cause settlement of new species from further south. |
| Increasing UV Radiation | • May inhibit photosynthetic activity or lead to the increased metabolic cost of producing UV-B blocking compounds. |
| Increasing $CO_2$ | • Increases their rate of photosynthesis over the short term but this will be species dependent.<br>• May be negatively impacted by 'knock-on' effect on coral reefs. |
| Heavier, less frequent rainfall events | • May cause suffocation if flooding excessive.<br>• May lead to increased aerial coverage. |
| More intense tropical storms | • Uproots mangrove trees or breaks them.<br>• Reduces water clarity and therefore the light levels required for photosynthetic activity. |

## 13.3 Impacts of Mangroves on GHG Emissions

Absorption of $CO_2$ by mangroves through photosynthesis is being globally recognized as an option for helping reduce greenhouse gas emissions, particularly as they release negligible amounts of greenhouse gases (methane and nitric oxide) themselves. In addition to $CO_2$ absorption, the organic matter generated by the mangroves is deposited to form peat which also stores carbon. It has been estimated that mangroves sequester 1.5 tonnes/hectare/year of carbon. With the loss of Bermuda's mangroves over time, this would mean that they currently only sequester about 26.25 tonnes carbon/year. Each hectare of mangrove sediment however is also believed to contain nearly 700 tonnes/carbon/metre depth. When this is disturbed the carbon is released, further contributing to our greenhouse gas emissions (http://www.mangroveactionproject.org/issues/climate-change).

***Table 17. Summary of impacts of Bermuda's mangroves on GHG emissions.***

| GHG | EXPECTED BENEFITS |
|---|---|
| Greenhouse gas (GHG) emissions | • Mangroves serve as a carbon sink.<br>• They reduce negligible amounts of GHG themselves.<br>• They generate organic matter deposited as peat which also stores approximately 700 tons/carbon/metre depth per hectare. |

## *13.4 Mitigation and Adaptation Measures*

The current health of any natural ecosystem will be an essential factor determining how well the system will adapt to the threat of climate change. Managing current threats therefore is an essential first step. It will also be necessary to prioritise action, so identifying and protecting swamps naturally positioned to survive climate change makes sense. However it will also be necessary to include a range of mangrove habitat types (coastal, fringing and pond). These would include those least vulnerable to anthropogenic stress and storm damage and with the capacity for landward migration with rising seas and good recruitment potential. Prudent land planning should also allow for a buffer zone behind the mangroves to allow for this in suitable areas. Modelling should be undertaken to determine the width of the buffer zones needed according to projections of sea level rise. Degraded swamps that have demonstrated resistance or resilience to climate change could also be restored. It will be important to build on existing baseline data so that future changes can be monitored, and a more comprehensive understanding of connectivity between habitats gathered. Vulnerability assessments can be developed from these. Communities in the vicinity of mangroves should also be encouraged to improve land use practices to decrease nutrient and sediment run-off and eliminate use of pesticides and garbage.

Ellison (1991) proposed a number of management actions specific to the Hungry Bay swamp. Some, such as the construction of a barrier to protect the widening gap emerging in the outer peninsula have been discussed but rejected by area residents due to the extreme scale of the barrier need to be effective. Stabilization of the eroded, seaward edge through use of friction matting and sediment deposited against the eroding edge and replanted with mangrove propagules could be undertaken and Ellison's idea of a floating boom across the creek entrance to increase leaf litter retention would be relatively easy to install. Creeks that are not in use by boating traffic could be infilled and replanted with propagules to aid stabilization. She suggests that boats with propellers and jet skis should be prohibited access to the creek and the eastern section of Hungry Bay.

## 13.5 Acknowledgements

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# 14. Impact of Climate Change on Seagrasses


**SUMMARY**

- Bermuda's seagrass meadows play an important role in our nearshore environment, providing critical ecosystem services including as a habitat for juvenile fish and turtles, stabilizing sediments and preventing coastal erosion, and filtering water, which facilitates coral reef growth. They are also important carbon sinks helping to mitigate greenhouse gas emissions.

- 23% of Bermuda's offshore seagrass beds have died in the past decade and it is possible that regional climate variables are responsible for this.

- Light is the primary factor controlling seagrass growth and distribution, so decreasing water quality and light availability through storm activity, sea level rise and changing precipitation will present the most significant challenges to this habitat.

- 3 of the 4 seagrass species found locally are at the most northerly limit of their geographical range. Rising temperatures may have less of an impact than in the Caribbean, and may actually promote their growth and productivity. However, they will also promote growth of competitive algae, reducing the amount of light reaching the seagrasses.

- Seagrasses may have an inherent ability to adapt to climate change if it occurs slowly enough.

- Adaptive management that seeks to maintain the health of the seagrass meadows is critical to promoting resilience or recovery. Managing water quality and light availability will support seagrass resilience.

## 14.1 Introduction

Seagrasses are marine flowering plants with leaves, stems, rhizomes (horizontal underground runners) and roots. They live and complete their whole life cycle submerged in seawater in a habitat where light levels are high, water is ever present and essential nutrients are plentiful. They undergo both sexual and asexual reproduction, the latter accomplished by elongation of their rhizomes so that a whole meadow may be one single clone resulting from one seedling.

Seagrasses play an important role in many shallow, near-shore marine ecosystems, providing a suite of ecosystem services that rank among the highest of all ecosystems on earth. They are intrinsically linked to coral reefs, mangroves and salt marshes, functioning as export ecosystems transferring a detrital food source derived from their decomposed leaves to these surrounding habitats. Seagrasses provide protective shelter for many animals including invertebrates and fish, and are a direct food source for turtles, some herbivorous fish and sea urchins. Many adult fish migrate from adjacent coral reefs and mangrove swamps, to the seagrass meadows at night to feed on the rich food sources within the seagrass meadows (Ward, 1999). The roots and rhizomes of seagrasses help stabilise sediments and prevent coastal erosion while the leaves filter suspended sediments and nutrients from the water column, resulting in the clear waters which are necessary for coral reefs to grow and flourish. Another physical benefit of seagrasses is their ability to attenuate waves, thereby protecting shores from erosion (Koch 2001).

*Photograph 6. Showing juvenile Black Grouper in seagrass.*

There are four species of seagrass, Bermuda's only marine flowering plants known locally. The various species differ in distribution, each having defined its own niche although there may be some overlap. They are: *Thalassia testudinum* (turtle grass), *Syringodium filiforme* (manatee grass), *Halodule wrightii* (shoal grass), and *Halophila decipiens* (paddle grass). Bermuda is the northern geographic limit for the first three of these species; *H. wrightii* occurs in slightly more northern, continental locations (Thayer *et al.,* 1984). In Bermuda, *T. testudinum*, *S. filiforme* and *H. wrightii* are limited to depths <12 m (Murdoch *et al.*, unpubl. data) whilst *Halophila decipiens,* which is able to grow at lower light intensities is patchily distributed across the platform to depths ≤18 m (Coates and Manuel, unpubl. data).

Together these species comprise a total area on Bermuda's shallow platform of 1,625 hectares, largely concentrated on the sheltered, lagoonal side of the island. Murdoch *et al*. (2007) reported that this was a significant decline in areal extent since 1997 when 2100 hectares of seagrass were documented. This precipitous decline appears to have occurred exclusively in lagoonal and offshore areas rather than inshore locations between 1997 and 1998. Although Ward (1999) noted changes to inshore seagrass beds from 1962 to 1997, their total area remained constant, despite increasing pressures being placed on them from inshore development, mooring installations, dredging and anchor damage. There continues to be no signs of meadow recovery at the offshore sites.

Murdoch *et al.* (2007) suggest that the broad spatial extent of the die-off across the platform may have resulted from region-wide climate or water-quality variables. Bermuda's seagrasses are at their extreme northerly extension and chronically low primary productivity has been reported (CARICOMP, 2004). Cool water temperatures and short day lengths in winter, as well as the low nutrient availability of the surrounding waters of the oligotrophic western North Atlantic (Bates, 2001) are believed to be primarily responsible for this low productivity. They suggest that combined with high herbivory by parrotfish, turtles and snails, this could result in a very low standing crop and total photosynthetic surface area affecting survival of the seagrass meadows. Alternatively, they suggest that colder than average winter sea water temperatures may have affected the entire system in 1996 (Cohen *et al*., 2004), coinciding with changes in regional climate (as indicated by a switch from a positive to negative North Atlantic Oscillation (NAO) index (Visbeck *et al.,* 2001)).

## 14.2 Impact of Climate Change on Seagrasses

Seagrasses are highly susceptible to disturbance and will die rapidly under excessive stress. Recovery, on the other hand, is comparatively slow. Seagrass productivity and spatial distribution is controlled primarily by light, which is affected by factors such as water depth, turbidity, the state of surface ripples and waves. Temperature and salinity are also important factors controlling seagrass production. With already declining seagrass meadows in Bermuda, climate change poses an additional stressor to this important habitat.

### Sea level rise

Sea level rise and the resulting increase in water depth will reduce the amount of light reaching existing seagrass beds. If this becomes limiting it will reduce their ability to photosynthesise and hence their productivity. The amount of light reaching the plants will also be affected by increasing turbidity from changes in water current speed, circulation flow patterns and tidal range brought about by rising seas. If these changes also stimulate growth in epiphytes growing on the seagrass, then photosynthesis may be further reduced. Within limits however, increases in current velocity may cause increases in plant productivity (Fonseca and Kenworthy, 1987; Short 1987). Changing current patterns may also erode seagrass beds or stimulate their colonization in new areas (Harlin *et al*., 1982).

### *Increasing temperature*

Sustained temperature stress on seagrasses will result in shifts in their distributional patterns, changes in patterns of sexual reproduction and their growth rates, as well as changes in their metabolism and carbon balance (Short and Neckles, 1999). The response of seagrasses to increased water temperatures will inevitably depend on their thermal tolerance, which may differ amongst species. Bermuda's seagrasses are at their lower thermal tolerance and might in fact be expected to benefit from elevated temperatures by increasing productivity. However, increased temperatures may at the same time enhance the growth of competitive algae causing increased shading.

Increased temperatures may cause more rapid respiratory breakdown of organic matter in the sediment, causing anoxic stress in the seagrasses from oxygen deficiency.

### *Increasing UV Radiation*

Seagrasses are also sensitive to ultraviolet-B (UV-B) radiation and laboratory experiments suggest that the response can vary from strong photosynthetic tolerance in *Halophila wrightii;* to moderate tolerance with *Syringodium filiforme* (Hader, 1993; Short and Neckles, 1998). Elevated UV-B radiation may inhibit photosynthetic activity or lead to the increased metabolic cost of producing UV-B blocking compounds within plant tissue.

### *Increasing carbon dioxide*

The effect of increased dissolved $CO_2$ in the seawater column will vary according to species (Beer and Koch, 1996). This may increase primary production in areas where seagrasses are carbon limited, although whether this increase will be sustained with long term $CO_2$ enrichment is uncertain. Some temperate seagrasses (eg. *Zostera marina* which was once recorded in Bermuda (Thomas, 2005)) appear to able to respond positively to increased $CO_2$ levels by increasing their rate of photosynthesis over the short term (Thom, 1996). On the other hand, in a long term experiment there was no effect of increasing $CO_2$ levels on the above-ground productivity of this species. However, this treatment led to increased reproductive outputs and relative below-ground biomass (Palacios and Zimmerman, 2007). In contrast, research on the tropical species *Thalassia testudinum* suggests that maximum photosynthesis is lower with higher $CO_2$ (Durako, 1993).

Increased $CO_2$ levels may benefit the algae attached to seagrasses leading to seagrass decline through shading. Bermuda's relatively cooler seawater temperatures will result in even more $CO_2$ uptake so the possible impact on local seagrass species remains uncertain.

With increased dissolved $CO_2$ levels, the pH of oceanic waters will decrease affecting the relative concentrations of the other dissolved inorganic carbon forms in seawater used by seagrasses. For example, $HCO_3$ – content will be reduced at lower pH, however as $CO_2$ is used by seagrasses at a higher affinity than carbonic acid ($HCO_3$ -), any reduction in $HCO_3$ - content of the seawater at lower pH values would not impede on photosynthesis or counteract any positive effect of increasing $CO_2$ levels (Beer *et al*., 2006).

### *Changes in precipitation*

Extreme changes in weather patterns may cause flooding, which may in turn cause increased turbidity and sedimentation as well as run-off. For example, extreme flooding events have become increasingly common in Eastern Africa and have been shown to cause large-scale losses of seagrass habitats (Bandeira and Gell, 2003). Similarly, seagrasses in Queensland, Australia were lost in a catastrophic flooding event and it took three years for them to recover (Campbell and McKenzie, 2004). Heavy rains may also lower salinity in enclosed bays which may have an adverse affect (Chollett *et al*., 2007).

### *More intense tropical storms*

Predicted increases in storm intensity are likely to significantly affect seagrasses. Typically growing in low energy environments, seagrass plants can easily be dislodged or buried by storms which cause increased turbulence and tidal surges. Subsequent changes in flow and sediment transport may redistribute sediments and smother the seagrasses, and reduce water clarity (often persisting long after the storm subsides) and therefore the light levels required for photosynthetic activity. With reduced photosynthesis, there will be less oxygen transported to the roots, and prolonged oxygen deficiency may lead to poisonous sulphides forming in the sediment leading to plant death (Borum *et al*., 2005).

***Table 18. Summary of impacts of climate change on Bermuda's seagrasses***

| CLIMATE CHANGE | EXPECTED IMPACTS |
|---|---|
| Sea level rise | • Leads to deeper water and changes in water current speed, circulation flow patterns and tidal range, which will lead to reduction in light reaching seagrasses.<br>• Changes current patterns causing erosion of seagrass beds or stimulation of their colonization in new areas. |
| Increasing temperature | • Results in shifts in distributional patterns.<br>• Changes patterns of sexual reproduction.<br>• Changes growth rates.<br>• Affects metabolism and carbon balance.<br>• Will likely result in increase in productivity.<br>• Enhances the growth of competitive algae.<br>• May cause more rapid respiratory breakdown of organic matter in the sediment, causing anoxic stress in the seagrasses from oxygen deficiency. |
| Increasing UV Radiation | • May inhibit photosynthetic activity or lead to the increased metabolic cost of producing UV-B blocking compounds. |
| Increasing $CO_2$ | • May increase their rate of photosynthesis over the short term but this will be species dependent.<br>• May lead to increased reproductive outputs and relative |

| | |
|---|---|
| | below-ground biomass.<br>• May benefit the algae attached to seagrasses leading to seagrass decline through shading. |
| Heavier, less frequent rainfall events | • Flooding causes increased turbidity and sedimentation as well as run-off which can lead to die-off. |
| More intense tropical storms | • Cause increased turbulence and tidal surges, which dislodge seagrasses or bury them.<br>• Changes flow and sediment transport which will redistribute sediments and smother the seagrasses.<br>• Reduces water clarity and therefore the light levels required for photosynthetic activity. |

## 14.3 Impact of Seagrasses on GHG Emissions

Seagrasses constitute an important carbon sink due to their slow rate of decomposition. It has been estimated that carbon fixation of seagrasses constitutes up to 1% of the total carbon fixed in the oceans but that they store 12% of it thereby helping to reduce greenhouse gases in the atmosphere (Duarte and Cebrian, 1996).

***Table 19. Summary of impacts of Bermuda's seagrasses on GHG emissions.***

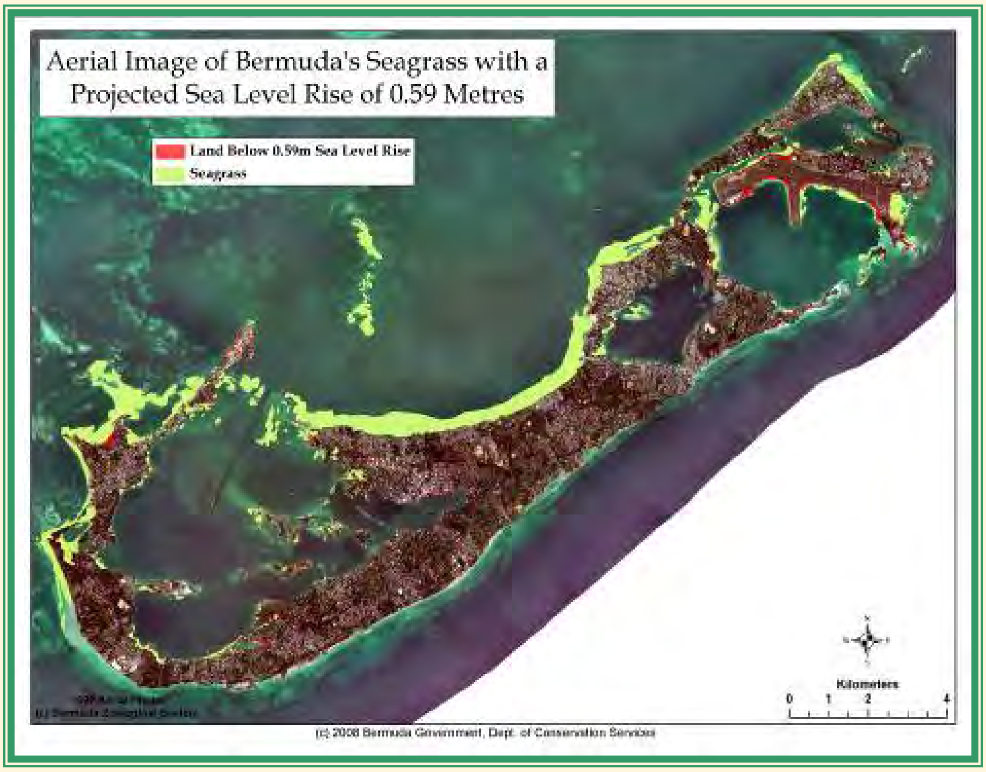
| GHG | EXPECTED BENEFITS |
|---|---|
| Greenhouse gas (GHG) emissions | • Seagrasses serve as a carbon sink.<br>• Fix 1% and store 12% of carbon fixed in oceans. |

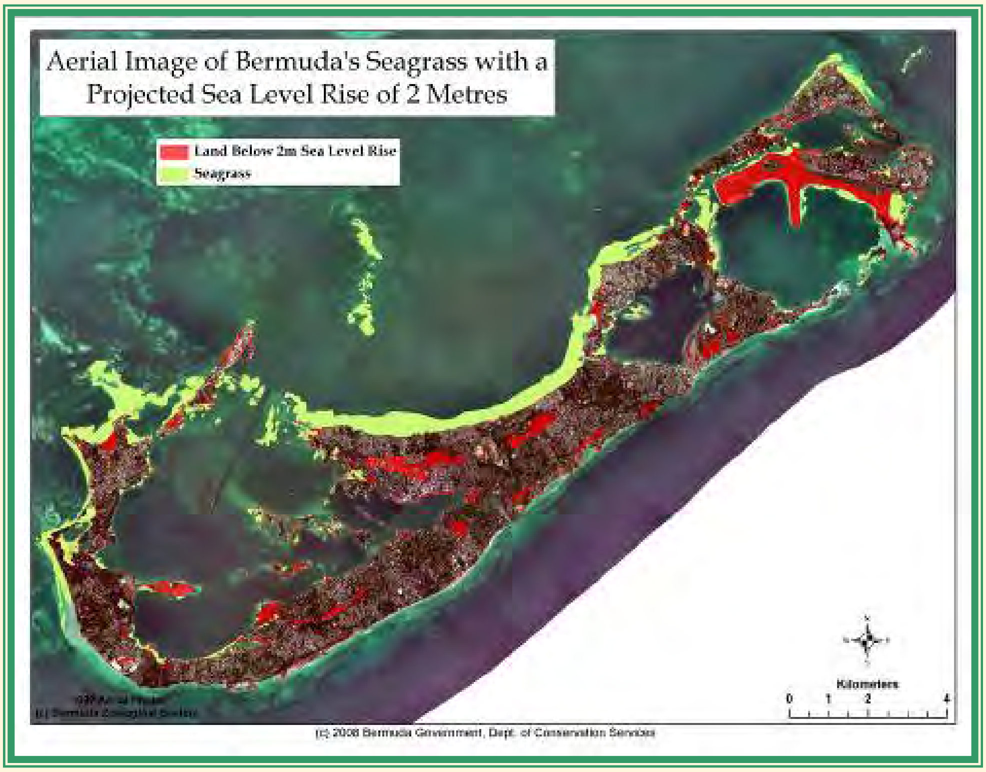
## 14.4 Mitigation and Adaptation Measures

Studies suggest that seagrasses possess inherent abilities to adapt to some of the stresses climate change will expose them to. High genetic diversity in *Zostera marina* for example could help the plants to cope better with high summer temperatures (Ehlers *et al*., 2008), and the same can be expected for tropical species. It has been shown that evolutionary change in a species can occur within a few generations (Rice and Emery, 2003), so if the climate changes occur at a slow enough rate the seagrasses may be able to adapt. However, one of the biggest issues for Bermuda's inshore seagrass meadows is that the majority of them are backed either by natural, or man-made hard vertical faces prohibiting landward retreat of the seagrasses in response to rising sea levels. Maps 19 and 20 show their distribution and the areas where they would be most impacted by a 0.59 m and 2.0 m sea level rise in terms of shoreward retreat.

However, there are also management strategies that can be developed and implemented to enhance the resilience of seagrasses. Actions that help to maintain the health of Bermuda's seagrass meadows are critical to promoting resistance to and/or recovery from additional stress. Managing water quality and maintaining light availability are critical approaches that support seagrass resilience. This can be accomplished by:

- Ensuring that land use policies and plans address potential impacts by stabilizing adjacent land areas, decreasing nutrient and sediment run-off, reducing use of fertilizers and pesticides and allowing for upward retreat of the seagrass meadows;
- Controlling activities that physically damage seagrass beds including prohibiting anchoring and dredging and only installing environmentally-friendly moorings;
- Continued monitoring of changes in seagrass distribution and abundance, turbidity and seagrass health;
- Identifying and fully protecting seagrass communities that are at low risk of succumbing to climate change and anthropogenic impacts because these seagrass communities will serve as refugia to help seed the recovery of damaged areas (including seagrasses producing a healthy supply of seeds/propagules);
- Identifying patterns of connectivity between seagrass beds and adjacent habitats, e.g., mangroves and coral reefs, to allow for ecological linkages and shifts in species distribution (gene flow between different seagrass populations is greatly enhanced by proximity between them (Alberte *et al.,* 1994);
- Restoring critical seagrass areas that are positioned to survive climate change impacts either by improving environmental conditions (e.g. water quality) to encourage natural regeneration or seeding or transplanting of seedlings or mature plants from donor beds;
- Raising awareness of the value of and threats to seagrasses.




*Map 19 (above) showing the impact of a 0.59 m sea level rise on Bermuda's nearshore seagrass beds and Map 20 (below) of a 2.0 m sea level rise (courtesy of Bermuda Biodiversity Project).*

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# 15. Impact of Climate Change on Reefs


**SUMMARY**

- Coral reefs are the most diverse of all marine ecosystems, but are globally threatened. 20% of the world's corals have already been destroyed through over-harvesting, coastal development, pollution, invasive species and more recently, climate change. A further 52% are under serious threat. Some scientists believe that climate change could eliminate most of the world's corals by 2050.

- Bermuda's reef system is the most northerly in the world and remains very healthy despite significant depletion of the Caribbean reefs. Covering an area of 550 $km^2$ Bermuda's reefs not only provide a protective barrier for the Island as well a suite of other ecosystem services, but are an essential natural resource asset supporting our economy.

- Increasing ocean acidity and sea surface temperatures are the major climate change threats. Bermuda's reefs comprise three main reef building organisms: calcareous algae, corals, and vermetid worm shells, which secrete calcium carbonate to form their skeletons and build the reef. Increasing acidity may lead to slower reef growth. Increasing temperatures may cause the corals to expel their symbiont algae causing them to bleach and starve.

- Sea level rise, more intense storm activity as well as increased incidence of disease, possible shifting of ocean currents and rises in the incident UV radiation all present lesser, but real threats to our reef system.

- Maintaining the current healthy status of Bermuda's reef ecosystem is believed to be a significant factor in determining how well the corals and associated reef organisms adapt to the threat of climate change. A continued conservative management approach makes sense. Further, research on reefs which show resilience to the various impacts of climate change may produce valuable information that can be applied to enhance resilience in other reefs.

## 15.1 Introduction

Coral reefs are the most diverse of all marine ecosystems, being particularly long lived and highly evolved. The ancestors of modern day stony (scleractinian) corals first appeared about 250 million years ago and like other ecosystems have been disrupted by the mass extinction events that also resulted in major climate changes. The last major disruption to reefs occurred during the last ice age (about 18,000 BP) when sea levels fell about 120 m, exposing the shallow living reefs to the air. However, for the past 8,000 years rising seas have greatly expanded the area for modern coral reef growth (Wilkinson, 2004).

Coral reefs are made of calcium carbonate (limestone) in the form of aragonite, which is secreted by the coral animal (polyp) to form a skeleton. Single-celled microalgae (zooxanthellae) live within the bodies of the coral polyps in a symbiotic relationship. The coral obtains food from the algae through photosynthesis during the daytime whilst the algae utilise nutrients released as waste by the coral.

Unfortunately it is estimated that 20% of the world's corals have been destroyed through overharvesting, coastal development, pollution, invasive species and more recently, climate change. A further 24% are believed to be on the verge of disappearing, whilst another 26% may disappear in the future (Wilkinson, 2004).

Bermuda's reef system is the most northerly in the world, supported by the prevailing warm oceanic conditions as a result of the passing Gulf Stream which links the island's reefs to those upstream in the Caribbean. However, as a northerly outpost, coral species diversity is limited in Bermuda with a reduced suite of only 22 shallow water hard coral species. Fortunately, a variety of marine organisms are capable of laying down these massive calcium carbonate reef structures and in fact in the shallower waters, it is the calcareous algae which are Bermuda's main reef builders, with corals and vermetid worm shells (a snail) performing a secondary role. Together these three groups have constructed a formidable protective barrier around the island, covering an area of approximately 550 $km^2$. They are Bermuda's most economically significant natural resource asset, providing a host of ecosystem services, as well as supporting local fisheries and the island's tourism industry.

*Photograph 7. Aerial image showing the Bermuda Reef Complex (courtesy Bermuda Zoological Society).*

Murdoch (2007) lists the environmental factors widely considered to most strongly influence coral species assemblages in Bermuda as, temperature, light, wave energy and suspended sediments. Nutrient availability rather than temperature is considered to be more of a limiting factor in high latitude reefs like Bermuda's compared with more tropical reefs. Bermuda's reef structure can be broadly divided into the fore reef, the main terrace, the rim reefs, lagoonal reefs, inshore reefs and cup reefs (Anderson *et al.,* 2001). Extending from a depth of approximately 75 m to 20 m the fore reef slope has an average coral cover of about 25% and is dominated by brain corals (*Diploria* species), great star corals (*Montastrea* species) and mustard corals (*Porites* species). The main terrace reefs are found between 25 m and 15 m and typically support 35-75 % coral cover (Murdoch *et al*., 2008). Brain and great star corals also dominate. With a coral coverage of over 20-40 %, and greater species diversity, the rim reefs encircle the North Lagoon at depths of 15 m to 1 m. Calcareous algae are a major component of these reefs and of the lagoonal reef found inside the rim reefs which range from small patches of coral to larger pinnacle reefs up to 50 m wide. A few larger structures exist, forming mini-atolls and faro reefs. The lagoonal reefs have a coral cover of 10-45 % and typically comprise smaller, branching corals such as ivory bush coral, the finger corals, and fire coral. Within the sounds and harbours, the coral coverage drops to below 10%. Reefs on the southern side of the island comprise the more unusual cup reefs, or "boilers" which differ from the other reefs described by being constructed largely by calcareous algae and a vermetid worm shells; they have very little coral in their structure. A few cup reefs are found to the north of the island too.

The reefs of the Caribbean are amongst those that have seen dramatic declines in live coral coverage. Unlike these, Bermuda's reefs are little changed and remain healthy. A comparison with the first surveys conducted on the island about 25 years ago confirms this stability. Hard coral cover on the terraces averaged 52.4% in 1981 versus 54.0% in 2005; and 22.5% in 1981 on outer rim coral-algal reefs versus 24% in 2005. Indeed the reef terrace in some areas supports coral coverage as high as 80% (Murdoch, pers. comm.). This may in part be due to the lack of temperature-sensitive branching acroporid (staghorn and elkhorn) corals in local waters and the predominance of slow growing massive growth forms *(Diploria, Montastraea* and *Porites* species); acroporid species were particularly impacted in the Caribbean in the 1980s and 1990s (Murdoch, 2007).

The health of Bermuda's reef system may also in part be the result of sound, very conservative management practices which have treated our marine ecosystem as a highly stressed, self-sustaining entity. Since the 1966 enactment of the Coral Reef Preserves Act, there has been complete protection of all attached animals and plants within two substantial areas of Bermuda's shallow waters. Further, in 1978 a protected species order was passed under the Fisheries Act that completely banned the harvest of any coral, stony or soft. With this action Bermuda became, in effect, a coral preserve.

## 15.2 Impact of Climate Change on Reefs

Tropical reef ecosystems are considered to be highly vulnerable to the impact of global climate change. In mature reefs, there is a natural balance between reef-construction (by bio-depositors) and reef-breakdown (by bio-eroders) which normally maintains the complex architecture of reefs. But this balance is now under threat primarily from increasing sea surface temperatures and increasing ocean acidity. Evidence suggests that with even mild warming (+1 -3$^{o}$C) tropical near-shore communities will change from coral dominance to algal-dominance. Sea level rise and the potential for more intense cyclonic storms also present a serious concern, whilst other climate-related stressors such as the increased incidence of disease, possible shifting of ocean currents and rises in the incident UV radiation are likely to be of lesser impact. Many scientists believe that climate change could eliminate most of the world's corals by 2050 (Hoegh-Guldberg, 2005). Climate change will not only affect the reef building species, but the suite of organisms intricately associated with the coral reef framework.

### *Sea level rise*

Sea level rise is not widely considered to present a huge threat to reefs although the extent of the impact this will depend on the speed at which it occurs and the ability of the reef-building organisms to keep up. Healthy reefs are more likely to be able to keep up with rising seas. Reefs may be classified as "keep-up", "catch-up" and "give-up" reefs in respect of sea level rise (Neumann and MacIntyre, 1985). Patch reefs, which are so abundant in Bermuda, are typically "catch-up" reefs whose development may be delayed until sea level has stabilized (Muhs *et al*., 2002) and there is some evidence that this is how Bermuda's reefs behaved during the last ice age. There is always likely to be something of a time lag between accelerating sea level rise and the ability of reefs to grow accordingly due to lack of suitable substrate, proximity to terrestrial influences and poor water quality. Potentially, sea level rise provides more space for corals to grow upwards without being exposed to the air.

### *Increasing temperature*

The most significant impact of increasing temperatures may be an increase in coral bleaching. Corals bleach when the coral animal host is stressed and expels the symbiotic zooxanthellae, which are what give the coral colony its colour. Although several different stresses cause bleaching, the most significant cause are elevated sea surface temperatures that exceed the normal summer maxima by 1 or 3 $^{o}$C for a period of several weeks (Buddemeier *et al*., 2004). This results in excessive production of toxic compounds in the algae, which are transferred to the host coral. The coral animal reacts by expelling the algae, effectively bleaching the coral and leaving it susceptible to starvation. The zooxanthellae may re-colonise the coral over several weeks or even months when temperatures decrease, but if there is prolonged stress re-colonisation may not happen and the coral will die. Even if the coral does recover, reproduction and growth may be negatively impacted for up to two years after a bleaching event, and corals that have been stressed by bleaching may also be more vulnerable to disease. It is important to note that not all corals are equally vulnerable to bleaching. Massive, boulder-shaped corals such as *Porites* and *Favia* tend to be more resistant to bleaching than branching and plate forming corals such as *Acropora* and *Pocillopora,* which are absent from Bermuda's waters.

Mass coral bleaching was not reported in the Caribbean prior to 1982/1983, but since then has been clearly linked to El Niño events (Walling, 2008). The most extreme coral bleaching and mortality event to hit the wider Caribbean and Atlantic coral reefs occurred in 2005. This was during the warmest year ever recorded, eclipsing the 9 warmest years that had occurred since 1995. The previous warmest year was 1998, which resulted in the death of 16% of the world's coral reefs, primarily in the Indian Ocean and Western Pacific. The various studies on climate change and coral bleaching conclude that the majority of the Caribbean is expected to experience conditions that currently lead to coral bleaching every 2 years, or more, within the next 20 to 50 years.

The ability of corals to adapt to increasing temperatures is still unclear. Corals may be able to evolve if they can acquire more thermally tolerant symbiotic algae. If new symbiotic relationships can be rapidly formed within a few decades, corals will become more thermally tolerant, allowing them to keep pace with temperature rise. Unfortunately there is no evidence that corals can form new symbiotic relationships easily. However, data does suggest that coral bleaching was much worse during the 1982-1983 El Niño than the 1997-1998 event, despite similar temperature extremes (Glynn *et al*., 2001). This implies some ability on the part of the corals to adapt, at least over a period of decades. Resilience may also be species-dependent.

Some largely sporadic coral bleaching has been observed on Bermuda's reefs, however seawater temperatures during 2005 were not unusual compared with previous summers and no widespread bleaching or disease of corals was observed. It is possible that Bermuda's northerly latitude may buffer the island from the temperature extremes experienced in Caribbean reefs, and that the wide natural temperature range experienced in Bermuda means that our corals have a greater resilience to such extremes. There is a natural temperature gradient across Bermuda. Rim reefs are exposed to an annual temperature range of between 18 or 19 $^{o}$C in winter and 29 $^{o}$C in summer; in contrast, lagoonal and nearshore reefs experience greater variation, with temperatures ranging between 17 $^{o}$C or less in winter and 31 $^{o}$C (Morris *et al*., 1977).

Warming temperatures have also been linked to increased incidence of disease in corals, as data suggests the optimal water temperatures for some of these disease vectors is at least 1 $^{o}$C higher than optimal temperatures for corals (Harvell *et al*., 2002). Various diseases do occur in Bermuda's corals; black-band disease and white plague on *Diploria, Montastraea* and *Porites astreoides* are the most common and occur mostly on the outer rim and lagoonal patch reefs, whilst yellow blotch disease is also relatively common in *Montastraea franksii*. We can expect that these might become more prevalent if temperatures increase significantly. There is evidence of a link between dust production from Africa and the incidence of disease in corals and this in turn has been linked to increasing aridity and desertification in Northern Africa (Prospero and Lamb, 2003).

*Photograph 8 showing black band disease in a brain coral*

### *Increasing carbon dioxide*

Ocean acidification is a threat to reefs that results from increased concentrations of $CO_2$ dissolving in seawater, so reducing its pH. The oceans have absorbed about a third of the excess $CO_2$ released into the atmosphere from burning fossil fuels and other human activities, helping to reduce the severity of the greenhouse effect and climate change. Unfortunately, by lowering pH, increased $CO_2$ levels result in decreased carbonate ion concentrations, instead forming more bicarbonate ion. The carbonate ion [$CO_3^{2-}$] is a major skeletal building block for the calcium carbonate ($CaCO_3$) skeletons of corals and other reef-building organisms.

Surface sea water chemistry adjusts to changes in atmospheric $CO_2$ levels on a timescale of about a year (Walling, 2008). It is believed that by the end of this century, ocean acidification may be proceeding at a rate that is 100 times faster and with a magnitude that is 3 times greater than anything experienced on the planet in the last 21 million years. The impacts on organisms relying on calcification could be considerable, and most significantly will affect the ability of reefs to grow.

Coral calcification is not only determined by sea water carbonate chemistry, but also by other factors such as temperature, light and nutrients. Calcification rates increase with rising temperatures to some optimal temperature, but then decline when temperatures exceed this maximum. Studies have shown that calcification rates of large heads of *Porites* sp. increased over the latter half of the 20$^{th}$ century (Lough and Barnes, 1997), responding more to warming (but sub-upper tolerance level) temperatures and so stimulating faster growth, than to decreases in the availability of the carbonate ion (Buddemeier *et al.,* 2004). However, calcification rates generally have started to decline over the past 15 years, most probably because of the combined impacts of increasing thermal stress and the reduced availability of carbonate ions.

Acid rain can also contribute to ocean acidification however this only contributes to about 2-5% of decreased pH values observed locally (Bates and Peters, 2007).

It is feared that high latitude reefs that already have a low surplus of carbonate production because of a limited growing season, may shift from net reef building to net reef loss, and lowered calcification rates will reduce their ability to keep up with rising sea levels. Bermuda's reefs grow 10 times slower than their southern counterparts in the Caribbean (Cook, 1988). Local evidence has shown that *Diploria strigosa* is putting down 30% less carbonate than 30-40 years ago (Knap, pers. comm.). *Diploria strigosa* grows about 2.5 mm per year; less than current rates of sea level rise. Ironically, one benefit of rising temperatures locally may be the fact that warmer water holds less $CO_2$ than colder water.

Whilst corals use aragonite to form their skeletons, the other major reef builders found in the Bermuda, the algal vermetid worms, utilize magnesium calcite (Baltimore, 2008). Magnesium carbonate within the calcite dissolves at a higher pH threshold than aragonite, placing these reef organisms at even greater risk from acidification (Jokiel *et al*., 2008)

It is not just Bermuda's shallow water reef organisms that will be impacted by ocean acidification. Deep sea corals are considered to be particularly sensitive to ocean acidification because they tend to grow just above depths where waters become under-saturated with calcium carbonate. As $CO_2$ concentrations rise, that depth is 'migrating' upwards, and many deep sea coral ecosystems will soon be immersed in under-saturated waters potentially causing them to disappear. Recent research has revealed that Bermuda supports quite a rich deep sea coral community (pers. obs.).

On a more positive note, preliminary studies at BIOS suggest that some coral species may be able to exploit the bicarbonate ion for skeletal growth instead of the carbonate, as long as the pH does not fall below the saturation state (Baltimore, 2008).

### *Changes in precipitation*

Global climate change predictions all emphasize greater variations in weather, such as more intense periods of rainfall followed by longer periods of drought. Terrestrial run-off resulting from heavy rainfall will impact Bermuda's nearshore reef ecosystems, smothering the corals with sediment and other debris, as well as increasing nutrients (including those in fertilisers) that influence growth rates of algae, and lowering salinity, which can stress corals.

### *More intense tropical storms*

Hurricanes can cause extensive damage to coral reefs (Stoddart, 1985). These effects are greatest at shallow depths, where wave action is greatest. However, shallow corals are adapted to wave action and often hurricanes may have a greater impact on deeper corals which are perhaps less well adapted. Hurricanes may also impact reefs through flooding caused on land, which leads to increased run-off into the shallow waters. Greater turbidity and changes in salinity may also have an impact.

Hurricane induced damage on Bermuda's reefs has not been reported to any great extent. This may largely be to the fact that Bermuda's reefs are dominated by massive boulder corals. In the Caribbean, where more fragile branching corals are prevalent, hurricanes may have a substantially greater impact. In fact, hurricanes may actually be beneficial by tending to lower surface temperatures by 1-2 °C, thereby reducing the impact of thermal stress in the summer months. However, a rise in storm intensity or frequency may put reefs into a permanent state of recovery. According to Gardner *et al*. (2003) reefs in the Caribbean take about 8 years to recover from a storm.

***Possible Shifting of Ocean Currents***

Changing climate conditions may cause oceanic currents to slow or even change direction. Given that Bermuda's reef system is connected via the Gulf Stream to Caribbean reefs, such changes could have a significant effect.

***Changes in UV Radiation Intensity***

Most coral reef animals are adapted to cope with UV radiation, however shifting ocean currents and sediment input may cause changes in the clarity of the water column, which will affect the amount of visible and UV radiation penetration.

***Table 20. Summary of impacts of climate change on Bermuda's reefs***

| CLIMATE CHANGE | EXPECTED IMPACTS |
|---|---|
| Sea level rise | • No immediate impact as long as reef growth is able to "keep up".<br>• May even provide more space for corals to grow upwards in shallow water. |
| Increasing temperature | • Will likely lead to increased incidence of mass coral bleaching cause coral stress or death.<br>• May make corals more susceptible to disease.<br>• May help reduce rate of ocean acidification. |
| Increasing $CO_2$ | • Increases ocean acidification thereby reducing rate of calcification of reef-building organisms.<br>• May cause shift from net reef building to net reef loss. |
| Changes in precipitation | • May result in increased run-off from land causing water turbidity and higher salinity which stress corals and promote harmful algal growth. |
| More intense tropical storms | • May directly damage reef structure from wave action.<br>• May help to reduce ocean temperatures thereby alleviating threat of bleaching. |
| Possible shifting of ocean currents | • May affect connectivity to Caribbean via Gulf Stream or change local oceanic conditions affecting the whole reef ecosystem. |
| Changes in UV radiation intensity | • Increasing UV radiation may trigger coral bleaching; decreasing UV radiation may impede coral growth. |

## 15.3 Mitigation and Adaptation Measures

The current health of the reef ecosystem will be an essential factor determining how well the corals and associated reef organisms adapt to the threat of climate change. After the massive coral bleaching in 1998, coral reefs recovered faster where other stresses such as poor water quality and over-fishing were well managed. For example, corals will repopulate damaged areas 2–3 times faster on reefs with a healthy community of grazing fish, than on over-fished reefs; similarly, growth rates of corals are faster in non-polluted waters. Managing local stresses on reefs cannot reduce climate change however, it may enhance their recovery.

Ecosystem condition, biological diversity, and connectivity all contribute to ability of the ecosystem to recover. High biological diversity, in which multiple species perform critical ecosystem functions, supports ecosystem recovery by increasing the chance that vital functions will still be performed despite some degradation of the system. Connectivity between habitats (reef, mangrove and seagrass) also reinforces the capacity of a system to recover by influencing the likelihood that damaged reefs will be replenished from 'seed' reefs or refugia.

Traditional management strategies may be based on the assumption that reefs are likely to continue in relatively stable condition. As reefs spend more time in recovery mode, management targets may need to become more conservative to sustain good water quality, fish abundances, and coral cover. Marine Protected Areas (MPAs) are widely considered to be the best management tool for conserving coral reefs. Bermuda's corals are already fully protected but establishing protected areas might afford protection to the whole ecosystem. The establishment of MPAs however, must be based on robust scientific data.

Research on reefs which show resilience to the various impacts of climate change may produce valuable information that can be applied to enhance resilience in other reefs. For example, some corals, especially species adapted to turbid environments rely heavily on food particles captured from the water column (heterotrophy) to supplement their energy requirements and are therefore less dependent on symbiotic zooxanthellae. A better understanding of coral nutrition could help managers identify more tolerant coral communities, allowing them to be incorporated into networks of refugia to enhance overall ecosystem resilience. Similarly, as some species are able to tolerate higher temperatures than others, patterns of natural tolerance need to be identified and built into management planning.

Finally, effectively communicating about the impacts of global climate change on our coral reef system will promote awareness among stakeholders and provide information about potential effects to livelihoods. Resilience in the local community to cope with changes in the availability or quality of the goods and services provided by coral reefs will be dependent in part on providing accurate information as soon as it is available.

## 15.4 Acknowledgements

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# 16. Impact of Climate Change on Coastal Habitats


**SUMMARY**

- Most of Bermuda's 290 km of shoreline comprises either rocky shore or beach and dune. Most beaches are located on the more exposed South Shore, providing critical habitat as being a core asset to the island's tourist industry. Associated sand dunes serve as natural reserves for beaches and act as a physical barrier to storm waves. They are essential in preventing long term erosion of beaches and inland areas

- Bermuda's rocky shores support a community of organisms that show remarkable adaptations to daily variation in environmental conditions associated with the tides. As a result, species are established in characteristic zones according to their exposure tolerance. Most animals are sessile making them good indicators of climactic variation.

- A projected 37.5% and 55.8% of Bermuda's beaches and dunes, and 32% and 52.7% of the rocky coastal habitat would be lost with a 0.59 m and 2 m sea level rise, assuming no capacity for landward retreat.

- Higher temperatures will result in shifting in timing of reproduction, metamorphosis, dispersal etc. which may cause 'mis-match' in food availability, physiological stress, upward land migration, increased susceptibility to invasive species, changes in species distributions and changes in species community composition.

- Increasing ocean acidification will lead to a reduction in shell growth in coastal molluscs and less available sediment for sand, whilst heavier rains will lead to waterlogging and cliff collapse. Stronger storms will cause direct habitat destructions and species loss.

- Guidelines for appropriate shoreline protection and shoreline development, taking consideration of the natural environment have already been developed but it remains for these to be fully implemented, so as to allow for sufficient vertical migration of the ecological communities comprising these coastal habitats as climate change accelerates.

## 16.1 Introduction

Most of Bermuda's 290 km of shoreline comprises either rocky shore or beach and dune.

**Beaches and Dunes**

Sandy shores and dunes develop in areas of high wave energy and where there is enough sand produced, either through local physical and biological erosion or through transport in alongshore currents. Beaches comprise 6% of Bermuda's coastline, formed from locally originating sand produced by a wide diversity or organisms on the reef platform (Thomas and Logan, 1992). Supply seems to balance loss from the beaches during storms.

Most of the beaches are located on the more exposed South Side of the island, providing critical habitat for a limited number of species as well as being a core asset to the islands' tourist industry. The constantly changing nature of the beach environment largely limits the range of organisms found there to ghost crabs (*Ocypode quadrata*) and beach fleas (*Orchestia* spp.).

Coastal sand dunes serve as natural reserves for beaches as well as being a physical barrier to storm waves. They are essential in preventing long term erosions of beaches and inland areas (Government of Bermuda, 2004). We know the extent of sand dunes in Bermuda is now at an all-time low (Thomas, 2004). Today, the only dunes remaining are in the area from Horseshoe Bay to Chaplin Bay on the southwest shore. These are virtually stable and almost entirely vegetated with specially adapted species, many capable of being smothered by sand, including; the Tassel plant (*Suriana maritima*), also called sea lavender (*Malotonia gnaphalodes*) beach lobelia (*Scaevola plumieri*), and Spanish bayonet (*Yucca aloifolia*). Various vines such as the morning glories (*Ipomea* spp.) and bay bean (*Canavali rosea*) are also present. The land crab (*Geocarcinus lateralis*) is the commonest animal found on the dunes.

**Rocky Shore**

Rocky shores are characteristic of areas of the coastline where wave action has removed the sediments leaving exposed bedrock. These shorelines can comprise a complex mosaic of habitats depending on aspect, the degree of exposure to the waves or currents and exposure to sunlight and air. In combination, these variables drive the 'zonation' of the largely sessile organisms inhabiting the rocky shore. The most resilient species are found highest up the shoreline, but all species have limits of tolerance. The fact that most species in this habitat are sessile means that they are good indicators of climactic variation.

The distribution of organisms on Bermuda's rocky shores has been well studied (Thomas and Logan, 1992). Whilst not as biologically diverse as the rocky coasts of more temperate climates, Bermuda's shores are home to an interesting community of organisms that show remarkable adaptations to the harsh daily variation in environmental conditions to which they are subjected, alternating between exposure to air, and submergence under the incoming tide, or storm waves. Typical species include two species of barnacle (*Chthamalus angustitergum and Balanus amphitrite*), a corroding worm shell (*Dendropoma corrodens*), three herbivorous snails or nerites

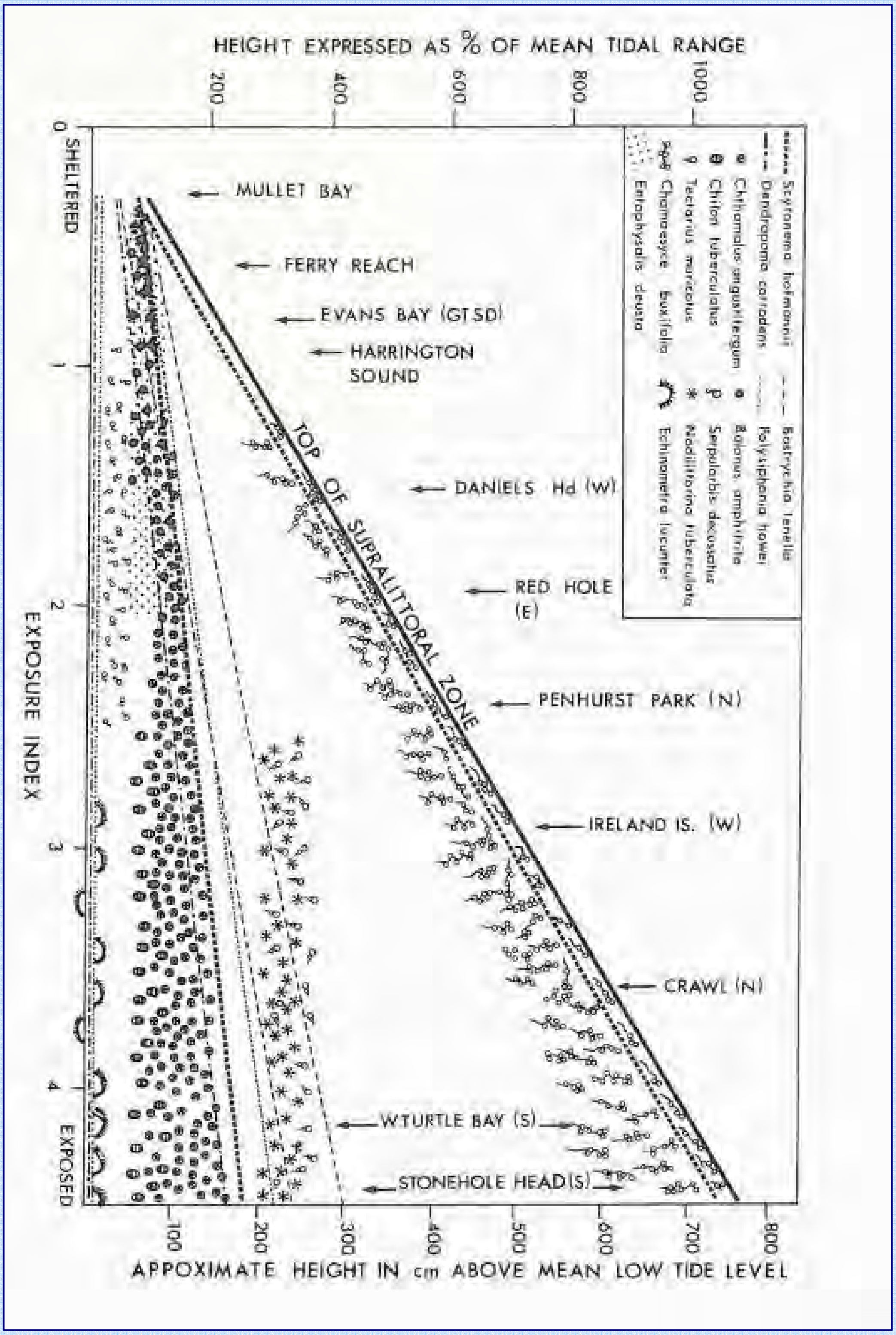



*Figure 22. Showing changes in zonation of common biota with exposure around Bermuda's rocky shores. (Source: Thomas and Logan, 1992)*.

(*Nerita versicolor*, *Nerita tessellata* and *Nerita peloronta*), the re-introduced West Indian topshell (*Cittarium pica*) which is protected, as well as various limpets, mussels and oyster species and periwinkles (*Nodilittorina tuberculata, Littorina ziczac* and *Tectarius muricatus*). Necessary adaptations to this harsh environment include morphological, physiological and morphological adaptations to deal with the daily variation in salinity, temperature, oxygen, pH and exposure to UV radiation. There are however occasions when conditions exceed these adaptations and Cook and Cook (1985) reported evidence of diebacks in association with windy or hot weather during low tides.

Plant life includes suitably adapted coast spurge (*Euphorbia buxifolia*), seaside oxeye (*Borrichia arborescens*), seaside goldenrod (*Solidago sempervirens*), sea purslane (*Sesuvium portulacastrum*), buttonwood (*Conocarpus erectus*), tamarisk (*Tamarix gallica*), and increasingly the invasive casuarina (*Casuarina equisetifolia*).

Clear zonation patterns have been identified around the island, (primarily with regard to the more sessile animals) in response to what Thomas and Logan (1992) refer to as probably the most diverse exposure range in the world for such a small geographical area. As expected, the northerly and eastern shores and inshore basins where wind energy drops off, show the least exposure and hence the narrowest intertidal range; the southerly shores are exposed for most of the year to considerable wave action and show much broader bands of habitation. This is illustrated in Figure 22.

## 16.2 Impact of Climate Change on Coastal Habitats

Without doubt, Bermuda's coastal habitats will be particularly susceptible to the impacts of climate change, with a loss of both critical ecosystem services as well as an impact on tourism.

### Sea Level Rise

As sea level rises, the rate of erosion will increase. If inland retreat is blocked by geology or a man-made structure, the beach will simply disappear. The resulting impact on native biodiversity could be significant, as habitat is lost. A basic projection using projected sea level rise of 0.59 m (the upper limit of the IPCC (2007) projections) and 2 m (the predicted maximum sea level rise likely this century (Pfeffer *et al*., 2008)), shows that approximately 37.5% and 55.8% respectively of beach and dune would be lost (Shailer, pers. comm.). Whilst in theory, intertidal organisms should be able to keep pace with changing sea level, providing it was spread over several generations of the organisms, much of our shoreline is so developed that upwards retreat may become restricted. If the same projections are applied to the rocky shore habitat and assuming there is no upward migration, it would result in a loss of 32% and 52.7% of the habitat respectively.

### *Increasing Temperature*

Responses to rising air and sea temperatures are likely to be markedly different between the animals inhabiting the sandy habitats, and those in the rocky shoreline. Whilst both groups are adapted to rapid changes in temperature, most aquatic sandy-shore animals seldom experience temperatures close to their upper tolerance limits and furthermore they are capable of burrowing and escaping below the sand if conditions at the surface become hostile.

Rocky intertidal species are also well adapted to dramatic temperature fluctuations on a daily basis. However typically they are more sessile and unable to escape in the same manner. Molluscs, perhaps the largest group of organisms represented on Bermuda's rocky shores, have been shown to be particularly vulnerable to changes in UV radiation, pH and water temperature (Przeslawski *et al*., 2005). Physiological stress was observed in the early life history stages of three rocky shore gastropods, but they noted particularly that it was when multiple stressors were applied simultaneously that the affects were most severely felt. They conclude that we are probably underestimating the ecological impacts of climate change by considering various stresses independently, instead of taking consideration of the complex interplay of environmental variables on organisms.

As is currently observed (Thomas and Logan, 1992) localised variations in the shoreline will also drive distribution changes in response to change, as temperatures in protected bays perhaps increase proportionally more than along more open coastline. So, whilst one might expect some upwards migration of species (assuming that this is unimpeded by man-made structures), each part of the shoreline will show different trends and there may be horizontal shifts.

It is also suggested that as with most other habitats rising temperatures may facilitate the colonization of invasives species which are able to extend their geographical ranges. Svensson *et al*. (2006) showed that increasing sea surface temperature caused a shift in the faunal community inhabiting rocky tidal habitats and that there was an increased possibility of invasive species establishing themselves among species of barnacles. This might also apply to non-invasive species that are able to extend their range naturally (and not through human introduction). Bermuda represents the northern–most limit of many marine species; so warming temperatures may actually encourage greater species diversification particularly if it takes the edge off the low wintertime temperature spikes. It may also accelerate larval development and survival and result in more consistent recruitment.

The impacts of climate change on beach and rocky shore faunal communities will also be closely tied to the impact on their prey and predator species, so these interactions need to be factored in. Many species will time their reproductive behaviours to coincide with food availability so changes could result in food 'mis-match'.

### *Increasing Carbon Dioxide*

Increasing ocean acidification is predicted to cause calcium carbonate to dissolve. This will have multiple implications for the coastal habitats. In the rocky tidal community, the majority of species are molluscs dependent on water supersaturated with calcium carbonate to ensure that once their calcareous shell structures are formed, they do not dissolve. Lower pH resulting from increasing $CO_2$ absorption by the oceans will make calcification harder. As far as our beaches and dunes are concerned, there will be less material available as sand, which will reduce deposition on our beaches.

### *Heavier, Less Frequent Rainfall*

Heavier rainfall may result in sudden cliff collapse along the shoreline. The cliff collapse in the photograph below occurred after an extremely heavy downfall in June 2008.

*Photograph 9. Cliff collapse on Charles Island due to heavy rain.*

### *Increasing Storm Activity*

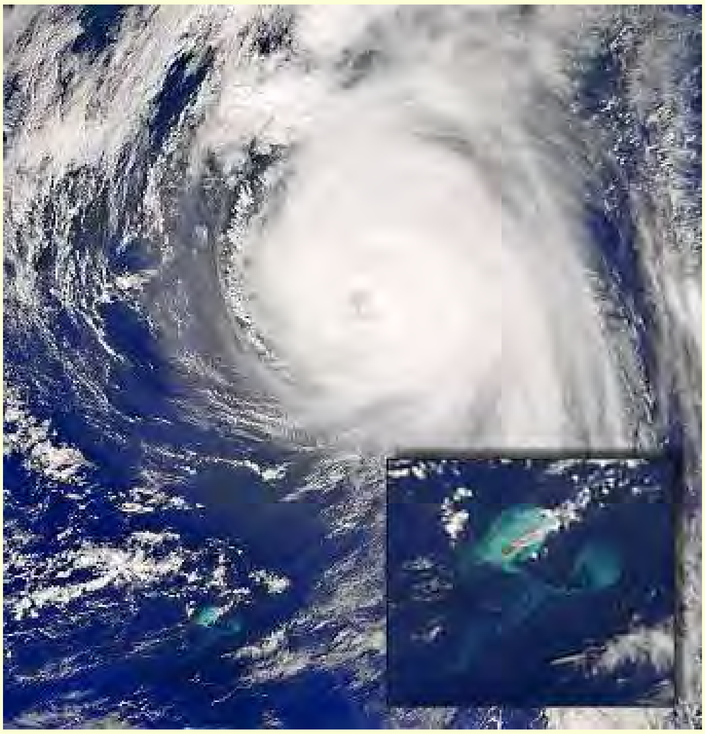
Bermuda's coastline has been experiencing significant erosion, which has been particularly apparent during recent hurricane events. Storm analysis showed that highest wave heights around Bermuda are from the south and south-east (Government of Bermuda, 2004). The rate of coastal erosion will clearly increase with increasing storm intensity and Table 21 shows inundation levels that can be anticipated in various parts of Bermuda at present as a function of static storm surge and wave run-up. These projections only allow for a sea level rise of 0.25 m. Along the high cliffs, inundation can be as high as 14 m; this explains the erosion of the South Shore road just west of John Smith's during Hurricane Fabian.

The impact of increasingly intense storms on our sandy beaches is direct loss of sediment. This was seen dramatically during Hurricane Fabian in the satellite image shown below. The image excerpt shows a very large plume of sediments originating on the island and extending to the south. The hurricane caused extensive erosion of the island's beaches, as well as stirring up the carbonate sediments from the North Lagoon. This combination of beach sand and lagoon sediments is the material in the sediment plume emanating from the island.

| Location | Inundation Levels (in metres) above Mean Sea Level (1984) | | | |
|---|---|---|---|---|
| | Beach | Flat Rock | Low Cliff | High Cliff |
| North Shore-East | 4.4-6.2 | 3.0-4.4 | 5.3-7.1 | 7.1-9.4 |
| North Shore-West | 4.6-6.4 | 3.2-4.6 | 5.3-7.3 | 7.3-9.6 |
| West Shore | 4.6-6.4 | 3.2-4.6 | 5.5-7.3 | 7.3-9.6 |
| South West Shore | 3.0-5.1 | 2.6-3.9 | 3.3-5.7 | 3.9-7.2 |
| South Shore | 5.1-9.6 | 3.3-6.6 | 6.9-11.1 | 9.3-14.9 |
| North East-Shore | 4.6-6.4 | 3.2-4.6 | 5.5-7.3 | 7.3-9.6 |
| St. George's Harbour | 2.7-4.8 | 2.3-3.6 | 3.0-5.4 | 3.6-6.8 |
| Castle Harbour-North | 4.8-6.6 | 3.4-4.8 | 5.7-7.5 | 7.5-9.6 |
| Castle Harbour-South | 3.0-5.1 | 2.6-3.9 | 3.3-5.7 | 3.9-7.2 |
| Harrington Sound | 2.8-4.9 | 2.4-3.7 | 3.1-5.5 | 3.7-6.9 |
| Great Sound-East | 2.6-4.7 | 2.2-3.5 | 2.9-5.3 | 3.5-6.7 |
| Little Sound | 2.7-4.8 | 2.3-3.6 | 3.0-5.4 | 3.6-6.8 |
| Great Sound-West | 4.5-6.3 | 3.1-4.5 | 5.4-7.2 | 7.2-9.5 |

*Table 21. An analysis of inundation levels at various locations around Bermuda. These are calculations summing the static storm surge with the wave run-up for a 150 year storm event (Wave run-up is dependent on the wave height and the slope and the roughness of the shoreline or beach). (Source, Government of Bermuda, 2004).*

Sediments, particularly nearshore sediments, can contain a large amount of organic matter. The net result of sediment resuspension is a release of nutrients that can foster increased phytoplankton productivity. This is not necessarily a problem, unless it provides nutrients for a bloom of toxic phytoplankton. However sedimentary material can also possess large surface areas on which metal ions can be absorbed and which can be released during re-suspension. For toxic metals such as mercury, cadmium, and lead, this is an environmental concern.



*Photograph 10. The day after the passage of Fabian over Bermuda, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) acquired this image. The island of Bermuda as at lower left, and the inset at lower right is a magnification of the island of Bermuda.*

It is not only Bermuda's beaches that are susceptible to storm erosion. Huge chunks of the rocky shoreline may also tumble. Prior to Hurricane Fabian, the double pinnacled Gurnet Rock, off South Shore stood as a noted landmark, remarked upon through the centuries by earlier inhabitants for its resistance to hurricanes. Yet the Category 3 storm managed to destroy the larger rear pinnacle. Facilitating this coastal erosion in many parts of the island is the shallow-rooting invasive tree, the casuarina. Toppling easily in high winds, the rampant spread of this problematic species along most of Bermuda's rocky shoreline is a real cause for concern.

*Photograph 11. Invasive casuarina trees growing along Bermuda's rocky shoreline are contributing to coastal erosions, particularly during tropical storms.*

Finally, it must be realised that impacts on coastal ecosystems are more severe when major storms occur in short succession, limiting the opportunity to rebuild natural resilience in-between.

*Table 22. Summary of impacts of climate change on Bermuda's coastal habitats*

| CLIMATE CHANGE | IMPACTS ON BEACHES | IMPACTS ON ROCKY SHORE |
|---|---|---|
| Sea level rise | • Loss of beach sand and dunes. | • Loss of habitat. |
| Increasing temperature | • Physiological stress.<br>• Upward land migration. | • Shifting in timing of reproduction, metamorphosis, dispersal etc. which may cause 'mis-match' in food availability.<br>• Physiological stress.<br>• Upward land migration.<br>• Increased susceptibility to invasive species.<br>• Changes in species distributions.<br>• Changes in species community composition. |
| Increasing $CO_2$ | • Increasing ocean acidification resulting in less material available for sand. | • Increasing ocean acidification causing reduction in shell growth in molluscs. |
| Heavier, less frequent rainfall events | • Impaired dune formation<br>• Waterlogging | • Waterlogging causing cliff collapse |
| More intense tropical storms | • Loss of beach sand and dunes.<br>• Uprooting of flora. | • Loss of habitat.<br>• Uprooting of flora. |

## 16.3 Mitigation and Adaptation Measures

After Hurricane Fabian the Bermuda Government commissioned a study on Bermuda's vulnerability to coastal erosion which was conducted by Smith Warner International (Government of Bermuda, 2004). Whilst their projections for future climate change were perhaps conservative based on the latest IPCC (2007) projections (they allowed for a 0.25 m rise by 2050), the report provided a comprehensive review of the island's shoreline and made strong recommendations regarding appropriate shoreline protection, appropriate shoreline development and ecological considerations (Government of Bermuda, 2004b). Recommendations for shoreline protection included the use of sea walls, revetments, breakwaters and dune restoration. They recommended that shoreline development needs to take into consideration appropriate setbacks, a community-based approach to shoreline defense and the need for functional integrity over aesthetics. Ecological considerations focused on the removal of the invasive casuarina trees, establishing the rate of coastal erosion by boring organisms, and the importance of the rim and boiler reefs in protecting the island. By dividing the shoreline into 13 sectors they provided a valuable means of calculating inundation levels in each sector and according to four shoreline types (beach, flat rock, low cliff and high cliff). This model can be used for regulating building location and elevation at, or close to the shoreline. The biggest challenge to this approach may be in retaining as much as possible of the natural appearance of the coast and allowing for sufficient vertical migration of the ecological communities comprising these habitats as climate change accelerates.

## 16.4 Acknowledgements

The author is especially grateful to Ms. Mandy Shailer, GIS Coordinator of the Department of Conservation Services for her sea level rise calculations and to Dr. Martin Thomas, Professor Emeritus of the University of New Brunswick for his helpful input.

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# 17. Impact of Climate Change on Plants


**SUMMARY**

- Plants are perhaps the single most important group of organisms influencing habitats and the physical environment for other species, as well as storing carbon. Plants are major regulators of global climate, removing 50% or our $CO_2$ through photosynthesis.

- Human colonization marked a significant transition in Bermuda's terrestrial vegetation and 22 invasive plant species now dominate 33% of the remaining undeveloped land.

- Island species, with specific habitat requirements or long generation times are particularly vulnerable to climate change and more prone to extinction. 25% of the world's vascular plant species are under threat and by the end of the century, as many as half of all plant species may become extinct.

- Sea level rise will cause upward migration of plants where possible, but will drown species in low-lying marshes. Increasing temperatures will lead to earlier onset of growth and a longer growing season and may accelerate loss of organic matter in soil, releasing more nitrogen and increasing plant growth. However, it may cause plants to switch from photosynthesis to photorespiration, limiting net primary production and increasing $CO_2$ production as well as reducing the local/global cooling effect of plants. The susceptibility of plants to pest and disease and invasive species will increase; poison ivy may thrive.

- Waterlogged soils may drown plants and stronger hurricanes will topple trees.

- Management action needs to continue to focus on reducing existing impacts on our plants and trees, providing space for them to adapt and migrate. This means increasing the available habitat either through dedicated nature reserves, land corridors or backyard plantings, culling of invasives and continuing to educate the community about the benefits plants give us.

## 17.1 Introduction

Plants are perhaps the single most important group of organisms influencing habitats and the physical environment for other species, as well as storing carbon. The impact of climate change on plant communities is therefore hugely significant and there is growing concern that they may in fact be losing their ability to act as a carbon sink. It should be realised however, that determining the impacts of climate change may be complicated by the extreme pressures already placed on our terrestrial habitats through development and invasive species.

Prior to colonisation Bermuda's low, hilly landscape and freshwater marshes were densely wooded with 15 species of endemic evergreen plants such as the Bermuda cedar *(Juniperus bermudiana),* Bermuda palmetto *(Sabal bermudana)*, olivewood bark *(Cassine laneana),* and about 150 native plants. Human colonization marked a significant transition in the terrestrial vegetation, through harvesting and also through experimentation with introduced exotic species. One of the most devastating impacts on the native flora was the accidental introduction of two invasive scale insects, the juniper scale (*Carulaspis minima*) and the oyster-shell scale (*Insulaspis pallida*) in the 1940s which resulted in the loss of nearly 94% of the islands' cedar trees. This prompted a huge reforestation effort which was initiated with a suite of invasive alien species, including casaurina (*Casuarina equisetifolia*), Brazil pepper (*Schinus terebinthifolius*) and Indian laurel (*Ficus retusa*) resulting in wholesale change of the landscape. Recent island wide vegetation surveys have revealed the extent of the changes to the island's native vegetation, with 22 invasive plant species now dominating 33% of Bermuda's remaining undeveloped land (Sterrer *et al*., 2004).

Though there is no clear evidence for global carbon cycle climate interactions on the timescale pertinent to current climate change (i.e. the past 150 years) in Bermuda (or at least any evidence that does exist is likely masked by local development pressures), evidence from elsewhere suggests that there have been shifts in the distribution and abundance of species over the past 30 years (Thomas *et al*., 2004; Root *et al*., 2005).

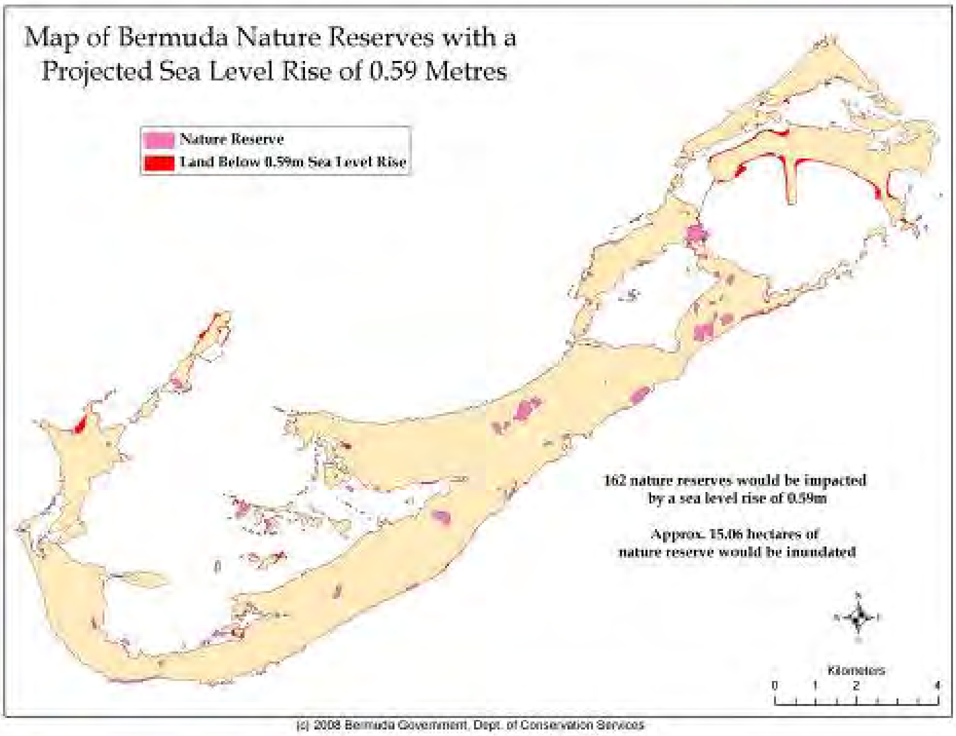
## 17.2 Impact of Climate Change on Plants

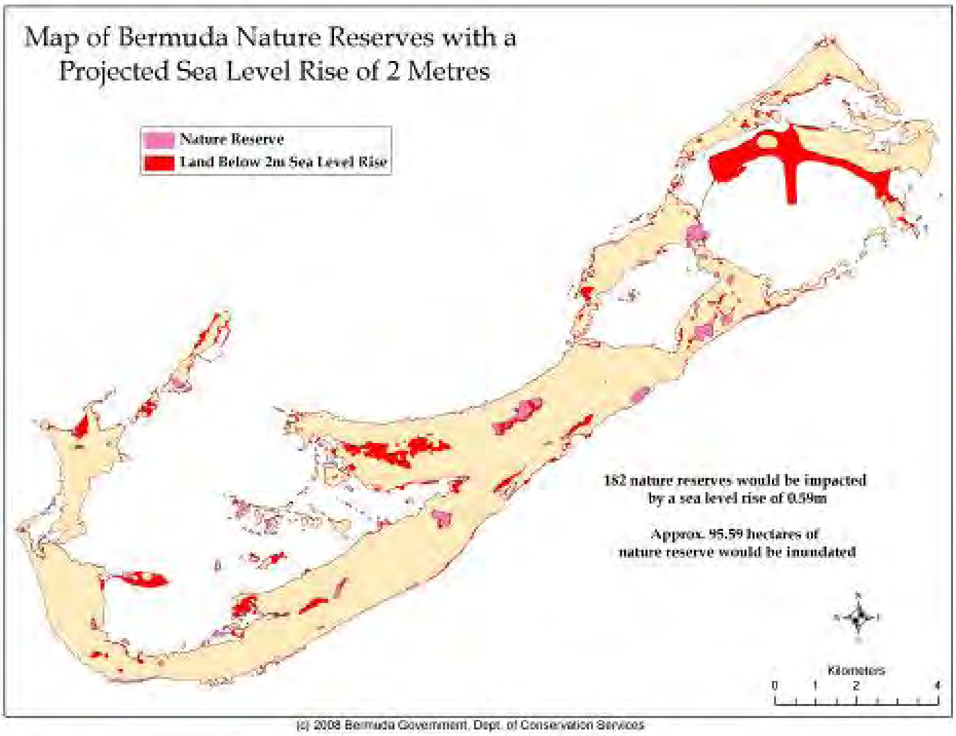
In responding to climate change, species can either migrate and establish themselves in a more suitable environmental, stay and adapt to the changing conditions or, failing either of these become extinct.  It is increasingly apparent that weedy species which have fast generation times and a wider range of ecological tolerances are more likely to adapt or migrate quickly and hence survive. Island species, with specific habitat requirements or long generation times are believed to be particularly vulnerable to climate change (Hawkins *et al*., 2008); thus Bermuda's endemic plant species may be more prone to the threat of extinction. It is currently estimated that 25% of the world's vascular plant species are under threat with predictions that by the end of the century, as many as half of all plant species may become extinct (Hawkins *et al*., 2008). One of the biggest concerns of this community re-organisation is the affect it will have on the food chain as well as on the relationships between a plant and its pollinator or seed disperser. If species that rely on each other no longer co-occur in the same time or space, both may be driven to extinction.

### *Sea level rise*

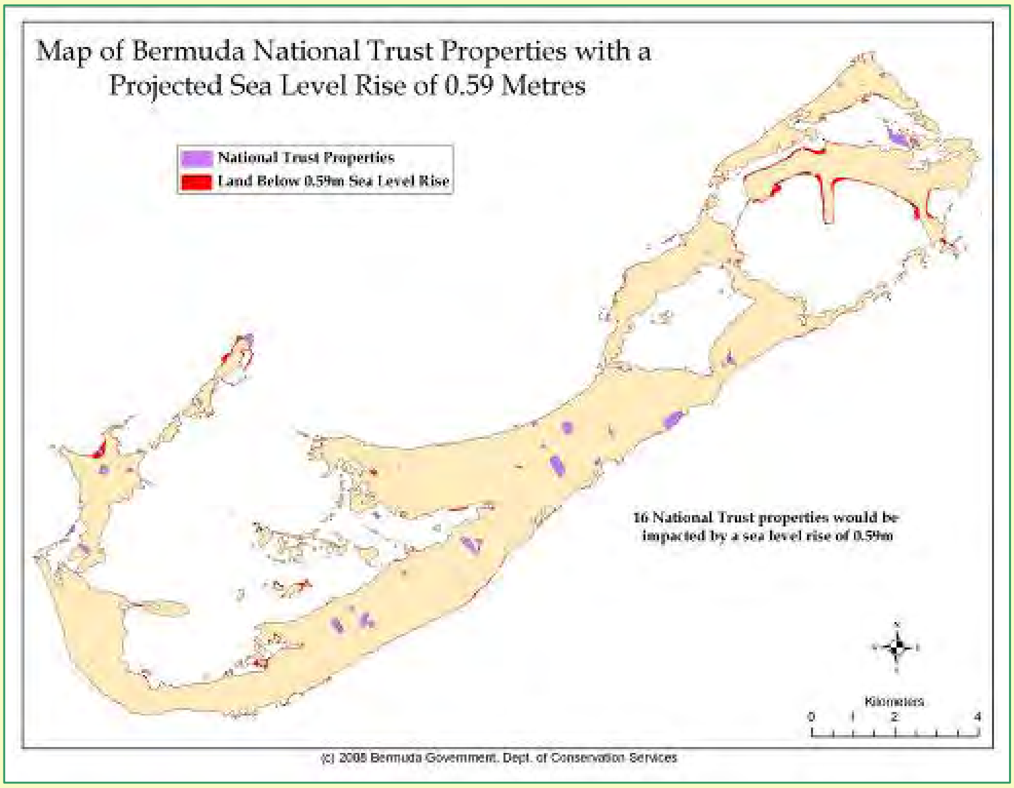
Rising seas will inevitably cause plants to migrate upwards. Higher seas combined with more intense tropical storms may cause the coastal hillside vegetation zone to widen, as many of the plants already show adaptation to some level of salt spray. Calculations on projected sea level rise reveal that with a rise of 0.59 m, only 4.6 % of our upland coastal zone and 0.6% of upland hillside will be inundated, but with a 2 m rise, this increases to 13.8% for upland coastal and 4.7% for upland hillside (M. Shailer, pers. comm.). Perhaps the most threatened species are those associated in inland areas where rising sea level will inundate low-lying lands; marshes will be particularly vulnerable. Whilst a 0.59 m rise will not impact Bermuda's peat marshes, a 2 m rise would impact 92% of their current area (see Map 21 below). According to Wingate (pers. comm.), the high sea level stand experienced in November 2003 caused the death of "hundreds" of cedars in Paget Marsh; many of these trees were over 100 years old. Sea level projections of 0.59 m would also impact 162 of the island's nature reserves and 16 National Trust properties. A projected rise of 2 m would impact 182 nature reserves (95.59 ha) and 34 Bermuda National Trust properties.

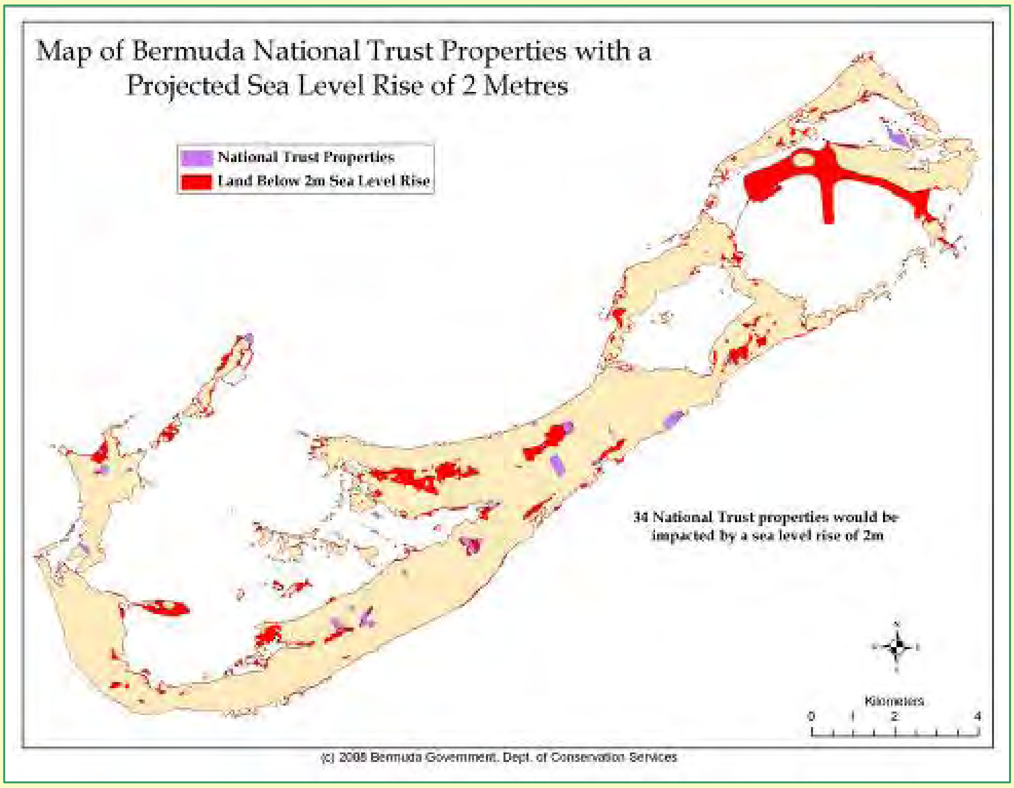

*Map 21 showing the impact of a 2 m sea level rise on Paget Marsh and Devonshire Marsh.*




*Map 22 (above) showing the impact of a 0.59 m sea level rise on Bermuda's nature reserves and Map 23 (below) of a 2 m sea level rise.*




*Map 24 (above) showing the impact of a 0.59 m sea level rise on Bermuda's National Trust properties and Map 25 (below) of a 2 m sea level rise.*

### *Increasing temperature*

Warmer temperatures are known to increase plant growth up to a limit. However, on hotter, drier days plants tend to resort to photorespiration rather than photosynthesis (using oxygen rather than $CO_2$), in an effort to minimise water loss through their stomata. Interestingly, herbarium records reveal that tree leaves collected from the early part of the industrial revolution have higher numbers of stomata than their present day counterparts, suggesting either that less stomata are now needed to receive equivalent amounts of $CO_2$ or that water conservation is more significant nowadays (Bisgrove and Hadley, 2002). Plants in increased $CO_2$ environments frequently either open their stomata less widely or keep their stomata completely closed more often, therefore reducing plant transpiration (Betts *et al*., 2007). While this will help plants to efficiently utilise limited water resources (most water evaporation occurs via transpiration), this response may limit predicted increases in net primary productivity, and thus limit carbon storage opportunities. Additionally, transpiration is largely responsible for the ability of plants to cool their local climate. On a global scale, the loss of this cooling effect could also be significant.

Temperature increases may also cause an earlier onset of growth in spring and a longer growing season, as well as accelerate loss of organic matter in soils, releasing nitrogen which may increase plant growth or, if leached from the soil increase pollution of our inshore waters or ponds.

Increasing temperature is also predicted to promote more severe pest and disease attacks on plants, as well as encouraging wider geographical distribution of species currently on the edge of their climate tolerance. We might therefore expect a proliferation of invasive species (especially the weedy ones), either through new arrivals, or through climatic triggering of 'dormant' invasives already in Bermuda. (Globally, the cost of damage caused by invasive species has been estimated to be US$1 trillion per year; close to 5% of global GDP).

### *Increasing carbon dioxide*

Increasing $CO_2$ in the atmosphere can increase plant productivity however it is believed that this will be a temporary effect, as plants acclimate to change. Elevated $CO_{2,}$ will lead to the accumulation of carbohydrates resulting in a reduction in photosynthetic rates (Bisgrove and Hadley, 2002). However, higher $CO_2$ levels may reduce the amount of water plants require for the same level of productivity (Hawkins *et al*., 2008). Mohan *et al*. (2006) demonstrated that increased $CO_2$ in an intact forest system increases photosynthesis, efficiency in water use, growth and population biomass of *Toxicodendron radicans* (poison ivy). Additionally, under higher $CO_2$ regimes the plants produced more allergenic form of urushiol which is the toxic compound found in poison ivy!

### *Increasing ozone*

Ozone ($O_3$) is a both a GHG and a pollutant; it is formed when nitrogen oxides (NOx), carbon monoxide (CO) and volatile organic compounds (VOCs) from pollution, especially exhaust fumes, react with water and sunlight (Hawkins *et al*., 2008) and is predicted to rise under IPCC (2007) scenarios. As far as plants are concerned, Booker (2005) reports that ground level ozone causes more damage to plants than all other pollutants combined, changing leaf biochemistry and physiology (Hawkins *et al*., 2008). High concentrations of $O_3$ also cause plants to close their stomata, thus inhibiting photosynthesis, altering plant structure and development and suppressing biomass and yield (USDA, 2000).

### *Changes in precipitation*

The knock-on effect of increased $CO_2$ reducing plant transpiration thereby helping plants to efficiently utilise limited water resources has been discussed above. However Bermuda is predicted to receive heavier rainfall events which may cause waterlogging of our soil. The result of this is a reduction in air spaces in the soil which in turn deprives plant roots of oxygen and prevents $CO_2$ being diffused away. With too much water, plants are unable to draw up soil moisture, leaves will wilt (Bisgrove and Hadley, 2002) and roots will rot and the plant will 'drown'. Plant species exhibit different tolerances to waterlogging, but this is also dependent on intensity, duration and at what stage in a plant's life cycle it occurs. This is probably not such a significant threat in Bermuda, given the porosity of our limestone.

### *Increasing storm activity*

Recent hurricanes in Bermuda, most notable Hurricane Emily in 1987, have revealed the extent of the damage that hurricanes can cause to plant life. One of the main reasons this particular storm had such an impact, was the speed at which it was moving. As a consequence, hurricane force winds hit the island with little preceding build-up in wind strength. Without this, trees were unable to sacrifice their leaves and peripheral branches to shed weight and reduce resistance and so succumbed to the full impact of the hurricane strength winds by toppling. Whilst many endemic trees were lost, it was equally noticeable that most of the species that were toppled were non-native. The shallow-rooting casuarina (*Casuarina equisetifolia*) was particularly vulnerable. Endemic trees showed a remarkable resilience to the storm as evidenced on Nonsuch Island and on the Mitchell property on South Shore Road, both of which are almost exclusively planted with endemics (Madeiros, pers. comm.; pers. obs.). Unfortunately, any vacuum left by downed trees is more likely to be filled by aggressive invasive species.

***Table 23. Summary of impacts of climate change on Bermuda's plants***

| CLIMATE CHANGE | EXPECTED IMPACTS |
|---|---|
| Sea level rise | • Will lead to upwards migration of plants.<br>• Will drown species in low-lying marshes. |
| Increasing temperature | • May cause plants to switch from photosynthesis to photorespiration, limiting net primary production and increasing $CO_2$ production.<br>• Will result in a reduction in the local/global cooling effect of plants. |

| | |
|---|---|
| | • Will lead to earlier onset of growth and a longer growing season.<br>• May accelerate loss of organic matter in soil, releasing more nitrogen which increases plant growth but may cause possible run-off problems in inshore waters.<br>• Increased susceptibility to pest and disease attacks and invasive species. |
| Increasing $CO_2$ | • Increasing plant productivity up to a point, however ultimately this will cause an accumulation of carbohydrates and a decrease in photosynthetic rates.<br>• May reduce the amount of water needed by the plant.<br>• Will increase growth and biomass of poison ivy (*Toxicodendron radicans*) and lead to production of more allergenic form of urushiol, the toxic compound found in the plant. |
| Increasing $O_3$ | • Changes leaf biochemistry and physiology, inhibits photosynthesis and suppresses biomass and yield. |
| Heavier, less frequent rainfall events | • May cause waterlogging of soil, leading to oxygen deprivation of roots and prevention of $CO_2$ being diffused away.<br>• Ultimately 'drowns' the plant |
| More intense tropical storms | • Causes broken branches and may uproot and kill trees.<br>• Salt spray burns leaves. |

## 17.3 Impact of Plants on GHG Emissions

Uptake of $CO_2$ during photosynthesis is the major pathway for the removal of $CO_2$ from the atmosphere. Approximately 50% of our emissions are removed this way (Hawkins *et al.*, 2008). Furthermore, the world's vegetation and soils combined harbour about three times as much carbon as the atmosphere and as such, are major regulators of global climate. However, increasing temperature can cause plant respiration rates to increase relative to photosynthesis, resulting in no net gain in biomass production, and potentially causing plants to become a source of $CO_2$.

There has been some evidence to suggest that plants do emit methane according to a study by Keppler *et al*. (2006), and further that methane emissions appear to double for each 10°C rise in temperature. Though the mechanisms of methane production by plants is still unknown, Lowe (2006) suggest that if true, it would help explain the large plumes of methane seen from space above tropical forests, as well as the current decrease in the growth rate of global methane (i.e from deforestation). However, another paper has disputed these findings (Dueck *et al*., 2007) and so plant methane fluxes remain uncertain.

***Table 24. Summary of impacts of plants on GHG emissions.***

| GHG | IMPACTS |
|---|---|
| Greenhouse gas (GHG) emissions | • Plants are major regulators of global climate, removing 50% or our $CO_2$ through photosynthesis.<br>• Increasing temperature can cause plant respiration rates to increase relative to photosynthesis, resulting in no net gain in biomass production, and potentially causing plants to become a source of $CO_2$.<br>• Plants may be emitters of methane, and if so, this may increase with increasing temperature. |

## 17.4 Mitigation and Adaptation Measures

There is growing evidence that species can and are responding to climatic changes. However the question remains as to the rate of these adaptations and whether they can keep up with the accelerating rate of climate change. The ability to adapt will depend on the species. Those with rapid growth rates may be more responsive than slower growing species. This may cause shifts in entire habitats.

Adaptation to climate change cannot be accomplished in isolation from other threats to Bermuda's plants. Indeed the resilience of our plant species can only be enhanced by removing these other pressures. Development and invasive species are the biggest local threat to plant communities, so increasing the amount of available land either through dedicated nature reserves, land corridors or in backyard gardens is critical. The continued culling of invasive species remains equally critical. Continuing public education must also be a key strategy. The fact that plant communities provide critical habitat for other species, are a sink for our carbon emissions and play an essential role in regulating our micro-climate should be a strong selling point for positive action.

## 17.5 Acknowledgements

The author is sincerely grateful to Ms. Mandy Shailer, GIS Coordinator, Department of Conservation Services for the production of the GIS projections.

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# 18. Impact of Climate Change on Birds


**SUMMARY**

- There is an escalating pattern of climate change-related impacts on bird species around the world and certain groups of birds have been flagged as being at high risk from climate change. Of relevance to Bermuda, these include migratory, island, wetland and seabirds.

- There are 360 locally recorded bird species. Only 22 are resident of which 2 are endemic, 3 are seabirds (including 1 of the endemics) and the remainder are land birds. The other birds observed in Bermuda are migrants or vagrants as the island lies in the pathway of major seasonal bird migrations.

- Historically, sea level rise has impacted Bermuda's birds. The critically-endangered short-tailed albatross (*Phoebastria albatrus*) used to breed here but its extirpation occurred about 405,000 years ago during a + 20 m high sea level stand and likely resulted from lack of nesting sites sufficiently protected from storm surges over the remaining land mass.

- Rising sea levels and intensive storm activity are already impacting Bermuda's seabirds causing loss of cahow and longtail nests in exposed cliffs and rocky islets and reducing breeding success in the latter.

- Hurricanes divert migrant birds, and may result in their death from starvation.

- Increasing temperatures may affect reproductive seasonality and may also lead to 'mis-match' with available food.

- Adaptation and mitigation must include protection of open space and specific bird habitats as well as corridors between them, and the provisional of artificial nests where possible.

## 19.1 Introduction

In a recent report compiled for the World Wildlife Fund (WWF-Australia, 2006) over 200 scientific articles were reviewed to assess the status of the impact of climate change on birds. The report finds an escalating pattern of climate change-related impacts on bird species around the world (declines of up to 90 per cent have been reported in some bird populations, as well as total and unprecedented reproductive failure in others), and warns of potentially major bird extinctions as a result. Certain groups of birds have been flagged as being at high risk from climate change, and of relevance to Bermuda, these include; migratory, island, wetland and seabirds.

In Bermuda, of 360 locally recorded bird species, only 22 are resident (and only half of these reached Bermuda naturally) and only 2 of these are endemic (Raine, 2003). These include the seabird, the cahow (*Pterodroma cahow*), rescued from the brink of extinction in the 1950s, as well as the white-eyed vireo (*Vireo griseus bermudiensis*), a sub-species of the American white-eyed vireo. There are two additional species of coastal seabird, the white-tailed tropicbird or longtail (*Phaethon lepturus catesbyi*) and the common tern (*Sterna hirundo*) whilst the remainder of the native bird species are land birds.

However, most of the birds observed in Bermuda are migrants or vagrants as the island lies in the pathway of major seasonal bird migrations. Some of these, like the greater shearwater (*Puffinius gravis*) and Cory's shearwaters (*Calonectris diomedea*) are pelagic birds, never actually stopping down on the islands. Others (waterfowl, plovers, sandpipers warblers, vireos, buntings and swallows) stop over during their migration between July and November and then again on their return between February and April (Raine, 2003). Wingate (pers. comm.) notes that the number of migrants to Bermuda has declined significantly in recent years, which he attributes to general global habitat loss.

The fossil records indicate that several other species no longer breed in Bermuda. This includes the critically-endangered short-tailed albatross (*Phoebastria albatrus*). Olson and Hearty (2003) propose that the extirpation of these albatrosses from Bermuda occurred about 405,000 years ago during a + 20m high sea level stand and resulted from lack of nesting sites sufficiently protected from storm surges over the remaining land mass. A number of other (probably endemic) birds species have become extinct including a crane, a duck, 4 species of rail, a woodpecker, hawk, a heavy-billed passerine and an owl (the latter two both having been recorded by the early settlers) (Anderson *et al*., 2001).

## 18.2 Impacts of Climate Change on Birds

Birds are considered to be susceptible to the impacts of climate change because, 1) they are homeothermic animals, keeping their body temperature at a roughly constant level, regardless of the ambient temperature; and 2) they have several separate phases in their annual cycle (breeding, moulting, autumn migration, wintering, spring migration) which have to adapt to variable changes of both climate and habitat simultaneously (http://users.utu.fi/karainio/projekti/index.htm). Bird species that can adapt easily to a new habitat are expected to continue to do well, however species with a narrow environmental range are expected to struggle.

### *Sea level rise*

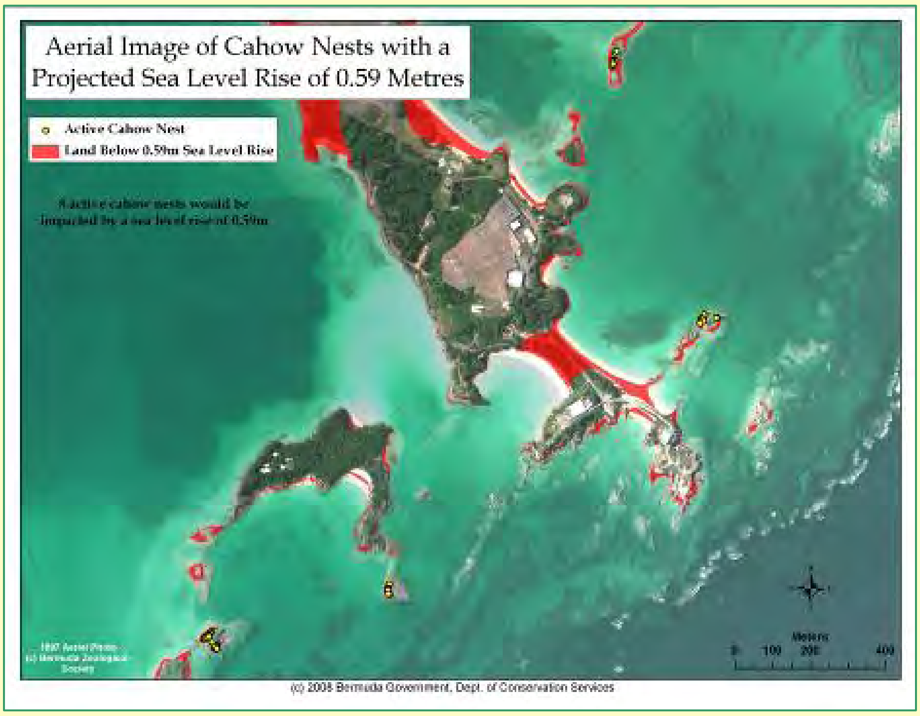
Sea level rise will have the most significant impact on coastal birds. The cahow and longtail are both philopatric, returning to the same nesting sites in coastal crevices to breed each year, whilst the common tern only nests on small rocky islets. Rising sea levels are resulting in the direct destruction of the nests of all 3 species, and this is magnified when coupled with intense storms. The cahow is particularly vulnerable as its nesting sites are restricted to just 5 islets in the Castle Harbour complex. Longtails are similarly impacted, and the issue is compounded by human development and the construction of defensive sea walls along the shoreline, which is limiting the availability of suitable nesting locations. The tern is limited by the number of available islets and erosion from sea level rise and storm activity is causing these to diminish. In a preliminary analysis, Wingate and Talbot (2003) document a 27% drop in breeding success in natural nest sites for the longtail, attributing this to loss of suitable nest sites. Maps 26 and 27 below illustrate the impact of a 0.59 m sea level rise (the upper limit of the IPCC (2007) predictions and a 2 m sea level rise (the maximum upper limit anticipated by the end of this century (Pfeffer *et al*., 2008)) on the cahow nesting islands. The projections show that even with a 0.59 m rise, three of the islands, Green Island, Long Rock and Inner Pear Rock are seriously impacted. The map does not show the distribution of cahow nests on Nonsuch Island as part of the translocation programme, but clearly this offers a much safer option for this critically endangered endemic.

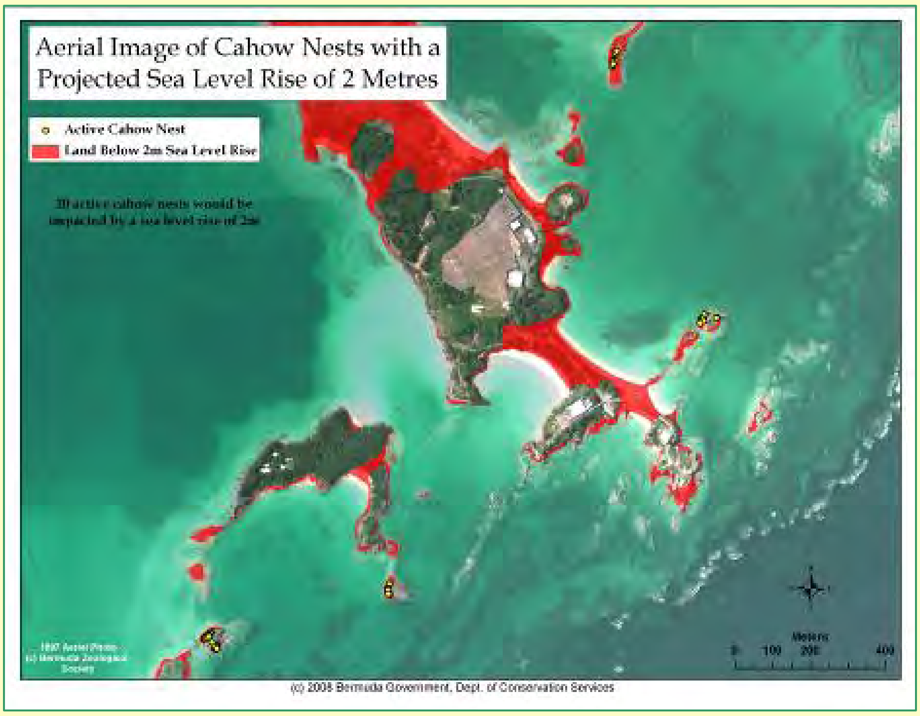
Sea level rise will also decrease beach habitat, which may affect shorebirds feeding by reducing the invertebrate communities found in the seaweed strand line.

### *Increasing storm activity*

Increasing storm activity is having the same impact on Bermuda's birds as rising sea levels. Between 1995 and 1999, storm surge from two passing hurricanes completely swamped two of the cahow nesting islands, destroying 40% of the (then vacant) nest sites each time. According to Wingate and Talbot (2003), if these storms had been later in the year during the breeding season, the impact on the population could have been catastrophic. In a preliminary analysis of longtail nesting sites on the Castle Harbour islands, they document a 27% drop in breeding success, attributing this to loss of suitable nest sites.

The dramatic increase in bird numbers and species recorded in Bermuda after major storms that coincide with migratory seasons is evidence of the diversionary affect storms can have on birds. Wingate (1993) reports "tens of thousands of bobolinks and 18 species of warblers" having been "dumped" on Bermuda during Hurricane Emily in 1987. He further reports that onshore observers watched "vast numbers of passerines and flocks of egrets inside the eye and being pushed ahead of the advancing eye wall". However, he proposes a "hurricane shadow effect" with hurricanes located south, southwest or west of the island, as birds seem to be deflected away from Bermuda. He suggests that the survival time of birds trapped in the eye of a hurricane will




*Map 26 (above) showing the impact of a 0.59 m sea level rise on the cahow nesting Islands and Map 27 (below) of a 2 m sea level rise.*

depend on their typical flight range and fat storage capacity during migration; if "capture" in the hurricane exceeds this then the bird will likely not survive.

### *Increasing temperature*

Increasing temperatures might be expected to affect the phenology or timing of reproductive activity in birds, resulting in earlier breeding. Anecdotal evidence suggests slight advancement in the breeding of longtails (Wingate, pers. comm.) and possibly bluebirds (Madeiros, pers. comm.). This may have two ramifications. Earlier breeding in both species was observed in 2008, probably triggered by unseasonably warm temperatures in February however a subsequent cold snap caused high chick failure. This resulted in a second nesting period which extended late into the start of the hurricane season, implying that an early hurricane could have seriously affected nesting success.

The second affect of advanced breeding may be a 'mis-match' with food availability. Such mis-match is most obviously seen in seabirds with relation to ocean productivity (Briggs *et al*., 1984; Duffy, 1993; Springer *et al*., 1999). Ocean productivity has naturally occurring seasonal, decadal and multi-decadal oscillations and during ENSO years, some seabirds postpone reproduction and incur higher mortality than in non-ENSO years (Duffy, 1993). The distribution and abundance of shorebirds has also been shown to be positively related to coastal zone productivity in waters adjacent to the coastal habitats where they spend the winter (Butler *et al*., 2001). Climate changes which affect ocean productivity may therefore impact Bermuda's seabirds and shorebirds.

There may be other knock-on effects of increasing temperatures if local bird habitats are negatively impacted.

### *Changes in precipitation*

The main impact of heavier downpours is flooding of nests or cliff collapse resulting from water-logging, and loss of nests as a result.

***Table 25. Summary of impacts of climate change on Bermuda's birds***

| CLIMATE CHANGE | IMPACTS ON SEABIRDS | IMPACTS ON RESIDENTS | IMPACTS ON MIGRANTS |
|---|---|---|---|
| Sea level rise | • Loss of nest sites.<br>• Erosion of sand and soil from nests affecting breeding success. | • Loss of habitat.<br>• Loss of food supply | • Loss of habitat.<br>• Loss of food supply |
| More intense tropical storms | • Loss of nest sites.<br>• Erosion of sand and soil from nests affecting breeding success.<br>• Drowning of adult, chick | • Loss of habitat.<br>• May cause death. | • May divert migrants to or from Bermuda.<br>• May kill migrants trapped in storm eye.<br>• Loss of habitat. |

| | | | |
|---|---|---|---|
| | or egg. | | |
| Increasing temperature | • May advance breeding.<br>• May cause 'mis-match' in food availability. | • May advance breeding.<br>• May cause 'mis-match' in food availability.<br>• Loss of specific habitat. | • May cause 'mis-match' in food availability. |
| Heavier, less frequent rainfall events | • Waterlogging causing cliff collapse and nest destruction | • May drown nests | |

## *18.3 Mitigation and Adaptation Measures*

Protecting Bermuda's known bird habitats and open space and ensuring corridors between them will be one of the primary measures that we can take to allow birds a chance to adapt to climate change. The ongoing provision of artificial nests for cahows and longtails (see photo) which has proved so successful to date must be considered an essential management activity, and homeowners must continue to be persuaded to incorporate these artificial longtail burrows into their property development plans. Likewise the translocation efforts which have seen cahow re-established on the much higher lying Nonsuch Island must be supported.

*Photograph 12. Showing artificial burrows placed on Horn Rock for cahows and longtails*

## 18.4 Acknowledgements

The author is most grateful to Dr. David Wingate (former Conservation Officer and Founder, Bermuda Audubon Society and Bermuda National Trust) and Mr. Jeremy Madeiros (Conservation Officer) for their helpful critique. Ms. Mandy Shailer (GIS Coordinator, Department of Conservation Services) kindly provided the GIS projections.

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# 19. Impact of Climate Change on Reptiles & Amphibians


**SUMMARY**

- Bermuda's remoteness has limited the colonization of the Island by land reptiles and amphibians; there are 4 terrestrial reptiles (1 endemic), 5 true native marine turtles, 1 native brackish water turtle, and 3 introduced amphibians.

- Globally both amphibians and now reptiles are declining, and some of this is being attributed to climate change. Locally, amphibians are showing serious decline, although the cause is currently a cocktail of contaminants (petroleum and metals). These may mask some of the impacts of climate change.

- Sea level rise will result in habitat loss for both groups, loss of reptilian nest sites and drowning of eggs and hatchlings, and saltwater inundation of amphibian breeding grounds. Compounding this will be increasing storm intensity, resulting in direct physical impact and death.

- Increasing temperatures may advance or extend the breeding season in both groups, cause shifts in the timing of reproduction, metamorphosis, dispersal etc., which in turn may cause mis-match in food availability. It may eventually lead to physiological stress, upward land migration and possible changes in sex rations in species with temperature-dependent sex determination.

- Heavier precipitation events may lead to waterlogging and subsequent cliff collapse and nest destruction.

- Adaptive measures should focus on alleviating existing pressures on these two taxonomic groups including habitat loss, pollution and the threat from invasive species. Better public education should also be a focus. Ex-situ breeding of skinks may be prudent.

## 19.1 Introduction

Bermuda's remoteness has limited the colonization of the island by land reptiles and amphibians, and those that are endemics or native would have arrived, probably accidentally by rafting. We can boast just one endemic reptile, the Bermuda rock lizard or skink (*Eumeces longirostris*). 5 native true marine turtles include; the green (*Chelonia mydas*), hawksbill (*Eretmochelys imbricata*), loggerhead (*Caretta caretta*), Kemps Ridley (*Lepidochelys kempi*) and the leatherback (*Dermochelys coriacea*). Only the green and the loggerhead (twice documented) are known to have bred locally, however the large breeding population of the green turtle originally documented in Bermuda at the time of the first settlers, was quickly decimated. Now Bermuda provides a critical foraging ground for juveniles of this species as well as the hawksbill from Caribbean nesting populations. The diamondback (*Malaclemys terrapin*), is a newly discovered native species found in Bermuda's 'landlocked' marine ponds (Mangrove Lake and Trotts Pond) and breeding predominantly in golf course sand bunkers (Parham *et al*., 2008). An introduced turtle, the red eared slider terrapin (Trachemys scripta elegans) is a known invasive and part of an eradication programme. Three other introduced lizards, all anolis species are also widely distributed on the island. These are the Jamaican anole (*Anolis grahami grahami*), the Antiguan anole (*Anolis leachii*) and the Barbadian anole (*Anolis extremus*) (Bacon *et al*., 2006). There is also a fossil record of a now extinct land tortoise (*Hesperotestudo bermudae*) described from the Pleistocene and dated to 300,000 years ago (Meylan and Sterrer, 2000).

Three species of amphibians, all introduced include the two whistling frogs *Eleutherodactylus johnstonei* and *Eleutherodactylus gossei* and the cane toad, *Bufo marinus*. It is likely however that *E. gossei* is now locally extirpated (Bacon *et al*., 2006).

Bermuda's amphibians and reptile populations have been the focus of significant local research. Amphibians have been documented to be experiencing global population declines (Bacon, 2008) and the Bermuda Amphibian Project has shown that local amphibian numbers are also declining. This has been closely linked with a skyrocketing incidence of deformity amongst the cane toad population. The causes of this are being explored but a lethal cocktail of petroleum hydrocarbons and metals is suspected both as a direct contaminant in the environment and through transgenerational transfer (Fort *et al*., 2006). Against such a backdrop, distinguishing any impacts of climate change on the local populations becomes challenging.

Similar global declines may now be emerging for reptiles (Gibbons *et al*., 2000). In the global marine turtle population this has historically been attributed to over-harvesting, collisions with boats, entanglement in fishing gear, ingestion of marine debris and possible habitat loss (Bacon *et al*., 2006) but even amongst these, new evidence is emerging to suggest that climate change may be having an impact. Bermuda's skinks have seen dramatic declines due to loss of habitat through development, trash, invasive species and the more aggressive introduced anolis lizards.

All the native and endemic reptiles (with the exception of the diamondback turtle) are locally protected either under the Fisheries Act 1972, and/or the Protected Species Act 2003.

## 19.2 Impacts of Climate Change on Reptiles

Reptile and amphibians are ectothermic meaning that their body temperatures and activity cycles are dependent on the presence of optimal environmental conditions. They are therefore sensitive to changes and variability in air and water temperature, precipitation, and the hydroperiod (length of time and seasonality of water presence) of their environments. Additionally, many amphibians require aquatic habitats in which to lay their eggs and for the larvae to develop. Because of this, amphibians typically have relatively small home ranges and low dispersal rates. Reptiles are generally more mobile and have a greater ability to withstand predicted warmer conditions.

The impact of emerging pathogens and invasive species triggered by climate change must also be considered. Recent research on amphibian declines has documented the role of emerging pathogens and in some cases epidemic outbreaks of particular infections and diseases (Daszak *et al.,* 2003), and changes in climatic regimes are likely to increase pathogens and the susceptibility of amphibians and reptiles to these.

### *Sea level rise*

The impact of sea level rise will have most impact on Bermuda's terrestrial reptile and amphibian populations. With limited suitable, undeveloped habitat remaining, Bermuda's skink population is now relegated to the South Shore coastal zone and a few isolated islands in Castle Harbour. Sea level inundation of these will drive the skinks upwards, reducing the amount of habitat available to them. Although none of the true marine turtles in Bermuda's waters now breed, rising seas will result in a loss of our beaches and dunes, eliminating any remote chance of breeding populations becoming re-established. A 0.59 m sea level rise (the upper limit of IPCC predictions) will result in a minimum loss of 37.5% of our beaches; a 2 m rise (the predicted possible upper limit likely this century (Pfeffer *et al*., 2008)) will result in the loss of at least 55.8% of this habitat. Bermuda's amphibian species appear to extend across multiple habitat types and will be least impacted by rising sea level, but may experience saltwater inundation of their breeding sites.

### *Increasing temperature*

The timing of reproduction, metamorphosis, dispersal, and migration may shift in response to higher temperatures (Beebee, 1995). If such shifts in amphibian and reptile activities occur out of step with other ecological events (e.g., the emergence of their insect prey), growth and survival rates would be affected.

Whilst there may be some short term benefits to climate warming if this leads to extended periods of optimal temperatures (for breeding for example), ultimately the threat of temperature changes extending beyond thermal optima could lead to physiological stress. A number of reptile species, including marine turtles exhibit temperature-dependent sex determination during egg incubation that could be influenced by changes and variability in global climates (Gibbons *et al*., 2000, Hawkes *et al.,* 2007). In green turtles for examples, higher temperatures lead to a predominance of females. The only breeding turtle population in Bermuda is that of the diamondback turtle; whether it is driven by temperature-dependent sex is not known at present.

Uphill migration is another predicted global response in reptiles and amphibians to increased temperatures. A study of 30 species of geckos, skinks, chameleons and frogs in Costa Rica, indicated an average shift uphill of 19 to 51 meters in a decade (Pound *et al*., 1999). When these results were compared with meteorological records and climate change simulations, the movement of animals could be linked to temperature increases of 0.1C to 0.37$^{o}$C over the same decade, corresponding to an expected upslope movement of 17 to 74 meters. Given Bermuda's limited vertical elevation, such shifts may not be possible. Bermuda's skink population is now confined to coastal locations, primarily isolated islets where there is little scope for such adaptive vertical shifts.

### *Changes in precipitation*

The timing of reproduction, metamorphosis, dispersal, and migration may change in response to changes in rainfall (Beebee, 1995), which may create a 'mis-match' with other ecological events such as emergence of insect prey. Additionally, species associated with shallow ponds (eg. the cane toad) may be particularly vulnerable to altered precipitation patterns. Waterlogging may cause cliff collapse and nest destruction in skinks.

### *Increasing storm activity*

The most significant impact of increased hurricane activity is likely to be in the destruction of habitat. This applies to both marine and terrestrial species. Photographs 13 and 14 below the damage done to known skink habitats (Southampton Island and Spittal Pond) by Hurricane Fabian in 2003. Southampton Island represents a crucial skink reserve and likely supports the largest remaining concentration of this critically endangered endemic (Davenport *et al*., 1997). A significant portion of the island was destroyed during this hurricane. Furthermore, a population assessment conducted in 2004 on the island revealed that the 2003 cohort was virtually missing; Hurricane Fabian hit the island right at the time the new hatchlings would have just started foraging for food (Glasspool and Outerbridge, 2005). There may also have been erosion of sand from their nesting burrows, or direct wash-out of eggs.

*Photograph 13 showing the impact of Hurricane Fabian on prime skink habitat on Southampton Island, and Photograph 14, at Spittal Pond.*

Meanwhile, storm damage to seagrass beds and coral reefs will affect the marine turtle populations in Bermuda, especially the green turtle and the hawksbill. There is already some concern that the significant die-off observed in Bermuda's offshore seagrasses (Murdoch *et al.*, 2007) may have driven the green turtle population inshore (Gray, pers. comm.). The native diamondback terrapin forages amongst the mangroves of Mangrove Lake and Trotts Pond (Thomas, 2004); whilst these mangroves are most sheltered from storm damage, any storm-driven impact on this habitat could affect the turtles.

***Table 26. Summary of impacts of climate change on Bermuda's reptiles and amphibians***

| CLIMATE CHANGE | IMPACTS ON REPTILES | IMPACTS ON AMPHIBIANS |
|---|---|---|
| Sea level rise | • Loss of habitat.<br>• Loss of nest sites.<br>• Erosion of sand from nests affecting breeding success.<br>• Wash-out of eggs from nests. | • Loss of habitat.<br>• Saltwater inundation of breeding areas. |
| More intense tropical storms | • Loss of nest sites.<br>• Erosion of sand from nests affecting breeding success.<br>• Drowning of hatchlings/eggs.<br>• Direct physical impact causing death | • Loss of habitat.<br>• Direct physical impact causing death. |
| Increasing temperature | • May advance/extend breeding season.<br>• Shifting in timing of reproduction, metamorphosis, dispersal etc. which may cause 'mis-match' in food availability.<br>• Physiological stress<br>• Upward land migration<br>• Changes in sex ratio in species with temperature dependent sex determination. | • May advance/extend breeding season.<br>• Shifting in timing of reproduction, metamorphosis, dispersal etc. which may cause 'mis-match' in food availability.<br>• Physiological stress.<br>• Upward land migration. |
| Heavier, less frequent rainfall events | • Waterlogging causing cliff collapse and nest destruction<br>• May drown nests | • May cause drowning. |

## 19.3 Mitigation and Adaptation Measures

The most obvious adaptive measures that can be undertaken to protect our reptilian and amphibian fauna are those that concentrate on reducing stress factors not associated with climate change including habitat loss, predation from invasives species, pollutions and toxins. Such actions would promote the greatest natural resilience in these species. Nature reserves both on land and in the marine environment spanning different habitat types to accommodate the various native and endemic species are critical. Particularly essential will be the creation of corridors and protected habitat that enable the terrestrial species to migrate vertically as coastal habitat is impacted. Ex-situ breeding of the endemic skink might also be prudent. More stringent policies and wider community education concerning the disposal of pollutants would be helpful as would more attention to culling of competitive invasive species (eg. the red eared slider terrapins and rats). Bermuda's inshore seagrass beds are experiencing increasing pressure from mooring placement, so protected areas as well as the promotion of safer boat handling practices might also go someway to safeguarding the marine turtle populations.

## 19.4 Acknowledgements

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