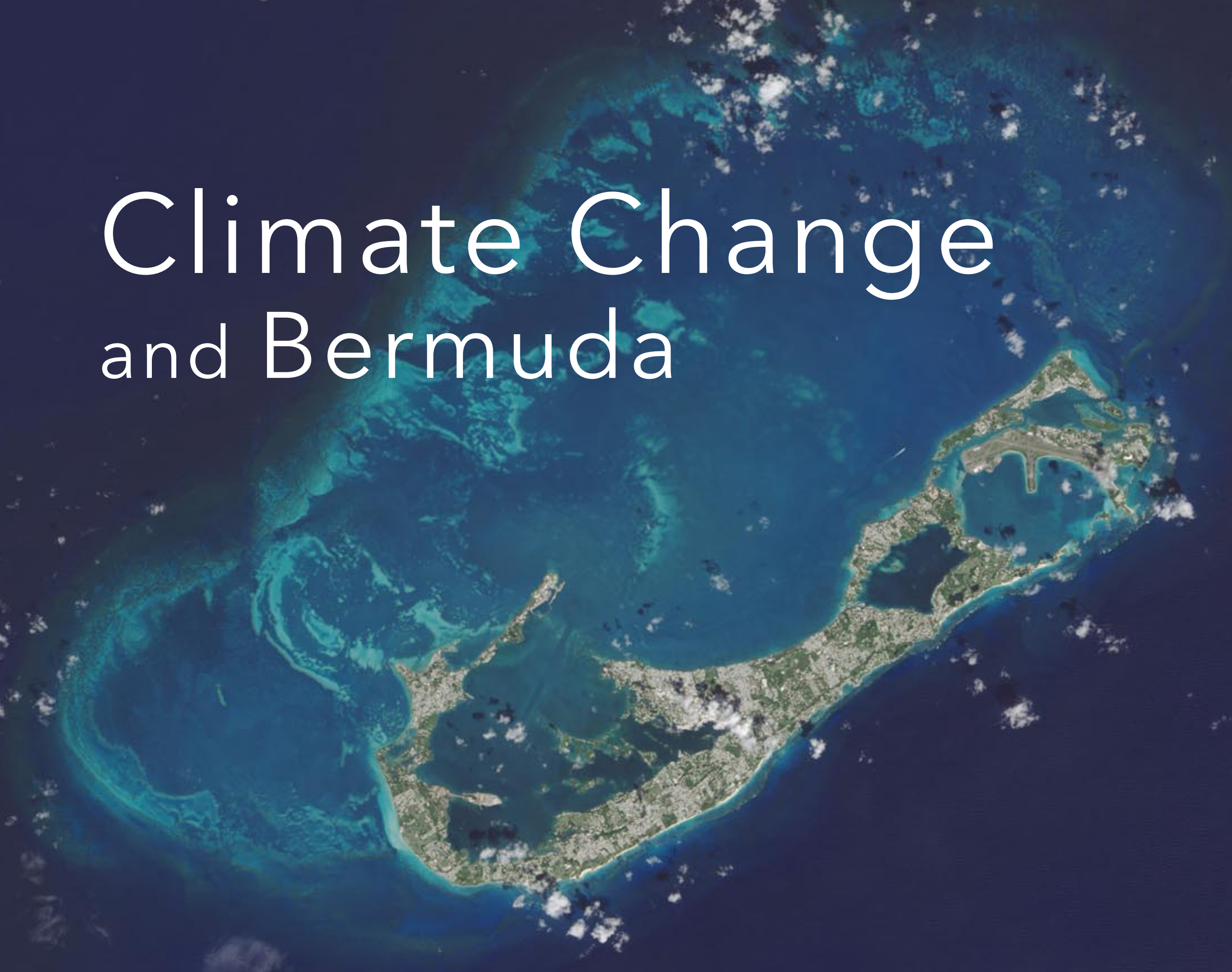

Climate Change and Bermuda

Part I

Science and Physical Hazards

BIOS

Bermuda Institute of Ocean Sciences (BIOS)
Compiled by Dr. Mark Guishard

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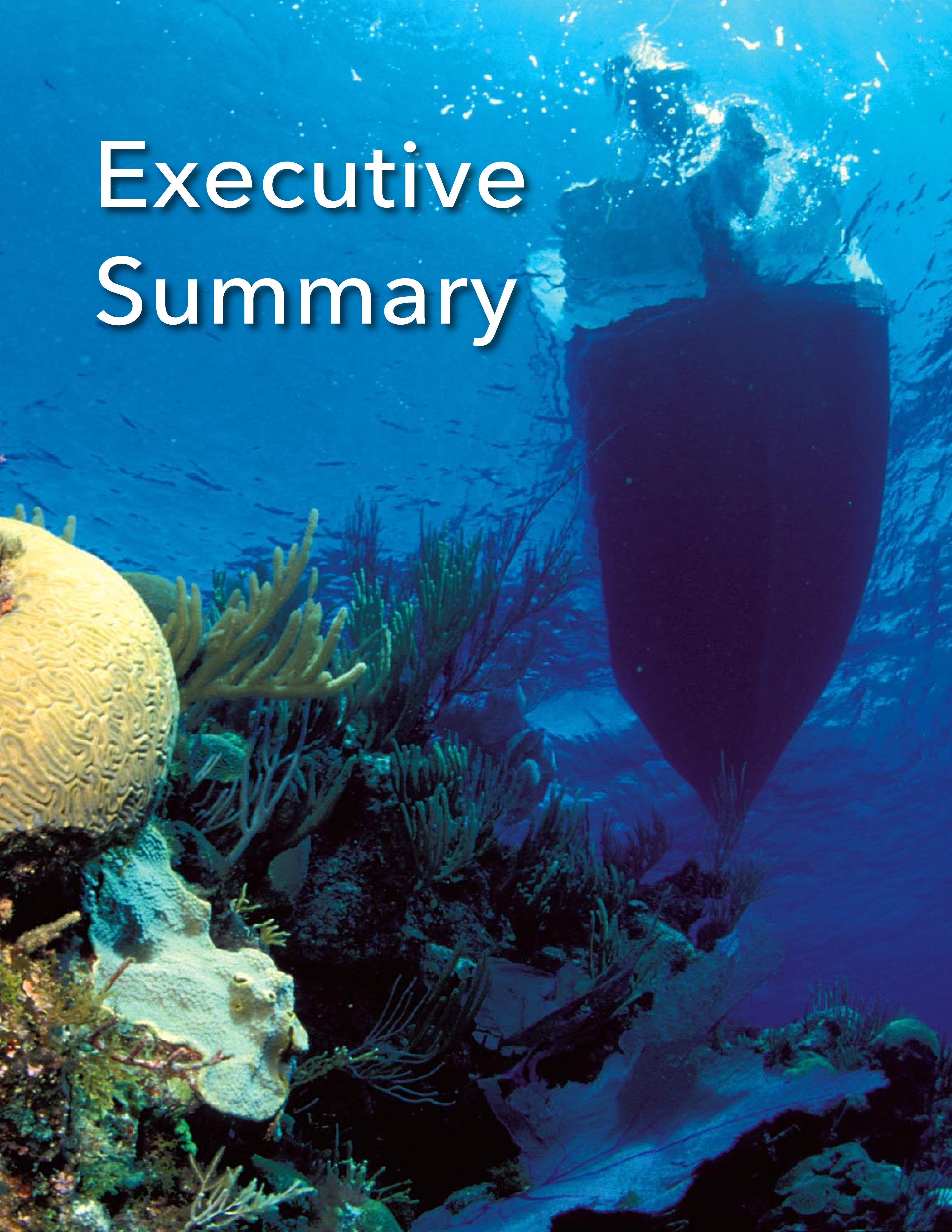
Cover image: satellite image of Bermuda courtesy of NASA

Executive Summary



Executive Summary
Event | Impact

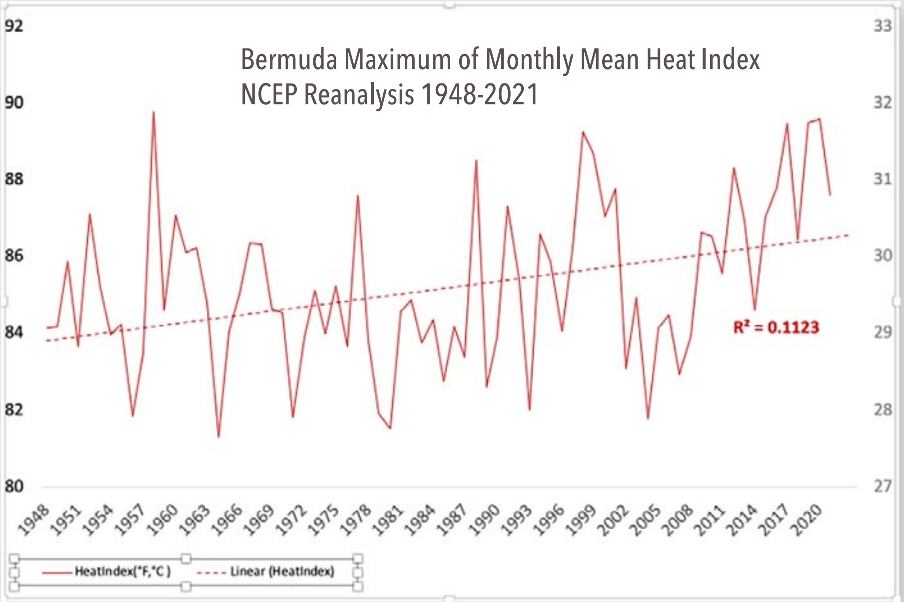
Event | Impact	Change in Hazard		
	Changes in intensity & characteristics	Confidence in Historical Trends	Confidence in Future change under climate influence (2050-2100)
Air temperature & humidity	Moderate Approximately 1°C warmer maximum monthly surface temperature in last 70 years. Increases in duration of summer.	High (observed)	High 2.1-3.5°C warming in North Atlantic Region under IPCC intermediate greenhouse gas emissions scenarios.
Ocean warming & marine heat waves	High >1°C sea surface warming since 1984	High (observed)	High 0.9-1.2°C average upper ocean (top 200m/656ft) warming by 2100 near Bermuda under IPCC intermediate greenhouse gas emissions scenarios. (Flowers, 2022)
Sea level rise	Moderate Gradual increases in baseline sea level, estimated at 0.25m (10″) 1900-2020	High (observed)	High Projections of another 0.24-0.26m by 2050, 0.5-0.7m by 2100 (Kopp et al., 2014)
Storm surges	Moderate Increase in surges, but some high values masked by low tide. Highest storm surge in record Hurricane Nicole 0.86m / 2.8 ft above mean sea level (at low tide) Note Hurricane Fabian 2003 absent from the record.	Moderate (data gaps reduce certainty in observed trend)	High (based primarily on sea level rise)
Hurricane activity	High Intensity and frequency increasing. Average Bermuda storm intensity increased 35 to 73 mph from 1955 to 2019 (Hallam et al., 2021).	High (observed)	Moderate Some model projections indicate 1 more major storm per decade near Bermuda under mid- to end-of-century warming scenarios

Executive Summary
Event | Impact

Event | Impact	Change in Hazard		
	Changes in intensity & characteristics	**Confidence in Historical Trends**	**Confidence in Future change under climate influence (2050-2100)**
Rainfall Seasonal & Annual	Moderate Annual accumulations and winter rain days increasing on average. Approx. 20 more rain days annual 1950-present on average.	Moderate (observed upward trends in seasonal & annual accumulations have high variability)	Low Local projected changes are uncertain
Rainfall Short duration (daily or shorter)	Unclear Insufficient data Annual thunderstorm occurrences increased from approx. 20 days in the 1950s to 50 days in the 2010s.	Low (data unavailable) Short duration events likely to be more frequent. Thunderstorm trends support the theory.	Low Local projected changes are uncertain
Mean winds & winter gales	Moderate Observed monthly mean surface wind speed increases of 1-2 mph since 1980s.	Moderate Observed local wind speed increases verified independently, but at odds with wider region	Low Projected decreases in average wind are uncertain Gale occurrence may slightly increase
Ocean waves & swell	Unclear No wave buoy data for Bermuda	Unclear No local data, conflicting reporting for North Atlantic	Low Projected decreases in average wave climate are uncertain

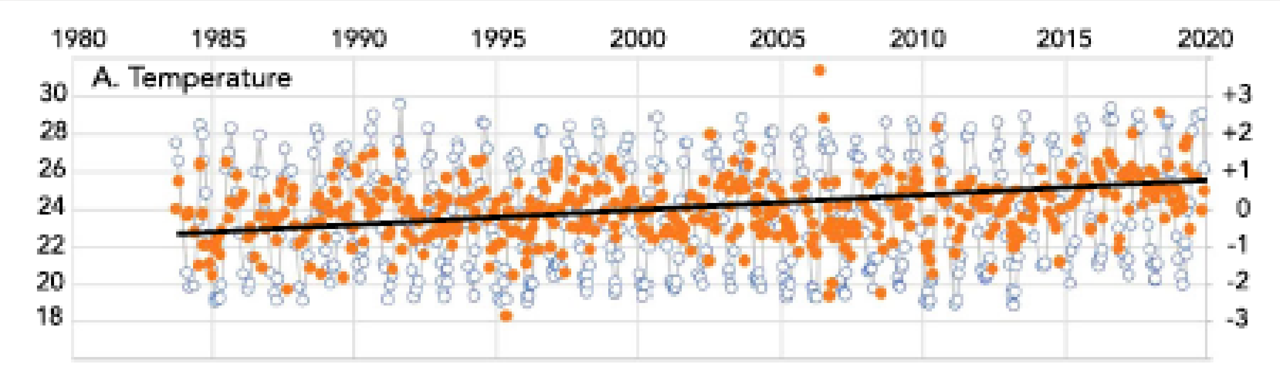
Executive Summary
Temperature and Humidity

- Due to an inconsistent surface temperature record in Bermuda, and the fact that the ocean has a moderating effect, the surface air temperature trends are less obvious than one might imagine under global warming.
- Examination of reanalyses (incorporating historical surface and weather balloon data) for Bermuda reveals a more distinct warming trend aloft.
- Maximums in monthly average temperature and humidity have been increasing o ver the last two decades, both at the surface and in the lower levels of the atmosphere aloft.
- Moisture in the air, as measured by specific humidity also shows an upward trend.
- Combined, the warming and moistening air trends (summarized by the heat index) are increasing during the hottest parts of the year.
- No specific projections exist for Bermuda; however the consensus of climate models, as summarized in the IPCC reports, is for continued warming of the North Atlantic through the end of the century.
- The oceans have absorbed over 90% of the excess heating produced by climate change.



The maximum of monthly average heat index for Bermuda (°F, left axis, °C, right axis). Data source: NCEP/NCAR Reanalysis, Time Series produced at NOAA Physical Sciences Laboratory, grid point 32.5N, 65.0W (Kalnay et al., 1996)

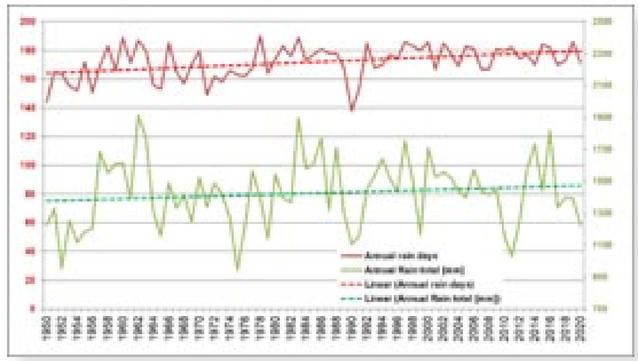
- The temperature of the upper ocean around Bermuda has been rising steadily over recent decades; also with robust evidence provided by the BIOS Bermuda Atlantic Time-series Study (BATS) and associated work.
- The trend in ocean warming near Bermuda has accelerated in the last decade.
- A recent examination of projections reveals that the ocean surrounding Bermuda is likely to warm on average 0.9-1.2°C (1.6-2.2°F) above the current average temperatures by the end of the century.
- Marine heatwaves have also become more prevalent and severe this century.



Observed ocean surface temperature and anomalies (°C) (left vertical axis; open blue symbols); anomalies and linear regression of anomalies (right vertical axis; orange symbols). Figure from (Bates & Johnson, 2020), their Fig.1 a, reproduced under Creative Commons Attribution 4.0 International License.

Executive Summary
Rainfall

- Rainfall is highly variable on an interannual basis, with seasonal peaks in summer through early autumn (shorter, heavier downbursts) and late winter, with lighter but more prolonged rainfall events than summer.

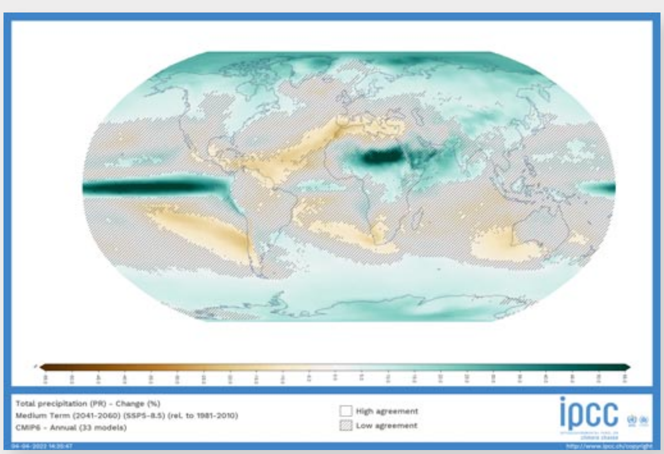


- Average Bermuda annual rainfall (1981-2010) is 58.66 inches or 1490 mm, gradually increasing over time on average.

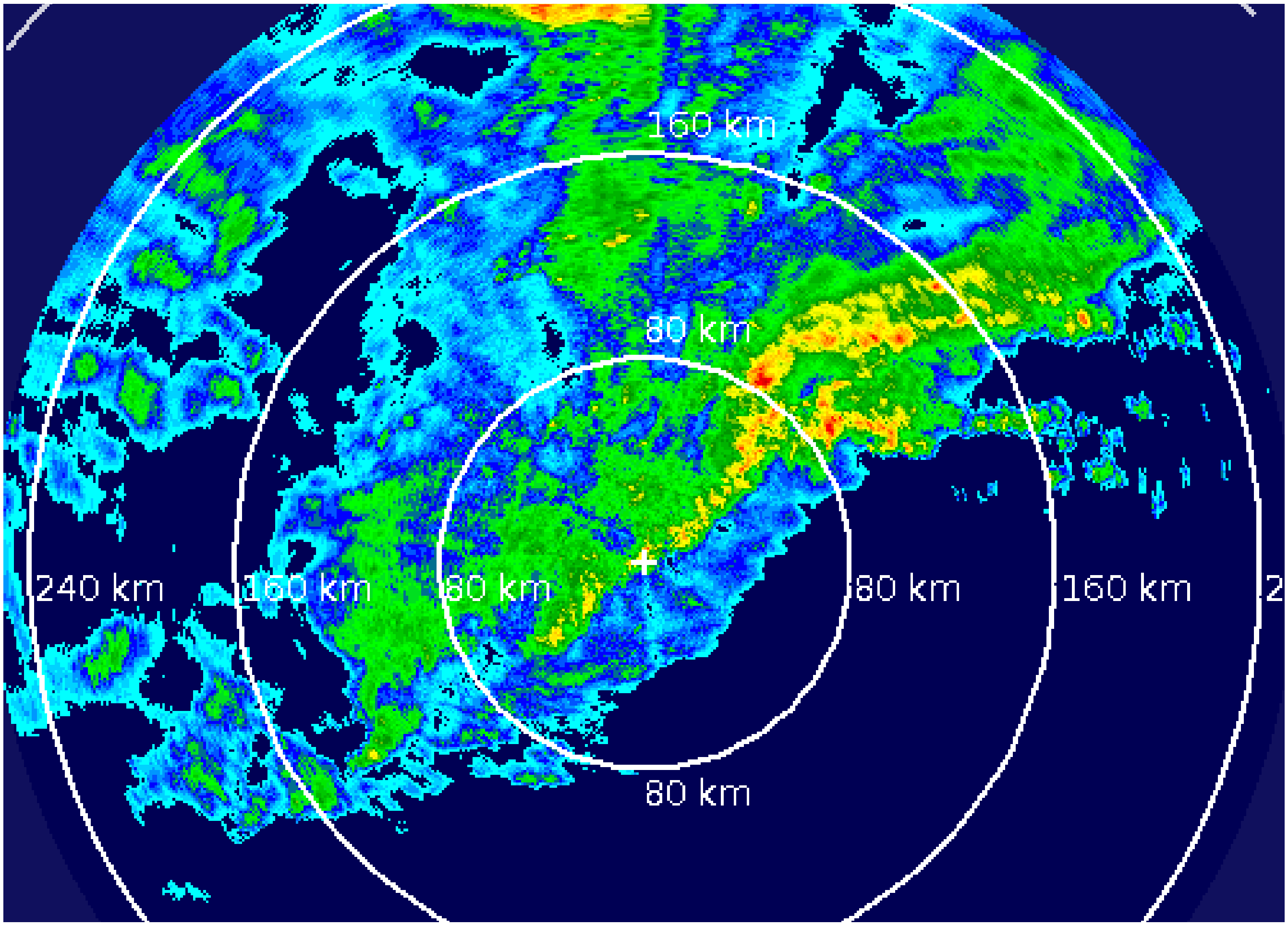
- Days on which it rains in Bermuda are also gradually increasing over time, but with high variability. On average, it would rain just over 160 days of the year back in the 1950s, whereas today (2020s), one would expect 180 days on which it would rain locally. However, there is low confidence in this finding.

- In winter, the North Atlantic Oscillation (medium confidence) likely influences the pattern and duration of weather systems regionally, and therefore has an effect on rainfall in Bermuda.

- Theory tells us that, over time, rainfall should get heavier as increased evaporation leads to a greater atmospheric water vapour abundance available for precipitation. This relationship has been documented to be 7% change in available water for precipitation for every 1°C of temperature change.



Source: The Royal Gazette



- A detectable (but low confidence) trend in measured local six-hour rainfall accumulations is in the right direction to be consistent with theory of greater rainfall variability. However, data are unavailable to robustly conclude this.
- Long term (multi-decadal) climate projections indicate a slight increase in rainfall over time in our region, but also an increase in evaporation.
- There is a low-confidence projection that the gradual rising trend of annual rainfall accumulation will continue.
- One would expect extreme rainfall events to gradually become more intense over time based primarily on theory vs. model-based climate projections which currently show little consensus.

Executive Summary
Hurricanes

- Global scientific consensus is for more intense tropical cyclones (tropical storms and hurricanes), but little change to overall frequency. Tropical cyclones are projected to move through the western North Atlantic with increasing frequency under climate warming, with one more major storm per decade in our region being projected by a few modelling studies. Moderate confidence exists for detected upward trends in frequency and intensity of Bermuda storms to continue.

- Warmer surface ocean waters and decreases in wind shear mean the conditions will continue to become more and more conducive to hurricane formation and intensification, with higher wind speed categories likely being attained through the decades to come. Ocean warming of >1°C since the 1980s supports storm intensities on the order of 15 knots greater today vs. then.

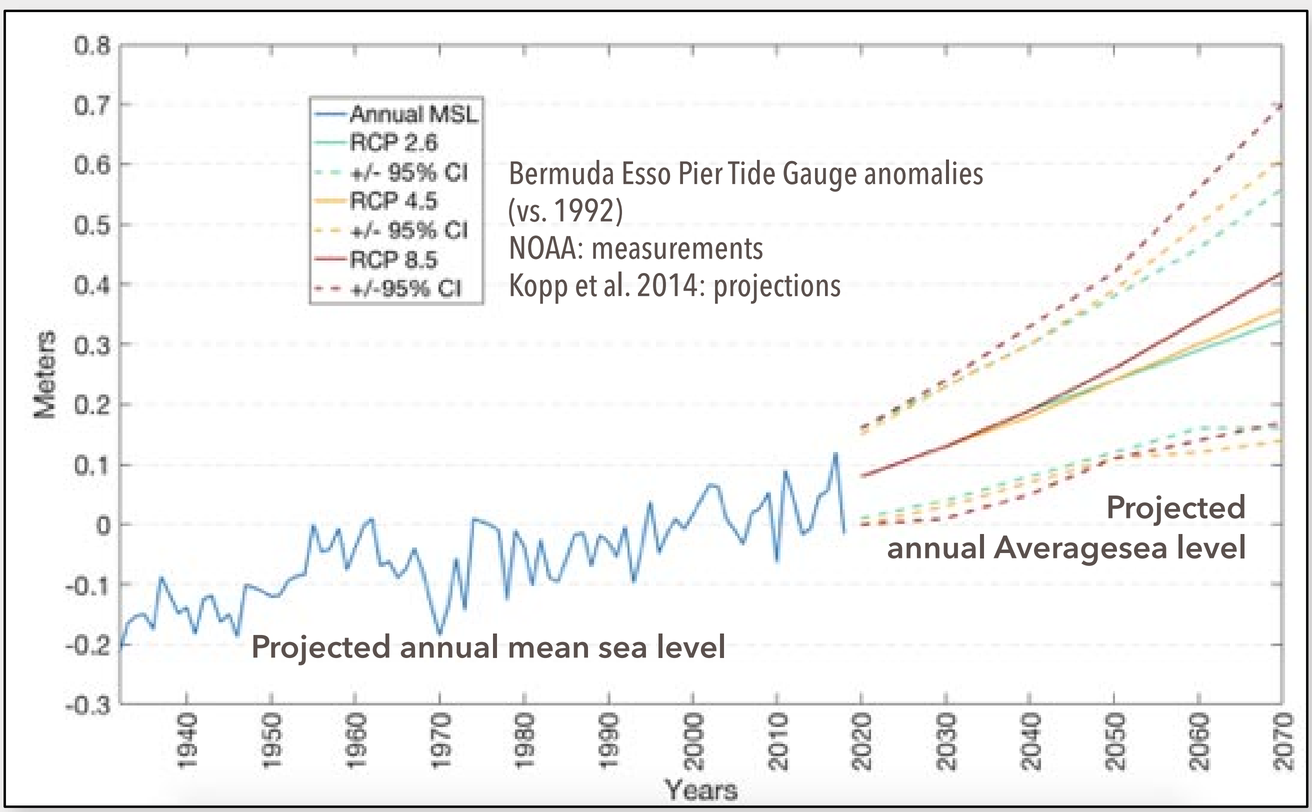
- Sea level rise will exacerbate storm surge and rainfall rates will also increase (high confidence). Storm surge events have increased from 0.4 m in the early 1990s to a peak of 0.8 m (Hurricane Nicole, 2016) exacerbated by sea level rise and increased frequency of storms nearby.

- Theory and modelling studies indicate that storm rain accumulations will also increase (high confidence). Hurricane Nicole is also distinguished by having the largest storm total rainfall of any Bermuda tropical cyclone – 172 mm on 13 October 2016 (Johnston et al., 2018), anecdotally supporting this conclusion for local events.

- Tropical cyclones' lifetime maximum intensities have moved closer to our latitude by 0.5° latitude per decade on average (detected – high confidence that this has occurred). Less certainty exists about whether this represents an ongoing future trend. In 2021, Hurricane Sam was the strongest storm on record to approach within 200 miles of Bermuda.

Executive Summary
Sea Level Trends and Extreme Events

- Global mean sea levels are increasing at an accelerated rate (high confidence). The local rate of increase is subject to regional variations in coastal geology, the speed of global glacial melt and the extent of ocean warming.
- There are high levels of uncertainty regarding the speed of glacial ice melt, which may increase the rate of sea level rise beyond the projections presented in this report.
- Mean sea level in Bermuda has been rising, as measured by monthly average sea levels at a tide gauge in St. George's from 1932 to 2018. This is the only extensive tide gauge record for Bermuda.
- Mean sea level in Bermuda is projected to continue to rise at an accelerating pace through the end of this century (high confidence).
- An examination of three decades of hourly tide gauge records reveal that extreme sea level events greater than 0.62 m above mean sea level occur in 2.5% of the observations. Those exceeding 0.79 m above mean sea level occur in 0.1% of the observations.
- Storm surge is treated as the departure from the predicted sea level. It does not account for tidal



phase or wave action. Local wave data are unavailable for analysis (there have been no long-term wave buoy deployments in Bermuda). We therefore focus on storm surge alone (sea level departure from predicted tide), as measured at the St. George's tide gauge.

- Hurricane Nicole (2016) represents the highest storm surge event in the hourly record from 1989 to 2018, at 0.86 m above the normal tide. However, its impact was minimized as it occurred at low tide. Note that this hourly dataset is for the same tide gauge location as the longer monthly record.

- Winter storms and oceanographic warm eddies also produce storm surge events in Bermuda. The maximum surge at high tide observed was 0.54 m above the normal tide, during a winter gale on 3 March 2018.

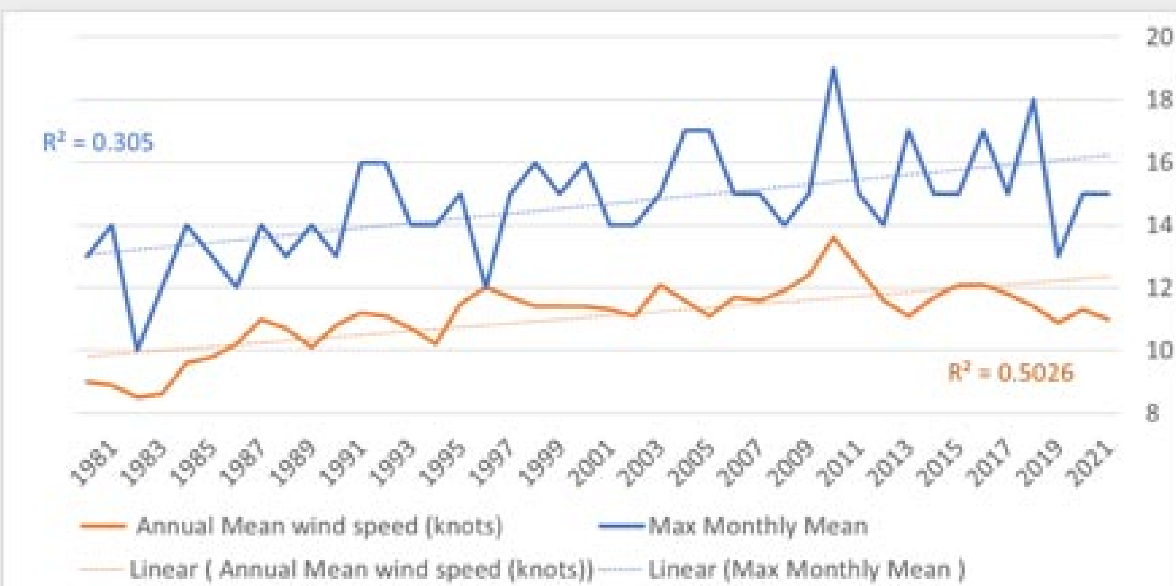
- Sea level anomalies due to oceanographic phenomena (vs. weather) can also raise the baseline sea level. Notable recent examples include coastal inundation due to warm eddies in the absence of adverse weather conditions in October 2017 and November 2019.

- Examination of surge events suggest an increasing trend in extreme sea level events in the hourly tide gauge record since 1989. However, this conclusion is not robust, due to data gaps from 2001 to 2003.

- Recent extreme high tides in the last decade, (such as those that flooded St. George's in October 2017) are projected to be within the normal high tide range within the next 2-3 decades.

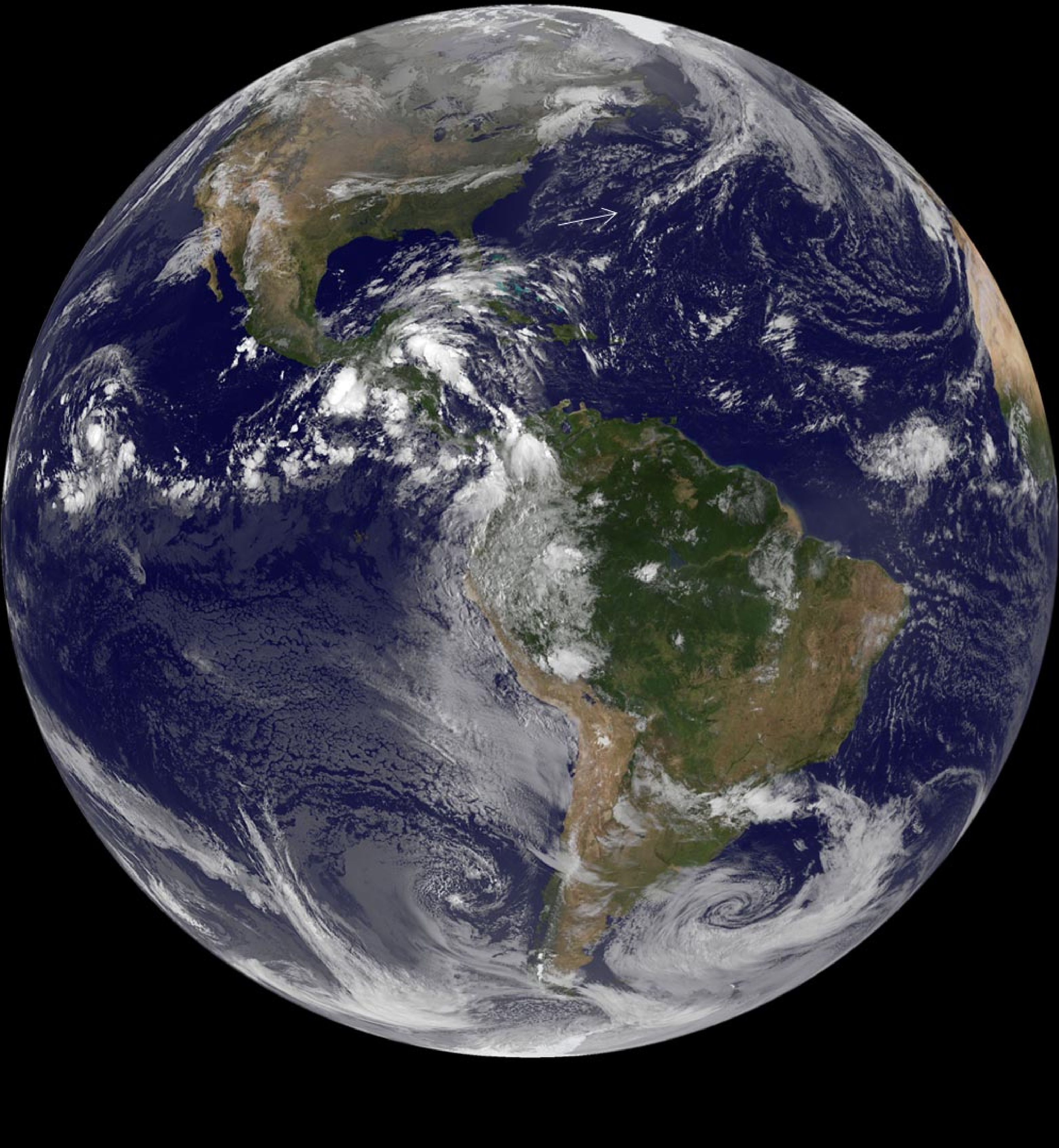
Executive Summary
Wind and Ocean Waves

- A robust upward trend of average wind speeds since the 1980s in Bermuda has been supported by independent local datasets and studies.
- This conclusion about local winds is at odds with the projected trend of future weak decreases in wind speeds in the wider North Atlantic (low confidence).
- Whether average wind speeds will continue to increase in Bermuda is unclear.
- Modelling studies indicate that the western North Atlantic may see a gradual increase in the intensity of extratropical (winter) gales, with their low pressure centres shifting slightly off the east coast of North America. This may increase the frequency or intensity of Bermuda's winter gales (low confidence).
- Maximums in local winds and gusts are likely to increase due to winter gales (low confidence) and more intense hurricanes regionally (medium confidence – see separate chapter).
- The few model studies of ocean waves consistently conclude a decrease in average significant wave height in the North Atlantic. This is a low confidence result, due to relatively few studies and the absence of robust projections of changes in average wind speeds.



Average monthly wind speeds and maximum of monthly averages (both in knots), based on measurements at LF Wade International Airport 1980-2021. Data from Bermuda Weather Service, Bermuda Airport Authority. Linear trends and R2 values also shown.

Introduction



Foreword

Climate change is readily identified in most sectors of society as being one of the existential threats to humanity, as well as vital global ecosystems supporting plant and animal species. The risks that we face from the warming of the planet cut across societal activities, and affect all sectors of the local economy. Hence, the effort to understand climate change and its impacts is necessarily apolitical, and not isolated to one stream of economic, social or governmental activity.

This report is the culmination of years of research and observations made locally, regionally and globally about the state of the climate, some academic, some anecdotal. The report is intended to be both evidence-based and multidisciplinary. Most of the scientific and societal insights in this report come from academic studies, many of them published in peer-reviewed literature. However, in some instances, the conclusions reached are made by using and displaying available data and surveys that are as yet unpublished. It is not the aim of this document to reproduce wholesale the excellent report produced by Dr. Anne Glasspool (Glasspool et al., 2008). Rather, it will focus on elements for which there are updates in our collective understanding.

Introduction

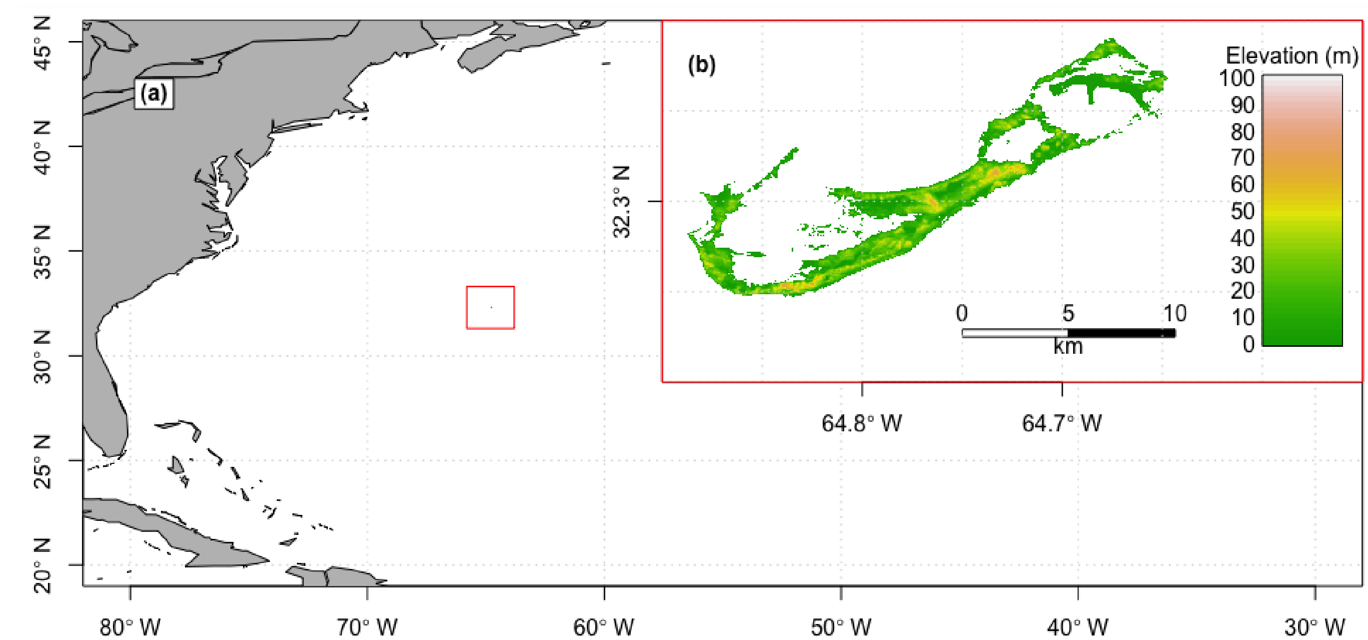
This introductory chapter will refresh and refamiliarize readers with some essential concepts that will provide context for the rest of this report. However, it will not aim to revisit the vast volumes of climate change educational material that already exist.

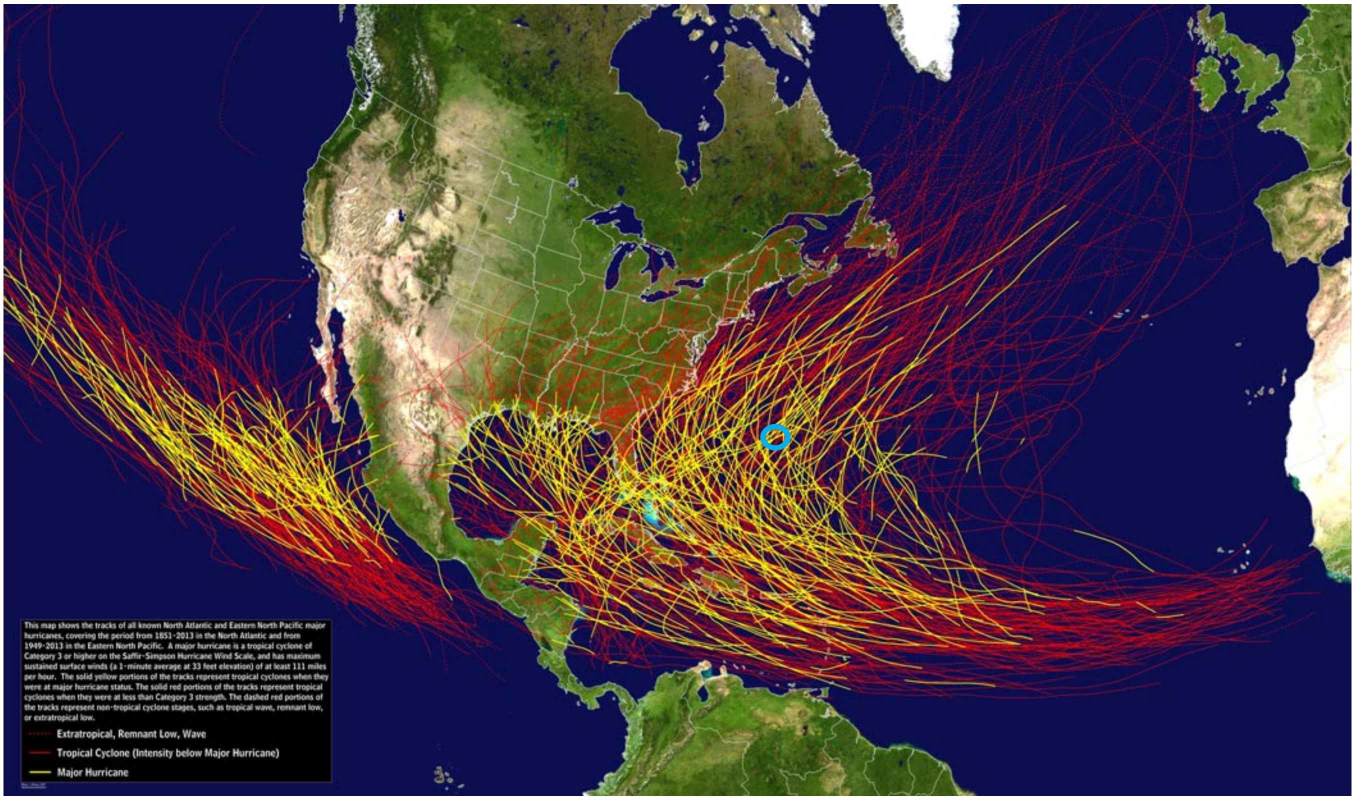
Background state of the climate

Bermuda is a small archipelago about 21 sq. miles / 54 sq. km in area, in the western North Atlantic Ocean. Its position, centred at approximately 32.30°N 64.75°W places it not quite in the tropics, but also not quite in the mid-latitudes – in other words, the 'subtropics'. In addition, it is in the western periphery of the Sargasso Sea, characterized by relatively warm water regionally, brought north by the Gulf Stream, a strong current of warm water moving out of the tropical Gulf of Mexico, past Florida to the open waters of the North Atlantic south of the Grand Banks off the Canadian Maritimes.

The warm ocean currents and the subtropical high pressure serve to produce a climate that is with a mild range of temperatures, from average monthly lows in the mid-teens Celsius in winter to the high 20s in summer (60s to 80s Fahrenheit). The moderating effect of the ocean, providing a consistent source of warmth means that the air temperature at the surface never gets cold enough to sustain snow, even though our continental neighbours in the US at similar latitudes can receive large snow accumulations in the winter.

Position and elevation of Bermuda (Johnston et al., 2018)





Tracks of major hurricanes (category 3 or greater) in the North Atlantic and East Pacific (US National Hurricane Center, NOAA). Bermuda is highlighted in the blue circle on the map.

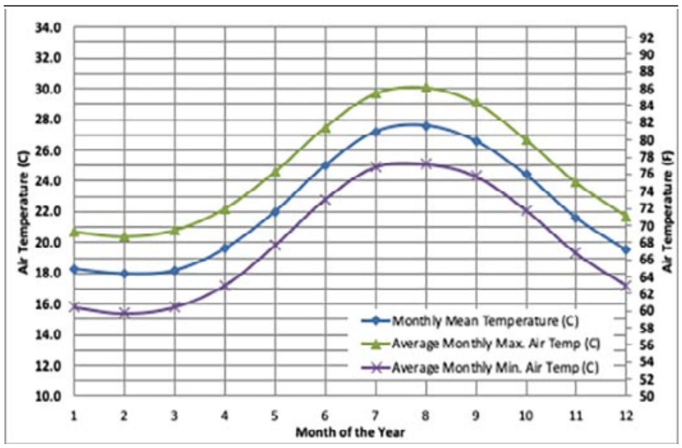
Bermuda experiences mid-latitude weather in winter (cool, breezy and frequently cloudy and wet), with frequent cold fronts moving from west to east through the area. Some of these weather systems can produce gales and even storm-force winds from time to time, most of which are short-lived. Bermuda's seasonal climate is more tropical in the summer, characterized by strong high pressure, lighter, mainly southerly, winds and bright sunshine punctuated by occasional heavy, short-lived showers.

Later in the summer and into autumn, when the hurricane season is most active, the island can suffer the impacts from tropical cyclones (tropical storms and hurricanes) tracking through the local area from the south. Bermuda, despite being a small 'target', has a long history of experience with hurricanes; its geology, strong building code and a tested hurricane response mean that the island is usually operational within a day or two, even after a major hurricane impact. A notable exception to this has been Hurricane Fabian, which dragged hurricane force winds across the island for several hours in September 2003. The intense winds and a major storm surge caused widespread damage and the tragic loss of four lives. Those are the only direct fatalities in Bermuda from a hurricane in living memory. In general, Bermuda is well-practiced at its hurricane preparedness, and is frequently reminded by the Government of Bermuda (and mother nature!) not to be complacent. As a later chapter will explore, Bermuda has been fortunate to be spared the worst effects of a hurricane in recent years.

The generally mild conditions are the main attraction of Bermuda to visitors in the winter months, and have traditionally been a great source of tourist revenue for Bermuda' economy, especially from colder climes in the nearby, easily accessible US. The stunning beaches, coastal and near-shore environment that the climate and local marine geology support are also major tourist attractions. The value of the coral reef alone has been estimated to be on the order of US$1 billion per year to Bermuda's economy (Sarkis et al., 2013). The role the climate plays in this economic contribution is yet unquantified, but is clearly a significant factor.

Introduction
Greenhouse gases

The atmosphere is a thin layer of gases surrounding Earth. Some of these gases trap heat, providing a protective blanket that shields us from the coldest conditions. Without these 'greenhouse gases', the average global temperature would be too cold to sustain life on Earth. There are numerous greenhouse gases including carbon dioxide (CO_2, the most abundant), methane (more effective at trapping heat, but far less abundant than carbon dioxide), and many others that are less impactful or abundant in the atmosphere. Note that these are gases that result from naturally occurring processes, such as respiration and outgassing. Even water vapour, a natural part of the water cycle resulting from evaporation, has a contribution to the greenhouse effect. There are also natural processes that absorb greenhouse gases, such as photosynthesis, in which plants take in CO_2, and produce oxygen. The ocean also absorbs about 25% of the CO_2 emitted.



Average monthly temperatures in Bermuda, 1981-2010. Source: Bermuda Weather Service.

Of course, greenhouse gases also occur from human-mediated processes, including the combustion of petroleum products, such as oil, coal, natural gas, and gasoline. These are fuels derived from large deposits of decomposed organic matter locked in the ground (hence the term 'fossil fuels'). They are extracted from the geologic structures that house them deep within the rock, refined, and used to produce energy. That energy, in turn, has become the basis for providing electricity, industry (mainly manufacturing and construction), and transportation to Earth's growing population, and the associated development of economic activity. The gaseous by-products of burning extracted fossil fuels include huge volumes of CO_2 and other greenhouse gases.

There are complex feedbacks resulting from human activity, such as:

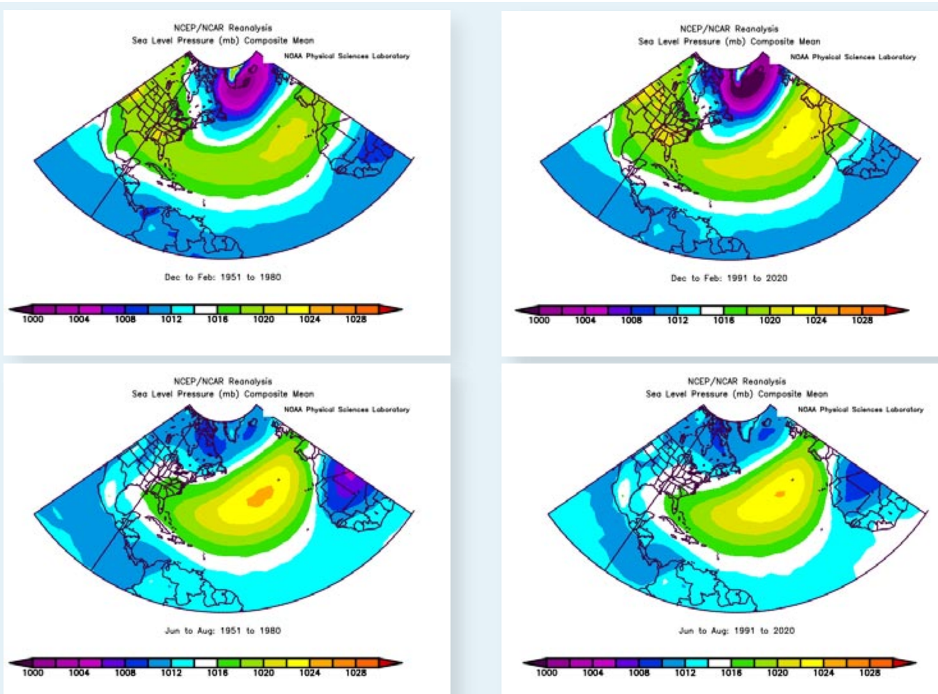
- Increased melting of tundra ice in polar regions which releases methane. The melting is accelerating as a result of climate warming, which itself is a result of greater greenhouse gas emissions.
- The burning of wood not only produces CO_2, but also removes a carbon sink, as wood absorbs carbon dioxide through photosynthesis and also acts as carbon storage.
- Decomposition of landfilled waste also produces methane. When burned, methane produces CO_2.

Introduction
Climate change

The most prevalent impact we note as a result of emitting more greenhouse gases into the atmosphere through combustion of fossil fuels, deforestation and other human activities, is the gradual warming of the atmosphere. The more greenhouse gas emissions we create, the warmer the global average surface temperature – thus the term Global Warming. This is a certainty, verified by decades of observations of the earth system by scientists in a wide variety of disciplines.

Climate change has a number of effects with a wide range of complexity. Sea level rise is perhaps one of the easiest to understand: Earth warms, land ice melts and flows into the ocean, more water ends up in the ocean, and water levels rise. Even within this simple explanation there are other factors. Hot water takes up more volume than cold water due to thermal expansion, so the warmer the ocean is, the more space it takes up, exacerbating sea level rise from land ice melt. Also, less sea ice means a less reflective planetary surface, allowing more heat absorption by areas of the ocean that would normally be reflecting more of the sun's radiation. This results in enhanced ocean warming. In addition, the rate of glacial melt at the coasts is accelerating due to undercut of glaciers by warmer and warmer waters, causing a higher rate of glaciers 'calving' into the sea, and ice sheets breaking away from the land to become part of the ocean ice.

The conditions that supports Bermuda's economy, attracting visitors to the island and contributing a



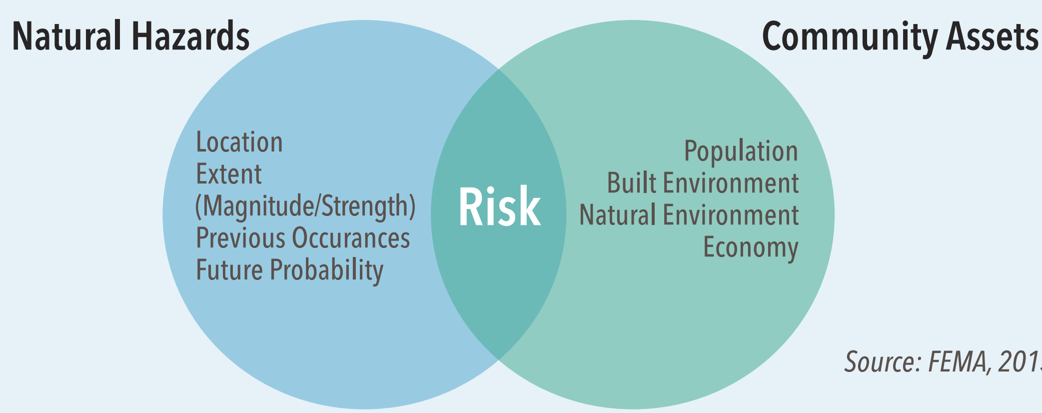
North Atlantic mean sea level pressure for (Top panels) winter months (December-February) and (Bottom panels) summer months (June-August) compared between (left panels) the averages for all the years 1951-1980 and (Right panels) the averages for the period 1991-2020 (data: NCEP/NCAR Reanalysis (Kalnay et al., 1996).

priceless value to our cultural identity, is demonstrably changing as a result of these effects on the global climate. The following panels show changes in 30-year average surface pressure patterns in the North Atlantic for the winter and summer months between the current climate average (1991-2020) and a past climate (1951-1980). The shifts in average pressure may signal less subtle changes in shorter periods in some of the factors that constrain important aspects of our local climate. Changes in the Bermuda-Azores subtropical high surface pressure pattern are evident over time. This is the surface pressure regime that weakens in the winter to allow cold fronts through the area, and steers hurricanes in the summer through autumn.

One of the most complex impacts of climate change are the changes in extreme weather events. Weather events have always been a fact of life, but the changes in the behaviour of the most impactful conditions are increasingly linked to the background changes in the climate. If we think of climate as the backdrop for weather, then it is clear that as the background conditions change, the extreme events linked to those conditions should also change. Near Bermuda, for example, the changes in hurricane activity over the last two decades have been remarkable, and documented. One does not need to be a climate scientist, oceanographer or meteorologist to note that, with a detected trend in warmer surface ocean waters, the likelihood of stronger hurricanes becomes greater over time. This is what we're seeing near Bermuda.

Introduction
Risk and Impacts

Much of the above focuses on the physical science of what is going on and why it's happening, but it doesn't speak to the effects these changes will have on modern society. As with our scientific understanding, some of the socioeconomic impacts are obvious already. Sea level rise will produce more frequent property and infrastructure exposure to seawater inundation. Major hurricane activity will continue to create more frequent impacts from wind, storm surge and rainfall. But, again, as with the science, there are more complex and subtle interactions that make the consequences and opportunities less clear. For example, a warmer atmosphere means more



Source: FEMA, 2013

evaporation, providing more atmospheric water vapour for rainfall. The balance of evaporation and precipitation is unclear for us in Bermuda, where we have few freestanding bodies of water. In addition, sea level rise will cause more saltwater intrusion into the fresh groundwater lenses (the water table). The net impact on local water supply is therefore more complex than it might appear at first glance.

This report (particularly *Part II*) employs a risk-based approach to assessing the impacts of climate change. Risk has been described as the adverse impact of a hazard. Mathematically, it may be thought of as probability of an event multiplied by the probability of a consequence (*Titley, personal communication*). The United Nations (UN) office for Disaster Risk Reduction often states in their public materials that "There's no such thing as a natural disaster". In order for a disaster to occur, human elements must be present; for example, a hurricane over the ocean, distant from land, does not constitute a disaster.

Quantifying risk can be a tricky proposition, but lessons can be learned not only from the disaster management community, but also the insurance and risk management industry. The field of catastrophe modelling can inform an approach to examining climate risk and impacts. Apart from the natural hazard aspects, the assessment of the risk of a particular disaster or catastrophe (as climate change is frequently referred to) must incorporate elements of exposure and vulnerability assessments.

Catastrophe Model Framework
Adapted from Diaz and Murnane (2008)

Introduction
The Report

All of the above aspects will be explored in this report, with a view to making the scientific understanding of what is happening, and the impacts resulting from climate change, accessible to the readers. The report is structured in two parts:

Part I - Science and Physical Hazards will deal with the physical science of climate change and realities of what is already being monitored in Bermuda, plus projection of changes to come. This section will leverage the most recent scientific studies and data, synthesizing the current body of knowledge on how Bermuda's climate is changing.

Part II – Societal Risk will explore effects of climate change on Bermuda with respect to different parts of society, focusing on exposure and vulnerabilities where possible. The impacts of climate change on society will shape any decisions we make on how to act in response to climate change. This section of the report is necessarily more focused on the people, activities and environment (built and natural) facing the changes that are already happening, as well as the changes to come.

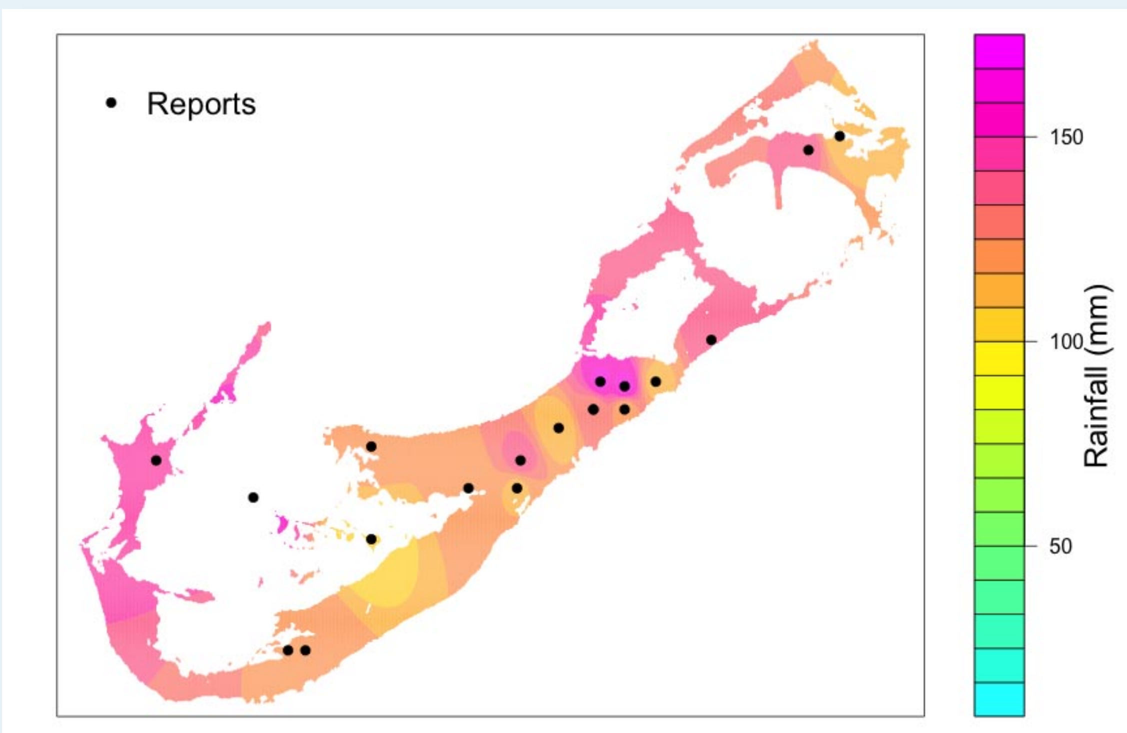
Importantly, this report also provides assessments of what we do not yet know. It is clear that much more research and investigation must be done to reveal all the facets of how climate change will impact our island home.

Introduction
Caveats | limitations and uncertainties

This report is not intended to fully explore every single aspect of Bermuda's climate change; for example, mitigation of greenhouse gas emissions and the policy actions that could/should be taken are not included. This document is intended as reference material for policymakers and individuals wanting to understand more about the hazards, exposures, and vulnerabilities in Bermuda associated with climate change.

Uncertainty is a necessary aspect of this report and some of the aspects of data collection in Bermuda are highlighted here. In some cases, measurements have not been fit for the purpose of climate scale analyses. Due to a large variability of physical parameters across the island, such as rainfall (see figure below), temperature and humidity, some of the instrument sites may not be representative of the island as a whole. In Bermuda, there may only be one measurement location for a climate parameter, so verification and validation processes are not available for many cases.

Trusted references and organizational documentation and datasets used include those presented by the Intergovernmental Panel on Climate Change (IPCC); Bermuda Institute of Ocean Sciences (BIOS); international non-governmental organizations and governmental organizations (e.g., US NOAA, NASA, the UK Meteorological Office,



Rainfall accumulations over 24 hours from different private and public sites around the island – adapted from Johnston et al. (2018). Note the high variability of rainfall amounts in different parishes.

EU Copernicus Climate Service, Caribbean Meteorological Organization, World Meteorological Organization, UN office for Disaster Risk Reduction, and the UN Framework on Climate Change, to name a few); Bermuda Weather Service (BWS) and Bermuda Airport Authority; and local government agencies. Where possible, we have referenced peer-reviewed publication material. It is not the intent of this report to question methods and uncertainties already documented elsewhere by these organizations and their documentation. In some cases, we specifically mention uncertainty in the methodologies of reference studies.

There is uncertainty built into the projections of future trends and variability because model simulations and studies are the only source from which we can draw information. The further in the future one projects, the greater the uncertainty. We have chosen to make conclusions based on projections to the end of this century, versus hundreds of years. We note that the IPCC is very much a consensus report of academic studies on the state of the science, and not necessarily what will definitely happen in the future. Scenarios are the basis for many projections used by the IPCC (e.g., Representative Concentration Pathways in IPCC, 2013 or Shared Socioeconomic Pathways in IPCC, 2021).

Many academic studies draw from climate models, but do not have a specific focus on Bermuda, and there are often broader projections; for example, the IPCC focuses on the North Atlantic Ocean as a reference region. Bermuda is, of course, in the North Atlantic Ocean, but we are not representative of the average conditions across the entire basin, from the tropics all the way up to the Arctic. So how Bermuda fares in the background of that broader context may introduce uncertainty. There are also trends in local datasets that may not be statistically significant (large variability) but are nonetheless detectable and noticeable. The projections are as confident as one can make them.

Introduction
Timescales

The interplay between changes in the background norms and the extreme events which sit atop them can often cause confusion. It is important to consider timescales of action.

Firstly, climate change is not a distant impact that we will suddenly feel in decades. It is already occurring, and the impacts are already being felt locally. The effects of climate change are getting more impactful, and will continue to accelerate in our lifetimes, and those of the next few generations, at least. The slow-moving changes will continue to set the backdrop for extreme events, which themselves are also changing. For example, the sea level will continue to rise slowly, so that the normal high tide in 30 years' time may be as much as half a metre above what it is today. More frequent occurrences of the most intense storm activity may also potentially add another meter on top of that.

This report will generally focus on timescales of 20-80 years to bring attention to trends that may become apparent within a lifetime, as well as associated impacts that are likely to affect large portions of the population. In addition, it is hoped that the conclusions and discussions in Part II of the report (on societal risk from climate change) will be relevant for design and infrastructure planning criteria.

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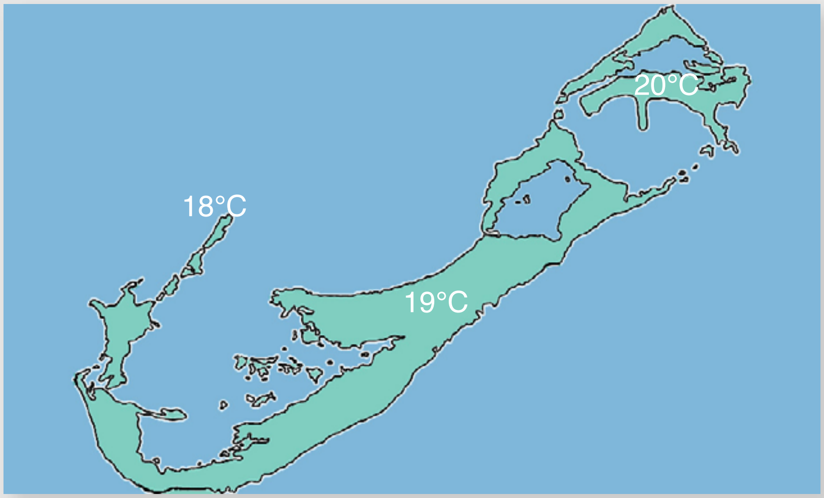
Temperature

Temperature
Surface Air Temperature and Humidity

Bermuda-based Record

The records of surface air temperature in Bermuda are not smooth or simple to analyze without some rigorous processing. The reason for this is that official records have been taken in multiple locations through the decades, and those locations have their own unique small-scale effects. In fact, one could say they have their own climate. To illustrate this, we examine how temperatures on a given day and time can vary dependent upon location. In the map below derived from a network of automatic weather stations, we see temperature on this particular day and time varying from 20°C near the airport on the East End of the island, to 18°C in Dockyard on the west end. The elevation, exposure to the wind and direct sunlight, and surface over which each thermometer sits all have an influence on the temperature. None of those factors are accounted for in this plot (nor should that be the intent), but one can see how using these basic readings for climate-scale purposes would be inappropriate without accounting for those factors.

In addition, it should be recognized that thermometers are placed in given locations to support the activities near the monitoring station, and are subject to the micro-scale effects experienced at each site. For example, temperature records taken on Kindley Air Force Base (and, subsequently, the US Naval Air Station Kindley Field) were conducted in support of aviation—take-offs and landings of military aircraft—and not intended to establish the basis for a long-term climate record. Likewise, measurements taken at the Botanical Gardens were intended to support the environment for horticulture at that site. When the Bermuda Weather Service (BWS) was formed in 1995, taking over from the US Navy, its measurements mirrored those of the Navy for a number of years, as the meteorology in support of civil aviation was being implemented for the first time in Bermuda. In 2000, BWS moved to a new location above the airfield. This included a 'meteorological instrument garden' in a better



Schematic of Maximum Temperatures on 29 January 2013, measured at Automated Weather Observing System sites: Commissioner's House, Fort Prospect, and St. David's (Data courtesy of Bermuda Weather Service)

site for the purposes of establishing a more robust climate record to go hand in hand with the measurements supporting safe aviation and air navigation. Here, the thermometers were less exposed to the temperature fluctuations that can result from jet engine exhaust, heating and cooling of the tarmac surface of the nearby runway and taxiways, and changes in wind direction (the airfield, being close to sea level, is exposed to temperatures more moderated by the ocean surface when winds are from the south, blowing across Castle Harbour).

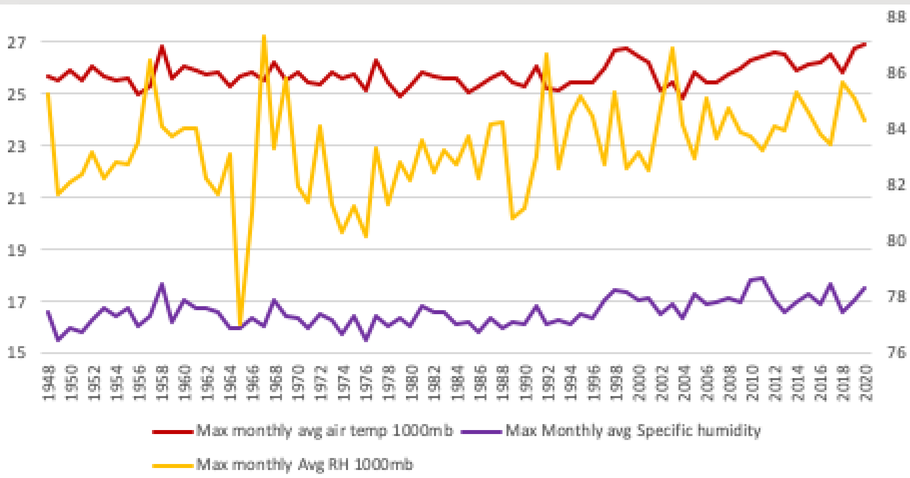
The elevation and exposure of the thermometers changed in that 2000 move 'up the hill' to the current location of the official record, which is now near the Air Traffic Control Tower. The technology itself has also changed through the years, as thermometers have evolved from mercury to alcohol to digital sensors.

All of this demonstrates how a temperature record for Bermuda, which we may have thought was a straightforward climate metric, is not as simple to reconstruct for climate-scale multi-decadal analysis.

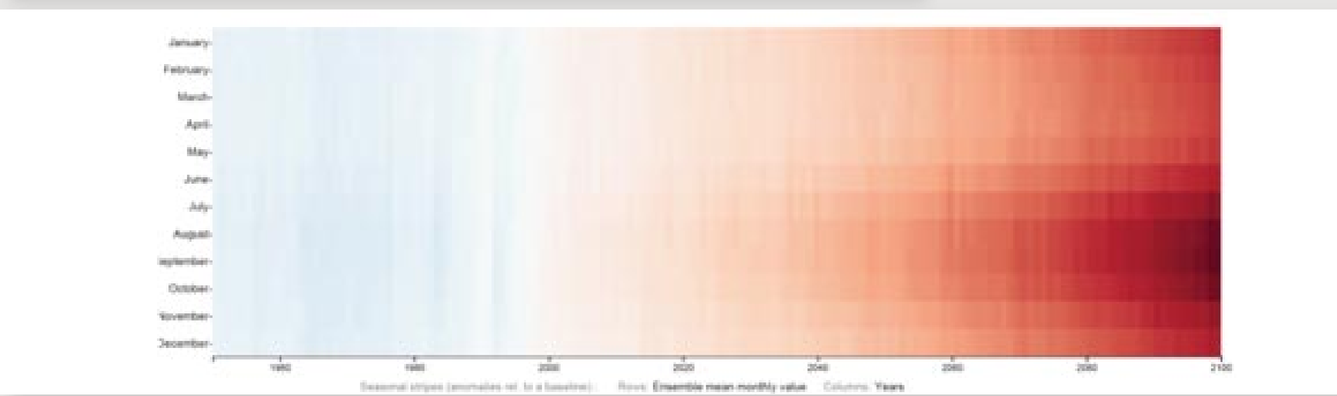
Fortunately, meteorological and climate research activities have resulted in the production of 'reanalysis datasets' (Kalnay et al., 1996). An atmospheric reanalysis is a standardized model representation of the climate, that incorporates 'ground truth' data, such as weather balloon measurements, surface observations, and automated instrument outputs. Reanalyses account for the vagaries of instrument siting, geographical variations and technological changes, providing a climate-scale dataset that is less sensitive to changes in the historical record that are not due to the atmosphere itself. The reanalysis datasets are carefully curated by different modelling centres around the world, who assimilate and sense-check ground truth data in the context of the background atmosphere. In this review of the climate scale temperature records in Bermuda, we can use reanalyses to discover any trends and variability in surface temperature.

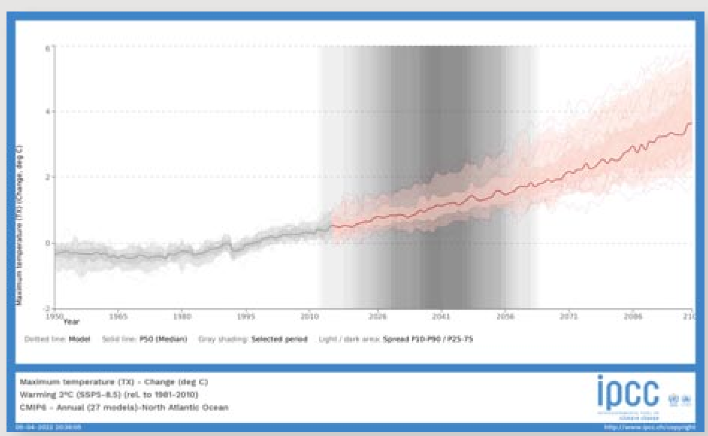
Temperature
Air Temperature and Humidity Trends

Noting the caveats above, the data from the National Centers for Environmental Predication (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis (Kalnay et al., 1996) indicate an upward trend in temperature and humidity (relative and specific) through the last few decades.



The maximum of monthly average temperature (°C, red, left axis), specific humidity (g/kg, orange, left axis), and relative humidity (%, purple, right axis) for Bermuda. Data source: NCEP/NCAR Reanalysis, Time Series produced at NOAA Physical Sciences Laboratory https://psl.noaa.gov/data/timeseries/, grid point 32.5N, 65.0W (Kalnay et al., 1996). All parameters are for the model level closest to the surface in the reanalysis.





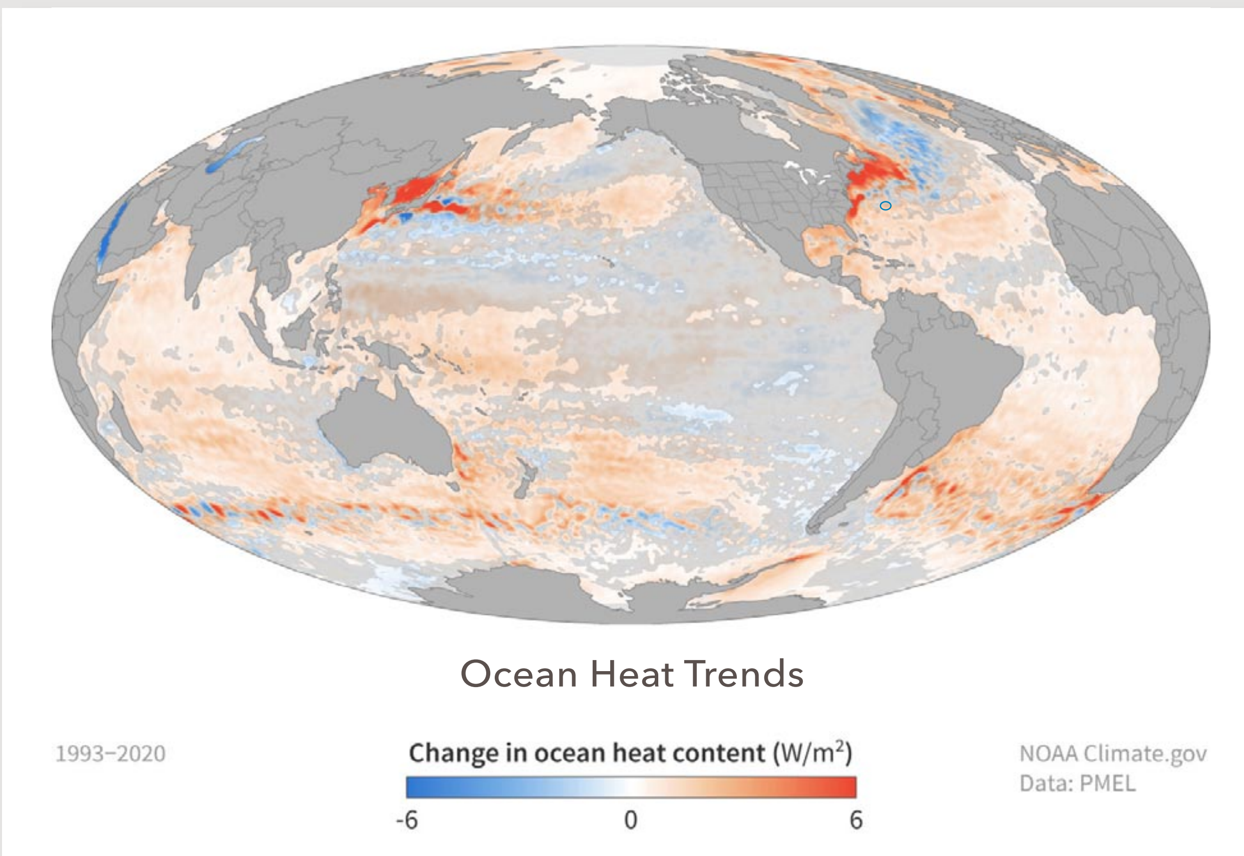
Top: seasonal changes of surface temperature in the North Atlantic Ocean region. Bottom: Annual maximum temperature change (°C) relative to 1981-2010 normal, in the North Atlantic Ocean region. Data from CMIP6 SSP5-8.5 scenario - (based on the mean of 27 models). Source: Gutiérrez et al. (in press), http://interactive-atlas.ipcc.ch/ Note, these are averages for the North Atlantic Ocean region as a whole, not specific to Bermuda.

Temperature
Upper ocean temperature

When one considers global warming, the ocean cannot be ignored. The same is true of regional trends, which are even more important to local climatic conditions for small islands. The ocean is both a sink and a source of atmospheric heat, and is estimated to have absorbed over 93% of the excess heat that anthropogenic global warming has produced (Laffoley & Baxter, 2016).

Trends in ocean warming are apparent worldwide, with notable maximums in heating near the western mid-latitudes.

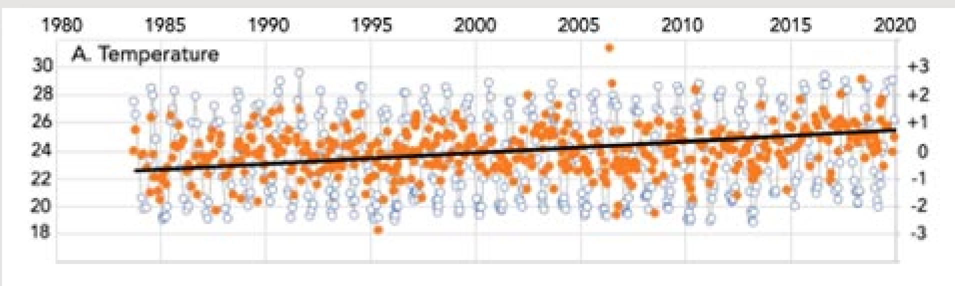
In Bermuda, the moderating effect of the surrounding ocean enables a mild climate relative to islands in the Caribbean, despite our subtropical latitude. It also helps us to avoid cold outbreaks of snowy weather that our neighbours in North America often experience, even at latitudes similar to ours and further south.



Temperature
Multidecadal trends in ocean temperatures near Bermuda

Many studies have been published through the decades on ocean temperature, based on the Bermuda Atlantic Time-series Study (BATS) and Hydrostation 'S' time-series (Bates, 2007; Bates et al., 2012, 2014; Stevens et al., 2016). Recent publications (Bates & Johnson, 2020; Hallam et al., 2021) show very clearly the accelerating trend of upper ocean temperature near Bermuda. There are some periods of cooling and warming that offset one another, resulting in an overall warming trend of approximately 0.85°C of the surface waters from the 1980s through 2019 (the period of the study). This trend has been dominated by a 1.18°C increase in surface temperature through the 2010s.

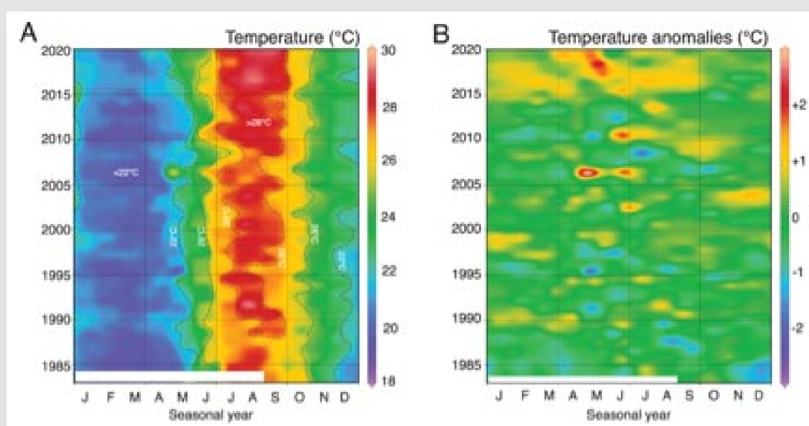
It is particularly striking to note that between 2015 and 2019, the surface temperature throughout the period from July to September remained close to or above 28°C (82°F) each year.



Observed data (left vertical axis; open blue symbols) and anomalies (right vertical axis; orange symbols) are shown. Regression lines are from anomaly data plotted in the right vertical axis. a Surface temperature and anomalies (°C).

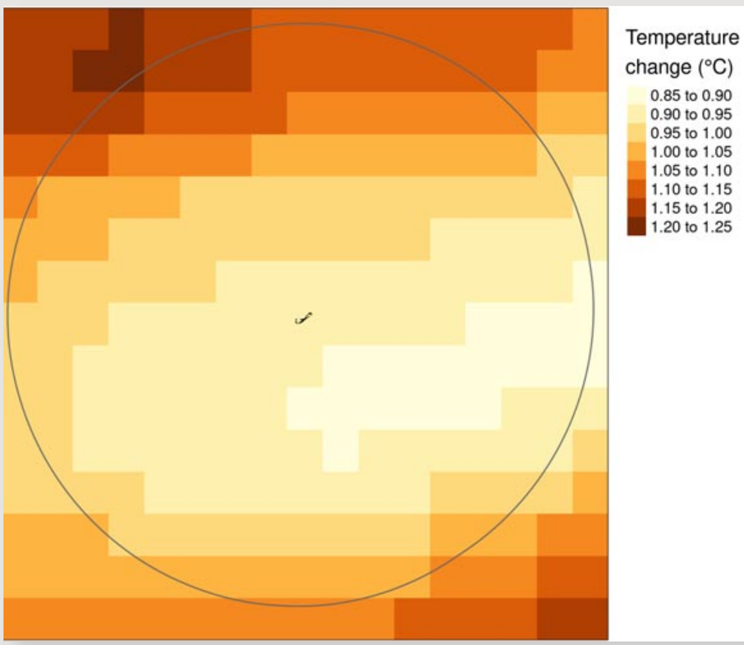
Physical properties at BATS (1988–present) with earlier data (1983–1988) from Hydrostation 'S'. A: Surface temperature (°C). B Surface temperature anomalies (°C).

Figures from (Bates & Johnson, 2020), their Fig.1 a, and Fig.3 a & b, reproduced under Creative Commons Attribution 4.0 International License



Temperature
Projected upper ocean warming

A recent examination of the IPCC projections of upper ocean temperatures by Flower (2022) indicates that the upper ocean (surface to 200m / 656ft depth) will experience warming of approximately 0.9-1.2°C (1.6-2.2°F) across Bermuda's Exclusive Economic Zone. The projection uses IPCC Shared Socioeconomic Pathways (SSPs) 2-4.5 (IPCC, 2021), representing intermediate greenhouse gas emissions and an estimated 2.1 - 3.5 ∘C of warming by 2100. Higher emission scenarios will result in greater projected warming.



Map of temperature change 2025 - 2095. This is the mean of the annual epipelagic temperature data for 2091-2100 minus the mean of the annual data for 2021 - 2030 (see following figure for those individual maps). Circle shows the boundary of Bermuda's Exclusive Economic Zone, and the land mass is shown in black in the middle. Graphic courtesy of Jason Flower, UCSB, 2022, using data from Brito-Morales et al. (2022)

Temperature
Marine heat waves

In addition to the steady background warming of the oceans, near-surface waters can be affected by marine heatwaves (Hobday et al., 2016). These extreme events can be tracked and monitored in a similar manner to atmospheric heatwaves.

Marine heatwaves are described using the following schematic from Hobday et al.(2016).

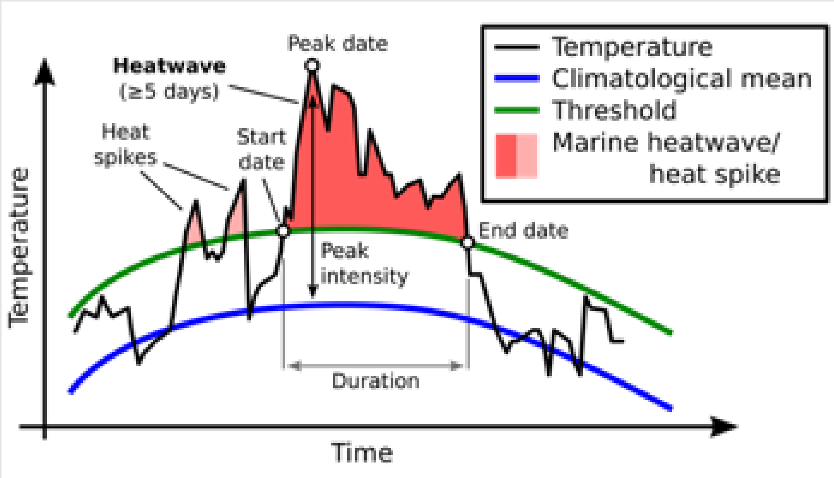
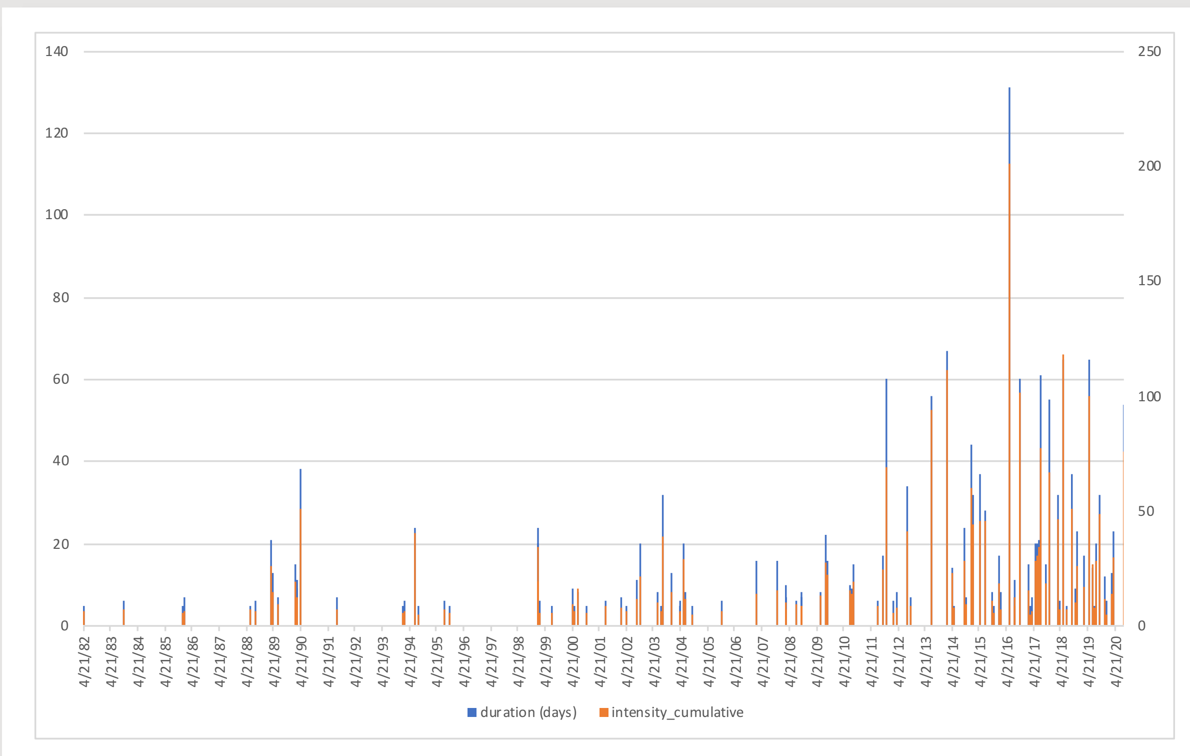


Figure 1. a) A marine heatwave is defined as when seawater temperatures exceed a seasonally-varying threshold (usually the 90th percentile) for at least five consecutive days. Successive heatwaves with gaps of two days or less are considered part of the same event. Source: www.marineheatwaves.org/all-about-mhws.html .



Preliminary Bermuda data for marine heat waves were downloaded from www.marineheatwaves.org/tracker.html , and plotted above. Marine heat wave data are calculated by applying the (Hobday et al., 2016) method to gridded sea surface temperature data (Reynolds & Smith, 1994).

Temperature
Discussion

It is useful to consider these phenomena as additive. To understand this, parallels may be drawn with other phenomena (e.g., sea level rise and storm surge lead to greater impact when occurring together). The implications of the combined effects of ocean warming and marine heat waves will be further explored in other chapters and *Part II* of this report. However, here we will highlight some implications of the background warming and extreme events in the ocean.

Hurricane activity has long been understood to be linked to sea surface temperatures (Elsner et al., 2013; Emanuel, 1986; Gray, 1968; Knutson et al., 2010; Vecchi et al., 2021). Recently, increases in the prevalence of tropical cyclones near Bermuda have been examined in the context of the warming upper ocean in the region (Hallam et al., 2021).

In addition, the impact of ocean warming and marine heatwaves together on coral reef communities has long been documented, and there is much reason for concern. Corals can survive in distinct temperature regimes that may be exceeded by the background ocean conditions under climate warming. This, in turn can lead to widespread loss of coral reefs (Dixon et al., 2022). However, locally there may be room for optimism, as studies indicate the deep and cooler waters around the Bermuda Platform may provide a refuge for corals that are otherwise stressed by warming temperatures (Goodbody-Gringley et al., 2021). The complex interactions of the reef environment with fisheries, and the downstream impacts on economic and societal well-being will also be discussed in *Part II*.

Regardless of the outcomes, addressing the impacts of a warming ocean has been described as potentially “the greatest hidden challenge of our generation”(Laffoley & Baxter, 2016).

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Rainfall

Rainfall
Introduction

In Bermuda, each property owner is responsible for their own water supply, as enshrined in law under the Public Health (Water Storage) Regulations 1951 (Government of Bermuda, 1951) and rigorously enforced at the planning and construction phase of any new buildings.

Given that Bermuda has no major sources of open fresh water, the vast majority of locally-sourced drinking water in Bermuda comes directly from rainwater harvesting. Rowe (2011) provides an excellent overview of this process. This provides motivation for understanding the current and future state of rainfall accumulations in Bermuda. Recent studies of rainfall by Johnston et al. (2018) and Peñate De La Rosa (2015) reveal trends and variability of Bermuda's rainfall, which will be summarized here.

Rainfall
Annual and Seasonal Rainfall Patterns in Bermuda

Bermuda's annual rainfall is recorded at LF Wade International Airport by BWS. Rainfall accumulations on average total 1490 mm (or 58.66 in) per year, based on the 1981 to 2010 average (http://weather.bm/climate.asp). The average seasonal rainfall pattern is indicated in the figure below.

A study by Peñate De La Rosa (2015) further outlines the somewhat random (stochastic) nature of Bermuda's annual rainfall patterns during the period from 1949 to 2011, with some broad seasonality evident. There are generally more, but lighter rainfall events in winter (December through March), a drier period from April through May, and heavier, but fewer rainfall events characterizing the summer and autumn (June through October).

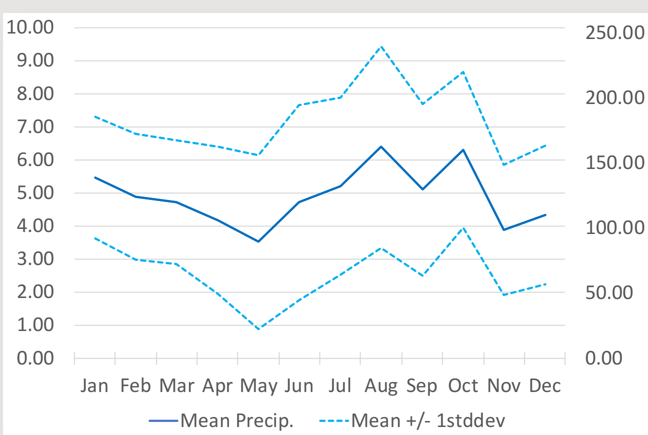


Figure 1. Average (1981-2020) Bermuda's monthly precipitation (solid blue line), +/- standard deviation of the monthly mean (dashed light blue line). Measurements are displayed in inches (left axis) and mm (right axis). Data from www.weather.bm/climate.asp - all measurements taken at LF Wade International Airport by BWS.

Examining interannual patterns more closely, Johnston et al. (2018) shows that there are some increasing trends in the period from 1949 to 2018, but they are not statistically significant. If one starts to examine the time series in different years, different trends become evident.

The trend in the number of rainfall days per year (i.e., the count of days on which rainfall was recorded at the airport) is more compelling, especially when focused on the winter months (December through March) but still lacks statistical significance. Peñate De La Rosa (2015) further found some correlation between the North Atlantic Oscillation (NAO) index and the number of winter rain days in Bermuda, based on the analysis period from 1949 to 2011.

The NAO is a pattern that describes the fluctuations in the jet stream which, in turn, controls the tracks of storms and other weather disturbances. In general, a negative NAO pattern describes when the pattern is 'wavy', blocking weather systems in the subtropical Atlantic near Bermuda from moving on; hence, a wet winter regime is prevalent in negative NAO patterns for Bermuda's region. In a positive NAO pattern, the jet is more conducive to the progress of weather disturbances from west to east. Therefore, more transient and less prolonged rainfall events would be expected in this pattern. While winter NAO indices have increased in recent decades, conclusions about the relationship between NAO and climate change should be treated with caution. In short, it is yet unclear whether the NAO patterns that affect our winter rainfall amounts will continue to trend upwards.

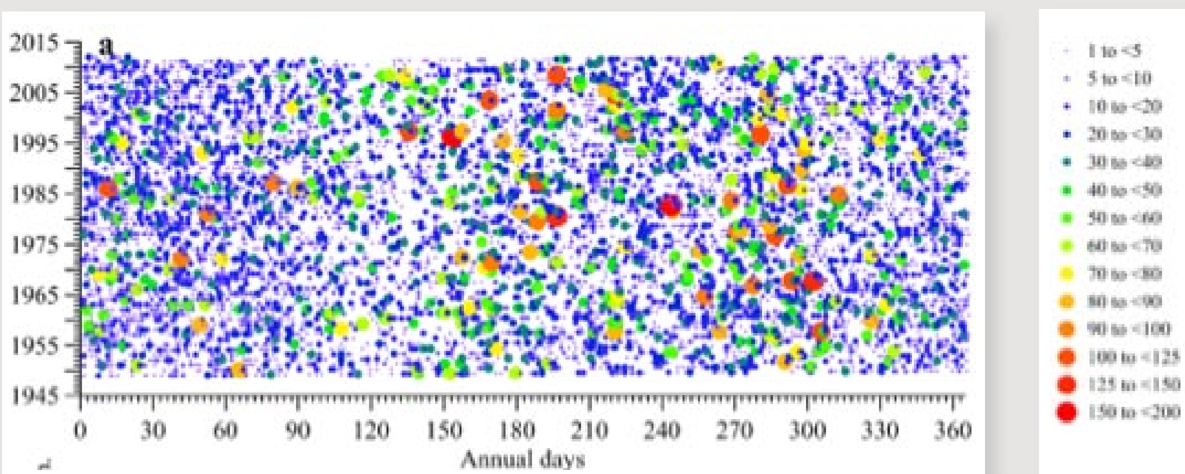


Figure 2. Annual and interannual variability of rainfall in Bermuda. Daily occurrence of rainfall on a day in a given year; intensity is given by colour and circle size, in mm/day. Daily data from BWS, for 1949 to 2011.

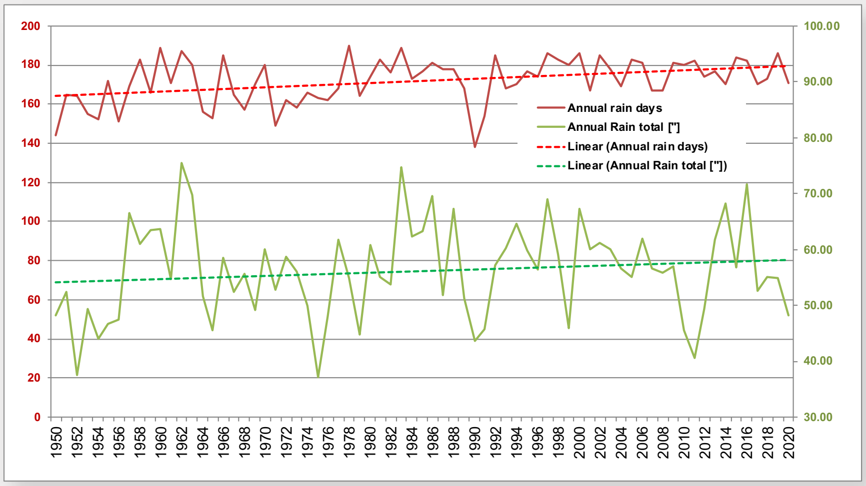
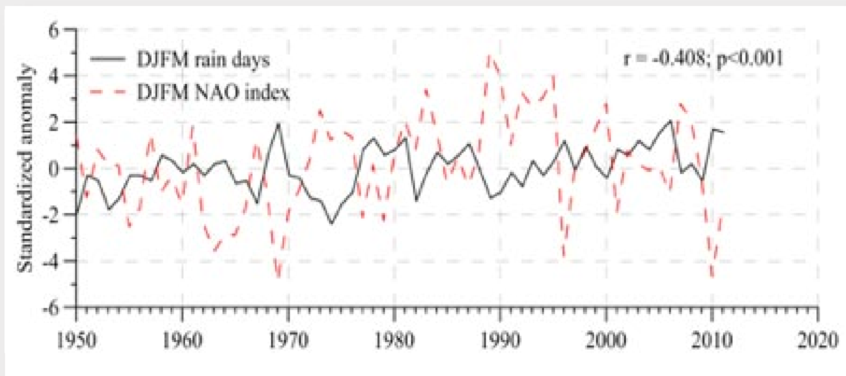


Figure 3. Bermuda's number of rain days per year and linear trend (red solid and dashed lines, respectively) – left axis; and annual rainfall accumulation and linear trend (green solid and dashed lines, respectively)- right axis. For the period from 1949 to 2020. Adapted from Johnston et al. (2018).



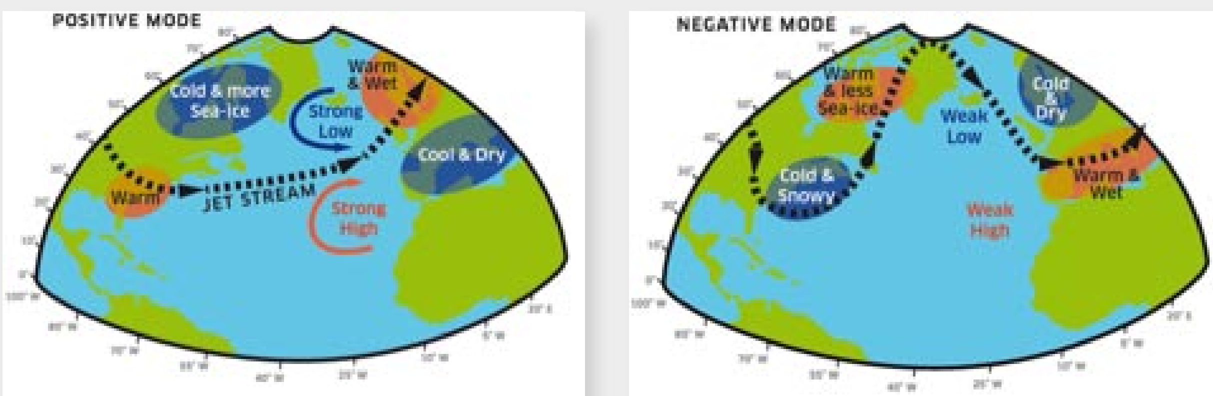


Figure 4: Number of rain days in Bermuda during winter (December through March), and the NAO Index for the same period, during the years 1949 to 2011 (top) – data from BWS, adapted from Peñate De La Rosa (2015). b) Schematic diagram of the positive (left) and negative (right) phases of the North Atlantic Oscillation (NAO), and their associated weather patterns (bottom). From Hughes et al. (2018)

Rainfall
Rainfall Rates

Theory indicates that ability of the atmosphere to 'hold' water vapour increases as the temperature increases, by about 7% per °C (Trenberth et al., 2003). In addition, evaporation will increase, intensifying the water cycle. Extreme precipitation events will become more extreme, and those regions prone to drought will become drier as the surface of the planet warms. In terms of extreme rainfall events, the average frequency of lower intensity events may decrease, and the higher intensity events will increase (Trenberth et al., 2003). This is an average effect, prone to regional and local variations.

In Bermuda, six-hourly rainfall observations have been recorded by BWS since 1995. As with all observational records, quality control (QC) is a key issue. At BWS, records of six-hourly rainfall accumulations are taken at 0000 hours, 0600 hours, 1200 hours, and 1800 hours (UTC). BWS does daily checks and follow-on sense-checking of its aviation observations and official daily climate datasets. However, some data, including the six-hourly rainfall accumulations, are not subject to the same rigour as the checks in the official (daily) record. While some obvious errors and outliers have been quality checked, much of the historical six-hourly rainfall data have only been checked once daily. In addition, it should be noted that these are sequential six-hourly records, versus six-hourly accumulations starting each hour (e.g. 0100-0700 hours, then 0200-0800 hours, etc.) – such 'rolling' measurements might more cleanly reveal trends or variability. Hence, there is an additional element of uncertainty in the conclusions. Nonetheless, the data do show some interesting high-level features.

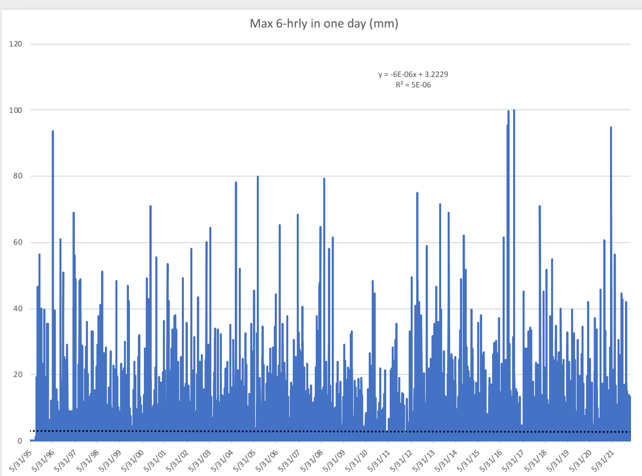
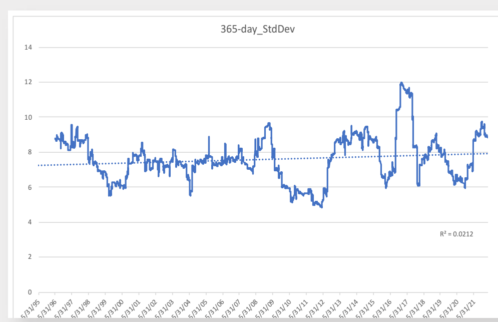


Figure 5. Maximum six-hourly rainfall accumulations (top) measured by BWS, June 1995-March 2022, and rolling 365-day standard deviation of the maximum six-hourly accumulations (bottom).

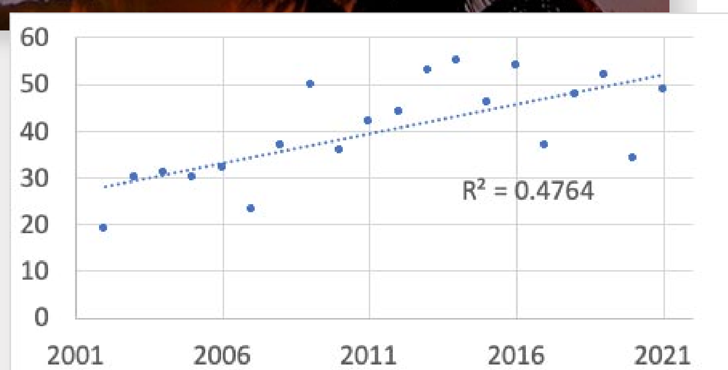


Notable conclusions include:

- There is no statistically significant trend in six-hourly rainfall accumulation during this period.
- There is a slight upward trend in the rolling annual standard deviation of maximum six-hourly accumulations. This is not statistically significant, but the detectable trend is the right direction to be consistent with theory of greater rainfall variability.

So, are downbursts getting heavier locally? There is some anecdotal evidence and some data to support/detect this but, without longer records, there is considerable uncertainty.

Thunderstorms



Number of days per year on which thunder was reported at LF Wade International Airport 2022-2021. Source: BWS.

Extreme rainfall events in Bermuda are often associated with vigorous updrafts that can create cumulonimbus clouds, which produce lightning and thunder – hence observations of these clouds usually precede reports of thunderstorms.

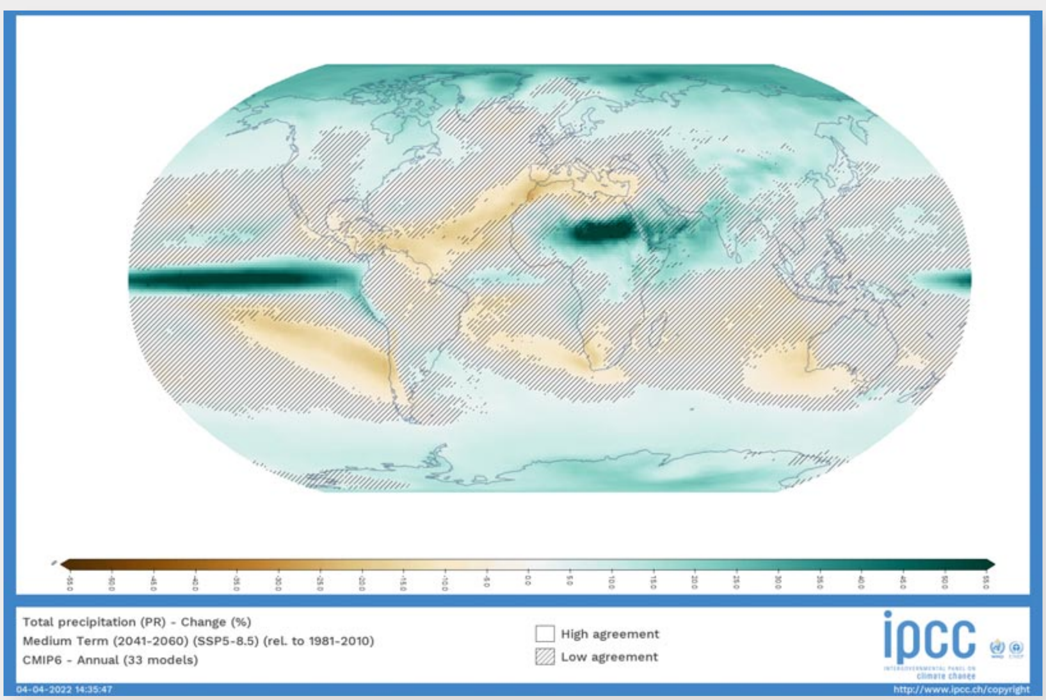
A trend that has been detected at LF Wade international Airport is the number of days on which thunder was reported annually. This trend can be treated with a reasonable confidence - thunderstorms have significant impacts to aviation operations, so their observations are critical to record. The fact that this is 'days upon which thunder was reported' vs. 'number of thunderstorm reports per day' further increases confidence in these data. This trend in thunderstorm occurrence aligns with our physical understanding that a warmer environment should support heavier short-duration rainfall events. As the surface ocean and air warms, the energy available for thunderstorm development and heavier rainfall rates increases.

Rainfall
Climate Projections

A recent study (Karnauskas et al., 2016) indicates projected increases in both precipitation and evaporation (historical vs future), resulting in a slight net positive increase in aridity (as measured by their 'Aridity Change Index') for Bermuda in the next 70 years. However, as Bermuda does not rely on large bodies of fresh water or riverine systems, the relevance of this study for the island's water supply remains a question.

The latest IPCC report and associated Atlas indicate that there is poor model consensus on the regional changes in precipitation, but that the overall sign is for an increase in annual rainfall locally (note Figure 6). Maps of IPCC-projected rainfall changes indicate a wetter trend over time over Bermuda. There is a projected drying trend over the Gulf Stream to the west, and also less rain over the tropical North Atlantic to the south.

There is considerable uncertainty about the projections of Bermuda's rainfall due to the island's small size and the competing controls on the local rainfall regime, which include long-term climate trends, seasonal variability and interannual variability (as exhibited by the NAO as one example). The fact that historical trends are detectable, but not robust or statistically significant, also introduces a lack of confidence in future climate-scale projections for local rainfall. Nonetheless, we know from theory that extreme heavy rainfall events may get more intense over time as the atmosphere warms. In addition, there is higher confidence that any tropical cyclone activity will also continue to aggregate higher rainfall accumulations (Gori et al., n.d.; Knutson et al., 2010; Zhu et al., 2021), meaning storms that affect Bermuda are likely to be wetter in the future.



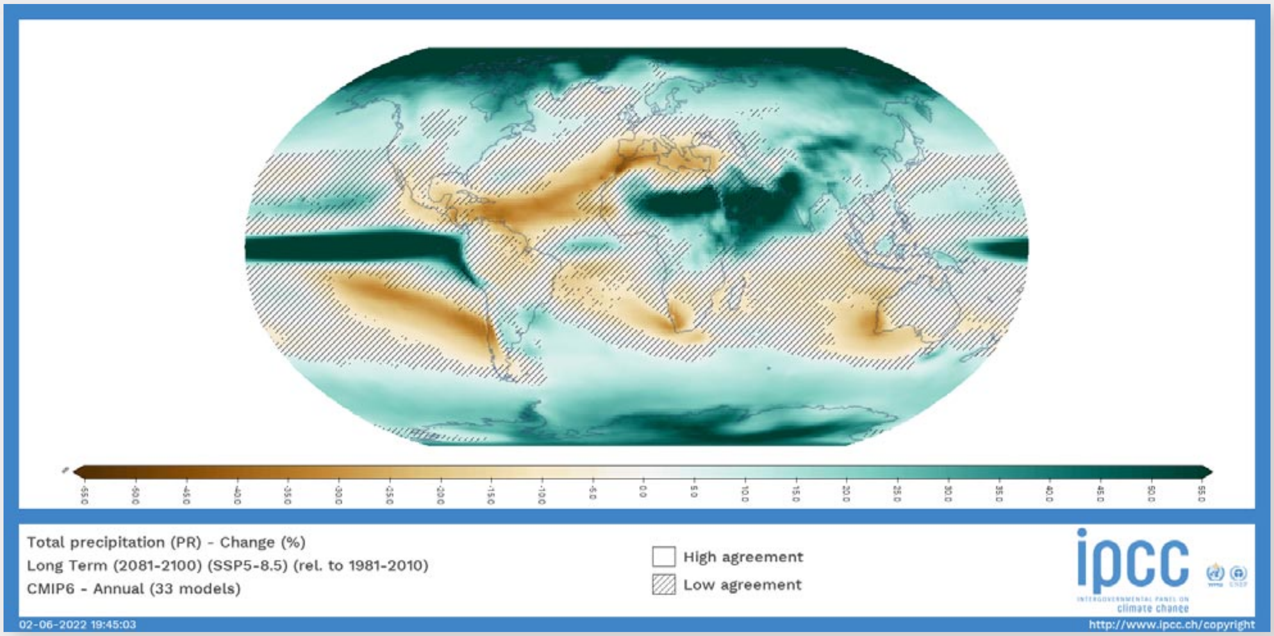


Figure 6. IPCC climate model projections of precipitation across the North Atlantic region show low agreement between models, indicating high uncertainty about how our precipitation regime might change in the medium-term (20-40 years), and long-term (60-80 years) futures. (Gutiérrez, 2021) https://interactive-atlas.ipcc.ch/

Rainfall
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Hurricanes

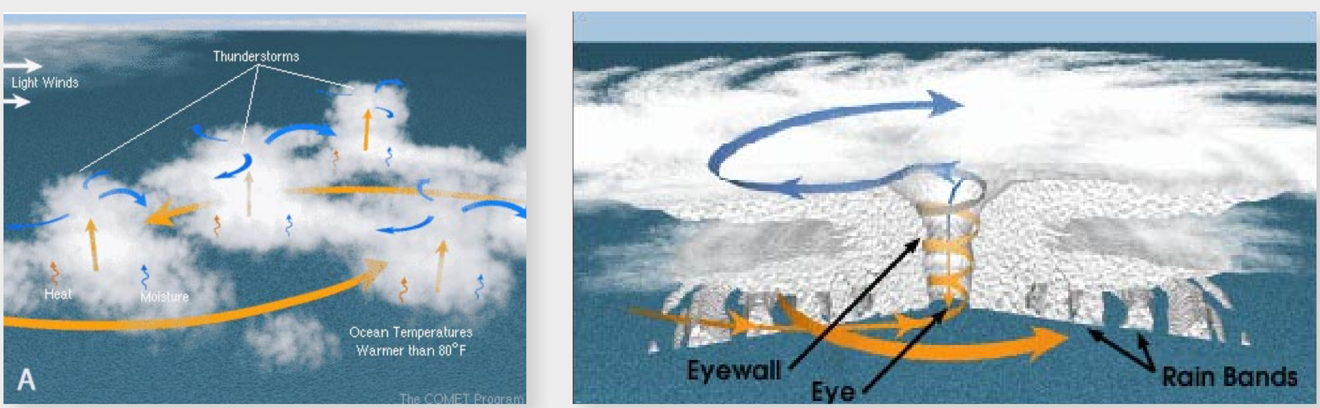
Hurricane Activity

Introduction | Hurricane basics

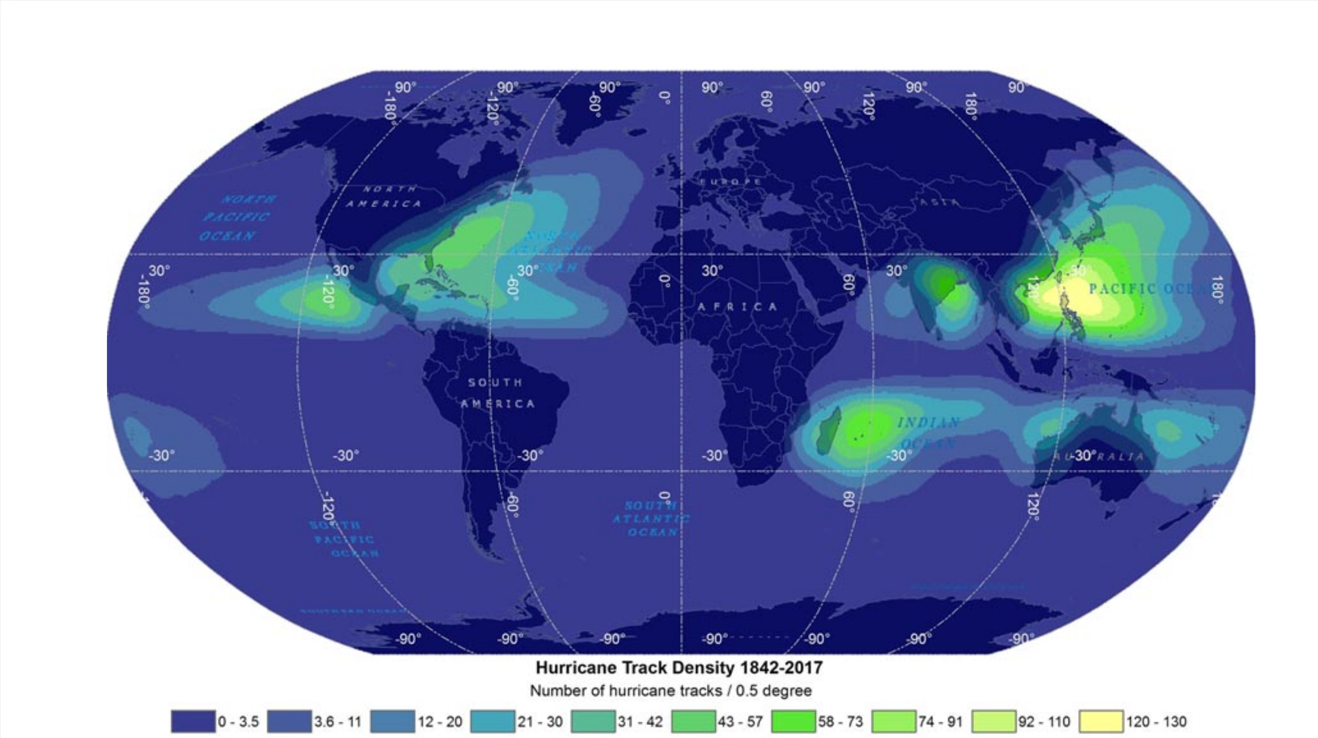
Hurricanes and tropical storms are likely recognized as the most impactful natural hazards faced by Bermuda. These weather phenomena, referred to by meteorologists as tropical cyclones, are large low pressure systems, hundreds of kilometres across, that produce potentially damaging winds and heavy rainfall. The rainfall stems from the aggregation of vigorous thunderstorm clouds into concentrated areas. The extreme winds build up the ocean surface into a storm surge, and additionally stir up large waves on top of it. The formation, track and intensification of tropical cyclones can be unpredictable relative to other weather systems, as well as being extreme in nature compared to daily conditions. Hence, impacts from tropical cyclones like hurricanes can be greater, and come with reduced advanced warning time. Consider these aspects combined with multiple hazards and a potentially long duration (due to their large size), and one can envisage that tropical cyclones can be extremely dangerous systems when they threaten coastal populations on islands such as Bermuda.

Necessary conditions (Gray, 1968) for the formation and/or strengthening of a tropical cyclone include:

1. Warm near-surface ocean temperature, with an often-quoted threshold of 26.5°C/80°F
2. Low vertical wind shear (changing environmental winds with height)
3. Moist lower atmosphere that supports rising air motions
4. Sufficient Coriolis effect – the 'spin' conveyed to the storm by the rotation of the Earth (this increases with distance from the Equator; therefore this loosely translates to sufficient distance from the Equator)
5. A precursor weather disturbance



Schematic depiction of A) Precursor conditions leading to B) development of a hurricane (cross-section). Image Source: University Corporation for Atmospheric Research (UCAR) - COMET Program, courtesy of NASA



Locations of tropical cyclone tracks from 1842 to 2017. Data Source: NOAA International Best Track Archive for Climate Stewardship (IBTrACS)

Tropical cyclones form under these conditions over the tropical oceans during the periods when surface waters are warmest. In the western North Atlantic, this time frame is climatologically during the months of August through October.

Hurricane Activity

North Atlantic hurricane trends under climate change

All of the above conditions are becoming increasingly conducive to more hurricane activity near Bermuda. Here, we outline how these are impacting hurricane activity specifically near Bermuda.

Warmer water → stronger storms

As a generally accepted observed and theoretical principle, warm upper ocean temperatures (>26.5°C/80°F) serve as a necessary condition for hurricane development (Emanuel, 1986; Gray, 1968). While that is an insufficient condition on its own, it is instructive to note that, around the world, tropical cyclones (called hurricanes in the Atlantic) form in warm tropical regions of the oceans. It can then be concluded that warmer water in greater abundance should provide more energy to the system that allows hurricanes to form. When researchers model future scenarios of hurricane activity, the near-surface ocean temperature is often one of the parameters they can change to help simulate hurricanes in a warmer world.

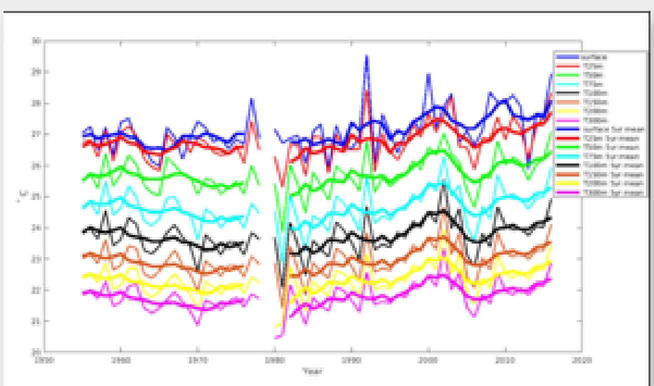
Higher ocean temperatures heavily feature in a number of studies that have used data from the BATS program at BIOS since the 1950s. Hallam et al. (2021) found that the upper ocean heat that Bermuda storms derive energy from ('feel') is represented well by temperatures averaged down to 50 m below the surface. These temperature profiles indicate consistent average warming in that layer of approximately 1 to 1.5 °C over the past 40 years.

It is worth pointing out that this is an aggregate effect of at least two human-related activities. The first is the enhanced greenhouse effect leading to more atmospheric warming. The upper ocean has been documented to have absorbed over 93% of the excess heat generated by anthropogenic global warming since the 1970s (Laffoley & Baxter, 2016). The upper ocean has also been well-documented to be warming since records of deep-ocean temperature began in the 1950s, as measured by researchers at BIOS (Bates et al., 2012).

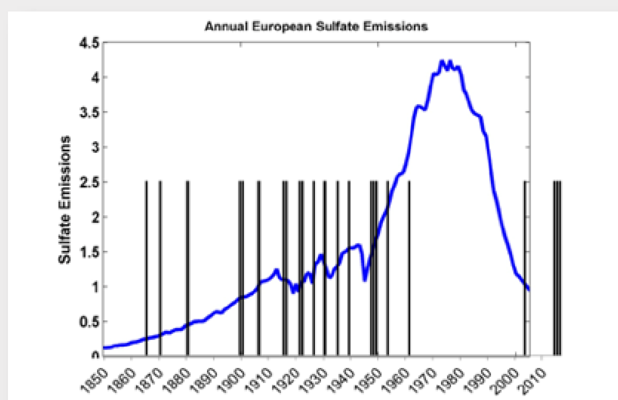
In addition, specific to our region, multiple studies have indicated the effect of mid-20th century peaks in sooty particulate pollution from Europe (Smith et al., 2011) leading to cooling of the surface waters of the tropical North Atlantic (Mann & Emanuel, 2006; Vecchi et al., 2021).

The subsequent implementation of clean air acts in Europe meant less near-surface pollution over the tropical Atlantic, and a resulting rebound of hurricane activity from the 90s. The overall record of ocean temperature, therefore, has a prominent dip during the 1960s-90s, which coincides with a peak in European pollution. The perhaps counter-intuitive result of this human-induced decrease in sea surface temperature was to suppress Atlantic hurricane numbers temporarily between the 1960s and the 1990s. There is a deficit in major Bermuda storms coincident with this period.

This, along with changes in observational technology through the hurricane record (e.g., weather satellites weren't commonly used before 1970), complicates the record of hurricane activity, so that



Average August, September and October upper ocean temperatures averaged down to different depths (32°N, 64°W). Note the warming trend through the decades (Hallam et al., 2021).



The blue graph indicates European sulphate aerosol (pollution) emissions in 1000s of metric tonnes (Smith et al., 2011), overlaid upon instances of major hurricanes within 200 km of Bermuda, through the historical record (NOAA).

long-term trends are difficult to infer without more complex analysis. The upshot of this complex analysis points to a 'masking' of the natural cycles and effects of global warming trends on Atlantic hurricane activity by the temporary influences of changing technology and the European pollution problem (Vecchi et al., 2021). Now that the trends are 'unmasked', we can proceed with more confidence in the projections of upper ocean temperature and, therefore, hurricane activity.

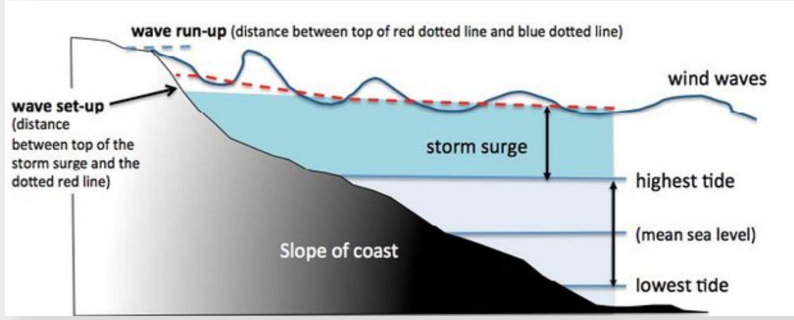
In many regards, Bermuda has benefitted from a hiatus in major hurricane activity that was previously unidentified until recently. Of course, this 'respite' is punctuated by some events that stick out in our collective memories, such as Hurricane Emily in 1987 and Hurricane Felix in 1995. These two storms, however, were not technically major hurricanes. Hurricane Emily in 1987 was notable for a few reasons:

- It intensified near Bermuda in the small hours of the morning and changed track from being 'not a threat' to being a 'direct hit' in a matter of hours.

- As a result, the warnings that were posted were done so while the population was largely asleep or unaware.

- Emily had tornadoes embedded in its circulation, so while the large-scale sustained winds were of Category 1 intensity, the winds that affected Bermuda were at least briefly very damaging.

Hurricane Felix was interesting because it made a close passage to Bermuda (with Emily still in the population's recent memory) during a major political event – the Independence Referendum.



Schematic of different elements of storm tide. Source: Australian Government National Climate Change Adaptation Research Facility.

The deficit in activity in the 1960s-90s was followed by more major hurricanes in the first two decades of the 21st century. This could perhaps be more accurately described as a return to normal levels of activity following the previous deficit of major storms. This new normal was kicked off by Hurricane Fabian in 2003, Bermuda's worst natural disaster in 50 years at that time.

Hurricane Fabian dragged across the area over a period of several hours as a major hurricane, with the island suffering the worst part of the storm (the eyewall). There was evidence of tornadoes embedded, but in a much worse background wind field than in Hurricane Emily. The resulting roof damage was widespread (Miller et al., 2013).

Storm surge and wave action induced by the long-duration extreme winds caused damage to some critical pieces of infrastructure, particularly the Causeway. This also caused the loss of four lives, the only direct fatalities from a storm in Bermuda in living memory.

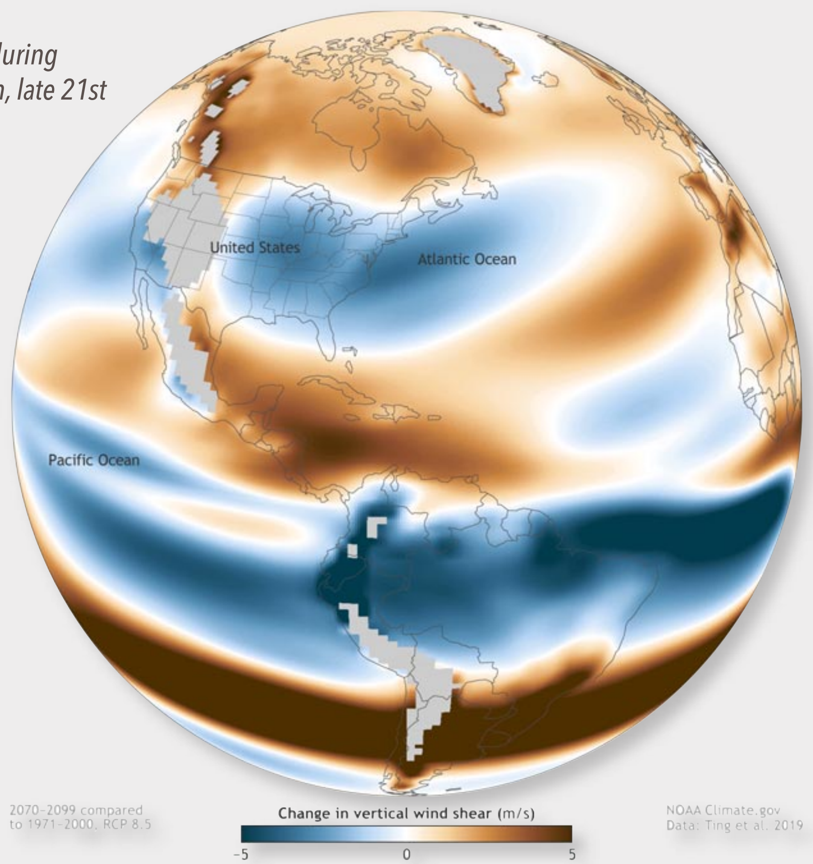
Poleward migration → more regional disturbances

Climate change results in greater accumulation of heat in subtropics, which leads to a 'poleward migration' of tropical cyclone activity in general, and an increase in track density in western Atlantic (Studholme et al., 2021). This also increases the latitude of incipient disturbances that can form hurricanes (Sharmila & Walsh, 2018). The locations of the lifetime maximum intensity of tropical cyclones have increased by approximately ½° latitude per decade since the 1970s (Kossin et al., 2014), but the science has not reached a consensus as to whether this is a trend that will continue under warming scenarios. If the poleward trend is maintained, it is feasible that hurricanes could reach their peak intensity nearer to the subtropics, where Bermuda is located.

Atmospheric environment | Less regional shear, increasing global humidity

If warm water is the 'fuel' that enables storms to develop, then wind shear acts as a 'brake' on hurricane intensity. There is evidence demonstrated in recent studies to suggest a relationship between Atlantic hurricane seasons with high numbers of storms basin-wide, and wind shear near the US east coast (Kossin, 2017). Wind shear is the change of environmental winds with height in the atmosphere and, generally, greater wind shear goes hand-in-hand with weaker hurricanes. In other words, during seasons when there are large numbers of hurri-

Changes in wind shear during peak of hurricane season, late 21st centruy



canes, conditions support greater wind shear along the US east coast into the western North Atlantic, giving an element of protection to our region. Research by Ting et al. (2019) indicates that this 'shear barrier' will diminish over time under simulated global warming scenarios.

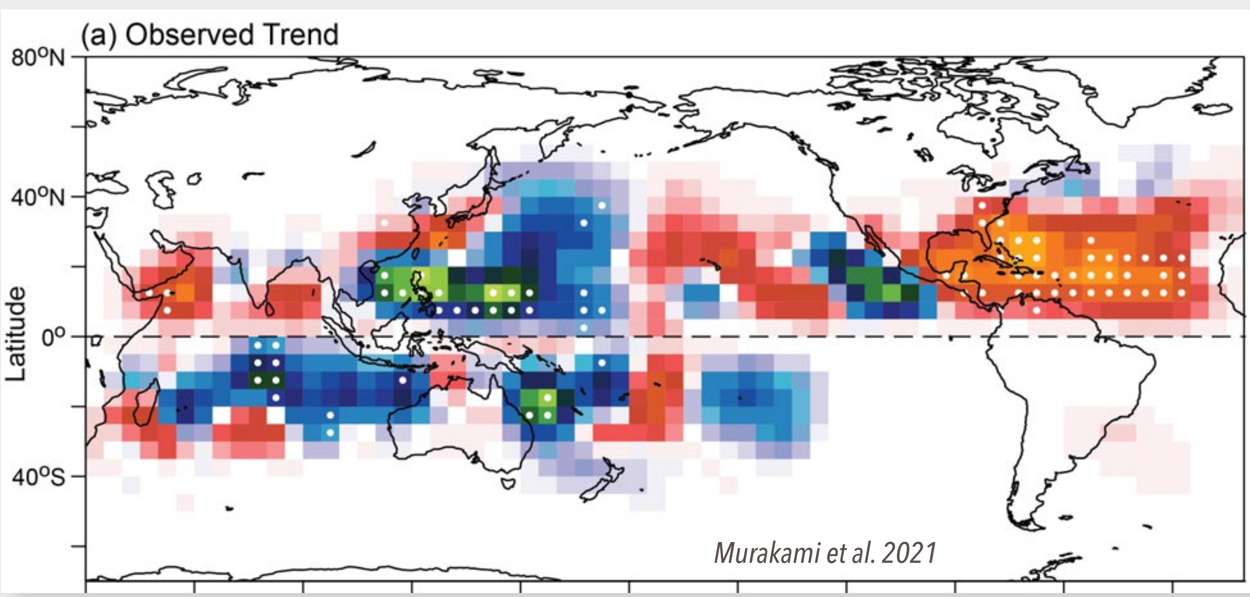
Another robust trend that has been detected is a deceleration in the forward speed of tropical cyclones globally, from the 1950s to the mid-2010s (Kossin, 2018). This is worrying as it means the time a tropical cyclone moves over an exposed location is prolonged compared with previous decades. This trend is greater over land than the ocean, and represents a decrease on average of a few kilometers per hour. As this is an area of active research and scientific debate, there is not yet consensus about these conclusions, and little understanding about the link with climate warming.

In addition to the changes in wind and steering patterns, increased evaporation in a warming world also means more water vapour is available in the atmosphere. This further supports the development of deep convective clouds (Karnauskas et al., 2016; Madakumbura et al., 2021) that are a necessary condition for hurricane formation.

All of these phenomena support a background environment becoming more and more conducive to tropical cyclone activity near Bermuda, with multiple contributing factors. Tropical cyclone activity has been shown to be on the uptick from late last century into this one, reflecting regional trends for the western North Atlantic (Murakami et al., 2020; Studholme et al., 2021).

This explains the fact that Bermuda tropical storms and hurricanes have been increasing in both frequency and intensity, with the maximum wind speed increasing at a rate of 7.7 knots per decade since 1980 (Hallam et al., 2021; Loizou et al., 2021).

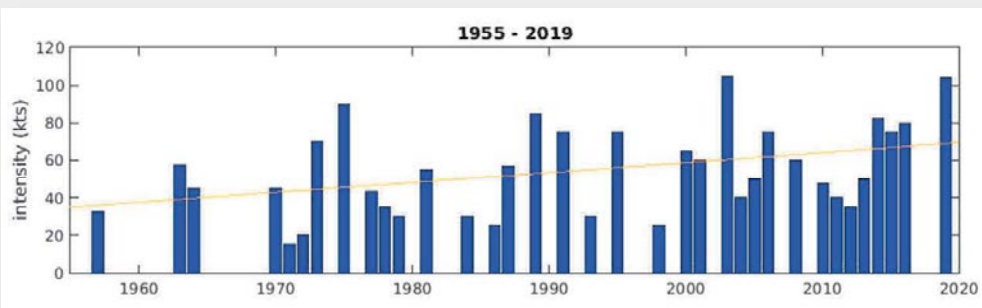
Linear Trend in Frequency of Tropical Cyclones from 1980 to 2018

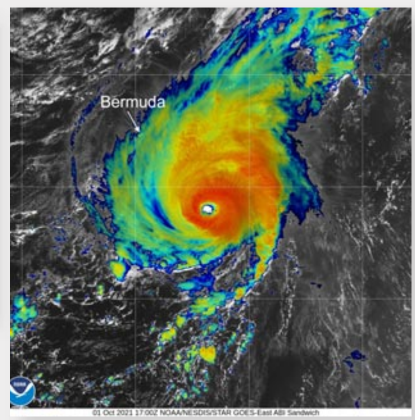


Hurricane Nicole was the strongest hurricane (on the Saffir-Simpson Scale) to have approached and caused impacts in Bermuda. We were spared the worst conditions from Nicole's passage, given that a) although it approached as a Category 4, it weakened to a Category 3 before its closest point of approach (Kimberlain & Latto, 2016); and b) it produced the largest storm surge locally on record, but it thankfully arrived at low tide.

It is just as alarming to note that Hurricane Sam in 2021 was the strongest storm on record to come as close to Bermuda as it did—just 7mph shy of a Category 5 hurricane (the highest rating on the Saffir-Simpson Scale) and moving within 200 miles of the island, according to the official US National Hurricane Center advisories (available at www.nhc.noaa.gov/data/ #advisories).

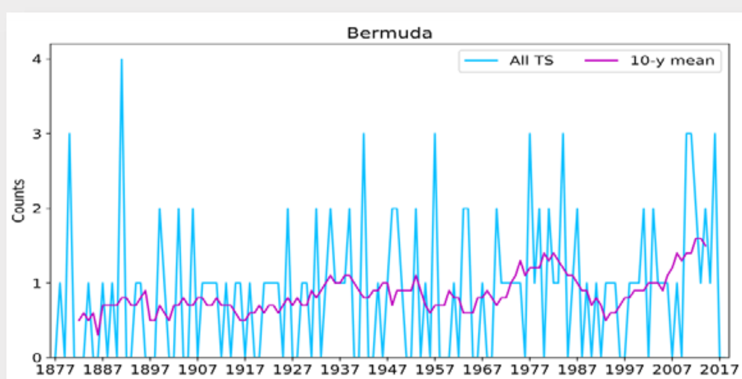
In the cases of each of these major storms, timing was everything, and well within the bounds of uncertainty/predictability. A subtle shift in track location and speed of arrival would have resulted in a different impact for the island.





Infrared Satellite Image of Hurricane Sam near Bermuda. Source: US National Oceanic and Atmospheric Administration (NOAA)

Top: Tropical cyclone intensity for tracks within 100 km of Bermuda. Orange line indicates linear trend (Hallam et al., 2021). Bottom: Blue line: time-series of annual number of tropical cyclones that came within 185 km of Bermuda. Purple solid line: 10-year moving average (Loizou et al., 2021).



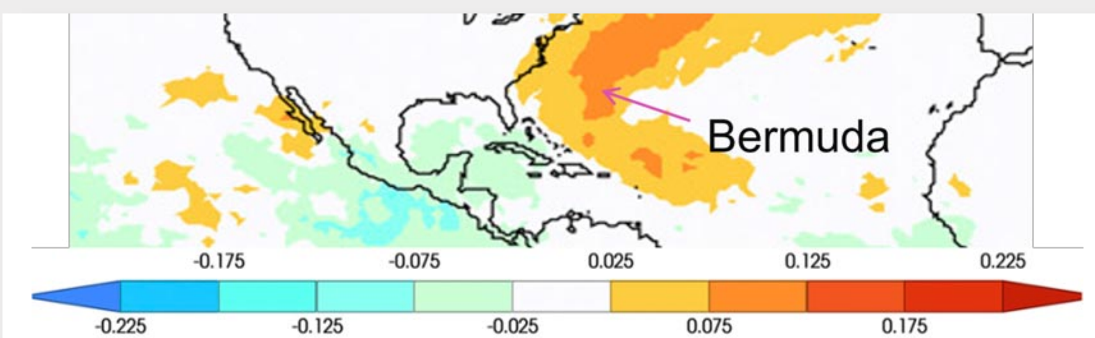
Hurricane Activity
Projected trends

Climate projections and modelling methodologies have become sophisticated enough to project regional changes in tropical cyclone activity. Some studies project more storm activity in the western North Atlantic under warming scenarios. Simulated tropical storms are indicated to increase in frequency by approximately 0.1/yr near Bermuda (1 more tropical cyclone per decade) under warming conditions, with proportionally more intense storms projected under a scenario of a 2°C warming of ocean surface temperature plus a doubling of CO_2 emissions (Wehner et al., 2015). This expectation may already have been exceeded given the more frequent major storm occurrences so far this century, and the advent of stronger storms coming closer (e.g., Hurricanes Nicole in 2016 and Sam in 2021) .

Under such trends, Bermuda should expect more extreme events as hurricanes become more intense (and more intense storms become more frequent) over time. Statistically, hurricanes at their highest intensities are on average 15 knots (18 mph or 28 kph) stronger for every 1°C of warmer sea surface temperature (Elsner et al., 2013). With that in mind, if the ocean temperature trends continue, Category 4 storms moving through our region will become much more frequent, and Category 5 storms reaching our latitude should no longer be considered out of the question. As we are in uncharted territory, we can no longer solely rely on past experiences to dictate future expectations.

It's too early to say whether the trend in Bermuda storm activity seen in the first 20 years of the 21st century will continue, or whether complex feedbacks will level the activity to a 'new norm'. However, the anticipated impacts that are fairly certain include heavier rainfall events. This conclusion is one of the most certain aspects of changes in hurricane activity under climate change. Knutson et al. (2010) and subsequent studies project increases in rainfall intensity on the order of 20% in the core of tropical cyclones under global warming scenarios.

All else being equal, higher storm surges will be a certainty as sea levels continue to rise globally. This is evident in the trend of surges measured at the tide gauge on the north side of St. George's. As mentioned, Hurricane Nicole had the highest surge on record and, thankfully, it came at low tide. Impactful wave action, such as the loss of life and major damage at the Causeway in 2003, should also be expected to increase in amplitude, as wave action from intense storms builds upon higher and higher baseline sea levels (Kopp et al., 2014, 2017).



Excerpt from Wehner et al. 2015, showing increases (warm colours) and decreases (cool colours) in tropical cyclone track density under a scenario of warming and increased emissions.

Hurricane Activity
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Sea Level

Sea Level
Trends and extreme events

Author's note: Much of the work conducted for this chapter is based on an unpublished BIOS intern project conducted in 2019, entitled 'Hurricane Storm Surge and Sea Level Rise Exposure Assessment in Bermuda'. The work was conducted by Ximena Boza, whose current affiliation is the Smithsonian Tropical Research Centre in the Republic of Panama.

Sea Level
Annual mean sea level | Trends and projections for Bermuda

Previous studies have shown that global mean sea level (MSL) has risen since 1870, mainly due to ther-mal expansion of the oceans and the loss of land-based ice as a result of melting. An increase of about 1.7 millimeters/year (mm/yr) was estimated for the 20th century and is projected to rise during the 21st century at a greater rate (Bindoff et al. 2007; Jenkins, Perry, and Prior 2009; IPCC 2021). However, projec-tions of global MSL may be insufficient information to plan adaptive responses; local decisions require local projections. Data from the St. George's tide gauge in Bermuda indicates that the sea level trend is 2.17 ± 0.36 mm/yr (1/12th of an inch per year) from 1932 through 2019. This amounts to a rise of 21.7 cm (8.5 inches) per century. This trend is sourced from monthly mean water levels measured in Ferry Reach St. George's (data obtained from NOAA tidesandcurrents.noaa.gov/sltrends/ - Figure 1). Hourly measurements are available since 1989, when a more recent instrument was installed at the oil dock pier on the north side of St. George's. More information on the tide gauge, its maintenance and usage, are available at tidesandcurrents.noaa.gov/stationhome.html?id=2695540. It should be noted that this is the only source of continuous long-term (multi-decadal) water level measurements for Bermuda. Some uncertainties result from gaps in the data, significantly from 2001 to 2003, during which Bermuda experienced a subtropical storm (Karen in 2001) and a major hurricane (Fabian in 2003). Unfortunately, these events were not captured in the tide gauge record.

Fortunately, the St. George's tide gauge is near a satellite-based reference station for elevation (Woodworth 2017), so uncertainties regarding its measurements are likely to be limited, compared with some other continental coastal sites (Vignudelli et al. 2019). This is not to say there are no uncertainties, but they are reasonably accounted for in the NOAA long term-trend for Bermuda's sea level.

Kopp et al. (2014b; 2017) provided projections of sea level rise in several locations, including Bermuda (specific to the tide gauge previously mentioned), from 2020 through 2200 under three greenhouse gas representative concentration pathways (RCP): 2.6, 4.5, and 8.5 and all indicate a rise in MSL through time (Figure 1a,b). One can then use the mapped projections from Kopp et al. (2014; 2017), and others to develop maps of projected coastal inundation (Figure 1). To gain more insights about specific regions of Bermuda at more or less threat from rising sea levels, one can use Climate Central's Coastal Risk Screening Tool (https://coastal.climatecentral.org/). Limitations of this analysis include not only uncertainties surrounding the future projections of sea level rise, which are continually being reviewed through scientific processes, but also the accuracy and precision of the digital models of coastal elevation (also under periodic refinement). For example, Bermuda's elevation model will benefit from recent aerial surveys conducted by the UK Hydrographic Office in 2021, using airborne light detection and ranging (LIDAR) technology. The analyses to which this report refers do not, as yet, incorporate these latest updates to Bermuda's coastal and seafloor mapping. Nonetheless, the refinements will only add subtle changes to the mapping of coastal inundation represented in Figure 1.

More recently, the IPCC has indicated that it is virtually certain that global mean sea level will continue to rise through the 21st century, and that increases of 0.63-1.01 m (2.1 to 3.3 ft) are likely, under the highest simulated emission scenarios by 2100 (IPCC 2021).

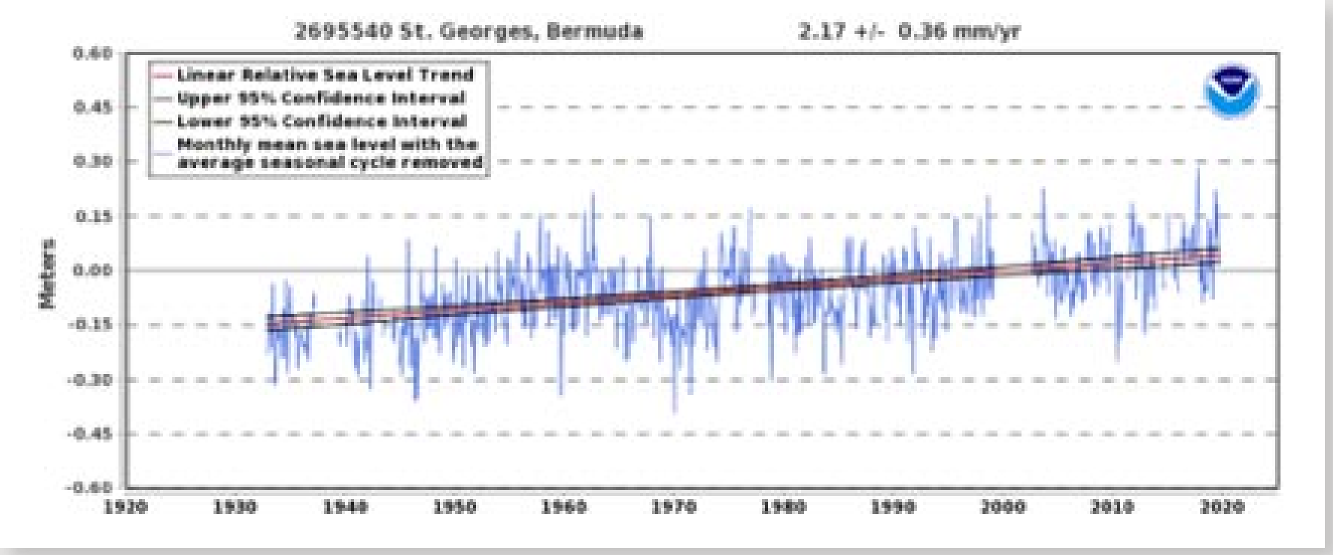
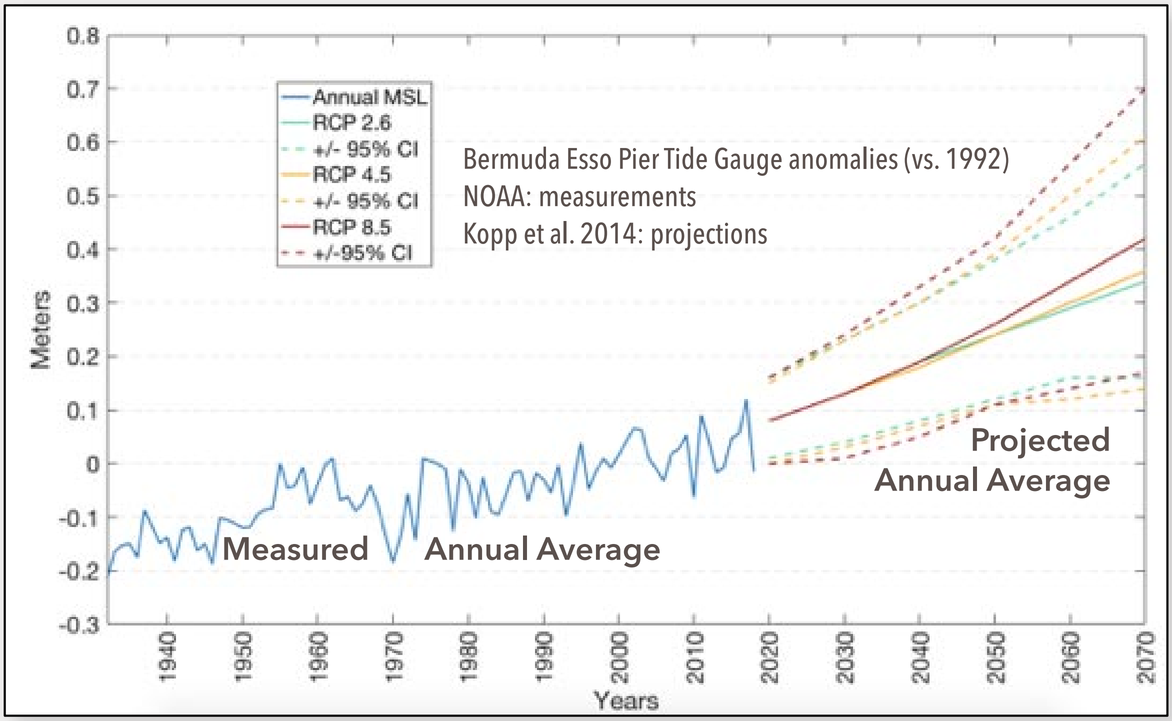


Figure 1. Annual MSL trend (1932-2019) based on NOAA's tide gauge at St. George's
https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=2695540 – this is referenced to a 1983-2001 Mean Sea Level datum. Middle panel: Annual MSL trend (1932-2019) and future projections of sea level rise for Bermuda (Kopp et al. 2014a) for Representative Concentration Pathway (RCP) 2.6, 4.5, and 8.5. (a) Dashed: low-sensitivity; solid: mid-sensitivity; dotted: high-sensitivity sea level projections; (b) RCP 2.6 at low-sensitivity, RCP 4.5 at mid-sensitivity, and RCP 8.5 at high-sensitivity; (c) Coastal Risk Screening Tool - Land projected to be below annual flood level in 2050 – https://coastal.climatecentral.org/ – accessed 31 March 2022.



Top panel: Blue line - Annual MSL trend (1932-2019) referenced to a 1983-2001 Mean Sea Level datum (NOAA); future projections of mean sea level for Bermuda (Kopp et al. 2014a) for Representative Concentration Pathways (RCP) 2.6 (green), 4.5 (yellow), and 8.5 (red). Dashed lines represent low and high sensitivity ranges for each RCP scenario.

Bottom panel: Coastal Risk Screening Tool - Land projected to be below annual flood level in 2050 – coastal.climatecentral.org/ – accessed 31 March 2022.

Sea Level

Hourly extreme sea levels

The sea level dataset used in this study comes from the St. George's tide gauge, operated by NOAA tidesandcurrents.noaa.gov/waterlevels.html?id=2695540. Hourly recordings of water levels (predicted and verified data)–using MSL tidal datum as the vertical reference–were used from June 1, 1989 until October 31, 2018 (~29 years). This period of time was chosen for the availability of hourly measurements. Nonetheless, within this time-frame there are periods during which there is a lack of verified data (i.e., 4 March to 31 May, 1994; 1 May, 1999 to 24 September, 2002; 23 August to 24 Sep-tember, 2003; 23 December, 2009 to 24 February, 2010; 24 January to 7 June, 2011; 1 January to 16 July, 2014; 22 December, 2014 to 15 January, 2015; 1 April to 6 July, 2015; 15 to 22 March , 2016; and 21 October to 18 November, 2016). This is unfortunate due to the lack of verified tide data during the impact of major Hurricane Fabian in September 2003.

The distribution of verified water levels was analysed (Figure 2a). However, only water levels above MSL were considered (Figure 2b), since the interest of this study is to identify the regimes that could lead to coastal inundation. The analysis of this hourly data defines 'Extreme Sea Level' thresh-olds as water levels that only occur in the highest 2.5% and 0.1% (two and the standard deviations [σ]) hourly observations. Within the ~29 years of sea level data, water levels that are ≥ 0.62 m ac-count for 2.5% of the observations. Further, 0.1% of the observations comprised measurements of ≥ 0.79 m above MSL. The maximum water level in the record was 1.07 m above MSL, which occurred on 26 October 1995. Note that this analysis does not account for tidal phase (the examination of surge later in the chapter does account for tides).

Extreme Sea Levels (as defined in this study) are fur-ther explored in terms of storm surges, wind-driven waves and oceanographic eddies, some or all of which may be influenced by climate trends.

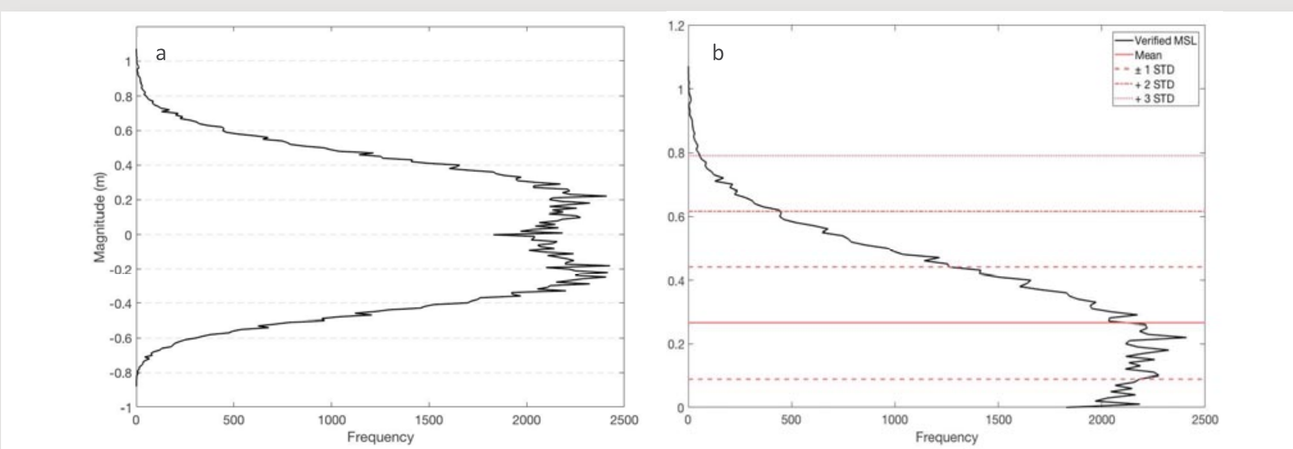


Figure 2. (a) Frequency of all verified water levels and (b) frequency of positive verified water levels with statistical analysis (mean, plus one, two, and three standard deviations [STD]).

Sea Level
Storm surge

Further analysis was undertaken to identify surge events that occurred, but that did not surpass the ESL thresholds because of tidal variations. The surge is calculated by subtracting the predicted sea level from the verified sea level (Pugh 1987). This study only considers positive surges, as they are of greater practical impact for inundation. The positive surges in low and high tide were extracted from the tide gauge data by filtering out the negative and positive predicted tides, respectively.

The frequency of the positive surges (regardless of tidal phase) were plotted and used the same analysis as for ESL, and two statistical thresholds were identified for the positive surge in both tides—two and three standard deviations (σ) above the mean. In this study, there is the assumption that the predicted water levels in the NOAA tide gauge are accurate predictions. Note that assumption is predicated on the tide gauge measurements being as robust as is feasible, in the absence of other data sources to verify against (see previous comments on uncertainty).

Within the 29 years of sea level data, in 2.5% and 0.1% of the observations, the surge above the predicted tide was ≥ 0.24 m and ≥ 0.31 m, respectively. These values are the same for both low and high tide. However, both tides have a different *maximum* surge. The record surge events were 0.86 m (2.8 ft) for events at low tide, on the 13 October 2016; and 0.54 m (1.8 ft) for events at high tide, on 3 March 2018. These surge records correspond to meteorological events Hurricane Nicole (2016), and a winter gale (2018), respectively.

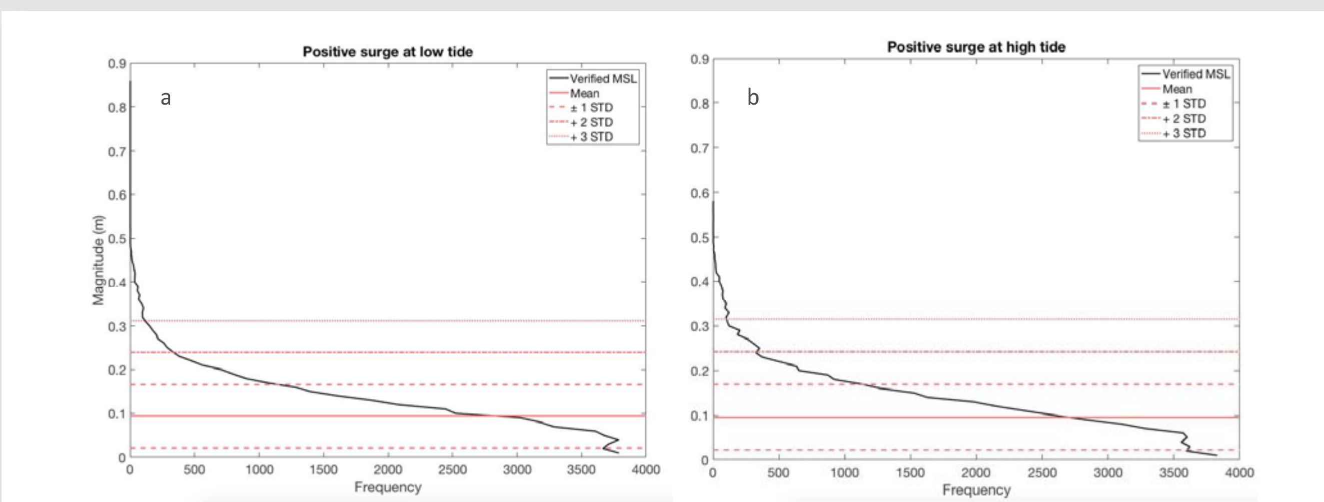


Figure 3. Frequency of positive surge levels with statistical analysis (mean, one, two, and three σ) at (a) low tide and (b) high tide.

Next, the historical hurricane events and the associated water levels in Bermuda were evaluated. Since 1989, 27 tropical storms (TS) and hurricanes passed within a 200 km range of Bermuda. However, three out of the 27 storms did not have water level measurements as there was no tide gauge data for those events (Hurricane Fabian, 2003; TS Karen, 2001; and Hurricane Florence, 2000). Out of the remaining 24 storms, only 14 surpassed the first threshold for surge (≥ 0.24 m), and 10 of those surpassed the second threshold (≥ 0.31 m).

It's worth noting that ESL and surge observations still occur without hurricanes. The surge time-series is displayed in Figure 4, and the occurrence of 14 selected events is highlighted, including two non-hurricane events (a winter storm and a warm eddy). In the interest of clarity of labelling, not all 24 storms recorded for the period are shown, and the colors of the selected events were arbitrarily plotted.

One conclusion that is clear is that not all events that meet the criteria for 'extreme sea level' necessarily meet the extreme surge thresholds (and vice-versa). For example, the water levels that TS Jose in 2011 created in Bermuda surpassed the first ESL threshold, yet did not surpass the first surge threshold. This is because the tide was unusually high, but the surge produced by Jose was minimal.

The converse was true during the peak of Hurricane Gonzalo in 2014—the highest surge occurred at the lowest tide, so the water level didn't reach our ESL criteria at the time of Gonzalo's passage. This is further highlighted in a plot of the water levels during Hurricane Nicole (Figure 5). The highest extreme sea level (the green line) comes after the peak of the highest surge (the purple line), which coincided with low tide.

Out of all positive surge values in the ~29 years of sea level data, the two record surges at low and high tide (0.86 m and 0.54 m, respectively), occurred relatively recently (13 October 2016 and 3 March 2018, respectively). These results may suggest a potential increase in ESL in

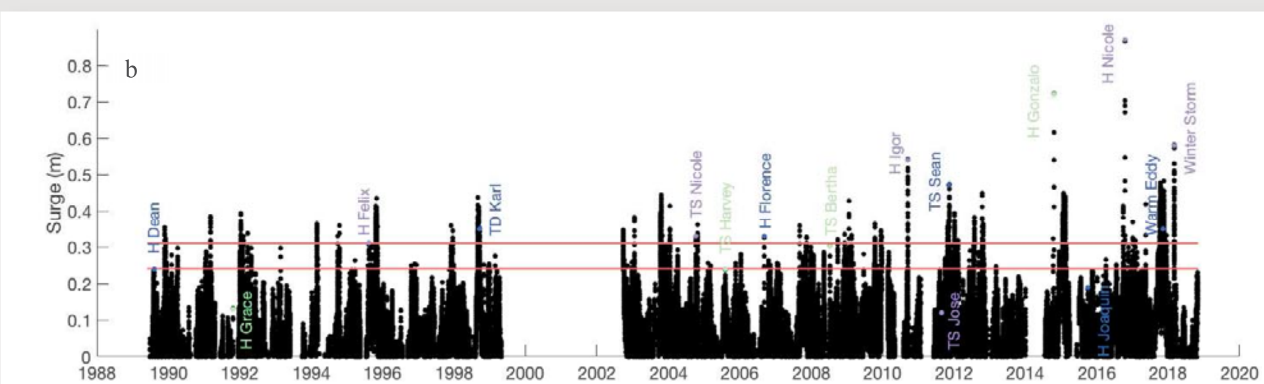
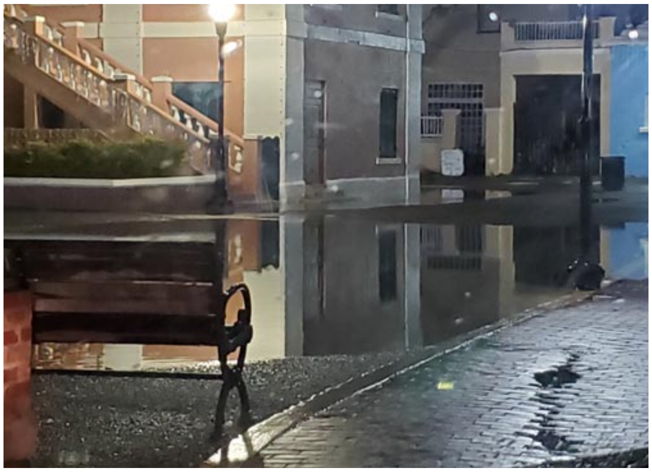


Figure 4 Time series of positive surge from the St. George's, Bermuda tide gauge, from June 1989 until October 2018. 14 selected TS and H events and two non-hurricane events (i.e., winter storm and a warm eddy) are incorporated within the time-series.

Bermuda through time. However, some notable events (Hurricane Fabian in 2003 and Hurricane Karen in 2001) are missing from the analysis due to a gap in data. Hence, such a conclusion should be treated with caution.

There is no correlation between tracks of hurricanes near Bermuda and local tidal phase; therefore, the timing of many of the largest surge events cannot be attributed to anything other than random chance (i.e., if the hurricane coincides with high or low tide). This could be more relevant for non-hurricane events, such as warm eddies, due to their longer duration. This idea is explored further in the next section of this chapter.

The timing of the closest passage of Nicole, and its consequent peak surge, allowed Bermuda to avoid the worst storm tide impacts. If the peak surge had been six hours earlier or later, Bermuda would have experienced approximately 1.4 m (4.6 ft) of water above mean sea level. The worst-case scenario would be for the peak storm surge associated with a hurricane's closest point of approach to coincide with a high tide, during a period when a warm eddy is inflating the background water level above the normal tide. The impacts of these plausible scenarios on coastal property and infrastructure will be further explored in *Part II* of this report.



A flooded street in St. George's.

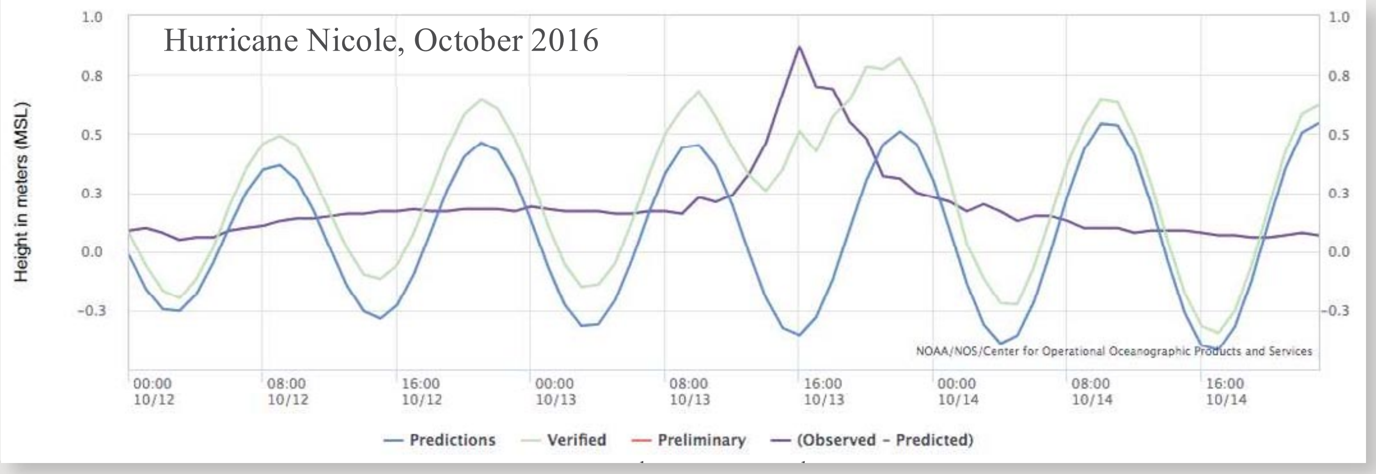
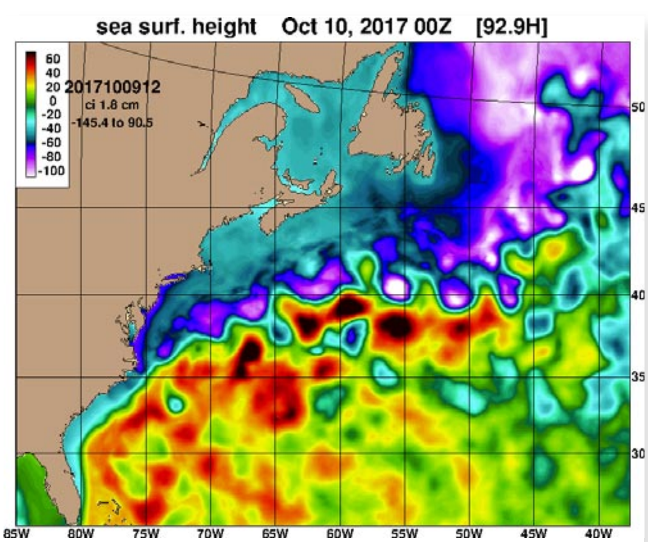


Figure 5. Example of tide gauge data from 12 to 14 October 2016 to show the water levels in Bermuda when Hurricane Nicole occurred.

Sea Level
Warm eddies

Sea level anomalies due to oceanographic phenomena (vs. weather) can also raise the baseline sea level. Notable recent examples include coastal inundation due to warm eddies in the absence of adverse weather conditions in October 2017 and November 2019. Recent extreme high tides in the last decade, (such as those that flooded St. George's in October 2017) are projected to be within the normal high tide range within the next two to three decades, based on Bermuda sea level rise projections developed by Kopp et al. (2014b). In this section, we present a case study and some context for 'sunny-day flooding' events that occur in the absence of storms developing a wind-driven surge.

Warm eddies in the North Atlantic are clockwise-rotating areas that have a higher-than-average sea surface height and can locally raise sea level. These warm eddies can be hundreds of kilometers in scale, and those that form in the eastern Sargasso Sea can occasionally affect Bermuda and raise the sea level locally (Johnson, personal communication). Conversely, cold eddies can suppress sea surface height, contributing to lower-than-average tides. It should be noted that warm eddies themselves are not caused by climate change, but their presence may exacerbate coastal flooding underpinned by broader-scale sea level rise, storm surge waves, and the astronomical tides.



In addition to warm eddies, spring tides occur twice each lunar month throughout the year, when the gravitational pull of the moon and sun work in concert with one another to increase water levels to higher heights than normal. The term 'spring tide' is unrelated to season, and refers more to when the tides 'spring up'. They are also commonly referred to as 'king tides'. The opposite effect is called a neap tide, which can lower water levels. oceanservice.noaa.gov/facts/springtide.html

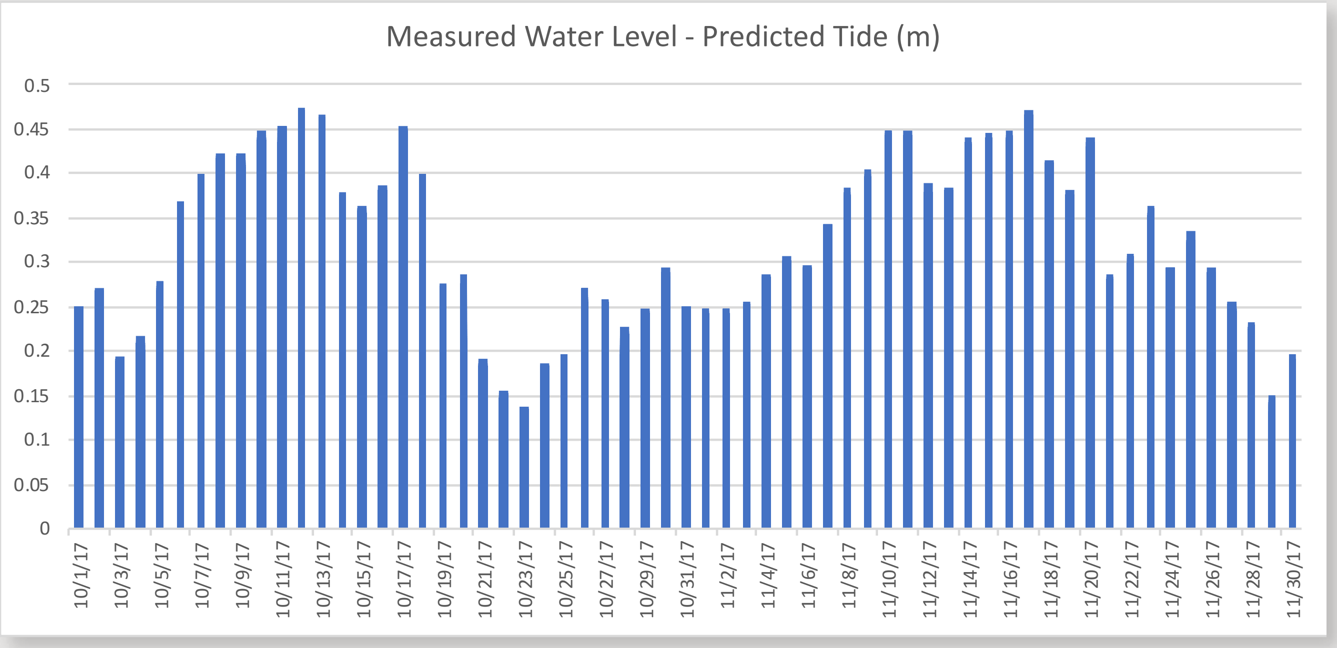
A long-term time-series of warm eddies in Bermuda has yet to be constructed, so no scientific conclusions can be made about the trends or variability of such eddies affecting Bermuda. However, it is known that they are spawned from the eastern Sargasso Sea, and can have wide-ranging effects on our local sea levels when coincident with other factors that temporarily raise these, such as hurricanes and spring tides. These warm eddies can provide significant sources of warmer near-surface water, which is a worrying revelation in the context of hurricanes. As warm water is the energy source for hurricane activity, it would be conceivable that the passage of a hurricane over a warm eddy could not only exacerbate local storm surge impacts, but also provide more energy for sustaining or strengthening the storm. Given that warm eddy events have occurred during hurricane season in recent years, the combination of these factors bears further scrutiny for disaster management.

The combination of spring tides and warm eddies in the area can greatly increase the water height compared to mean sea level, causing coastal flooding in the absence of any apparent weather effect. Incidents of coastal seawater inundation that are induced by the presence of warm eddies provide us with a useful advanced perspective on what are likely to be more frequent occurrences under future sea level rise. Accordingly, the next section examines an extreme instance of sunny day flooding, as a preview of what is to come.

Sea Level
A case study of 'sunny day' coastal flooding

October 2017 saw the development of a large-scale warm eddy moving through the Bermuda area, raising mean sea levels above the normal tide. Water levels over 30 cm (1 ft) above the predicted tides were experienced for 29 days during October and November 2017. Tide gauge measurements reaching 47 cm (just over 1.5 ft) above the predicted tide level were observed during this period.

This event was coincident with a spring tide and the combined effect was localized seawater flooding in low-lying coastal areas, such as King's Square and areas of Ordnance Island in St. George's. Other instances of localized coastal flooding and impacts were noted in the local press.



Water level departures above the normal (predicted) tide levels for October through November 2017 at the NOAA Tide Gauge on the north side of St. George's

The magnitude of this event is corroborated by measurements of sea surface height conducted from satellites. The presence of a warm eddy in the vicinity of Bermuda is evident on models of the ocean surface shown below, indicating anomalously high temperature, clockwise currents and sea surface heights exceeding 40cm (15") above the normal sea level around the island.

Similar conditions were noted periodically in subsequent years, especially 2019.

Left: King's Square St. George's, 7 Oct 2017. Source: Ralph Richardson. Right: Long-term airport parking flooding. Source: http://bernews.com/2017/10/long-term-airport-closed-due-flooding/ Source: Bernews

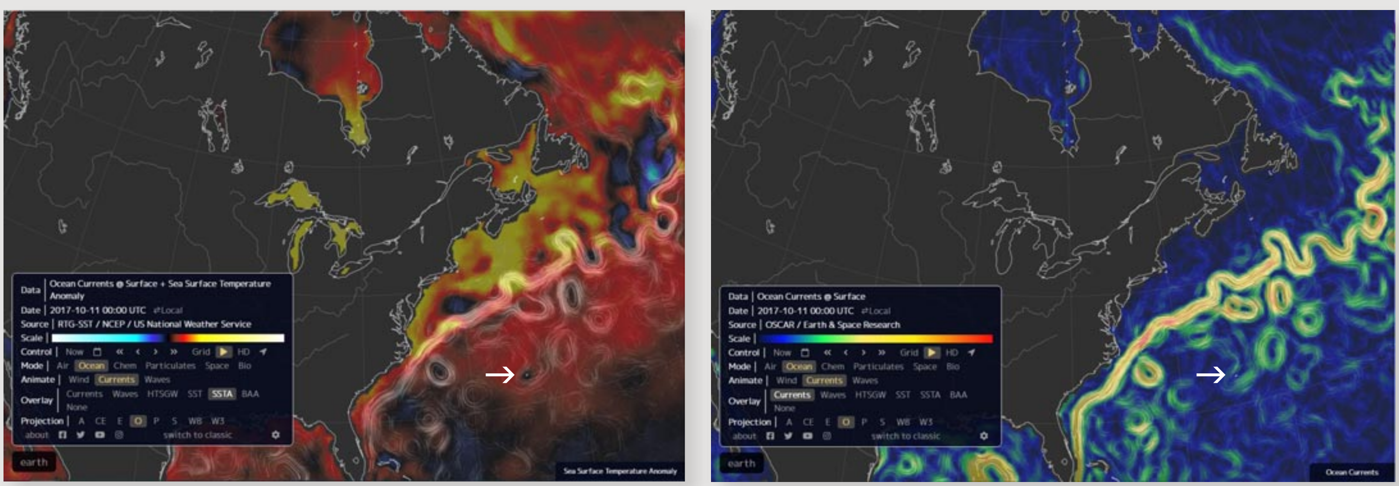
Sea Level
Conclusions

'Sunny day' coastal flooding events have been documented in recent years as being due to oceanographic features known as warm eddies that have raised the sea surface height up to 0.3 to 0.47 m (1 to 1.5 ft) above the normal tide. These events meet the thresholds for what are considered extreme events, exceeding the highest 0.1% of hourly surge measurements in the last 29 years.

Rising sea levels have been conclusively observed in the tide gauge record for Bermuda. Annual mean sea level in Bermuda is robustly projected under different warming scenarios (Kopp et al. 2014b), and may reach as high as 0.33 m (1.1 ft) by 2040, and 0.42 m (1.4 ft) by 2060. This puts the background annual sea level to the scale of today's extreme hourly events in as short of a time frame as less than 20 years.

One only needs to then add the highest record hurricane surge of 0.86 m (2.8 ft) for Hurricane Nicole in 2016 onto this backdrop of rising sea levels to reveal the threat of growing surge hazards, even without considering the potential changes in hurricane surges themselves. It's worth noting that the highest surge of Hurricane Nicole was measured at low tide, sparing Bermuda the worst impacts.

The combined effects of sea level rise with storm surge and warm eddy scenarios paint an alarming picture of Bermuda's future potential for coastal inundation. The impacts of these scenarios on Bermuda's coastal property and infrastructure will be explored further in *Part II* of this report.



Left - Sea surface height anomaly map for 10 October 2017; Middle – Model ocean Currents with sea surface temperature anomaly for 11 October 2017; Right - Model surface current speed for 11 October 2017. White arrows indicate location of Bermuda. Source: US Navy, earth.nullschool.net

Sea Level
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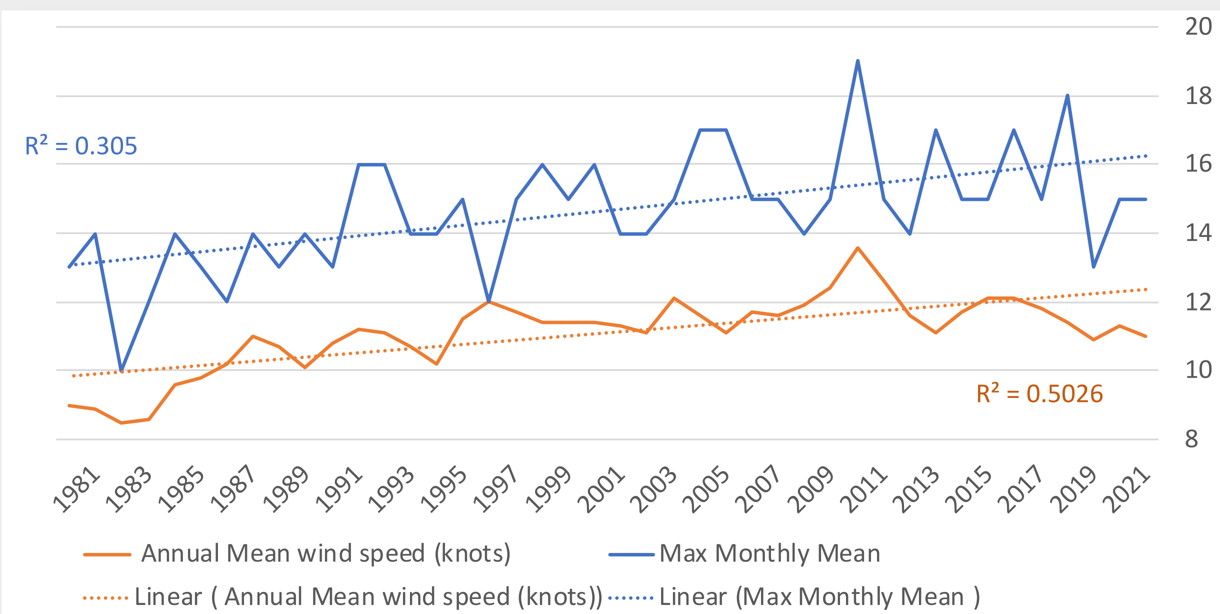
Wind and Waves

Wind and Waves

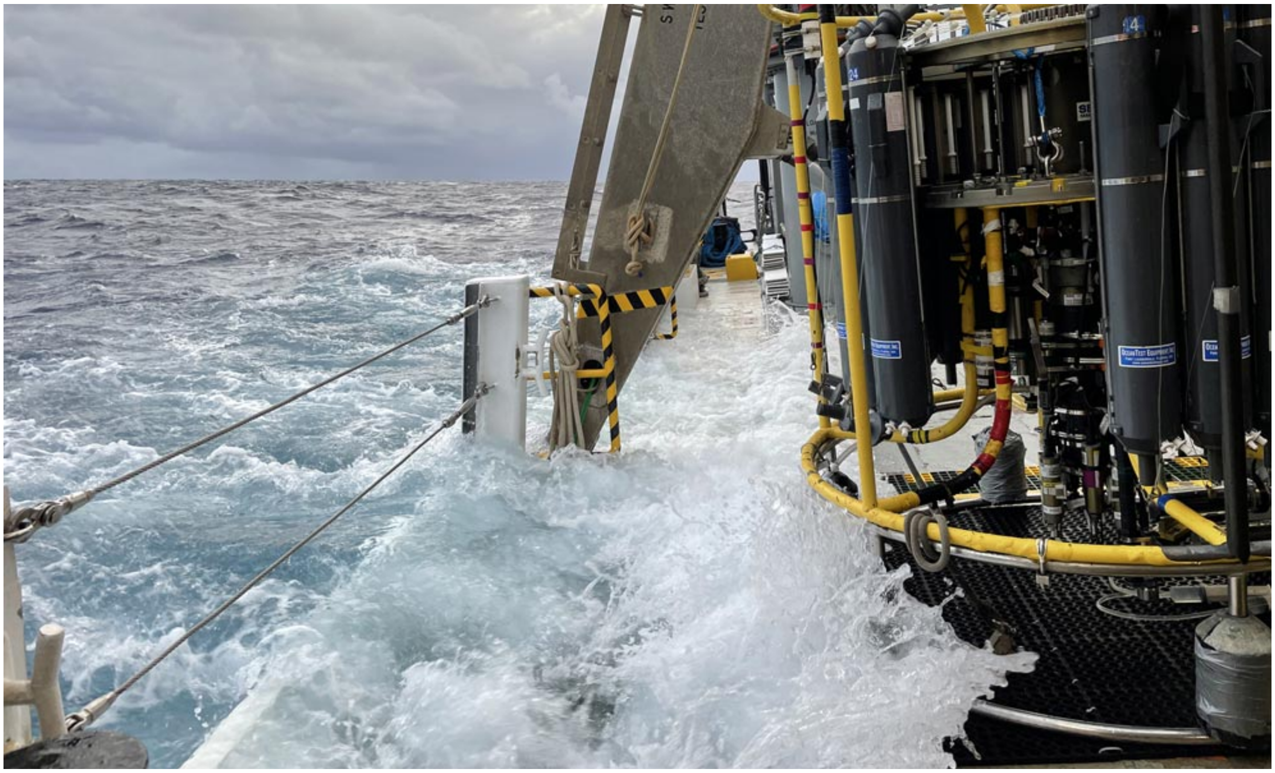
Average surface wind speeds

Wind speeds in the North Atlantic have been found to increase over the last few decades (Bates, 2007), and that trend has continued into the first 20 years of the 21st century. However, it should be noted that challenges posed by movement of instrument sites, changes in averaging period and more generally measurements that are not fit for the purpose of climate-scale analyses, make conclusions based on raw measurements from BWS less certain. For example, the wind speed monitoring instruments (called anemometers) at LF Wade International Airport are sheltered by hills to the north of the airfield. This means that winds observed at the airport by BWS are appropriate for aircraft landing and take-off meteorological reports, but not representative of many parts of Bermuda, and are not suitable for analysis of climate-scale changes without further processing. Doney (1996) found that wind speed measurements taken at sea by ships at buoys near Bermuda were 'systematically' stronger by as much as approximately 1.2 mph or 1.9 km/h. These challenges of siting instruments are explored in greater detail in the chapter of this report on temperature.

The increase in wind speed was a specific focus of Bates (2007), who found an increase in wind speed of 10-17% over the period of the study (1984-2005). Seasonality was also detected in the trends of Bermuda wind speeds during the



Average monthly wind speeds and maximum of monthly averages (both in knots), based on measurements at LF Wade International Airport from 1980 to 2021. Data from BWS, Bermuda Airport Authority. Linear trends and R2 values also shown.



Waves crash on the deck of R/V Atlantic Explorer along the CTD, a large piece of oceanographic equipment which is used to collect samples of seawater for the Bermuda Atlantic Time-series Study. Photo by Yuuki Niimi

same period, as seen in the following table.

Noting the challenges in measurement of wind speeds, these studies and datasets support an increase in average wind speed from the 1980s to the 2020s. As with other variables, this trend is not statistically significant, especially if one examines earlier measurements. Suffice to say a cohesive multi-decadal time-series of wind speeds is not available for Bermuda.

Considering the wider North Atlantic and longer-term records, Wohland et al. (2019) asserts that reanalysis datasets are inconsistent with one another for making conclusions about long term trends in North Atlantic-wide wind speeds. In the previous IPCC reports, confidence was low in surface wind speed trends. This may lead to uncertainty in forward looking projections that use reanalyses as a baseline.

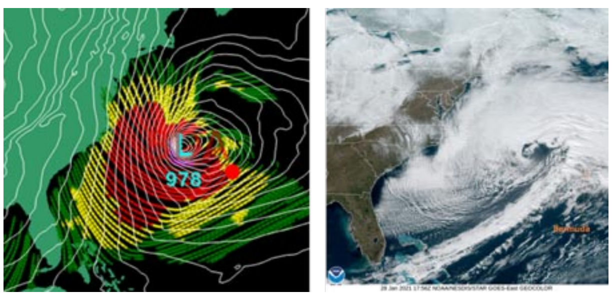
1984-2005	Change (mph)	Change (km/h)
Annual	2.24-2.75	3.60-4.43
Winter (JFMAM)	1.54-3.38	2.49-5.44
Summer (JJAS)	0.18-1.34	0.29-2.16
Autumn (OND)	2.55-2.98	4.11-4.79

Increases in wind speed in Bermuda, analyzed from one observational (BWS) and two reanalysis (ECMWF, NNR) datasets. From Bates (2007).

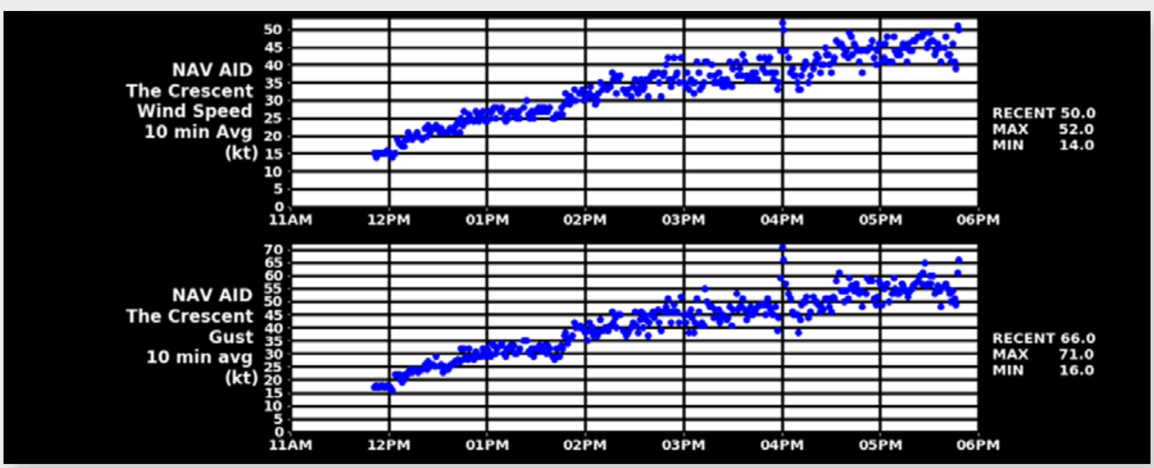
Wind and Waves

Winter gales

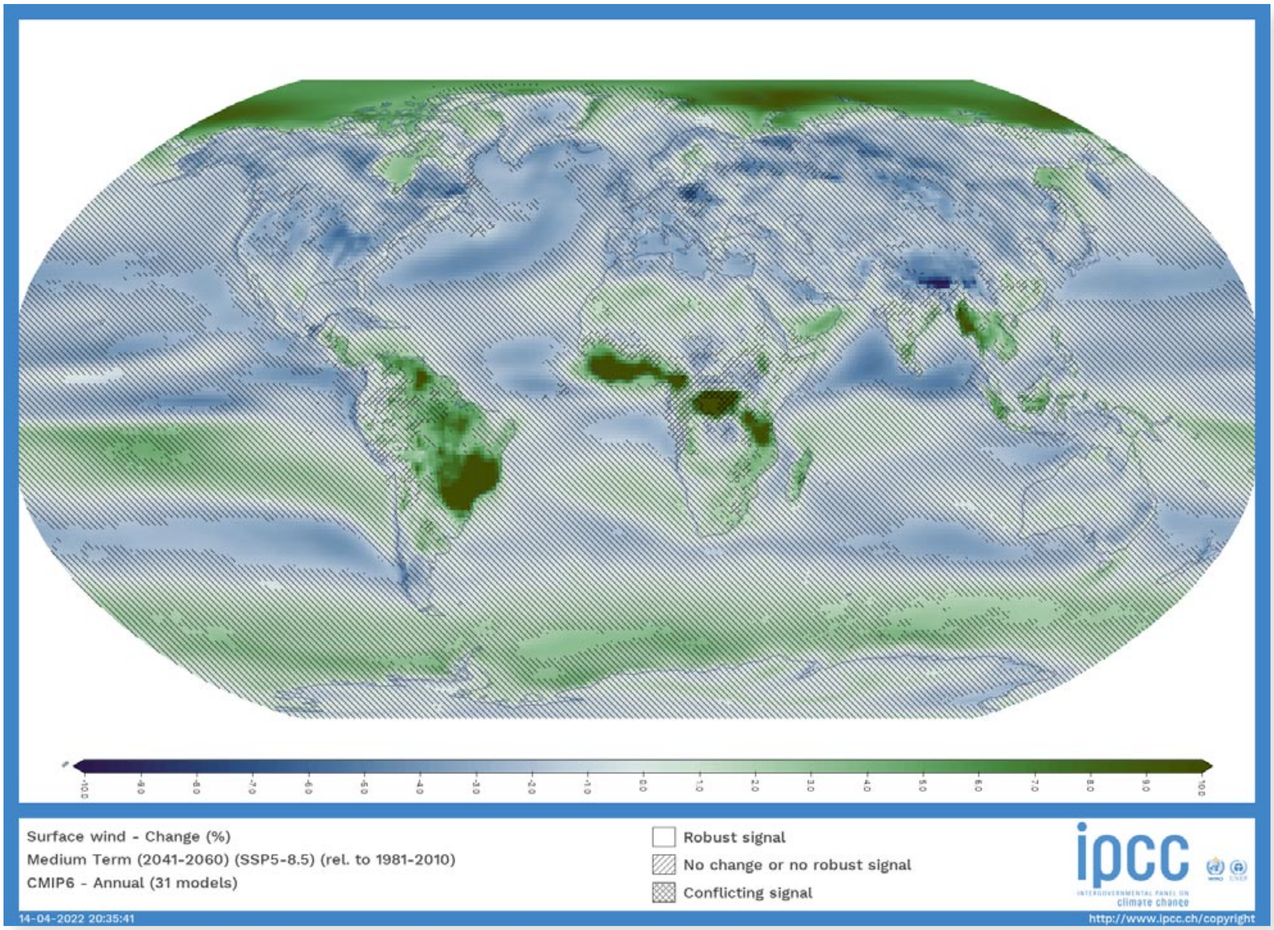
Beyond tropical systems (addressed in a separate chapter), impactful winds can be produced by winter weather. Large winter low-pressure systems (extratropical cyclones) in the western North Atlantic give rise to strong winds in Bermuda, sometime reaching gale force (34 knots / 39 mph / 63 km/h), especially in the winter. These systems can easily extend strong winds thousands of kilometers away from the low pressure centre (Colle et al., 2015). Hence, extratropical cyclones near the east coast of North America may produce gales over Bermuda. An example of this, from 28 January 2021, is shown in the figure below.



Much of the focus in the academic literature on change in extratropical cyclones has been centred on North America or Europe, but there are some useful conclusions to be gleaned from US-centric studies. Model simulation studies of storms along the US East Coast under present and future conditions (C. Marciano, 2014; C. G. Marciano et al., 2015) reveal a potential slight northeastward shift in storm track that might put more prevalent strong and gale force winds near Bermuda. However, there is much uncertainty in these conclusions, due to extratropical storms having multiple ingredients and influences, all of which may be changing under climate warming. It is worth noting that climate models inconsistently resolve aspects of extratropical cyclones in the North Atlantic (Colle et al., 2015), to the extent that any conclusions about their changes over time are tentative, and of low confidence.



Developing gale near Bermuda, 28 January 2021 – Top left: model representation of wind speeds (shaded – red displays gale-force winds) at 2:00 PM (local time) on 28 Jan 2021 and sea level pressure (solid lines); red dot is the location of Bermuda. Top right: Satellite image for same time, with Bermuda highlighted. Bottom panels: Graph of sustained wind speeds and gusts measured at the Crescent navigation aid north of Bermuda on 28 January 2021 11:00AM to 6:00 PM (local time). Sustained winds reached gale force at approximately 2:00PM.



Wind and Waves

Will winds continue to increase?

There is a high degree of uncertainty and complexity about the projections of average surface winds in the North Atlantic. This uncertainty may stem from disagreement between multiple climate-resolving models, themselves with their own varying sources of inputs and resolutions, as mentioned in the last section.

There appears to be a low confidence in projections of surface winds over much of the world, according to the recent datasets and resulting reports (Gutiérrez, 2021; IPCC, 2021). The trend of projections is for a slow-down of average surface wind speeds. However, as discussed previously, extreme winds, such as those stemming from the most intense hurricanes, should become more prevalent over time. Indications of the shifts in extratropical winter storms under climate warming simulation studies also hint that winter gales may become more prevalent in future (low confidence). There is a juxtaposition of regional extreme events, against a backdrop of projected slowing windspeeds in the wider North Atlantic, and the seemingly robust upward trends measured locally. This, all against the background of global uncertainty of historical trends, leads us to low confidence about the future regime of wind speeds in and around Bermuda.

Wind and Waves
Waves and swell

Background
Surface ocean waves are usually characterized by two main regimes–wind waves and swell. Wind waves are generally represented in observations, models and forecasts as 'Significant Wave Height', the average of the top one-third of the wave heights from trough to peak (Bureau of Meteorology, 2015). Swell waves (often simply referred to as 'swell') are wind waves that have moved away from where they were generated, frequently characterized by longer periods between wave peaks (US National Weather Service, n.d.). Swell can move thousands of kilometres away from the original weather system that produced it.

Trends
Unfortunately, there are no wave buoy measurements for Bermuda, so local historical trends are unavailable.

Model reanalysis datasets are gradually improving, with reanalyses that assimilate observations of marine observations and that have coupled ocean-atmosphere physics showing recent promise. However, technological improvements over time have caused spurious long-term trends in the datasets (Meucci, Young, Aarnes, et al., 2020). In other words, a reporting bias is introduced, simply because we have more and better ways to observe the ocean's winds and waves today than existed decades ago.

There is some consensus in the scientific literature about historical trends in surface wave activity in the oceans. Significant wave heights and swell have been increasing historically, although this information must be taken with a grain of salt, considering the uncertainty from winds in model reanalyses (Wohland et al., 2019) mentioned above. Wave power has been shown to have recently increased, with a link to ocean warming (Odériz et al., 2021; Reguero et al., 2019). This seems consistent with older studies that indicate a net positive increase in wave activity for the North Atlantic (Semedo et al., 2011).

It should not be surprising that, in the absence of robust projections of changes in average wind speeds, there are limited studies that confidently produce conclusions about the future of ocean waves and swell. Nonetheless, those that do focus on model projections of ocean waves consistently conclude a decrease in average significant wave height in the North Atlantic (Morim et al., 2019; Semedo et al., 2012). It is worth noting that studies focusing on coastlines exposed to waves and swell show little change or even a decrease in wave and swell activity for Bermuda (Amores & Marcos, 2020; Meucci, Young, Hemer, et al., 2020).

Wind and Waves
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