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# Cayman Islands Climate Change Evidence Report

**Report of Task 1:**

**Climate Change Risk Assessment (CCRA)**

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## Executive Summary

- The Cayman Islands Government (National Climate Change Committee) published a draft ‘Climate Change Policy’ in September 2011, aimed at facilitating the transition toward a climate-resilient, low-carbon economy. This ‘Climate Change Policy’ included a commitment to “Integrate hazard vulnerability and risk assessments into development planning processes and utilize environmental impact assessments (EIAs) to assist with decision making”.
- The present report commissioned by the Cayman Islands Government comprises the first step towards a systematic update for the (now decade old) National Climate Change Policy as well as providing key evidence ahead of a planned Climate Change Risk Assessment (CCRA) to be completed in summer 2022. The primary purpose was to generate a ‘long list’ of risks that can subsequently be scored and prioritised as part of the risk assessment process.
- This ‘evidence report’ draws on varied sources including, but not limited to, peer review scientific journals, technical reports, book chapters, monitoring datasets, IPCC model outputs, and public media communications. Systematic monitoring and local studies provide the most accurate characterisation of baseline conditions and trends, but in many cases, this level of detail was not available for the Cayman Islands.
- This ‘evidence report’ offers the most detailed assessment of climate change impacts ever undertaken for the Cayman Islands. Indeed, this is probably the most detailed assessment for any island group in the Caribbean.
- The datasets examined suggest that average annual air temperatures have increased by  $\sim 2.2^{\circ}\text{C}$  over the past 40 years in the Cayman Islands, at a rate of around  $0.06^{\circ}\text{C}$  per year. Similarly, for the period 1982-2016, Sea Surface Temperatures (SSTs) warmed at a rate of between  $0.01^{\circ}\text{C}$  and  $0.04^{\circ}\text{C}$  annually. Mean annual temperatures for the Cayman Islands are projected to increase in the future, irrespective of scenario, through to the end of the century.
- Historical records indicate that there is considerable variation in the rate of Sea Level Rise (SLR) throughout the Caribbean. Tide gauge data for South Sound (near George Town) suggest a rising trend of  $1.76 \pm 1.5$  mm/year. The dataset for North Sound (1976-2003) exhibited a rising trend of  $2.76 \pm 0.9$  mm/year that is closer to the Caribbean average of  $2.5 \pm 0.4$  mm/year and was closer to the Caribbean-wide average of  $2.5 \pm 0.4$  mm/year, with future SLR projections of 0.29 to 0.32 metres by the 2050s relative to 1986-2005.
- There is strong evidence for an increase in the frequency and intensity of tropical cyclones (hurricanes) since the 1970s in the North Atlantic. While it is likely that overall global frequency will either decrease or remain essentially unchanged in the future, it is more likely than not that strong hurricanes will become more commonplace.
- Rainfall data collected at the Owen Roberts International Airport suggest fewer, but more severe rain events in recent years. However, Global Climate Models (GCMs) suggest little change in annual rainfall for the Cayman Islands through to the 2080s, but a drying trend sets in toward the end of the century with up to 11% less total rainfall for the year under the most severe Representative Concentration Pathway (RCP) scenario (RCP8.5).
- Some natural habitats have received much more research attention than others, for example since 1997, the Cayman Islands Department of Environment (DOE) has systematically assessed coral health around the Cayman Islands, with ongoing surveillance of reef status at designated

sites as part of the Coral Watch programme. By contrast, very little is known about seagrass beds in the Cayman Islands, and even less about offshore and deep-water ecosystems that make up the bulk of the Cayman Islands' territory.

- Rises in sea temperatures together with other stressors including land run-off, clearance of mangroves, storm damage and disease have caused catastrophic increases in coral bleaching throughout the Caribbean. Recent data from the Cayman Islands specifically, show that coral cover has declined across all three islands, and that there has been a corresponding increase in algal cover in Grand Cayman and Cayman Brac.
- Since the early 2010s, mass strandings of *Sargassum* seaweed have occurred on Caribbean beaches including the Cayman Islands. The causes behind the recent increases are not fully understood, but are thought to be related to increased eutrophication and sea temperature increases in the wider Atlantic. In the future, *Sargassum* could be recycled for biofuel-making through anaerobic digestion to make biogas and/or fermentation to make bioethanol. As such, this could (eventually) represent one of the few 'opportunities' presented by climate change in the Cayman Islands.
- The Cayman Islands witnessed a six-fold increase in the number of Ciguatera fish poisoning (CFP) cases between 2002 and 2007 compared to 1996–2001, and this coincided with a 0.4–0.8°C positive temperature anomaly in the Caribbean during 2001–2005.
- Previous hurricanes in the Cayman Islands have flooded coastal mangroves, causing them to retreat or die-back in areas. Mangroves receded 7m in Little Sound in Grand Cayman after Hurricane Ivan (2004) and were drowned in Tarpon Lake in Little Cayman following Hurricane Gilbert (1988). Some of these have subsequently recovered, but the recovery can be slow.
- Periods of high temperatures already lead to incidences of heat stress in livestock, affecting both health and productivity. Future temperature rises are expected to lead to more frequent heat stress events, affecting both livestock and humans.
- Storm surges leading to land-surface inundation by marine over-wash can cause salinisation of coastal soils, aquifers and water bodies, particularly in low-lying areas. Freshwater lens contraction and soil salinisation can have serious negative consequences for terrestrial vegetation, as well as for freshwater ecosystems. Losses of seedlings due to salt spray and deposition on soils has been observed, and recondition of livestock pasture crops has been reported following storm surge over-wash associated with Hurricane Ivan.
- In many cases the only evidence available about past or present climate change impacts in the Cayman Islands relates to observations made following the passage of Hurricane Ivan in September 2004. Hurricane Ivan caused a reported CI\$2.86 billion (US\$3.4 billion) in damages in the Cayman Islands (183% of 2003 GDP). Whether or not it is safe to draw such inferences from a single event, or whether the occurrence/magnitude of Hurricane Ivan can be related back to long-term global warming remains a matter of conjecture.
- Settlements and urban centres along the coast and in low-lying inland areas already suffer damage from strong winds and flooding during storms. These effects are likely to worsen under future climate scenarios. Depending on the sea level rise projections considered, the inundation risk to built-up areas of the Cayman Islands ranges from 0.5% to 47%, with the worse-case scenario affecting not just residential properties but also educational and religious buildings on the majority of the West Bay peninsula, George Town, Bodden Town, and Cayman Kai on Grand Cayman, and the coastal and low-lying areas of Cayman Brac and Little Cayman.

- Opportunities raised by future climate change include a potential decrease in mosquito populations and associated illnesses (e.g. zika, dengue and chikungunya) as a result of increased aridity and reduced precipitation, however, the role of sporadic events (rainfall events/hurricane incidence/ drought occurrence) in the future remains uncertain. Indeed the potential for greater salinisation of water bodies may favour populations of the nuisance Black Salt-Marsh mosquito (*Aedes (Ochlerotatus) taeniorhynchus*) over species with lower salinity tolerances. Certain strains of harmful algae that are associated with ciguatera fish poisoning (CFP) might also become less prevalent.
- Fifty discrete risks were identified in the 'long list' (see section 5) of climate change risks (and opportunities) based on this evidence review. Twenty-two risks relate to biodiversity and habitats, and twenty-eight risks relate to economy and society. Many of the risks are highly relevant to all three islands, whereas some are more relevant to one of the islands than in the others (e.g., 'shortage of water for agriculture and irrigation', which is high for Grand Cayman, but 'low' for Little Cayman where very little agriculture is practiced).
- All risks have been categorised in terms of the level of agreement among researchers, as well as the level of evidence. An overall confidence score has been assigned based on this categorisation. Of the fifty-two risks included in the 'long list', eight were scored as having high confidence, twenty-two were scored as having medium confidence and nineteen were scored as low confidence.
- On the basis of this report and the initial 'long list' of climate change risks (and opportunities) (section 5 of this report), the next step was to convene a group of stakeholders and regional experts from the Cayman Islands (in May 2022) to score these risks in terms of 'proximity' (urgency) and 'magnitude' (seriousness).
- Following the expert workshop, risks were rationalised and additional evidence was sought (and added to this report) concerning pollinators and telecommunications. A final report will be produced (by October 2022) describing the risk-assessment process and containing the prioritised risks. This will take the form of a short summary document (8-12 pages) written for a broad non-technical audience.

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# 1 Introduction

While Caribbean countries and territories contribute less than 0.1% to global greenhouse gas (GHG) inventories, they will be amongst the earliest and worst affected by climate change impacts in the future. In the WGII report of the 6<sup>th</sup> Assessment (AR6) of the Intergovernmental Panel on Climate Change (IPCC), published in February 2022 it was concluded that ‘Small islands are increasingly affected by increases in temperature, the growing impacts of tropical cyclones (TCs), storm surges, droughts, changing precipitation patterns, sea-level rise (SLR), coral bleaching, and invasive species, all of which are already detectable across both natural and human systems’ (Mycoo et al., 2022).

In the present report we summarise observed evidence of climate change impacts in the Cayman Islands, a self-governing Overseas Territory (OT) of the United Kingdom (“the UK”), in the western Caribbean Sea. This report has been commissioned by the Cayman Islands Government, together with the UK Foreign, Commonwealth and Development Office (FCDO) team based in the Cayman Islands.

## 1.1 Cayman Islands – climate change policy context

The United Nations Framework Convention on Climate Change (UNFCCC) (“the Convention”) is an international environmental treaty that came into force on 19 March 1994. It was one key outcome of the 1992 Rio Earth Summit. The aim is to stabilise global levels of greenhouse gases that may cause deleterious anthropogenic changes to the Earth’s climate systems. At subsequent meetings since 1995, parties to the Convention have strengthened its provisions. In 1997, the Kyoto Protocol was agreed. This set legally binding emission reduction targets for greenhouse gases for signatory countries over the period 2008-2012. The 2010 conference in Cancún agreed that a limit of no greater than a 2°C rise in the Earth’s global average temperature above pre-industrial levels should be the aim of signatories to the Convention, with a further target of limiting the rise to 1.5°C. The Paris Agreement came into force on 4 November 2016. It crystallized the well below 2 degree Celsius goal and encouraged global pursuit of 1.5 degree Celsius from 2020 onwards (Article 2). The UK, as part of its obligations under the UNFCCC, must provide annual inventories of anthropogenic emissions by sources and removals by sinks of all GHG emissions not controlled by the Montreal Protocol, as well as outlining progress on mitigating climate change and preparing for adaptation, among other commitments. The UK must also report on behalf of Crown Dependencies and Overseas Territories, and this obligation has included the Cayman Islands since 7 March 2007. A second commitment period under the Kyoto Protocol (2013-2020) of legally binding QERLOs (quantified emission limitation and reduction objectives) for Annex B countries was negotiated under the Doha Amendment to the Kyoto Protocol, adopted 8 December 2012, this entered into force on 31 December 2020. The UK’s ratification of Doha was extended to the Cayman Islands on 14 December 2020.

A working group on adaptation to climate change (National Climate Change Adaptation Working Group), led by the Cayman Islands Department of Environment of the local government, was created in 2007 to develop a strategy for adaptation in the islands. The Cayman Islands Government’s National Climate Change Committee published a draft Climate Change Policy in September 2011 (Cayman Islands Government, 2011). This was the product of a three-year consultation convened under the Enhancing Capacity for Adaptation to Climate Change (ECACC) in the Caribbean Overseas Territories project, funded by the UK Department for International Development (DFID) with additional technical support provided by the Caribbean Community Climate Change Centre (CCCCC). The Policy was based on an extensive technical review contained in the Green Paper – Climate Change Issues for the Cayman Islands: Towards a Climate Change Policy (Hurlston-McKenzie, 2011), which was the most

comprehensive reference document to date on the potential implications of climate change for the Cayman Islands' economic, social and environmental sectors.

The Cayman Islands' Climate Change Policy (2011) outlined interventions required to address priority adverse impacts faced by the Islands. It included a high-level risk assessment, broadly comparable to that described in this report, whereby the risks, as perceived in 2009/2010 were ranked by national stakeholders. The bulk of the measures and action plan remained in the Green Paper for later adoption and implementation. Additionally, the Climate Change Policy contained suggested measures to curb GHG emissions from activities that contribute to the problem of continued climate change. The stated aim of the National Climate Change Policy was to foster, direct and enable an integrated, holistic, informative and participatory national process that will achieve low-carbon, climate-resilient development while protecting and enhancing our economic prosperity, livelihoods, human health, culture and environment for present and future generations.

This policy aimed to facilitate the transition to a climate-resilient, low-carbon economy by implementing measures that will:

- reduce GHG emissions, in line with agreed national targets, through promoting energy conservation, reducing energy use and encouraging greater use of renewable energy;
- enhance the resilience of existing critical infrastructure to climate change impacts, while avoiding the construction of new infrastructure in vulnerable areas or with materials prone to climate hazards;
- promote water conservation and improved rainwater harvesting while reducing impacts from flooding and enhancing the resilience of natural water resources;
- enhance the resilience and natural adaptive capacity of terrestrial, marine and coastal biodiversity and ecosystems;
- minimise the vulnerability of insured and mortgaged properties to climate change impacts;
- strengthen food security by promoting increased use of locally produced food products and appropriate technologies;
- and create and maintain a more environmentally responsible tourism industry while enhancing the resilience of tourism infrastructure and facilities to climate change impacts.

This policy was intended to guide the work of all governmental, statutory, private sector, non-governmental and civic entities, supporting the transition to climate-resilient low-carbon development in the Cayman Islands (Cayman Islands Government, 2011).

## 1.2 Cayman Islands – geographical context

The Cayman Islands are located in the western Caribbean Sea to the south of Cuba, and comprise the three islands of Grand Cayman, Cayman Brac and Little Cayman (Figure 1). The Cayman Islands are considered to fall within the Western Caribbean Zone and to be part of the Greater Antilles. They comprise the peaks of an undersea mountain range called the Cayman Ridge (or Cayman Rise). This ridge flanks the Cayman Trough, a seabed depression 7,686 m deep which lies 6 km to the south.

Grand Cayman (at 196 km<sup>2</sup>) encompasses 76% of the territory's entire land mass. The island is approximately 35 km long with its widest point being 13 km wide. The elevation ranges from sea level to 18m maximum above sea level on the North Side's Mastic Trail (Figure 2).

Grand Cayman's two "Sister Islands", Cayman Brac and Little Cayman, are about 120 km east north-east of Grand Cayman and have areas of 38 and 28.5 km<sup>2</sup> respectively. All three islands are mostly flat and were formed by coral accretion on top of submerged peaks (i.e., western extensions of the

Cuban Sierra Maestra range). One notable exception to this is 'The Bluff' on Cayman Brac's eastern part, which rises to 43 m above sea level, the highest point on the islands.

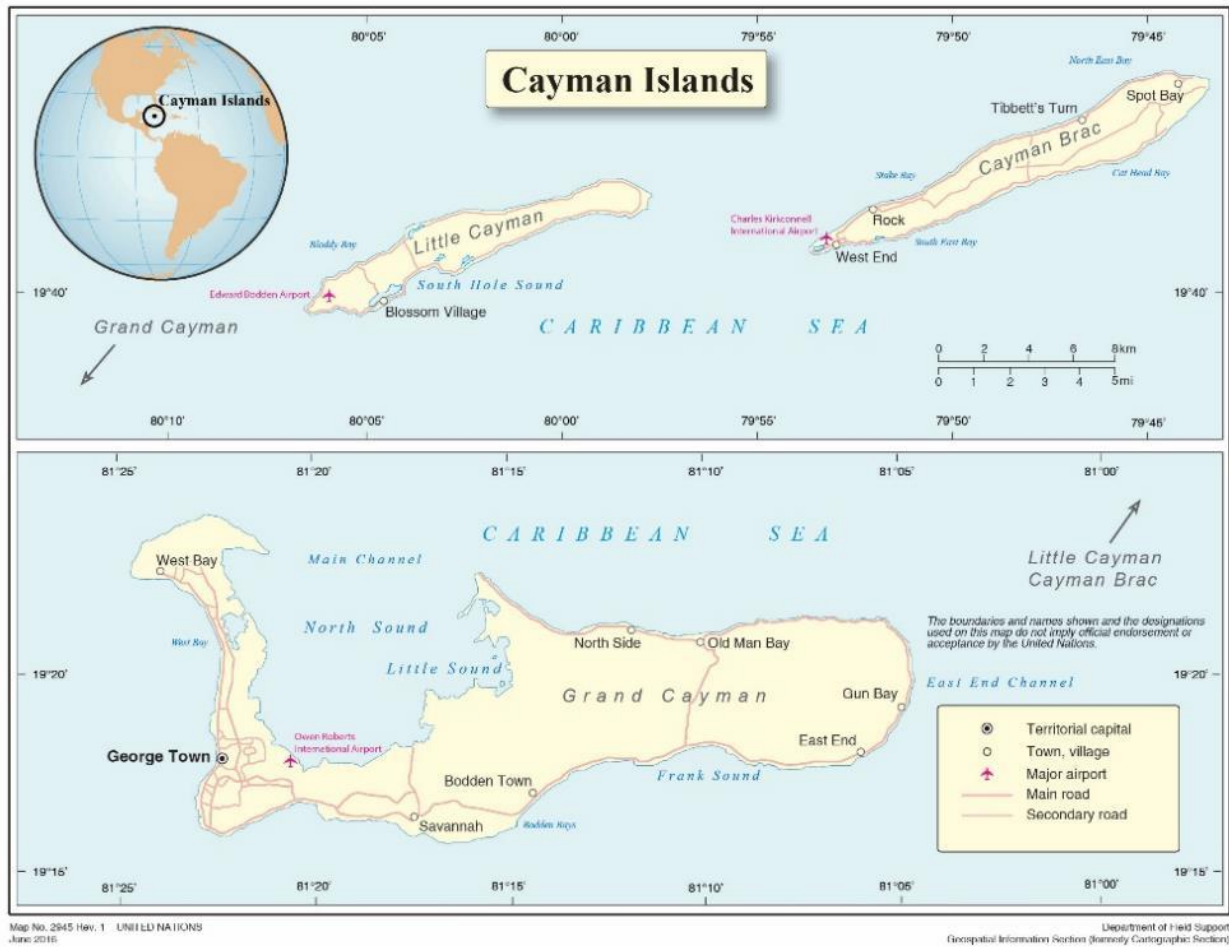
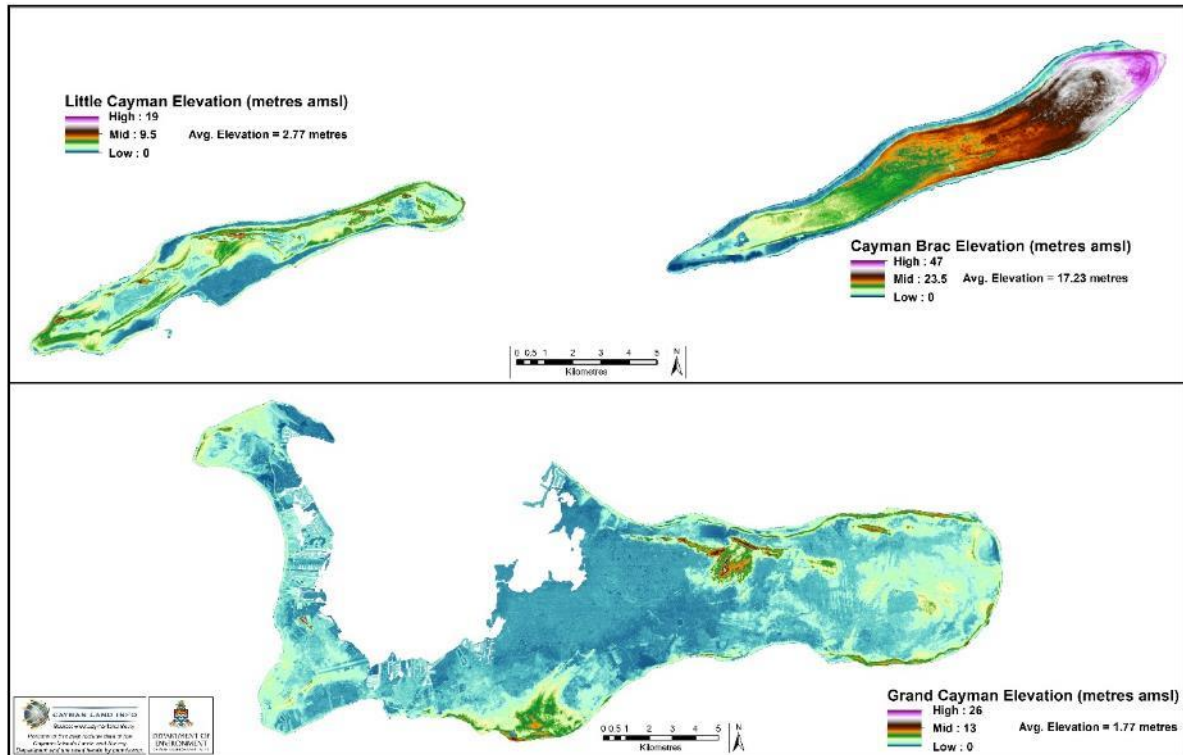


Figure 1. Outline map of the Cayman Islands.

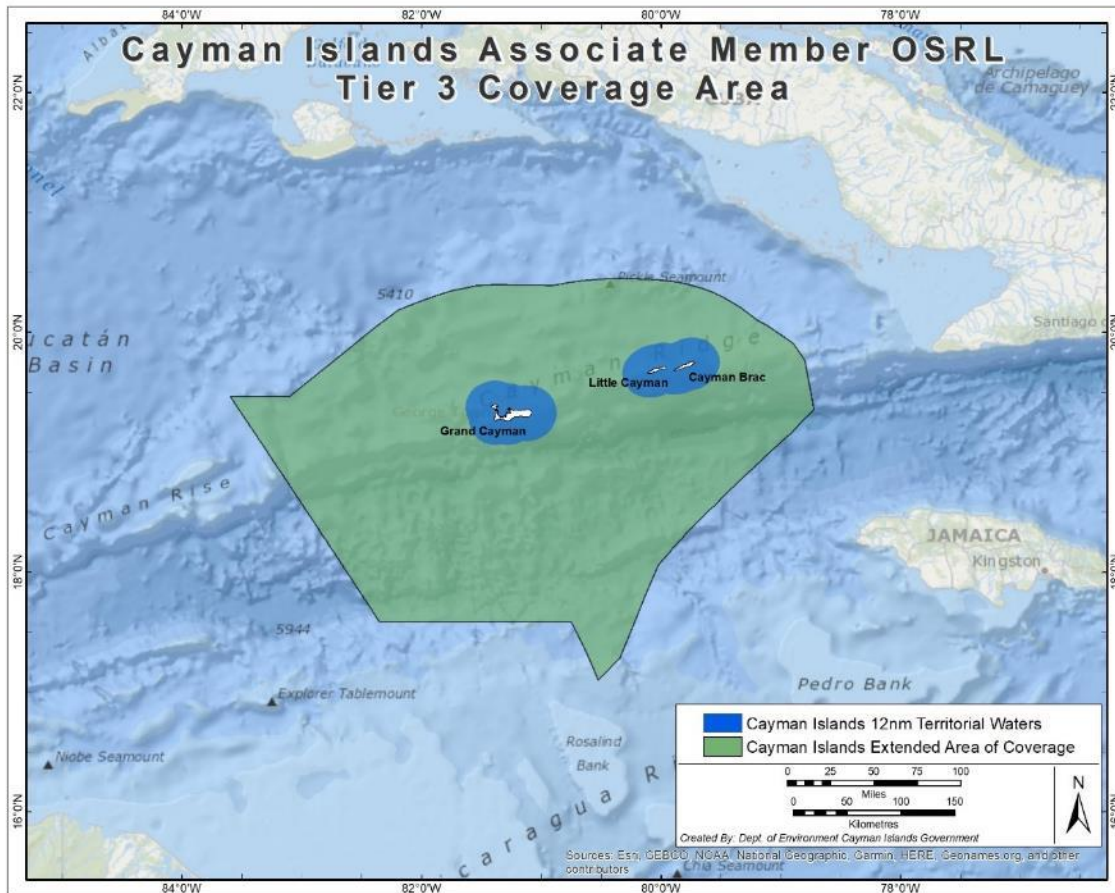


**Figure 2.** Elevation of the Cayman Islands. Source: Lands & Survey Department, map produced by Department of Environment (2022)

The Cayman Islands have a tropical wet and dry climate. Rainfall in the Cayman Islands has a bimodal ('double peak') pattern over the course of the year, with an early rainfall season occurring in May-June and a late rainfall season centered in October.

Seasonally, there is little temperature change. A major natural hazard is tropical cyclones that form during the Atlantic hurricane season from June to November. On 11 and 12 September 2004, Hurricane Ivan (known locally as 'Ivan the Terrible') struck the Cayman Islands. The storm resulted in two deaths and caused great damage to the infrastructure on the islands (ECLAC, 2004).

Rather than considering the Cayman Islands as a "small island state," it might be more accurate to consider it as a "large ocean state" (LOS), recognising the central role that the ocean plays in the Cayman Islands' development (Hume et al., 2021). The Exclusive Economic Zone covers 119,023 km<sup>2</sup>, and as such, exceeds the total land area by 450 times (Figure 3). Cayman territorial waters comprise 5,875 km<sup>2</sup> (DaCosta-Cottam et al., 2009).



**Figure 3.** The Exclusive Economic Zone (EEZ, shaded green) and Territorial Waters (shaded dark blue) of the Cayman Islands.

According to the Economics and Statistics Office of the Government of the Cayman Islands, the Cayman Islands had a population of 69,565 as of fall 2021. The population has doubled in less than 20 years. The majority (98%) of the population resides on Grand Cayman (64,083 residents) followed by Cayman Brac and Little Cayman (1,703 residents, 2%). Approximately half of the population (34,789 residents) lives in the capital city George Town, located at the western end of Grand Cayman. The islands cannot produce enough food and consumer goods to support the population, hence 90% of food must be imported. In addition, the islands have few natural freshwater resources. Desalination of sea water is used to solve this. Despite those challenges, the inhabitants of the Cayman Islands enjoy one of the highest standards of living in the world.

Finance and tourism are commonly identified as the two supporting pillars of the Cayman Islands economy. Financial and insurance services dominate the economy (32.3% of GDP in 2019). More than 65,000 companies were registered in the Cayman Islands as of 2017, including more than 280 banks, 700 insurers, and 10,500 mutual funds. The tourist industry is aimed primarily at the luxury market and caters mainly to visitors from North America. Total tourist arrivals exceeded 2.3 million in 2019. Fishing and agriculture represent a very minor part of the economy (0.4% of GDP in 2019).



### 1.3 Purpose and scope of this report

This report comprises the first task towards a systematic Climate Change Risk Assessment (CCRA) for the Cayman Islands, and a first step in updating the (now decade old) National Climate Change Policy and Strategy for the islands (Cayman Islands Government, 2011). The Cayman Islands 'Climate Change Policy' published in September 2011 included a commitment that the Government of the Cayman Islands will 'Integrate hazard vulnerability and risk assessments into development planning processes and utilize environmental impact assessments (EIAs) to assist with decision making.'

According to Governor Martyn Roper, 'This [project] forms part of the UK/Cayman Climate Change/Environment Partnership Agreement which allows for collaboration in areas such as biodiversity, disaster resilience and renewable energy.'

'The report will describe the current available knowledge on climate change impact risks that pose the greatest threats to communities and sectors in the Cayman Islands, such as fisheries, tourism, coastal infrastructure, agriculture, settlements and inland infrastructure, to identify an initial 'long-list' of risks and/or opportunities.'

The risk assessment methodology used in the present analysis was informed by the first UK Climate Change Risk Assessment (CCRA) carried out in 2012 (CCRA, 2012), which has subsequently guided a specific simplified marine climate assessment for the UK seafood industry (Garrett et al., 2015), a climate change risk assessment carried out within the United Arab Emirates (MOCCAE, 2019), and a regional risk assessment of marine climate change risks to biodiversity and society in the Arabian Gulf region (Maltby et al., 2022). This report was drafted by a panel of experts from the Centre for Environment, Fisheries and Aquaculture Science (Cefas), an executive agency of the UK Department for Environment, Food and Rural Affairs (Defra) specialising in marine research and resource management, together with the UK Centre for Ecology and Hydrology (UKCEH), an independent, not-for-profit research institute and strategic delivery partner for the Natural Environment Research Council (NERC), part of UK Research and Innovation (UKRI) that conducts environmental research across water, land and air.

To prepare this review, the authors have made use of quantitative and qualitative information at a variety of spatial scales, from detailed local studies through to global trend analyses. Firstly, this review describes the observed and predicted changes in meteorological or oceanographic conditions of the Cayman Islands. Next, observed and predicted climate-driven changes in terrestrial, freshwater, marine and coastal biodiversity are reviewed, followed by an assessment of potential impacts on human systems. Finally, the report concludes with a 'long-list' of collated climate change risks to the Cayman Islands and by identifying key evidence gaps.





When determining the scope for this evidence report, it was agreed that impacts on banking, insurance and other parts of the financial services sector would not be considered, as this topic would require specialist knowledge that is beyond the expertise of Cefas and UKCEH. Climate change poses a major risk to the global economy; it affects the wealth of societies, the availability of resources, the price of energy and the value of companies. Several existing reports do examine the possible impact of climate change on the global financial services sector, most notably a report by Allianz Group and WWF in 2005 (Allianz Group/WWF 2005).

### 1.4 Data sources and method

This report for the Cayman Islands Government has made use of information about climate change and climate change impacts from varied sources including, but not limited to, peer review scientific journals, technical reports, book chapters, monitoring datasets, IPCC model outputs, and public media communications. The types of evidence can be categorised according to increasing geographical scale,

from site-specific monitoring/surveillance programmes and local research studies, to regional overviews and global studies (Table 1). In the present report we have made use of this categorisation, to indicate (using a series of icons) the types of evidence available for each sub-section. For example, the ‘coral reefs’ section has been able to draw on a wealth of different sources, including systematic surveys of reefs around all three islands every few years as well as regional and global modelling studies. By contrast, the ‘deep sea and offshore environments’ section was only able to call on inferences from global-scale model outputs and studies.

**Table 1:** Categories of data used in this report.

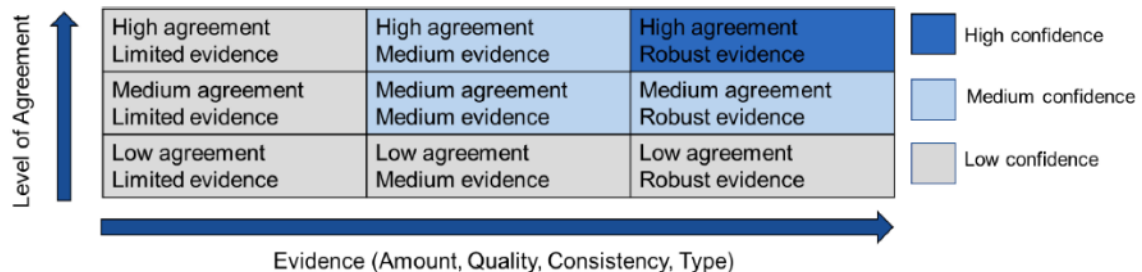
Data Type (and icon)	Description	Example
 <b>SITE-SPECIFIC STUDIES</b>	Time-series of site-specific data collected for monitoring status and trends of ecosystem components	Outputs from tide gauges and weather stations: four tide gauge stations have been installed across all three Cayman Islands to collect data on sea levels (Gun Bay Public Dock in East End, Royal Watler Cruise Terminal in George Town, Creek Dock in Cayman Brac, and Bloody Bay Dock in Little Cayman).
 <b>LOCAL STUDIES</b>	Research studies and surveys conducted within the Cayman Islands that provide information and understanding on the impact of climate change on ecosystem components	Local-scale studies of coral bleaching and climate change impacts on Little Cayman (ongoing CCMI reef surveys)
 <b>REGIONAL STUDIES</b>	Monitoring or research studies that do not come from the Cayman Islands specifically but from the wider Caribbean region	Regional modelling studies on observed and projected trends in temperature, salinity, and sea-level
 <b>GLOBAL STUDIES</b>	Studies conducted Internationally that identify trends that can be used to broadly evaluate changes in the Cayman Islands	IPCC assessments based on global climate models.

Systematic monitoring and local studies provide the most accurate characterisation of baseline conditions and trends, but in many cases, this level of detail was not readily available for the Cayman Islands. Given that the main purpose of this evidence report was to generate a ‘long list’ of risks that can be scored and prioritised as part of a systematic risk assessment (see above), it was necessary to gather even very anecdotal information about ‘known un-knowns’, since poorly studied risks could pose a significant threat to the islands when considered in terms of ‘magnitude’ and/or ‘urgency’.

Particularly useful sources when considering climate change impacts in the Cayman Islands included: (a) the State of the Caribbean Climate (SOCC) report published in 2020 (MONA, 2020); (b) the Climate Profile for the Cayman Islands modelling report published in 2014 (MONA 2014); (c) the Commonwealth Marine Economies Programme: Caribbean Marine Climate Change Report Card published in 2017 (Commonwealth Marine Economies Programme 2017); and (d) the 2021 climate change report card produced by the Marine Climate Change Impacts Partnership (MCCIP) for UK Overseas Territories in the Caribbean and Mid-Atlantic (Murray et al. 2021).

Given the very different geographic and land-use characteristics of the three islands (Grand Cayman, Cayman Brac and Little Cayman), the authors were asked to judge (on a scale of high, medium, low) whether the particular topic was of relevance to each island. Some industries or habitats are only present on one of the three islands, and thus any climate change impacts would be pertinent at the scale of only one island (relatively localised). For example agriculture is largely absent from Little Cayman. In other cases, threats are more ubiquitous and thus climate impacts would be relevant

across the entire Overseas Territory and all three of the islands. Risks were also assigned a confidence rating to reflect the level of agreement among researchers and across evidence sources, as well as the level of evidence for the impacts associated with each risk. The confidence levels assigned were based on the scheme used by the IPCC (Mastrandrea et al., 2011), whereby authors were asked to select what they viewed as the most appropriate answer from a 9-cell grid (Figure 4).



**Figure 4.** IPCC matrix used for qualitative scoring of confidence associated with each risk. Adapted from Mastrandrea et al. (2011).

From the text of each section in this evidence report the authors have assembled a **‘long list’ of climate risks (and opportunities) facing the Cayman Islands**. It is important to note that several distinct risks may be associated with a single habitat or economic sector (e.g., risks to fisheries associated with coral reefs and inshore habitats, versus risks to offshore pelagic fisheries or those in deep water). Where possible, these have been pulled out and identified separately.

Collation of this evidence report, and the associated ‘long list’ of risks, comprises the first task of a systematic **Climate Change Risk Assessment**. The next step in the process (in Phase 2 of this project) will be to convene a workshop of stakeholders and experts from the Cayman Islands (in May 2022) to:

- Refine and rationalise the ‘long list’ of climate change risks ahead of scoring and prioritisation.
- Identify the primary climate drivers associated with each risk to ecosystems or society.
- Score each risk in terms of ‘proximity’ (urgency). Proximity indicates the time horizon after which substantial impacts are anticipated to be felt (i.e., ranging between 1, likely to occur in the more distant future (50 years +), and 4, already happening now).
- Score each risk in terms of ‘magnitude’ (seriousness). Magnitude scores were based on the perceived significance and consequences of a particular risk happening, based on an assessment of combined environmental, economic and social impacts.
- Collate the scores to provide a ranked list of most serious climate change threats to the Cayman Islands (both collectively and for each individual island).

## 2 Observed and projected trends in climate variables

A number of key sources are available when considering trends in climate variables for the Cayman Islands; these include observations from meteorological stations and tide gauges throughout the islands, but also previous collations of climatic datasets, most notably:

1. Climate and Weather Assessment for the Cayman Islands (2011). Appendix 2 of the National Climate Assessment. [includes outputs from the Hadley PRECIS Regional Climate Model (RCM)] (NCA, 2011)
2. Climate Profile for the Cayman Islands: Variability, Trends and Projections (2014), produced by the Climate Studies Group Mona, University of the West Indies. [includes some weather station data and future projections] (MONA, 2014)
3. The State of the Caribbean Climate (SOCC) report (2020) produced by the Climate Studies Group Mona, University of the West Indies. [includes some weather station data and future projections] (MONA, 2020)
4. Caribbean Weather Impacts Group (CARIWIG) online climate change portal. [includes historic data (for Grand Cayman) and projections at 25 km resolution.]
5. NOAA's Climate Change Web Portal (2021) - CMIP5 and CMIP6 projections (1 degree resolution) for many different variables.
6. NOAA Historical Hurricane Tracks portal (2018). [150 years of hurricane data] <https://oceanservice.noaa.gov/news/historical-hurricanes/>
7. IPCC Sixth Assessment Report, Climate Change 2021: The Physical Science Basis. Published in August 2021. [in particular section TS.4.3.2.7 Small Islands (page TS-96)]
8. IPCC Special Report on Global Warming of 1.5°C (2018). [in particular chapter 3 – impacts on natural and human systems]

The National Weather Service operates several meteorological stations throughout the islands, most notably at Owen Roberts International Airport (Grand Cayman), Charles Kirkconnell International Airport (Cayman Brac), and Edward Bodden Airfield (Little Cayman). Four new tide gauge stations have recently been installed to collect data on sea levels (Gun Bay Public Dock in East End, the Royal Watler Cruise Terminal in George Town, the Creek Dock in Cayman Brac, and at Bloody Bay Dock in Little Cayman), with previous long-serving tide gauges employed at South Sound (George Town), and North Sound – both in Grand Cayman.

The Central Caribbean Marine Institute's Little Cayman Research Centre hosts the region's only permanently moored oceanographic monitoring station. The Coral Reef Early Warning System (CREWS) was conceived by the US National Oceanic and Atmospheric Administration (NOAA) to continuously measure ocean conditions, and has been in place off Little Cayman since 2009. The CREWS buoy continually collects information about weather and marine conditions and transmits these data in real-time to NOAA for integration and analysis, while also being made available online to researchers, policy-makers, and to the public.

### 2.1 Air and sea temperature

#### *Current climate impacts*

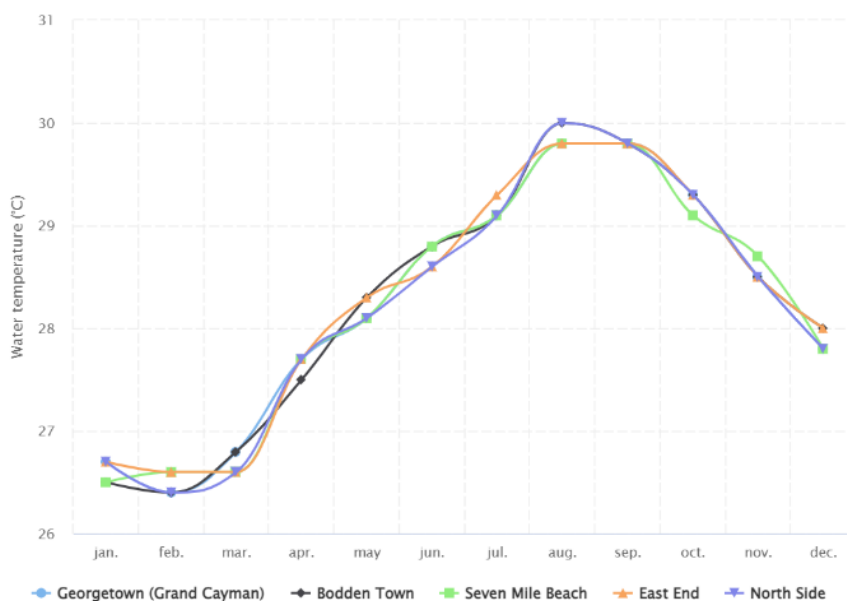
Several reports have characterised air and sea temperature change in the Cayman Islands. Notably the National Climate Assessment (2011) included an initial investigation of observed air temperatures recorded by the National Weather Service at the Owen Roberts International Airport between 1971 and 2009. This analysis revealed an increase in annual average air temperature from approximately 26.3°C in 1971 to 28.5°C in 2009. This is an increase of 2.2°C in 39 years or 0.06°C per year. Annual average minimum temperatures appeared to increase more markedly than average maximum

temperatures and rose from 22.3°C in 1971 to 25.2°C in 2009. This is an increase of 2.9°C in 39 years or 0.07°C per year, compared to only 0.01°C per year for average maximum temperatures (NCA 2011).

A similar exercise, using the same dataset was carried out by the MONA group at the University of the West Indies spanning the period 1982-2010 (MONA, 2014). When calculated for this shorter time period, minimum temperatures were observed to be increasing faster (~0.16°C/decade) than maximum temperatures (~0.50°C/decade). Using annual means over 1976 and 2010, the calculated rates of increase were much smaller but reflect the same pattern of a decrease in daily temperature range. The occurrences of ‘hot’ days and ‘hot’ nights have increased, whereas those of ‘cold’ nights have decreased (MONA, 2014).

The SOCC report provides air temperature time series at the regional scale spanning the period 1900 to 2014. This study detected a strong linear warming trend of approximately 0.09°C/decade for the Caribbean as a whole, which is statistically significant and is consistent with other studies that have similarly noted a dominant linear trend in the temperature records of the region (Jones et al., 2015; Stephenson et al., 2014). The Cayman Islands are located towards the southern edge of ‘Zone 2’ in this report; this zone exhibited a less clear warming trend compared to other zones in the Caribbean, with considerable inter-annual variability.

Trends in Sea Surface Temperature (SST) are less clear, given that monitoring stations have been in place for a much shorter period of time. Figure 5 shows average monthly sea water temperatures from five monitoring stations around Grand Cayman. Temperatures reach a high of around 30.1°C in August but a low of 26.3°C in February and are remarkably similar irrespective of the location (figure 5).



**Figure 5.** Average monthly sea surface temperature (SST) for five monitoring sites around Grand Cayman. Source: NOAA portal <https://www.seatemperature.org/central-america/cayman-islands/>

According to the SOCC report (MONA, 2020), over the period 1982-2016, SSTs have warmed at a rate of between 0.01°C and 0.04°C annually across the Caribbean Region. Higher rates of warming can be observed in the Gulf of Mexico and the eastern Caribbean, whereas for the Cayman Islands, the warming trend is between 0.01°C and 0.02°C annually.

Booker et al. (2019) used core samples from large corals around Grand Cayman and Cayman Brac to reconstruct trends in SST over the last ~540 years. Paleotemperatures were derived from the oxygen isotope composition of annual bands within these corals. An overall 3°C ± 0.96°C increase in SST was

detected since 1815, and this is consistent with the Caribbean and global temperature increases reported since the 1850s. Smaller scale deviations in the Cayman temperature profiles from the general Caribbean/global temperature trends probably reflect local factors, such as increased storminess and/or cold-air front frequencies, a reduction in the size and/or intensity of the Atlantic Warm Pool, shifts in the phase of the Atlantic Multidecadal Oscillation (AMO), and/or weakening of the Cayman Basin current (Booker et al., 2019).

### *Expected future climate impacts*

The National Climate Assessment (2011) included outputs for future climate of the Cayman Islands using the Hadley PRECIS Regional Climate Model (RCM), forced by the HADCM3 and ECHAM4 Global Climate Model (GCM) at a resolution of 50 km. These projections were improved upon in the MONA (2014) study, again using the PRECIS model (as well as a Global Climate Model), but with a resolution of 25 km.

Based on Global Climate Models (GCMs), mean annual temperatures for the Cayman Islands are projected to increase, irrespective of scenario, through to the end of the century (Table 2 & Figure 6). Mean temperature increase will be 0.42-2.25°C for 2041-2060 and 0.07-4.23°C for 2081-2100. Increases will be of similar magnitude for maximum temperatures and minimum temperatures (Figure 6). The RCM results suggest similar magnitude increases in the near term (2030s). Annual mean temperature increases range from 0.8-1.4°C under an A1B (medium emissions) scenario. The magnitude of change is similar for minimum and maximum temperatures. ‘Cool days’ and ‘cool nights’ disappear by mid-century for the summer months. There are no ‘cool days’ or ‘cool nights’ between May and November by mid-century (2046-2065), where ‘cool’ is in reference to the present climate. ‘Hot days’ and ‘hot nights’ increase in frequency by mid-century for the summer months. By mid-century (2046-2065), there are approximately 30 ‘hot days’ and 30 ‘hot nights’ in every month between July and October (i.e. every day for the respective months), where ‘hot’ is in reference to the present climate.

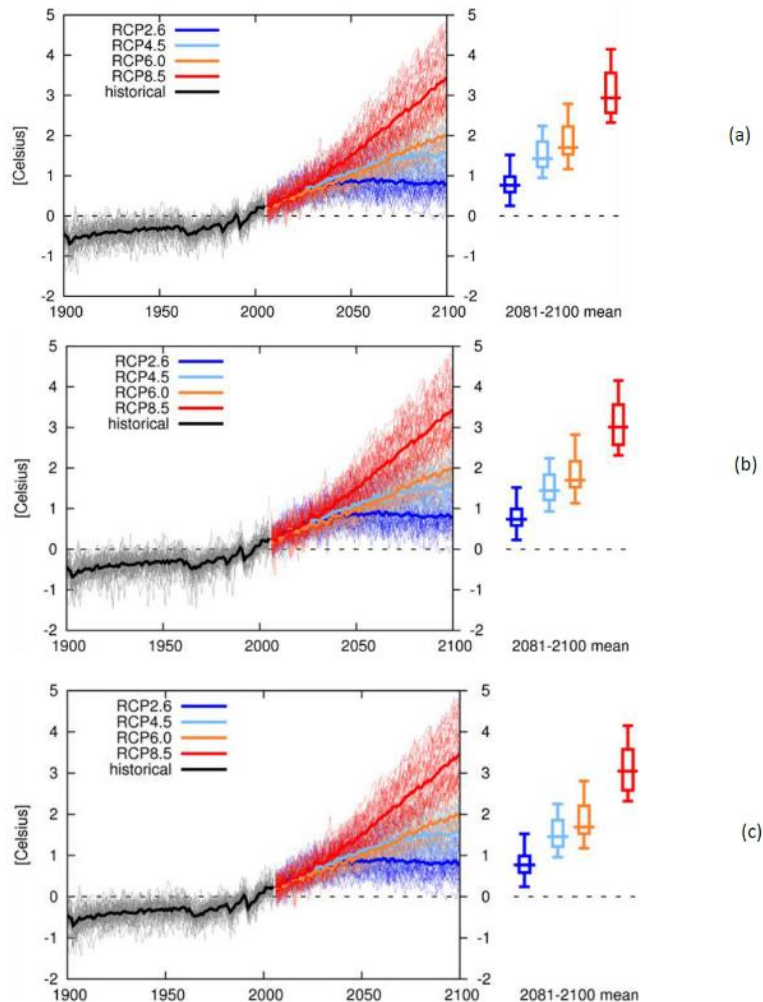
**Table 2.** Mean annual air temperature change (°C) for the Cayman Islands with respect to 1986-2005 AR5 CMIP5 subset. Change shown for four Representative Concentration Pathway (RCP) scenarios.

Tmean	2021-2040			2041-2060			2061-2080			2081-2100		
	min	mean	max	min	mean	max	min	mean	max	min	mean	max
rcp26	0.39	0.69	1.16	0.42	0.86	1.55	0.34	0.86	1.67	0.07	0.81	1.64
rcp45	0.37	0.74	1.22	0.57	1.11	1.77	0.78	1.40	2.27	0.81	1.53	2.47
rcp60	0.41	0.66	1.10	0.72	1.01	1.61	0.98	1.44	2.18	1.13	1.86	2.87
rcp85	0.49	0.86	1.30	0.95	1.54	2.25	1.60	2.32	3.26	2.12	3.09	4.23
<b>Range:</b>	0.37-1.30			0.42-2.25			0.34-3.26			0.07-4.23		

The Representative Concentration Pathways (RCPs) describe four different 21st century pathways of GHG emissions and atmospheric concentrations, air pollutant emissions and land use. The RCPs represent the range of GHG emissions in the wider literature well; they include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and one scenario with very high GHG emissions (RCP8.5).

The RCMs suggest that all zones will warm going toward the end of the century. The levels of warming as projected by RCMs are slightly higher than projected by the Global Climate Models (GCMs). The far western Caribbean (Zone 1) and the southern Caribbean (Zone 6) show slightly higher warming than

the rest of the region running the A1B (medium emissions) scenario. Zone 2, which includes the Cayman Islands, is anticipated to witness a 1.57 – 2.40°C temperature rise by the 2050s (relative to the baseline period 1961-1990) and 2.53 – 3.72°C rise by end-of-century (MONA, 2020).



**Figure 6.** (a) Mean annual temperature change (°C), (b) mean annual minimum temperature change (°C), (c) mean annual maximum temperature change (°C) for Cayman Islands with respect to 1986-2005 AR5 CMIP5 subset. On the left, for each scenario one line per model is shown plus the multi-model mean, on the right percentiles of the whole dataset: the box extends from 25% to 75%, the whiskers from 5% to 95% and the horizontal line denotes the median (50%).

With regard to future projections for seawater temperature (SST) around the Cayman Islands, there is a general lack of high-resolution downscaled climate model outputs. Recent, but low spatial resolution outputs (1° latitude by 1° longitude grid) can be obtained from NOAA's Climate Change Web Portal - CMIP6 ensemble of models. These outputs suggest that in 2070-2090, sea surface temperatures around the Cayman Islands could increase by >2.5°C compared to the historic reference period of 1985-2014, under either an SSP5-8.5 (very high emissions) or SSP3-7.0 (high emissions) scenario.

### Scoring

Site-based monitoring studies + Regional studies. High agreement, medium evidence.

## 2.2 Sea level rise (SLR)

### *Current climate impacts*

Both the SOCC report (MONA, 2020) and the “Climate Profile for the Cayman Islands” (MONA, 2014) include sections on sea level rise (SLR). There is an increasing trend in the sea level of the Caribbean Region more generally. A regional rate of increase of  $1.8 \pm 0.1$  mm/year was recorded between 1950 and 2009 (MONA, 2020). Larger sea level increases have been observed for the post 2000 period during which hurricane intensity and sea level interannual variability have both increased (MONA, 2020). Torres and Tsimplis (2013) determined the rate of sea level rise to be  $1.7 \pm 1.3$  mm/year over the period 1993-2010. These rates are similar to the global rate of  $1.7 \pm 0.2$  mm/year. As measured by satellite altimetry and corrected for Global Isostatic Adjustment, the mean Caribbean sea level trend is estimated to be approximately  $2.5 \pm 0.4$  mm/year (Torres & Tsimplis, 2013).

Historical records indicate that there is regional variation in the rate of sea level rise (i.e., this is not uniform across the whole Caribbean) (Figure 8). The rate of sea level rise varies from 0.26 mm/year off the coast of Venezuela, to 10.76 mm/year for the Port-au-Prince, Haiti station. Interannual variations are evident in the time series plots. Caribbean sea level is highly correlated with El Niño-Southern Oscillation (ENSO), especially since the mid-1980s, with larger increases in sea levels occurring during stronger El Niño events (Blunden & Arndt, 2016; Palanisamy et al., 2012; Torres & Tsimplis, 2014). This may have led to sea levels reaching as high as 11.3 cm above mean sea level during the 2015 El Niño event. Recent studies showed a significant correlation between the interannual variability in sea level and hurricane activity (Torres & Tsimplis, 2014). Palanisamy et al. (2012) observed interannual sea-level variability to be higher in the north Caribbean (including the Cayman Islands) than in the south Caribbean, and strongly correlated with El Niño. Becker et al. (2019) provided an update of the study by Palanisamy et al. (2012) over the 1960–2014 period, and again detected strong positive sea level rise trends throughout the Caribbean, of about 2.5–3.0 mm/year.



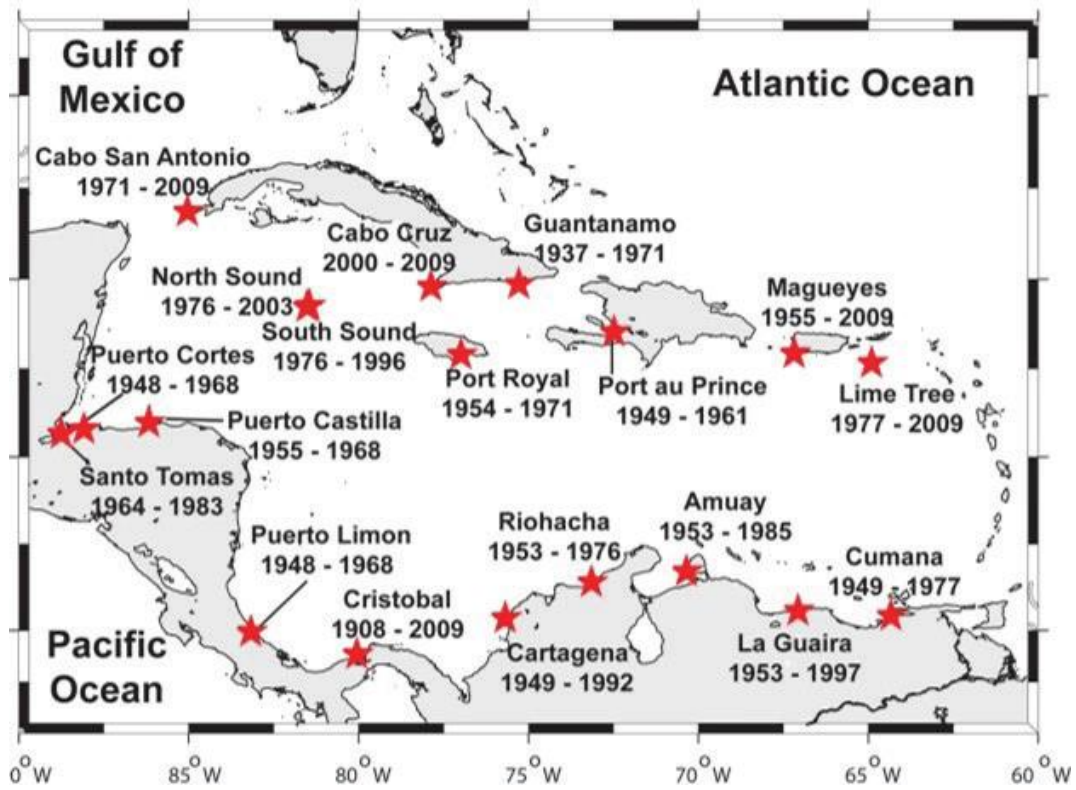
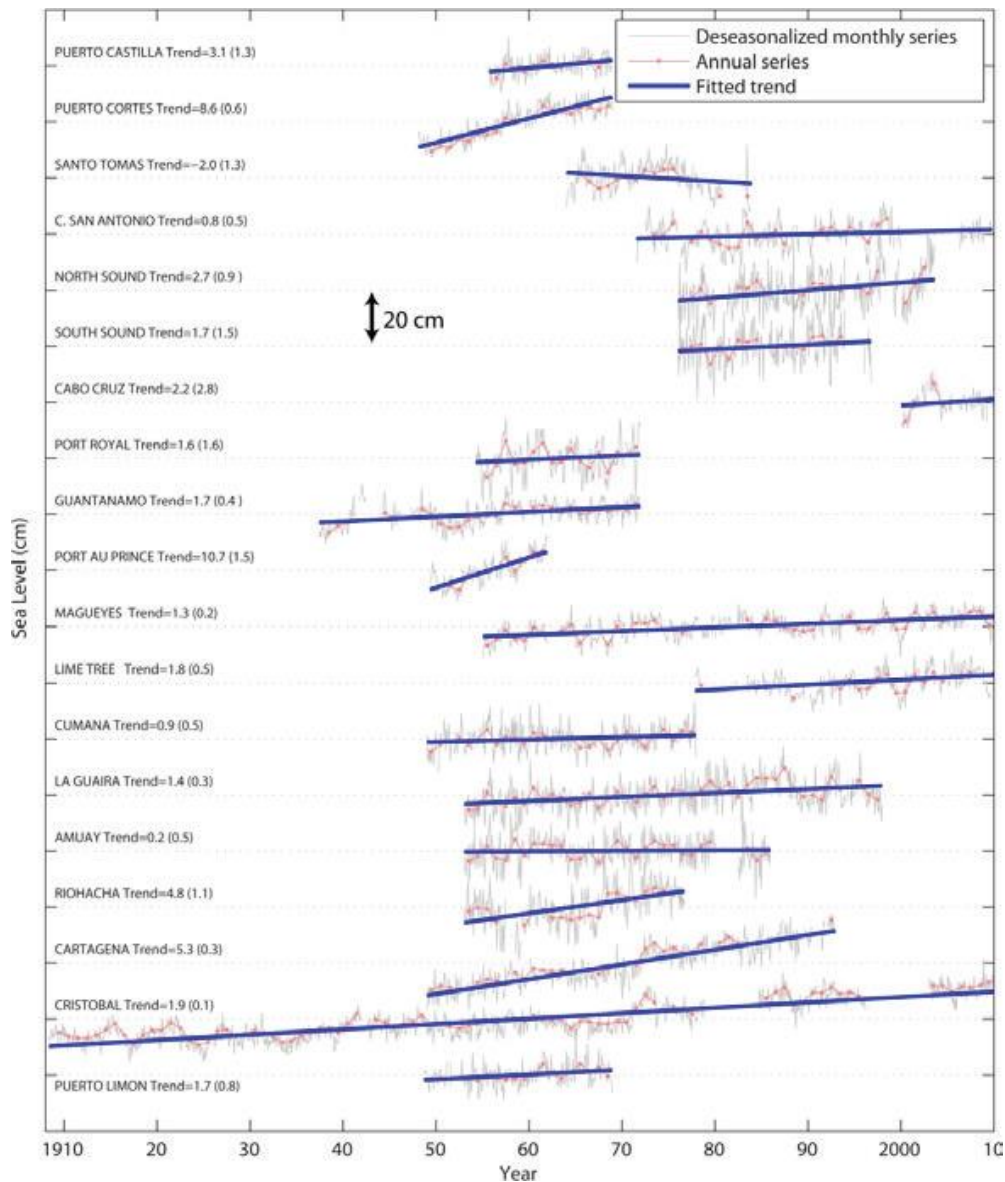


Figure 7. Locations of tide gauge stations and time series start and end years. Source: MONA (2020).



**Figure 8.** Tide gauge observed sea-level trends in the Caribbean. Monthly time series after the removal of the seasonal cycle (grey), linear trends across each time series (blue), and annual averages (red) are also shown. For each trend line, values indicate the mean (with 95% CI) annual rise in sea level (in mm/year). Source: MONA (2020).

Tide gauge coverage in the Caribbean islands (Figures 7 & 8) is poor with only 7 gauges having data >30 years duration between 1950 and 2009. All time series suggest upward trends in sea level over the periods where records are available. The Cayman Islands are represented by two gauges in the long term historical record (North Sound and South Sound), both on Grand Cayman. The trend for each station is not statistically different from the basin-wide trend. The available dataset (Torres & Tsimplis, 2013) for South Sound (near George Town) covered a 21 year period (1972-1996) and exhibited a rising trend of around  $1.76 \pm 1.5$  mm/year. The dataset for North Sound covered a 28 year period (1976-2003) and exhibited a rising trend of around  $2.76 \pm 0.9$  mm/year.

### *Expected future climate impacts*

Detailed projections of sea level rise are not currently available for the Cayman Islands, and hence previous reports (e.g. MONA 2014, MONA 2020) have tended to cite regional or global studies. Table 3 provides a range of estimates for end-of-century sea level rise globally and in the Caribbean Sea specifically under a number of scenarios. The values are taken from the IPCC's Fourth, Fifth and Sixth Assessment Reports (IPCC 2007, IPCC 2013, IPCC 2021). Future sea level rise projected for the Caribbean is not significantly different from the projected global rise. The combined range of sea level rise projections, across all scenarios, spans 0.18-1.01 m by 2100 relative to 1980-1999 levels. However, several other studies (Horton et al., 2008; Rahmstorf, 2007; Rignot & Kanargaratnam, 2006) suggest that the upper bounds for the global estimates are possibly an underestimate.

**Table 3.** Projections of global and Caribbean-specific mean sea level rise (m). Note that AR4 SLR values (IPCC 2007) are relative to 1980 – 1999, but that AR5 (IPCC 2013) and AR6 (IPCC 2021) SLR values are relative to 1986-2005, and that IDB SLR values are relative to the year 2000. Within the Caribbean, Zone 2 refers to the region that includes the Cayman Islands.

Source	Emissions scenario	Global sea level rise by 2100 (m)	Caribbean-specific sea level rise by 2100
IPCC AR4 (2007)	B1	0.18 – 0.38	0.13 – 0.43
IPCC AR4 (2007)	A1B	0.21 – 0.48	0.16 – 0.53
IPCC AR4 (2007)	A2	0.23 – 0.51	0.18 – 0.56
IPCC AR5 (2013)	RCP2.6	0.26 – 0.55	
IPCC AR5 (2013)	RCP4.5	0.32 – 0.63	0.55 (Zone 2)
IPCC AR5 (2013)	RCP6.0	0.33 – 0.63	
IPCC AR5 (2013)	RCP8.5	0.45 – 0.82	0.72 (Zone 2)
IPCC AR6 (2021)	SSP1-2.6	0.32 - 0.62	
IPCC AR6 (2021)	SSP2-4.5	0.44 - 0.76	
IPCC AR6 (2021)	SSP5-8.5	0.63 - 1.01	
IDB (2018)	RCP2.6		0.46 – 0.61
IDB (2018)	RCP8.5		0.74 – 0.91

The SOCC report (2020) included sea level rise projections for each of the six zones into which the Caribbean had been divided using the AR5 ensemble of 21 CMIP5 models. For Zone 2, sea level rise estimates of 0.29 and 0.32 m by the 2050s were obtained relative to 1986-2005 for emissions scenarios RCP4.5 and RCP8.5, respectively. For the 2090s, sea level rise estimates of 0.55 and 0.72m were obtained. In 2018, a study of "Sea-Level Rise Threats in the Caribbean" by the Inter-American Development Bank used outputs from the K14 model by Kopp et al. (2014) to generate downscaled outputs for specific countries (not including the Cayman Islands). The K14 model has been widely used to provide local sea-level projections in the United States, from city through federal levels. This analysis considered high, moderate and low greenhouse gas emissions scenarios (RCP8.5, RCP4.5 and RCP2.6), and reported that median sea-level projections for southern Cuba (Guantanamo Bay) ranged from 0.26 to 0.29 m by 2050 and 0.51 to 0.79 m by 2100, relative to the year 2000.

According to the IPCC Sixth Assessment Report published in August 2021, it is virtually certain that global mean sea level will continue to rise over the 21st century. Relative to 1995-2014, the likely global mean sea level rise by 2100 is projected as 0.32-0.62 m under the low GHG emissions scenario (SSP1-2.6), as 0.44-0.76 m under the intermediate GHG emissions scenario (SSP2-4.5), and as 0.63-1.01 m under the very high GHG emissions scenario (SSP5-8.5).

### *Scoring*

Site-specific monitoring studies + Regional studies. High agreement, medium evidence.

## 2.3 Sea circulation and currents

### *Current climate impacts*

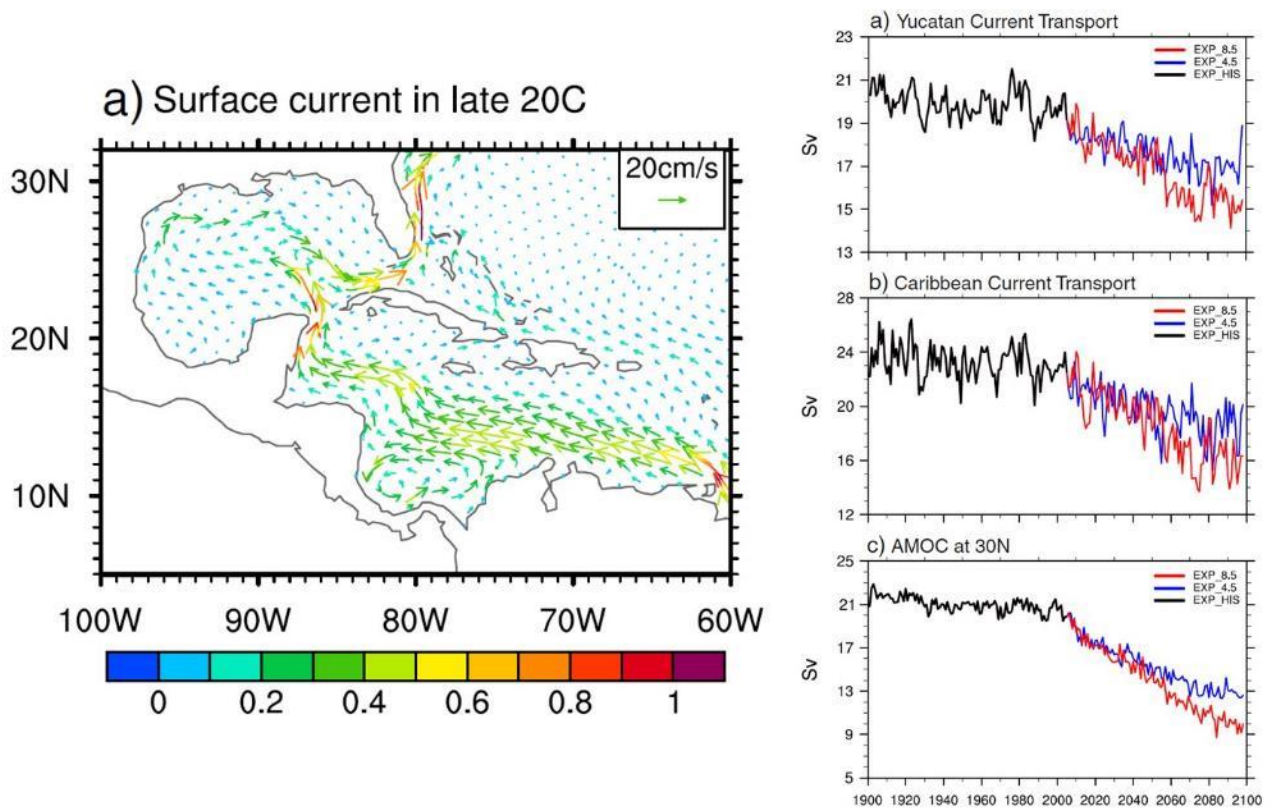
Oceanographic circulation around the Cayman Islands is dominated by the Caribbean Current. This current travels north-westwards through the Caribbean Sea (Figure 9) from the Lesser Antilles near Grenada with speeds of 0.5–1.0 m/s (Carrillo et al., 2017), eventually leading towards the Gulf of Mexico. Where the Caribbean Current passes through the Cayman Basin south of the Cayman Islands, it is referred to as the Cayman Current and when this approaches the coast of the Yucatan Peninsula, it becomes the Yucatan Current (Carrillo et al., 2017). The Loop Current is an area of the Cayman Current that travels up from the Caribbean, past the Yucatan Peninsula and into the Gulf of Mexico.

There is little understanding of how climate change could impact currents in the Caribbean. Jury (2020) examined trends over the period 1980–2016 in flows through the Lesser Antilles near Grenada that eventually constitute the Caribbean current. This study revealed an extended spell of weak westward currents in 1998–2000, stronger westward currents in 2003–2008 and again in 2013–2015, however there was little trend overall. A large seasonal cycle was noted with peak westward flow in April–July each year. Principal component analysis revealed two distinct regimes that influence Caribbean through-flow. The first mode reflects the North Atlantic gyre and phases of the North Atlantic Oscillation (NAO). The second mode reflects multi-year ENSO variability focused on the tropical South Atlantic. Jury (2020) also made use of the HADLEY-2 ESM (Earth System Model) coupled model (Collins et al., 2011) to make projections of future Caribbean through-flow assuming an RCP8.5 high emissions scenario of rising GHGs.

### *Expected future climate impacts*

According to Jury (2020), the HADLEY-2 ESM (Earth System Model) RCP8.5 projection was characterised by a significant slowing of Caribbean through-flow near Grenada in the 21<sup>st</sup> century. The linear decreasing trend in current strength holds 19% variance; westward currents are projected to weaken by ~0.1 m/s by 2100 compared to 1980–2016.

Similarly, Liu et al. (2015) attempted to understand potential impacts of climate change on currents in the Caribbean, by downscaling Coupled Model Intercomparison Project phase-5 (CMIP5) model simulations under two future emission scenarios (RCP4.5 and 8.5). According to this study, transport by the western boundary current system, including the Caribbean Current, Yucatan Current, and Loop Current, will be reduced by 20-25% during the 21st century (Figure 9), and this is consistent with a similar rate of reduction in the Atlantic Meridional Overturning Circulation (AMOC). Reversal in the Caribbean Current is anticipated south of the Cayman Islands (Figure 9). Future weakening of the Loop Current causes a reduced warming in the Gulf of Mexico, particularly during spring in the northern deep basin, in agreement with an earlier dynamic downscaling study (Liu et al., 2012).



**Figure 9.** Long-term averaged annual mean surface currents in the late 20th century (1990 - 1998). The unit for the surface current is cm/s. (a) Time series of simulated annual mean volume transport (Sv) for the Yucatan Current and (b) for the Caribbean Current for the period 1900-2098, obtained from EXP\_HIS, EXP\_4.5 and EXP\_8.5. (c) Time series of simulated Atlantic Meridional Overturning Circulation (AMOC) at 30°N for the period 1900-2098, obtained from EXP\_HIS, EXP\_4.5 and EXP\_8.5.

### Scoring

Regional studies. Medium agreement, limited evidence.

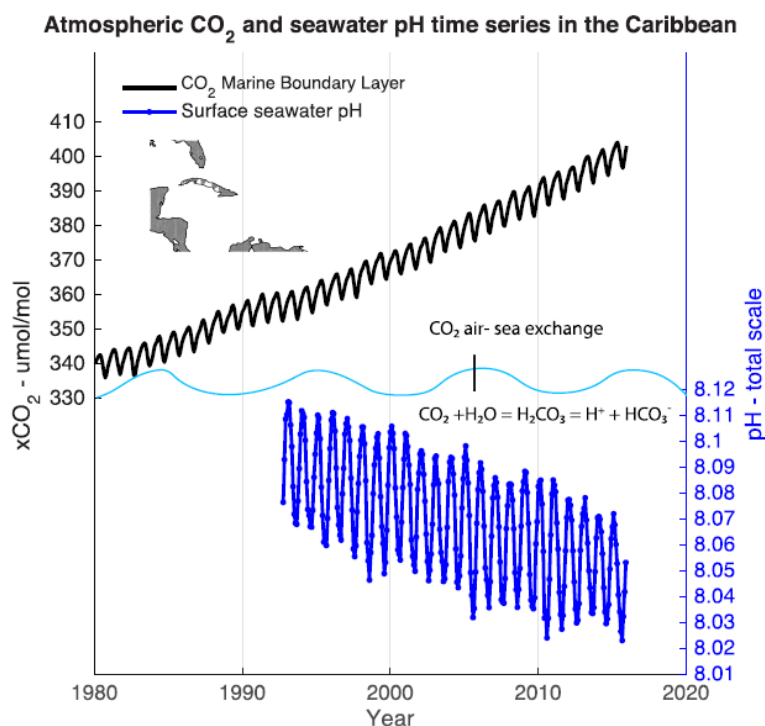
## 2.4 Ocean acidification and pH

### Current climate impacts

Atmospheric carbon dioxide ( $\text{CO}_2$ ) concentrations have increased by 42% since the onset of the Industrial Revolution due to emissions from burning fossil fuels, cement production, and land-use change (Tanhua et al., 2015). Since the beginning of the Industrial era, human activity has added 4 kg of carbon dioxide per day per person on average to the ocean. This anthropogenic  $\text{CO}_2$  reacts with water to form a weak acid. As atmospheric  $\text{CO}_2$  continues to increase, more and more  $\text{CO}_2$  enters the ocean, which reduces pH (pH is a measure of acidity) in a process referred to as ocean acidification. Along with the increase in acidity (higher concentrations of hydrogen ions,  $\text{H}^+$ ), there is also a simultaneous decrease in concentrations of carbonate ion ( $\text{CO}_3^{2-}$ ). Reductions in  $\text{CO}_3^{2-}$  reduce the chemical capacity of the ocean to take up further  $\text{CO}_2$  while also degrading the ability of many marine organisms to produce and maintain shell and skeletal material (Tanhua et al., 2015).

Declines in surface ocean pH are already detectable and accelerating (Tanhua et al., 2015). Measurements gathered at biogeochemical time-series sites around the world reveal similar decreasing trends in ocean pH (reductions between 0.0015 and 0.0024 pH units per year), but datasets are only available for the last few decades (Tanhua et al., 2015). A full account of ocean acidification in the Caribbean is given by Melendez and Salisbury (2017). Few empirical measurements have been taken in waters surrounding the Cayman Islands, however using the Caribbean model of Gledhill et al. (2008), Melendez and Sainsbury (2017) demonstrated a sustained regional increase in surface ocean acidity from 1992 – 2015 (Figure 10) of ~10% (a decline in pH) and a concomitant decrease in the surface ocean aragonite saturation status ( $\Omega_{arg}$ ) of ~8%. The IPCC (IPCC 2014, Chapter 8) assigned a *high confidence* assessment to the finding that the Caribbean region had experienced a sustained decrease in aragonite saturation state from 1996 to 2006.

In a 2008 study by Gledhill et al. (2008), NOAA scientists used four years of ocean chemistry measurements taken aboard the Royal Caribbean Cruise Line ship *Explorer of the Seas* together with daily satellite observations to estimate changes in ocean chemistry over the past two decades in the Caribbean region, and this included transects near to the Cayman Islands. The results revealed considerable spatial and temporal variability throughout the region. Despite this variability, the authors observed a strong decrease in aragonite saturation state ( $\Omega_{arg}$ ) at a rate of approximately  $0.012 \pm 0.001 \Omega_{arg}$  per year.



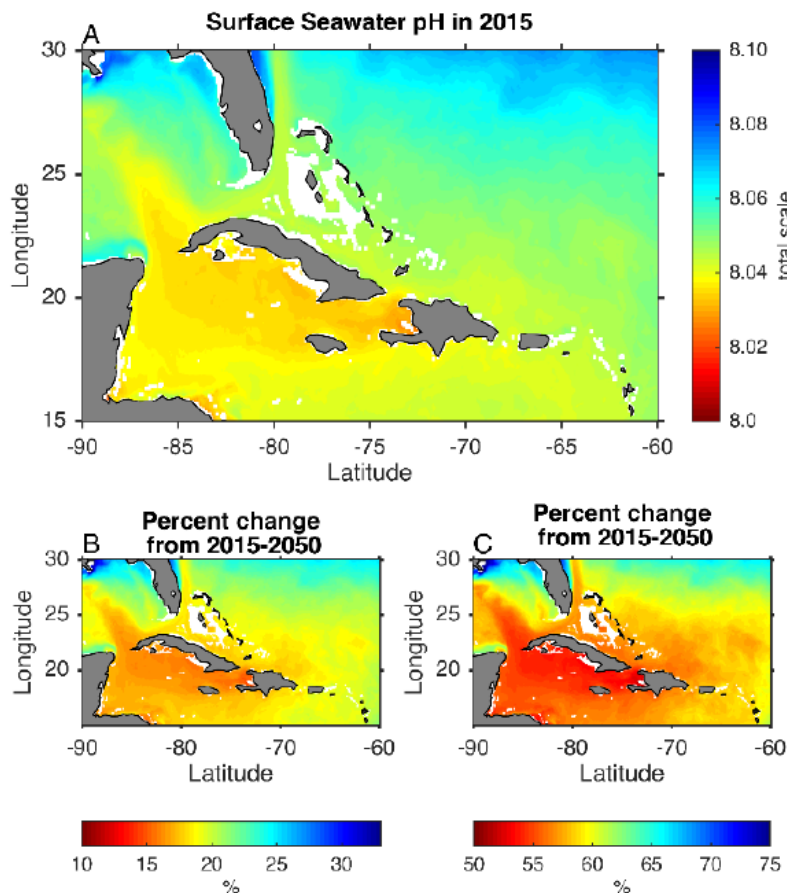
**Figure 10.** Time series of atmospheric CO<sub>2</sub> and seawater pH in the Caribbean. Black line, left axis scale: monthly regional mean of dry atmospheric CO<sub>2</sub> mole fraction (umol/mol) in the Caribbean. Blue line, right axis scale: monthly regional mean of seawater pH (total scale). Data covered the domain defined as [30°N, 15°N, 90°W, 60°W]. Source: Melendez & Salisbury (2017).

### Expected future climate impacts

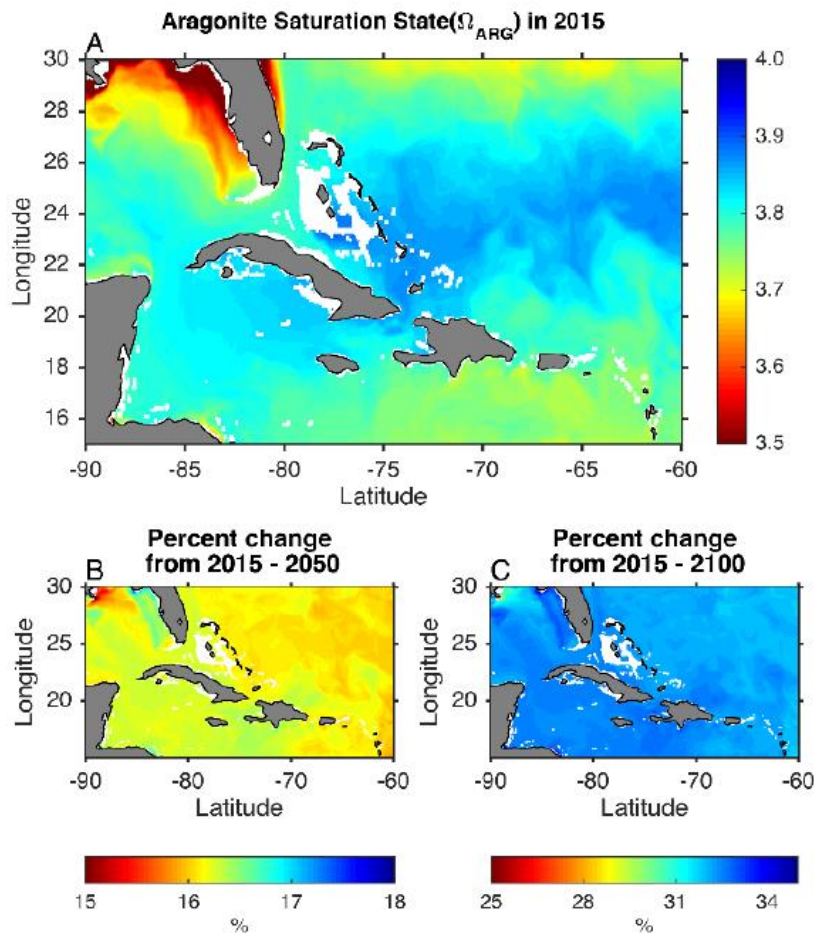
Over the course of the 21st century, pH of the global ocean is expected to decrease due to increasing concentrations of CO<sub>2</sub> in the atmosphere. For the Caribbean region, based on the 13 models included in the CMIP5 ensemble, the suggested trend is a decrease in pH of around 0.1 unit for the 2006-2055

period, and of 0.2 units for the 2050-2099 period versus the previous five decades (NOAA's Climate Change Web Portal - CMIP5 projections).

Melendez and Salisbury (2017) used the Caribbean regional empirical model of Gledhill et al. (2008) and trends in SST, sea surface salinity and atmospheric  $pCO_2$  (partial pressure of carbon dioxide) to make projections of surface seawater pH and  $\Omega_{arg}$  in the Caribbean region. Results show the percent change in pH (Figure 11b, c) and  $\Omega_{arg}$  (Figure 12b, c) projected to take place from the years 2015-2050 and 2015-2100. The results are notable with the Caribbean becoming more acidic by 20% and 58% in 2050 and 2100, respectively. Sea surface  $\Omega_{arg}$ , also declines (16% and 32%) to an average of 3.3 in 2050 and 2.6 in 2100. Most coral reef systems currently only persist above a value of 3.0, which has been suggested as a potential threshold to maintain net reef accretion (Guinotte et al., 2003). Model projections of  $\Omega_{arg}$  are concerning as prior to 2100, Caribbean values are projected to drop below this threshold.



**Figure 11:** (a) Modelled pH for 2015, (b) Percent change in pH from 2015 to 2050, (c) Percent change in pH ( $-\log_{10}(pH)$ ) from 2015 to 2100. Note the scale change on (b) and (c) colour bars. Source: Melendez and Salisbury (2017).



**Figure 12:** (a) Modeled  $\Omega_{\text{arg}}$  for 2015. (b) Percent change in  $\Omega_{\text{arg}}$  from 2015 to 2050. (c) Percent change in  $\Omega_{\text{arg}}$  from 2015 to 2100. Note the scale change on (b) and (c) colour bars. Source: Melendez and Salisbury (2017).

### Scoring

Regional studies. Medium agreement, limited evidence.

## 2.5 Hurricanes and storms (frequency and severity)

### Current climate impacts

During the Atlantic Hurricane Season (June–November), it has been estimated that between 1887 and 1987, one tropical cyclone passed within 100 miles of Grand Cayman on average every 2.7 years (Clark, 1988). For the same time period, tropical storms passed within 50 miles of Grand Cayman every 4.3 years on average, and a tropical storm passed directly over Grand Cayman every 12.5 years. Most measures of Atlantic hurricane activity show a substantial increase since the early 1980s, which is when high-quality satellite data became available (Bender et al., 2010; Emanuel, 2007; Landsea & Franklin, 2013). These include measures of intensity, frequency, and duration as well as the number of strongest (category 4 and 5) storms (MONA, 2014).

The IPCC (IPCC 2013) suggested strong evidence for an increase in the frequency and intensity of tropical cyclones (hurricanes) since the 1970s in the North Atlantic. Additionally, empirical studies have noted overall higher North Atlantic tropical cyclone activity (+60% during this period, Goldenberg

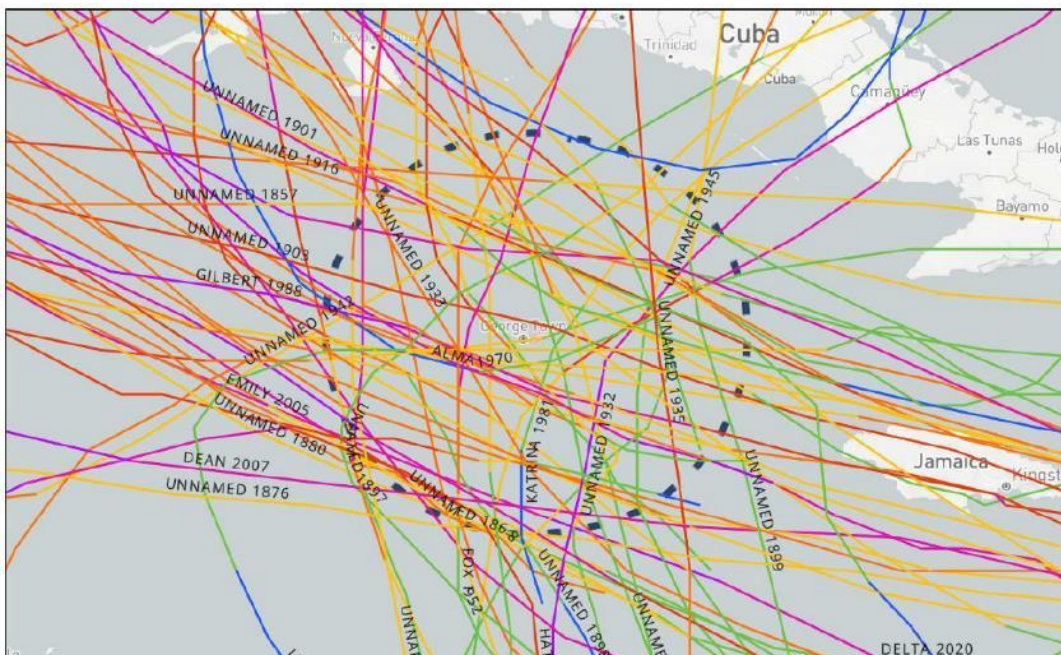


et al., 2001) and increased frequency of very intense tropical cyclones (~+17%) (Emanuel, 2007; Bender et al., 2010).

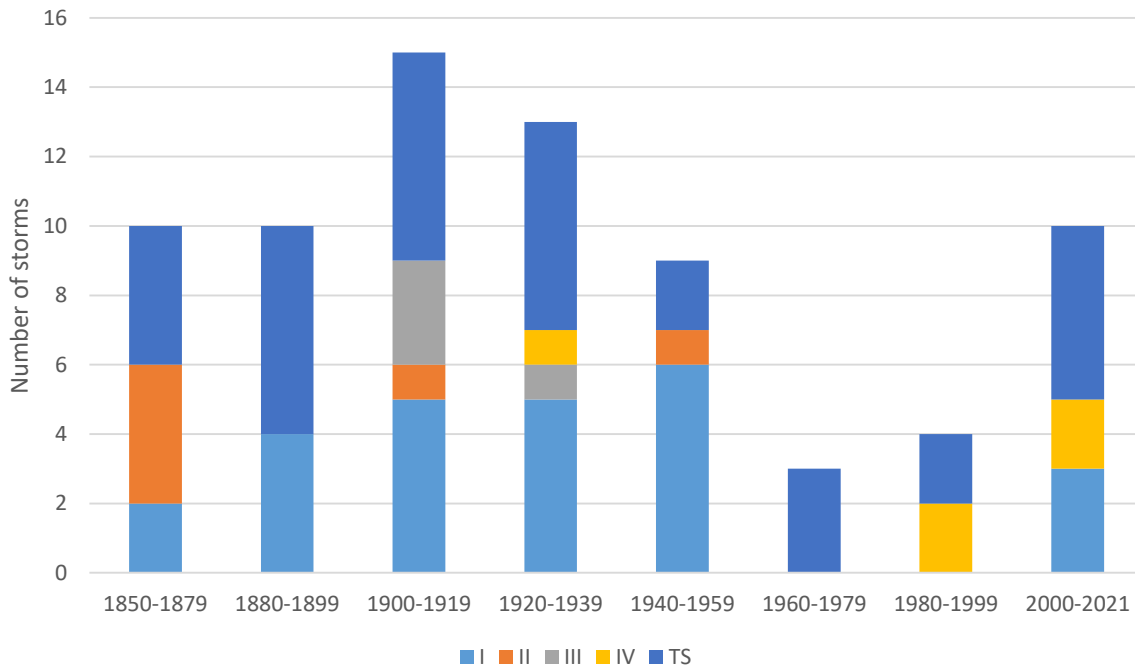
Though the historic record of Atlantic hurricanes dates back to the mid-1800s and indicates other decades of high activity, there is considerable uncertainty in the record prior to the satellite era (early 1970s). PDI (Power Dissipation Index) is an aggregate measure of hurricane activity, combining frequency, intensity, and duration of hurricanes in a single index. Both Atlantic sea surface temperature (SST) and Atlantic hurricane PDI have risen sharply since the 1970s (MONA, 2014). However, there is little consensus that the increases in hurricane activity are attributable to global warming, especially since modulators of SST such as the AMO are currently in a positive phase (MONA, 2014).

For the Cayman Islands specifically, the trajectories of storms (categories 1-4) passing within 150 miles (241 km) of George Town are summarised in Figures 13. The recent upswing in severe Category 4 storms is evident in Figure 14, which shows ‘direct hits’ within 75 statute miles on the Cayman Islands between 1852 and 2021 (CINWS, 2022). This follows a relatively ‘quiet’ period in the 1960s and 1970s. Particularly notable storms passing near to the Cayman Islands include Ivan (2004) [category 4], Gilbert (1988) [category 4], Allen (1980) [category 4], Paloma (2008) [category 4] and an un-named category 4 hurricane in November 1932 that passed directly over both Cayman Brac and Little Cayman. The most recent hurricane passing within 150 miles (241 km) of George Town was Delta (category 4) in October 2020.

The Saffir-Simpson Hurricane Wind Scale consists of a five-point scale of hurricane intensity and starts at 74 mph. Below this, tropical cyclones with wind speeds up to 38mph are classified as tropical depressions and those with wind speeds from 39-73 mph are classified as tropical storms (TS).



**Figure 13.** Storms tracks passing within 150 miles (241 km) of George Town, Grand Cayman, between 1850 and 2020. Only Category 1 - 5 storms are shown. Source: NOAA Historical Hurricane Tracks portal.



**Figure 14.** Number of storms (category TS, I, II, III, IV) passing within 75 statute miles (121 km) of the Cayman Islands between 1850 and 2021, i.e. those considered a ‘direct hit;’. Source: CINWS (2022).

Beyond the recent upward trend in the number and magnitude of storms directly impacting the Cayman Islands, there is also some evidence of hurricanes forming outside of the traditional ‘hurricane season’ in the wider Caribbean. NOAA currently defines the hurricane season as occurring between June 1 and November 30 each calendar year, which is when 97% of all Atlantic tropical cyclones occur. Peak activity is known to occur between August and October. In the off-season, storms are most likely to occur in May, with approximately 60% of such storms occurring during that month. Occasionally, however, storms develop in or persist until December. The longest streak of consecutive years featuring at least one pre-season storm is currently 7, from 2015 through at least 2021. The most recent off-season storm is Tropical Storm Ana in May 2021, though this did not impact the Cayman Islands. Hernández Ayala and Méndez-Tejeda (2020) identified climate change variables as the dominant forces behind increasing trends in off-season TC decadal counts, yet they also showed that climate variability factors like ENSO and AMO also account for a portion of the variability. Late-season storms, especially those occurring to the west and southwest of Grand Cayman, such as Paloma (category 4) in November 2008 and TS Eta in November 2020, coincide with particularly large swell waves that present a risk to coastal infrastructure both in Grand Cayman and for the Sister Islands.

#### *Expected future climate impacts*

The IPCC reported (IPCC 2013) that while projections indicate that it is likely that the global frequency of tropical cyclones will decrease or remain essentially unchanged in the future, there is lower confidence in region-specific projections of frequency and intensity (Stephenson & Jones, 2017). The IPCC Special Report on Extremes (IPCC 2012) stated that ‘While it is likely that overall global frequency will either decrease or remain essentially unchanged, it is more likely than not that the frequency of the most intense storms will increase substantially in some ocean basins.’ The downscaling experiments of Bender et al. (2010) projected a 28% reduction in the overall frequency of Atlantic storms and an 80% increase in the frequency of Saffir-Simpson category 4 and 5 Atlantic hurricanes over the next 80 years using the A1B scenario. Downscaled projections using CMIP5 multi-model scenarios (RCP4.5) as input (Knutson et al., 2013) still projected increases in category 4 and 5 storm

frequency, but these are only marginally significant for the early 21st century (+45%) or the late 21st century (+40%) using CMIP5 scenarios (MONA, 2014).

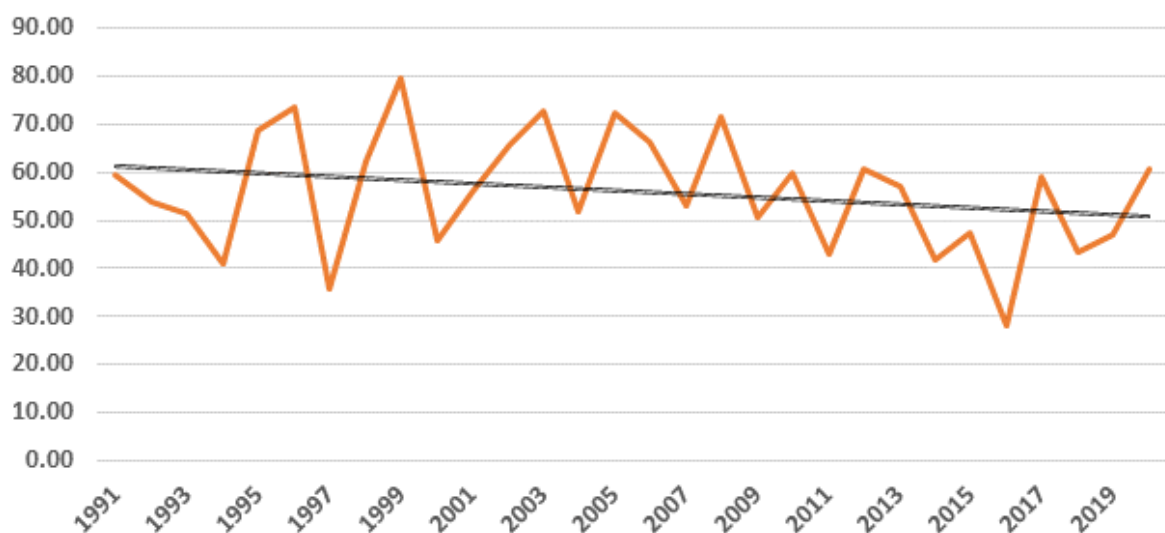
### Scoring

Regional studies + Global studies. Low agreement, medium evidence.

## 2.6 Rainfall and runoff

### Current climate impacts

Interannual variability is a dominant part of the Cayman Islands’ rainfall record. Figure 15 shows total (average) rainfall for the years 1991-2020 using data from the Owen Roberts International Airport (Grand Cayman) weather station (MONA, 2014). Although there was a slight downwards trend, this was not statistically significant, and the record at the time was too short to attribute any trend to global warming.



**Figure 15.** Total annual rainfall (inches) for Cayman 1991-2020. Data from the Owen Roberts International Airport. Source: CINWS (2022).

Rainfall in the Cayman Islands has a bimodal (‘double peak’) pattern over the course of the year, with an early rainfall season occurring in May-June and a late rainfall season centered in October. About 70-80% of total annual rainfall occurs between May and November, and about 40-50% is between September and November (the late wet season) (MONA, 2014). The late wet season also coincides with the peak in Atlantic hurricane activity. The Cayman Islands’ rainfall climatology is largely conditioned by changes in features of the tropical Atlantic such as the position of the North Atlantic High (NAH) pressure system, tropical SSTs, the passage of mid-latitude cold fronts early in the year, the strength of the trade winds, and the passage of easterly tropical waves. During an El Niño event, the Caribbean tends to be drier and hotter than usual, and particularly during the late wet season from August through November. However, in the year after an El Niño (the El Niño + 1 year), the Caribbean tends to be wetter than usual during the early rainfall season (May to July). In general, a La

Niña event produces the opposite conditions in both the late wet season (i.e., wetter conditions) and the dry season (i.e., a wetter south Caribbean) (MONA, 2014).

In contrast to MONA (2014), the SOCC report (MONA 2020) suggests a slight downward trend in rainfall over the Caribbean as a whole for the period 1900-2014, which is not, however, statistically significant. For rainfall in 'Zone 2', which includes the Cayman Islands, the SOCC report (MONA 2020) suggests a slight downward trend, although again, not statistically significant at the 5% level. These results mirror the findings of Jones et al. (2015) who also provided an extensive analysis of long-term trends in Caribbean rainfall. Jones et al. (2016) noted that annual and decadal variability appear to be the dominating influences in the Caribbean rainfall time series.

Extreme indices are often used to provide more information about the mean climate of a region. Four commonly cited rainfall extreme indices are: (a) Maximum number of Consecutive Dry Days (CDD); (b) Rainfall amount on Very Wet Days (i.e., days when total rainfall exceeded the 95th percentile) (R95p); (c) Monthly Maximum One Day Rainfall Amount (RX1); and (d) Monthly Maximum Consecutive Five Day Rainfall Amount (RX5). The extreme rainfall indices calculated from data collected at the Owen Roberts International Airport are generally reflective of the swing toward drier conditions in the most recent two decades. The trend suggests fewer, but more severe rain events. These 'trends' should, however, be interpreted cautiously given the relatively short period over which they were calculated, and the large year-to-year variability in rainfall and its extremes (MONA, 2014).

**Table 4.** Trends in extreme rainfall indices. Historical extremes calculated using data from the Owen Roberts International Airport (1982-2010). Source CINWS (2022).

<b>Descriptive Name</b>	<b>Indices</b>	<b>Slope (1976 - 2020)</b>
Max 5-day precipitation (mm)	RX5day	1.041
Days above 10mm	R10mm	-0.222
Consecutive dry days	CDD	0.236
Consecutive wet days	CWD	0.015
Very wet days	R95P	1.963
Extremely wet days	R99P	-0.542
Annual precipitation (mm)	PRCPTOT	-2.36

#### *Expected future climate impacts*

The MONA modelling team provided rainfall projections from both the Hadley PRECIS Regional Climate Model (RCM) and from Global Climate Models (GCMs) in their 2014 Cayman Islands-specific report (MONA, 2014) and the SOCC report (MONA, 2020). For the Caribbean as a whole, GCM projections suggest a decreasing trend in annual rainfall. Across all scenarios, this drying trend is already established by the 2020s (up to 2% drier for the mean of all models). By the 2050s, the region is in the mean up to 6% drier, and by the end of the century the region may be up to 17% drier (MONA, 2020). The Caribbean drying trend is mostly driven by drying in the late wet season. The RCM projections suggest sub-regional variation in projections with some parts of the region being more significantly impacted by drier conditions than others. Changes to mean annual rainfall in 'Zone 2' (including the Cayman Islands) suggest slightly wetter conditions through to mid-century, which changes to drier conditions by the end of the century (MONA, 2020).

For the Cayman Islands specifically (MONA, 2014), GCMs suggest little change in annual rainfall through to the 2080s. A drying trend sets in toward the end of the century with up to 11% less total rainfall for the year under the most severe RCP scenario (RCP8.5). The GCMs suggest that changes in summer rainfall will be greater than changes in annual rainfall. The drying trend will set in earlier with up to 3% less rainfall by 2021-2040, 6% less rainfall by 2041-2060, 10% less rainfall by 2061-2080, and

17% less rainfall by 2081-2100 (Table 5). RCM projections do not indicate significant changes in rainfall across seasons for the near term (2030s), however, using these same models under two different climate scenarios (A2 and B2), the extreme rainfall indices generally suggest more intense but fewer rain events in the more distant future (Table 6).

**Table 5.** Mean percentage change in annual rainfall for Cayman Islands with respect to 1986-2005 AR5 CMIP5 subset. Change shown for four RCP scenarios. Source: MONA (2014).

(a) Rain	2021-2040			2041-2060			2061-2080			2081-2100		
	min	mean	max	min	mean	max	min	mean	max	min	mean	max
rcp26	-10.98	2.22	13.9	-16.02	2.16	32.38	-15.78	2.9	21.59	-24.51	2.55	22.11
rcp45	-19.55	-0.04	15.94	-21.74	-1.5	17.25	-23.99	-2.74	19.72	-28.92	-1.21	35.27
rcp60	-14.89	-0.82	18.48	-16.65	-0.22	13.22	-16.6	-0.99	30.68	-29.81	-2.8	19.98
rcp85	-19.61	-1.03	16.41	-18.37	-2.18	25.46	-34.65	-4.53	23.98	-47.98	-11.25	31.9
<b>Range for the Means:</b>	-1 - +2%			-2 - +2%			-4 +3%			-11 +3%		

**Table 6.** Change in rainfall trends for 2071-2099 relative to a 1961-1989 baseline assuming an A2 (high emissions) and B2 (low emissions) climate scenario. Positive values indicate increasing trend. Source: PRECIS RCM, MONA (2014).

Descriptive Name	INDICES	Units	Change in Slope (A2)			Change in Slope (B2)		
			80.0°W; 19.5°N	81.5°W; 19.5°N	81.0°W; 19.5°N	80.0°W; 19.5°N	81.5°W; 19.5°N	81.0°W; 19.5°N
Max 5-day precipitation	RX5day	mm	0.239	1.254	1.112	0.889	0.560	0.827
Days above 10mm	R10mm	days	0.179	0.143	0.227	-0.511	0.471	0.542
Consecutive dry days	CDD	days	-0.258	0.023	0.018	-1.000	0.096	0.376
Consecutive wet days	CWD	days	-0.157	-0.007	-0.008	0.172	-0.497	-0.694
Very wet days	R95P	mm	-1.716	0.558	0.247	0.627	0.315	0.896

### Scoring

Site-specific monitoring studies + Regional studies + Global studies. Low agreement, medium evidence.

## 2.7 Transboundary Influences

Inter-regional transboundary impacts are those generated by processes originating in another region or continent well beyond the borders of an individual archipelagic nation or small island. Some transboundary processes may have positive effects on the receiving small island or nation, though most that are reported have negative impacts (Mycoo et al., 2022). Very little is known about transboundary influences on the Cayman Islands, although dust clouds and large ocean waves from distant sources are both thought to have an occasional impact.

Unusually large ocean swells generated from sources in the mid and high latitudes by extratropical cyclones (ETCs) are known to cause considerable damage on the coasts of small islands thousands of

kilometres away in the tropics. Impacts include inundation of settlements, infrastructure, and tourism facilities, as well as severe erosion of beaches. These waves can propagate to and influence reef islands in equatorial areas not usually exposed to high energy waves (Jury, 2018).

The transport of airborne Saharan dust across the Atlantic into the Caribbean has been intensively studied (Mycoo et al., 2022; Prospero & Lamb, 2003). In the West African Sahel where drought has been persistent since the mid-1960s, analysis has shown that there have been remarkable changes in dust emissions since the late 1940s. Variability in Sahel dust emissions may be related not only to droughts, but also to changes in the NAO, North Atlantic SSTs and the AMO. The frequency of dust storms has been on the rise during the last decade. Forecasts suggest that their incidence will increase further. Transboundary movement of Saharan dust into the Caribbean has been associated with human health problems such as asthma cases (Akpınar-Elci et al., 2015; Goudie, 2014).

## 3 Impacts of climate change on biodiversity

### 3.1 Plankton productivity

#### *Current climate impacts*

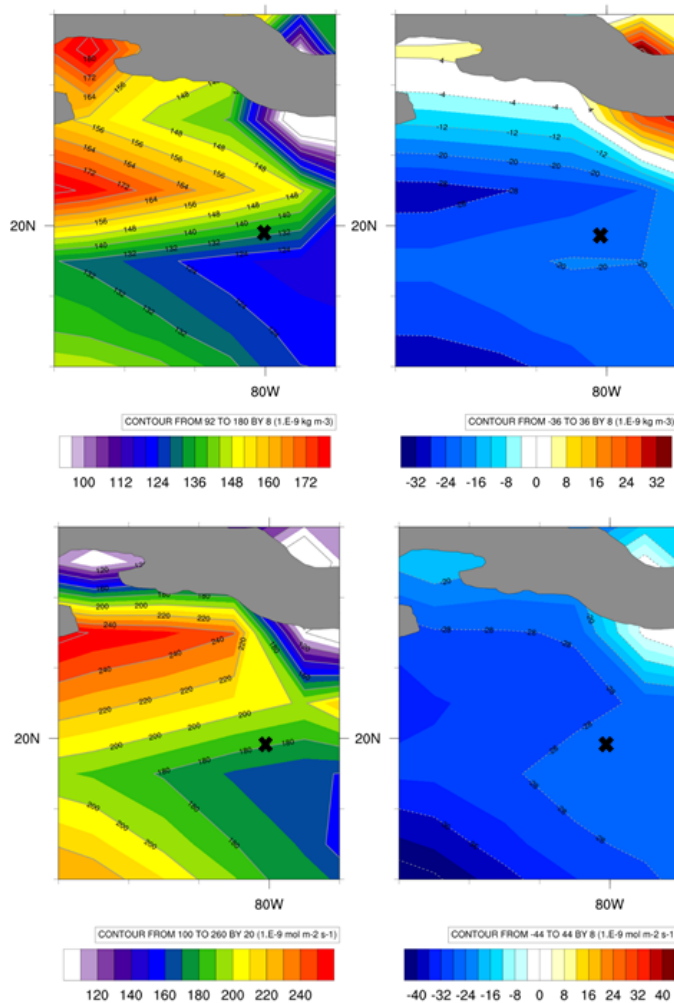
There is low confidence in past trends in net primary production globally, with studies reporting only relatively small changes (Bindoff et al., 2019). In the Cariaco Basin off the coast of Venezuela in the southern Caribbean, changes to wind patterns have reduced ocean upwelling in recent years (1996-2010), with subsequent reduction in nutrients leading to a Caribbean-wide decrease in plankton production (Taylor et al., 2012). In addition, there has also been a state shift in the plankton system with previously dominant diatoms, dinoflagellates and coccolithophores, giving way to smaller plankton, and a concomitant collapse in the commercial landings of planktivorous sardines. In the Cayman Islands specifically, little is known about changes in plankton communities.

#### *Expected future climate impacts*

In the future, net primary productivity is projected to decline in the tropics (Bindoff et al., 2019). In addition, ocean acidification may hinder the ability of certain phytoplankton to make their skeletons, reducing growth and survival (Brown, 2008). There may be shifts in the distribution of plankton species, and changes to the timings of the seasonal plankton blooms (Monnereau et al., 2017). CMIP5 model outputs suggest that, under an RCP8.5 scenario, both total chlorophyll mass concentration and primary organic carbon production by all types of phytoplankton combined will decline around the Cayman Islands by 2050-2099 compared to the historic reference period (Figure 16).

#### *Scoring*

Global studies + regional studies. Medium agreement, limited evidence. Relevance: Grand Cayman = medium; Little Cayman = medium, Cayman Brac = medium.



**Figure 16.** Top: Total Chlorophyll Mass Concentration at sea surface interpolated on a 1x1 grid for the entire year; (top left) mean Chlorophyll Mass Concentration ( $\mu\text{g m}^{-3}$ ) from the historical experiment for the period (1956-2005); (top right) difference in the Chlorophyll Mass Concentration in the future time period (RCP8.5: 2050-2099) compared to the historical reference period (1956-2005). Bottom: Primary Organic Carbon Production by all types of Phytoplankton interpolated on a 1x1 grid for the entire year; (bottom left) mean production ( $\text{nmol m}^{-2} \text{s}^{-1}$ ) from the historical experiment for the period (1956-2005); (bottom right) difference in the mean climate in the future time period (RCP8.5: 2050-2099) compared to the historical reference period (1956-2005). The approximate location of the Cayman Islands is shown by the black cross. Source: NOAA Climate Change Web Portal – CMIP5 ensemble of models.

### 3.2 Harmful algal blooms and associated risks to humans and biodiversity

#### *Current climate impacts*

Harmful algal blooms (HABs) in the Caribbean and Latin America have increased since the 1980s, and 80% are caused by dinoflagellates, followed by diatoms (Mendez et al., 2018). In the Caribbean, Paralytic Shellfish Toxins (PST), Diarrhetic Shellfish Toxins (DST), Ciguatera Poisoning (CP) Amnesic Shellfish Toxins (AST), and Neurotoxic Shellfish Toxins (NST) have all been recorded (Hallegraef et al., 2021). As well as implications for human and fish health, HABs can affect tourism by being unsightly or causing odours. Increases in HABs have been linked to warming, increased nutrient loading, and

hypoxia, with studies showing an increase in warm-water species, such as the ciguatera-causing dinoflagellate *Gambierdiscus* (Bindoff et al., 2019).

Since the early 2010s, mass strandings of Sargassum seaweed (*Sargassum natans* and *S. fluitans*) have occurred on Caribbean beaches, including the Cayman Islands. The cause is thought to be a combination of long-term climate change, changes in West African upwelling, and increased eutrophication from South America, as rafts of the algae form in the Atlantic get carried by currents into the Caribbean (Lapointe et al., 2021; Oxenford et al., 2021; Wang et al., 2019). The seaweed causes problems for tourism (Figure 17) and human health, and there are considerable economic costs associated with removal.



**Figure 17.** Sargassum seaweed accumulation on Seven Mile Beach, Grand Cayman.

#### *Expected future climate impacts*

It is expected that rising sea temperatures and reduced oxygen could cause a further increase in HAB occurrences (Bindoff et al., 2019). However, modelling suggests that Caribbean temperatures may become less suitable for the dinoflagellates that cause Ciguatera, and so the incidence of Ciguatera may remain stable or reduce in the future (Kibler et al., 2015).

The causes behind the recent increases in Sargassum seaweed are not fully understood, but are thought to be a combination of increased eutrophication in the wider region (including possible influence of nutrients from Amazon River floods and/or Sahara dust [Oviatt et al. 2019]), changes in upwelling and sea temperature increases (Lapointe et al., 2021; Oxenford et al., 2021; Wang et al., 2019). The extent and timing of the blooms are affected by these factors each year (Wang et al., 2019). As such, further changes to any of these may alter the influx of Sargassum into the region, and further research is urgently needed (Low agreement, limited evidence).



### *Scoring*

Regional studies. Medium agreement, medium evidence. Relevance: Grand Cayman = medium; Little Cayman = medium, Cayman Brac = medium.

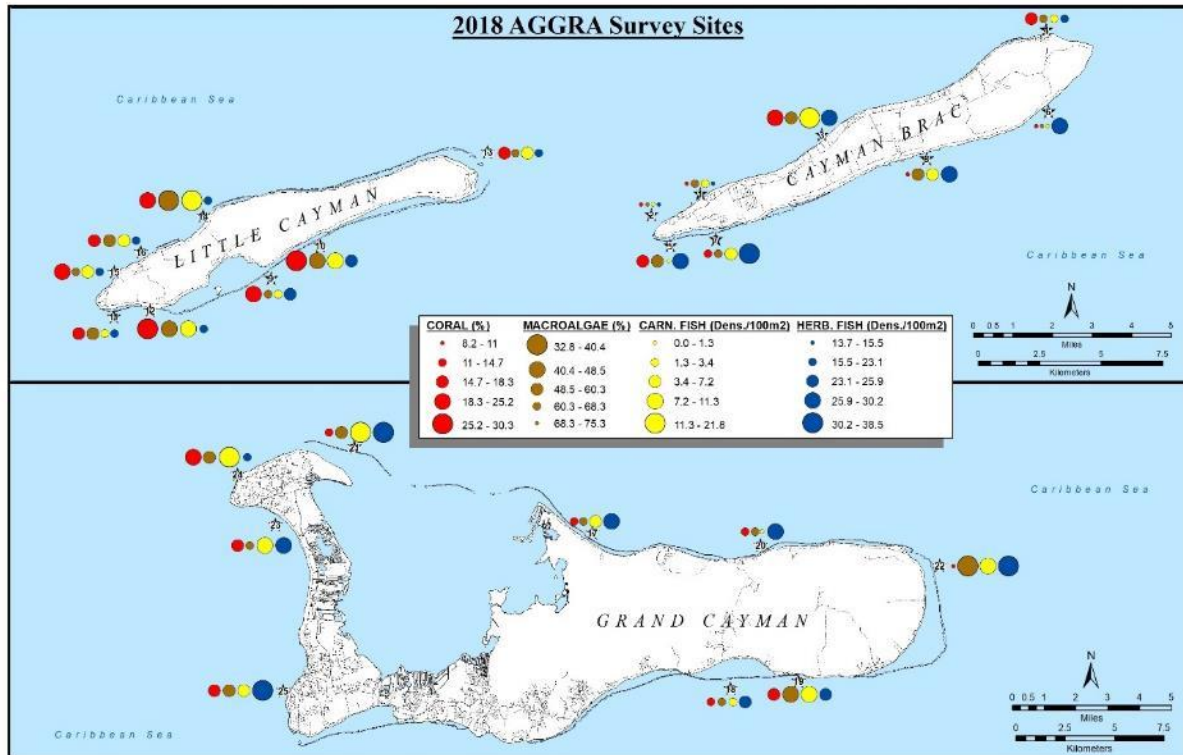
## 3.3 Fish

### *Current climate impacts*

Monnereau and Oxenford (2017) examined the impacts of climate change on each of the four main groupings of commercially important fish species considered to typify the Caribbean Community and Common Market (CARICOM) region. The 'reef-associated shallow shelf group' includes many essentially benthic or site-attached species such as the reef fishes. The 'deep slope group' includes a number of essentially benthic species such as deep-water snappers, deep-water groupers that live, at least as adults, in deep (>100 m) waters along the shelf edge or around offshore seamounts. The 'groundfish group' refers to a number of species of finfish and shellfish, the latter including penaeid shrimps/prawns, that rely on shallow, muddy, or sandy continental shelf areas and associated estuaries and mangroves. The 'oceanic pelagics group' includes the more-offshore, open-water, highly migratory, species such as tunas, marlin and dolphinfish that occur throughout the warmer Atlantic and Caribbean Sea in open water (Murray et al., 2021).

A review of available literature confirmed a dearth of studies on the impacts of climate change on fishery species specific to this region, perhaps with the exception of coral reef fishes (Nurse, 2011). Reef habitats have already been degraded because of climate change, most notably coral bleaching and storm damage, and made worse by other human pressures, such as pollution and overfishing. These impacts have threatened the survival of some valuable fish species. Decline in live coral cover, caused largely by temperature-induced mass coral bleaching, has already been linked to declines in herbivorous reef fish biomass across the Caribbean including in the Cayman Islands (Bruno et al., 2019). Historical declines in the abundance of other large Caribbean reef fishes likely reflect centuries of overexploitation. Bruno et al. (2019) analysed time series of reef fish density obtained from 48 studies that included 318 reefs across the Caribbean (including 5 sites in Grand Cayman) and spanned the time period 1955–2007. Overall, reef fish density has been declining significantly for more than a decade, at rates consistent across all subregions of the Caribbean basin (2.7% to 6.0% loss per year).

Reef fish populations, in particular snappers, groupers and parrotfish, are monitored at a number of sites around the Cayman Islands on an occasional basis as part of the Atlantic and Gulf Rapid Reef Assessment (AGRRA) programme. The objective of AGRRA is to count and quantify the abundance and community composition of key fish species along standardised, 30-m long × 2-m wide belt transects and measure the relief of the reef. Fish teams survey a total of 10 transects/site, and the most recent assessment of the Cayman Islands was in 2018 (Figure 18). Combining all fish families, total density has not changed statistically speaking on any of the Cayman Islands using the 1999 and 2018 data (Manfrino & Dell, 2019). Separately, grunts, snappers, filefish, parrotfish and surgeonfish showed no significant differences in density between 1999 and 2018. However, grouper density has declined on Little Cayman. This is attributed to a major over-fishing event that occurred at the western grouper spawning aggregation site (SPAG) between 2000 and 2002 (Manfrino & Dell, 2019).



**Figure 18.** Outputs from the Atlantic and Gulf Rapid Reef Assessment (AGGRA) Program in 2018 for the Cayman Islands, showing % coral and algal cover as well as the density of carnivorous fish (groupers and snappers) and of herbivorous fish (mostly parrotfish).

Monnereau and Oxenford (2017) suggest that the most obvious impacts of climate change on the reef-associated shallow shelf group of fish are indirect, and result from the significant impacts already witnessed in the Caribbean on their essential benthic habitats, especially coral reefs and, to a lesser extent, mangrove wetlands and seagrass meadows. The reliance of this group on highly vulnerable and already damaged habitats puts them at the greatest disadvantage for withstanding climate-change stressors (Murray et al., 2021).

Much less is known about the deep-slope group of fish species. As with the reef-associated group, these species would be similarly vulnerable to changes in ocean currents and surface water temperatures, potentially affecting the dispersal of their spawn, and ultimately the settlement success and survival of their young recruits (Monnereau & Oxenford, 2017). Food supply to the deep seafloor has been impacted by declines in oceanic plankton productivity at certain localities and this could affect the productivity of benthic food-webs (Levin et al., 2020). In addition, deep-water snappers and groupers could be affected through impacts of increased SST on the timing and location of spawning aggregations (Erisman & Asch, 2015).

Many finfish and shellfish (e.g., shrimp) species rely on estuarine nursery areas, including mangroves and seagrass beds. This so-called groundfish group, although much less studied in the region than other fish or shellfish groups, consists of species that often have bi-phasic life cycles, with a free-floating pelagic early life stage and a benthic adult stage. This means that they will share the same potential threats posed to early life stages as all the other fishery groups (Monnereau & Oxenford, 2017).

The oceanic pelagic group comprising large highly migratory species (e.g., billfishes, large tunas) as well as smaller or medium-sized, more-regionally migrating species (e.g., flyingfish, dolphinfish, wahoo, small tunas) is the only group in which the members remain in pelagic environments for their

entire life histories as eggs, larvae, juveniles, and adults. They also generally have extended spawning periods, being multiple batch spawners, and have relatively diffuse spawning areas that are not well defined and/or poorly known in the literature (Monnereau & Oxenford, 2017). Of all the groups, Monnereau and Oxenford (2017) suggest that this one will be the least affected, in the short term, by climate change. The early life stages are perhaps less affected by ocean acidification and increasing SST than some of the other species groups and are not reliant on finding and settling in benthic coastal habitats (Monnereau & Oxenford, 2017). Adults can migrate over large distances and avoid adverse conditions.

#### *Expected future climate impacts*

As the ocean becomes warmer, less oxygenated, more thermally layered and more acidic, there are likely to be shifts in the distribution of marine fish and shellfish species, as well as changes in community structure, spawning rates, growth of fish, and coral reef habitats.

The Cayman Islands are home to some of the largest remaining spawning aggregations for the culturally and economically important Nassau Grouper (*Epinephelus striatus*) (Murray et al., 2021). Preliminary results from laboratory experiments conducted on larvae of this species suggest that rising water temperature will impact larval success (Waterhouse et al., in prep; Waterhouse et al., 2020). Data showed that above the 'ideal' 26°C–27°C water temperatures, early life stage mortality increases dramatically. For example, when temperatures increased by 4°C (to 31°C), starvation time decreased from 6–7 days to 3–4 days. Grouper larvae do not start feeding until around four days after hatching, and this represents a significant problem; if under warmer conditions the starvation time becomes shorter than what is required for larvae until onset of feeding, it is unlikely they will survive at all, which would result in recruitment failure. Increasing water temperatures predicted due to climate change over the next 20 to 50 years, may have devastating consequences for this, and other species' populations in the Cayman Islands and in the wider Caribbean region (Asch & Erisman, 2018).

Asch and Erisman (2018) provided projections of how climate change may affect distributions and phenology of Nassau Grouper (*Epinephelus striatus*). Species distribution models of spawning and non-spawning adults were compared to determine which environmental variables exerted the greatest influence on grouper distribution. While the two life stages exhibited similar ecological niche breadth, the thermal niche was narrower for spawners. By 2081–2100 under a business-as-usual scenario, potential habitat for spawners was projected to decline by 82% relative to 1981–2000, whereas that for non-spawners was projected to decrease by 46%. Poleward shifts in latitude occurred 3.8–4.2 times faster for spawners than for non-spawners.

A global analysis predicting changes in maximum body weight averaged over fish assemblages showed that fish size in the Caribbean region is expected to decrease significantly by 5–19% from the year 2000 to 2050 as a result of oxygen-limited growth of individual fish, as well as a change in community composition towards smaller-sized species (Cheung et al., 2012). This study also demonstrated considerable variation within the region, showing the greatest size decreases by as much as -49% in the northern Caribbean Sea.

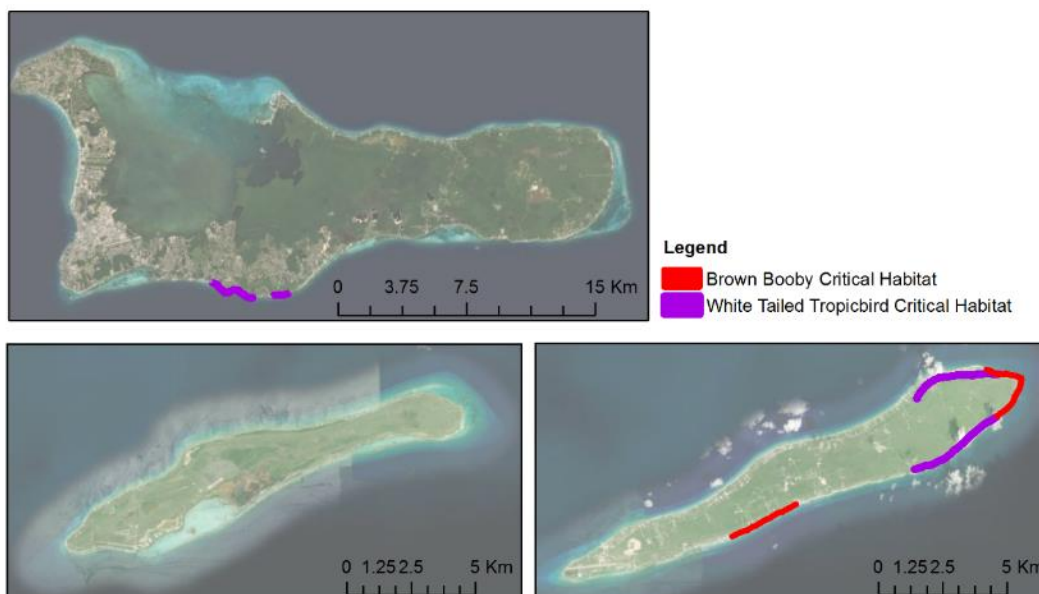
Erauskin-Extramiana et al. (2019) reported poleward shifts in distribution for 20 out of 22 tuna stocks between 1958 and 2004 at an average rate of ~6.5 km per decade in the northern hemisphere. Further, perhaps even larger shifts are expected in the future, especially by the end-of-the-century (2080–2099). This could take fishery resources beyond the reach of small scale fishing vessels in the Cayman Islands, or perhaps even beyond the limits of the EEZ, although no fine-scale projections are provided for the Cayman Islands or Caribbean specifically.

### Scoring

Local climate impact studies + Regional studies. Medium agreement, medium evidence. Relevance: Grand Cayman = high; Little Cayman = high, Cayman Brac = high.

## 3.4 Marine mammals, seabirds and turtles

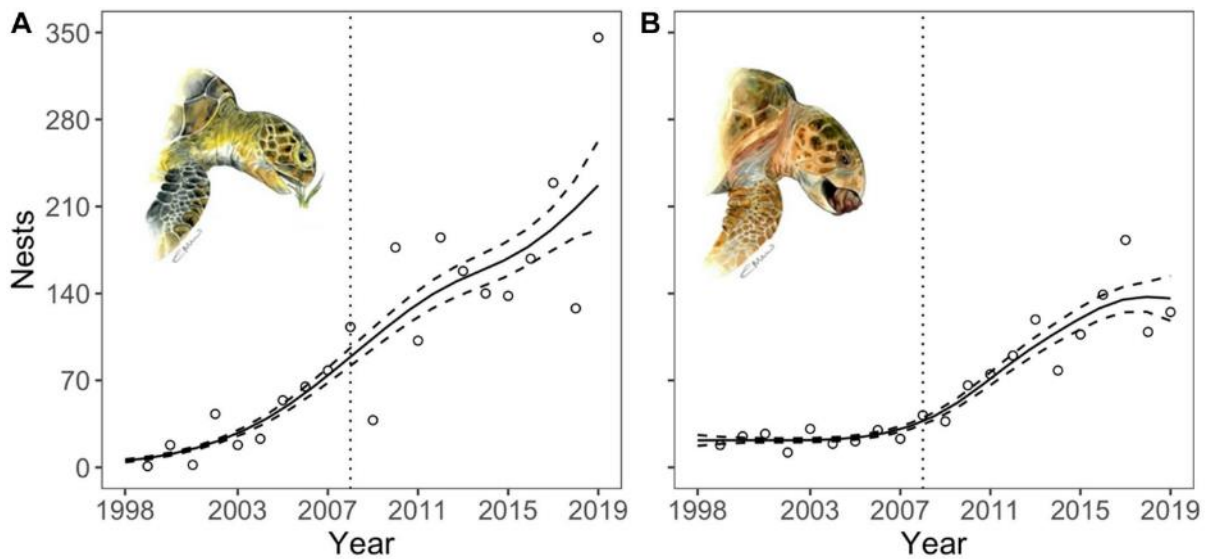
Around all three of the Cayman Islands, there are important coastal breeding habitats for resident and migratory seabirds, including the White-tailed tropicbird (*Phaethon lepturus*) in Grand Cayman and Cayman Brac, the Brown booby (*Sula leucogaster*) on Cayman Brac (Figure 19), and the Red-footed booby (*Sula sula*) on Little Cayman (Hurlston-McKenzie, 2011). There are a number of designated protected areas around the Cayman Islands that protect breeding and roosting areas for seabirds, as well as turtle nesting and foraging areas (DaCosta-Cottam et al., 2011).



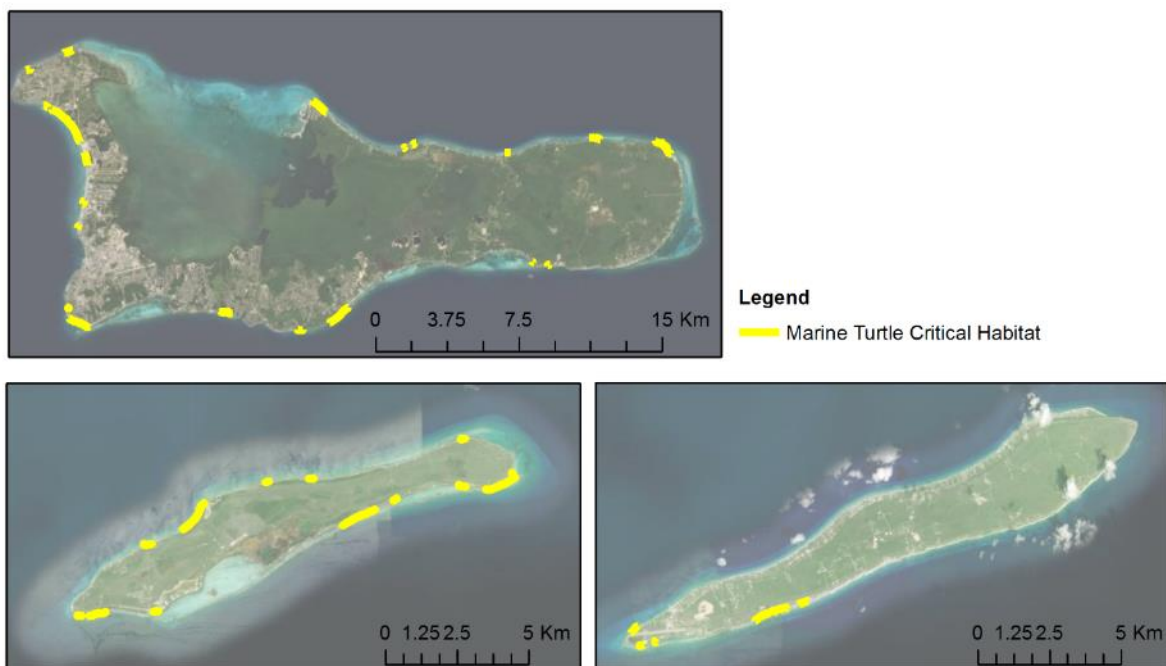
**Figure 19.** The nesting habitat for white-tailed tropic birds and brown booby on Cayman Brac (right) and the tropicbird on Grand Cayman (top). Data source: Department of Environment, Cayman Islands Government, March 2022. Aerial imagery: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus, DS, USDA, USGS, AeroGRID, IGN, and the GIS user community.

The Cayman Islands have historically supported large numbers of nesting Green (*Chelonia mydas*), Hawksbill (*Eretmochelys imbricata*), Loggerhead (*Caretta caretta*), and Leatherback turtles (*Dermochelys coriacea*), however, they have been depleted by harvesting. In the 1980s, nesting Green turtles were considered locally extinct (Blumenthal et al., 2021). Legal harvest of wild turtles ceased in 2008. Helped by a captive breeding programme for Green turtles, populations have increased around the islands (Blumenthal et al., 2021). Surveys by Blumenthal et al. (2021) from 1999 to 2019 across the three islands show that nesting turtle numbers have increased during this time, although no leatherback nests were recorded. Green turtle nests increased by 1126% and 906%, and Loggerheads by 487% and 3800% in Grand Cayman and Little Cayman, respectively (Figure 20). In Cayman Brac, numbers have increased from no nests in 1998 to a total of 221 nests in the last five

years. Nest numbers for Hawksbill turtles remain low across all islands. Critical habitats for nesting turtles are found around the coasts of all three islands (Figure 20).



**Figure 20.** Nest counts for green (A) and loggerhead (B) turtles in Grand Cayman. Source: Blumenthal et al. (2021).



**Figure 21.** Nesting habitat for turtles around Grand Cayman (top), Little Cayman (left) and Cayman Brac (right). Source: Department of Environment, Cayman Islands Government, March 2022. Aerial imagery: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus, DS, USDA, USGS, AeroGRID, IGN, and the GIS user community.

While turtle numbers have increased dramatically, they remain far lower than prior to human disturbance, and there are still a number of non-climatic threats to turtles. Some turtles are taken illegally, including mature females, and artificial lighting on nesting beaches can reduce hatchling survival by disorientating them as they try to reach the sea (Blumenthal et al., 2021). This is especially

the case on the more developed Grand Cayman. The Department of Environment has drafted a conservation plan for turtles but it has not yet been adopted. Until it is, there is an Interim Directive that protects critical turtle nesting habitat on Grand Cayman, especially associated with new developments (The National Conservation Council of the Cayman Islands, 2022).

There have been sightings of whales and dolphins around the Cayman Islands, including Orcas (*Orcinus orca*), Sperm whales (*Physeter macrocephalus*), Bottlenose dolphins (*Tursiops truncatus*), Gervais' beaked whales (*Mesoplodon europaeus*), Great White sharks (*Carcharodon carcharias*), Whale sharks (*Rhincodon typus*) and Manta rays (*Manta birostris*) (DaCosta-Cottam et al., 2009).

#### *Current climate impacts*

In 2004, 84% of Green turtle (*Chelonia mydas*) nests and 25% of Loggerhead (*Caretta caretta*) nests were lost because of beach profile changes caused by Hurricane Ivan (ECLAC, 2004). It is thought that fewer nests were lost on the northern side of the islands.

After Tropical Storm Grace in August 2021, a Pygmy Sperm whale (*Kogia breviceps*) was found washed ashore on the Cayman Islands (Miami Herald, 2021). It was thought by the Department of Environment to be a foetus that was aborted because the mother was caught in the storm. Sperm whale (*Physeter macrocephalus*) populations in the eastern Caribbean declined between 2005 and 2015, with both fewer adults and calves, however, the exact cause of this decline is unclear, and so it may not be attributable to climate change (Gero & Whitehead, 2016).

#### *Expected future climate impacts*

For seabirds, any changes in the abundance or distribution of their prey will have knock-on effects for survival, fitness and reproductive success. Overall, evidence suggests that climate change will impact each bird species differently (Bindoff et al., 2019). Changes in prey availability may be advantageous to some seabirds. For example, survival rates of Audobon's shearwaters (*Puffinus lherminieri*), which breed in Martinique, have increased in the last 20 years, linked to increased sea temperatures and discharges from the River Amazon (Precheur et al., 2016). Models indicate that for the next 50 years, the species will have a stable or increasing population as sea temperatures increase further. Seabird breeding may be affected by climate change, if availability of breeding habitat, such as mangroves, is reduced (e.g., for boobies) (Bindoff et al., 2019). The White-tailed tropicbird lays a single egg directly onto the ground or a cliff ledge. As such, it could be vulnerable to adverse weather conditions or coastal erosion (e.g., storms). However, this species does not have a yearly breeding cycle. Instead, breeding frequency depends on the climate and availability of suitable breeding sites. The bird can reproduce 10 months after the last successful breeding, or 5 months after an unsuccessful one.

Beach erosion, flooding, and temperature are all expected to affect turtle nesting and breeding patterns. Climate change is expected to impact the reproduction of turtles because the temperature of the sand determines the sex ratio of the offspring (i.e., proportion of males to females) (Cayman Islands Government, 2011; Fuller et al., 2013). As such, an increase in air and sea temperatures in the Cayman Islands may affect the number of male versus female turtles born, affecting future reproduction rates. Increases in beach flooding, caused by sea level rise and storms, will affect the survival of turtle eggs and hatchlings, and impacts on their foraging habitat and prey will affect their fitness and survival.

Climate change impacts on the plankton, squid, and fish prey of cetaceans will impact cetaceans (Birchenough et al., 2017), including those in the Cayman Islands. In response, cetaceans may alter their migrations and feeding grounds in order to find prey. Changes to sea temperature, salinity, extreme weather, and sea levels are expected to decrease the range of many marine mammal species

(Elliot & Simmonds, 2007) and lead to changes in migration patterns, abundances, and distributions (Lambert et al., 2010).

### Scoring

Global studies + Regional studies. Medium agreement, limited evidence.

- Relevance (seabirds): Grand Cayman = high, Little Cayman = high, Cayman Brac = high.
- Relevance (turtles): Grand Cayman = high, Little Cayman = high, Cayman Brac = high.
- Relevance (cetaceans): Grand Cayman = medium, Little Cayman = medium, Cayman Brac = medium.

## 3.5 Deep sea and offshore environments

The Exclusive Economic Zone (EEZ) of the Cayman Islands includes 119,023 km<sup>2</sup> of open ocean (DaCosta-Cottam et al., 2009). This offshore region contains important spawning sites for Nassau grouper (*Epinephelus striatus*) and other fish species, and a seamount called Twelve Mile Bank that rises to around 30 m below sea level. The offshore waters surrounding the Cayman Islands are, moreover, important as feeding habitats for seabirds, marine mammals, and turtles (DaCosta-Cottam et al., 2009).

Within the Cayman Islands' EEZ lies the Cayman Trough or Trench, which contains the Caribbean Sea's deepest point at 7,686 m (Britannica, 2022). The Cayman Trough contains some of the world's deepest hydrothermal vents at 5,000 m in depth. Deep-sea vents are considered hotspots of biodiversity, with many species that occur nowhere else in the oceans and some that can live for hundreds or even thousands of years (Levin & Le Bris, 2015). There have been numerous expeditions in recent years to the Cayman Trough, but little information is available as to the species found.

### Current climate impacts

From 1982 to 2016, the average warming trend of offshore waters around the Cayman Islands was between 0.01°C and 0.02°C per year (MONA, 2020). Measurements in some deep basins globally have shown that waters have warmed by 0.01 °C per year (Purkey & Johnson, 2010). Food supply to the deep seafloor has been impacted by declines in oceanic plankton productivity at certain localities and this could affect the productivity of benthic food-webs (Levin et al., 2020).

### Expected future climate impacts

The open ocean is expected to experience changes to temperature, low oxygen, and pH (IPCC, 2022). In deep sea waters, there may be impacts from temperature change, ocean acidification, deoxygenation, and particulate organic carbon flux, all of which could impact biodiversity (Bindoff et al., 2019, Levin & Le Bris, 2015). The warming deep sea temperature signal is projected to emerge from background variability around the year 2040 (Bindoff et al., 2019). Under the highest emissions scenario (RCP8.5), all deep-sea ecosystems are expected to be subjected to moderate risk from climate change by the end of the century (IPCC, 2022).

In 2021, it was announced that marine scientists from the University of Heriot-Watt will work with partners from the Cayman Islands Department of Environment, as part of a UK government Darwin Initiative project to enhance understanding of these critical deep-sea habitats (Heriot-Watt, 2021). Over two years, the team will assess sites offshore from the Cayman Islands, undertaking surveys up

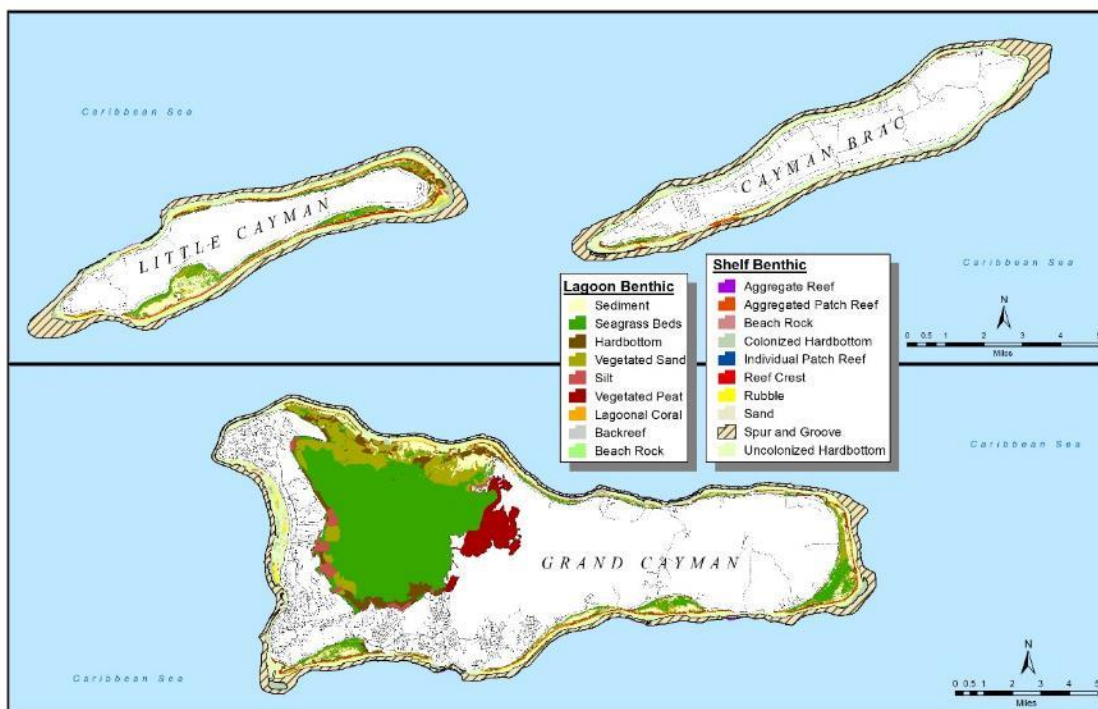
to 2000 m deep. The work will focus on threatened and commercial fish species, including sharks, and map the distribution of deep-water coral and other biotopes (Heriot-Watt, 2021).

### Scoring

Global studies. Medium agreement, limited evidence. Relevance: Grand Cayman = low; Little Cayman = low, Cayman Brac = low.

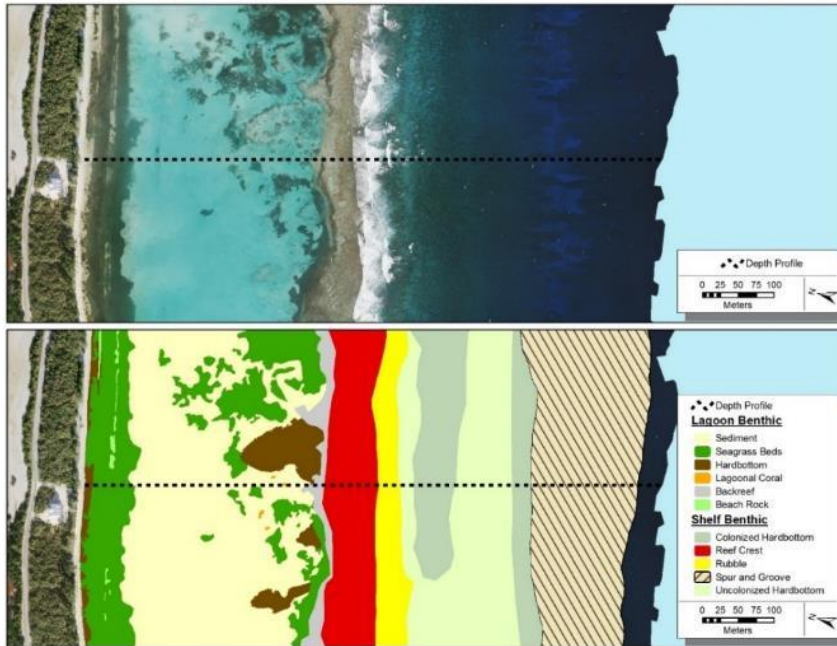
## 3.6 Corals and coral reefs

A fringing reef exists around much of the Cayman Islands and is characterised by a shallow terrace reef at 5-10 m depth, and a deep terrace at 15-20 m (DaCosta-Cottam et al., 2011). This is followed by a deep fore-reef with a steep drop-off at around 22 m. The shelf is around 500 m wide around the islands. Coral reefs occur at Grand Cayman, Little Cayman, and Cayman Brac, although fringing reefs surround around three quarters of Grand Cayman and Little Cayman’s coastlines, compared with only a quarter of Cayman Brac’s (Hurlston-McKenzie, 2011). There are also more diffuse coral communities that inhabit the seagrass beds (Lohr et al., 2017). The reefs of the islands are regularly monitored and any changes are documented (ECLAC, 2004). The different benthic habitats of the Cayman Islands, including reef habitats are shown in Figure 22, and a typical profile is provided (Figure 23) showing the habitats changing with depth for Little Cayman.



**Figure 22.** The benthic habitats around the Cayman Islands. Source: Department of Environment.





**Figure 23.** A typical benthic profile of Little Cayman, showing the shelf and benthic habitats at different depths. Source: Department of Environment.

Around the Cayman Islands, 48% of coastal waters are protected as no-take zones (Marine Conservation Society, 2021). Figures 24 and 25 show the protected areas around the three Cayman Islands. There are different types of protection within Cayman waters that prevent some activities, such as fishing or anchoring, or allow others, such as catch and release fisheries.

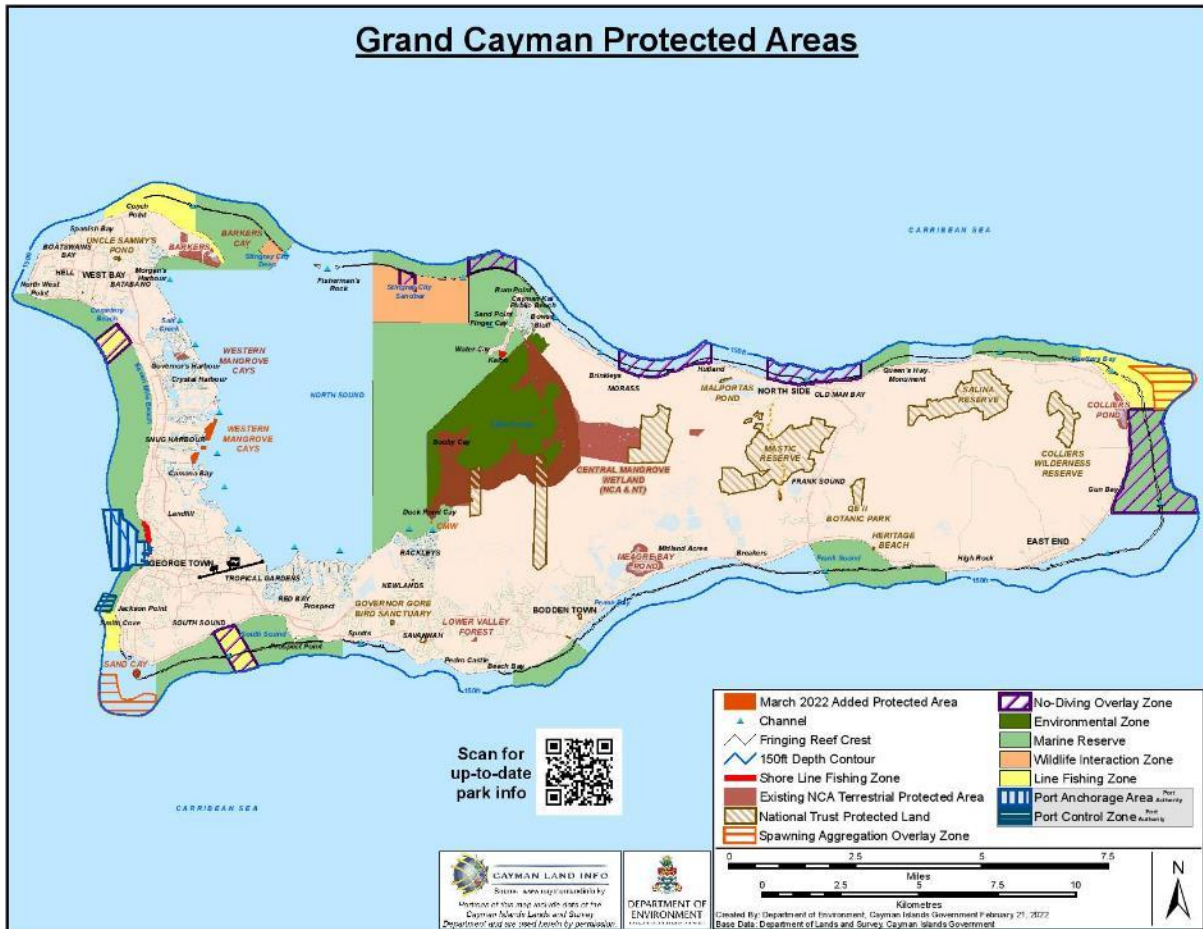


Figure 24. Protected Areas of Grand Cayman (2022). Source: Department of Environment.

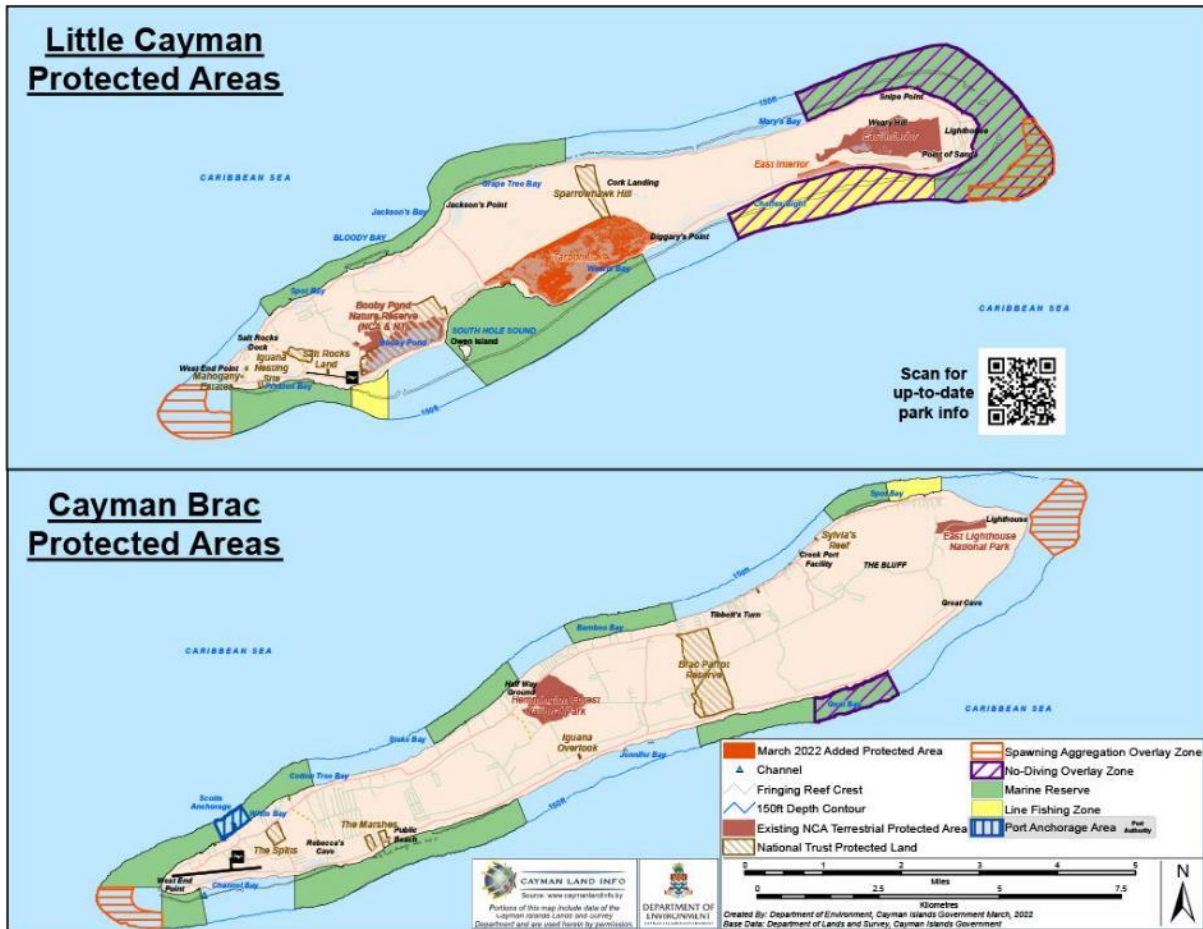


Figure 25. Protected areas of Little Cayman and Cayman Brac (2022). Source: Department of Environment.

In June 2020, a deadly disease causing stony coral tissue loss was found in Grand Cayman that has since spread around the island (Department of Environment, 2022a). Surveys in September 2021 found that it was not yet present in Little Cayman or Cayman Brac (Figure 26) but was widespread in Grand Cayman. The disease has also devastated corals elsewhere in the Caribbean, and so the Department of Environment have put in place measures aimed at preventing any further spread. The combined anthropogenic and natural pressures on coral reefs in the Cayman Islands could influence how resilient corals are to future climate change pressures.



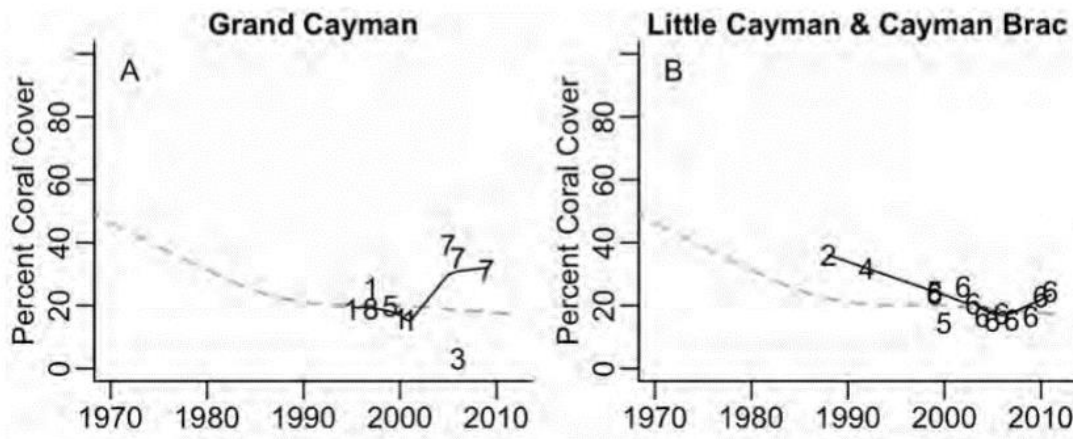
**Figure 26.** Survey results of stony coral tissue loss disease (SCTL D) around the Cayman Islands in September 2021. Source: Department of Environment.

### *Current climate impacts*

Rises in sea temperatures have caused catastrophic increases in the extent and frequency of coral bleaching episodes, and have accelerated a rise in coral disease and death (DaCosta-Cottam et al., 2011). There have also been major storms that have caused substantial damage to the shallow and fringing reef environments (DaCosta-Cottam et al., 2011) of the Caribbean. Hurricane Ivan in 2004 caused damage to the Cayman Islands' coral reefs, including direct damage to reef structures and organisms, and in particular to soft corals (gorgonians) and sponges. The hurricane further caused scour from debris and smothering from deposited sediment (ECLAC, 2004). Most areas of the Cayman Islands saw some damage, although less on the leeward (west) side of the islands. After the hurricane, there was also an apparent reduction in numbers of fish on the reefs.

Surveys have shown that although declining from the 1970s to around 2000, coral cover in the Cayman Islands then increased to 2010 (Jackson et al., 2014) (Figure 27). In Little Cayman, corals were affected by bleaching and white spot disease between 1999 and 2004. However, the reefs recovered by 2010, despite some localised bleaching events; live coral cover increased further to 2012 (Manfrino et al., 2013). More recent data shows that coral cover then declined to 2019 across all three islands, and that there was an increase in algal cover in Grand Cayman and Cayman Brac (Manfrino & Dell, 2019). At Andes Reef in Grand Cayman, monitoring from 1997 to 2013 showed a 55.5% loss in coral cover, mainly attributed to bleaching in 1998. A further 32.3% loss of coral cover from 2013 to 2016 has been recorded and has been attributed to elevated summer sea temperatures causing bleaching and disease outbreaks (Murray et al., 2021).

An additional study showed that by 2019, no reefs in Little Cayman were classified as poor and all were rated fair, good, or good+; an improvement on recent years (Goodbody-Gringley & Manfrino, 2020). In addition, unlike in other parts of the Caribbean, algal cover had declined, no reefs had moved to an algal-dominated state, and parrotfish numbers had increased. Half of the coasts of Little Cayman are in marine protected areas contributing to healthy populations of herbivorous fish, and there are considered to be few other anthropogenic stressors, which is thought to be a significant factor why these corals have been resilient and able to recover.



**Figure 27.** The trend in coral cover in the Cayman Islands from 1970 to 2010. Source: Jackson et al. (2014).

#### *Expected future climate impacts*

An increase in number of intense hurricanes and storms plus sea level rise are to likely damage and degrade coral reefs, and an increase in sea temperatures and ocean acidification is likely to increase the frequency of bleaching and coral mortality (Cayman Islands Government, 2011). Modelling studies of coral richness to the end of the century project that species richness will remain largely the same in the Caribbean under the lower emissions Paris Agreement scenario (SSP1-2.6), but it will decline under the high emissions scenario emission (SSP5-8.5) (Couce et al., submitted). Local coral richness is projected to decline under both scenarios.

The coral communities located within the seagrass beds in Little Cayman are exposed to highly variable temperature and pH compared to fringing coral reefs, which may give them some tolerance to future conditions (Lohr et al., 2017). It is also thought that seagrass beds will provide a buffer against ocean acidification, and so the seagrass beds may continue to provide suitable conditions even if pH levels outside the beds are lower (Lohr et al., 2017). On Little Cayman there are few human stressors and half of the coastline is protected (Manfrino et al., 2013). As such, the corals here may have more resilience to future climate change. On the other islands, reducing non-climatic stressors, such as pollution and disturbance is needed to increase the resilience of corals to climate change (Manfrino et al., 2013), particularly the case for Grand Cayman (Bruckner, 2010).

Little Cayman has been suggested a possible refuge for coral health where corals can adapt and acclimate to changing conditions because they are impacted less by other pressures (Goodbody-Gringley & Manfrino, 2020).

#### *Scoring*

Global studies, Regional Studies, Local climate impact studies, Regular monitoring. High agreement, robust evidence. Relevance: Grand Cayman = high; Little Cayman = high, Cayman Brac = high.

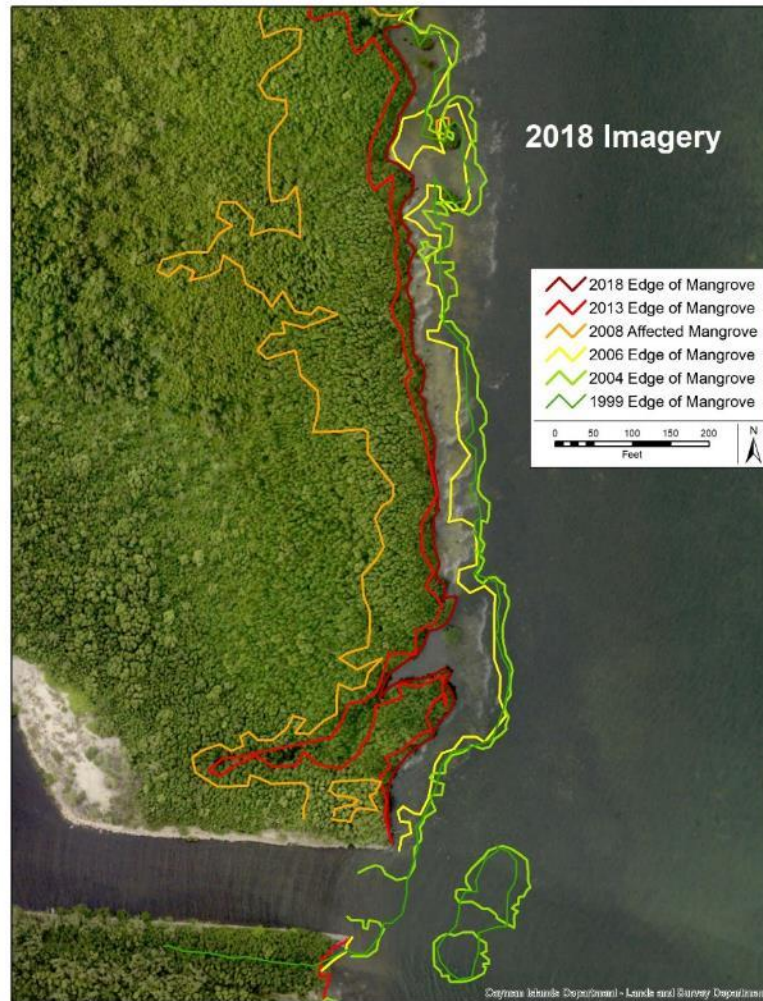
### 3.7 Mangroves

Twenty-six and a half percent of the Cayman Islands is covered by mangrove forest, with a total cover of 70.9 km<sup>2</sup>. Thirty-three percent of Grand Cayman is covered by mangrove forest and shrubland, with a total cover of 65.6 km<sup>2</sup> (UNESCO, 2022). Mangroves occur on all three of the Cayman Islands; they occur along the coast of Grand Cayman and Little Cayman (not Cayman Brac), and there are inland mangroves on all three islands. As of September 2022, 24% of Grand Cayman mangrove habitat and 25% of the Cayman Islands' mangrove habitat were protected. The Central Mangrove Wetland on Grand Cayman covers 8,655 acres, 3,292 of which are protected by a combination of the National Conservation Act and the National Trust for the Cayman Islands. The mangroves of the Cayman Islands support a range of wildlife, including nesting birds, crustaceans, fish, Agoutis (*Dasyprocta punctata*), and sliders or hickatees (Cuban slider, *Trachemys decussata*) (National Trust for the Cayman Islands, 2022). Mangroves are hugely valuable for coastal protection, dissipating wave energy from the sea, reducing coastal erosion, and flooding (Department of Environment, 2016). Moist air from the Central Mangrove Wetland is also thought to be largely responsible for much of western Grand Cayman's rainfall. Mangrove forests are also valuable as an important blue carbon habitat, locking away carbon in the sediment and removing it from the atmosphere (Department of Environment, 2016) (see section on Carbon sequestration and storage by terrestrial, coastal, and marine habitats).

In the Caribbean, the main threats to mangroves are coastal development, agriculture, and aquaculture (habitat destruction); pollution and environmental degradation; local exploitation for fuel or building materials; and sea level rise (Wilson et al., 2017). Between 1976 and 2018, 72% of mangroves and marshes at the western end of Grand Cayman were lost (Department of Environment, 2016). Mangroves are now protected under the National Conservation Act (2013), which aims to conserve the remaining mangroves (The National Conservation Council of the Cayman Islands, 2022).

#### *Current climate impacts*

Mangrove cover across the Caribbean has reduced in recent decades, however, this has mainly been caused by non-climatic actors (Wilson et al., 2017). Figure 28 shows how mangrove cover has changed in the Camana Bay area in Grand Cayman over recent years.



**Figure 28.** Mangrove extent from 1999 to 2018 in Camana Bay, Grand Cayman. The orange line shows the extent of mangrove still showing impacts in 2008, four years after Hurricane Ivan. Source: Department of Environment.

Previous hurricanes in the Cayman Islands have flooded coastal mangroves, causing them to retreat or die-back in areas (Hurlston-McKenzie, 2011). Some of these have recovered, but the recovery can be slow. Following Hurricane Ivan, some narrow areas of mangrove, which had been reduced through construction and development, were not able to provide protection from the hurricane or to withstand the winds in comparison to larger, contiguous areas of mangrove (Hurlston-McKenzie, 2011).

Mangrove fringed coastal pools are generally formed by hurricane storm surges and floodwaters overtopping beach ridges leading to the death of mangroves and their replacement by standing water. Their extent could increase with increased frequency of hurricanes and storm surges. For example, mangroves receded c. 7 m in Little Sound (Grand Cayman) after Hurricane Ivan (2004) and were drowned in Tarpon Lake (Little Cayman) following Hurricane Gilbert (1988) with the pace of recovery extremely slow (Hurlston-McKenzie, 2011). The impact of such occurrences can be amplified by losses of coastal mangroves and coral reefs via reduced capacities for buffering storm surges with reduced hurricane return times and SLR as further exacerbating factors (Wood Group UK Ltd., 2021b).



### *Expected future climate impacts*

Mangroves, along with coral reefs, are one of the most vulnerable habitats to climate change and are expected to experience severe impacts (IPCC, 2014). It is likely that hurricanes, sea level rise, and storm surges will cause damage to and loss of mangroves around the Cayman Islands, which in turn could exacerbate flooding on the islands because mangroves are a natural flood barrier (Cayman Islands Government, 2011). Mangroves would suffer more damage if severe hurricanes become more frequent in the region, as they would not have the time in between storms to recover, subsequently providing less storm protection to the islands (Hurlston-McKenzie, 2011).

There are studies suggesting that mangrove growth might not be able to keep up or accrete sediment as fast as rising sea levels this century, although others show that if sea level rise is limited or slowed, this may be possible (Wilson et al., 2017). In some areas, roads have been cut through coastal mangroves or there are man-made structures that would prevent them from retreating as sea level rises (Hurlston-McKenzie, 2011). On small islands, such as the Cayman Islands, inland retreat of mangroves is likely to be limited by land area and development. However, the Department of Environment considers that Cayman Islands mangroves are currently accreting at the same pace as sea level rise (UNESCO, 2022).

### *Scoring*

Global studies, Regular monitoring, Local climate impact studies. Medium agreement, robust evidence. Relevance: Grand Cayman = high; Little Cayman = high, Cayman Brac = medium.

## 3.8 Seagrass

The fringing reefs around the Cayman Islands enclose shallow lagoons filled with seagrass and sand (DaCosta-Cottam et al., 2011), with seagrass occurring around all three of the Cayman Islands (Figure 23). The North Sound in Grand Cayman is a particularly large lagoon area containing seagrass (Hurlston-McKenzie, 2011). Much of Grand Cayman's seagrass is protected, either in Environmental Zones or Marine Reserves, particularly in North Sound and South Hole Sound Reserve on Little Cayman (Figure 24 & 25).

As with mangroves, healthy seagrass beds are a blue carbon habitat, acting as a carbon sink by locking carbon into the sediment (Blue Carbon Initiative, 2021; IPCC, 2022). They also absorb wave energy, reducing storm and wave impacts on coastlines (IPCC, 2022). Non-climatic threats to seagrass in the Caribbean are direct physical damage, such as anchor damage or coastal development, and pollution and siltation from land-based run-offs (Birchenough et al., 2017). Blooms of Sargassum have also caused mortality and damage to seagrass beds in the Caribbean (IPCC, 2022). Surveys of seagrass in Grand Cayman have shown that the high number of visitors are causing degradation to the beds (van Tussenbroek et al., 2014). Some of the seagrass beds are within No-Diving Zones or contain public moorings (Figure 24 & 25), which will help to prevent damage, as will the ban on anchoring around the Cayman Islands. Across the Caribbean, seagrass bed restoration efforts are taking place as an example of climate adaptation.

### *Current climate impacts*

Around 30% of seagrass beds have been lost globally, caused by a combination of climate change and other human impacts (Brodie & N'Yeurt, 2018). Sea temperatures have caused seagrass meadows in low-latitude areas globally to contract in some areas by as much as 43% following heat waves (Bindoff

et al., 2019). However, it is not clear to what degree climate change has contributed to the overall decline to date (IPCC, 2022).

In the Cayman Islands, Hurricane Ivan caused damage to the seagrass beds around the islands causing blades to be torn off and the increased turbidity after the hurricane reduced light availability, photosynthesis, and therefore, productivity (ECLAC, 2004).

#### *Expected future climate impacts*

If severe storms become more frequent in the Caribbean with climate change, seagrass beds may not be able to recover between storms (Hurlston-McKenzie, 2011). Increased sea temperatures, changes in salinity, and sea level rise may all affect seagrasses and result in their loss or decline (Hurlston-McKenzie, 2011). Marine heatwaves can also cause mass mortality of seagrass and result in a regime shift away from seagrass beds, especially in areas where there are other human impacts, such as pollution acting on the seagrass (IPCC, 2022). Sea level rise may impact seagrass beds by changing the physical conditions they live in, such as reducing the shelter that lagoons provide (Brodie & N'Yeurt, 2018). However, an increase in CO<sub>2</sub> may increase photosynthesis and growth rates of seagrass, and warmer sea temperatures may increase flowering rates, both of which will benefit seagrasses (Bindoff et al., 2019). Lower pH may even increase thermal tolerance of some seagrass species (IPCC, 2022).

#### *Scoring*

Global studies, Regional studies. Low agreement, medium evidence. Relevance: Grand Cayman = high; Little Cayman = high, Cayman Brac = medium.

### 3.9 Marsh and wetlands

Wetlands are widespread on Grand Cayman and Little Cayman, where a series of interconnected tidal and wetland habitats exist. They are a rare feature on Cayman Brac, being found only in the south west corner. There are no rivers on the islands and so these wetlands are the only source of fresh, or more typically brackish, water. Indeed, natural freshwater pools are a rarity and of key conservation interest, and thus of key concern in terms of their exposure to risk from climate change impacts. Note that truly freshwater systems have dissolved salts of <1 part per thousand (specific conductance < 2.5 mS/cm), while seawater contains c.32-35 ppt, and brackish water lies between these values (DaCosta-Cottam et al., 2009). On all islands, only limited areas are officially protected, meaning wetland systems face many risks beyond climate change.

The 2009 National Biodiversity Action Plan (NBAP) identifies different types of wetland vegetation. These include salt-tolerant succulents and pools, and ponds and mangrove lagoons (note that mangrove vegetation is dealt with elsewhere in this report). The salt-tolerant succulent vegetation type is defined by areas of succulent-dominated forb vegetation (non-woody plants other than grasses, sedges, and rushes) influenced by regimes typically of high salt and temporary or occasional water immersion. In coastal areas, this may include tidal areas or those influenced by the tide. Further inland, this habitat forms in association with temporarily flooded pastures and moderately elevated rocky cays often at the edges of 'true' wetlands and mangroves. According to the NBAP, salt-tolerant succulents are generally patchy and occupy an extremely restricted area (DaCosta-Cottam et al., 2009). Many are only a few metres square, making them vulnerable to localized disturbance. They incorporate the following vegetation formations, as per Burton (2008):

- Tidally flooded perennial forb vegetation V.B.1.N.e
- Tidal tropical or subtropical annual forb vegetation V.D.1.N.d.

Key sites for salt-tolerant succulents are Barkers, Salt Creek, Meagre Bay Pond/Midland Acres wetlands, Bowse Land, North Side in Grand Cayman, and Preston Bay in Little Cayman. Indeed, this latter site has a subtropical annual vegetation known only in this location due to percolation of tidal sea water through underground fissures, supporting an almost monospecific stand of *Salicornia bigelovii* (DaCosta-Cottam et al., 2009). Two species tend to be dominant, *Sesuvium portulacastrum* and *Salicornia virginica*, which attract a number of butterflies, including the rare endemic subspecies, the Cayman Pygmy Blue butterfly (*Brephidium exilis thompsoni*). This very small butterfly, possibly the smallest in the world, is highly dependent on salt-tolerant succulents at all stages of its life-cycle. In its larva form, the caterpillars feed on *Salicornia perennis*, while adults depend on *Sesuvium portulacastrum* for nectar. Salt-tolerant succulents also support the West Indian Whistling-duck (*Dendrocygna arborea*).

The ponds and pools vegetation type is defined in the NBAP as natural and man-modified areas of standing permanent and temporary water and associated vegetation. The classification also includes ditches and flooded marl pits but we do not consider these further here.

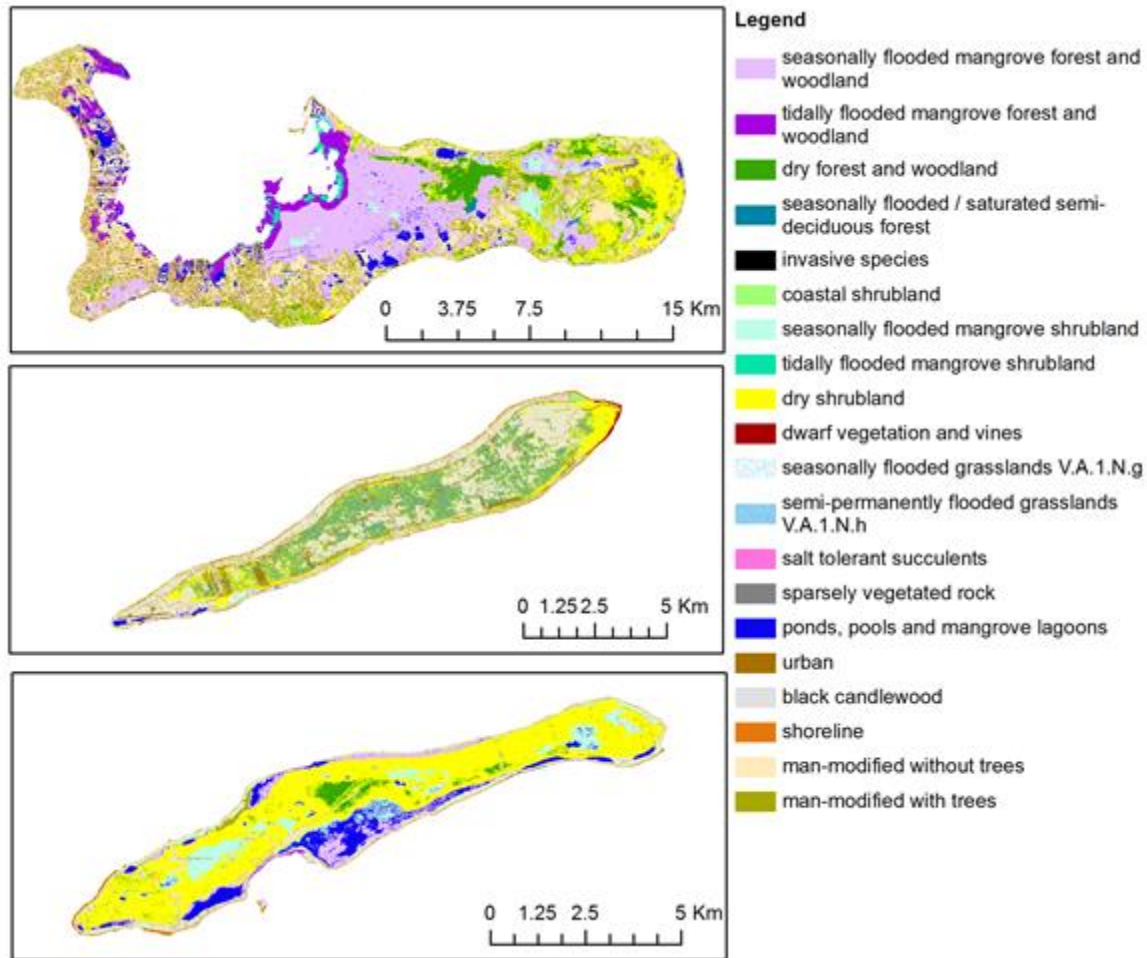
The following vegetation formations are included:

- Semi-permanently flooded grasslands V.A.1.N.h 31
- Aquatic vegetation V.C.1.N.a.

There are also managed, agricultural areas that can be seasonally flooded, described by Burton (2008) as “Seasonally flooded grasslands V.A.1.N.g”. According to the NBAP, pools and ponds are abundant in buttonwood wetlands, as well as in mangrove areas. Animals and plants are highly sensitive to salinity gradients, and modest fluctuations can have profound consequences on distributions. This sensitivity has clear implications for wetland responses to climate change and associated salinity changes. The freshwater pools are particularly vital as a source of drinking water for birdlife and other animals, and thus support flora and fauna not found elsewhere (DaCosta-Cottam et al., 2009).

Any of the main wetland systems (e.g., salt tolerant succulents/pools, ponds, and mangrove lagoons) can vary in salinity through the course of the year. Following heavy rains, salinity tends to decrease, while hypersalinity (i.e., that wetlands become saltier than seawater) can be caused by excessive evaporation in the dry season. Salinity dynamics are accompanied by changes in wetland extent over the course of a year, given the pronounced wet and dry season to the Cayman Islands climate. Changes in extent depend on the depth of the waterbody, as well as the amount, intensity, and duration of preceding rains and intensity of evaporation over the subsequent dry season.

Between six and two thousand years ago, stratigraphic records indicate the currently marine North Sound lagoon was characterised by fresh-brackish water; c.2000 years ago, it adopted its marine status (Booker & Jones, 2020). In the more recent past, wetland prevalence and its associated biodiversity have been affected by human development and pollution. These pressures have led to reductions in wetland distribution and their current status across the three islands (Figure 29). Wetland reclamation on Grand Cayman has involved extensive dredging of the aforementioned North Sound lagoon (28% of the shallow transitional marine habitat as delineated in the 2002 CH2MHill Aggregate and Fill Study). In 2018, approximately 76.5% of the upland natural wetland and forested areas within the western shores of the North Sound and 81.0 % of the southern shores had been lost through alterations.



**Figure 29.** Wetland distribution (this section; focus on salt tolerant succulents and ponds and pools) together with other land cover classifications for Grand Cayman, Cayman Brac and Little Cayman. Source: Department of Environment, Cayman Islands Government (March 2022).

### Current climate impacts

Climate change would be expected to have a number of impacts on wetlands and their associated biodiversity. Raised atmospheric temperatures could increase soil and water temperatures, while increased evaporative demands may change water levels, which may be offset by some changes in precipitation at certain times of year (i.e. wetter winters). Likely of more concern would be increases in salinity associated with storm surges/hurricanes bringing saline water across the coast in low-lying parts of the Caymans and compounded by slower onset sea level rise and potential changes in the few freshwater lenses that underlie parts of the islands.

The impact of climate change on groundwater, including freshwater lenses, is dealt with elsewhere in this report. However, in terms of links to vegetation, it is noteworthy that recent work from the Palmyra Atoll in the Pacific Ocean shows that *Pisonia* trees (a genus found in the Cayman Islands, notably the Grand Cayman endemic, *Pisonia margaretae*) are likely threatened by lens volume decreases of 40 % during dry cycles (Briggs et al., 2021). Overall, the Caribbean has become more arid over time (Gregory et al., 2015) and this trend is expected to continue, albeit with variability associated with ENSO and the AMO, whose influences on Caribbean climate have changed over time (Burn et al., 2016).

Negative impacts of reduced precipitation leading to freshwater lens contraction and coastal salinisation upon coastal strand vegetation have been observed in two islands of the Bahamas (Greaver & Sternberg, 2010). In this study, reduced precipitation increased the water table depth to beyond that accessible by plants and for recharge of overlying soil areas so that plants were increasingly reliant upon infrequent rain events and moisture in surficial soils. Greaver and Sternberg (2010) note that, 'Quantifying species tolerances to ocean water intrusion and drought are necessary to determine a threshold of community sustainability.' This observation is underscored by a variety of studies of the Florida Keys and Everglades. Goodman et al. (2012) highlight the role of coastal soil-water salinisation as a driver of an endangered tree species decline (of *Pilosocereus robinii*), while Willard and Bernhardt (2011) and Meeder et al. (2017) show that sea-level rise over the last century was accompanied by saltwater intrusion based on palaeoecologic and stratigraphic approaches with alterations to wetland community composition.

Ross et al. (1994) show the replacement of former freshwater dependent vegetation by halophytic plant assemblages due to salinisation of soil and groundwater due to sea level rise. Ross et al. (2020) highlight the role of coastal inundations and associated increases in coastal soil-water salinity due to hurricane events in the decline of freshwater dependent coastal pine forests. Sah et al. (2018) demonstrate the importance of altered hydrologic gradients through drying in the succession, expansion, and contraction of coastal flood intolerant woody and flood tolerant herbaceous plants. Williams et al. (1999) show relationships between tidal flooding frequency and zonation of tree species, and notably that decades may elapse between cessation of regeneration and local elimination of a tree species (based on *Sabal palmetto*) due to absence of seedling recruitment in newly flooded stands that ultimately result in forest retreat and replacement by halophytes.

There is very limited information (essentially none) in the published literature concerning wetland and associated species responses to climate change within the Cayman Islands. However, at least one species (*Agalinis kingsii*) is a rare Grand Cayman species that is limited by habitat availability within sedge wetlands. With only two populations, both found within a narrow geographic and ecological range, authors have concluded that this species is very sensitive to extinction by a stochastic event (Diochon et al., 2003). Such 'stochastic' events may be more likely with the determinism of climate change.

Interactions among species can be important in determining wetland response to climate change. Anurans (frogs and toads) in a neotropical wetland find refuges from high temperatures due to the presence of crab burrows and termite thermal chimneys. Without these structures created by other organisms, anurans would find it difficult to tolerate higher temperatures (Simioni, 2014). Species themselves can act to improve conditions associated with climate change. Thus, Allen and Conner (2021) showed how shrubs located on hummocks in a salinity-affected freshwater marsh in South Carolina channelled freshwater to their roots by intercepting precipitation, thus avoiding any deleterious consequences that would be associated through exposure to the mesohaline waters. They raise the intriguing possibility that stemflow funnelling is an ecophysiological important mechanism that increases freshwater availability and facilitates shrub persistence in an otherwise stressful environment.

### *Expected future climate impacts*

We found no published research predicting future climate change impacts on wetland flora and fauna within the Cayman Islands, and limited relevant research from the wider Caribbean area.

There are data available on expected changes in habitat distribution associated with different sea level rise scenarios from 0.25 to 1 m with a most likely expectation of 0.75 m rise. However, as noted in the forest, woodland, and shrubland section, these scenarios don't consider effects of sea level rise beyond inundation of elevations below the expected level, nor do they consider possible alterations

to existing land cover boundaries. Nonetheless, these scenarios suggest a high risk of habitat loss for the different wetland habitats where they are relevant across the different islands (i.e., excluding Cayman Brac) (Table 7).

**Table 7.** 2010 wetland habitat extent on each of the Cayman Islands, and percentage loss of habitat associated with 0.25, 0.5, 0.75 (the most likely scenario) and 1 m sea level rise. Source: Figures extracted from Hurlston-McKenzie et al. (2011).

Habitat type	2010 extent (acres)	% loss associated with sea level rise of x m			
		0.25	0.5	0.75	1
<i>Grand Cayman</i>					
Pools, ponds and mangrove lagoons	1398	52.84	85.66	95.71	97.74
Salt tolerant succulents	33.6	5.89	28.4	67.02	90.23
Seasonally flooded semi-deciduous forest	164	0.06	1.29	8.02	29.3
Seasonally flooded grasslands	99.6	0.01	0.49	32.09	74.5
Semi-permanently flooded grasslands	122.7	3.44	10.88	26.52	56.67
<i>Cayman Brac</i>					
Pools, ponds and mangrove lagoons	-	-	-	-	-
Salt tolerant succulents	-	-	-	-	-
Seasonally flooded semi-deciduous forest	-	-	-	-	-
Seasonally flooded grasslands	1.3	72.91	97.66	98.42	99.25
Semi-permanently flooded grasslands	0.17	28.79	67.1	72.27	77.36
<i>Little Cayman</i>					
Pools, ponds and mangrove lagoons	241	3.95	50.62	94.32	99.56
Salt tolerant succulents	9.25	0	0	1.38	17.37
Seasonally flooded semi-deciduous forest	-	-	-	-	-
Seasonally flooded grasslands	50.5	0	0.01	0.04	2.77
Semi-permanently flooded grasslands	1.99	0	0	4.57	45.2

The figures reported in Table 7 assume that habitats maintain their 2010 distribution in the face of multiple climate change and other threats, and that the only impact of sea level rise is on inundation of land lying below the amount of sea level rise. It is likely that these assumptions are unrealistic, and

we anticipate other changes to habitat distribution in light of climate change impacts as noted in the main text.

Of particular interest for vegetation is numerical modelling work by Chui and Terry (2013), who examined the influence of sea-level rise on freshwater lenses of different atoll island sizes and their resilience to storm-induced salinisation through wave washover of low-lying land (i.e., a situation very pertinent to the Cayman Islands). Steady-state solutions indicate that smaller islands develop much more restricted lenses than larger islands, and these lenses are more vulnerable to anticipated sea level rise. Counterintuitively, freshwater lens vulnerability to storm-induced washover salinisation may be reduced after sea level rise. This is because of the thinner layer of unsaturated substrate lying above the water table into which saline water can infiltrate and accumulate during a storm (Chui & Terry, 2013).

It might be expected that increased salinity in the brackish waters of much of the Cayman Islands will favour the expansion of salt-tolerant succulents. However, their patchy distribution (see description text) may limit the extent of any response. Furthermore, sea level rise may result in inland migration of wetlands. In many areas, this will possibly be constrained by infrastructural development and the geological characteristics of the Cayman Islands, further squeezing the area available for these important habitats for biodiversity. Salinisation and the general increase in aridity in the Caribbean can be offset, at least partially, by heavy precipitation events. It remains unclear to what extent biodiversity will be maintained by these dynamics and whether, for example, there are species that can channel freshwater to their roots, as observed for shrubs in South Carolina wetlands. Alternatively, groundwater salinity can be modified by freshwater uptake, as observed for phreatophytes on some coral islands (Comte et al., 2014).

#### *Scoring*

*Evidence: Regional studies. Medium agreement. Low evidence.*

Relevance: Grand Cayman = high; Little Cayman = high, Cayman Brac = low (very limited wetland extent).

### 3.10 Evergreen thicket and woodland

Forest and woodland represent some of the most important habitats for terrestrial biodiversity on the Cayman Islands. Elements of biodiversity (e.g., invertebrates, birds, bats) found within these habitats are dealt with elsewhere (sections on Terrestrial mammals, birds, and reptiles; Endemic species; Non-native species). In this section, having described the habitat characteristics and distribution, we concentrate on the climate risks to the habitats as a whole. We also consider dry and/or coastal shrublands, as they are not dealt with elsewhere in the report.

Forest, woodland, and shrubland refer to habitats that have the presence of woody vegetation, typically including trees. The cover of trees determines whether an area is forest (60-100% tree cover), woodland (25-60%) or shrubland (<25%). Although in common usage, the height of the vegetation would typically be considered important as trees can be of stunted form. Indeed, the NBAP notes that shrubland is a class of vegetation dominated by flora ranging in height between 0.5 and 4.25 m (DaCosta-Cottam et al., 2009). The shrubs themselves tend to grow as separate individuals or clumps of individuals. The canopy cover of shrubs has to be greater than 25% for it to constitute shrubland. The Cayman Islands are home to all three types of woody vegetation habitat, with shrubland being divided into coastal shrubland and dry shrubland according to the NBAP (DaCosta-Cottam et al., 2009).

In Grand Cayman, using protected areas as of September 2022 and 2013 landcover/habitat, dry forest and woodland covered 7% of the island (13.3% of habitat was protected), while dry shrubland made up 12% of the land mass (6.8% of habitat was protected). Xeromorphic semi-deciduous forest is prevalent on Cayman Brac (32% of the land mass, 11.9% of habitat protected), while dry shrubland made up 18% of the land mass (7.1% of habitat protected), while Little Cayman has 54% cover of dry shrubland (13.3% of habitat protected) and 4% dry forest and woodland (7.5% of habitat protected). Examples of seasonally dry tropical forest on oceanic islands are rare, meaning that the Cayman Islands, with associated endemic species, are important representatives. The forests on the Cayman Islands also contain much biodiversity that is considered culturally important, such as the Ironwood (*Chionanthus caymanensis*); the National Tree, Silver Thatch palm (*Coccothrinax proctorii*); the National Bird; the Cayman parrot (*Amazona leucocephala*); and the National Flower, the Banana orchid (*Myrmecophila thomsoniana*) (DaCosta-Cottam et al., 2009). Coastal shrubland is a very important habitat for the endemic Grand Cayman Blue iguana (*Cyclura lewisi*).

According to the NBAP, key coastal shrubland habitat categories are (DaCosta-Cottam et al. (2009) and after Burton (2008)):

- Hemi-sclerophyllous evergreen shrubland III.A.1.N.b
- Sclerophyllous evergreen shrubland III.A.1.N.c
- Mixed evergreen: drought-deciduous dwarf-shrubland IV.C.1.N.a.
- Low tropical / subtropical perennial forb vegetation V.B.1.N.b

Dry shrubland found elsewhere in the Cayman Islands can be related to drought stress, meaning there is insufficient water for trees to grow. According to the NBAP, key habitat categories are (DaCosta-Cottam et al. 2009)) (after Burton 2008):

- Tropical or subtropical broad-leaved evergreen shrubland III.A.1.N.a
- Mixed evergreen-drought deciduous shrubland with succulents III.C.1.N.a

Key dry shrubland sites are East End and High Rock on Grand Cayman, Lighthouse on Cayman Brac, and the Interior of Little Cayman. As of 2022, the Salina Reserve and Colliers Wilderness Reserve on Grand Cayman (7% of dry shrubland habitat is protected), the East Interior of Little Cayman (13% of dry shrubland habitat is protected), and The Splits and East Lighthouse National Park on Cayman Brac (7% of dry shrubland habitat is protected) are protected areas that contain significant portions of dry shrubland. Nine percent of all dry shrubland is protected for the Cayman Islands.

Most of the forest/woodland on the Cayman Islands, like the shrubland, is seasonally dry. It occurs where the water table is more than 2 m below the ground surface. These habitats are typified by a mix of evergreen (i.e., maintaining their foliage throughout the year) and drought-deciduous trees that shed their leaves during the dry periods. The forests/woodland are structurally complex, with the main canopy, some emergent species, and an understorey layer. Dry forest is regarded as the most biodiverse terrestrial habitat on the Cayman Islands, closely followed by the dry shrublands (DaCosta-Cottam et al., 2009). Interestingly, dry forest habitats are most biodiverse when adjacent to wetlands. Humidity from the wetlands provides conditions in the understorey conducive to profuse epiphytic growth, including of bromeliads and orchids. Ancient trees provide cavities for birds and bat species; notably, the white-shouldered bat (*Phyllops falcatus*) is found in this habitat (Cottam et al., 2009).

Notable forested areas on Grand Cayman are The Mastic region (North side) and the Ironwood forest (George Town). As of 2009, the latter was unprotected, despite having Grand Cayman's most significant populations of the bromeliad Old George (*Hohenbergia caymanensis*) and Ghost orchids (*Dendrophylax fawcettii*). Little Cayman has the Central Forest and Cayman Brac the Bluff forest as noted forest areas (DaCosta-Cottam et al., 2009).



Key habitats for forest and woodland (according to the NBAP (2009) and after Burton (2008b)) are:

- Lowland semi-deciduous forest I.C.1.N.a
- Seasonally flooded / saturated semi-deciduous forest I.C.1.N.c
- Xeromorphic semi-deciduous forest I.C.4.N.b (only found on Cayman Brac)
- Lowland / submontane drought-deciduous woodland II.B1.N.a.
- Tropical or subtropical semi-deciduous woodland II.C.1.N.a

#### *Current climate impacts*

As with other sections, there is a general lack of evidence of climate change impacts on these vegetation types in the Cayman Islands. Indeed, Heartsill-Scalley and Lopez-Marrero (2021) make clear from their research in Puerto Rico that this lack of evidence applies to forests more widely, with research needed on a range of forest types and landscape compositions. Long-term monitoring data is important. In a study of the El Yunque National Forest (Puerto Rico), Campos-Cerqueira and Aide (2021) showed that drought preceding a hurricane had a stronger effect on forest fauna than the hurricane itself. Prior observations allowed the authors to properly interpret observations of post-hurricane effects by explicitly integrating multiple and previous disturbances into their analyses (Heartsill-Scalley & Lopez-Marrero, 2021). Spacing between disturbances induced by climate change is likely very important in forest dynamics.

Despite the lack of direct evidence from the Cayman Islands, we have found some observations of past climate change impacts in similar contexts relevant to seasonally dry forest, woodland, and shrubland. Work comparing leaf and stem traits of 22 species in the Brazilian caatinga showed divergence in the physiology and climate responses of deciduous species, and cautioned that categorizing species based solely on their leaf phenology may be an oversimplification (de Souza et al., 2020). More particularly, those deciduous species with a high wood density had xylem water potential that continued to drop during the dry season, meaning they are more resilient to drought effects. In addition, deciduous species with longer leaf life span are less vulnerable to hydraulic conductivity loss than early deciduous species, as there was a negative linear relationship between leaf life span and the transpiration rate per unit of hydraulic conductivity (de Souza et al., 2020). De Souza et al. (2020) found that evergreen trees are only sensitive to soil drought, while deciduous trees are sensitive to both soil and air drought.

Tree or shrub species can respond differently at gene expression level due to drought stress (Sobreiro et al., 2021). Among four neotropical Bignoniaceae tree species (two from savanna [*Handroanthus ochraceus*, *Tabebuia aurea*], and two from seasonally dry tropical forests [*Handroanthus impetiginosus*, *Handroanthus serratifolius*]), all showed different mechanisms of response to water deficit and had transcription factors shared with other families suggesting a wider relevance (Sobreiro et al., 2021). The *Tabebuia* genus is found on the Cayman Islands. Interestingly, savanna species seem to be less responsive to drought at the transcriptional level, which the authors argue is likely due to morphological and anatomical adaptations to seasonal drought in such habitats. In contrast, the species with the largest geographical range, including being found on the neighbouring island of Cuba, and widest edaphic-climatic niche (*H. serratifolius*) was the most responsive, exhibiting the highest number of differentially expressed genes and up- and down-regulated transcription factors (Sobreiro et al., 2021).

Long-term vegetation dynamic investigations certainly suggest that dry forest has a degree of resistance to drier conditions, albeit with species turnover to drought-tolerant taxa (Plumpton et al., 2020). However, this evidence does come from Bolivia, where results also indicated the importance of fire in determining the distribution of savanna and dry forest. Fire and drought dynamics could be important in determining transitions among dry forest and shrubland and other habitats in the Cayman Islands in the future, as fire (usually anthropogenic in origin) becomes more prevalent

(DaCosta-Cottam et al., 2009). The importance of fire and drought driving recovery processes in forest edges was observed in New Caledonia (Blanchard et al., 2021). The extent to which these findings from a steep volcanic island can be transferred to the low-lying, karstic Cayman Islands remains uncertain.

Transitions among habitat types could also relate to ground water dynamics. As highlighted earlier, where the saturated zone is more than 1 m below the ground surface, trees can thrive. However, ground water levels may rise in response to climate change driven increase in sea level (section Freshwater Environments and Resources), although with a high degree of uncertainty and localised variation. Any ground water rise may lead to an expansion of shrub habitat at the expense of woodland and forest. Sea level rise, along with disease, invasive non-native species, and other anthropogenic disturbances, has been identified as a threat to the cacti genus *Consolea* (Majure et al., 2021).

As well as habitat distributions depending on interactions among drivers related to climate change, plant responses may also depend upon legacies of previous events. Umana and Arellano (2021) showed across an elevational gradient on Puerto Rico (from 250 to 1000 m above sea level) that trees from six different species have consistent declines in their performance when subjected to successive and different major climatic stresses, in this case drought and hurricanes. However, they also showed that species showed differential susceptibility to hurricanes, while being generally susceptible to droughts. Individual trees that showed reduced growth during droughts tended to show reduced growth following hurricanes too (Umana & Arellano, 2021).

Recent research from Guanica dry forest in Puerto Rico notes how important stand characteristics are, such as spacing of trees and/or species composition, in determining resilience to climate change events (Gao & Yu, 2021). In more detail, damage from major hurricanes in 2017 was small in places with high stem density or high tree cover. Ground-observed damage in terms of height reduction significantly increased with the standard deviation of stem height, but decreased with the mean stem diameter of the plots. The fraction of lost stems significantly decreased with stem density, while the fraction of damaged stems significantly increased with canopy roughness and plot elevation (Gao & Yu, 2021). Gao and Yu (2021) also highlight that tropical dry forests differ from wet forests in their response and resistance to tropical storms because of their lower diversity, larger root to shoot ratios, and lower height to diameter ratios (i.e., taper/slenderness). This reiterates the point made by Heartsill-Scalley and Lopez-Marrero (2021) that more and different forest types need investigating to understand risk exposure to climate change.

### *Expected future climate impacts*

Projections of climate change impacts on the forest, woodland, and shrubland of the Cayman Islands are again relatively scant, especially in relation to risks to biodiversity and compositional change. The NBAP (2009) suggests that the orchids found in some humid understories may be vulnerable to hurricanes due to canopy exposure and a lack of underground storage organs and seed banks. More generally, increases in extreme events and the cumulative impacts of storms will likely affect the adaptation responses of forests on tropical islands in the short term where regeneration is often slow. The ability of terrestrial species to migrate is limited by the nature of the islands, also constraining natural adaptation (DaCosta-Cottam et al., 2009).

Spatial predictions of habitat loss due to climate change-induced sea level rise are available for each of the islands within the group (Table 8). It appears that most habitat types are resistant to sea level rise, except for a loss of around a tenth of the dry shrubland habitat on Grand Cayman and Cayman Brac, associated with a 1 m sea level rise. Woodland habitats on Little Cayman appear resistant to change under likely sea level rise. However, these projections are based on land cover remaining static within 2010 boundaries, and only consider the ingress of water based on the elevation of the island.

As noted in the freshwater and wetland sections, sea level rise will likely be accompanied by changed groundwater and freshwater lens dynamics, possibly altering habitat distributions. If depth to groundwater becomes shallower, it is likely that forest and woodland habitats will turn into shrubland over time as trees will die in the anoxic conditions. The role of enhanced evaporation with respect to the future impacts on the vadose zone is somewhat uncertain, as well as the potential for greater salinity of groundwater (see Freshwater section).

**Table 8.** 2010 habitat extent on each of the Cayman Islands, and percentage loss of habitat associated with 0.25, 0.5, 0.75 (the most likely scenario) and 1 m sea level rise. Source: Figures extracted from Hurlston-McKenzie et al. (2011).

Habitat type	2010 extent (acres)	Sea level rise (m)			
		0.25	0.5	0.75	1
<i>Grand Cayman</i>					
Coastal shrubland	268	0.43	1.34	2.63	4.65
Dry forest and woodland	7367	0.02	0.27	2.15	8.59
Dry shrubland	2974	0.22	1.52	3.91	10.28
Xeromorphic semi-deciduous forest	-	-	-	-	-
<i>Cayman Brac</i>					
Coastal shrubland	208	1.57	3.3	5.49	8.08
Dry forest and woodland	-	-	-	-	-
Dry shrubland	391	1.71	5.38	8.69	10.59
Xeromorphic semi-deciduous forest	4559	0.02	0.04	0.07	0.13
<i>Little Cayman</i>					
Coastal shrubland	400	0	0.02	0.61	2.2
Dry forest and woodland	1927	0	0	0.05	0.64
Dry shrubland	2248	0	0	0.04	0.87
Xeromorphic semi-deciduous forest	-	-	-	-	-

Salinity changes associated with sea level rise and/or storm surges may favour some species at the expense of others. De Sedas et al. (2020), examined eight neotropical species from Panama and showed that coastal species were better able to withstand salinity gradients as compared to inland species, and that this resistance was likely related to a species' ability to manage toxicity associated with foliar sodium (Na<sup>+</sup>) or chloride (Cl<sup>-</sup>). The extent to which their findings apply to the Cayman Islands is not clear; much of the Cayman Islands vegetation may be considered coastal rather than truly 'inland', while only two of the eight species they examined are found on the Cayman Islands (according to Plants of the World Online (Kew); *Terminalia catappa* are introduced).

*Leptocereus* species are cacti native to the Caribbean, including the Cayman Islands, and are considered in the woodland/xeromorphic vegetation type. Barrios et al. (2021) investigated how four Cuban endemics of this genus responded to decreased water potentials and increased temperature from 25°C to 35°C. No seeds germinated at 35°C, regardless of water potential. At 25°C, germination occurred, but germinability and seedling mass were drastically affected when water potential changed from 0 to -0.2 MPa. Together, these results suggest that if climate change is accompanied by increased temperature and decreased rainfall, as projected, a reduction in germination and establishment of *Leptocereus* species would be expected, including in the Cayman Islands.

Introduced (but not necessarily invasive) as well as native species to the Cayman Islands may be affected by climate change. Investigations on *Tabuleia rosea*, a widespread neotropical tree species with sparse canopies and minimal self-shading, showed a degree of resilience to altered atmospheric conditions, with temperature increase of 4°C warming and CO<sub>2</sub> concentrations of 800 ppm (Slot et al., 2021). Consistent with acclimation, optimum temperatures for photosynthesis were higher in treatment compared to control plants, while photosynthetic capacity was 8-25% lower. However, stomatal density and leaf-to-air vapour pressure deficit were not affected by growth conditions. The authors suggested that despite tropical vegetation having experienced millions of years of relative stability in terms of temperature, there is not, in this species at least, a lack of physiological plasticity to respond to changes in mean temperature effectively. They suggest that carbon gain can likely be maintained (Slot et al., 2021).

#### Scoring

Global studies, Regional studies. Medium agreement, limited evidence. Relevance: Grand Cayman = high; Little Cayman = high, Cayman Brac = high.

### 3.11 Terrestrial birds, mammals and reptiles

The Cayman Islands are home to 36 resident species of terrestrial bird including waterfowl, of which five are classed as Near Threatened. The islands also play host to 138 species as passage migrants, such as the vulnerable Chimney Swift (*Chaetura pelagica*), and species that overwinter (BirdLife International, 2022). All three Islands provide important habitat for terrestrial birds and a number of nature reserves exist across the islands to protect key habitats. In contrast to the diversity of bird species in the Cayman Islands, bats are the only extant native mammal, of which there are nine species (Bradley et al., 2005), though it is possible there are others as yet undiscovered. All nine species are believed to be distributed across the Cayman Islands, however, colony locations of the majority of species are unknown (Department of Environment, 2022). Of native terrestrial reptiles and amphibians, the Cayman Islands are known to be home to circa 14 species of lizard, nine species of snake, and three species of frog, a number of which are unique to the islands (Echternacht et al., 2011). This includes endemics such as the Blue iguana (*Cyclura lewisi*) which is endangered and found only on Grand Cayman (Burton, 2012).

Although some of the terrestrial birds, mammals, reptiles, and amphibian species are found across all the Cayman Islands (or potential habitat exists for them in the case of unknown distribution), the geographical nature of the Cayman Islands mean their populations are generally smaller and do not interact, or interact only when accidentally transferred between the islands. This increases the vulnerability of terrestrial species in the Cayman Islands to population reductions resulting from climate change and human activities (Foden et al., 2013; Parmesan et al., 2000). Two distinct populations of subspecies status of the Near Threatened Cuban parrot (*Amazona leucocephala*) exist: one on Grand Cayman (Cayman parrot, *Amazona leucocephala caymanensis*) and the other on

Cayman Brac (Brac parrot, *Amazona leucocephala hesternae*). A population of Brac parrot that existed on Little Cayman is now extinct (Bradley et al., 2005).

#### *Current climate impacts*

Severe storms and hurricanes have caused the direct death of individuals, particularly those relying on exposed and coastal cliff habitats. The Brown booby (*Sula leucogaster*) colony on Cayman Brac lost a number of individuals in Hurricane Paloma in 2008 (Godbeer et al., 2008). On Cayman Brac, Hurricane Paloma devastated dry forest habitat within the Brac Parrot Reserve. The loss of cover and food drastically threatened populations and resulted in the Department of the Environment implementing an emergency feeding program to prevent starvation (Hurlston-McKenzie, 2011). Despite these interventions, there was a significant population decline of the Brac Parrot following this event.

Habitat salinisation poses a direct threat to amphibians due to their permeable skin and poor ability to osmoregulate (i.e., internal maintenance of salt and water balance), and has been found to reduce the survival rate of neotropical anuran species (Boutilier et al., 1992; Kearney et al., 2012; Rios-López, 2008). In addition to threats posed by salinity are changes in freshwater resources. Lowered water depths have been found to result in higher trematode infections of amphibian populations and increased mortality from water mould (*Saprolegnia ferax*) (Kiesecker et al., 2001). Increases in drought duration or number have consequences for migratory bird populations within the Cayman Islands, directly affecting body condition (Akresh et al., 2019; Angelier et al., 2011; Strong & Sherry, 2000). Reduced body condition can affect survival during migration, breeding success (Latta et al., 2016), and timing of migration if individuals have been unable to build up sufficient fat reserves (Studds & Marra, 2011). Interestingly, Angelier et al. (2011) found that body condition can be recovered in female American redstarts (*Setophaga ruticilla*) (which overwinter in the Cayman Islands) within a few weeks of increased water availability. Drought affected the body condition of redstarts by lack of drinking water, strong control of water on insect (food) abundance, and increases in energy expenditure to find water and food. Bats are also highly affected by drought, as water dependency is higher during reproductive phases, especially for lactating females (Adams & Hayes, 2008; Adams, 2010).

Extreme temperatures can cause mortality events across species (e.g. McKechnie & Wolf, 2010; McKechnie et al., 2012; Welbergen et al., 2008). In Australia, temperatures over 42°C led to widespread mortality in tropical black flying-fox (*Pteropus alecto*) and grey-headed flying-fox (*Pteropus poliocephalus*) populations (Welbergen et al., 2008). Changes to the temperature of the environment can also increase susceptibility to pathogens. For instance, neotropical amphibians are threatened by the disease chytridiomycosis caused by the chytrid fungus (*Batrachochytrium dendrobatidis*). The climate of the Caribbean is suitable for the chytrid fungus, and chytridiomycosis has been detected across the region, for example in Tobago (Alemu et al., 2008), Puerto Rico (Burrowes et al., 2004), and Cuba (Cádiz et al., 2019), but the situation in the Cayman Islands is unknown.

#### *Expected future climate impacts*

Depending on population size, mortality events resulting from climate change could drastically weaken population resilience by reducing number of breeding individuals, increasing mortality of young individuals, and reducing genetic diversity and loss of beneficial adaptations. Habitat degradation or destruction resulting from more frequent and intense storms will lead to loss of key breeding, nesting, and foraging habitat for a number of terrestrial species. Most vulnerable to habitat destruction and degradation are habitat specialists and isolated populations. For instance, the breeding population of the Cayman Islands brown booby colony is located solely on the bluffs of Cayman Brac, and the White-shouldered bat (*Phyllops falcatus*) (also known as Cuban fig-eating bat

(Solari et al., 2019)) is potentially solely located within the Lower Valley remnant forest on Grand Cayman (Hurlston-McKenzie, 2011). Restricted to these areas, storm damage to specific locations could potentially decimate populations. Land loss from predicted sea level rise will have a direct impact on ground dwelling/utilising terrestrial species, such as the Blue iguana (*Cyclura lewisi*). Generally, habitat loss can increase the concentration of individuals, which can lead to conflict and competition for resources (Tilman, 1994). Increased population density also enables the spread of disease. Bats are considered to carry the highest number zoonotic viruses across all mammal species (Irving et al., 2021; Luis et al., 2013), and loss and degradation of appropriate habitat could cause an increase in human-wildlife interactions and occurrence of zoonosis (Plowright et al., 2021).

Inundation of seawater resulting from sea level rise, coastal flooding and storm surges, and reduced precipitation accompanied by increased evaporation (via temperature increase) are likely to increase salinity levels of coastal freshwater and wetland habitats. This may cause degradation of the habitat (see relevant sections) and affect terrestrial species indirectly by collapse of food chains and lack of drinking water or, in the case of amphibians, cause direct death by exceeding their tolerance thresholds. In terms of species found on the Cayman Islands, native Cuban tree frogs (*Osteopilus septentrionalis*) have a relatively high salinity tolerance (tadpoles surviving up to 12 ppt), and can potentially adapt to increased salinity, whereas tadpoles of the eastern narrowmouth toad (*Gastrophryne carolinensis*), an introduced species in Cayman, did not survive exposure above 5 ppt (Brown & Walls, 2013; Lukens & Wilcoxon, 2020). There is evidence that beetles have also been affected by changing salinity. Research on a small Mediterranean island of Cavallo, Corsica showed that coleopteran species richness and diversity declined over the Holocene consistent with relative sea level rise over the period and associated transitions from fresh to saline conditions (Poher et al., 2017).

In addition to salinisation of freshwater, there is the risk to freshwater resources resulting from droughts and long-term changes in the balance and seasonality of precipitation to evaporation (see section Freshwater Environments and Resources). Drought and other climate induced declines in insects, plants, or changes within prey species will cascade throughout the food chain (e.g. Rosenblatt, 2018). The diet of tropical snakes includes amphibians, invertebrates, lizards, snakes, birds and mammals. Zipkin et al. (2020) found that snake diversity in a neotropical community drastically declined following collapse of the amphibian population resulting from chytridiomycosis. Insects and other invertebrates support a vast number of terrestrial species, as well as providing a wide range of ecosystem services for the benefit of humans (Wagner, 2020). They are highly vulnerable to climate change, which has been implicated in many species' declines, with increases in drought frequency and intensity potentially an insurmountable hurdle for insect populations (Wagner, 2020 and references therein). In addition to declines, changes in insect phenology (i.e., the timing of life-history events) can lead to predator-prey and host-parasite mismatches with direct consequences for secondary consumer survival (Damien & Tougeron, 2019).

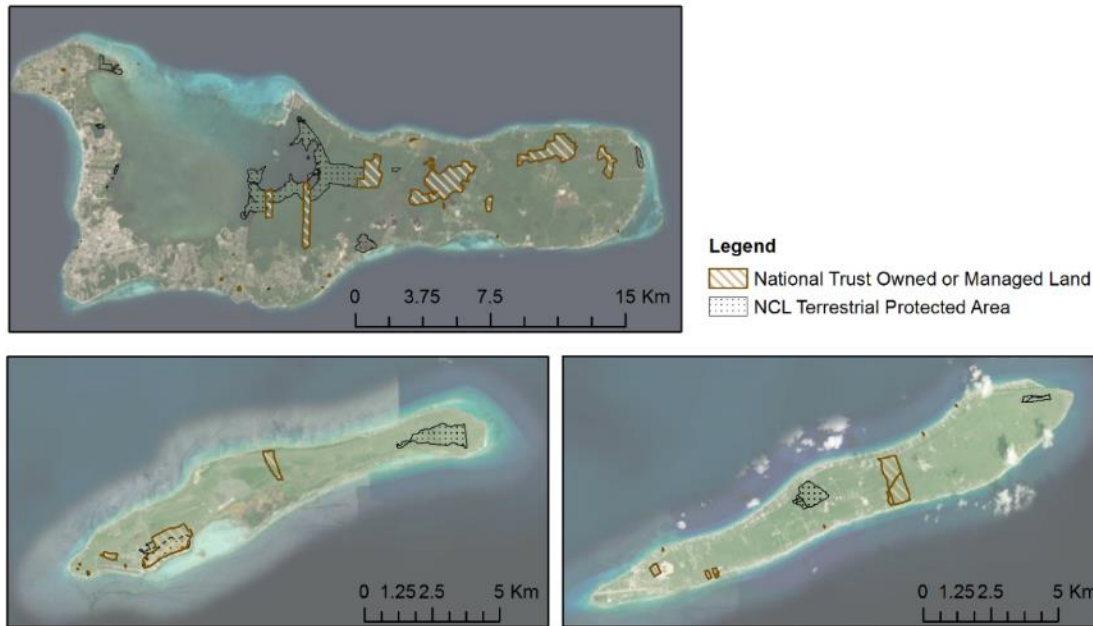
Increases in temperature can change the “operating” environment for a species, subjecting it to temperatures or moisture levels outside of its physiological tolerance. Exceeding environmental ranges does not necessarily lead to sudden death; rather, it increases the vulnerability of species, allowing other proximate factors to cause decline (Cahill et al., 2013; Pounds et al., 1999). For instance, lizards that need to retreat to cool refuges to avoid overheating will lose foraging time, which will affect growth, maintenance, and reproduction, thereby undermining population growth rates. Sinervo et al. (2010) found a correlation between maximum air temperature during breeding periods and local extinctions of lizard species in Mexico. Amphibians and reptiles are ectothermic, which increases their vulnerability to changes in temperature or moisture levels outside of their tolerance range. Subtropical species, such as those found in the Cayman Islands, are closer to their thermal maxima, and consequently more susceptible to smaller changes in temperature, and have a low capacity to accommodate future temperature increases (Li et al., 2013). Interactions among species can be important in determining response to climate change. Anurans in a neotropical wetland find

refuges from high temperatures due to the presence of crab burrows and termite thermal chimneys. Without these structures created by other organisms, anurans would find it difficult to tolerate higher temperatures (Simioni et al., 2014).

The spread of chytridiomycosis is principally due to human activity (e.g., whereby fungal spores are transported via clothing, footwear, and exotic pets) and reservoir hosts. However, there is some thought that temperature variability and climate influences its occurrence or amphibian susceptibility (Li et al., 2013). The growth of Chytrid fungus is currently inhibited at 28°C and prolonged exposure above 30°C proves lethal (Piotrowski et al., 2004). The Cayman Islands already experience temperatures above 30°C, therefore predicted increases in minimum temperatures could render parts of the Cayman Islands “resistant”, however, this would be highly dependent on microclimate; amphibians are in and around aquatic habitats where temperatures might be lower, and evolution of the fungus to more extreme temperatures cannot be ruled out.

Species can adapt to climate change over time through genetic adaptation (i.e., natural selection passing of traits), physical and behavioural change (i.e., phenotypic plasticity), and range shifting (Bellard et al., 2012; Dawson et al., 2011). In response to changing seasonality, many species have altered their phenology (Komdeur & Daan, 2005; Post et al., 2018). There is a concern that island populations, being small and isolated, may be unable to adapt to climate change or exhibit phenotypic plasticity due to lower genetic diversity (Bouzat, 2010; Frankham, 2005). However, Taylor et al. (2021) found the Mauritius kestrel (*Falco punctatus*), whose sole population is on the Island of Mauritius, has altered its timing of egg-layering in response to changes in temperature to ensure egg survival. Shifts in range to higher elevations and poleward migrations to track climate suitable niches have been observed in many species (Parmesan & Yohe, 2003), however, the restricted elevation range of the Cayman Islands negates this as an option (Nurse et al., 2014). The impact of increasing temperatures, radiation, and drier environments on terrestrial species of the Cayman Islands will depend largely on how environmental factors (such as vegetation that provides shade) also respond to and affect the impact of climate change on local conditions (Valenzuela-Ceballos et al., 2015).

Signals of climate-related impacts can be difficult to discern from other drivers and ecological interactions. Terrestrial birds, mammals, reptiles, and amphibians are greatly affected by habitat destruction, fragmentation, and disturbance resulting from human activities, as well as predation by introduced dogs, cats, rats, and other invasive alien species (Bradley et al., 2005). These often pose a greater threat to the existence of terrestrial birds, mammals, reptiles, and amphibians on islands, generally exacerbating climate change impacts. Indeed, biological invasions are known to be particularly problematic on oceanic islands (Moser et al., 2018). If the impact of human activities and associated anthropogenic change, land use, and biological invasions were addressed, then the ecosystem would be more resilient to climate change impacts and the risks for climate change may not be as severe. In the case of Hurricane Paloma and the impact on the Cayman Parrot population, historically the population has been robust enough to recover from such storms, but habitat loss restricts the ability of the population to recover naturally (Godbeer & DaCosta-Cottam, 2009). In Grand Cayman, National Trust-owned or managed Mastic Reserve, and Salinas and Colliers Wilderness Reserves (where captive bred iguanas are released), and in Little Cayman, the Booby Pond and Rookery, are substantial in area (Figure 30) and of ecological importance, as are parks such as the Queen Elizabeth II Botanic Park.



**Figure 30.** National Trust owned and managed land and NCA protected areas within the Cayman Islands. Source: Department of Environment, Cayman Islands Government (March 2022). Aerial imagery: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus, DS, USDA, USGS, AeroGRID, IGN, and the GIS user community.

### Scoring

Local monitoring, plus regional and global studies. High agreement, robust evidence. Relevance: Grand Cayman = high; Little Cayman = high, Cayman Brac = high.

## 3.12 Insect and vertebrate pollinators

Pollination and seed dispersal in the Cayman Islands is aided by a range of insects, mammals, and birds. There are 57 species of butterflies recorded in the Cayman Islands (52 from Grand Cayman, 31 from Little Cayman, and 34 for Cayman Brac) (Askew, 1994). Butterflies are important ecologically as major pollinators of native plants and trees. Five sub-species are endemic to the Cayman Islands, including the spectacular Cayman swallowtail (*Heraclides andraemon tailori*) and the Cayman pygmy blue (*Brephidium exilis thompsoni*), possibly the world's smallest butterfly. Similarly, moths have a special role in pollinating orchids, and Rose-Smyth et al. (2022) have recently reviewed hawkmoth pollinators for the Cayman Islands ghost orchid *Dendrophyllax fawcettii*. *D. fawcettii* is a rare, critically endangered, endemic, leafless orchid found only in Grand Cayman. Pollinators of *Myrmecophila thomsoniana*, the Cayman endemic banana orchid (the national flower), have been identified, including a newly discovered species of weevil, *Lachnopus vanessablockae* (Girón et al., 2018). Honey bees (*Apis mellifera*) are not native to the Cayman Islands, although they have been widely introduced (Askew, 1994) to provide honey and to act as pollinators in the fruit industry. Honey bees are known to exhibit both swarms and die-offs in response to environmental variability, and are arguably themselves a threat to native pollinating insects, including the small number of native solitary bees. Elsewhere in the Caribbean, hummingbirds perform an important role in pollination (Lehmann et al., 2019), however hummingbirds are rarely encountered in the Cayman Islands, and so this function is primarily carried out by insects and bats.

Bats are considered to be “keystone” species in Grand Cayman (Morgan, 1994), which means that many organisms, even plants, are very dependent on bats to survive, especially as they play a crucial



role in seed dispersal and pollination. The two most common species are the Jamaican fruit bat and the Pallas's mastiff bat. Until 1994, the Cayman Islands' bats faced a crisis as the target of exterminators. Since velvety free-tailed bats roost in large colonies, they were easily killed by misguided efforts to remove them from roof spaces (Morgan, 1994). Of special concern are the three bat species endemic to the Caribbean: the Buffy flower bat (*Erophylla sezekorni*), the White-shouldered bat (*Phyllops falcatus*), and the Antillean nectar bat (*Brachyphylla nana*). Pollination and seed dispersal of hundreds of native plants occur through bat activity, for example the agaves and cacti on the Bluff are pollinated by the buffy flower bat. Other native plants relying on bat pollination and seed dispersal include calabash, neem, silk cotton, naseberry, and vine pear.

Historic colonies of bats in Cayman were reported to consist of thousands of individuals, especially the Brazilian free-tailed bat that was found in numbers reaching over 30,000 in a single cave (Morgan, 1994). Today, the same cave is inhabited only by approximately 40 Jamaican fruit bats who live in the entrance. The drastic decline of bats in the Cayman Islands is due mainly to habitat loss and disturbance (Morgan, 1994).

### *Current climate impacts*

A global analysis by the United Nations found that more than 40% of pollinator species may be at risk of extinction (IPBES, 2016). While habitat degradation, pesticides, and disease all contribute to pollinator decline, climate change is an increasingly significant stressor that may interact with these to further drive the decline of pollinators (Xerces, 2018). A loss of pollinators in the Cayman Islands would affect both agricultural and natural ecosystems.

Climate change will have a variety of effects on pollinators (Ackerman & Moya, 1996; Xerces, 2018):

- 1) Species range shifts: Species may change their distributions to track more optimal climates. In general, species are expected to shift poleward or to higher elevations. However, not all species will respond in the same way, meaning that range shifts can lead to mismatches between pollinators and their host plants. Most species on remote, low-lying islands cannot shift poleward or to higher elevations.
- 2) Altered phenology: Phenology is the timing of biological events. Shifts in phenology in response to climate change may be especially problematic if pollinators and the plants they rely on respond differently, leading to phenological mismatches.
- 3) Changes to species' physiological processing rates: Processes such as metabolism or growth are temperature-dependent in insects, meaning that climate change can affect pollinator performance (e.g. survival, fecundity, size at maturity, etc.).
- 4) Altered species interactions: Climate change can affect the outcome of species interactions, such as competition, predation, and disease.
- 5) Changes to the diversity, quantity, and quality of floral resources: Plants will also respond to climate change. Drought, heat waves, temperature rises, and increasing atmospheric CO<sub>2</sub> concentrations can all affect the quality and quantity of pollen and nectar.

Increased rainfall has the potential for population-level effects, but there is also wide scope for individual-level effects, which have received surprisingly little attention (Lawson & Rands, 2019). Changes in rainfall patterns could alter the timings of phenological phases, while also increasing the likelihood of pollen degradation and nectar dilution, each having detrimental effects to the fitness of the plant, the pollinator, or both parties. Pollinators could also be affected through mechanical and energetic constraints, along with disruption of foraging patterns and disruption to sensory signals (Lawson & Rands, 2019).

Very little is known about climate impacts on pollinators in the Cayman Islands specifically, however, disruption to pollinator-plant relationships have been studied elsewhere in the Caribbean following the passage of a severe hurricane. The consequences of a direct hit by Hurricane Hugo (September 1989), a category 4 storm, on a plant-pollinator interaction was investigated by comparing pre-hurricane (1981–1985) with post-hurricane data (1989–1990) in Puerto Rico (Ackerman & Moya, 1996). The orchid *Epidendrum ciliare* is pollinated by a large hawkmoth, *Pseudosphinx tetrio*. Despite severe habitat alteration and some plant damage (e.g., uprooting, breakage and sun scorching), flowering phenology was apparently unaltered. Pollinator service was different from that of previous years in that more flowers were visited (57% vs. 28–41%). The higher number of effective visits increased pollen removals, but the number of pollen depositions remained about the same (11% vs. 11–15%). Fruit fates differed among seasons. Post-hurricane loss of fruits to rat predation was higher than previous years, but the proportion of fruits reaching maturity was similar to pre-hurricane seasons. In conclusion, although details of the plant-pollinator dynamics were altered, the short-term consequences of hurricane induced damages were apparently minimal (Ackerman & Moya, 1996).

Strong hurricanes can cause population reductions in West Indian birds and bats (Fleming & Murray, 2009). Immediately after Hurricane Ivan (September, 2004), many bat populations on Grand Cayman were reduced by up to 60–90 percent. Despite being smaller than pre-hurricane levels, the population of *Artibeus jamaicensis* on Grand Cayman contained greater mitochondrial haplotype diversity compared to pre-Ivan levels. Fleming & Murray (2009) suggest that hurricane-aided dispersal from Cayman Brac introduced two new haplotypes into the Grand Cayman population. Similarly, in the Bahamas, two other phyllostomid bats (*Erophylla sezekorni* and *Macrotus waterhousii*) did not suffer population losses or changes in genetic diversity as a result of Hurricanes Frances and Jeanne (both in Sep 2004), suggesting that strong hurricanes usually have greater demographic than genetic effects (Fleming & Murray, 2009).

#### *Expected future climate impacts*

Plants and pollinators might respond differently to changes in climate, and thus plant-pollinator relationships are vulnerable to spatial, temporal, morphological, and recognition mismatches. Gonzalez et al. (2021) assessed the spatial distribution of nine species of five genera of Colombian stingless bees used in meliponiculture under present and future climate scenarios. Stingless bees are major pollinators in tropical areas and their use in managed pollination to produce high-value honey and as recreation is increasingly popular worldwide. Using intermediate (RCP 4.5) and high (RCP 8.5) GHG emission scenarios, models predict that seven of the nine species would experience a significant reduction in their climatically suitable areas, and thus will likely influence agriculture and rural livelihoods (Gonzalez et al., 2021).

The thermal niche of a species is one of the main determinants of its ecology and biogeography. Ortega-Garcia et al. (2017) determined the thermal niche of 23 species of Neotropical nectar-feeding bats using temperature data obtained from collection records by generating a distribution curve of the maximum and minimum temperatures per locality (presence datasets). This study found large variation in the limits of thermal niches. The two clades inside the Glossophaginae differ in their evolution of thermal niches, with most members of the clade Choeronycterines evolving 'colder' thermal niches, while the majority in the clade Glossophagines (including *Erophylla sezekorni*) evolving 'warmer' thermal niches (17.7–28.1°C), and that all species could be affected by an increase of 1 °C in temperature at the end of the century (Ortega-Garcia et al., 2017).

#### *Scoring*

Regional studies. Medium agreement, limited evidence. Relevance: Grand Cayman = high; Little Cayman = high, Cayman Brac = high.

### 3.13 Freshwater environments and resources

Freshwater ponds and pools are an important source of drinking water for many terrestrial species, notably birdlife, and these support a variety of plant and animal communities, including a range of non-native, non-resident, endemic, and globally threatened species. Environmental gradients of water availability and water salinity are key factors driving species distributions globally, and particularly within small islands and coastal environments (Bauer-Gottwein et al., 2008; Greaver & Sternberg, 2010; Fay et al., 2016; Osland et al., 2016). The terrestrial and freshwater biodiversity of the Cayman Islands is thus linked to surface and groundwater abundance and quality via associated habitats where the mosaics of fresh to brackish wetlands and dry habitats contribute to relatively high overall diversity (Bass, 2003, 2009; Churchyard et al. 2016; DaCosta-Cottam et al., 2009; Falkland, 1991; Matthews et al., 2019; Russell & Kueffer, 2019). Future alterations to water quality and availability thus have implications for species assemblages, which are underscored by non-linear tolerance responses.

Freshwater lenses occur on each of the Cayman Islands and are unconfined but land locked. They are limited in extent due to the small size, relatively low elevation, and elongated dimensions of the islands, particularly in the case of Little Cayman and Cayman Brac. Accordingly, lenses on Grand Cayman are largest. These predominantly underlie grassland and woodland land cover within the Bluff formation in the east (North Side Lens and East End Lens), but in the central regions (Lower Valley Lens) and west, they partly underlie urban areas of West Bay, South Sound, and Bodden Town. Those on Little Cayman are not appreciable due to the low elevation and width of the island. On Cayman Brac, the only appreciable lens underlies woodland in the east at greater elevation.

Freshwater lenses are recharged by infiltration of rainfall not lost via evapotranspiration or surface runoff, so that inter-annual and long-term variations in precipitation and the balance of precipitation to evaporation (P:E) affect their quantity and extent. The high transmissivity of the aquifers results in limited freshwater storage so that they are predominantly occupied by brackish water. The average water table elevation of the freshwater zone is c.0.5m above mean sea-level on Grand Cayman (Ng et al., 1992). The thickness of the freshwater lens has been found to approximate a 1:20 ratio of freshwater above to below sea-level that reflects heterogeneity of the aquifers, and the mixing effect of tidal oscillations that contribute to wide brackish water transition zones (Bugg & Lloyd, 1976; Ng et al., 1992). Water tables fluctuate with tides such that in deeper wells (>2m below water table) responses to precipitation are not discernible from tidal cycles at rainfall intensities <50mm day<sup>-1</sup>, whereas in shallower wells less influenced by tides measurable changes occur with rainfall >25mm day<sup>-1</sup> (Ng et al., 1992).

Open fractures, fissures, and joints formed under tectonic stress in conjunction with associated root and solution channels and caverns are important secondary elements of porosity and permeability that contribute to rapid freshwater recharge via rainfall, as evidenced by rapid declines in groundwater salinity after rainstorms (Mylroie et al., 1995; Ng et al., 1992). They can also provide direct hydraulic connections to the sea, exemplified by variable well water salinity responses to abstraction due to the presence or absence of fissures as avenues for seawater intrusion, and constitute situations for mixing of water from different hydro-chemical zones via tidal oscillations, reflected by broad and extensive transition zones of brackish water. The heterogeneity of the aquifers suggests that future changes to the extent of freshwater lenses may not occur uniformly. These aspects of porosity give a high potential for groundwater contamination. For example, the thin freshwater lenses of West Bay and South Sound of Grand Cayman were unsuitable as public water supplies by 1975 due to human sewage contamination (Kreitler & Browning, 1983; Hurlston-McKenzie, 2011 and references therein).

Freshwater resources for human consumption and agricultural irrigation are detailed in the relevant section of this report. Under conditions of reduced freshwater availability, regulated abstraction volumes for these purposes may need revision for continued avoidance of impacts on dependent ecosystems (Water Production and Supply Law, 2018 Revision; Water Authority Law, 2018 Revision).

### *Current climate impacts*

The superimposition of extreme events upon rising baselines of sea level is a key mechanism that amplifies climate threats to small islands (Nurse et al., 2014). For example, storm surges leading to land-surface inundation by marine over-wash can cause salinisation of coastal soils, aquifers, and waterbodies, particularly in low-lying areas, and are likely to increase in frequency and severity with SLR. In turn, this is expected to result in landward migration, horizontal range shifts, and/or reduction of habitats, and reductions to freshwater lens volumes (Nurse et al., 2014). Indeed, paleo-ecological evidence shows that mangroves moved landward into subaerial or seasonally flooded environments with the Holocene eustatic rise in sea level on Grand Cayman (Booker & Jones, 2020; Woodroffe, 1981; Woodroffe and Grindod, 1991).

Inundation of large areas of the Cayman Islands have occurred in response to storm surge and precipitation associated with hurricanes, characterised by extensive low-velocity ponding in low-lying regions (<1m amsl; Wood Group UK Ltd., 2021b). Mobilisation of debris and other organic matter into coastal waters has occurred, and their subsequent degradation has driven declines in dissolved oxygen resulting in fish kills, as well as wider physiochemical impacts on water quality (Sybersma, 2014; Wood Group UK Ltd., 2021b). Such mechanisms for deoxygenation are also likely to occur in low-lying inland and coastal waterbodies if translocation of such matter to these habitats occurs, with increased salinity further driving declines in equilibrium (saturation) dissolved oxygen concentrations.

Ponding of surface water with variable salinities in response to intense rainfall and hurricane events, as well as accumulations of organic debris, increases the abundance of suitable habitats for mosquitos in the Cayman Islands.

Negative impacts of reduced precipitation and SLR leading to freshwater lens contraction and coastal salinisation upon coastal vegetation have been documented in a number of studies of the Bahamas and Florida Keys and Everglades (Goodman, 2010; Greaver & Sternberg, 2010; Meeder et al., 2017; Ross et al., 1994; Ross et al., 2020; Sah et al., 2018; Willard & Bernhardt, 2011; Williams et al., 1999).

Climate change impact studies on island water resources are generally based on modelling informed by limited, but in some cases extensive empirical data and before-after event monitoring (e.g., hurricanes/over-wash events). These consider the role of individual, interacting, or superimposed climate change responses, comprised predominantly of SLR and balances of precipitation to evaporation (P:E), and include high intensity events such as hurricane related precipitation, storm surges, and over-wash, and drought frequency and severity (e.g., as associated with ENSO). The role of modulating factors, typically topography, hydrogeology, island size and dimensions, seasonality, and event sequence and return time are also generally included. As no direct evidence based on monitoring or local climate modelling were identified for the Cayman Islands, efforts are made to place available evidence in the local context.

Fresh water lens degradation can result from inundation with marine water via storm surges and over-wash, the impacts of which have been found to be greater and more persistent when low water tables precede inundation events, and when over-wash occurs during the dry season (Bailey & Jenson, 2014; Chui & Terry, 2012; Gingerich et al., 2017, Holding & Allen, 2015). The duration of increased salinisation of ground waters is then controlled by the incidence of post inundation dry spells whereby lens replenishment is controlled by subsequent rainfall infiltration so that recovery times are partly a function of annual precipitation (Alsumaiei & Bailey, 2018; Gingerich et al., 2017). If followed by sustained droughts, as associated with ENSO for example, then recharge may be particularly slow. A further factor is the hydraulic conductivity of the vadose zone, which can limit saltwater reaching the freshwater lens, whereas greater aquifer hydraulic conductivity can speed aquifer recovery from salinisation (Chui & Terry, 2015); only the latter of these factors is pertinent to the Cayman Islands.

Observations from Pacific atolls indicate recovery times to potable levels of salinity of c.1-2 years (Gingerlich et al., 2017; Terry & Falkland, 2010;). Holding and Allen (2015) explored simulated coastal

aquifer responses to over-wash events among island types, aggregated based on climatic, hydrogeologic, and topographic differences. The Cayman Islands fall between two of these typologies on the basis of low-lying areas (<5 m amsl), as well as areas at greater elevation, bearing most similarity to types 3 and 5 (exemplified by Andros Island of the Bahamas and Jamaica, respectively). These locations differ most notably with regard to vadose zone thickness and hydraulic heads, being lower for Andros in each case, which bears resemblance to low lying areas of the Cayman Islands (e.g., Little Cayman; Lower Valley, Grand Cayman), whereas greater elevation area is closer to the Jamaica analogue (e.g., Bluff formation, Grand Cayman). Recovery times to potable and pre-inundation quality and extent following a simulated 1m inundation and natural recharge (c.900 mm year<sup>-1</sup>) for these island types were similar at respectively, c. 470 days and 2-3 years. However, the type 5 scenario (Jamaica analogue) exhibited a greater maximum salinity response on account of the greater vadose zone depth. The values of Holding and Allen (2015) are generalised and provide process understanding and ball-park values, but nonetheless give a good match to the findings of more numerically complex studies (e.g., Alsumaiei & Bailey, 2018).

### *Expected future climate impacts*

Storm surge and flood modelling for the Cayman Islands indicate widespread flood risk across the islands in areas with elevations <1 m (Wood Group UK Ltd., 2021b). These areas are extensive in the central North Side wetlands and the eastern nature reserves in the East End regions of Grand Cayman (they partially overlay freshwater lenses); the central and coastal low elevation land on Little Cayman, such as Tarpon Lake; and the west of Cayman Brac where the east-west elevation gradient can amplify ponding in lower elevation areas if large precipitation inputs occur (Figures 32) (Wood Group Ltd. UK, 2021b). With sea-level rise, over-wash events are expected to occur more frequently due to non-linear interactions with wave dynamics over reefs and potentially a greater frequency of storm surges (Cheriton et al., 2016; Quataert et al., 2015; Storlazzi et al., 2015). Their impacts on aquifers may exceed those expected from decades of sea-level rise alone, particularly when return time of storm surges is reduced (Hoeke et al., 2013; Robins, 2013; Xiao & Tang, 2019). The combined impacts of SLR and storm surges can also have direct ecological impacts; for example, SLR alone is expected to reduce habitat availability for seabirds of Pacific islands, while storm-surge over-wash events reduce reproduction and survival (Reynolds et al., 2015).

Existing lowland depressions and wetlands that become inundated would be expected to exhibit low infiltration rates of over-washed saline water due to existing saturation (i.e., absence of a vadose zone), so that such surface waters would increase in salinity via evapo-concentration and continue contribute saline water to aquifers unless diluted by rainfall (Chui & Terry, 2015). In such incidences, the duration and levels of salinity might exceed the tolerance thresholds of aquatic and wetland species. However, storm surges and marine wash-over may be accompanied by high intensity rainfall events such that inundations can be brackish, detracting from pronounced aquifer salinisation and leading to shortened recovery times (Alsumaiei & Bailey, 2018; Terry & Falkland, 2010). Disaggregating the likelihood of marine water over-wash independent of high rainfall inputs is difficult. In the theoretical case of a late wet season marine over-wash event in the absence of intense rainfall, ground and surface water salinisation in low lying areas (<1m elevation) would be expected to persist and intensify during the following dry season, with full recovery on the basis of studies for similar hydrogeological settings and climate in c.1-3 years.

*Sea Level Rise* – A review of small island studies of SLR impacts on freshwater lenses (White & Falkland, 2010) concluded that, in the absence of changes to rainfall, shoreline recession, and human impacts, and given sufficient vertical space (i.e., vadose zone depth above groundwaters), minimal impacts would be expected, reflecting upwards movement of the lens as the level of the underlying saline water increases with sea level. White and Falkland (2010) also suggest that freshwater lenses may increase with SLR under such conditions if they rise to occupy less permeable geology where

transmissivity is reduced, but this is unlikely to be a widespread feature of the Cayman Islands as there are not pronounced depth-transmissivity differences (Ng et al., 1992).

Shoreline recession is a key factor in aquifer responses to SLR as the extent and depth of freshwater lenses are related to island geometry, such that declining land areas and widths impact freshwater lenses via an enhanced role for saltwater intrusion and tidal mixing (e.g., Ataie-Ashtiani et al., 2013; Bailey et al., 2013; Budd & Vacher, 1991). In the context of the Cayman Islands, the paleo-evidence for landward mangrove migration provides relatively strong evidence for future land surface inundations with future SLR. In a modelling study that did not include shoreline recession, the effect of a 0.4m SLR scenario on the freshwater lenses of generic islands of different widths suggested that smaller islands would be less resilient to the effects of SLR, but with relatively limited impacts on freshwater lenses overall (Chui & Terry, 2015). Conversely, where land surface inundation (i.e., shoreline recession) is included, the effects of SLR on freshwater lenses are considerable and potentially as severe as those of alterations to recharge rates on the basis of reduced P:E (Alsumaiei & Bailey, 2018; Ketabchi et al., 2014). Accordingly, there is an inversely proportional relation between average freshwater lens reduction and island surface area reduction (Alsumaiei & Bailey, 2018).

Comte et al. (2014) performed a three-dimensional numerical modelling study for a small (5 km<sup>2</sup>) Indian Ocean coral island with a maximum elevation of 15m. An end of century scenario of 0.35m of SLR (and including the associated reduction in land area) with +3% and 6% increases to precipitation and evaporation respectively, indicated that all groundwater would be rendered non-potable within 15–20 years of implementation of this scenario, and that the impacts of rising sea level and falling recharge on groundwater were similar.

The limited elevation of the Cayman Islands with extensive low-lying areas suggest that there may be limited island-wide capacities for upward migration of freshwater lenses, as well as brackish water present in the transition zones of groundwaters. In such cases, freshwater lenses would be expected to thin, and surface fresh and brackish waters might expand in areal extent depending on the impact of associated increases to evaporation, which in turn would be expected to increase in salinity and reduce in volume due to increased evapo-concentration.

*Precipitation, evaporation and groundwater recharge* – Comte et al. (2014) also describe a major control exerted by vegetation via evapotranspiration on island groundwaters. For phreatophytes (i.e., plants whose roots investigate groundwater) transpiration can be coupled with water-table fluctuations and the selective uptake of freshwater can increase groundwater salinity (Bauer-Gottwein et al., 2008). Groundwater uptake by plants reduces with increasing salinity but varies between species, the chronic effects of which may ultimately lead to their death (Bauer-Gottwein et al., 2008; Trapp et al., 2008). However, the results of Comte et al. (2014) suggest that reduced vegetation activity due to salt toxicity can act as a spatio-temporal buffer to groundwater salinisation, so that plants may exert a degree of imposed self-regulation on groundwater quality. Several studies pertaining to coconut trees summarised by Werner et al. (2017) highlight the potentially strong contribution that vegetation can make to annual evapo-transpiration: 400-700 mm year<sup>-1</sup> in the case of coconut trees. On Roi-Namur Island (Marshall Islands), freshwater recharge was 84% lower on the densely vegetated island side by comparison to that on the grass dominated side where vegetation was removed by human development (Gingerich, 1992).

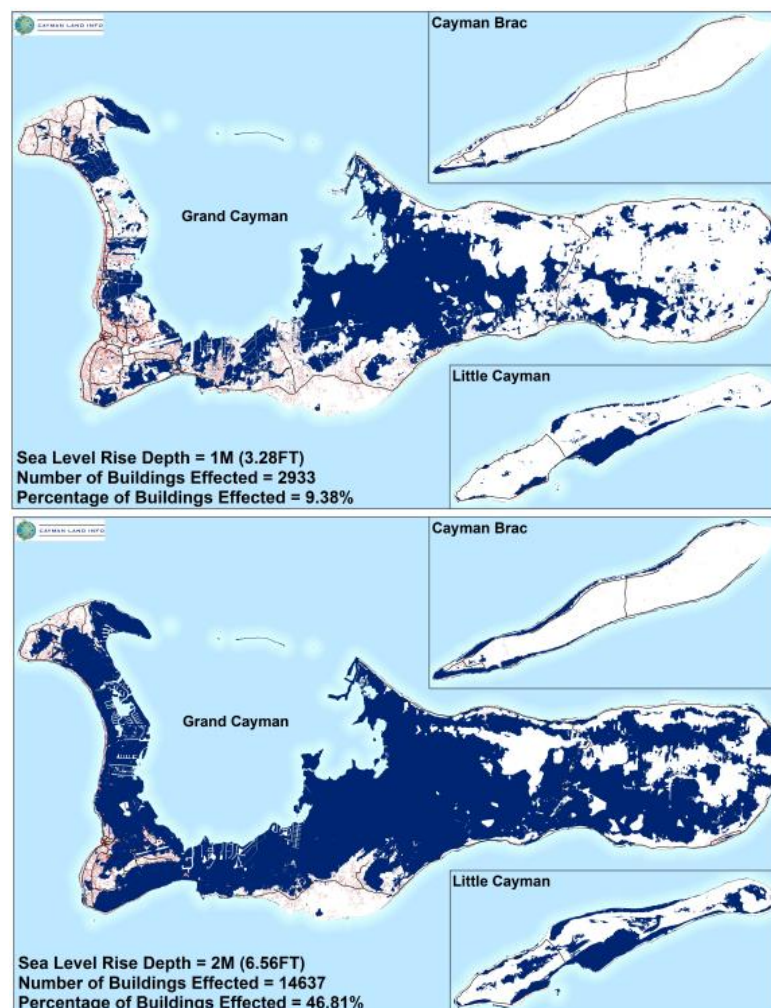
Vacher and Wallis (1992) found that climate drivers were important drivers of dissimilar freshwater lenses on two low-lying Atlantic islands (Bermuda and Great Exuma) with distinctly different climates but otherwise similar properties. On Great Exuma, which bears similarity to dry seasonal characteristics of the Cayman Islands, negative effective precipitation leads to small thin freshwater lenses, where surface waterbodies of fresh to brackish water “act like pumping wells” via enhanced evaporation. Similar effects of low topography depressions are described by Ayers and Vacher (1986). Van der Velde et al. (2006) demonstrate the role of inter-annual rainfall variability on the salinity of

the freshwater lens of a larger Pacific atoll (Tongatapu), whereby groundwater salinity could be predicted relatively well 10 months in advance via consideration of ENSO.

### Scoring

Local monitoring, plus regional and global studies. High agreement, robust evidence. Relevance: Grand Cayman = high; Little Cayman = medium, Cayman Brac = medium.

**Island relevance** – Dictated largely by island specific topography. Areas of each island inundated by 1 and 2 m increases in SLR, as shown in Figure 31, provide an indication of potential extent of storm surge related landscape inundation. The landscape extents inundated at 2 m SLR are informative given end of century SLR in the range 0.32-1.0m.



**Figure 31.** Land surface inundation of Cayman Islands in response to SLR of 1m (top panel) and 2m (lower panel). Source: Simpson et al. (2009).

### 3.14 Endemic species

The Cayman Islands are characterised by a high level of endemic species and/or sub-species most likely associated with geological changes during the Pliocene and Pleistocene epochs (Brunt & Davies, 1994). It is thought that the Cayman Islands play host to around 17 endemic vertebrate, 61 invertebrate, and 28 terrestrial plant and marine species (Churchyard et al., 2014). For example, the Cuban Parrot

(*Amazona leucocephala*) species has two subspecies endemic to Grand Cayman and Cayman Brac: *Amazona leucocephala caymanensis* and *Amazona leucocephala hesternae*. The emblematic Blue iguana (*Cyclura lewisi*) is found only on Grand Cayman, whereas the Sister Islands Rock iguana (*Cyclura nubila caymanensis*) is native only to Cayman Brac and Little Cayman and is classified as a subspecies of the Cuban Rock iguana. The land snail (*Cerion nanus*) is known only from a single 300 m<sup>2</sup> patch of Dwarf morning glories (*Evolvulus squamosus*) on Little Cayman.

#### *Current climate impacts*

Current climate impacts on endemic species are encapsulated in the relevant sections, and with respect to impacts on habitats that support these species. Of particular threat to endemic species is hybridisation with invasive species. For the endemic Blue iguana (*Cyclura lewisi*) that was declared functionally extinct, there is currently a successful recovery program in place (DaCosta-Cottam et al., 2009). Key species are monitored by the Department of Environment and eradication of invasive species, where deemed appropriate, is undertaken.

#### *Future climate impacts*

Future climate impacts on endemic species occur via impacts identified in the relevant sections. For example, climate threats to the near-threatened fish, *Limia caymanensis*, and the endangered fish *Gambusia xanthosoma*, have been identified as pertaining to shifts and alterations to habitat abundance and quality (Lyons, 2021a, Lyons, 2021b, as detailed in the relevant section of this report). Indeed, endemic species are often at greater risk of extinction as they have restricted geographic ranges, limited dispersal abilities, and lower population size (so potentially reduced adaptive capacity) (Benscoter et al., 2013, Chichorro et al., 2019, Staude et al., 2020). Manes et al. (2021) in their global study predicted that terrestrial endemic species are projected to be 2.7 times more impacted by climate change than native non-endemic species (i.e., also occurring elsewhere), and up to 10 times more impacted than invasive non-native species. Again, endemic island species face a much higher extinction risk than non-island or montane terrestrial endemics. Marine endemic species are also predicted to be significantly more impacted than marine native species under predicted global warming scenarios. The climate change impacts posed to the Cayman Islands' diverse endemic flora and fauna will depend upon individual species and interaction with other variables (e.g., land use change).

#### *Scoring*

Local monitoring, plus regional and global studies. High agreement, medium evidence. Relevance: Grand Cayman = high; Little Cayman = high, Cayman Brac = high.

Endemic species are widespread throughout the Cayman Islands, therefore, climate change impacts have a high relevance.

### **3.15 Invasive non-native species (marine and terrestrial)**

Churchyard et al. (2014) recorded a total of 264 terrestrial and marine invasive non-native species in the UK Overseas Territories (Table 9), and a number of these are causing major problems within the Cayman Islands. Key invasive vertebrate species identified on the Cayman Islands are feral cats, dogs, black rats, and green iguanas. Native species particularly affected by these are Sister Islands Rock Iguana and other endemic reptiles, West Indian whistling duck, red-footed booby, brown booby, green



turtle and loggerhead turtle (RSPB, 2014). Key invasive invertebrates affecting the Cayman Islands are *Solenopsis invicta* (a species of fire ant), which preys on other invertebrates and affects small native lizards and iguanas, and the Red lionfish (*Pterois volitans*), which impacts native reef fish (GB Non-Native Species Secretariat, 2022). Key invasive plant species include the tree *Casuarina equisetifolia*.

**Table 9.** Total number of species and known non-natives recorded by RSPB stocktake in the UK Overseas Territories (Churchyard et al., 2014). Further breakdown is available within the report.

Taxon	Total species	Known non-native species
<b>Invertebrates</b>	1,992	2
<b>Vertebrates</b>	611	19
<b>Plants</b>	658	243

#### Current climate impacts

The Cayman Islands have already experienced a number of invasions. Hurricane events have assisted with population increase of the invasive green iguana (*Iguana iguana*). Originally imported to the Cayman Islands as pets, the wild introduced population exploded following Hurricane Ivan when cages became damaged and many escaped (GB Non-Native Species Secretariat, 2022). Green iguanas pose a threat to the native endangered Blue Iguana through hybridisation and potentially resource competition (RSPB, 2014). They also impact upon infrastructure by climbing telegraph poles and shorting power lines (GB Non-Native Species Secretariat, 2022). In Florida, their invasion has caused flooding concerns as they burrow into levees and canals, potentially weakening flood defences (Sementelli et al., 2008). A government extermination program began in the Cayman Islands in 2018 in an effort to eradicate this species, and currently over a million individuals have been culled (Knapp et al., 2021).

Many terrestrial invasive non-native species that are present have not occurred or been assisted by climate change events. For instance, *Casuarina equisetifolia* (Australian pine tree/whistling pine tree /ironwood/weeping willow) was likely introduced to the Cayman Islands around the late 1800s (DaCosta-Cottam et al., 2009). It is so widespread that it is possible to map its distribution. On Grand Cayman alone, just over 5000 stands covered approximately 320 acres, representing tens of thousands of trees. The presence of this invasive plant has a number of functional effects when compared to native habitats (Hata et al., 2012, 2016), and its replacement of deep-rooted native species (such as *Coccoloba uvifera* (sea grape)) indirectly contributes to enhanced erosion (DaCosta-Cottam et al., 2009). However, research by de Vos et al. (2019) on beaches of the Indian Ocean and South-East Asia suggested that beaches with *Casuarina* present were not more vulnerable to erosion compared to beaches where the genus was absent. It is not always clear that the spread of *Casuarina* (as a genus) is causal in biodiversity decline; it may be spreading due to existing declines in native species due to other drivers (e.g. as discussed for *Allocasuarina* in Australia, and shifting fire regimes) (Shackelford et al., 2015). This is also true of changes in other system properties. As Buehler and Rodgers (2012) highlighted in their research on the Bahamas, soil characteristics in *Casuarina*-dominated sites were different to sites dominated by native vegetation. Two possible explanations were postulated: were certain soil properties initially more conducive to *Casuarina* invasion, and/or did establishment of *Casuarina* lead to alterations of soil properties themselves (Buehler & Rodgers, 2012)?

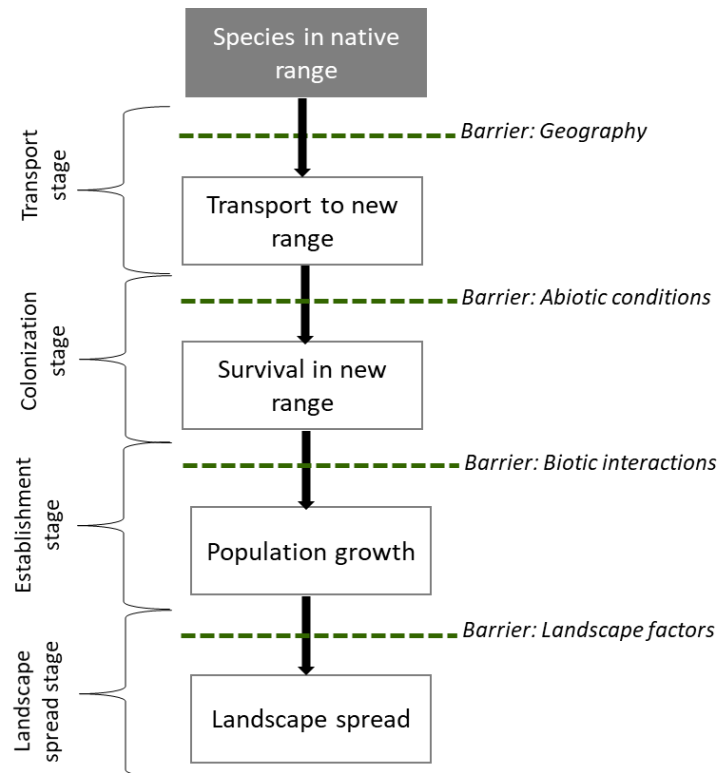
Fishes of the genus *Tilapia* (c.70 species of cichlid fishes) are common in pools, ponds, and mangrove lagoons across the Cayman Islands, following introductions associated with aquaculture (Bartley, 2006). These omnivorous fishes have relatively broad salinity and temperature tolerances, up to maxima of 8 ppt and 42°C respectively, and their presence has been associated with increased turbidity via bottom-feeding bioturbation, which also increases nutrient release from sediments, contributing to eutrophication. The hardiness of these species and their omnivorous nature mean that they are generally associated with negative ecosystem impacts in habitats that they invade. With respect to Sammy's Pond in West Bay Grand Cayman, DaCosta-Cottam et al. (2009) suggest they have contributed to eutrophication, while the Protected Area Management Plan for Meagre Bay Pond states that these fish entered from the neighbouring closed quarry. Present climate impacts on the distribution and abundance of these fishes have not been explicitly documented. However, flooding events associated with storm surges and high precipitation events have likely contributed to their spread via intermittent connection of suitable habitats. Potentially notable impacts may pertain to the persistence of two endemic fish species, *Limia caymanensis* and *Gambusia xanthosoma*, for *Tilapia* can predate the eggs and juveniles of other species. However, these endemic species have greater salinity tolerances, so many habitats that they inhabit may be ecologically unsuitable for *Tilapia*.

The lionfish (*Pterois volitans*) is a voracious predator native to the Pacific and Indian Oceans that eat large numbers of reef fish and shellfish, severely impacting native populations (Department of Environment, 2022b). The species is present in the Cayman Islands, although control measures are in place to reduce its spread (DaCosta-Cottam et al., 2011). These include reef biomass monitoring, culling by divers, culling competitions and promotion of lionfish as food. Evidence suggests that hurricanes may have hastened the invasion of lionfish throughout the Caribbean, following their initial introduction in Florida and the Bahamas (Johnston & Purkis, 2015).

Weeping willow or Australian pine (*Casuarina equisetifolia*) and beach naupaka (*Scaevola sericea*) are invasive coastal plants that are found on all three Cayman Islands (DaCosta-Cottam et al., 2011; Kew UKOTs Team, 2022). The beach naupaka is replacing areas of native vegetation and has greatly reduced the bay balsam (*Scaevola plumieri*) population on Grand Cayman (Kew UKOTs Team, 2022).

#### *Future climate impacts*

The impact of future climate change on new invasive non-native introductions depends on how climate change within and surrounding the Cayman Islands affects the key stages in the invasion process outlined in Figure 32.



**Figure 32.** Conceptual model of the process of species invasion and stages that could be affected by climate change. Source: Hellmann et al. (2008).

For the Cayman Islands, invasion routes for terrestrial species are either via humans (e.g. stowaways, escaped pets, imports of foodstuffs, ornamental plants) (Roy et al., 2019) or during hurricane events (Bellingham et al., 2005). Van den Burg et al. (2020) found that post hurricane aid deliveries enabled the introduction of two invasive species (Green iguana and Cuban tree frog) to Dominica resulting from a lack of biosecurity implementation due to urgency of delivering aid supplies. Islands are particularly vulnerable to invasive species, where native species may be naïve or easy prey and potentially inferior competitors (Moser et al., 2018). On the Cayman Islands, following invasion of exotic Brown anoles (*Anolis sagrei*), the native Blue-Fanned anole (*Anolis conspersus*) changed its behaviour and shifted its habitat (Losos et al., 1993). On the Sister Islands, Sister Islands Rock iguanas declined 39% between 2015 and 2019 most likely due to feral cat predation of hatchlings (Haakonsson, 2020) (see Roy et al. (2019) for invasive non-native species with a high likelihood of arrival, establishment and impact within the Cayman Islands). Once in the “landscape spread stage” (Figure 33), the only method of removing invasive non-native species is via eradication, manually, or via biocontrol (Hellmann et al., 2008), and the economic cost of doing so can be high; currently the Green iguana eradication program has cost 7.2 million USD (Knapp et al., 2021). However, climate change also has potential implications for eradication methods, for example, the efficacy of pesticides and biocontrol agents may be reduced under projected climate changes (Hellman et al., 2008, and references therein).

Beyond the potential for new introductions, a crucial consideration is how climate change will affect existing invasive non-native species on the Cayman Islands. Invasive non-native species may be less vulnerable to climate change due to their adaptability (Oduor et al., 2016). Many invasive species have been selected for traits that facilitate long-distance dispersal, therefore, shifts in environmental conditions will tend to favour invasive species (Hellmann et al., 2008). Rios-López (2008) contrasted two anurans (frogs) on Puerto Rico, the native Caribbean White-Lipped frog (*Leptodactylus albilabris*) and the introduced Marine toad (*Bufo marinus*). Neither of these species are currently known to be on the Cayman Islands (although other anurans are). Unsurprisingly, the marine toad was found to

increase in abundance as salinity increased, while the native frog showed the opposite pattern (Rios-López, 2008). The future climate impacts are predicted to have less of an impact on existing invasive non-native species (Manes et al., 2021), however, trajectories are expected to be highly species-specific and dependent on the multiple environmental and trophic interactions.

Climate change is likely to exacerbate the impacts of the Australian pine *Casuarina equisetifolia* as increased disturbance and/or decline of native habitat will likely enhance opportunities for colonisation. The species itself appears somewhat resistant to likely climate change effects, it is salt-tolerant and adapts to coastal stress by altering its tree shape and dry mass density (Lin et al., 2017). The presence of various mycorrhizae has been shown to improve drought tolerance in seedlings under glasshouse conditions (Zhang et al., 2010) and may also improve adaptation to flooding (Osundina, 1997). Therefore, when considering the pine's response to climate change, the response of symbiotic partners to environmental changes also needs to be borne in mind (e.g., Sayed et al., 1997). It apparently copes well with increased carbon dioxide concentrations (Warrier et al., 2013) (again, when symbiotic partners are present (Karthikeyan, 2017)) and can maintain growth through branchlet changes in the face of blown sand (Chen et al., 2018). A category 3 storm on San Salvador Island of the Bahamas had minimal impact on *C. equisetifolia* distribution. The authors argued that more powerful storms (as is predicted for the Cayman Islands) would be needed to have a significant effect on *C. equisetifolia* populations (Rodgers & Gamble, 2008). On the other hand, Lee et al. (2019) found that sustained wind stress significantly decreased the growth performance, root anchorage capability, and tensile strength of *C. equisetifolia* seedlings, but this was from a wind tunnel test environment.

### Scoring

Local monitoring, plus regional and global studies. Medium agreement, limited evidence. Relevance: Grand Cayman = medium; Little Cayman = low, Cayman Brac = low.

## 4 Current and future impacts of climate change on economy and society

In the following section, a categorisation scheme for ecosystem services to human society has been adopted based on the Environmental Benefits Assessment approach suggested by Hooper et al. (2014). Environmental benefits are identified where a direct gain in human welfare is provided by environmental goods and services. For the purposes of this report, benefits are analysed from an anthropocentric perspective and include not only goods, but also intangible gains (e.g., health and wellbeing). Environmental benefits to society have been grouped into four main types of services (provisioning, carrier, cultural and regulating), each of which provides different benefits or values.

### 4.1 Provisioning services/benefits

#### 4.1.1 Fisheries and aquaculture

According to the UN Food and Agriculture Organisation (FAO), no major commercial fishery exists in the Cayman Islands, although there is artisanal and recreational fishing (FAO, 2018) and all three islands have fish landing sites. Catches by the artisanal sector are small and includes catches for subsistence purposes (approximately 25%), for commercial purposes (approximately 25%), and for recreation (approximately 50%). The species targeted by this sector are mainly of the Lutjanidae

(snappers) and Serranidae (groupers) families. Historically there was a fishery focussed on Nassau grouper (*Epinephelus striatus*) (FAO, 2018). Fishing practices include use of hand lines and diving to collect Spiny lobster (*Panulirus argus*) and Queen conch (*Strombus gigas*). Scuba diving (spearfishing) is prohibited for all species, except the invasive lionfish. Recreational fisheries are an important part of the Cayman Islands tourism industry. Sport fishing takes place year-round offshore of all three islands where the ocean floor drops off sharply, creating a natural thoroughfare for the large migratory pelagic species prized by anglers. Popular gamefish include Blue marlin, Yellowfin tuna, Wahoo, Dolphin (dorado), and barracuda. Occasional catches of white marlin and, very rarely, Atlantic sailfish and Atlantic long-billed spearfish are also reported. Annual fishing derbies target Blue marlin (*Makaira nigricans*) and other pelagic sportfish (Brunt & Davies, 1994).

Total annual capture production for the Cayman Islands is reported to be only 125 tonnes, although this is thought to be a considerable under-estimate and no species breakdown of catches is available. As part of the 'Sea Around Us' project, Harper et al. (2009) attempted to reconstruct Cayman Islands fisheries catches between 1950 and 2007 and their estimates were 3.2 times larger than the amount officially reported to the FAO on behalf of the Cayman Islands. Henshall (2009) attempted to provide a quantified examination of the characteristics and spatial distribution of the recreational and artisanal fisheries of Grand Cayman using interviews with fishers. One hundred and seventy-two resident fishers indicated that they had caught 11,140 fish during the last month alone, of which 87% were reef species, suggesting that substantial fishing pressure does occur in Caymanian waters. The most heavily fished area is located at North-West Point (Grand Cayman), and the most frequently caught species are snapper. Fishers are exploiting vulnerable species such as those that form spawning aggregations (respondents reported catching 3792 snapper and 153 grouper in the last month), and are targeting herbivorous species (parrotfish and surgeonfish). Many of these reef-associated species have been identified as being especially sensitive to climate change, as well as overfishing pressures (see relevant section of this report; Bruno et al., 2019; Waterhouse et al., 2020), and there has been anecdotal evidence from fishermen of reduced catches.

Historically, little attention was paid to the monitoring of marine resources, including fish, but there is now a stronger focus on marine protection with several marine conservation laws enacted in 1986 in response to coastal developments in the Cayman Islands. Fishing for Nassau groupers is now closed between December through 30 April each year at 6 known and 2 potential spawning aggregation sites (Bush et al., 2006), as well as a moratorium on trading as this species was severely depleted through recreational, artisanal, and subsistence fishing (Waterhouse et al., 2020).

Aquaculture production is not a major feature of the Cayman Islands. Operations include Tilapia aquaculture (*Oreochromis niloticus*) on Grand Cayman, such as the Cayman Turtle Centre, a conservation facility and tourist attraction located in the district of West Bay. First established in 1968 as "Mariculture Ltd" and later called "Cayman Turtle Farm" by a group of American and British investors, the facility was initially used to breed the endangered green sea turtle for commercial purposes. By raising the turtles in a farming operation, the turtle meat could be produced for local consumption without depleting the wild population of the species. Although still in operation as a farm for raising turtles to sell product, the Cayman Turtle Centre is now also the largest land-based tourist attraction in the Cayman Islands.

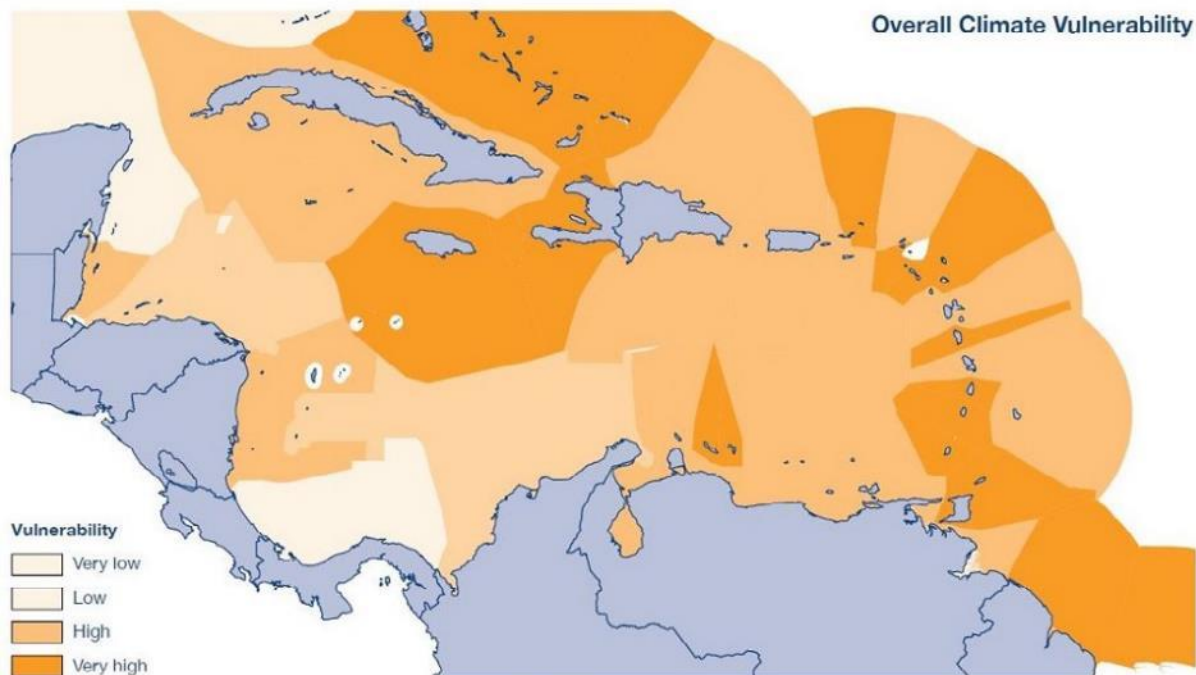
### *Current climate impacts*

Hurricanes in the region impact fisher safety at sea and cause damage to coastal communities, as well as to fishing gear, vessels, and coastal fisheries infrastructure (Sainsbury et al., 2018; Shelton et al., in press). Recovery of the fishing sector after a hurricane often takes a long time. In the Cayman Islands, Hurricane Ivan in 2004 caused considerable direct damage to boats, fish pots, and other equipment, as well as income losses for fishermen (ECLAC, 2005).

A severe setback to the success of the Cayman Turtle Centre occurred on November 4, 2001, when large waves generated by Hurricane Michelle inundated the facility. The hurricane was located 90 miles southwest of Grand Cayman and produced little wind, but the waves washed turtles of all sizes out to sea. Cayman residents responded to help rescue the turtles and for months thereafter, the yellow-tagged turtles from the Centre were spotted around the island, although 75% of the breeding turtles were lost. A nascent venture of Tilapia farming also incurred significant loss (CIG, 2005).

### *Expected future climate impacts*

Cheung et al. (2018) used a range of different models to make projections of future fisheries catch potential (%) assuming an RCP2.6 (low emissions) and RCP8.5 (high emissions) climate change scenario over the 21st Century. For the Cayman Islands, the Dynamic Bioclimate Envelope Model (DBEM) models suggest a 9.33 and 12.35% decline in catch potential by mid-century under these scenarios, but prospects in the longer-term (end of century) are more divergent, with declines of 5.20% under RCP2.6 and 52.49% under RCP8.5. Monnereau et al. (2015) set out to examine the relative 'vulnerability' of the fisheries sector in 33 Caribbean countries or territories (Figure 33) by considering 'exposure' to climate change risk (temperature and sea level rise), 'sensitivity' (reliance on fisheries), and 'adaptive capacity' (governance, economic resilience). Fisheries in the Cayman Islands were considered to have a high vulnerability to climate change, based on the fact that species are highly exposed to temperature and sea level rise, but the territory is only moderately dependent on marine resources and has access to sufficient financial resources to adapt.



**Figure 33.** Overall Climate Vulnerability of the fisheries sectors in 33 Caribbean countries or territories. Each country is delimited by its EEZ boundary. These boundaries are subject to some objections which have been submitted to the UN. Source: Redrawn from Monnereau et al. (2015).

Future climate change could threaten the recreation fishing industry which is an important income stream. Changes in species distribution and/or changes in offshore weather (e.g., more frequent or severe storms) could deter participation in this activity (Townhill et al., 2019).

### Scoring

Local climate impact studies and Regional studies. Medium agreement, medium evidence. Relevance: Grand Cayman = high; Little Cayman = low, Cayman Brac = low.

#### 4.1.2 Agriculture

Eleven point three percent of the Cayman Islands land area is agricultural (c.27km<sup>2</sup>), with 2.1% as permanent cropland and agriculture. Forestry and fishing together account for c. 0.4% GDP and employ less than 2% of the working population (Cayman Islands Compendium of Statistics, 2020). Agriculture ranges from small traditional crop and livestock production to more intensive operations, albeit on a relatively small scale. Crops predominantly consist of bananas, plantain, breadfruit, sweet potato, avocados, mangoes, yam, papaya, cassava, and citrus fruits. Bananas, citrus, and mangoes together account for around 70% of crop outputs (ECLAC, 2005). Vegetables and herbs such as tomatoes, pumpkin, peppers, and melons are also grown, with production increasingly employing shade houses, drip-irrigation, and fertigation. Tilapia aquaculture (*Oreochromis niloticus*) is also conducted on Grand Cayman. Livestock production comprises cattle, goats, pigs, and poultry with no dairy operations. Most agriculture is located on Grand Cayman and Cayman Brac, while that on Little Cayman is negligible and conducted at the individual household level (Table 10).

Imports account for most food consumed, increasingly so as the population has risen. Efforts are underway to promote local produce towards increasing food security and human health, but the land area is insufficient to meet population food needs. On Grand Cayman, expansion of this sector is challenged by increasing use of agriculturally suitable land for residential development and aggregate mining (Hurlston-McKenzie, 2011). Given the high reliance on food imports, the Cayman Islands are sensitive to exogenous shocks, particularly as growth has led to greater capacity for dependence on imports and trade (Armstrong & Read 2002; Read, 2004). Food imports also incur the risk of invasive and pest species introductions.

In contrast to many Caribbean islands and small island developing states, the development of domestic and smallholder farming systems are not constrained by export-oriented agriculture (Griswold, 2021; Rhiney, 2018; Saint Ville et al., 2015 ); rather land availability and its competition with tourism, residential, and protected areas services are the present limitations to expansion of the sector, as well as marketing.

Small soil areas within forests constitute the most agriculturally suitable and fertile land on the islands, and many of these were initially cleared by hand for fruit trees. Clearance of larger expanses was also conducted for seeding with grass for rough grazing of cattle. Small, historically farmed areas have been reduced by suburban development, and in more remote areas some have been abandoned and reverted to shrub and woodland. Cattle tend to be pastured at low elevation during the dry season when forage quality is relatively poor with intakes supplemented by imported feeds, but are moved to higher elevation during the rainy season where forage quality improves and when lower elevation pastures can be flooded. Agriculture relies on rainfall during the wet season but shifts to abstraction from wells and cisterns during the dry season. The abstraction of groundwater for any purpose, other than single residential use, requires a licence under section 22 of the Water Authority Law (2018 Revision), whereby maximum abstraction rate, well design, and requirements for the protection of

groundwater resources from contamination by agricultural wastes are determined. Water for human consumption and agricultural irrigation is covered in a different section of this report.

**Table 10.** Numbers and types of livestock and associated farmers for 2020. Source: Cayman Islands Compendium of Statistics (2020)

	Grand Cayman		Cayman Brac		Total	
	No.	No. Farmers	No.	No. Farmers	No.	No. Farmers
Goats	1646	82	746	8	746	90
Pigs	1091	20	58	6	1149	26
Cattle	1426	116	93	7	1519	123
Poultry - Layers					19302	
Poultry - Broilers					2522	

#### *Current climate impacts*

Hurricane Ivan in 2004 is reported to have destroyed 90-95% of crops on Grand Cayman, although some agricultural areas situated within the more protected eastern bluff of Cayman Brac were unaffected (ECLAC, 2005). The predominance of shallow soils means that fruit trees are highly susceptible to uprooting, and crop recovery times are species-dependent, with banana recovering most rapidly (<1year). The plant propagation system of the governments' Agricultural Experimental and Research Unit was also destroyed by Hurricane Ivan, incurring the loss of most seedlings for restocking. Livestock were less affected by comparison, being largely housed in sheds prior to the incidence of the hurricane, with loss estimates of 100 goats and 50 cattle. However, the poultry industry suffered severe damage to infrastructure, with some operations destroyed. This situation is also reported for the Dominican Republic by Benson et al. (2001), who also note that pigs were hardier and able to survive on fruit waste generated after hurricanes, whereas commercial poultry was vulnerable to disruption in feed and power supplies. Feral chickens are considered problematic on the Cayman Islands, and there are concerns that expansion of the chicken sector, notably via more intensive housed operations, could lead to large escapes during storm and hurricane events. Some Tilapia aquaculture facilities suffered significant losses due to saltwater intrusion and flooding.

Flooding associated with storm surges and high precipitation can devastate ground and lower storey crops, particularly if prolonged. Saltwater intrusion from the Hurricane Ivan storm surge resulted in inundation of the low-lying duck pond pastures (Grand Cayman). Recondition of this area to grazing suitability is reported to have taken several seasons (Hurlston-McKenzie, 2011 and references therein). Indeed, soil salinisation associated with saltwater intrusion is problematic in some areas, and the Cayman Islands' government subsidises gypsum in response. Losses of seedlings due to salt spray and deposition on soils has been observed, and irrigation and foliar spraying with freshwater after such events is practiced to mitigate such impacts. Climate change has been identified as a major precursor for increases in soil salinity via the associated impacts of sea-level rise and salt-water intrusion, changing rainfall, and increased evaporation at higher temperatures (Eswar et al., 2021). These aspects of water availability and quality are examined further in the section on Freshwater Environments and Resources.

High temperatures can lead to heat stress and health impacts on livestock, mitigated through increased provision of shade, water, electrolytes via salt licks, and ventilation. Ortiz-Colón et al. (2018)



identify heat stress as the primary constraint to beef and dairy production in the Caribbean, via its negative effects on productivity, fertility, dry matter intake, and increased disease risk. Heat stress also decreases poultry egg production and quality, and broiler productivity and has adverse impacts on goats in the tropics (Lallo et al., 2018, and references therein).

Drought periods have increased in frequency since 2000 across the Caribbean with impacts including reduced crop yields, losses of livestock, increases in plant pests and diseases, and increases in the number of fires and land extent burned (Farrell et al., 2010; Trotman et al., 2018, 2021). The unintended spread of fires employed for land clearance can also lead to significant fire damage of dry forest, which are often adjacent to agricultural land, and such fire-damaged areas can be susceptible to colonisation by invasive species (DaCosta-Cottam et al., 2009). Wildfires can also be indirectly problematic for livestock. For example, the extreme 2014 dry season in the US Virgin Islands led to wildfires affecting both livestock and ranchers in turn, where low rainfall and high temperatures in the subsequent period reduced grassland pasture forage in 2015, leading to reliance on unconventional fodder such as palm fronds, tree branches, and imported feeds.

Globally, climate change impacts on agricultural production as assessed against general temperature trends indicate a reduction in agricultural production of c.21% since 1961, with more pronounced effects (-25.9%) for warmer regions, such as Latin America and the Caribbean (Cerri et al., 2007; Ortiz-Bobea et al., 2021; Reyer et al., 2017). Lenderking et al. (2021) reviewed studies of food security in Caribbean small island developing states published since the 2014 IPCC AR5 report, highlighting that climate change has, and will continue to significantly affect Caribbean agriculture and fisheries with lower yields and total production values, principally due to changing weather patterns, air and sea surface temperatures, and water availability.

Several studies have documented severe impacts on agriculture by hurricanes and extreme events in the Caribbean region. Weiner et al. (2020) explored these impacts for the south-east of the USA and the Caribbean and highlighted the potential for both short- and long-term impacts of devastation to crops and agricultural outputs, citing the example of an 80% loss of nutmeg trees with Hurricane Ivan in Grenada, which took several years before their first harvest again and only recently reached full production. Similarly, Trotman et al. (2009) has provided a detailed breakdown of the high economic costs of extreme events, particularly drought, floods, and hurricanes with regard to food security in CARICOM states. These authors also suggest that projections for reduced precipitation and rising temperatures across the region will reduce agricultural yields due to reduced soil and irrigation water availability, as well as saltwater intrusion caused by sea level rise and groundwater extraction. Hurricane return times are also of significance.

The role of hurricanes is also stressed by Strobl (2012) who used earth observation approaches to assess hurricane impacts on Caribbean-wide cropland for the period 2000-2006, finding substantial declines in production post hurricanes. By disaggregating drivers in an analysis of 28 Caribbean-basin countries, Hsiang (2010) found that temperature impacts on agricultural production alone equated to a reduction of  $-0.1\%/^{\circ}\text{C}$ , and as a notable aside, that this temperature response was lower than losses assigned to non-agricultural productivity via associated thermal stresses to the workforce ( $-2.5\%/^{\circ}\text{C}$ ).

As noted previously, extreme events can have differential impacts on different crops types. Spencer and Polachek (2015) examined hurricane impacts on crop production in Jamaica for the period 1999-2008 and found that while above ground crop production was severely reduced, several below ground crops were unaffected (e.g., tubers such as dasheen, coco, and cassava), while yams and potatoes responded negatively to increased water saturation of soils. On a similar vein, Chen and McCarl (2009) found that hurricane impacts on crops across southern states of North America varied by crop and state, with both positive and negative responses that may reflect differing precipitation inputs during and after hurricanes.

Annually, around 10-13% of global crop yield is lost due to disease and pests, with greatest losses in the topics where high temperature and humidity favour disease and pest development (Oerke et al.

2006; Strange & Scott, 2005). The spatial and temporal distribution and abundance of pest and diseases is largely determined by climatic conditions, as temperature and moisture are key controls upon growth, development, reproduction, and dispersal. However, high diversity of pest and pathogen species, variation of species responses to climatic conditions, and potential for multiple trophic level dependencies make general characterisations of such relationships difficult (Jeger & Pautasso, 2008). Consequently, there is limited substantive evidence for climate change impacts on plant pathogens and pests, with most studies on latitudinal and altitudinal range expansions in response to temperature increase (Bebber et al., 2015, 2019). Efforts to control pests and disease are also subject to climatic influences. For example, pesticide efficacy can be affected by temperature, light, and rainfall.

Bebber et al. (2019) found that infection risk for bananas by Black Sigatoka disease has increased by a median value of 44% across Latin America and the Caribbean since the 1960s, reflecting improved temperature conditions and increased canopy wetness for the pathogen. However, drying trends in some regions (e.g., Mexico, Central America) decreased infection risks. Given the limited evidence base in this area, a general summary of pathogen and pest responses to climate change is given below, relying largely on the comprehensive review of Skendžić et al. (2021).

The physiology of insects is sensitive to changes in temperature, and there is a wide body of evidence showing that increases tend to accelerate insect activity, in turn affecting population dynamics via fecundity, survival, development rates, and distribution (e.g., Bale et al., 2002). The availability of host plants can also be influenced by temperature, which further serves to modulate pest population dynamics. While insect herbivory can be expected to increase with temperature, temperatures in tropical regions are generally already in the optimum range for insects so that future warming is expected to result in decreased insect growth rates and herbivory (Deutsch et al., 2008; 2018; Lehmann et al., 2020). Temperature increases can also have more pronounced impacts on above ground insects by comparison to below-ground insects due to the buffering influence of soils (Bale et al., 2002).

Experimental studies involving elevated CO<sub>2</sub> concentrations have shown positive growth and an increase in the ratio of carbon to nitrogen in crop species. In such circumstances some insects (predominantly foliar feeders) have been shown to increase plant matter consumption to meet dietary nitrogen needs resulting in increased crop damage (Cotrufo et al., 1998; Lincoln et al., 1993). A meta-analysis of herbivore responses to elevated CO<sub>2</sub> of 550-1000 pm indicated consumption rates increased by 17%, abundance declined by 22%, development times increased by 4%, and relative growth rate declined by around 9%. Comparisons between herbivore guilds (e.g., chewers such as caterpillars and sap-suckers such as hemiptera) were constrained by the prevalence of data pertaining to chewers, however, effects tended to be greater for this group (Stiling & Cornelissen, 2007).

In general, future climate projections suggest an increasing likelihood of both droughts and floods. Droughts are generally thought to have positive effects on insect pests via conducive environmental conditions, and also increased plant susceptibility due to reduced production of secondary defensive metabolites (Yihdego et al., 2019). In contrast, heavy rainfall can physically remove small pests such as whiteflies, aphids, mites, and eggs and larvae on the surfaces of vegetation (Ramos et al., 2019).

Insects are vectors for transmission of many plant diseases (e.g., viruses and bacteria) so that direct climate change effects on insects can have indirect impacts via the spread of plant disease. The homopteran families of aphids (Aphididae), leafhoppers (Cicadellidae), and whiteflies (Aleyrodidae) are the major vectors of viral diseases (Nault et al., 1997); for example, Tomato yellow leaf curl virus, which can also affect peppers and beans. Temperature increases above optima for insects may thus in turn reduce the incidence of pathogens that they transmit (Ghini et al., 2011).

### *Expected future climate impacts*

Climate change is predicted to have a negative impact on agricultural sectors across Latin America and the Caribbean (Reyer et al., 2017). Mohan and Strobl (2017) estimate that future hurricane wind induced losses in the agriculture sector of Caribbean island economies, in the absence of adaptation measures, are expected to be large but vary across the region according to island size, the structure of the agricultural system (e.g., tree vs. root based crops), and the return times and probabilities of hurricane incidence, where smaller islands are much more likely to be negatively impacted. Similarly, Lachaud et al. (2022) forecast reductions in agricultural productivity among crops and livestock across Latin America and the Caribbean of 9-13% over the period 2015-2050. This reflects the negative impacts of increases to average monthly and yearly temperatures and reduced precipitation across the region, and implies that pressures on water resources will increase, necessitating more efficient water use and uptake of sustainable irrigation technologies and infrastructure to maintain yields.

Curtis et al. (2014) assessed CMIP5 projections (IPCC 2013) with respect to crop water requirements in Jamaica and demonstrated that requirements will increase with rising temperatures and falling precipitation. They will also vary with future seasonality, although all scenarios lead to decreased crop suitability with the greatest impacts projected for the March-August period. Gohar and Cashman (2018) used a modelling framework to investigate hypothetical climate impacts on agriculture in Barbados incorporating both climate change reductions to precipitation and future variability. They concluded that changes in rainfall due to climate change result in lower yields and total production. Whilst climate change reduces water availability, climate variability can partly negate the overall impact of climate change, where 'flood' years and events can serve to recharge aquifers. On this basis, they suggest potential for adaptation via adoption of irrigation technology such as drip irrigation, and modification to the types of crops produced.

Rhiney et al. (2018) employed a niche model to estimate how predicted changes in future climate could affect the growing conditions of several commonly cultivated crops in Jamaica in response to future temperature increase scenarios of +1.5 and +2°C. The approach indicated that a 1.5°C increase would negatively impact crop suitability and reduce the range of crops that can be successfully grown, with greater increases leading to extensive changes to the agricultural system. Additionally, the study suggests that short-rotation crops that extend into the dry season will be most impacted if farmers do not have reliable sources for irrigation, while the most pronounced negative impacts will occur in low elevation areas owing to greater temperature increases and reductions to precipitation. Similarly, Machovina and Feeley (2013) modelled the impact of climate projections on areas suitable for banana cultivation across Central America using species-distribution modelling and predict that climate change (temperature and rainfall under a variety of projection models) will cause large shifts in the locations and land areas suitable for banana plantation production over the next 50 years. Temperature tolerances of typical Caribbean crops are set out in Table 11 to provide context considering climate projections for the Cayman Islands. Impacts of changes to climate seasonality on crops, such as rainfall distribution and amount, are also underscored by the individual growth characteristics and requirements of certain species. For example, the growing period of yams (*Dioscorea* spp.) coincides with the onset of the rainy season, and lengthened dry (storage) periods can lead to proliferation of pests such as Mealy Bugs and nematodes that destroy tuber meristems and prevent the growth of shoots and roots (Wickham, 2019).

**Table 11.** Temperature tolerances for common Caribbean crops. Optimum maximum temperature is the highest temperature where physiological processes remain at an optimal level; absolute maximum temperature is the temperature above which permanent damage occurs. Source: Adapted from Rhiney et al. (2018).

Crop type	Crop	Optimum max (°C)	Absolute max (°C)
Oilseed crop	Coconut	~34	~38
Fruit -Permanent	Avocado, coconut, mango	30-40	38-48
Fruit -Temporary	Banana, papaya, pineapple	30-32	36-44
Citrus	Orange, grapefruit, tangerine, Lime	28-34	36-42
Temporary	Hot pepper, ginger	26-29	32-35
Leguminous	Pigeon pea, cow pea, common & broad bean	25-38	32-45
Root crops /Starch	Sweet potato, 'Irish' potato, cassava, yam	25-32	30-40
Fruit	Tomato, peppers, eggplant, okra, pumpkin, watermelon	27-35	35-40
Leaf & stem	Cabbage, broccoli, lettuce	21-30	30-45
Root	Carrot, onion	24-25	~30

Lallo et al. (2018) used temperature humidity indices (THI) for four types of livestock and poultry (broiler and layer chickens, pigs, and ruminants) to assess the potential for present and future potential heat stress in Jamaica. They found that livestock can already experience considerable periods of heat stress. Future temperature projections of +1.5°C lead to categorisation of all months as very severe for broilers and ruminants. For layers and pigs, 7 and 9 months respectively fell into high stress categories. For +2°C, all months were classed as very severe for broilers and ruminants and most months for layers and pigs. For +2.5°C, all months are classed as very severe for all livestock. The mean year of occurrence of a +1.5°C increase among the models employed was 2027, with +2°C increases indicated for beyond 2050. These authors also note that THI values were calculated using maximum daily values so that factors that influence heat stress experienced by livestock, such as diurnal variation, duration and accumulation of heat stress, and extent of recovery periods, were not considered. Future reductions in humidity may reduce heat stress, however, future rainfall predictions suggest negligible alterations to humidity over the next 50 years. The common trend across all livestock suggests that the future Caribbean climate is expected to produce steadily increasing heat stress for animals. Similar impacts have been predicted to affect livestock production elsewhere. For example, +2 and +3°C warming scenarios are projected to reduce beef cattle production by 16–27 % in Paraguay (ECLAC, 2010). Direct interpretation of the literature in the Cayman Islands context would also require consideration of humidity data.

Insect pests in low latitudes have a lower capacity to benefit from future temperature increase given that environmental temperatures are at or close to optimums, such that insect pest severity may reduce under future climate change (e.g., Sunday et al., 2014). Inter and intra-annual seasonality is a common feature of many pest species. For example, the polyphagous Whitefly (*Bemisia tabaci*), a notable global pest, exhibits population trends dictated to a large degree by environmental suitability, principally temperature (with an optima of 15-35°C) and moisture availability (Ramos et al., 2019).

However, *B. tabaci* is also known to exhibit phenotypic plasticity and rapid adaptive evolution, evidenced by genetic divergence in response to climatic conditions (Díaz et al., 2014). Zidon et al. (2015) suggests that such features, which include heritable heat-resistance traits, make it difficult to predict climate change impacts on such pests.

Blight caused by a bacterium (*Xanthomonas axonopodis* pv. *Manihotis*) is the most important disease of Cassava (*Manihot esculenta*) and has an optimum temperature range of 22–26°C, so that the incidence of the disease is expected to remain similar or lower in regions where it is cultivated above this temperature range (Ghini et al., 2011, and references therein). Panama disease (*Fusarium oxysporum* f. sp. *cubense*; Fusarium wilt) is prevalent in most banana-growing regions and is expected to increase in the future due to rising temperatures and periods of drought that alter plant physiology, causing stress and susceptibility to the disease (Ghini et al., 2011, and references therein). Garrett et al. (2006) also note concern with respect to potential impacts of race TR4 emerging from Asia on banana exports from Latin America and the Caribbean.

Fusarium Wilt is of less importance as a pest of bananas by comparison to Black Sigatoka Disease (fungus), which causes the greatest yield losses in plantations globally, and can reduce yield in infected plants by up to 80% (Garrett et al. 2006, and references therein). Projected changes to favourable areas for the Black Sigatoka pathogen based on temperature and humidity will gradually decline from 2020-2080 in the region (Cecilio et al., 2008; Júnior et al., 2008). However, while future trajectories towards drier conditions suggest reduced incidence of this disease (although extreme events and changes to seasonality incur uncertainty), as noted previously, production of bananas may be reduced under warmer drier conditions in the absence of irrigation systems with wider implications for water resources.

The Papaya Mealybug (*Paracoccus marginatus*) is problematic for a range of crop species in the Cayman Islands and is an emerging pest globally (reported on 134 genera of 49 families of plants) with temperature amongst the most influential variables affecting its distribution (Heya et al., 2020, and references therein). Finch et al. (2021) employed niche modelling to accurately predict the present and potential global distribution of the species, based on an optimum temperature range of 27-32°C with lower and upper thresholds of 13-38°C, as well as other environmental parameters. Likewise, Heya et al. (2020) were also successful in applying similar approaches to Kenya that has a recent invasion history. Heya et al. (2020) note that the probability of occurrence was considerably lower where the maximum temperature of the warmest month was above 33°C. These observations are more pertinent to colder regions that may increase in suitability for both crop host plants and *P. Marginatus* with future warming, for example, as described for the Pink Hibiscus Mealy Bug in Chile (Jara et al., 2013). However, in the context of the Cayman Islands, the optimum temperature range for *P. Marginatus* is similar to that for many crop species (Table 11). Observations for the Pink hibiscus Mealy Bug (*Maconellicoccus hirsutus*) are similar with predominant temperature control, although Chong et al. (2008) document reduced survival and reproduction at temperatures over 30°C suggesting greater negative impacts on populations with future warming by comparison to *P. Marginatus*.

### Scoring

#### *Risk1: Increasing heat stress for livestock*

Regional studies and Global studies. High agreement, robust evidence. Relevance: Grand Cayman = high; Little Cayman = low, Cayman Brac = high.

#### *Risk2: Increasing heat and water stress for crops and forage plants*

Regional studies and Global studies. High agreement, robust evidence. Relevance: Grand Cayman = high; Little Cayman = low, Cayman Brac = high.

*Risk3: Storm damage to arable and horticultural agriculture*

Regional studies and Global studies. High agreement, robust evidence. Relevance: Grand Cayman = high; Little Cayman = low, Cayman Brac = high.

#### 4.1.3 Mining and sand extraction

Growing demand for building materials within the construction sector has stimulated interest in maritime mining of and sand extraction in the Cayman Islands, although not yet on a large scale. Evaluations are underway of the potential environmental impact and mechanical disturbance of the seabed, including physical and biological effects of marl (calcareous clay) mining, as well as extraction of sand and other aggregate materials (CSA Ocean Sciences, 2022). Benthic recolonisation has also been reviewed in terms of recolonisation adaptations, succession, and recovery (CSA Ocean Sciences, 2022).

*Expected future climate impacts*

If marine mining was to develop into an active sector, climate change could potentially disrupt operations nearshore and offshore, particularly during extreme weather conditions. Furthermore, climate change conditions in the future could aggravate the physical effects of extractions and their impacts on benthic communities in the vicinity of extraction pits, for example, reefs or seagrass meadows already under thermal stress. Similarly, it could affect recovery of extraction areas and their recolonisation by benthic communities following cessation of activities, for example, if climate change interfered with dispersion and deposition of mined material (CSA Ocean Sciences, 2022) through changes in weather patterns and their influence on ocean circulation, or intensification of short-term extreme events. Sea level rise or changes in storminess may mean more sand and gravel are needed to construct hard sea defences and for beach (re)nourishment, especially at chronic erosion/hot spots in some localities in the Cayman Islands.

*Scoring*

Regional scoping studies. High agreement, medium evidence. Relevance: Grand Cayman = medium; Little Cayman = low, Cayman Brac = low.

#### 4.1.4 Energy production

The Cayman Islands is heavily dependent on imported fossil fuels for energy needs. In 2014, renewable energy accounted for 0.9% of electricity generation, whereas diesel accounted for 95% of electricity generation (National Energy Policy Unit, 2022). Currently, 3% of electricity generation is from renewable energy. Diesel is also used for transport and in desalination plants (which produces 99% of potable water on Grand Cayman) (Hurlston-McKenzie, 2011). Electricity is provided by two power generation companies: Caribbean Utilities Company (provides 94% of energy for lighting) in Grand Cayman and Brac Power & Light in Cayman Brac (Hurlston-McKenzie, 2011).

*Current impacts*

Energy production within the Cayman Islands has not yet been explicitly impacted by climate change, despite critical infrastructure such as fuel storage terminals and electricity generation plants being situated in vulnerable coastal locations (see section on Inland settlements and infrastructure). Storms

and hurricanes have the potential to cause direct damages to energy generating plants, power lines, and other transmission infrastructure (MONA, 2020). A loss of electricity witnessed after Hurricane Ivan was due to hurricane damage of CUC's overhead transmission and the distribution system rather than damage to the plant itself (Hurlston-McKenzie, 2011). Indirectly, heat waves can increase energy demand for cooling.

The Caribbean region derives the majority of its energy (up to 90% in 2008) from imported crude oil (Bueno et al., 2008). This reliance on imported fuel and the exposure of most of the energy infrastructure to climate change impacts on the coastal zone highlight the challenges faced by the region (Bueno et al., 2008; CMEP, 2017). Table 12, derived from the SOCC report (MONA, 2020) provides a useful summary of how climate change could impact the energy sector in the Cayman Islands.

**Table 12.** Summary of how climate change could impact the energy sector in the Caribbean. Source: MONA (2020)

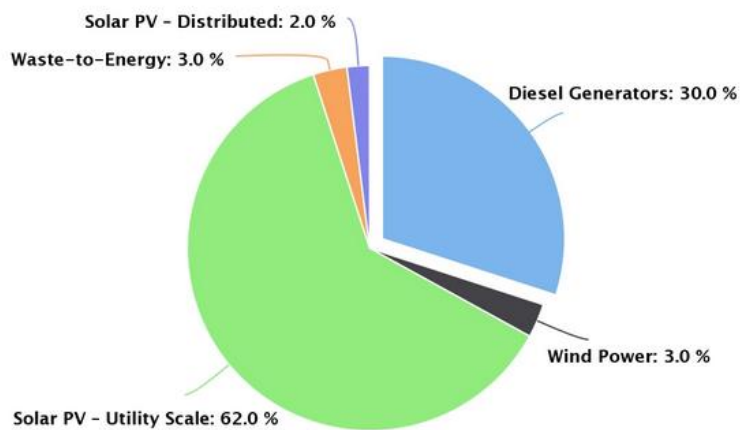
CLIMATE CHANGE VARIABLE/EXTREME EVENT	IMPACT
INCREASING TEMPERATURE	<p>Higher temperatures will reduce efficiency of electricity production and further increase demand for cooling systems. Extreme temperatures will likely increase energy demand for air conditioning (in both cars and buildings), as well as change our ability to supply adequate fuel, produce electricity, and deliver it reliably (WEC, 2014). As temperatures increase the efficiency of power production for many existing fossil fuel and nuclear power plants will decrease, because these plants use water for cooling. The colder the water the more efficient the generator; so warmer (air and water temperatures) will reduce the efficiency with which these plants convert fuel into electricity (WEC, 2014; EPA, 2017).</p> <p>Higher temperatures are less favourable for harnessing of solar energy; photovoltaic solar voltage and power decrease with increased temperature (Arjyadhara et al., 2013).</p> <p>Increased sea surface temperatures will increase the efficiency of Ocean Thermal Energy Conversion (OTEC) systems (CSGM, 2012).</p>
LOW RAINFALL	<p>Low rainfall and drought conditions will affect reliability of energy supplies. This includes decreases in river flow, and ultimately, power output for hydropower plants (CSGM, 2012).</p> <p>Increased evaporation, and drought may increase the need for employing energy intensive methods (e.g. desalinization) to meet critical needs (e.g., drinking and irrigation water) (CSGM, 2012). Irrigation water may also have to be pumped over longer distances, further increasing energy demand.</p>
INCREASED NUMBER OF SEVERE HURRICANES/ TROPICAL STORMS	<p>More intense hurricanes and storm events may damage energy infrastructure. This includes both onshore and offshore (distribution) equipment, wind turbines and power lines. These events may also delay repair and maintenance work and disrupt fuel transportation (WEC, 2014).</p>
SEA LEVEL RISE	<p>Sea level rise may impact coastal power plants. Many power plants in the Caribbean are located within the coastal zone (Bueno et al. 2008; CMEP, 2017). Sea level rise in the Caribbean is projected to be between 1-2m by end of century (Chen, 2011).</p> <p>Critical infrastructure including oil and gas pipelines could be adversely affected by damage from increased storm surge, which will be exacerbated</p>

	by more intense storm events (CSGM 2012; United States Senate Committee on Energy and Natural Resources 2015).
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*Future impacts*

Dependence on fossil fuels for energy production makes the Cayman Islands extremely vulnerable to climate change and political impacts (e.g., global shortages or price rises) on wider fossil fuel supply. Storms, hurricanes, and predicted sea level rise in the Caribbean has the potential to cause direct damage to energy generating plants (Table 12) (MONA, 2020). A preliminary vulnerability assessment by the Natural Disasters Assessment Consulting group (NDAC, 2009) highlights the exposure of fuel terminals within George Town. Damage to these would have a domino effect on energy production within the Cayman Islands. Increases in storm frequency and intensity could hamper delivery, as well as causing damage to marine ports and infrastructure (see section on marine ports) (Hurlston-McKenzie, 2011).

The Cayman Islands government intends for 70% of total electricity generation to come from renewable sources by 2037, predominately from solar power (Figure 34) (National Energy Policy Unit, 2022). This would decrease the risk of climate change to Cayman Islands’ energy production, but all sources of solar energy generation are themselves sensitive to climate change (Solaun & Cerdá, 2019, and references within). There is a potential risk to future solar energy generation from extreme weather events, changes in atmospheric particles and dust, wind speed, precipitation, and temperature (see Table 5 in Solaun & Cerdá, 2019, and references within for a comprehensive assessment of impacts). For example, mean temperatures within the Cayman Islands are predicted to increase and higher temperatures are less favourable for harnessing solar energy as photovoltaic solar voltage and power decrease with increased temperature (Arjyadhara et al., 2013). For all proposed renewable sources, more intense hurricanes may damage distribution networks and infrastructure. This includes both onshore and offshore distribution equipment, wind turbines, and power lines. These events may also delay repair and maintenance work (WEC, 2014). A more diverse energy portfolio and decentralized or more distributed energy production systems would vastly increase the resilience of the Cayman Islands energy production to climate change.



Source: Cayman Islands Government National Energy Policy 2017-2037

**Figure 34.** Proposed energy generation mix for the Cayman Islands by 2037, where predicted energy need is 730,423 MWh. Source: National Energy Policy Unit (2022)



In recent years, and especially in 2022, the Cayman Islands have witnessed a massive influx of Sargassum seaweed. Sargassum is very suitable as a substrate for biofuel-making through processes like anaerobic digestion to make biogas and fermentation to make bioethanol. The seaweed is rich in polysaccharides, a good source of energy, and low in lignin and cellulose, which are otherwise difficult to digest. This could represent one of the few ‘opportunities’ presented by climate change in the Cayman Islands. In addition, Beacon Farms is partnering with academics in the chemistry department at the University College of the Cayman Islands to collect data on the potential usefulness of composted Sargassum in agriculture.

### Scoring

For the Cayman Islands’ current energy production system: local knowledge and impact studies plus global evidence = high agreement, medium evidence. Relevance: Grand Cayman = high; Little Cayman = high, Cayman Brac = high.

#### 4.1.5 Water for human consumption and agricultural irrigation

Freshwater lenses are insufficient in extent and recharge potential to meet present human population requirements in the Cayman Islands. On Grand Cayman, most water and potable water demands are met by desalination plants abstracting from saline aquifers and a piped distribution network with some areas reached by water truck, although a relatively small quantity of freshwater is also abstracted from the East End lens (Table 13). The abstraction of groundwater for any purpose other than single residential use requires a licence under section 22 of the Water Authority Law (2018 Revision), whereby maximum abstraction rate, well design, and requirements for the protection of associated habitats and groundwater resources from contamination by agricultural wastes are determined.

**Table 13.** Water production in Grand Cayman 2012-2020. Source: Reproduced from the Cayman Islands Compendium of Statistics (2020).

	Water Production in Grand Cayman 2012-2020								
	2012	2013	2014	2015	2016	2017	2018	2019	2020
Potable Water	2,014.0	1,997.5	2,054.4	2,061.2	2,193.6	1,381.0	1,459.5	1,542.3	1,537.6
Desalinated Water Produced									
Cayman Water Company	854.9	801.4	803.1	791.2	888.6	..	..	..	..
Water Authority	1,158.3	1,194.8	1,250.7	1,269.2	1,304.2	1,381.0	1,459.5	1,542.3	1,537.6
Ground Water									
East End	0.8	1.3	0.6	0.8	0.8	0.6	0.6	0.7	0.7
Potable Water distributed by									
Pipeline	1,763.6	1,639.0	1,715.5	1,776.5	1,038.1	1,381.7	1,451.6	1,533.6	1,527.3
Truck	6.9	7.1	6.3	7.9	9.2	15.3	8.5	9.4	10.3
Non-Potable Water									
Cayman Water Company	30.7	17.4	26.6	18.3	..	..	..	..	..

Source: Water Authority Cayman and Cayman Water Company

Desalinated water demands are predominantly for residential supply (Table 14). As the population has increased, new homes have increasingly been served by desalination rather than cisterns and wells.

For drinking water, despite a widespread distribution network, the 2010 census found that although 88% of households had access to piped potable water, 79% still consumed bottled water (Hurlston-McKenzie, 2011, and references therein).

**Table 14.** Desalinated water consumption by consumer group 2010-2020. Source: Reproduced from the Cayman Islands Compendium of Statistics (2020).

20.08	Desalinated Water Consumption by Consumer Group, 2010-2020										
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
	<i>Million US Gallons</i>										
<b>Water Authority Users</b>											
Total	907.6	929.0	999.4	935.4	933.0	992.3	1,046.6	1,092.5	1,130.3	1,172.1	1,177.6
Residential	689.8	709.2	751.3	697.7	690.3	744.3	788.0	819.5	841.9	880.9	927.1
Multi-Residential	19.6	20.5	25.3	24.5	26.5	25.5	28.2	26.3	26.5	26.1	25.9
Commercial/Industrial	140.9	133.5	148.1	148.2	149.5	151.1	156.1	157.5	175.3	177.8	143.6
Public Authority	50.9	58.3	68.6	59.2	61.0	64.4	65.9	74.5	78.7	78.6	71.3
Truckers	6.4	7.5	6.1	5.8	5.7	7.0	8.4	14.7	7.9	8.7	9.7
<b>Cayman Water Co. Users</b>											
Total	797.7	768.9	754.6	695.5	717.8	726.1	807.4	..	..	..	..
Residential	209.6	216.9	217.1	215.9	222.1	236.6	263.9	..	..	..	..
Commercial/Industrial	489.5	502.5	491.1	448.3	453.9	455.2	504.0	..	..	..	..
Irrigation	36.8	33.4	30.7	17.4	26.6	18.3	23.5	..	..	..	..
Public Authority	61.8	16.1	15.7	13.9	15.2	16.0	16.0	..	..	..	..

Source: Water Authority Cayman and Cayman Water Company

On Cayman Brac, a single desalination plant supplies water in the region of the western tourism enclave, with some larger tourism facilities elsewhere operating on-site desalination that supplies water to the public in their vicinity. Distribution is increasingly through a piped network. Rainwater collection in cisterns and abstraction from wells nonetheless remains important for many residents of Cayman Brac and most residents of Little Cayman. Agriculture ranges from small traditional crop and livestock production to more intensive operations for which rainfall is the principal source during the rainy season, with farmers reliant on abstraction and cisterns during the dry season.

### Current impacts

Given the reliance on desalinated water, published historical observations of climate-related impacts in the Cayman Islands mostly pertain to hurricane impacts on production and distribution infrastructure. With Hurricane Ivan, high winds and storm surge affected all water production plants and power outage ceased water production at all sites, although damage to infrastructure varied by location (ECLAC, 2005). In the Seven Mile Beach area, the Consolidated Water Company (CWCO) headquarters (West Bay Rd.) was severely damaged with staff evacuated, with the nearby Britannia plant requiring considerable repair due to seawater inundation. By comparison, the Water Authority-Cayman (WAC) headquarters and associated plant (Red Gate Rd.) located further inland were impacted less due to their greater elevation, although they also suffered seawater inundation from the storm surge. Storage tanks at CWCO and WAC premises suffered only minor damage (ECLAC, 2005). Water services could not be immediately resumed due to a lack of power and damage to distribution infrastructure. Water distribution pipes and mains supplies became exposed by storm surge with some being damaged. Although many did remain intact, replacement and re-laying was required to ensure their structural integrity. Around 2km of main pipelines became exposed, which were vulnerable due to their situation along coastal transport routes, notably on the south and east

coast of Grand Cayman with mains running between South Sound to Colliers (ECLAC, 2005). Electricity supply was restored 5 days after the hurricane, partly reliant on portable on-site generators; from thereon, water production at plants was resumed depending on the nature and extent of repairs required. Piped distribution to households was restored to 67%, 90%, and close to 100% of households at around 17, 19, and 36 days after the hurricane respectively, and was available for collection from plants in the interim. Complete repair of facilities was achieved about 5 months after the hurricane.

No published evidence was identified regarding historical climate-related impacts on potable water supplies from cistern and well sources for the Cayman Islands. There is nonetheless post-hurricane evidence from other Caribbean countries. Jiang et al. (2020) assessed impacts on cistern water quality after the impact of two back-to-back Category 5 hurricanes (Irma and Maria) in 2017 in the US Virgin Islands. Rainwater collection in cisterns is the principal source of household water on St. Thomas Island, and many were damaged by these hurricanes with limited availability of electricity and chemicals for disinfection at the time. Centralised wastewater treatment ceased due to lack of electricity, leading to high risks of contamination of water supplies. Sampling conducted three months after the hurricanes identified that faecal indicator bacteria were prevalent in household cisterns, with *Legionella* present in 86% of those sampled. *Legionella* is found throughout natural soils and leaf litters and floodwater, even in the absence of wastewater contamination, and may still contaminate exposed water supplies (van Heijnsbergen et al., 2015). Pieper et al. (2021) examined microbial contamination of private drinking water wells totalling 8842 in the 10 months after Hurricane Harvey in the Gulf Coast of Texas (USA) that led to widespread and severe flooding from the storm surge and high precipitation. By comparison to baseline levels, *Escherichia coli* and total coliforms in wells were found respectively to be 2.8 and 1.5 times greater than normal.

#### *Future impacts*

As detailed by Hurlston-McKenzie et al. (2011), critical infrastructure that supports the main population centres, which includes water desalination plants, has developed along main transport routes along the coast and at low elevation, so are exposed to hurricanes, storms surges, precipitation driven flooding, and sea level rise. A vulnerability assessment of Grand Cayman water utilities to hurricane-related flooding and storm surges by the Natural Disasters Assessment Consulting Group in 2009 indicated that CWCO plants, offices, and storage facilities are exposed to a relatively high level of hazard. Overall though, their vulnerability is moderate based on return periods of categories 4 and 5 hurricanes. The Water Authority infrastructure at George Town, Lower Valley, and at East End have a moderate hazard level as they are further inland and at a higher elevation.

Sea-level rise is expected to amplify the frequency and severity of storm surges and flooding (see section Freshwater Environments and Resources), increasing both the hazard and vulnerability. Figure 31 (also present in Freshwater Environments and resources) shows land areas that would be inundated by sea level rise of 1 and 2 m. End of century global projections for sea level rise range between 0.32 and 1.01 m.

Temperature changes can also affect efficiency of water produced by desalination owing to effects on viscosity, as well as biofilm development in distribution networks, with implications for quality at customer taps. However, present feed-water temperatures are relatively high in the Caymans Islands and future temperature increases are unlikely to constrain water production rates. Present temperatures within distribution networks, if they broadly match sea water temperatures, are likely to already lie in the optimum range for biofilm communities. However, there is some uncertainty as to the extent to which tropical biofilm communities may exhibit higher temperature tolerances (MacAree et al., 2009).

As detailed in section on Freshwater Environments and Resources, future trajectories of sea-level rise and its amplifying effects on storm surge and marine over-wash incidences, in conjunction with

declining precipitation compared to evaporation and reduced freshwater recharge, suggest increased saltwater intrusion and contraction and thinning of freshwater lenses in the future. The impacts on well water quality and availability would be expected to be more profound and occur sooner for those sites closer to the coast and at lower elevation, where hydrologic connections to the ocean are more direct with reduced freshwater availability and increases in salinity. Continued or increased abstraction from such sources could also promote such trajectories. Historical observations of abstraction from the Lower Valley wells show a deterioration of water quality through increased salinity 6 months after abstraction began. This was suggested by Ravenscroft (1984) to reflect the development of a saltwater intrusion zone from which water was increasingly drawn in response to high abstraction from a nearby farm. However, well salinities in this area were variable and reconsideration of local geology, namely photo-lineaments by Ng et al. (1992), led these authors to conclude that the quality deterioration reflected occurrence of karst fractures and fissures that lead to varying degrees of connectivity with the sea at different wells. Over-extraction from wells is also underscored by observations from Jamaica, where uncontrolled abstraction from the Lower Rio Cobre aquifer led to the freshwater-saltwater interface advancing 8 km inland between 1930 and 1973 (Cashman, 2013).

These observations imply a reduction of groundwater resources for both human consumption and agricultural irrigation in future and are most pertinent to the Sister Islands where limited use and distribution of desalinated water and greater reliance on wells and rainwater catchment increases vulnerability to projected reductions in rainfall and greater evapotranspiration. Furthermore, future residential and commercial expansion on the Sister Islands could exceed present capacities.

Lachaud et al. (2022) stress that pressures on water resources will increase across Latin America and the Caribbean and necessitate more efficient water use, including the uptake of sustainable irrigation technologies and infrastructure, especially given forecast reductions in agricultural productivity of 9-13% for the period 2015-2050 due to temperature increase and reduced precipitation. In Jamaica, Curtis et al. (2014) assessed projections with respect to crop water requirements and showed that requirements will increase with rising temperatures and falling precipitation, with the greatest impacts in the dry season. Gohar and Cashman (2016) also suggest the potential for adaptation through adoption of technology such as drip irrigation, and modification of crops produced with regard to the individual growth requirements (Wickham, 2019). Reductions in abstraction volumes of freshwater from the East End lens may be necessitated by climate changes in the future, with continued monitoring needed to inform trajectories and water balance models.

### *Scoring*

Local impact studies plus global evidence. High agreement, medium evidence. Relevance: Grand Cayman = medium; Little Cayman = high, Cayman Brac = high.

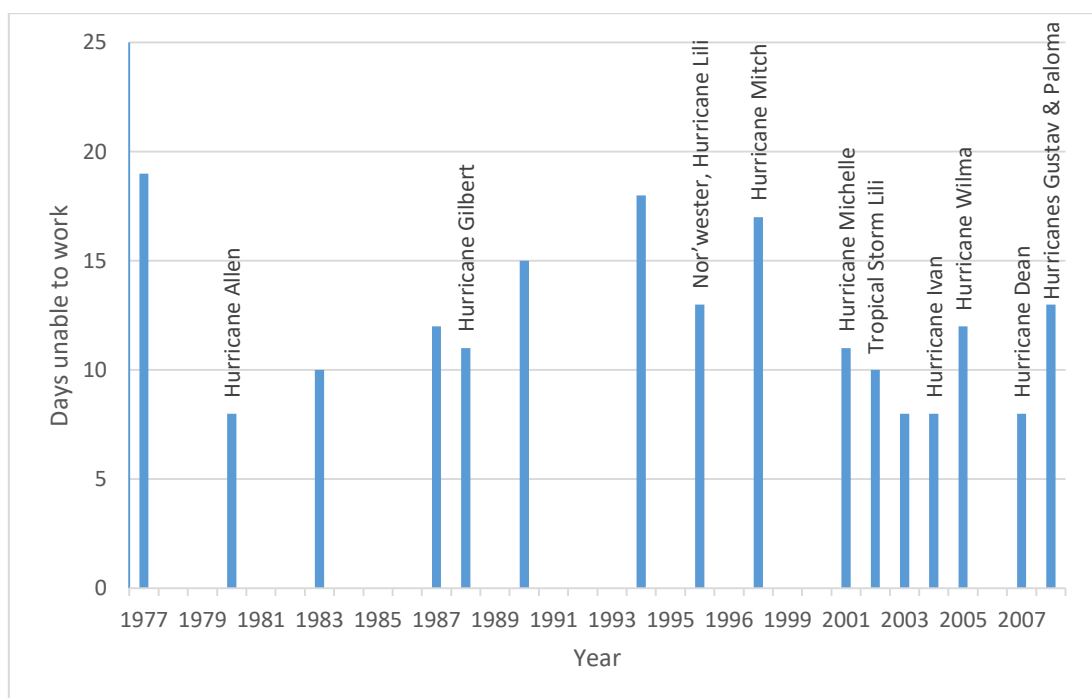
## 4.2 Carrier services/benefits

### 4.2.1 Maritime transport (ports and shipping)

Compared to other Caribbean nations, the Cayman Islands enjoy a relative high standard of living and with modern infrastructure, telecommunications, and transportation systems (MACI, 2022). George Town cruise port is located on Grand Cayman and is a popular port of call for large cruise companies with regular scheduled visits.

### Current climate impacts

The Cayman Islands economy relies heavily on primary imports (Cayman Islands Government, 2011). Disruption to maritime transport due to extreme weather represents a significant security risk to the import of goods (including food), and could significantly impact tourism services (including cruise visitors), upon which future GDP growth relies (Cayman Islands Government, 2011). The Cayman Islands seaports are their lifeline, and any damage or disruption at the ports affect the availability of other vital commodities necessary for recovery and reconstruction, the only alternative being expensive airfreight (Hurlston-McKenzie, 2011). A record of working days lost per year from the Cayman Islands Port Authority for the period 1977 to 2008 includes those days lost due to poor weather or forced closure due to other activities. This reveals that loss of working days due to the passage of storms, hurricanes, or strong winds has become almost an annual occurrence in the 2000s (Figure 35).



**Figure 35.** Working days lost at George Town Port due to weather or forced closure due to other activities in the period 1977–2008. Source: Hurlston-McKenzie (2011) and Port Authority of the Cayman Islands (2009).

### Expected future climate impacts

Operational vulnerabilities at the George Town port have been reduced through lessons learnt from Hurricane Ivan, as well as other recent hurricanes, but any future increase in storminess is likely to mean that the port becomes inoperable more often (Hurlston-McKenzie, 2011). An additional risk factor is disruption to regional major ports such as Miami and Jamaica where most commodities dispatched to the Cayman Islands are shipped from or through, which would have a cascading effect on the economy (Hurlston-McKenzie, 2011). For Cayman Brac and Little Cayman, the main port serving the islands is located at the Creek, Cayman Brac. It can handle the same size vessels as the George Town facilities.

### Scoring

Regional studies. Medium agreement, medium evidence. Relevance: Grand Cayman = high; Little Cayman = high, Cayman Brac = high.

#### 4.2.2 Roads and airports

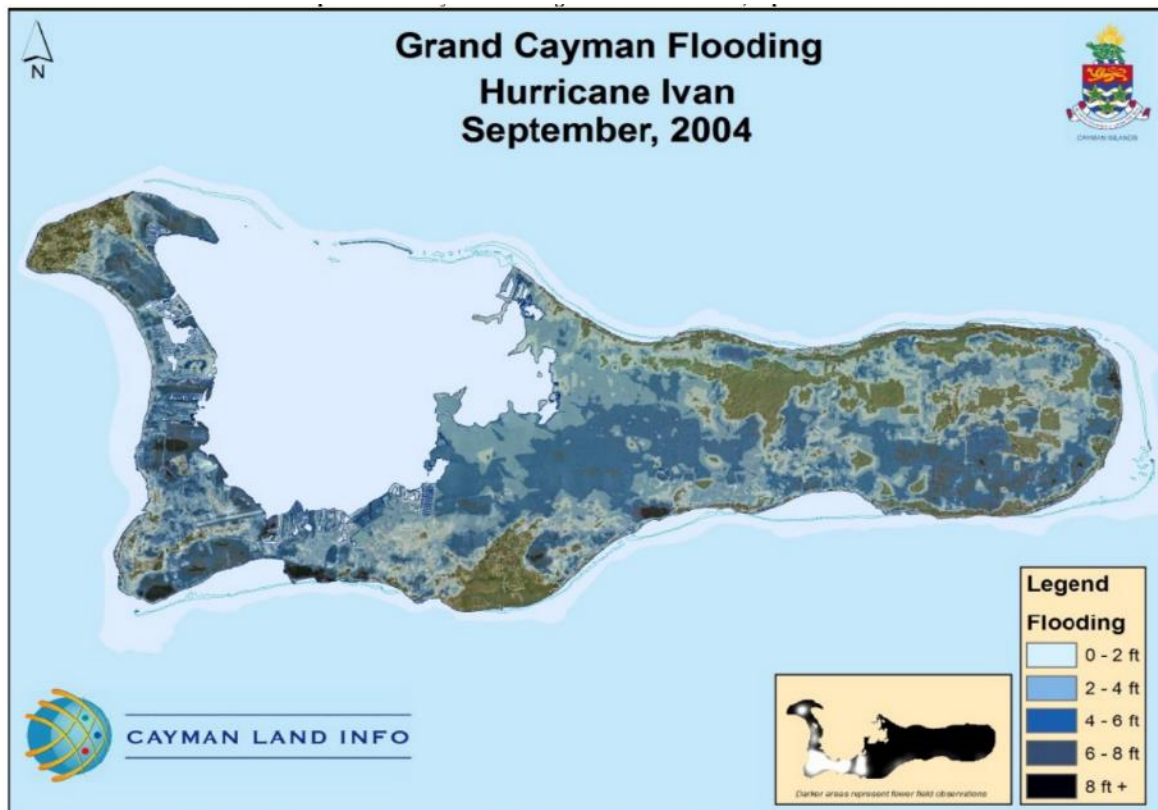
##### *Current climate impacts*

Grand Cayman has a network of primary, secondary, unclassified, access, and unpaved roads that sustained substantial damages over CI\$146 million during Hurricane Ivan, with sections of road washed away or buried under sand or rubble and debris; asphalt carpeting removed or damaged; drainage structures eroded or silted; and coastal protections destroyed (ECLAC, 2004; Hurlston-McKenzie, 2011). These impacts severely restricted emergency services access and ground transport of much needed food, supplies, and construction materials, and limited the mobility and daily commuting of local people for days and even weeks. Successive severe weather events have debilitated certain areas due to overtopping and flooding, creating regular cut-off points. Some new roads have been constructed as alternate routes to exposed coastal roads (Hurlston-McKenzie, 2011).

Three airports exist across the Islands. The main airport, Owen Roberts International Airport on Grand Cayman, serves 18 international destinations and has over 1 million passenger movements per year (i.e., arrivals and departures). Charles Kirkconnell International Airport serves Cayman Brac and Edward Bodden Airfield serves Little Cayman. Charles Kirkconnell International Airport on Cayman Brac sees on average ~70,000 passenger movements (Cayman Airport Statistics, 2022). There are daily inter-island flights to Edward Bodden Airfield on Little Cayman, but no passenger statistics available. Owen Roberts Airport is only yards from the shore and therefore is highly susceptible to flooding and surge impacts (Hurlston-McKenzie, 2011).

As well as the airports, the coastal roads on all three islands are highly vulnerable to flooding and storm surge, and impacts from category 4 and 5 hurricanes. There is strong evidence for an increase in the frequency and intensity of tropical cyclones (hurricanes) since the 1970s in the North Atlantic (IPCC 2013). The year 2004 saw hurricane Ivan flooding the majority (>70%) of Grand Cayman (figure 36), with Owen Roberts Airport operable again within a day after passage, illustrating some effectiveness of coping strategies in place for current climatic conditions (Hurlston-McKenzie, 2011). However, it is not just direct strikes that are of concern, but the frequency with which the Cayman Islands experiences Category 4 and 5 hurricanes developing and passing south and west of Grand Cayman. With large and powerful hurricanes from this direction, even a 'wide miss' can do significant damage, especially to Little Cayman and Cayman Brac, which are particularly vulnerable. Cayman Brac has applied lessons from Hurricane Ivan with 76% of new construction not sited on the beach, and with new road networks linking shelters and other critical infrastructure for risk reduction (Hurlston-McKenzie, 2011).

Stormwater from intense rainfall events can also be a problem for roads and airports. This issue has been exacerbated by the loss of wetlands and other surface water storage areas to development (e.g., pastureland and natural ponds). Heavy rainfall events in George Town often lead to recurrent flooding of some major roads, disrupting traffic and businesses, commercial areas, and residential neighbourhoods (NCA 2011), highlighting the need for improved stormwater management.

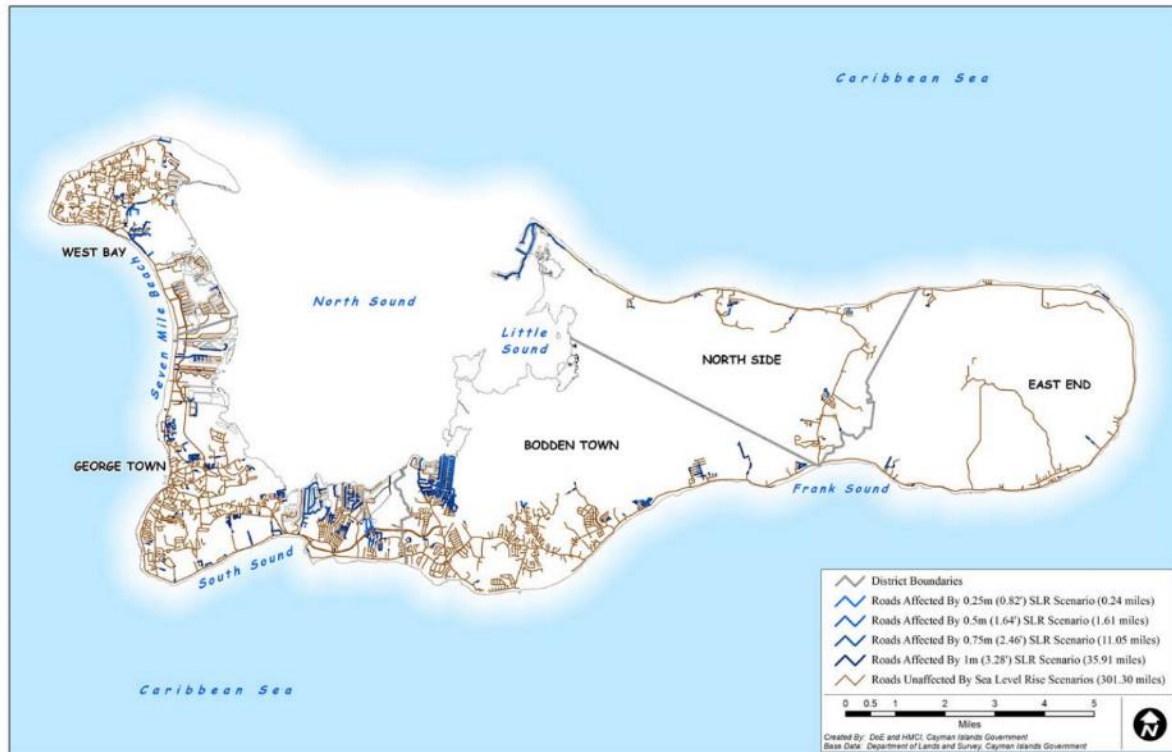


**Figure 36.** Grand Cayman flooding from Hurricane Ivan, September 2004.

#### *Expected future climate impacts*

Increased temperatures and intensification of weather extremes will put additional strains on roads and airport infrastructure. Higher temperatures can cause pavement to soften and expand, with important implications for airport runway conditions. High temperatures can create rutting and potholes, particularly in high-traffic areas and can place stress on bridge joints (e.g., Mulholland & Feyen, 2021). Heat waves can also limit construction activities, particularly in areas with high humidity. With these changes, it could become more costly to build and maintain roads (Hurlston-McKenzie, 2011). Climate change is also projected to concentrate rainfall into more intense events across the Caribbean (IPCC, 2021). Heavy rains may result in flooding that could disrupt traffic, delay construction activities, and weaken or wash out the soil and culverts that support roads, tunnels, and bridges.

Road infrastructure in coastal areas will be particularly sensitive to more frequent and permanent flooding from sea level rise and storm surges. Low-emission climate change scenarios (SSP1-2.6, with a 'very likely' global temperature increase of 1.3-2.4°C by end of century) lead to projected sea-level rise of 0.32-0.62m by 2081-2100 relative to the 1995-2014 period. This increases to 0.44-0.76m for higher climate change scenarios (SSP2-4.5, with a 'very likely' global temperature increase of 2.1-3.5°C by end of century) (IPCC, 2021). A 1 m rise in sea level would directly affect ~10% of roads on Grand Cayman, particularly roads bordering the North Sound (Figure 37). On Little Cayman and Cayman Brac, coastal roads with an elevation less than 1 m will be most susceptible to inundation, which includes parts of the south-eastern Guy Banks Rd on Little Cayman and the western tip of Cayman Brac, including its airport. Overall, large parts of the interior of Grand and Little Cayman lie at an elevation susceptible to plausible limits of sea level rise over this century, while this applies to Cayman Brac's West End only.



Source: Department of Environment, 2010

**Figure 37.** Grand Cayman road infrastructure affected by sea-level rise scenarios.

As noted previously, the airports on all three islands are susceptible to flooding and storm surge, as well as extreme hurricanes. Thunderstorm intensities are expected to increase across the tropics (Singh et al., 2017), which can produce hazardous wind downbursts and extreme rain (Coffel & Horton, 2015), causing closures or delays, and flooding may damage airport facilities, including airstrips. Periods of extreme heat can affect aircraft performance and may cause airplanes to face cargo restrictions, flight delays, and cancellations, and cause heat stress for construction workers or road crews, delaying infrastructure repairs.

### Scoring

Local studies, Regional studies, Global studies. Medium agreement, medium evidence. Relevance: Grand Cayman = high; Little Cayman = high, Cayman Brac = medium.

#### 4.2.3 Coastal settlements and infrastructure

##### *Current climate impacts*

Sea-level rise is a widespread threat to low-lying small islands across the Caribbean where most human communities and infrastructure are located at the coast, and warming is already affecting the region, especially in urban areas (MONA, 2020). Coastal erosion and flooding from extreme weather combined with rising sea levels threatens critical public infrastructure and human settlements in the Cayman Islands (Cayman Islands Government, 2011). Past storms and hurricanes highlight the vulnerability of the Cayman Islands to surges and coastal flooding. Hurricane Ivan in 2004 incurred the



greatest losses to date, valued at CI\$2.8 billion or 183% of GDP, and caused coastal inundation and heavy rainfall resulting in over 70% of Grand Cayman being flooded, with water depth reaching over 3 m in some areas (Cayman Islands Government, 2011). Some 83% of the total housing on Grand Cayman was damaged or destroyed (Hurlston-McKenzie, 2011), particularly old and poor constructions with galvanized roofs exposed to sustained high wind speeds (Young & Gibbs, 2005). Most of the monetary loss from Hurricane Ivan though was from water damage due to a combination of extreme rainfall and the slow progress of the hurricane causing widespread flooding, affecting all types of housing from substandard to luxury (Hurlston-McKenzie, 2011; Simpson et al., 2009).

Critical infrastructure in the Cayman Islands is also at risk from hurricane damage, seawater inundation, and extreme rainfall because of dependencies and vulnerabilities in energy supply. Over 90% of households throughout the islands rely on electricity for cooking and cooling provided by the two power generation companies. Use of private generators are limited to only the wealthy, and renewable sources are negligible (see section Energy Production; Hurlston-McKenzie, 2011). The main generation facility in Grand Cayman is located in an area exposed to flooding and storm surge (Caribbean Utilities Company Ltd., 2008), and the impact of Hurricane Ivan exposed the vulnerability of streetlight poles and power lines to intense wind hazards. Most telecommunications lines on the islands are now buried underground (Hurlston-McKenzie, 2011).

Fuel storage and distribution systems are critical to the energy security and economic prosperity of the Cayman Islands. Fuel storage terminals are located on the coast and highly exposed to flooding and storm surges from category 3 storms and above (Natural Disaster Assessment Consulting Group, 2009). Fuel distribution lines are buried and are therefore more resilient, as is the main propane gas terminal in Grand Cayman, which is further inland and well above sea level (Hurlston-McKenzie, 2011).

Most households in Grand Cayman and a growing proportion in Cayman Brac now rely on mains piped water, and desalination is their primary source of drinking water (Hurlston-McKenzie, 2011). Sister Island communities still rely on wells and rainwater cisterns (Hurlston-McKenzie, 2011). While mains water supply in the main island is exposed to disruption during and following hurricane impacts until water services can be restored, the communities in the other islands are more vulnerable to water shortages caused by changes in rainfall in the rainy season and less annual rainfall overall (Hurlston-McKenzie, 2011).

### *Expected future climate impacts*

Settlements and urban centres along the coast and in low-lying inland areas already suffer damage from strong winds and flooding during storms. These effects are likely to worsen under future climate scenarios as exposure to major storms and hurricanes increases and sea level rise expands inundation risk areas (Hurlston-McKenzie, 2011; Nurse & Sem, 2001). According to a Preliminary Vulnerability Assessment of Grand Cayman conducted in 2009, a small but significant percentage of emergency response facilities, infrastructure, and assets are highly vulnerable to natural hazards owing to their physical locations (Cayman Islands Government, 2011).

The immediate concern for most island residents is the impact of sea level rise on their personal property, communities, and businesses (Hurlston-McKenzie, 2011). Depending on the sea level rise projections considered, the inundation risk to built-up areas of the Cayman Islands ranges from 0.5% to 47%, with the worse-case scenario would affect not just residential properties, but also educational and religious buildings on the majority of the West Bay peninsula, George Town, Bodden Town, and Cayman Kai on Grand Cayman, and the coastal and low-lying areas of Cayman Brac and Little Cayman (Hurlston-McKenzie, 2011). Regional projections of sea level rise for the Cayman Islands over the 21<sup>st</sup>

Century are broadly consistent with projections for the Caribbean region (Cayman Islands Government, 2011; MONA, 2020).

The passage of major hurricanes (category 3 and above) is expected to increase in a warming world, bringing higher wind and rainfall intensities and higher storm surges, which will exacerbate losses from coastal erosion, flooding, and submergence of beaches and coastal lowlands affecting recreational areas and residential and commercial real estate, as well as public infrastructure (Cayman Islands Government, 2011). Excess rainfall will exacerbate the risk of subsidence and damages to the foundation of homes and buildings (MONA, 2020). Direct hurricane strikes are not the only concern, but also the projected increasing frequency with which category 4-5 storms are expected to track south and west of Grand Cayman in the future. Particularly vulnerable communities include those on narrow or shallow gradient sandy beaches or within canal developments and those in the smaller Sister Islands (Hurlston-McKenzie, 2011).

Water security will be further challenged as groundwater aquifers become increasingly exposed to intrusion of saltwater, and coastal erosion and subsidence exposes water piped distribution systems to structural integrity damages, which could impact the quality and availability of drinking water and water for agricultural production (Cayman Islands Government, 2011; Hurlston-McKenzie, 2011). Many households throughout the islands still rely on the use of septic tanks, and many require the use of pumps, which can be inundated and overflow during and following storms or be affected by power outages, posing a significant risk to public health and the environment (Hurlston-McKenzie, 2011).

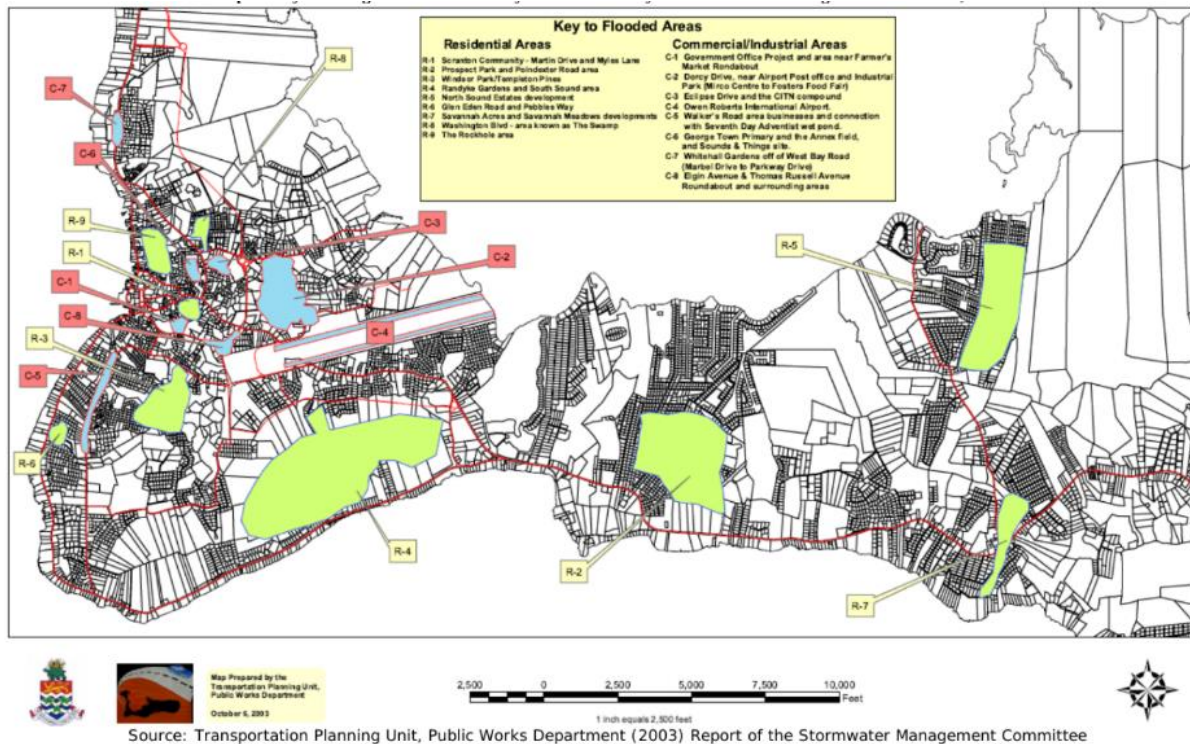
#### *Scoring*

Local studies and Regional studies. High agreement, robust evidence. Relevance: Grand Cayman = high; Little Cayman = high, Cayman Brac = high.

#### 4.2.4 Inland settlements and infrastructure

##### *Current climate impacts*

West Bay and George Town on the southwestern tip of Grand Cayman has the densest inland infrastructure and settlements, including the main airport (Figure 38) that are at risk from flooding, although nowhere in the Cayman Islands is far from the coast. On Little Cayman and Cayman Brac, most settlements and infrastructure are clustered along the coast. Settlements and urban centres in low-lying areas inland are already impacted by damaging winds and coastal flooding from tropical storms and hurricanes or heavy and prolonged rainfall events. At present, such areas witness extreme high-water levels under storm surges, storm tides, and waves (Hurlston-McKenzie, 2011), which will be further adversely affected by SLR ( $1.7 \pm 1.3$  mm/year over the period 1993-2010) (Torres & Tsimplis, 2013). In 2004, Hurricane Ivan flooded Grand Cayman almost in its entirety, highlighting the risk for inland settlements and infrastructure (Figure 38). Inland flooding resulting from moderate to heavy rainfall events ( $>25\text{mm hour}^{-1}$ ) is quite common and predictable in many low-lying areas on Grand Cayman under current climatic conditions (Hurlston-McKenzie, 2011; Wood Group UK Ltd, 2021b). Critical infrastructure includes electricity provided by the two power generation companies: Caribbean Utilities Company (provides 94% of energy for lighting) in Grand Cayman and Brac Power & Light in Cayman Brac.

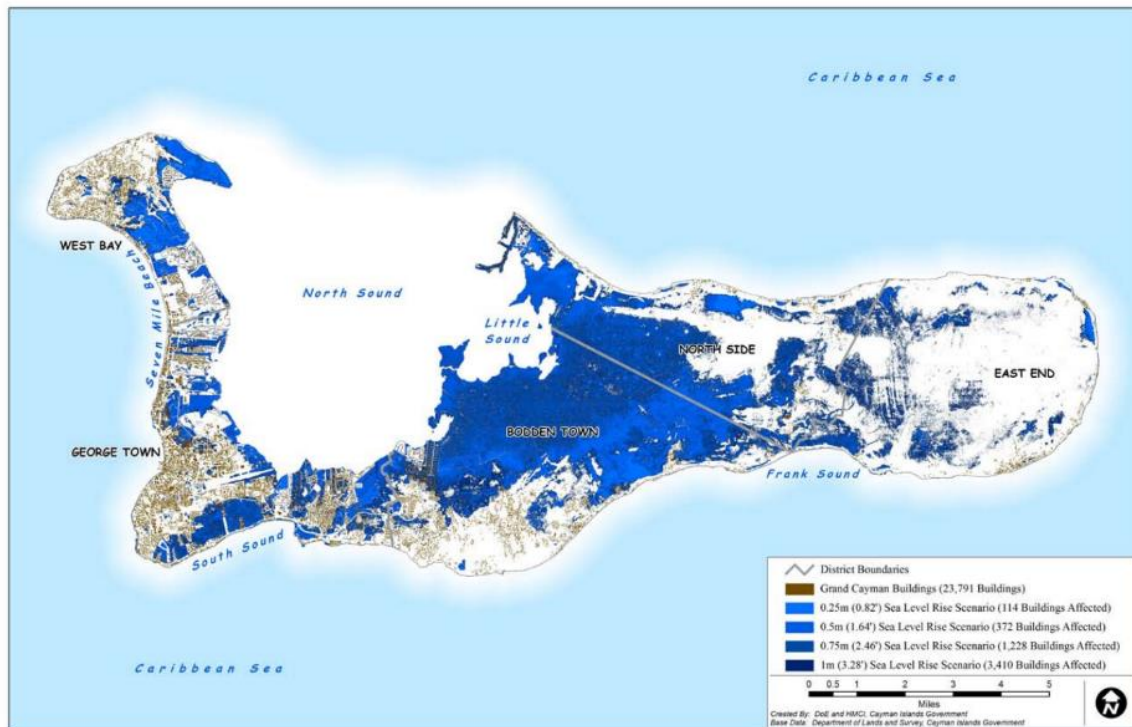


**Figure 38.** Key flooding areas of Grand Cayman identified by the Stormwater Management Committee, 2003.

### *Expected future climate impacts*

Inland settlements and infrastructure are likely to be impacted by increased intensity of hurricanes, storm surges, and more frequent flooding potential compounded by sea-level rise (IPCC, 2021). Most houses in the Cayman Islands are less than 40 years old and have been constructed to a high standard in terms of wind resistance (Hurlston-McKenzie, 2011). However, with design standards now intended to withstand up to 150 mph, there is likely to be increased costs associated with climate-proofed homes, even in the short-term. Based on 2010 infrastructure, up to 3410 buildings on Grand Cayman could be affected by SLR of up to 1m beyond 2100 (Figure 39). For Cayman Brac and Little Cayman respectively, 232 (Map 25, Table 24) and 3 (Map 30; Table 29) buildings could be affected by a 1m SLR (Hurlston-McKenzie et al., 2011). Although, like in Grand Cayman, this information is now somewhat out of date.

Critical inland facilities on Grand Cayman are predominantly located outside of the low-lying coastal zones prone to storm surge effects around the North and Little Sound (Figure 39). However, several moderately vulnerable water facilities are in present-day zones of high hazard, where hazard frequency will likely increase with more intense storms and sea-level rise. Consolidated Water Company plant and water storage facilities are both exposed to a relatively high degree of hurricane-induced flooding, but overall their physical vulnerabilities are considered moderate (i.e., impacted by categories 4 and 5 hurricanes every 100 years). This preliminary assessment of the physical vulnerability of utilities on Grand Cayman also found that Caribbean Utility Company's generation facility is in a zone that is impacted by hurricane categories 4 and 5 producing flooding and storm surge hazards of a moderate exposure level, giving it a present-day moderate level of physical vulnerability overall (Hurlston-McKenzie 2011).



Source: Department of Environment, 2010

**Figure 39.** Buildings affected by a 0.25m, 0.5, 0.75 and 1m increment sea level rise (SLR), Grand Cayman.

Smaller Caribbean islands where social and economic infrastructure are densely concentrated tend to be more impacted (Bertinelli et al., 2014), as is the case for West Bay and George Town in Grand Cayman. While a tendency to drying is predicted for future annual rainfall by the end of century, the report section on rainfall also suggests more intense but fewer rain events (Table 6). Facilities prone to pluvial flooding from high rainfall events under current climate conditions may become more at risk if rainfall extremes intensify as projected across the tropics (IPCC, 2021). Where already a problem, inland flooding will not be resolved unless buildings are re-sited elsewhere and such issues are better considered in the planning process (Hurlston-McKenzie, 2011).

Of the Water Authority's physical infrastructure, the main plant and office, and reservoirs at East End and Lower Valley have a low vulnerability to a moderate level of hazards given their location further inland and well above sea level. The wastewater treatment works next to the landfill is more exposed to flooding from hurricanes and therefore has a moderate level of physical vulnerability. Inland settlements will be most at risk from hurricane impacts and pluvial flooding from high rainfall events. A similar level of vulnerability is assumed for centralised electricity infrastructure and inland settlements on Cayman Brac, which are mostly situated well above sea level.

### Scoring

Global studies, Regional studies, Local reports. Medium agreement, robust evidence. Relevance: Grand Cayman = medium; Little Cayman = medium, Cayman Brac = medium.

#### 4.2.5 Waste treatment and disposal

A Department of Environmental Health landfill site is located on each island. The one at George Town is unlined but follows international standards of operation. The Cayman Brac Landfill, located on the south side of the island, follows similar waste management procedures as the George Town Landfill, as does the Little Cayman Landfill; however, municipal waste at the latter site is combusted, with metals separated and shipped to Grand Cayman for further processing. Hazardous materials at each site are stored and processed for shipping to the United States for disposal following United States Environmental Protection Agency regulatory stipulations. The DEH recycles a standard range of materials. Those collected on the Sister Islands are stored at their landfills for shipping to Grand Cayman, where they are prepared for onward shipping to the United States. Work began on the Integrated Solid Waste Management System (ISWMS/Project ReGen) on Grand Cayman in 2021 and is projected to take three and a half years to complete. This aims to create a sustainable long-term waste management solution, with the electricity generated estimated to account for c. 8% of present demands. The elevation of the development site ranges from 2m to 7m above mean sea level (Wood Group UK Ltd., 2021a) and will include a new lined landfill to receive incinerated waste. The existing landfill will continue to expand laterally according to height capacity until this new infrastructure becomes operational.

Approximately 20% of the wastewater generated across the Cayman Islands is treated at a centralised wastewater treatment plant on Grand Cayman employing sequencing batch reactors. Premises along the main West Bay Road corridor and within some adjacent neighbourhoods are connected via sewerage to this plant. The remainder is treated using on-site treatment systems comprised of septic tanks and aerobic treatment units. In all cases, treated wastewater is disposed to effluent disposal wells discharging to brackish to saline groundwater far below the water table, which then travels laterally to the sea (Crabb, 2009). Deep well disposal from properly functioning and designed systems does not pose a threat to fresh groundwater or surface quality (Maliva et al. 2011), and is also the destination for brines derived from reverse-osmosis desalination on Grand Cayman (Missimer & Winters, 1998, 2003). However, many older septic tank systems probably do not meet present standards given that in 2008-2009, over 80% of systems sampled failed to meet stipulated standards for effluents (Crabb, 2009), and contamination of well supplies has occurred on Cayman Brac (Cayman News Service, 2018).

##### *Current climate impacts*

The wastewater collection system (i.e., sewerage network), which is exposed to flooding from hurricanes and judged to have a moderate level of physical vulnerability, was flooded with seawater by Hurricane Ivan, which damaged the electrical components of 90% of pumps employed for moving septage to the plant, hampering treatment for several days. However, no discharge to roads or properties was reported (Hurlston-McKenzie, 2011). Portable pumps and sewage vacuum trucks were used to convey wastewater to the treatment facility in the interim period during which mains power was unavailable. Many septic tanks were damaged by the hurricane, and septic tanks and on-site aerobic treatment units were inundated by flood waters arising from high precipitation events and storm surges.

Although pollution may occur due to hurricane damage to infrastructure, or with poorly functioning and maintained septic tanks, little formal evidence was identified. The potential for surface and groundwater contamination is high, as exemplified by historical observations of degradation to the thin freshwater lenses of West Bay and South Sound (Grand Cayman) that were made unsuitable as public water supplies by 1975 due to human sewage contamination (Kreitler & Browning, 1983). Similar observations of freshwater lens contamination are found globally for small island states (Werner et al., 2017, and references therein).

At the Grand Cayman landfill complex, a significant hydrocarbon release occurred from the waste oil storage area due to storm surge from Hurricane Ivan overtopping the containment bund, whereby perimeter canals became contaminated with oil until remediated (Amec Foster Wheeler, 2016). Beyond hurricane impacts, there is evidence of pollution originating from the present George Town Landfill site (Sybersma, 2014), and it is reasonable to expect that mobilisation and transfer of contaminants to North Sound would be increased by high precipitation events and flooding due to both precipitation and storm surge.

#### *Expected future climate impacts*

Accelerated development across the Caribbean since the 1960s has generally led to critical infrastructure being sited in low-lying coastal areas that are prone to multiple natural hazards, the impacts and frequency of which are expected to be exacerbated by climate change (Cashman & Nagdee, 2017). The Cayman Islands are not an exception in this respect (Hurlston-McKenzie, 2011). The proposed development site for the ISWMS is low-lying, so tidal flooding and hurricane or tropical storm associated flooding are significant potential hazards (Novelo-Casanova & Suarez, 2012) exacerbated by future sea-level rise. Storm surges may also exacerbate inland flooding through blockage of the outfalls of drainage systems with hurricane debris. Wood Group UK Ltd. (2021a) stated with respect to the new ISWMS that, 'Detailed consideration should be given to ensure that the stormwater drainage system, including discharge points, is resilient to the effects of climate change. Key impacts to take account of include an increase in both the design rainfall rate and the sea level at the discharge point.'

Sea-level rise will raise water tables so that inundation of on-site wastewater treatment systems can be expected to occur more frequently, with potential for increased damage and consequent effects on public health and the environment. Such impacts are partly dependent on elevation, with low-lying coastal areas most prone. Deep well disposal is more resilient by comparison to typical septic tank soakaway systems (Luh et al., 2017). Future changes in precipitation, both increases and decreases, and drought frequencies have implications for wastewater treatment technologies. With more droughts and declining precipitation, septic tanks and aerobic treatment systems that are reliant on climatic water inputs are susceptible to increased failure and requirements for increased maintenance (Luh et al., 2017, and references therein). This is a particular issue for households and premises that do not use mains water supply derived from desalination. Parallels can be drawn from a case study on Barbados based on future projections of reduced water availability (Nurse et al., 2012).

Bove et al. (2020) examined the utility of Shuttle Radar Topography Mission (SRTM) by comparison to a LIDAR digital elevation model for classifying future climate risks to infrastructure, including wastewater for the US Virgin Islands based on exposure according to elevation, location, and modelled storm and sea-level rise. Their study shows considerable exposure of transport and utility infrastructure to sea level rise and modelled storm impacts from climate change. SLR scenarios for the length of mains sewerage inundated on Grand Cayman are given by Hurlston-McKenzie et al. (2011). This is similar to conclusions of flood modelling for Grand Cayman where flooding mechanisms at the building scale were not captured due to the resolution of the WorldDEM employed, with use of a more detailed elevation model recommended (Wood Group UK Ltd., 2021b). Hurricane frequency and severity in conjunction with SLR together pose risks for centralised and on-site wastewater treatment infrastructure, and in turn to public health and the environment due to storm surge and pluvial flooding from high rainfall events. Contaminant leaching from present landfill sites may be exacerbated by high precipitation and flooding events, particularly in the non-lined waste site, but would be expected to be lowered in locations where combustion of solid wastes is conducted.

### *Scoring*

**Wastewater** - Local reports and Regional studies. Medium agreement, robust evidence. Relevance: Grand Cayman = medium; Little Cayman = medium, Cayman Brac =medium.

**Solid wastes** - Local reports and Regional studies. Medium agreement, robust evidence. Relevance: Grand Cayman = medium; Little Cayman = medium, Cayman Brac =medium.

#### 4.2.6 Telecommunications

The Cayman Islands are at the forefront of modern developments in telecommunications. Under the country code +345, there were a total of 136,000 connections in 2020. Among them were 100,000 mobile phones, which corresponds to an average of 1.5 per person (in the US, this figure is only 1.1 mobile), plus 36,000 Landlines (54.78 %). The Cayman Islands is doing very well in the expansion of broadband (32,000 connections by 2020, 48.69 %). Around 81% of all residents now have access to the Internet, including 49% who have their own fast Internet connection.

Cayman currently has two subsea cables that provide internet service within the country and also connects the islands to the world: the Cayman-Jamaica Fiber System (CJFS) that was laid in 1997 by C&W Networks and runs from Jamaica to the Cayman Islands, and the Maya-1 consortium cable that runs from Florida in the US to Colombia via Mexico, Costa Rica, Honduras, Panama, and the Cayman Islands and went live around the year 2000. Together, these two cables provide connectivity to about 99%of the English-speaking Caribbean, as well as Central and South America. However, both pieces of technology are approximately 20 years old and have an estimated lifetime usage of 25 years. In its 2022-2024 Strategic Policy Statement, the Cayman Islands Government highlighted that one of its broad outcomes is to build a modern infrastructure, which included funding for a new subsea cable. In its latest two-year budget, the government has allocated \$15 million for a submarine cable in 2022 and another \$15 million in 2023.

There are 4 internet service licensees in the Cayman Islands. Two of the licensees provide service coverage to all three of the islands either via a wired or wireless solution.

#### *Current climate impacts*

After Hurricane Ivan, all of the Cayman Islands' telecom companies scrambled to improve their disaster plans to ensure that another hurricane would not cause the same kind of problems (ECLAC, 2004). The strong winds of the hurricane combined with the intrusion of seawater from the storm surge caused extensive damage to the telecommunications, in addition the temporary lack of electricity played a role in delaying the restoration of services. The winds caused the collapse of three major telecommunications towers whose utilization was shared by several of the licensees. Entry of seawater into base stations damaged the electronic equipment at many cell sites, which required replacement. The landline network was damaged by the winds that brought down poles shared with the electric utility, and by flooding of telephone exchanges and underground optical fibre cable lines. The Maya-1 submarine fibre optic cable that provides international telecommunications traffic sustained damage in the Half-Moon Bay area, and the Cayman-Jamaica Fibre System (CJFS) cable was partially damaged at its shore end. No total traffic interruption occurred, however, since partial capacity was maintained throughout until repairs were completed (ECLAC, 2004). Estimates conducted by ECLAC indicate that the telecommunications sector sustained a total impact of CI\$ 79.5 million, of which 60% were damage to assets 40% are business losses (ECLAC, 2004).

The Cayman Islands has had an Official Hurricane Plan since the early 1970s. Regular revision kept the plan current and lessons learned from Hurricane Ivan in 2004 changed the approach to Disaster

Management. In January 2007, Hazard Management Cayman Islands was established as the government agency responsible for coordination of all programs dealing with national disasters, whether natural or man-made, and implementing the National Hurricane Plan. The National Hurricane Committee was transitioned to the National Hazard Management Council.

Hurricane Paloma (November 2008), passing directly over Cayman Brac and Little Cayman, caused heavy damage in both in the Cayman Islands and Cuba (ECLAC, 2009). Destructive winds were the primary cause of damage across Cayman Brac and Little Cayman, where nearly all homes were affected. The electrical grid sustained major damage, with all residents on Cayman Brac and Little Cayman losing service. Roughly 400 power poles fell during the storm. Telecommunications experienced similar damage, with landline services disrupted for two to three weeks (ECLAC, 2009).

The 2017 Atlantic hurricane season was one of the worst ever recorded in the Caribbean (though not significantly impacting the Cayman Islands), causing widespread destruction, loss of life, and long-term economic damage to multiple Caribbean small island states (GSMA, 2018). The telecommunications industry felt the force of the hurricanes to varying degrees across their operating countries, with a number of mobile network operators (MNOs) experiencing unprecedented impact (GSMA, 2018). Fifty percent of MNOs in the Caribbean were directly impacted and some experienced over 95% damage to infrastructure across several markets. In the worst-affected countries, Hurricanes Irma and/or Maria impacted every part of MNO operations. Challenging geography, transportation disruptions, and extreme weather hampered restoration efforts. A huge amount of telecommunications equipment suffered irreparable damage, requiring equipment to be imported and experienced emergency personnel to be deployed. The overriding challenge faced was reliance on power grids that were completely destroyed in some areas, resulting in huge expense for MNOs. Nearly 60% of people in the Caribbean subscribe to a mobile service, relying on their mobile phones to access essential information and communication services, which proved to be an important lifeline during the hurricane season. The destructive force of Hurricanes Irma and Maria exposed gaps in stakeholder coordination and communication, and highlighted multiple interdependencies (GSMA, 2018).

### *Scoring*

Regional studies. Medium agreement, medium evidence. Relevance: Grand Cayman = high; Little Cayman = high, Cayman Brac = high.

## 4.3 Regulating services/benefits

### 4.3.1 Human health and welfare

#### *Current climate impacts*

Flooding, storm surges, and strong winds associated with hurricanes and other extreme climate events can cause direct mortality to humans. These events can affect human health indirectly, for example, through disruption and damage to medical facilities, power and water supply, and sewerage overflow that may increase pathogen risk (Novelo-Casanova & Suárez, 2010). Hurricane Ivan directly killed two individuals from Grand Cayman (Novelo-Casanova & Suárez, 2010). It also caused wastewater collection systems to flood with seawater, although no sewage discharge occurred (Hurlston-McKenzie, 2011, Novelo-Casanova & Suárez, 2010).

Insect vectors widely impact human health in the tropics. Approximately 36 species of mosquito are present on the Cayman Islands that transmit many diseases affecting humans. The Cayman Islands are at risk of zika, dengue, and chikungunya epidemics for which the mosquito *Aedes aegypti* (and in the



case of dengue, also the *Aedes albopictus*) is a vector (Hurlston-McKenzie, 2011; WHO, 2016). West Nile Virus can be spread by *Culex* and other species of mosquitos (Komar & Clark, 2006). *Anopheles albimanus*, the malarial vector, is also present on the Cayman Islands. However, reported cases of malaria have only ever been imported from outside the Cayman Islands in recent years (Hurlston-McKenzie, 2011). Arboviruses (i.e., virus transmitted by an arthropod vector such as a mosquito, from a vertebrate disease reservoir such as a sloth) transmitted by *Aedes aegypti* mosquitos have been restricted to Grand Cayman as this species is not found on the Sister Islands. Other islands within the Caribbean have recorded a vast number of arboviruses such as yellow fever, malaria, eastern and Venezuelan equine encephalitis, and oropuche to name a few (Mavian et al., 2018). In 2016, in response to the increasing threat of zika virus which has more severe impacts, the Cayman Islands government with Oxitec released genetically modified male *Aedes aegypti* to produce offspring that will not survive to adulthood (Associated Press, 2016). The Centre for Disease Prevention and Control suggest that the Cayman Islands overall are no longer considered a major risk for contracting the Zika virus (Borgen Project, 2019).

While not a human disease vector, the euryhaline Black Salt-Marsh mosquito or saline-mosquito, *Aedes (Ochlerotatus) taeniorhynchus* (a vector for dog heartworm and equine encephalitis) is the most abundant and mobile human pest species in the Cayman Islands, reflecting the predominance of stagnant brackish to saline surface waters across the islands (Clark et al., 2004). *Culex quinquefasciatus*, the Southern House mosquito, is also primarily a human nuisance species, but also a vector of filarial worms and breeds in organic and nutrient rich waters.

Mosquito phenotypic traits (e.g., growth and larval development rates) are affected by gene–environment interactions, such that salinity and temperature influence mosquito growth and development (Clark et al., 2004). As summarised by Fuller et al. (2012), ‘While temperature can be considered to exert a direct effect on mosquito development, rainfall timing and amount function as indirect environmental factors that condition the environment in ways that affect the fitness of mosquitos.’ This statement is borne out by time-series observations of mosquito abundance in the Cayman Islands. For example, *Aedes aegypti* and *Aedes albopictus* mosquitos both breed where small amounts of stagnant waters collect, such as in buckets, barrels, flow pots, and discarded tyres. Their abundance typically increases with high rainfall events and hurricanes (Chadee et al., 1998). Post Hurricane Ivan, a 14-fold increase in *Aedes aegypti*, and a 10-fold increase in *Aedes albopictus* were observed, consistent with greater abundance of standing waters and garbage and debris piles (Hurlston-McKenzie, 2011 and references therein). The abundance of *Aedes taeniorhynchus* has been high in recent years, reportedly reflecting high tidal ranges, several storms including Hurricane Grace in 2021, and reduced control activities in response to COVID-19, among other potential factors (Cayman News Service, 2021). Broken septic tanks following Hurricane Ivan contributed to elevated abundance of *Culex quinquefasciatus*, however, existing pre-packaged septic tank systems are also foci for control efforts of this species (Clayson & Nelder, 2010, Hurlston-McKenzie, 2011 and references therein). Temperatures of 25–30°C are optimum for development, with larval development rates increasing with temperature (Medlock et al., 2006; Straetemans, 2008).

As seas become warmer due to climate change, blooms of toxic microalgae are expected to increase and could present a health risk to humans. Ciguatera fish poisoning (CFP) is the most common non-bacterial cause of human illness associated with seafood consumption globally and is associated with bioaccumulation of toxins in predatory fish species such as groupers, barracuda, and snappers. Distribution and abundance of the organisms that ultimately produce these toxins, chiefly dinoflagellates of the genus *Gambierdiscus*, are reported to correlate positively with seawater temperature (Kibler et al., 2017). Consequently, there is growing concern that increasing temperatures associated with climate change could increase the incidence of CFP in the island regions of the Caribbean. There are indications that warmer sea temperatures may drive outbreaks of CFP (Nurse et al., 2014; Tester et al., 2010). The Cayman Islands witnessed a 6-fold increase in the number of CFP cases between 2002 and 2007 (131) compared to 1996–2001 (22) (Tester et al., 2010), and this

coincided with a 0.4–0.8°C positive temperature anomaly in the Caribbean during 2001–2005. When asked, public health officials in the Cayman Islands attributed this increase to human population growth (Tester et al., 2010). The Cayman Islands have experienced a doubling of the population in the last 20 years and this has increased demand for fish. This factor could result in an increased number of people being exposed to CFP, especially those who are not familiar with it. A contact at the Cayman Islands Department of the Environment indicated that native islanders are somewhat more aware and concerned about CFP and the types of fish that might be ciguatoxic than are new residents or tourists (Tester et al., 2010). Also, increased reports of CFP cases in the Cayman Islands could be due to increased reporting rates because of heightened awareness in recent years (Tester et al., 2010).

Heat exposure, most often associated with heat waves, can lead to heat exhaustion, stroke, and in the worst case, mortality (PAHO, 2019). Average monthly temperature between 1971 and 2017 for the Cayman Islands ranged from 25.5°C to 29.3°C, with an annual average of 27.5°C (MONA, 2020). The Cayman Islands regularly experiences temperatures above 30°C, with highest maximum temperature recorded (up to 2013) as 33°C (MONA, 2020). As reported in the earlier section, from 1961 to 2010, the Caribbean region has experienced an increase in intensity, duration, and frequency of hot and warm days (MONA, 2020).

#### *Future climate impacts*

Hurricane strength and frequency are likely to increase, which will increase risk to health and mortality. The risk of impacts on human health resulting from damaged infrastructure depend on how climate-proofed and prepared the Cayman Islands' infrastructure is (see section Inland Settlements and Infrastructure). The predicted climate impacts on clean water and air have direct consequences for human health, and contaminated freshwater and larger areas of stagnant water can increase the risk of water-borne diseases (Hurlston-McKenzie, 2011). In Haiti, Eisenberg et al. (2013) found that periods of increased rainfall is followed by an increased cholera risk 4-7 days later, most likely due to contamination of surface and groundwater by sewage runoff/mixing due to heavy rains. The cholera outbreak that began in Haiti in 2010 was a result of a recent introduction. Prior to 2010, Haiti had been cholera free for 100 years (Chin et al., 2010; Piarroux et al., 2011). This shows that although the Cayman Islands may not be at immediate risk due to absence of bacterium, if introduced into the environment it will pose a risk to health.

Being an island nation protects the inhabitants of the Cayman Islands from rapid overland spread of epidemics transmitted by mosquitos (arboviruses) or other vectors. However, there is a risk that increases in hurricanes within the region could introduce new mosquitos or bird species and individuals temporarily as they are blown off course that may lead to the introduction of novel pathogens and disease from these novel individuals (Mavian et al., 2018). Mavian et al. (2018) state that tropical islands are a source for emerging arboviruses, however, the exact number of arboviruses currently present on the Cayman Islands is likely to be much lower than somewhere with higher vertebrate diversity such as the Brazilian Amazon, where 187 species of arbovirus were identified.

High intensity rainfall events, projected to occur more frequently in the future, can lead to widespread but temporary expansion of freshwater habitats, as well as ponding of surface water with variable salinities when combined with hurricane associated storm surges. Accumulations of organic debris are also a general feature of hurricane impacts. These environmental changes increase the abundance of habitats suitable for mosquitos in the Cayman Islands. *A. aegypti*, *A. albopictus*, and *A. albimanus* can all breed and develop in brackish water, however, salinity tolerance is greater for *A. albopictus* (Kengne et al., 2019, Ramasamy et al. 2011). Future trajectories of the various pest, disease vector, and other mosquito species in response to climatic change are difficult to predict, even in the absence of control efforts. Increases in temperature are unlikely to benefit mosquitos (and insects in general), as present temperatures are already close to the maximum optimum temperature. Increased aridity in response to temperature increases and reduced precipitation may lead to reductions in freshwater

extent and transitions towards more saline conditions. While these may not eradicate species, larval development rates will tend to decline for most with increasing salinity. An exception may be the Black Salt-Marsh mosquito, *Aedes (Ochlerotatus) taeniorhynchus*, based on its wider salinity tolerance.

Future increases in drought frequency and severity, as well as lengthened and drier dry seasons could have negative impacts on less salt tolerant mosquito populations, however, projections for greater intensity rainfall events in the wet season could mean that suitable habitats will persist into the future. The result may be future amplification of seasonal mosquito abundances, to some extent mirroring the impacts of habitat expansion in response to hurricane events. If this is the case, control efforts might be able to exploit such changes to seasonality. The capacities for mosquitoes to adapt to future conditions are uncertain, however, Chadee and Martinez (2016) found that *Aedes aegypti* utilised underground drains and septic tanks for breeding, altering their behaviour and ecology in response to droughts reduction of their typical surface water habitats.

In the Caribbean (Belize and Mexico), the occurrence of *A. albimanus* has been positively associated with the occurrence of cyanobacterial mats that are favoured for egg-laying and negatively associated with the presence of filamentous algae (Rejmánková et al., 1992, 1993, 1996). These observations are notable given studies have found that benthic cyanobacterial mats of hypersaline coastal pools in the Bahamas respond positively in terms of production to freshening events associated with high rainfall inputs (Paerl et al., 2003; Pinckney et al., 1995), and that cyanobacteria in general exhibit more rapid responses to temperature increase than other algal taxa (Carey et al., 2012; Hofer, 2018). While not directly interpretable considering relatively low salinity tolerances for *A. albimanus*, these studies nonetheless suggest that intense rainfall and aquatic freshening events may expand the abundance of preferred habitats for oviposition and larval development for this species.

Kibler et al. (2015) used projected sea water temperatures to forecast potential effects of climate change on the growth, abundance, and distribution of *Gambierdiscus* and *Fukuyoa* species, dinoflagellates associated with ciguatera fish poisoning (CFP) in the Gulf of Mexico and Caribbean Sea. Growth rates of five dinoflagellate species were estimated through to the end of the 21st century using experimentally derived temperature versus growth relationships for multiple strains of each species. The projected growth rates suggest the distribution and abundance of CFP-associated dinoflagellate species will shift substantially through 2099. In the Caribbean Sea where the highest average temperatures correlate with the highest rates of CFP, it is projected that *Gambierdiscus caribaeus*, *Gambierdiscus belizeanus*, and *Fukuyoa ruetzleri* will become increasingly dominant. Conversely, the lower temperature-adapted species *Gambierdiscus carolinianus* and *Gambierdiscus* ribotype 2 are likely to become less prevalent. The risks associated with CFP are also expected to change regionally, with higher incidence rates in the Gulf of Mexico and U.S. southeast Atlantic coast, with stable or slightly lower risks in the Caribbean Sea (Kibler et al., 2015).

Predicted increases in average temperature mean more record hot weather for the Cayman Islands (IPCC, 2001). As higher temperatures are reached and the Cayman Islands experiences increased frequency or duration of heat waves, it may be assumed that risk of heat-related mortality will increase (Honda et al., 2014, Mora et al., 2017). Of particular concern to human health is if the wet-bulb temperature exceeds 35°C (i.e., the lowest temperature that can be reached by evaporative cooling (sweating)). Humans are unlikely to be able to tolerate wet-bulb temperatures over this threshold for long periods of time without significant interventions (Sherwood & Huber, 2010). Wet-bulb temperatures are predominately affected by air temperature and humidity, with the Caymans Islands already experiencing maximum temperatures above 30 °C and monthly relative humidity reaching 80% in October (National Weather Service, 2022), so dangerous thresholds could be crossed. Between 20°S and 20°N latitude, Zhang et al. (2021) predicted that web-bulb temperatures on land could increase by 1.33-1.49 °C under a 1.5°C warmer world (RCP1.9-RCP2.6). Mora et al. (2017) calculated a threshold of temperature and humidity beyond which climate conditions become deadly and applied this threshold to mean daily surface air temperatures and relative humidity projections to predict the number of “deadly heat” days that could occur under different emissions scenarios.

Although this is a global analysis and the Cayman Islands are too small to appear explicitly, considering the control of wider atmospheric dynamics on wet-bulb temperatures rather than local variations (Zhang et al., 2021 and references therein), predictions for the Caribbean can be considered indicative; the number of days per year exceeding the threshold of temperature and humidity beyond which climatic conditions can become deadly, will exceed 200 days under a high-emissions RCP8.5 scenario.

The actual impact is highly dependent on individual health and age. For example, those with underlying medical conditions and the elderly are deemed more at risk. Overall socio-economic status of a country is an important factor, such as having air conditioning and occupation (e.g., farming versus office work). Honda et al. (2014) – when modelling global heat-related deaths using an air temperature-mortality based model and not an air temperature-humidity-mortality based model associated with the IPCC Special Report on Emissions Scenarios A1B climate scenario – estimated anywhere between an additional 73-281 associated deaths in 2030 and 259-820 associated deaths in 2050 for the over 65s in the Caribbean.

### *Scoring*

Local reports and Regional studies. High agreement, robust evidence.

- Increase disease transmission and occurrence (arboviruses, waterborne pathogens). Relevance: Grand Cayman = high, Little Cayman = medium, Cayman Brac = medium.
- Increase in seafood associated illnesses and poisonings. Relevance: Grand Cayman = medium, Little Cayman = low, Cayman Brac = low.
- Increase in heat related mortality. Relevance: Grand Cayman = low, Little Cayman = low, Cayman Brac = low.
- Increase in direct mortality from hurricane/storm/flood events. Relevance: Grand Cayman = low, Little Cayman = medium, Cayman Brac = medium.
- Changes in mosquito populations and associated illnesses. Relevance: Grand Cayman = high, Little Cayman = medium, Cayman Brac = medium.

#### 4.3.2 Tourism industry and infrastructure

The Caribbean is the most tourism-dependent region of the world (Layne, 2017). In 2014, direct contribution to the Caribbean region's GDP was calculated at over USD \$50 billion. Overall, tourism represents over a quarter of the Cayman Islands' total GDP, and jobs related to tourism and travel represent about a third of the total employment of the islands (Hurlston-McKenzie, 2011).

### *Current climate impacts*

Tourism is a climate-dependent industry (Layne, 2017) and Caribbean islands are already experiencing beach erosion, more vector-borne diseases, and property damage from hurricanes and storms (Taylor et al., 2020). There is evidence of beach retreat in the Cayman Islands, particularly in the area of Boggy Sand where the beach area used to support a number of buildings, but there is no longer sufficient land (Hurlston-McKenzie, 2011). During the severe hurricane season of 2016, there was damage to several tourism properties across the Caribbean, and tourism operations and jobs were affected (Taylor et al., 2020). Hurricanes Delta and Eta in 2020 caused beach erosion and coastal retreat at Seven Mile Beach in Grand Cayman, with no recovery seen by the time of the following tourism season in 2021 (Murray et al., 2021). Indeed, southern Seven Mile Beach is in a chronic erosion state, prompting the current administration to establish a taskforce to fully assess the situation and investigate solutions. As a result, the reduced usable beach areas give rise to overcrowding (Hurlston-

McKenzie, 2011). An example of shoreline retreat from another part of Grand Cayman, Kaibo Beach on the eastern shore of the North Sound lagoon, can be seen in Figure 42.



**Figure 42.** Shoreline retreat in Kaibo Beach, Grand Cayman between 1994 and 2020. Source: Department of Environment.

Increased threat of storms and resultant damages are already behind substantial drops in visitor expenditure. Hurricanes such as Ivan cause extensive damage to hotels and apartments from flooding and wind that often results in permanent loss of room stock as some properties do not reopen or become repurposed to other uses, such as residential housing (ECLAC, 2004; Hurlston-McKenzie, 2011). As a result of the closure of port facilities and the reconditioning and rebuilding work that follows before surrounding restaurants, attractions, and roads can reopen, additional economic losses are incurred (Hurlston-McKenzie, 2011). The indirect impact of hurricanes adds on the lost revenue and the additional lost income during rebuilding, and in the case of Ivan, the loss of stay over tourism extended into the following year (Hurlston-McKenzie, 2011).

For the Cayman Islands, Hurricane Ivan led to a drop in the number of tourists and associated income in the following year (ECLAC, 2004; Hurlston-McKenzie, 2011). There was also a large drop in accommodation available due to loss and damages and the need to lodge workers during the emergency relief and recovery operations, as well as construction crews and others. The estimated cost of damages to the tourism sector from Hurricane Ivan were CI\$281.9 million, including loss and damage of accommodation, boats, and yachts, while there was an additional CI\$180,531.20 in losses to income from the lack of tourists (including cruise visits) (ECLAC, 2004).

To diversify the sector, other niches are being explored, although they also tend to be very weather-dependent, such as weddings, music and sports events, and food fairs (Hurlston-McKenzie, 2011). Equally, off-season tourist deals and offers often result in visitors caught in unpredictable and uncomfortable weather, becoming unwell, and placing extra demands on the health care system (Hurlston-McKenzie, 2011).

### *Expected future climate impacts*

The impact of future climate change on the tourism sector needs to consider not just the damages and disruption to resorts, infrastructure, and services, but also the degradation or loss of natural resources, such as beaches, coral reefs and even fisheries (see previous sections) as it is founded around ‘sun, sand and sea’ (Cayman Islands Government, 2011). A list of the potential climate change impacts on tourism sites in the Cayman Islands was compiled by Hurlston-McKenzie (2011) (Table 15), showing the potential range of impacts. The Caribbean region is likely to be particularly affected by climate change because of hurricanes, with additional impacts from beach loss, coral health, and flooding (Bindoff et al., 2019). Climate change is likely to cause increased risk of flooding to tourism facilities due to sea-level rise and storm surges in the Cayman Islands (Cayman Islands Government, 2011). An increase in severe hurricanes would cause more damage to tourism facilities, such as museums or the Cayman Turtle Centre (see section 4.1.1), meaning that they would have to pay for repairs, as well as losing income for the periods that they are closed for repair (Hurlston-McKenzie, 2011).

Sea-level rise and changing wind patterns may further exacerbate beach erosion, but due to the encroachment of built areas, sea defences, and swimming pools along the coast, there is limited area for the beach to retreat into (Hurlston-McKenzie, 2011). A loss of fringing corals will further increase the vulnerability of beaches to erosion during strong wave events since coral reefs provide a natural shoreline buffer and help to slow wave action (Layne, 2017). Beach retreat will affect tourism by reducing the area where new tourism facilities can be built and will also downgrade the beaches which draw tourists to the Cayman Islands, or ultimately cause their loss altogether (Hurlston-McKenzie, 2011). Regular beach nourishment may be needed in the future to retain the Cayman Islands’ attraction as a beach resort (Hurlston-McKenzie, 2011), as beach erosion may overtake natural beach replenishment and shoreline stabilisation (Hurlston-McKenzie, 2011). Increases in the size or frequency of Sargassum seaweed blooms reduces the appeal of Caribbean beaches, and an increase in HABs occurrence could also harm tourism (Bindoff et al., 2019).

**Table 15.** Potential climate change impacts on Cayman Island Tourism Sites. Source: Reproduced from Hurlston-McKenzie (2011).

Attraction	Effect of climate change	Impact on attraction
<b>Stingray City / Sandbar</b>	Sea level rise	Deeper sites, ability to stand at Sand Bar reduced
	Increased storminess	Reduced no. of trips
	Change in wind patterns	
<b>Beaches</b>	Sea level rise	Reduced area, overcrowding, user conflicts
<b>Dive tourism</b>	Sea level rise	Deeper sites
	Increased storminess	Reduced no. of trips
	Stronger hurricanes	Physical damage to reefs
	Increased sea temperatures	Coral bleaching, die-off or disease
<b>Botanic Park</b>	Increased drought	Irrigation issues

	Wind damage	Reduced site attractiveness
	Increased temperature	Risk of heat stress to visitors
<b>Blow Holes</b>	Sea level rise	Submerged cavities, no dramatic pictures
<b>Hell</b>	Increased rainfall intensity	Flooding
<b>Pedro St. James</b>	Increased storm intensity, wind and rainfall	Flooding, wind-borne debris, damage to structures & property
		Event cancellations
<b>Cayman Turtle Farm</b>	Increased storm intensity, wind and rainfall	Flooding, damage to structures & exhibits
	Increased temperature	Water quality affected within turtle & other enclosures
<b>CI National Museum</b>	Sea level rise, increased storminess, storm surge and hurricanes	Damage to structures & property from flooding and wind-borne debris
<b>Pirates Weeks Festival</b>	Increased storminess, rainfall	Event cancellations
<b>Maritime Heritage Trail</b>	Stronger hurricanes, wave action	Destruction, dislodgement or burial of historic shipwrecks and artefacts
	Change in wind patterns	
<b>Heritage Sites (Lighthouses, Mission House)</b>	Increased storm intensity, wind and rainfall	Wind and water damage
	More intense rainfall events	Flooding
	Higher temperatures	Terminate, deterioration of structure

### Scoring

Global studies, Regional studies, Local climate impact studies. High agreement, medium evidence. Relevance: Grand Cayman = high, Little Cayman = high, Cayman Brac = medium.

#### 4.3.3 Clean Water and Air

Note overlaps with sections on “Freshwater environments and resources”, “Water for human consumption and agricultural irrigation” and “Waste treatment and disposal”.

### *Current climate impacts*

Clean water in inland as well as coastal regions is crucial for supporting diverse species habitats, and along coastal areas affects recreational activities, tourism, and economy. Water quality of ground- and sea water is currently monitored by the Water Authority-Cayman on Grand Cayman. While air quality can be an important factor for respiratory health, it is not currently monitored on the Cayman Islands (AirZOne, 2018). Air pollution potential is greatest on Grand Cayman in the more built up George Town area, caused by cruise ship and road traffic emissions.

Without rivers, upland agriculture or heavy industry marine pollution remains a limited threat and consequently, ocean and coastal waters surrounding the Cayman Islands remain largely pollution-free. The Cayman Islands Government have been proactive in limiting the impact of coastal and ocean water pollution with strictly enforced laws that prevent the discharge of any kind of pollutants to the surrounding waters. However, although direct sewage disposal to the surrounding ocean is illegal, sewage treatment and septic tank deep well disposal to ground water remains the most significant cause for water quality concerns (Hurlston-McKenzie, 2011). Water quality, excluding infrastructure for potable water, is predominantly affected by illegal sewage disposal and temporarily by extreme weather events, such as hurricanes or pluvial flooding after thunderstorms, when unchecked runoff may carry pollutants into habitats and affect coastal waters and groundwater (Hurlston-McKenzie, 2011; Sybersma, 2014). The karst limestone geology of the islands means groundwater impacted by nutrients (e.g., phosphate and nitrates) can leach to surrounding marine waters through underground caverns and fissures, which in turn can drive prolific algal growth on coral reefs and potentially introduce disease pathogens (e.g., Kreitler & Browning, 1983; Ng & Beswick, 1994). Mangrove forests fringing some of the Cayman Islands' coast help maintain coastal water quality by retaining suspended particles from land sources and removing and recycling nutrients and pollutants (Cusack et al., 2018).

### *Expected future climate impacts*

A combination of habitat degradation and climate change impacts (increased sea temperature and salinity, ocean acidification, sea-level rise, erosion and coastal flooding, changing storminess, and altered rain patterns) are contributing to the loss of important habitats and their filtering and uptake capacity. As these impacts are anticipated to intensify in future decades, they will have negative repercussions for water and air quality.

Water quality will be affected by storm surge events or runoff after intense rainfall. Such events temporarily affect water quality with potential for health risks and disease spread. Such impacts may occur more often due to storm intensification and sea-level rise. Typically, where management practices have existed at all, vertical deep wells and dykes have been the predominant means of stormwater control both on public roads and within newer subdivisions across the Cayman Islands (Hurlston-McKenzie, 2011). It is now widely accepted that this engineering technique is, and increasingly will be, inadequate in dealing with the quantity of stormwater in low-lying areas with water tables near the surface. This mechanism is also ineffective at addressing stormwater quality as water is not treated before it enters the ground, potentially contaminating groundwater resources with hydrocarbons, fertilizers, and other chemicals, as well as sediments from urbanized areas. More intense rainfall events associated with climate change will increase the rate of overland flow resulting in greater magnitude of runoff to be handled by these means (Hurlston-McKenzie, 2011).

Air quality on the Cayman Islands benefits from sustained easterly winds, with days with stagnant air flow (<0.5 m/s mean daily wind) making up less than 0.2% of the time based on 5-year measurements from Owen Roberts International Airport (AirZOne, 2018). There is to date no evidence for expected climate change effects on air quality, though it should be monitored going forward with dispersion modelling recommended for build-up areas in George Town, as increasing traffic and further development of cruise terminals may have local adverse effects (AirZOne, 2018).



### *Scoring*

Global studies, Regional studies, Local study (air), local reports (water). Medium agreement, medium evidence. Relevance (water): Grand Cayman = high, Little Cayman = medium, Cayman Brac = medium. Relevance (air): Grand Cayman = low, Little Cayman = low, Cayman Brac = low.

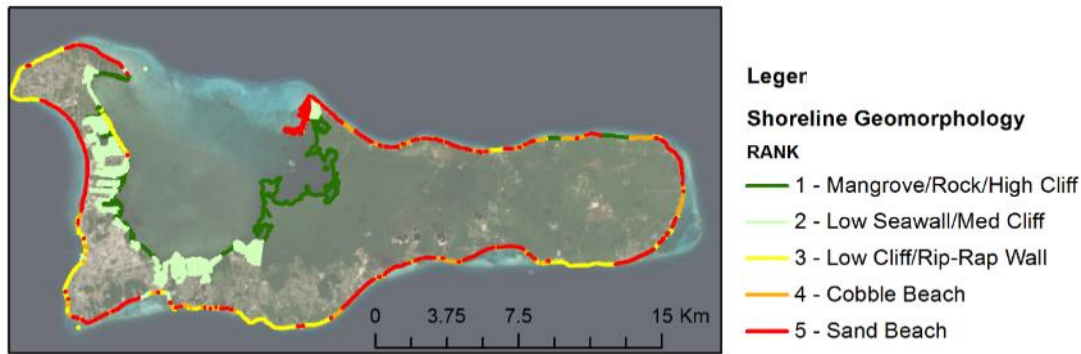
#### 4.3.4 Natural flood and erosion control

The Cayman Islands are mostly surrounded by fringing reefs enclosing shallow, sand, and seagrass filled lagoons. The Central Mangrove Wetland on Grand Cayman represents the most significant area of wetland in the islands and remains largely intact (DaCosta-Cottam et al., 2009).

The beneficial role that coral reefs play in coastal protection through wave attenuation, and therefore enhancing climate resilience in small islands, has been extensively studied (e.g., Elliff & Silva, 2017; Harris et al., 2018; Reguero et al., 2018). Indeed, it has been demonstrated that in small islands, such as the Cayman Islands, Grenada, and the Bahamas, averted damages as a result of protecting intact coral reefs can be considerable when expressed as a percentage of GDP (Beck et al., 2018). Ferrario et al. (2014) conducted a global meta-analysis including many small islands across the Atlantic, Pacific, and Indian Oceans and found that coral reefs reduce wave height by an average of 84% (and wave energy by 97%) and that reef crests alone dissipate most of this energy. Based on another meta-analysis of 69 case studies worldwide (wave heights measured before and after the habitat), Narayan et al. (2016) observed that coral reefs, mangroves, and seagrass reduced wave height by 70%, 31%, and 36%, respectively, and thus perform an essential role in protecting human lives and livelihoods (Mycoo et al., 2021).

### *Current climate impacts*

In the Cayman Islands, elevated sea temperatures over the past two decades have resulted in significant increases in major coral bleaching episodes and a subsequent rise in coral disease and mortality (Cayman Islands Government, 2011; DaCosta-Cottam et al., 2009). Major storms have also resulted in substantial impacts to the shallow and fringing reef environments (Cayman Islands Government, 2011; DaCosta-Cottam et al., 2009). Other local long-range implications of climate change remain largely understudied (DaCosta-Cottam et al., 2009), so the potential effects of ocean acidification or sea level rise on the Cayman reefs are unknown. Globally, coastal mangrove stands and other wetland areas have been exposed to losses from hurricane impacts and through impoundment and outpacing by sea level rise, which results in loss of their natural storm buffer and coastal protection function (Cayman Islands Government, 2011). This report earlier notes 'Department of Environment considers that Cayman Islands mangroves are currently accreting at the same pace as sea level rise' (UNESCO, 2022). Figure 41 shows the extent of protective coastal mangrove areas in Grand Cayman, which are mostly located within the lagoon area.



**Figure 41.** Shoreline geomorphology map of Grand Cayman combined with aerial imagery showing the extent of natural coastal protective structures including mangrove stands, rocky and or raised shores. Data is from 2013. Source: Department of Environment, Cayman Islands Government (March 2022)

In low-lying, small Caribbean islands, coastal mangrove forests provide shoreline stabilization, wave and wind reduction, and protection from extreme weather (Wilson, 2017). Recent research has demonstrated how exactly mangrove stands attenuate wave energy (McIvor et al., 2012) and protect from storms as well as from sea level rise, saline intrusion, and erosion (Barbier, 2016). When faced with sustained erosion and inundation from sea level rise and limited accretion as those expected under future climate change conditions, mangroves may not be able to keep pace (Wilson, 2017), as studies reconstructing ancient Holocene mangroves conducted in small islands in the Caribbean including the Cayman Islands have shown extending back over 1000s of years (Ellison & Stoddart, 1991; Ellison, 1993).

Flooding from rainfall has contributed to island flood events (Hurlston-McKenzie, 2011), but the geology of the Cayman Islands helps mitigate this hazard. The Cayman Islands consists of bluff limestone, which is a dense karstic limestone, and a coastal limestone terrace called “ironshore”, which is a formation of coral, mollusc shells, and marl with some limestone. The soil layer of the Cayman has an irregular distribution and is not particular deep where present, and limestone is highly porous allowing rain to quickly percolate (Folk et al., 1973) (see section on Freshwater Environments and Resources).

#### *Expected future climate impacts*

Fringing coral reefs and coastal wetlands act as natural coastal defences against coastal flooding and erosion. However, these habitats are also vulnerable to the impacts of climate change and their resilience is under further pressure from other human activities. It is likely that the Cayman Islands will continue to lose natural coastal protection through the degradation of its fringing reefs and coastal mangroves (see relevant sections), although more research is needed to understand the magnitude of this risk.

Although limestone is highly porous, low-lying areas where the water table is high will prevent rainwater from draining away during rapid downpours. When rainfall continues for extended periods, this will lead to severe surface water flooding (Novelo-Casanova & Suárez, 2010). With rainfall intensity predicted to increase, there is an increased risk from pluvial flooding, although this poses less of a threat to Cayman Brac with its high bluff and karstic caves compared to Grand and Little Cayman.

### *Scoring*

Regional and local studies. High agreement, limited evidence. Relevance: Grand Cayman = high, Little Cayman = high, Cayman Brac = medium.

#### 4.3.5 Carbon sequestration and storage by terrestrial, coastal and marine habitats

Mangroves contribute to stabilization of coastal sediments and to the long-term sequestration and storage of atmospheric carbon. A vast amount of literature exists that quantifies the size and value of the carbon stocks, the economic value of this ecosystem service, and the main threats to it (Wilson, 2017). Seagrasses are also recognized as important primary producers (Duarte & Chiscano, 1999), and along with mangroves and salt marshes they are recognised as “blue” carbon sink habitats (Duarte et al., 2013). The blue carbon sequestered and stored in coastal and marine ecosystems such as mangroves, tidal marshes, and seagrass meadows, despite their comparatively small extent relative to other terrestrial vegetated ecosystems, is now recognised to amount to more carbon per unit area than terrestrial forests and therefore has an important role in mitigating climate change (IUCN, 2017). If these ecosystems are degraded or damaged, for example, because of climate change impacts, their carbon sink capacity is lost or adversely affected, and the carbon stored is released, resulting in additional emissions of carbon dioxide that further contribute to climate change (IUCN, 2017). Alongside tropical forests and peatlands, coastal ecosystems offer opportunities for countries to achieve their emissions reduction targets and Nationally Determined Contributions under the Paris Agreement, and they provide numerous other benefits and services that are essential for climate change adaptation, including coastal protection and food security for many communities globally (IUCN, 2017). To our knowledge, however, there is no publicly available data on blue carbon estimates for any of the coastal or marine habitats in the Cayman Islands. Similarly, a terrestrial carbon inventory of the Cayman Islands has not yet been conducted. In this environmental setting, the majority of carbon stocks are likely to be in above-ground vegetation rather than in soils.

#### *Current climate impacts*

Grand Cayman has the largest area of seagrass beds comprising nearly 59% of the island’s benthic lagoon habitat, while seagrass beds account for 25% of the benthic habitat of Little Cayman (Hurlston-McKenzie, 2011). Seagrasses can suffer damage during storms and can take a long time to recover, particularly if they also lose the protection of neighbouring coral reefs and mangroves (Hurlston-McKenzie, 2011).

According to an Ecosystem Service Assessment carried out by local stakeholders using a toolkit for site-based assessment (TESSA) (Childs et al., 2014), of eleven natural habitat sites, all except one (Crown Cliff Faces of the Bluff) was identified as important for carbon storage. Current impacts are likely dominated by the loss of carbon through habitat destruction activities, whether associated with urban development or aggregate industries (which will also influence inorganic carbon storage). As noted in DaCosta-Cottam et al. (2009), the ‘removal of woody vegetation from the developmental footprint of urban and suburban areas and associated infrastructure constitutes the loss of a significant carbon sink.’ Childs et al. (2015) demonstrates the importance of below-ground biomass and soil organic carbon stores, especially the latter top 1m, often removed entirely through de-mucking development activities.

### *Expected future climate impacts*

The short to medium outlook for mangroves is of increased loss as a result of hurricanes, drowning by storm surge and impoundment, and being “outpaced” by sea level rise, resulting in loss of natural carbon storage (Hurlston-McKenzie, 2011). In a study for Grenada, results revealed that under business-as-usual scenarios, mangrove habitats will release 12,450 tonnes more carbon back into the atmosphere than they sequester between 2020 and 2070 (McHarg et al., 2022). No comparable estimates are available for the Cayman Islands.

Earlier sections describe risks posed by climate change to terrestrial habitats, including wetlands. Threats from hurricanes and drought are relevant to the forest, woodland, and shrubland systems. Changes in habitat from forest to shrubland induced by a decreasing depth to anoxic conditions from the surface will likely reduce carbon sequestration potential as well as having implications for existing carbon stocks. Increased aridity, a trend expected to continue in the Caribbean, will likely reduce net primary productivity, and thus, the potential for carbon sequestration. However, drier conditions may slow decomposition and thus lead to the potential for increases in soil carbon stock. Conversely, priming of decomposition may occur with heavier rainfall events under higher temperatures. There is no evidence from a Cayman Islands context specifically to assess the likely implications of how the combination of climate change factors will affect overall carbon sequestration or on existing above-ground and soil carbon stocks. However, Childs et al. (2015) provides baseline data for a limited area in the Central Mangrove Wetland.

Of note is the general finding that carbon storage in forested systems tends to increase with increasing biodiversity (van der Sande et al., 2017). The threats to biodiversity identified in earlier sections and associated loss may compromise future carbon sequestration potential, although the presence of a particularly high-yielding species can maintain carbon sequestration. This may be the case with the non-native invasive *Casuarina equisetifolia*, which can perhaps out-yield native species by virtue of its capacity to fix nitrogen. How this species and habitat responds to climate change may have an influence on future carbon storage potential on areas of the island. Interventions aimed at removing this species may need to consider how they affect multiple outcomes, including carbon sequestration and storage. On the scales concerned in Cayman (i.e., restricted mainly to coastal beach ridges other than some transient populations on land under development), this is probably trivial compared to the carbon stores under mangroves (deep peat) and in primary forests.

In the Ecosystem Service Assessment using TESSA (Childs et al., 2014), text in the main document suggested wetland areas will increase their storage of carbon associated with groundwater changes and sea-level rise (e.g., at Colliers Wilderness Reserve). However, Appendix B of the same report suggested that carbon storage will decline across these different terrestrial areas, including wetlands, under a combination of threats (Childs et al., 2014). These threats included drivers associated with climate change, including extreme weather events, sea-level rise, and other climate extremes, although the main drivers of change were land clearance associated with development and invasive species. Only Booby Pond, Crown Cliff Faces of the Bluff, and the Mastic Forest are expected to remain unchanged, and as noted, Crown Cliffs has negligible carbon storage potential (Childs et al., 2014), although inorganic forms of carbon storage should not be ignored (see below).

The carbon sequestration potential of the native vegetation is particularly at risk due its slow rates of regeneration (Childs et al., 2014). Once vegetation is lost through events induced by climate change (e.g., salinity levels or sea-level rise) or exacerbated by climate change (e.g., fire risk), recovery will likely take significant time, notwithstanding the resilience shown by certain species. Events such as fires and hurricanes may potentially limit regeneration and carbon sequestration, and affect stored carbon through removal of organic matter.

In the global context, the area of the Cayman Islands is very small and therefore, the impact of climate change on global levels of carbon sequestration is limited. However, all carbon storage is important,

so loss of native habitat and associated processes in anthropogenic habitat (e.g., increased fires, invasive species) will compromise carbon sequestration in these islands.

#### *Scoring*

Regional and local studies. High agreement, limited evidence. Relevance to global carbon inventories will be negligible, therefore initially scored low for all three islands (subsequently raised to medium in Grand Cayman and Little Cayman following workshop with regional experts).

## 4.4 Cultural services/benefits

### 4.4.1 Wildlife tourism and recreation (marine and terrestrial)

Wildlife tourism in the Cayman Islands includes sport fishing, bird watching, snorkelling, and scuba diving. There are many tour operators in the islands offering guided tours ranging from a few hours to full weeks. There are also charter boats and boat tours offering snorkelling and diving trips, including coral planting and conservation courses. The Species Conservation Plan for Mangroves, aimed at conserving Cayman Islands' mangroves, explicitly mentions protecting Little Cayman mangroves as a nature tourism asset, as they are a key bird habitat. Protecting core assets of the tourism industry (coral reefs, beaches, marine wildlife) is Goal 1 of the National Tourism Plan 2019-2023.

#### *Current climate impacts*

The coral reefs of the Cayman Islands are in a better condition than many in the Caribbean, and so continue to support a thriving snorkelling and diving industry. Unsettled weather has caused closures of tourism activities, reducing income for charter boat operators and other linked sectors such as ground transport (Hurlston-McKenzie, 2011). However, coral bleaching is a great concern with the Cayman Islands being a major dive destinations (Layne, 2017). While overall customer satisfaction with scuba diving, snorkelling, and recreational fishing activities in the Cayman Islands appears to be relatively high, the revenue losses as a result of the mass coral bleaching events experienced in the last 25 years are not clear (Hurlston-McKenzie, 2011).

The main wildlife attraction for the Cayman Islands is its marine wildlife. However, its diverse terrestrial flora and fauna, and specifically endemics such as the Blue iguana, are still important for tourists. Habitat loss and destruction, and subsequent impacts on terrestrial fauna resulting from climate change are the main threats currently facing terrestrial wildlife tourism and recreation (see sections on climate change impacts on terrestrial wildlife).

#### *Expected future climate impacts*

It has been shown in the Caribbean that if the coastal and marine environment are negatively impacted by climate change, this will affect tourism value. A survey of tourists in Bonaire and Barbados showed that if the islands were affected by coral bleaching or reduced beach area, then 80% of respondents said they would be unwilling to pay the same price for their holiday (Uyerra et al., 2005). Climate change is expected to cause reduced tourism value of coral reefs caused by bleaching and coral mortality degrading the reefs and reducing their aesthetic and wildlife value (Cayman Islands Government, 2011; Taylor et al., 2020). If the health and extent of mangrove forests are negatively impacted by climate change, this is likely to impact the bird watching value of the Cayman Islands. Some tourism businesses such as dive boats or boat tours cannot operate in bad weather, and so they may lose money each year if there is more adverse weather in the future (Hurlston-McKenzie, 2011).

If the distributions of sport fish change in the future, then this could impact the recreational fishing industry in the Cayman Islands.

Climate change could lead to declines in terrestrial wildlife populations and potentially cause their extinction from the Cayman Islands, although this depends on the interaction of climate change with other drivers (e.g., land-use change). The vast number of migratory and overwintering birds are a tourism draw of the Cayman Islands, and therefore climate change effects on terrestrial breeding, foraging habitats, and on migration routes, as well as species alteration of phenology, will directly affect wildlife tourism and recreation of the Cayman Islands.

Climate change could have impacts on wreck diving, either by impacting participation levels or tourism assets, that is significant for all three islands. For example, USS Kittiwake, was placed upright in Seven Mile Beach Marine Park in 2011 specifically to attract tourists, however, the ship tipped onto its side and closer to a natural reef during the passage of Tropical Storm Nate in 2017.

### *Scoring*

Global studies, Regional studies. Medium agreement, limited evidence. Relevance: Grand Cayman = high, Little Cayman = high, Cayman Brac = high.

#### 4.4.2 Archaeology and cultural heritage

With its abundance of turtles, accessible fresh water supply and location on the windward passage, the Cayman Islands became a popular resupply point for European sailors and merchants in the 16<sup>th</sup> Century. Settlers from the UK are known to have established themselves in the 17<sup>th</sup> century following the conquest of Jamaica from the Spanish (Wells, 2018). There is no archaeological evidence of permanent inhabitants on the Cayman Islands prior to the 17<sup>th</sup> century arrival of European and African colonists (Wells, 2018).

The Cayman Islands maritime heritage is evidenced in its place names. On Little Cayman, Sparrowhawk Hill is named after HMS Sparrowhawk which surveyed the Islands in 1882, and Blossom Village is named after HMS blossom (Richard Owen's ship, which carried out the first hydrographic survey of the island in 1831) (Wells, 2018). Around 300 shipwrecks have been recorded off the Cayman Islands, and a number have historical significance.

Heritage sites on the Cayman Islands, namely historic buildings, date from the 18<sup>th</sup> century onwards and are predominately located in or near population centres. Examples are the historic church in Blossom Village on Little Cayman, Heritage House on Cayman Brac, and Pedro St James historic site on Grand Cayman. Other important heritage sites are the National Gallery, National Museum, and smaller museums on all three islands, which contain information on cultural heritage and national identity, and the historical district of Bodden Town, which has Pedro St James great house, the oldest remaining stone structure in the Cayman Islands (Hurlston-McKenzie, 2011).

### *Current climate impacts*

Historical sites have suffered immediate damage because of wind-borne debris and flooding from hurricanes and storm surges. In 2004, 70% of Grand Cayman was flooded because of Hurricane Ivan (Figure 36) and the Pedro St. James historic site was severely damaged (Hurlston-McKenzie, 2011). Similarly, Miss Izzy's Schoolhouse in West Bay, a National Trust historic building of wattle and daub construction, was destroyed beyond repair by the extreme winds of Hurricane Ivan. In 2008, Hurricane Paloma devastated buildings on the Sister Islands, and while no specific reference is made to buildings

of cultural importance, due to their age and location with inland settlements clustered along the coast, they most likely experienced some damage.

#### *Expected future climate impacts*

Flooding and strikes from wind-borne debris because of increases in hurricane intensity, sea-level rise, storm surges, and surface water collation pose the greatest risk to heritage sites on the Cayman Islands. Furthermore, wind speed alone, without the aid of debris strikes, is significant enough to cause major damage to historic buildings and sub-standard structures. Consideration of Figure 39 (0.25m flood increments) for Grand Cayman shows that historic buildings and museums located in the west of George Town, such as the National Museum, could survive a one metre increase in sea level, and also Pedro St James historic site (located on Bluff formation 6m amsl; will not be directly impacted by a 2m SLR) on the south coast. National Museum located in Hog Sty Bay is currently susceptible to coastal flooding from wave overtopping during Nor'westers and hurricanes from the southwest, causing temporary closures, and lost revenue and access by the public and tourists. Part, or all, of Bodden Town historical district would be affected by a 0.25m increase in sea level. A 2m increase in sea level (Figure 32) would affect numerous historical sites, not only within Grand Cayman, but also on the Sister Islands.

As well as the immediate damage caused by climate change events, there is also the longer-term impact of water damage on structures and potentially artefacts stored within buildings, exacerbated by heavier rainfalls that may penetrate buildings. Constant water damage may lead to deterioration of structures beyond repair. Of particular concern to historical buildings is the specialist repair required (Hurlston-McKenzie, 2011). Where new homes can be built with climate-proof designs (see section Inland settlements and infrastructure), retro-fitting historical buildings to be climate-proof or providing external climate-mitigating structures sympathetic to their history is more challenging.

The Cayman Islands benefit from a rich maritime heritage. Historic shipwrecks /marine artefacts could potentially be damaged, lost to deeper waters or buried under sand moved by hurricane-force wave action, although this topic has been little studied.

#### *Scoring*

Local studies. High agreement, medium evidence. Relevance: Grand Cayman = high, Little Cayman = medium, Cayman Brac = medium.

## 5 'Long-list' of identified risks (and opportunities)

**Table 16.** 'Long list' of climate risks (and opportunities) facing the Cayman Islands. Blue text indicates risks to biodiversity and habitats, black text indicates risks to human society and economies. List refined by regional experts at workshop in May 2022.

Risk (description)	Confidence Categorisation	Overall Confidence Score	Relevance		
			Grand Cayman	Little Cayman	Cayman Brac
Changes to plankton productivity and plankton species composition	Medium agreement, limited evidence	Low	Medium	Medium	Medium
Changes to the occurrence and frequency of Harmful Algal Blooms (HABS)	Medium agreement, medium evidence.	Medium	Medium	Medium	Medium
Increases in the occurrence of Sargassum seaweed	Low agreement, limited evidence	Low	Medium	Medium	Medium
Changes in the distribution and abundance of reef, deep-slope, coastal fish and shellfish populations	Medium agreement, medium evidence.	Medium	High	High	High
Changes in the distribution and abundance of large offshore pelagic fish	Medium agreement, limited evidence.	Low	High	High	High
Disruption of turtle distribution and population dynamics	Medium agreement, medium evidence.	Medium	High	High	High
Disruption of seabird population dynamics	Medium agreement, limited evidence.	Low	High	High	High
Change in the abundance and distribution of whales and dolphins	Medium agreement, limited evidence.	Low	Medium	Medium	Medium
Impacts on deep-sea fish and invertebrate communities	Medium agreement, limited evidence.	Low	Low	Low	Low
Increased frequency and severity of coral bleaching and coral disease outbreaks	High agreement, robust evidence.	High	High	High	High
Decline of coral reef structure and integrity	High agreement, robust evidence.	High	High	High	High
Loss and damage to mangroves	Medium agreement, robust evidence.	Medium	High	High	Medium
Loss and damage to seagrass beds or change in seagrass distribution	Low agreement, medium evidence.	Low	High	High	Medium
Freshwater lens contraction and salinisation of surface and groundwaters	High agreement, robust evidence.	High	High	High	Medium
Impact on forest, woodland and shrubland communities	Medium agreement, limited evidence.	Low	High	High	High
Impact of (more frequent) wildfire events on forest, woodland and scrub communities	Medium agreement, limited evidence.	Low	High	High	High



Changes to populations of resident and migratory bird species (terrestrial)	High agreement, robust evidence	High	High	High	High
Impacts on insect and vertebrate pollinators	Medium agreement, limited evidence	Low	High	High	High
Changes in amphibian populations	High agreement, robust evidence	High	High	High	High
Impacts on fresh (but brackish) water wetland vegetation and biodiversity	High agreement, robust evidence	High	High	High	Medium
Loss of endemic species and sub-species as a result of habitat degradation (animals and plants)	High agreement, medium evidence	Medium	High	High	High
Impacts on the introduction and spread of non-native and invasive species (animals & plants)	Medium agreement, limited evidence	Low	Medium	Low	Low
Impact on sport fisheries for large pelagic fish species	Medium agreement, medium evidence.	Medium	High	Medium	Medium
Losses in artisanal fisheries yield, with impacts on food security and incomes	Medium agreement, medium evidence.	Medium	Medium	Medium	Medium
Storm damage to arable and horticultural agriculture	High agreement, robust evidence	High	High	Low	High
Increasing heat and water stress for crops and forage plants	High agreement, robust evidence	High	High	Low	High
Impacts on livestock	High agreement, robust evidence	High	High	Low	High
Impacts of on demand for, and supply of building materials	High agreement, medium evidence	Medium	Medium	Low	Low
Disruption to fossil fuel imports, power generation and distribution	High agreement, medium evidence	Medium	High	High	High
Impacts on communications infrastructure	Medium agreement, medium evidence.	Medium	High	High	High
Impact on (future) renewable energy production – mostly solar	Medium agreement, limited evidence	Low	Medium	Medium	Medium
Shortage of water for human consumption	High agreement, medium evidence	Medium	Medium	High	High
Shortage of water for agriculture and irrigation	High agreement, robust evidence	High	High	Low	Medium
Disruption to ports and shipping traffic	Medium agreement, medium evidence	Medium	High	High	High
Damage to roads, airports & infrastructure	High agreement, medium evidence	Medium	High	High	Medium
Damage to coastal settlements and buildings	High agreement, robust evidence	High	High	High	High
Damage to inland settlements and buildings	High agreement, robust evidence	High	Medium	Medium	Medium
Damage & inundation to the sewerage system and release of waste-water	High agreement, robust evidence	High	Medium	Medium	Medium

Damage and inundation of landfill sites, wash-out of contaminated wastes	Medium agreement, medium evidence	Medium	Medium	Medium	Medium
Increased disease transmission and occurrence (e.g. water-borne pathogens)	High agreement, robust evidence	High	High	Medium	Medium
Changes in mosquito populations and associated illnesses	Low agreement, medium evidence	Medium	High	Medium	Medium
Changes in seafood associated illnesses and poisonings	Medium agreement, medium evidence	Medium	Medium	Low	Low
Heat & humidity related health impacts & mortality	High agreement, medium evidence	Medium	Low	Low	Low
Increase in direct mortality & injury from hurricane/storm/flood events	High agreement, robust evidence	High	Low	Medium	Medium
Disruption & damage to the tourism sector (and related infrastructure)	High agreement, medium evidence	Medium	High	High	Medium
Deterioration of air quality (indoor & outdoor)	Medium agreement, medium evidence.	Medium	Low	Low	Low
Loss of coastal protection function associated with removal of coral reefs, mangroves, seagrass & beaches	Medium agreement, medium evidence.	Medium	High	High	Medium
Decline in carbon sequestration and storage function of vegetative habitats	High agreement, limited evidence.	Low	Medium	Medium	Low
Decline in natural assets that underpin tourism	Medium agreement, medium evidence.	Medium	High	High	High
Damage to archaeological and cultural heritage sites as well as disruption of cultural events	High agreement, medium evidence	Medium	High	Medium	Medium

## 6 Knowledge gaps

Examination of the available literature on climate change impacts in the Cayman Islands has revealed a number of clear evidence gaps, making it difficult to assess the relative level of threat. For example, with regard to 11 of the 37 topics featured in this evidence report, it was judged that only ‘limited evidence’ was available (sea circulation and currents; ocean acidification and pH; plankton productivity; marine mammals, seabirds and turtles; deep sea and offshore environments; evergreen thicket and woodland; invasive non-native species; mining and sand extraction; maritime transport; natural flood and erosion control; carbon sequestration and storage; wildlife tourism and recreation), as compared to 2 topics where the level of evidence was judged as ‘robust’ (corals and coral reefs;

freshwater environments and resources). Notably, region-wide or even global studies were the only sources of information available for many topics, and in particular there was no Cayman-specific monitoring or modelling of certain meteorological parameters such as seawater pH (ocean acidification). There is a general lack of downscaled climate model outputs available for the Cayman Islands with the territory being located beyond the southern edge of modelling 'Zone 2' in the SOCC report (MONA, 2020). Generally, the Cayman Islands are not even shown on many maps, such as those generated within NOAA's Climate Change Web Portal providing outputs from the latest generation of CMIP6 models. This lack of high-resolution climate model outputs, as well as sea level rise projections, could hamper efforts to assess risks and build resilience to climate change within the Territory going forward.

In many cases the only evidence available about past or present climate change impacts in the Cayman Islands relates to observations made following the passage of Hurricane Ivan in September 2004. Hurricane Ivan caused a reported CI\$2.86 billion in damages in the Cayman Islands (183% of GDP) (ECLAC 2005). Ivan's winds and storm surge caused widespread property damage. A quarter or more of the buildings in the Cayman Islands were rendered uninhabitable, with 95% having some degree of damage (ECLAC, 2005). Hence, Ivan has been viewed as a 'case study' of what might happen in the future should the frequency or severity of storms increase and as a general test of vulnerabilities and sensitivities across natural ecosystems and human infrastructures within the Cayman Islands. Whether or not it is safe to draw such inferences from a single event, or whether the occurrence/magnitude of Hurricane Ivan can be related back to long-term global warming remains a matter of conjecture.

Some natural habitats have received much more research attention than others. For example, since 1997, the Cayman Islands Department of Environment (DOE) has systematically assessed coral health around the Cayman Islands, with ongoing surveillance of reef status at designated sites as part of the Coral Watch programme. By contrast, very little is known about seagrass beds in the Cayman Islands and even less about offshore and deep-water ecosystems that make up the bulk of the Cayman Islands territory. This latter research gap will be partly addressed in the coming years by marine scientists from the University of Heriot-Watt who will work with partners under a UK government 'Darwin Initiative' project to enhance understanding of these critical deep-sea habitats (Heriot-Watt, 2021). Over two years, the team will assess sites offshore from the Cayman Islands, undertaking surveys up to 2000m deep. The work will focus on threatened and commercial fish species, including sharks, and map the distribution of deep-water coral and other biotopes (Heriot-Watt, 2021).

Climate change impacts on certain human activities, such as mining of sand and gravel seem to be particularly poorly studied in the Cayman Islands, yet there is growing demand for building materials within the construction sector, and sea level rise or changes in storminess might also mean that more sand and gravel are needed to construct hard sea defences at some localities. There is also a lack of reliable data on fisheries catches (either subsistence or recreational) within the islands and hence, it is difficult to determine how these sectors might be impacted in the future. One issue that has received very little attention in this report is the potential impact of future climate on maritime safety. When a ship or boat runs aground, it can cause harm to coral reefs, seagrass meadows, mangroves and other essential habitats. These environments are critical to the economy and culture of the Cayman Islands. Ships that ground on coral reefs may cause immediate and long-term harm and can destroy hundreds of years' worth of coral growth. Ship groundings might be expected to occur more frequently in the future if severe hurricanes become more commonplace.

Another topic that has received only scant attention in the present report is issue of food insecurity. The Cayman Islands currently imports almost all of the food it consumes. The majority of this food is imported from the United States, and therefore climate change impacts on US agricultural production will affect availability and price of these goods with costs indirectly borne by residents and visitors alike. The most recent assessment of the Intergovernmental Panel on Climate Change (IPCC 2022), suggests that climate change has affected crops across North America through changes in growing seasons, extreme heat, precipitation, water stress, and soil quality. Without adaptation, climate change is projected to reduce overall yields of important North American crops (e.g., wheat, maize, soybeans) and to cause declines in livestock production (Hicke et al., 2022). This, together with changes in hurricane frequency (e.g., increased frequency of Category 4 and 5 hurricanes), could greatly disrupt food supplies to the Cayman Islands, with corresponding impacts on health and resilience.

According to the Cayman Islands Compendium of Statistics 2020, 'Financial & Insurance Services' contributed 30.4% to the national income in 2019. When determining the scope for this evidence report, it was agreed that impacts on banking, insurance, and other parts of the financial services sector would not be considered, as this topic would require specialist knowledge that is beyond the expertise of Cefas and CEH. Climate change poses a major risk to the global economy. Several recent reports do examine the possible impact of climate change on the global financial services sector, most notably Battiston et al. (2017), Campiglio et al. (2018) and Dietz et al. (2016).

## 7 Discussion

This evidence report offers the most detailed assessment of climate change impacts ever undertaken for the Cayman Islands and provides a thorough update to the earlier Green Paper 'Climate Change Issues for the Cayman Islands: Towards a Climate Change Policy' (Hurlston-McKenzie, 2011). Indeed, this is probably the most detailed assessment available for any island group in the Caribbean, although it should be noted that the original Green Paper dealt with the Financial Services and banking sector, in particular the issue of and measures to avoid un-insurability, and opportunities for private sector actors in these arenas.

Fifty discrete risks were identified in the 'long list' of climate change risks (and opportunities) based on this evidence review. Twenty-two risks relate to biodiversity and habitats, and twenty-eight risks relate to economy and society. Many of the risks are highly relevant to all three islands, some have less relevance (e.g. 'impacts on deep-sea fish and invertebrate communities'), and some are more relevant to one of the islands than in the others (e.g. 'Shortage of water for agriculture and irrigation' which is high for Grand Cayman, but 'low' for Little Cayman where very little agriculture is practiced). In some cases, risks were generally scored as being of 'low' relevance (e.g., 'Increase in direct mortality from hurricane/storm/flood events' or 'Increase in heat related mortality') because inhabitants of the Cayman Islands are generally considered to be sufficiently affluent to be able to offset or mitigate these risks (i.e., they have sufficient 'adaptive capacity', although perhaps not newcomers or visitors/tourists). In the case of 'Decline in carbon sequestration and storage function of vegetative habitats,' this was scored as 'low' relevance because the contribution of Cayman Islands natural carbon sinks to global carbon inventories will be negligible.

All risks have been categorised in terms of the *level of agreement* among researchers, as well as the *level of evidence*. An overall confidence score (Figure 4) has been assigned based on this categorisation as used by the IPCC (Mastrandrea et al., 2011). Of the fifty risks included in the 'long list', fifteen were scored as having *high confidence*, twenty-three were scored as having *medium confidence*, and twelve were scored as *low confidence*. The risks categorised as having the lowest confidence overall were: (a) changes in the occurrence of Sargassum seaweed; and (b) impacts of changed storminess on demand and supply of building materials.

It should be noted that this evidence report has primarily been compiled using available literature, and that no additional statistical analysis or data collation has been attempted. The assessment relied heavily on a 2011 modelling and data collation exercise by the Climate Studies Group, Mona at the University of the West Indies (MONA, 2014). However, this information is now ten years old and there would be considerable merit in providing a quantitative update. In particular, time-series for sea level, temperature, pH, rainfall, etc. would all benefit from 11 years of additional data (Figures 6, 8, 10, 15), during which additional insights might have emerged. Furthermore, new monitoring stations have now been established, including four new tide gauges (Gun Bay Public Dock, the Royal Watler Cruise Terminal, the Creek Dock in Cayman Brac and at Bloody Bay Dock in Little Cayman), as well as the region's only permanently moored oceanographic monitoring station at the Central Caribbean Marine Institute's Little Cayman Research Centre. Several major tropical storms (e.g., Eta in November 2020, and Grace and Ida in August 2021) have passed by the islands since 2011, offering additional insights into system resilience and preparedness.

Now that a 'long list' of fifty-two potential climate change risks (and opportunities) has been assembled, the next step will be to convene a workshop of stakeholders and experts from the Cayman Islands (in May 2022) to score these risks in terms of 'proximity' (urgency) and 'magnitude' (seriousness). Risks will be rationalised at the stakeholder workshop to identify any areas of perceived duplication or to identify where more detail might be warranted. In addition, the key climate drivers behind each risk will be identified. Then, participants will be asked to consider the time horizon after which substantial impacts are anticipated to be felt (i.e., ranging between 1 (likely to occur in the more distant future, 50 years +) and 4 (already happening now)), and to specify 'magnitude' (seriousness). Magnitude scores will be based on the perceived significance and consequences of a particular risk happening based on an assessment of combined environmental, economic, and social impacts. In the first UK Climate Change Risk Assessment (CCRA) carried out in 2012 (CCRA, 2012), 'magnitude' was scored/bracketed on the basis of how many people might be affected by each risk, the level of economic losses anticipated, or the spatial area affected (Table 17). Clearly, this categorization scheme will need to be tailored and substantially revised before it can be used in a Cayman Islands context, although the broad principals will remain the same. A final report will be produced by September 2022 describing the risk-assessment process and containing the prioritised risks. This will be in the form of a short summary document (8-12 pages) written for a broad non-technical audience.

**Table 17.** Summary of the classification scheme used to assess ‘magnitude’ in the first UK Climate Change Risk Assessment (CCRA). Source: CCRA (2012).

Class	Economic	Environmental	Social
<b>High</b>	<ul style="list-style-type: none"> <li>Major and recurrent damage to property and infrastructure</li> <li>Major consequence on regional and national economy</li> <li>Major cross-sector consequences</li> <li>Major disruption or loss of national or international transport links</li> <li>Major loss/gain of employment opportunities</li> </ul> <p>~ £100 million for a single event or per year</p>	<ul style="list-style-type: none"> <li>Major loss or decline in long-term quality of valued species/habitat/landscape</li> <li>Major or long-term decline in status/condition of sites of international/national significance</li> <li>Widespread Failure of ecosystem function or services</li> <li>Widespread decline in land/water/air quality</li> <li>Major cross-sector consequences</li> </ul> <p>~ 5000 ha lost/gained ~ 10000 km river water quality affected</p>	<ul style="list-style-type: none"> <li>Potential for many fatalities or serious harm</li> <li>Loss or major disruption to utilities (water/gas/electricity)</li> <li>Major consequences on vulnerable groups</li> <li>Increase in national health burden</li> <li>Large reduction in community services</li> <li>Major damage or loss of cultural assets/high symbolic value</li> <li>Major role for emergency services</li> <li>Major impacts on personal security e.g. increased crime</li> </ul> <p>~million affected ~1000s harmed ~100 fatalities</p>
<b>Medium</b>	<ul style="list-style-type: none"> <li>Widespread damage to property and infrastructure</li> <li>Influence on regional economy</li> <li>Consequences on operations &amp; service provision initiating contingency plans</li> <li>Minor disruption of national transport links</li> <li>Moderate cross-sector consequences</li> <li>Moderate loss/gain of employment opportunities</li> </ul> <p>~ £10 million per event or year</p>	<ul style="list-style-type: none"> <li>Important/medium-term consequences on species/habitat/landscape</li> <li>Medium-term or moderate loss of quality/status of sites of national importance</li> <li>Regional decline in land/water/air quality</li> <li>Medium-term or Regional loss/decline in ecosystem services</li> <li>Moderate cross-sector consequences</li> </ul> <p>~ 500 ha lost/gained ~ 1000 km river water quality affected</p>	<ul style="list-style-type: none"> <li>Significant numbers affected</li> <li>Minor disruption to utilities (water/gas/electricity)</li> <li>Increased inequality, e.g. through rising costs of service provision</li> <li>Consequence on health burden</li> <li>Moderate reduction in community services</li> <li>Moderate increased role for emergency services</li> <li>Minor impacts on personal security</li> </ul> <p>~100s thousands affected, ~100s harmed, ~10 fatalities</p>
<b>Low</b>	<ul style="list-style-type: none"> <li>Minor or very local consequences</li> <li>No consequence on national or regional economy</li> <li>Localised disruption of transport</li> </ul> <p>~ £1 million per event or year</p>	<ul style="list-style-type: none"> <li>Short-term/reversible effects on species/habitat/landscape or ecosystem services</li> <li>Localised decline in land/water/air quality</li> <li>Short-term loss/minor decline in quality/status of designated sites</li> </ul> <p>~ 50 ha of valued habitats damaged/improved ~ 100 km river quality affected</p>	<ul style="list-style-type: none"> <li>Small numbers affected</li> <li>Small reduction in community services</li> <li>Within ‘coping range’</li> </ul> <p>~10s thousands affected etc.</p>

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# Centre for Environment Fisheries & Aquaculture Science



## About us

We are the Government's marine and freshwater science experts. We help keep our seas, oceans and rivers healthy and productive and our seafood safe and sustainable by providing data and advice to the UK Government and our overseas partners.

We are passionate about what we do because our work helps tackle the serious global problems of climate change, marine litter, over-fishing and pollution in support of the UK's commitments to a better future (for example the UN Sustainable Development Goals and Defra's 25 year Environment Plan).

We work in partnership with our colleagues in Defra and across UK government, and with international governments, business, maritime and fishing industry, non-governmental organisations, research institutes, universities, civil society and schools to collate and share knowledge.

Together we can understand and value our seas to secure a sustainable blue future for us all, and help create a greater place for living.

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Innovative, world-class science is central to our mission. Our scientists use a breadth of surveying, mapping and sampling technologies to collect and analyse data that are reliable and valuable. We use our state-of-the-art Research Vessel Cefas Endeavour, autonomous marine vehicles, remotely piloted aircraft and utilise satellites to monitor and assess the health of our waters.

In our laboratories in Lowestoft and Weymouth we:

- safeguard human and animal health
- enable food security
- support marine economies.

This is supported by monitoring risks and disease in water and seafood; using our data in advanced computer models to advise on how best to manage fish stocks and seafood farming; to reduce the environmental impact of man-made developments; and to respond to serious emergencies such as fish disease outbreaks, and to respond to oil or chemical spills, and radioactivity leaks.

Overseas, our scientists currently work in Commonwealth countries, United Kingdom Overseas Territories, South East Asia and the Middle East.

Our customer base and partnerships are broad, spanning Government, public and private sectors, academia, non-governmental organisations (NGOs), at home and internationally.



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