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Projecting the Reoccurrence of Major Caribbean Hurricanes under the Paris Agreement Goals

By

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A dissertation submitted to the University of Bristol in accordance with the requirements of the degree of MASTER OF RESEARCH in the Faculty of Science.

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Abstract

Hurricanes are among the most destructive extreme weather events affecting humanity, in both social and economic terms. Hurricane Maria devastated Puerto Rico in 2017 with the most rainfall to hit the country from a hurricane in 40 years, whilst secondary impacts such as flooding, landslides and disease were estimated to have claimed over a thousand lives. Since a large proportion of the Caribbean's coastal communities are affected by these systems and particularly vulnerable to their impact, it is critical that we develop an understanding of whether hurricane activity and associated impacts will change as a result of a warming climate – and if so, how – such that these countries can be informed when preparing for the impacts of climate change.

This thesis explores the influence of a 1.5°C and 2°C global warming above the pre-industrial average (the Paris Agreement scenarios) on hurricane rainfall using a dynamical hurricane model applied to future projection simulations from four global circulation models (GCMs). Results indicate that extreme hurricane rainfall events affecting the Caribbean region are more likely in the Paris Agreement scenarios. The Eastern Caribbean region displays a strong global warming signal for example, a rainfall event consistent with hurricane Maria is 57% more likely in the Paris Agreement goal of 2°C compared to the present climate. Overall, rainfall events resonant with hurricanes, Irma, Georges and Matthew become more likely under both Paris Agreement scenarios compared to the present climate. The likelihood of a hurricane with rainfall matching or exceeding that of hurricane Ivan, which hit Jamaica in 2004, does not largely differ between scenarios.

It should be noted that a large bias was present in the rainfall estimations. Though bias was corrected by applying a correction factor to fit estimations to observed return periods of hurricane rainfall events, readers should be aware of reduced confidence in the results.

Acknowledgements

I would like to thank my supervisors Dann Mitchell and Paul Valdes for their dedicated support and guidance throughout this project. I would also like to thank the HAPPI project, for funding me to go to the Frontiers of Science conference and the Alumni Grant Group for allowing me to present at the RMetS Early Career Scientist Conference. Finally, a special thanks goes to Kerry Emanuel for his help with generating the hurricane tracks and advice during the year.

Author's declaration

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

SIGNED: ..[redacted]......... DATE: ....06/11/2019..................

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1 Thesis Introduction

This thesis is based on a publication pending submission to Journal of Climate: Vosper, E., Mitchell, D., Emanuel, K., (to be submitted), 'Projecting the Reoccurrence of Major Caribbean Hurricanes under the Paris Agreement Goals'. The introduction and conclusion to the paper are framed largely upon the literature review and conclusion of this thesis, but have been left in for completeness. Author collaboration on this future publication include supervisory roles and a review of work conducted. All analysis and preliminary work was undertaken by the lead author, however hurricane tracks were generated by Kerry Emanuel.

2 Literature Review

Current greenhouse gas mitigation ambition is consistent with a ~ 3°C global mean warming above pre-industrial levels (1850 - 1900) by the year 2100 (Rogelj et al. 2016). The Intergovernmental Panel on Climate Change (IPCC) Special Report on 1.5°C presents a clear picture that limiting global warming to 1.5°C over 2°C significantly decreases the risks associated with the impacts to both human and natural systems brought about as a result of an increased mean global temperature (Hoegh-Guldberg et al. 2018).

There is broad consensus among the scientific community that small island developing states (SIDS) are extremely sensitive to climate change impacts (Ourbak and Magnan 2018; Campbell and Barnett 2010) such as heavy precipitation (Peterson et al. 2002), sea level rise (Lal et al. 2002) and coral bleaching (Ourbak and Magnan 2018).

Current greenhouse gas concentrations are consistent with a 1°C warmer world compared to pre-industrial levels (Haustein et al. 2017). Over the past 50 years, small island states have already been feeling the effects of a 1°C warming in terms of increased occurrence of warm temperature extremes, fewer cool temperature extremes and increased precipitation intensity (Stephenson et al. 2014). With this in mind, at the more ambitious target of 1.5°C warming, SIDS stand to be disproportionately affected by the corresponding impacts to human and natural systems while being among those who have made the smallest contribution to anthropogenic climate change (UNFCCC 2005). They are likely to suffer irreconcilably from the adverse impacts that it will bring, meaning adaptation and resilience planning are paramount to maintaining habitability while mitigation and coastal management will be required to preserve marine biodiversity and current coastal infrastructure. It is crucial that the international community band together to support these endeavours such that small island states can receive the much-needed knowledge and support they require in order to prepare effective and targeted resilience plans in the face of climate change.

2.1 Future climate change impacts to small island developing states

SIDS stand to benefit from increased mitigation efforts to stabilise global warming to the lower target of 1.5°C versus 2°C, especially when combined with enhanced action toward climate resilience (Hoegh-Guldberg et al. 2018).

By 2150, lands home to approximately 60,000 people would avoid inundation due to sea level rise in a 1.5°C scenario compared to 2°C (Rasmussen et al. 2018). Indeed, by restricting global warming to the lower target, the risk of coastal flooding could be decreased by as much as 80% for SIDS compared to the 2°C goal (Rasmussen et al. 2018).

A rise in sea level is likely to contribute to an increased storm surge risk from tropical cyclones (Walsh et al. 2015). Coral reefs provide vital coastal protection to SIDS by forcing waves to break away from the shore, thereby preventing the most powerful part of the wave from breaking on the coast. Coral reef systems are slow-growing, complex ecosystems which provide shelter and food to millions of marine species and are important for biodiversity and as a result attract tourism which is vital to economies of many SIDS across the world. Coral reefs are particularly susceptible to the impacts of increased atmospheric CO_2 concentrations: the resulting global and ocean warming causes coral bleaching and ocean acidification which makes it harder for corals to form skeletons, leaving them more vulnerable to breaking (Pörtner et al. 2014). If global temperatures were limited to 1.5°C above pre-industrial levels, in 2050 just 10% of the worlds coral reefs would still reside in an environment which fosters healthy conditions. However, in a 2°C warmer world, temperature-induced bleaching, which leads to severe coral deterioration, would pose a serious risk to virtually all coral reefs (Schleussner et al. 2016). Reefs form a natural coastal barrier offering protection against many natural hazards such as storm surges from tropical cyclones which often affect regions in which SIDS are found.

A tropical cyclone is a rapidly rotating storm characterised by winds of at least 119 km/hr and a low-pressure centre. Hurricanes, typhoons and cyclones are all tropical cyclones formed in the North Atlantic, Northwestern Pacific and the South Pacific & Indian Oceans respectively. In the North Atlantic basin, tropical cyclones are called hurricanes and on average there are 6

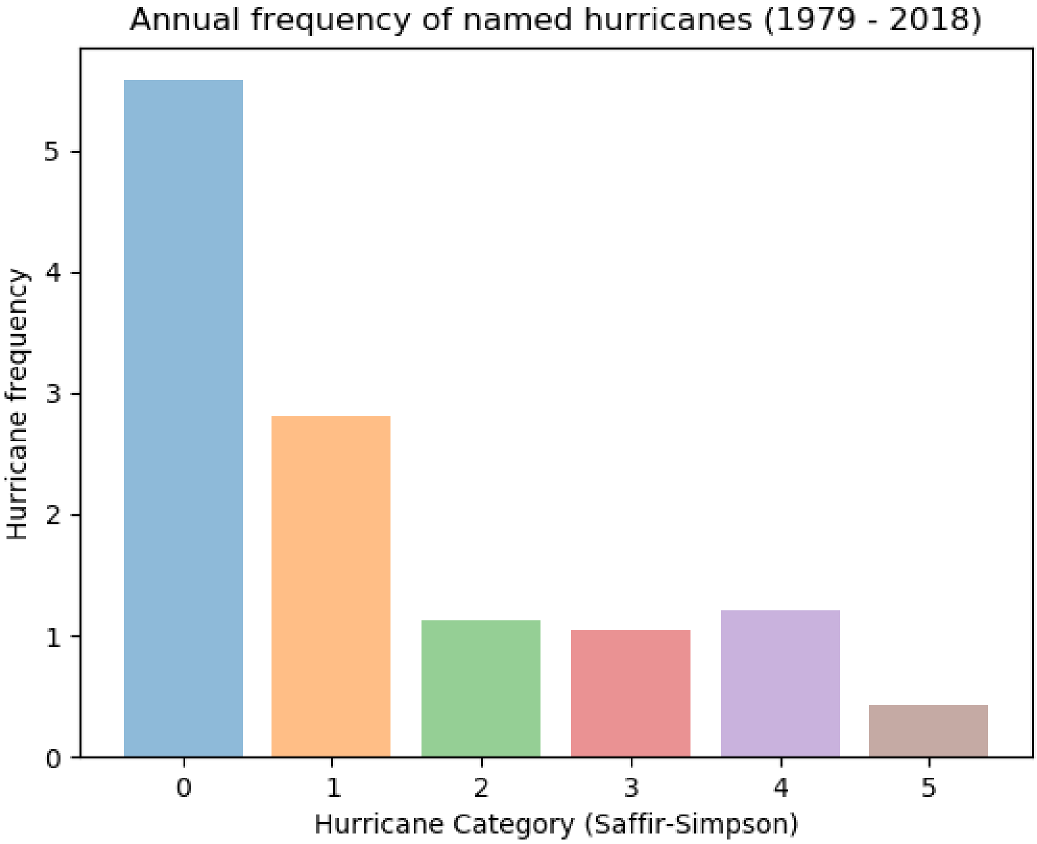

Figure 1: The average annual number of hurricanes derived from Best-Tracks data during the period 1979-2018. The y-axis is the average number of tropical storms occurring per year in the North Atlantic basin, categorised by the Saffir-Simpson scale on the x-axis.

hurricanes per season with 2.5 becoming category 3 or greater (Figure 1). Tropical cyclones will hereafter be referred to as hurricanes when in the context of the North Atlantic basin. Otherwise, when describing physical processes and general characteristics, they will be referred to as tropical cyclones.

Although tropical cyclones are a normal part of life for many SIDS, compound extreme weather events could pose more of a threat in the face of climate change. A “TC-heat” event occurs when a tropical cyclone, which can often wipe out local power infrastructure, is followed by a heatwave, leaving the affected population vulnerable to heat stress in its wake (Matthews et al. 2019). While rare, occurring approximately three times per 30-year period, the impact of just one event can be enormous; for example, Typhoon Haiyan caused 6.1 billion customer hours of power losses when it hit the Philippines in 2013 (Matthews et al. 2019). If global mean temperature warming can be kept to 1.5°C then the expected 30-year frequency of TC-heat events would be four fewer than under a 2°C warming scenario (Matthews et al. 2019).

In the more general case, heat-related hazards pose a wide threat to SIDS under global warming. For example, warm-spell duration — the duration of time surface temperatures is greater than the 95^{th} percentile — has shown an increasing trend this century (Perkins et al. 2012). A 1.5°C warmer world is projected to host very warm days for up to half the year in the Caribbean region, with an additional increase by as much as 70 days in a 2°C warmer world (Taylor et al. 2018). Warm spells can also impact freshwater resources, which are limited in size on small islands and highly responsive to climate stresses (Stocker et al. 2013), through higher evaporation losses and reduced water quality due to phenomena such as algal blooms which thrive during warm spells (Metz et al. 2007). Overall, Freshwater stress could be significantly reduced by limiting global warming to 1.5°C instead of 2°C: for example, the Caribbean region would benefit from this scenario more than any other region, with a 25% reduction in projected water stress at the lower target (Karnauskas et al. 2018). Additionally, it is important to note that a reduction in water stress would prove beneficial in terms of improving SIDS climate resilience (Benjamin and Thomas 2016).

2.2 The Caribbean Region

One region which hosts a large collection of small island states is the Caribbean. Organised into 28 territories, the region consists of over seven thousand islands, including islets, reefs and cays, which are sorted into three main island groups: the Greater Antilles, the Lesser Antilles and the Bahamas (Rogoziński 1999). Home to around 44 million people (Mimura et al. 2007), the Caribbean sits within the North Atlantic basin (figure 2) whose hurricane season runs approximately from the 1^{st} of June to the 30^{th} November and naturally coincides with the Caribbean's rainy season (Emanuel 2005a).

Since 1960, the Caribbean has experienced 264 hurricanes which make up 71.4% of all natural disasters affecting the region (Burgess et al. 2018). Furthermore, hurricanes cause the most damage in the Caribbean — accounting for 94.5% of the total damages from all natural disasters (Burgess et al. 2018) and for the vast majority of extreme rainfall events and extreme sea levels experienced in the region (Khouakhi et al. 2017; Walsh et al. 2015; Peterson et al. 2002).

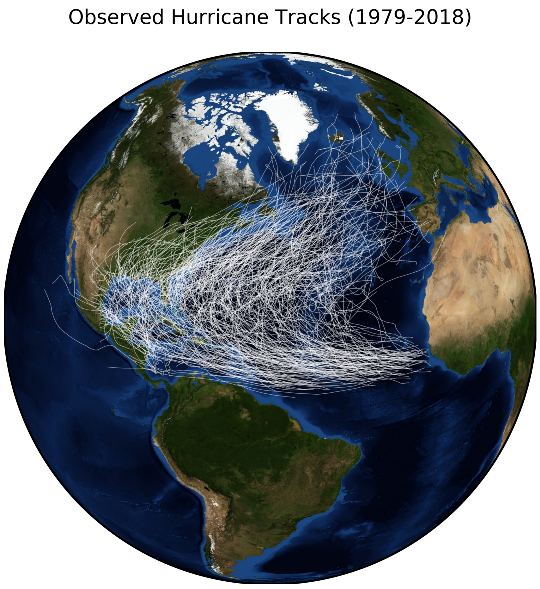

Figure 2: Hurricane tracks (in white) derived from the 620 hurricanes which formed during the period 1979-2018 according to best-tracks data.

2.3 Assessing the Caribbean's vulnerability to hurricanes

More than half of the regions population of 44 million reside within 1.5 km of the coast leaving the Caribbean particularly vulnerable to hurricanes (Mimura et al. 2007). Critical infrastructure such as major roads, air and seaports, utilities and communication networks tend to be constrained to low-elevation coastal zones (LECZs; Cruz et al. 2007; Mycoo 2018). Neumann et al. (2015) define LECZ as "the contiguous area along the coast that is less than 10 m above sea level" and estimate that the LECZ population in the Latin America and Caribbean LECZ will double by 2060 compared to 2000 with current population projections. These areas are at risk of storm surges, some of which can be extreme and wipe out crucial services. For example, Hurricane Ivan (2004) brought storm surges of up to 3 m to some regions, particularly in Jamaica where the main road to the airport was blocked and residential properties were damaged or destroyed (Cashman and Nagdee 2017).

The reason for such a pattern of settlement is due to the rise in tourism becoming the main economic activity for the region with the dense building of beachfront resorts, services and supporting infrastructure (Zappino 2005). Population shifts and continued development of new properties have contributed to encroachments onto flood prone areas and steep slopes, often lacking in adequate drainage (Lewsey et al. 2004; Holcombe et al. 2012). This, coupled with the inherently steep topography, deep soils and small size of the majority of the Caribbean states, means that rainfall accumulates quickly causing flash flood events and often landslides (Cashman and Nagdee 2017; Anderson et al. 2008). Such coastal settlement patterns inhibit natural drainage, e.g. concrete replacing soil, which leads to increased water run-off while buildings also restrict natural flood channel size meaning that lagoons and floodplains — i.e. natural forms of flood retention — cannot cope with an increased load resulting in inundation of a wider area (Cashman and Nagdee 2017).

Not only does the distribution of population play a part in the region's vulnerability, but the post-hurricane recovery time can be slow and roughly coincides with the average hurricane return time of approximately 5-10 years (Johnson and Watson 1999). In the tourism sector, which generated 56.4bn USD towards the GDP for the region in 2016 (15.2% of total GDP), recovery time can take up to four years (World Travel and Toursim Council 2017) and this can be even longer in the case of agriculture. The island of Grenada, for example, was once the world's second largest exporter of nutmeg after Indonesia. Before hurricane Ivan struck in 2004, over 27% of the island's population relied on nutmeg as an income source but in Ivan's aftermath national production declined by more than 60% (Barker 2012). Unlike bananas, which can fully mature in less than 12 months with prompt replanting, nutmeg takes several years to recover from severe wind damage and even in 2009 the total production of nutmeg was still only 12% of pre-Ivan levels (International Trade Centre 2010). In terms of property, Grenada took over five years to recover as the vast majority of housing, public schools and health infrastructure was severely damaged (World Bank 2005).

Hurricanes bring with them large, powerful waves which disrupt coral reefs by breaking off branches while increased water run-off flowing into the sea can bring sediments and nutrients (fertilisers from agriculture) which aid the growth of algae – a competing species (Heron et al. 2005). Though local coral reefs are accustomed to the effects of hurricanes, having survived in the region for millions of years, when coupled with a rapidly changing climate, increased thermal stress, ocean acidification and over fishing, the corals ability to recover from severe storms will become exhausted (Heron et al. 2005). Coral reefs cause incoming waves to break offshore and dissipate most of their energy before reaching the shoreline thus they form a natural coastal protection (ARC Centre of Excellence in Coral Reef Studies 2018). Moreover, they play a crucial role in the regions flourishing tourism industry (WRI 2006) and sustaining their health is paramount in order to preserve the status quo in the region.

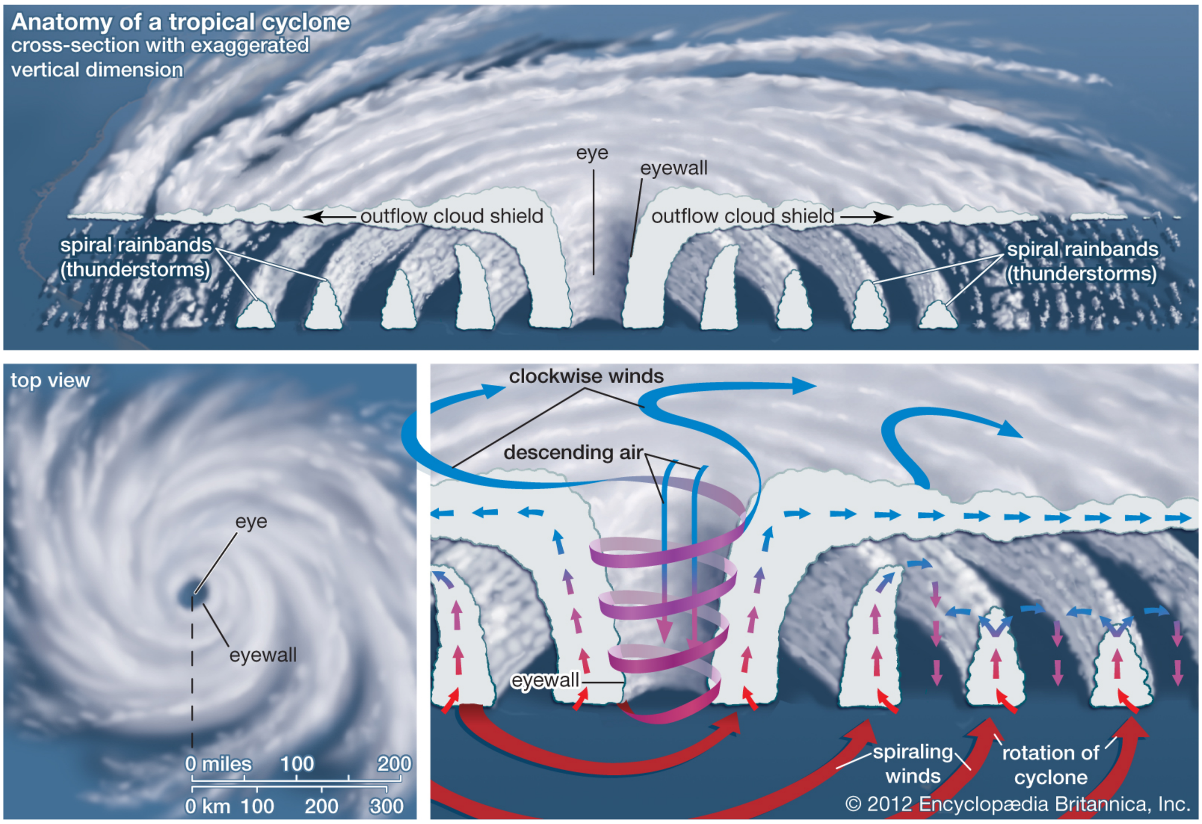

Figure 3: A schematic of tropical cyclone characteristics (Figure credit: Encyclopedia Britannica 2012)

As a collection of SIDS already feeling the effects of global warming, the Caribbean region is clearly vulnerable to hurricanes and their corresponding secondary impacts. To explore this natural phenomenon in the context of climate change, the study must look at the underlining processes which aid in the formation and intensification of tropical cyclones and how these might change in a warming world.

2.4 Tropical cyclone characteristics, formation and metrics

Tropical cyclones span a 2-300 km radius centred around a warm-core, low-pressure centre named the eye. Typically, the eye is an area of very calm weather with a diameter of around 30-60 km and is surrounded by the eyewall — an area of warm, humid and rising air where the most intense winds rains and thunderstorms occur. Rain bands form the recognisable swirl pattern, visible in satellite imagery (figure 3), produced as a result of air travelling outward at the upper levels and move by the Coriolis effect.

Tropical cyclones form in tropical regions as a result of atmospheric disturbances such as tropical waves. Such tropical waves propagate and create a series of eddies which go on to form clusters of thunderstorms. These clusters can begin to converge and become more organised while they travel over warm tropical waters, moving westerly in the Northern Hemisphere and easterly in the Southern Hemisphere due to the Coriolis effect. The Coriolis effect causes the clusters to rotate around each other and become more vigorous. As they rapidly intensify, a low pressure centre forms and air from the surround area travels towards it while being heated by the sea surface. Humidity increases as the air travels inward and builds up latent heat – the most powerful source of heat driving the tropical cyclone (Emanuel 2005a). For example, hurricane Sandy which hit the US coast in 2012, generated more than twice the energy of the Hiroshima atomic bomb (McNoldy 2012). Once the air reaches the eyewall it can no longer travel towards the centre due to the temperature gradient, so instead it travels upwards and forms cumulus nimbus clouds as the water condenses (figure 3). Once the air reaches the upper troposphere or lower stratosphere it sinks to reach equilibrium, some air also dissipates its heat outward, this is known as the outflow. As the air at this level cools, it then sinks towards the surface as it further dissipates heat to its surroundings (Emanuel 2005a).

Tropical cyclones form in the presence of certain favourable conditions. In order to develop, they require a sea surface temperature (SST) greater than 26.5°C, although some studies report the threshold to be lower under certain circumstances (Tory and Dare 2015). Sufficient SST provides enough heat energy in the system to create and sustain convection. High lower-tropospheric relative humidity is required so that enough moisture is kept in the atmosphere to allow convection to continue. Should dry pockets of air be swallowed by a hurricane, convection is inhibited, and cooler downdrafts can result (Emanuel 2005a). High vertical wind shear i.e. high difference in wind speed and direction between 250 and 850 hPa of above 10 ms^{-1}, is detrimental to tropical cyclones' development as it can cause the vortex-like shape of the tropical cyclone to tilt exposing the mid-levels to calmer, drier air pockets which mixes with the inner core of the storm undercutting the updrafts and eventually disrupting the tropical cyclone (Tang and Emanuel 2012).

Tropical cyclones in the Northern Hemisphere rotate anticlockwise, while those in the Southern Hemisphere rotate clockwise and in fact no tropical cyclones will form in the region surrounding the equator. The reason for this is the Coriolis Effect i.e. the disparity between the rotation of the Earth and the "disconnected" atmosphere which causes tropical cyclones to move westward and towards the poles (Emanuel 2003). Tropical Cyclones also move with the surrounding large-scale wind fields (Marks 1992) and occasionally this wind field can weaken which can lead to a tropical cyclone stall event whereby the translation speed will slow or the

Table 1: Saffir-Simspon Hurricane Wind Scale. Table from National Oceanic and Atmospheric Administration

Category	Sustained Winds	Damage Sustained
1	119-153 km/h	Very dangerous winds will produce some damage
2	154-177 km/h	Extremely dangerous winds will cause extensive damage
3	178-208 km/h	Devastating damage will occur
4	209-251 km/h	Catastrophic damage will occur
5	>252 km/h	Catastrophic damage will occur

tropical cyclone track will loop. If this happens in the case of major tropical cyclones, this process can cause widespread devastation such as in the case of Hurricane Harvey (2017) which stalled over Texas bringing large amounts of rainfall to the region over a period of four days (Emanuel 2017). Hall and Kossin (2019) analysed the activity of stalling hurricanes on the coast of the United States and found a moderately increasing trend in the number of hurricane stalls in this region, this is in line with Kossin (2018) who indicated a decreasing trend in hurricane translation speed throughout the century.

An individual storm is most commonly categorised using the Saffir-Simpson scale – a system where a tropical cyclone is rated between 1-5 based on its sustained wind-speed (Table 1; National Oceanic and Atmospheric Administration). Other metrics exist which arguably better estimate a storm's total energy and highlight cases where large tropical storms have caused more damage than weak hurricanes, for example the Integrated kinetic energy (IKE; Powell and Reinhold 2007) and the Hurricane Severity Index which takes both intensity and size into account (HSI; Hebert et al. 2010). IKE is calculated by integrating the 10 m kinetic energy over the domain of the storm providing an objective way to compare hurricanes and calculate the destructive potential irrespective of hurricane category. However, due to the wide adoption and understanding of the Saffir-Simpson scale it will be used throughout this study.

To summarise the activity of an entire tropical cyclone season, two widely used metrics exist: Accumulated Cyclone Energy (ACE; Bell et al. 2000) and the Power Dissipation Index (PDI; Emanuel 2005b). Both can also express an individual storm's activity by an integral of a storm's maximum sustained 10 m wind speed over its lifetime (every 6 hours), however PDI is the velocity cubed and the ACE is the velocity squared. The sum of each individual storm's measure makes up the seasonal result, thus these metrics comprehensively evaluate many tropical cyclone features such as total number, intensity and duration (Villarini and Vecchi 2012).

2.5 Major hurricanes in the Caribbean

This study looks at five major hurricanes to hit the Caribbean region in the past 40 years. These hurricanes were chosen as they were calculated to have brought the largest hurricane total rainfall to their respective country during this period.

Hurricane Georges (15 September – 1 October 1998) began life after the disturbance of a tropical wave which originated off the coast of Senegal on the 13^{th} of September. It gradually strengthened as it moved westward and made seven landfalls over the Caribbean and the USA. Georges was prolific for rainfall, satellite estimates suggest that as much as 990mm of rainfall fell in 24 hours over parts of the Dominican Republic and Haiti, where the majority of the 602 fatalities occurred due to flash flooding and resulting landslides (Guiney 1999).

Hurricane Ivan (2 September – 24 September 2004) reached category 5 strength on three separate occasions throughout its journey from the east of Africa, through the Caribbean and up to Florida. Ivan released the most rainfall over Jamaica, where over 635 mm of rainfall was recorded in many locations across the country. At least 47,000 homes were damaged or completely destroyed as a result of the category 4 winds and extreme rainfall with costs approximated at roughly 360mn USD for the country as a result of Ivan (Stewart 2004).

Matthew (28 September – 9 October 2016) hit Haiti as a category 4 hurricane, before moving to Cuba, the Bahamas and then South Carolina causing widespread devastation throughout its journey. Although, no official values for storm surges in Haiti or the Dominican Republic were available, media outlets reported considerable inundation and Cuba measured a storm surge of 3-4 m along its south coast (Stewart 2017). The majority of human fatalities occurred in Haiti where some 340,000 people were evacuated. Over 350,000 animals were killed by the hurricane. Some locations in Haiti received more than 500 mm of rainfall resulting in flash flooding and mudslides contributing to the destruction of around 29,000 out of 210,000 damaged homes (Stewart 2017). There was a cholera outbreak following Matthew, with around 10,000 cases according to the Pan American Health Organisation (PAHO). Overall damages to Haiti were estimated at around 1.9bn USD which is approximately 10% of the country's GDP (World Bank).

Hurricane Irma (30 August - 12 September 2017; Figure 4) a long-lasting hurricane which originated from a tropical wave that departed the west coast of Africa on 27^{th} August 2017

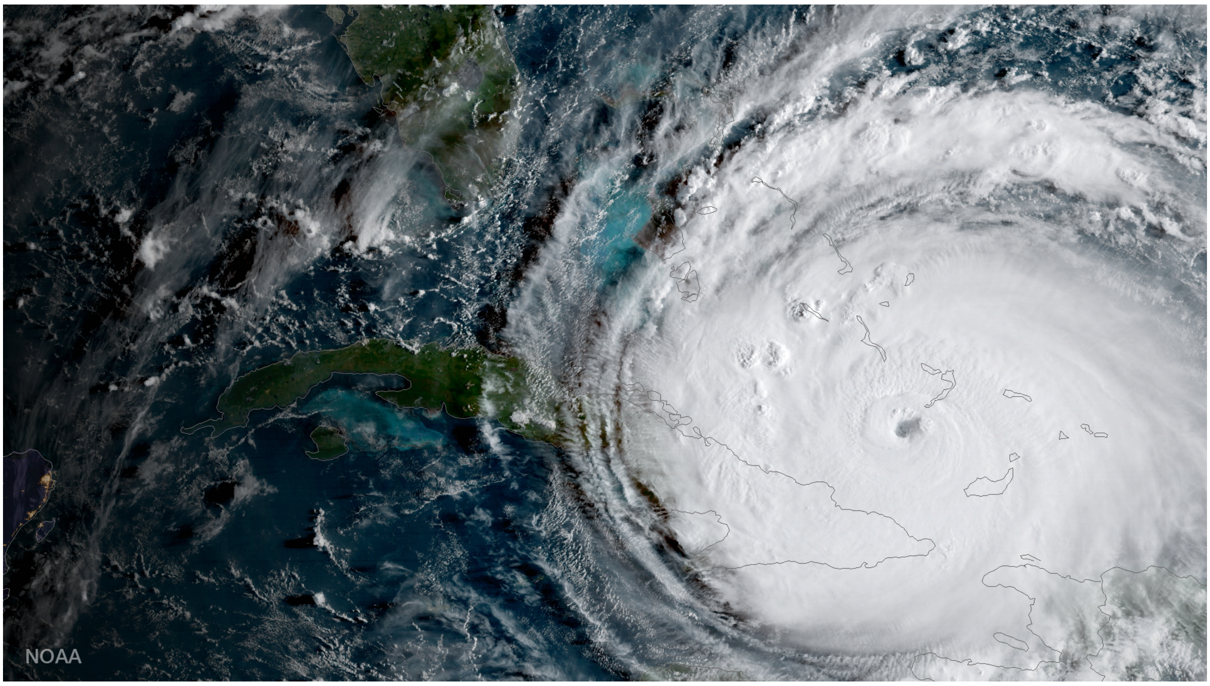

Figure 4: Hurricane Irma approaching Eastern Cuba as a category 4 storm on the 8^{th} of September 2017. (Credit: NOAA).

(Shuckburgh et al. 2017). The hurricane had peak winds of 180 mph and made landfall seven times, four of which hit the Northern Caribbean region at category 5 strength (table 1). Consequent storm surges resulted in some areas being inundated by at least 8 ft of water with catastrophic consequences (Shuckburgh et al. 2017). Irma caused extensive damage to many Caribbean islands and parts of the US with estimated losses of around 2.8bn USD in the Caribbean alone (Cangialosi et al. 2018).

Hurricane Maria (2017) followed shortly after Irma and caused tumultuous damage to the island of Dominica. Figure 5 portrays the relative scale of hurricane Maria compared to the countries it made landfall. The destruction was estimated to cost at least 1.31bn USD with the agricultural sector more or less eliminated, most trees and vegetation destroyed and intense structural damage to infrastructure (Pasch et al. 2019). Hurricane Maria was a particularly rare event which also hit Puerto Rico with an unprecedented amount of rainfall and had an official death toll of 64 (Kishore et al. 2018) however, the mortality is likely to have exceeded 1100 due to related impacts such as disease outbreaks (Santos-Lozada and Howard 2018). Moreover, in the following 15 years since Maria, Puerto Rican incomes could reduce by as much as 21% (Hsiang and Houser 2017), a possible driving factor for the predicted outward migration of 14% of the population in the wake of hurricane Maria (Meléndez and Hinojosa 2017).

Overall, 2017 was a particularly catastrophic year for the North Atlantic basin: it was the

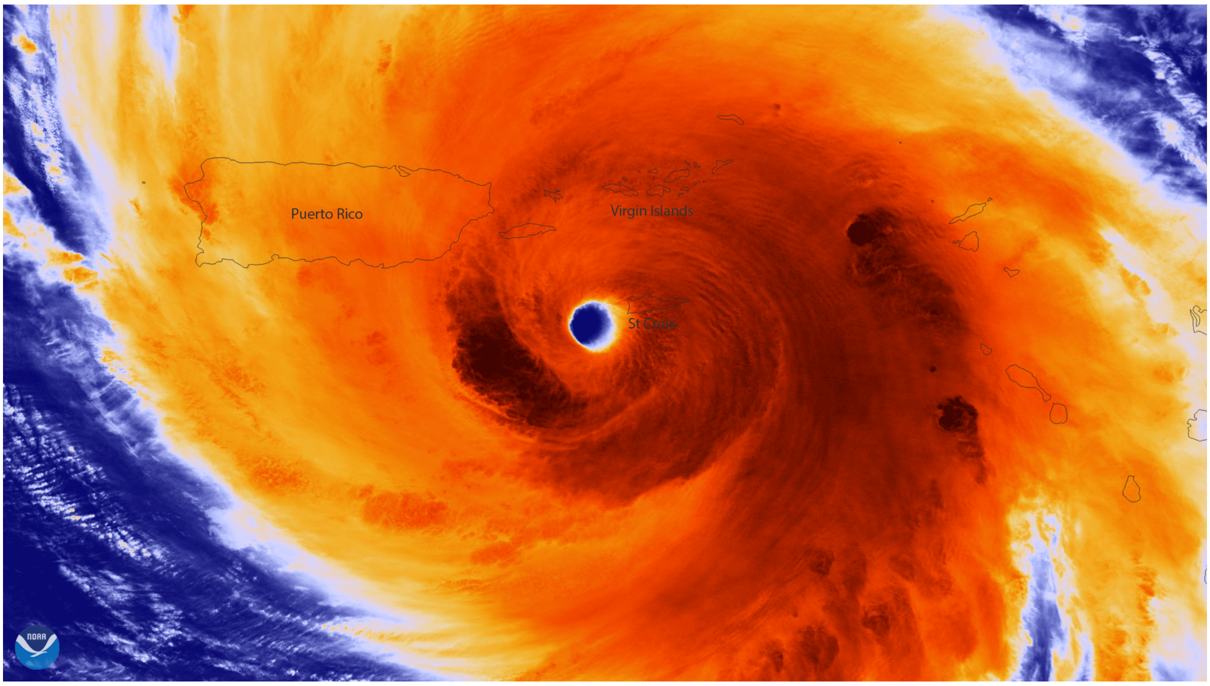

Figure 5: A colourised infrared image of Hurricane Maria taken on the 20th of September 2017. Approximately three hours later, the category 4 hurricane made landfall in Puerto Rico with maximum wind speeds of 150 mph (Credit: NOAA).

costliest season since records began in 1851, costing around 370bn USD according to best estimates, the majority of this caused by hurricanes Maria, Irma and Harvey (Halverson 2018; Rahmstorf 2017). Harvey, Irma and Maria crossed highly populated areas which would have made a significant contribution to the economic damage. Hurricane Harvey (17 August – 1 September 2017) was notable due to the profound amount of rainfall it brought to the Texas coast, it stalled over the region for four days and dropped over 1500 mm of rain over South-Eastern Texas (Blake and Zelinsky 2017). With six hurricanes making landfall, the Accumulated Cyclone Energy (ACE) for the 2017 season was 226 x 10^4Kn^2 which is the seventh most powerful season. The month of September contributed 175 x 104Kn^2 — the largest on record for the Atlantic basin (Hallam et al. 2019). September 2017 broke other records including 41 hurricane days (sum of hurricane duration in days) and hosted the warmest sea surface temperatures on record with 0.96°C warmer waters compared to average (1901-2017) (Lim et al. 2018). This anomaly, caused by weaker heat loss at the ocean surface and reduced ocean upwelling of cooler water, was the main contributor in the severity of the 2017 hurricane season and the late onset of the SST anomalies made this season particularly hard to predict (Hallam et al. 2019).

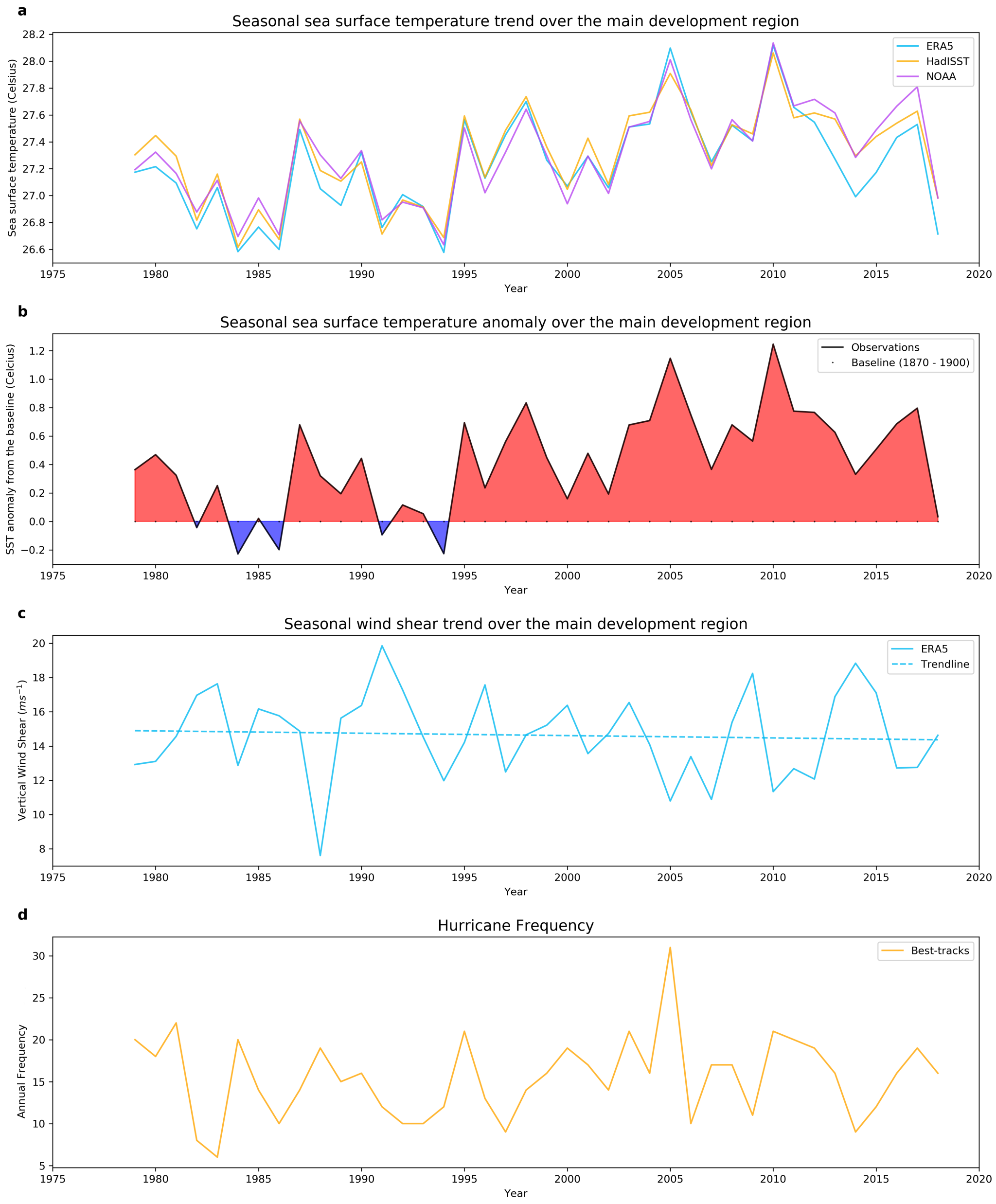

Figure 6: Seasonal sea surface temperature (**a**), vertical wind shear (**c**) trends for the period 1979-2018 over the main development region defined as the area of ocean enclosed between 10-20°N and 20-70°W. Graph **a** shows the seasonal SST trend from ERA5 reanalysis (blue), HadISST (orange) and NOAA (purple). Seasonal SST anomaly over the MDR is shown in plot **b**, the red shading depicts years where SST is over the pre-industrial baseline (1870-1900) and blue shading represents years where SST is under the baseline. Observations are calculated by the average between the three observational and reanalysis datasets. Graph **c** shows the seasonal mean vertical wind shear over the MDR derived from the ERA5 reanalysis data set. Graph **d** is the annual frequency of hurricanes over the same time period.

2.6 Modes of variability in the North Atlantic basin

Though a single tropical cyclone is not itself caused by global warming, significant long-term changes in oceanic and atmospheric conditions might create more favourable conditions for tropical cyclone intensification and influence activities such as rainfall, duration, frequency, size and tracking. Sea surface temperatures exhibit an increasing trend over the past 40 years (figure 6a), while vertical wind shear shows no significant trend over the region (figure 6c) and detecting a trend in hurricane frequency can prove challenging due to large variability in the current record (figure 6d). Furthermore, attributing any changes in long-term trends to global warming is challenging due to a relatively short observable record and several modes of variability, especially in the North Atlantic, which affect hurricane behaviour.

The Atlantic basin experiences fluctuations in hurricane activity, for example there were 45 major hurricanes in the years between 1995 and 2005, this 11-year period is characterised as the highest level of hurricane activity in the reliable record (Zehr and Knaff 2007). The basin is recognised for having significant multidecadal variability in tropical cyclone activity which is largely due to the Atlantic Multidecadal Oscillation (AMO; Zhao et al. 2018b; Xie and Carton 2004).

The AMO is a sea surface temperature fluctuation which occurs approximately every 60-80 years in the North Atlantic Ocean (Knight et al. 2006) and some studies suggest that the AMO plays an important role in hurricane activity over the Atlantic region (Hetzinger et al. 2008; Zhang and Delworth 2006). Wang et al. (2008) related the link between the AMO and hurricane activity to the Atlantic Warm Pool (AWP). According to Wang et al. (2010) the AWP is a "large body of warm water that comprises of the Gulf of Mexico, the Caribbean Sea and the Western Tropical North Atlantic" which was shown to coincide with the sign of the AMO i.e., an anonymously large AWP concurs with a warm phase of the AMO and vice-versa. In such cases, this reduces the vertical wind shear in the main development region which creates favourable conditions for hurricanes to form, and the reverse is true when the AWP is smaller than normal (Wang et al. 2008).

Vertical wind shear is also affected by the El Niño-Southern Oscillation (ENSO), a recurring climate pattern of change in sea surface temperature in the Eastern Tropical Pacific. On periods ranging from roughly three to seven years, the ocean surface goes through a warming phase (El Niño) or a cooling phase (La Niña) where sea surface temperatures over the pacific vary around 1°C to 3°C from the norm (Goldenberg and Shapiro 1996). Many studies have shown that La Niña years favour stronger and more destructive hurricane events, while the El Niño suppresses hurricane activity in the North Atlantic basin (Pielke and Landsea 1999; Bove et al. 1998), this is due to increased vertical wind shear during El Niño events caused by a strengthening in upper tropospheric westerly winds which result from the warmer than average pool of water in the

Eastern Pacific (Gray 1984; Shapiro and Shapiro 1987). During La Niña years, vertical wind shear is lower than average over the Caribbean basin — a more favourable environment for hurricanes to form and intensify. Both La Niña and El Niño events are projected to be more extreme in a warmer world (Cai et al. 2015), suggesting hurricane seasons could become more variable i.e. more (fewer) genesis events in future La Niña (El Niño) years.

While the ENSO has been seen to influence factors favourable for hurricane genesis, the North Atlantic Oscillation (NAO) appears to effect hurricane tracks (Elsner et al. 2001). The NAO is a source of interannual variability which refers to a fluctuation in atmospheric air masses over the North Atlantic and can be defined by the pressure difference between the Azores and Iceland (Hurrell et al. 2001). The Azores typically experiences an area of a high pressure while Iceland experiences low pressure and the NAO is in positive phase when this pressure difference is larger than average, it's in negative phase if the difference is smaller than average. A large negative NAO during spring tends to lead to the Azores high being displaced further south west than usual in the hurricane season which follows (Elsner and Kocher 2000; Elsner et al. 2001). In this circumstance hurricanes tend to form and intensify at lower latitudes and typically cross the Caribbean en route to North America (Elsner 2003).

A tropical atmospheric mode of intra-seasonal variability, the Madden-Julian oscillation (MJO), propagates from west to east every 40 to 50 days and is characterised by a large area of storminess and clouds (Madden and Julian 1972, 1994). There are many studies which have indicated a relationship between the MJO and hurricane formation (Klotzbach 2010; Maloney and Hartmann 2001). Maloney and Hartmann (2001) uncovered that hurricane genesis in the western Caribbean region and Gulf of Mexico increase four-fold when lower-tropospheric winds in the Eastern Pacific are more westerly than usual.

These modes of variability mean that a distinguishable trend may be challenging to detect with the current observational data set. That being said, some studies have shown a recent shift in hurricane activity. The season of 1995 is often a marker for the start of a heightened period of activity (Goldenberg et al. 2001) but changes in behaviour have been detected as early as 1980 with a higher proportion of storms which form at the lower latitudes with a strong Westward component compared to those which form almost exclusively in the Gulf of Mexico (Kossin et al. 2010). Looking to the future, changes in hurricane activity are likely to be highly non-linear and extreme events could be more likely if the appropriate modes of variability line up to create more favourable conditions that have so far rarely occurred.

2.7 Modelling tropical cyclone activity

The IPCC AR5 report presents a robust body of evidence that stronger tropical cyclones are becoming more frequent with more intense winds and the projected sea level rise will likely contribute to an elevated storm surge risk. There is higher confidence in findings from global studies compared to results from basin-wide studies which continue to exhibit disagreement (Walsh et al. 2016).

There are three main ways in which to model the effect of global warming on tropical cyclone activity: 1. by resolving and tracking them directly in global circulation models (GCMs), 2. using an offline statistical tropical cyclone model and 3. using an offline dynamical tropical cyclone model. The offline tropical cyclone models use a subset of GCM output as the initial and boundary conditions in a statistical or a dynamical model which allows for high resolution simulations of the storms core (Emanuel 2013).

Studies which resolve tropical cyclones directly within GCMs, with resolution ranging from 25km to 100km, have shown a fall in the global frequency of tropical cyclones with high intensity tropical cyclones more likely (Zhao and Held 2010; Zhao et al. 2009). Although the monthly climatologies of observed North Atlantic storms have been reasonably well reproduced in some GCMs, for example, the Community Atmospheric Model (CAM5) (Wehner et al. 2014), GCMs struggle to consistently replicate observed annual frequency in all basins due to biases present in some of the models (Shaevitz et al. 2014). Moreover, the resolution of these global models, whilst not being fine enough to accurately resolve the intensity spectrum of the most powerful tropical cyclones (Bryan and Rotunno 2008; Emanuel 2006; Camargo 2013), have a high computational cost making statistical significance difficult to demonstrate (Wehner et al. 2014).

Therefore, evaluating the projected changes in tropical cyclone activity via direct resolution of tropical cyclones in GCMs can prove challenging as the high-resolution models are computationally expensive and can only be run for a small number of years.

Alternatively, a statistical approach can be used to model tropical cyclone activity. These rely on historical relationships between tropical cyclone activity and environmental conditions, for example, sea surface temperature and power dissipation index (Villarini and Vecchi 2013). Villarini and Vecchi (2013) used a statistical tropical cyclone model (Villarini and Vecchi 2012) and found a considerable rise in hurricane intensity and an increasing likelihood of extreme hurricane seasons over the next 100 years. Villarini et al. (2016) developed a hybrid statistical and dynamical forecasting model for seasonal hurricane activity which uses Atlantic SST and also tropical SST — due to a link with wind shear (Latif et al. 2007) — as predictors, with the forecasts taken from the ECMWF climate model ensemble. It reproduces observations well in terms of frequency and ACE, though has not yet been used in climate projections. Both of these models primarily look at SST as the main driver for tropical cyclones and do not account for factors which also influence tropical cyclone activity such as outflow temperature. The outflow temperature is defined by Emanuel (2011) as "the absolute temperature attained by streamlines flowing upward and outward from the storm's core as they asymptotically level out at large radii", which has been shown to have a significant contribution to tropical cyclone activity (Emanuel et al. 2013).

Alternatively, dynamical tropical cyclone models are used such as those developed by Emanuel et al. (2006) and Geophysical Fluid Dynamics Laboratory (GFDL) (Emanuel et al. 2006; Emanuel 2006; Emanuel et al. 2008; Bender et al. 2010; Knutson et al. 2008). This approach works by embedding a high-resolution dynamical model within GCMs and has been shown to produce highly resolved tropical cyclones with a more realistic intensity spectrum than their statistical counterparts (Emanuel et al. 2006; Knutson et al. 2013, 2015). Employing a regional model, fed with boundary conditions from GCM projections (CMIP3&5; RCP4.5) Knutson et al. (2013) simulated hurricanes via two versions of the GFDL hurricane model. The first, originally used by Bender et al. (2010) and a more recent used by the US Navy. Moreover, the model accounts for hurricane-ocean interaction via ocean coupling allowing hurricanes to have a cold wake, an important intra-seasonal mechanism; the cooling of SST in the wake of a passing hurricane can last for several weeks and has been shown to reduce intensity of subsequent hurricanes by 3-6% on average (Balaguru et al. 2014). In both the CMIP3 and CMIP5 scenarios, tropical cyclone frequency showed a significant reduction and CMIP3 displayed a highly significant increase in very intense storms while CMIP5 less so. In addition, rainfall rates increased in both scenarios as much as 30% in the inner core region (Knutson et al. 2013).

The technique developed by Emanuel et al. (2006) begins by embedding weak, hurricane-like vortices randomly throughout space and time within the world projected by the GCM. These seed vortices move with the large-scale wind flows in the upper atmosphere and have a poleward and westward component which accounts for the Coriolis effect (Marks 1992). Intensity is generated using a circularly symmetric hurricane model utilising SST, relative humidity and atmospheric temperature at a variety of levels. When the intensity model is applied to the seed vortices, only those with favourable conditions strengthen to become hurricanes while the others dissipate. The model performs particularly well when comparing metrics such as intensity, frequency and duration to historical events and is computationally cheap allowing for many thousands of tracks to be simulated (Emanuel et al. 2008; Emanuel 2017).

Conversely, Emanuel (2013) reported an increase in hurricane frequency over the North Atlantic basin under the CMIP5 ensemble at RCP8.5, perhaps as the tropical cyclone coldwake is not taken into account in this model. It is important to note that a different emissions pathway and set of models were used here to Knutson et al. (2013) so the results are not strictly comparable.

2.8 Projections of hurricane activity under 1.5°C and 2°C warming scenarios

Some studies suggest that global warming may play a more dominant role in influencing tropical cyclone activity (Mann and Emanuel 2006; Webster et al. 2005) and given the devastating impact of hurricanes to life in the Caribbean region, there is a motivation to understand the response of tropical cyclone activity to anthropogenic global warming over the North Atlantic basin with many studies undertaken (Zhang et al. 2017; Mann and Emanuel 2006; Strazzo et al. 2013; Knutson et al. 2015). However, to date, only a handful of impact studies have explored tropical cyclone activity under 1.5°C versus 2°C scenarios (Burgess et al. 2018; Wehner et al. 2018; Wen et al. 2018; Muthige et al. 2018) and there are no impact studies which have explored this solely in the North Atlantic basin under these set-ups.

On a global scale, these studies report an increase in the frequency of category 3-5 tropical cyclones and a decrease in the number of weaker tropical storms under a 1.5°C warming scenario (Burgess et al. 2018; Wehner et al. 2018; Muthige et al. 2018) which bring with them more intense wind and rainfall (Hoegh-Guldberg et al. 2018).

Those studies exploring tropical cyclone activity under the Paris Agreement goals project a higher occurrence of the most intense storms with an overall decrease in frequency under the warmer scenarios consistent with the majority of studies assessing larger scales of warming (Burgess et al. 2018; Wehner et al. 2018; Muthige et al. 2018). Looking only at “influential tropical cyclones” (those which cause a significant economic loss to China), Wen et al. (2018) reported an increase in frequency under both Paris Agreement scenarios. Under the assumption that influential tropical cyclones are inherently among the most intense storms, this finding

Table 2: HAPPI models and reanalysis data selected for use in this study

Dataset	Type	Vertical Resolution (number of levels)	Horizontal Resolution (longitude x latitude)	Lid Height
CanAM4	Model	37	2.81° x 2.81°	10 hPa
CAM5-1-2-025degree	Model	17	0.31° x 0.23°	100 hPa
NorESM1-HAPPI	Model	17	1.25° x 0.94°	100 hPa
ECHAM6-3-LR	Model	17	1.88° x 1.88°	100 hPa
ERA5	Reanalysis	17	0.25° x 0.25°	100 hPa

would indeed be in line with the other studies. Tropical depressions are more common in a 2°C scenario compared to 1.5°C however statistics do not vary significantly between the 1.5°C and 2°C scenarios (Wehner et al. 2018). A global mean temperature of 1.5°C versus 2°C results in a potential 359mn USD saving (or $\sim$ 42% of current natural event damages) of which hurricanes and flooding events account for the most damage in the Caribbean region (Burgess et al. 2018). Similarly, an estimated annual saving of 120bn CNY could be achieved by limiting global warming at 1.5°C (Wen et al. 2018).

Wehner et al. (2018) used the Community Atmosphere Model simulations (CAM5) from the HAPPI protocol in stabilised 1.5 and 2 degree scenarios where tropical cyclones were recognised and traced using the Toolkit for Extreme Climate Analysis (TECA2). This method ensures aerosol concentrations remain consistent among both scenarios as the HAPPI protocol uses the same aerosol forcing in both scenarios (Mitchell et al. 2017), however Muthige et al. (2018); Burgess et al. (2018); Wen et al. (2018) generated the Paris Agreement scenarios using transient simulations (where the 10 years before and after the year the GCMs reached a 1.5°C/2.0°C/3.0°C warmer world were selected). While this method has its advantages, different models will reach the threshold temperature at different times which leads to different levels of forcing (e.g. ozone hole, aerosols).

2.9 Motivation

There is currently a limited pool of evidence to suggest a discernible difference in tropical cyclone activity between the Paris Agreement scenarios, moreover, there have been no studies which evaluate hurricane climatology and impacts in the North Atlantic basin under these scenarios to date, with the exception of (Wehner et al. 2018) who looked at global patterns.

Therefore, there is ample opportunity to further explore the projections of hurricane activity in 1.5°C versus 2°C scenarios. Rain rates of tropical cyclones are projected to increase in the inner core region (Knutson et al. 2010, 2013). Additionally, both the mean and peak rain rates of tropical cyclones have been shown to increase with storm intensity and for major tropical cyclones (category 3-5) the radius of maximum rainfall is smaller than for weaker tropical cyclones and tropical storms (Lonfat et al. 2004; Yu et al. 2017). With a projected shift towards more intense tropical cyclones in a warming world (Wehner et al. 2018; Zhao et al. 2009; Walsh et al. 2016), it is therefore likely that a global warming to 1.5°C or 2°C above pre-industrial levels could lead to more rainfall during a hurricane event.

In Caribbean small island developing states, substantial differences are present in planned adaptation and resilience to hurricanes (Hoegh-Guldberg et al. 2018), such as **retreat** development away from areas at risk, **accommodate** by raising buildings above flood levels (Nicholls 1998) and **protect** with coastal defence (Mycoo 2018). Choosing an adaptation method relies on knowledge of the scale and longevity of the threat to infrastructure and life, thus it is necessary to build up robust evidence across the board to paint a reliable and detailed picture of the path ahead.

Therefore, this study explores the projected rainfall from hurricanes across the Caribbean region and attempts to quantify a possible increase in rainfall in the context of a selection of Caribbean countries. The overarching aim of this project is to identify the changes in future projections of hurricane activity in the context of the Caribbean. Crucially, the project aims to identify and communicate uncertainty trends in hurricane activity to acknowledge its importance in the context of decision making for resilience policies. Within this there are three key objectives:

- Compare hurricanes simulated via a dynamical tropical cyclone model to observations
- Determine how return periods of past hurricane-rainfall events would change in the targeted climate simulations of the Paris Agreement
- Perform the first analysis of hurricane stalling projections under the Paris Agreement goals

3 Projecting the Reoccurrence of Major Caribbean Hurricanes under the Paris Agreement Goals

Vosper, E., Mitchell, D., Emanuel, K.

Abstract

Hurricanes are among the most destructive extreme weather events affecting humanity, in both social and economic terms. Hurricane Maria devastated Puerto Rico in 2017 with the most rainfall to hit the country from a hurricane in 40 years, whilst secondary events such as flooding, landslides and disease were estimated to have claimed over a thousand lives. The influence of 1.5°C and 2°C global warming above the pre-industrial average on hurricane rainfall is explored using a dynamical hurricane model applied to future projection simulations from four global circulation models (GCMs). These simulations are taken from the Half a degree Additional warming, Prognosis and Projected Impacts (HAPPI) super-ensembles, which comprise of bias-corrected climate model output for the present day, 1.5°C and 2°C warmer worlds. Results indicate that extreme hurricane rainfall events, which affect the Caribbean region, are more likely in both of the Paris Agreement scenarios compared to the present climate with four of the five hurricanes studied occurring more often under these simulations. In particular, the Eastern Caribbean region displays a strong global warming signal; a rainfall event associated with hurricane Maria is 43% less likely in the more ambitious Paris Agreement goal of a 1.5°C warming compared to the 2°C case. Confidence in the results is reduced as the simulations underestimate return period data compared to observations. A bias correction factor was applied to fit data to observations, but in the absence of knowledge around how the bias might change in warming scenarios, it is assumed to be constant with global temperature increase.

3.1 Introduction

Current greenhouse gas mitigation ambition is consistent with a $\sim$ 3°C global mean warming above pre-industrial levels (1850 - 1900) by the year 2100 (Rogelj et al. 2016). The IPCC Special Report on 1.5°C presents a clear picture that limiting global warming to 1.5°C over 2°C significantly decreases the risks associated with the impacts to both human and natural systems brought about as a result of an increased mean global temperature (Hoegh-Guldberg et al. 2018).

There is broad consensus among the scientific community that small island developing states (SIDS) are extremely sensitive to climate change impacts (Ourbak and Magnan 2018; Campbell and Barnett 2010) such as heavy precipitation (Peterson et al. 2002), sea level rise (Lal et al. 2002) and coral bleaching (Ourbak and Magnan 2018).

Current greenhouse gas concentrations are consistent with a 1°C warmer world compared to pre-industrial levels (Haustein et al. 2017). Over the past 50 years, small island states have already been feeling the effects of a 1°C warming in terms of increased occurrence of warm temperature extremes, fewer cool extremes and increased precipitation intensity (Stephenson et al. 2014). With this in mind, at the more ambitious target of 1.5°C warming, SIDS stand to be disproportionately affected by the corresponding impacts to human and natural systems while being among those who have made the smallest contribution to anthropogenic climate change (UNFCCC 2005). As they are likely suffer irreconcilably from the adverse impacts that it brings, adaptation and resilience planning are paramount to maintaining habitability while mitigation and coastal management are required to preserve marine biodiversity and current coastal infrastructure. Therefore, it is crucial that the international community band together to support these endeavours such that small island states can receive the much-needed knowledge and support they require in order to adequately deal with climate change and the impacts that it brings.

Since 1960, the Caribbean has experienced 264 hurricanes which make up 71.4% of all natural disasters affecting the region (Burgess et al. 2018). Furthermore, hurricanes cause the most damage in the Caribbean — accounting for 94.5% of the total damages from all natural disasters (Burgess et al. 2018) and for the vast majority of extreme rainfall events and extreme sea levels experienced in the region (Khouakhi et al. 2017; Walsh et al. 2015; Peterson et al. 2002).

More than half of the regions population of 44 million reside within 1.5 km of the coast leaving the Caribbean particularly vulnerable to hurricanes (Mimura et al. 2007). Critical infrastructure such as major roads, air and seaports, utilities and communication networks tend to be constrained to low-elevation coastal zones (LECZs; Cruz et al. 2007 Mycoo 2018). Neumann et al. (2015) define LECZ as “the contiguous area along the coast that is less than 10 metres above sea level” and estimate that the LECZ population in the Latin America and Caribbean LECZ will double by 2060 compared to 2000 with current population projections. Hurricane Ivan (2004) brought with it storm surges of up to 3 m in some regions, particularly Jamaica, blocking the main road to the airport and damaging residential infrastructure (Cashman and Nagdee 2017).

The IPCC AR5 report presents a robust body of evidence that stronger tropical cyclones are becoming more frequent with more intense winds and the projected sea level rise will likely contribute to an elevated storm surge risk. There is higher confidence in findings from global studies compared to results from basin-wide studies which continue to exhibit disagreement

(Walsh et al. 2016).

3.1.1 Projections of hurricane activity under 1.5°C and 2°C warming scenarios

Some studies suggest that global warming may play a more dominant role in influencing tropical cyclone activity (Mann and Emanuel 2006; Webster et al. 2005) and given the devastating impact of hurricanes to life in the Caribbean region, there is a motivation to understand the response of tropical cyclone activity to anthropogenic global warming over the North Atlantic basin with many studies undertaken (Zhang et al. 2017; Mann and Emanuel 2006; Strazzo et al. 2013; Knutson et al. 2015). However, to date, only a handful of impact studies have explored tropical cyclone activity under 1.5°C versus 2°C scenarios (Burgess et al. 2018; Wehner et al. 2018; Wen et al. 2018; Muthige et al. 2018) and there are no impact studies which have explored this solely in the North Atlantic basin under these set-ups.

On a global scale, these studies report an increase in the frequency of category 3-5 tropical cyclones and a decrease in the number of weaker tropical storms under a 1.5°C warming scenario (Burgess et al. 2018; Wehner et al. 2018; Muthige et al. 2018) which bring with them more intense wind and rainfall (Hoegh-Guldberg et al. 2018).

Those studies exploring tropical cyclone activity under the Paris Agreement goals project a higher occurrence of the most intense storms with an overall decrease in frequency under the warmer scenarios consistent with the majority of studies assessing larger scales of warming (Burgess et al. 2018; Wehner et al. 2018; Muthige et al. 2018). Looking only at “influential tropical cyclone” (those which cause a significant economic loss to China) Wen et al. (2018) reported an increase in frequency under both Paris Agreement scenarios. Under the assumption that influential tropical cyclones are inherently among the most intense storms, this finding would indeed be in line with the other studies. Tropical depressions are more common in a 2°C scenario compared to 1.5°C however statistics do not vary significantly between the 1.5°C and 2°C scenarios (Wehner et al. 2018).

A global mean temperature of 1.5°C versus 2°C results in a potential 359mn USD saving (or $\sim$ 42% of current natural event damages) of which hurricanes and flooding are the most significant events accountable for damages in the Caribbean (Burgess et al. 2018). Similarly, an estimated annual saving of 120bn CNY could be achieved by limiting global warming at 1.5°C (Wen et al. 2018).

Wehner et al. (2018) used the Community Atmosphere Model simulations (CAM5) from the HAPPI protocol in stabilised 1.5 and 2 degree scenarios where tropical cyclones were recognised and traced using the Toolkit for Extreme Climate Analysis (TECA2). This method ensures aerosol concentrations remain consistent among both scenarios as the HAPPI protocol uses the same aerosol forcing in both scenarios (Mitchell et al. 2017), however Muthige et al. (2018); Burgess et al. (2018); Wen et al. (2018) generated the Paris Agreement scenarios using transient simulations (where the 10 years before and after the year the GCMs reached a 1.5°C/2.0°C/3.0°C warmer world were selected). While this method has its advantages, different models will reach the threshold temperature at different times which leads to different levels of forcing (e.g. ozone hole, aerosols).

3.1.2 Motivation

There is currently a limited pool of evidence to suggest a discernible difference in tropical cyclone activity between the Paris Agreement scenarios. Moreover, there have been no studies which evaluate hurricane climatology and impacts in the North Atlantic basin under these scenarios to date, with the exception of Wehner et al. (2018), who looked at global patterns. Therefore, there is ample opportunity to further explore the projections of hurricane activity in 1.5°C versus 2°C scenarios. Rain rates of tropical cyclones are projected to increase in the inner core region (Knutson et al. 2010, 2013). Additionally, both the mean and peak rain rates of tropical cyclones have been shown to increase with storm intensity and for major tropical cyclones (category 3-5) the radius of maximum rainfall is smaller than for weaker tropical cyclones and tropical storms (Lonfat et al. 2004; Yu et al. 2017). With a projected shift towards more intense tropical cyclones in a warming world (Wehner et al. 2018; Zhao et al. 2009; Walsh et al. 2016), it is therefore likely that a global warming to 1.5°C or 2°C above pre-industrial levels could lead to more rainfall during a hurricane event.

Across the small island developing states of the Caribbean, there are a number of different plans and approaches regarding climate change adaptation and resilience (Hoegh-Guldberg et al. 2018), such as to **retreat** development away from areas at risk, **accommodate** by raising buildings above flood levels (Nicholls 1998) and **protect** with coastal defence (Mycoo 2018). Choosing an adaptation method relies on knowledge of the scale and longevity of the threat to infrastructure and life, thus it is necessary to build up robust evidence across the board to paint a reliable and detailed picture of the path ahead.

Therefore, the overarching aim of this study is to identify the changes in future projections

Table 3: HAPPI models and reanalysis data selected for use in this study.

Dataset	Type	Horizontal Resolution (longitude x latitude)
CanAM4	Model	2.81° x 2.81°
CAM5-1-2-025degree	Model	0.31° x 0.23°
NorESM1-HAPPI	Model	1.25° x 0.94°
ECHAM6-3-LR	Model	1.88° x 1.88°
ERA5	Reanalysis	0.25° x 0.25°

of hurricane rainfall in the context of the Caribbean as well as to explore hurricane stalling projections in order to gain an understanding of the proportion of projected hurricane rainfall that is likely to fall over land and therefore contribute to secondary events such as flooding. Crucially, the project aims to identify and communicate uncertainty trends in hurricane activity to acknowledge its importance in the context of decision making for resilience policies.

3.2 Methods

3.2.1 Observational data

Hurricane data was taken from the International Best Track Archive for Climate Stewardship (IBTrACS; Knapp et al. 2010). Often referred to as "best-tracks" data, this dataset consists of the amalgamation of several tropical cyclone databases recorded over the years by individual agencies across different basins. The archive contains track and intensity information for tropical cyclones over the globe and stretches back to the mid-1800s. It is the first and most comprehensive database of its kind and is therefore appropriate for use in this study. It should be noted, however, that this dataset relies on the best available observations at a given time which are ever evolving, and have not been homogenised in this study.

Global precipitation, sea surface temperature (SST) and atmospheric data were taken from the ERA5 dataset (Copernicus Climate Change Service (C3S) 2017). ERA5 is an expansive archive of global reanalysis data spanning from 1979 to 2–3 months before the present at 31km resolution (see table 3). Although not strictly an observational dataset, ERA5 combines vast historical observations with advanced modelling and data assimilation techniques, the consistency across all of its products provides a useful comparison for analysis across the board.

Observed hurricane total rainfall return periods for each country were calculated by tagging a hurricane track after intersection with the country and a 1° buffer (approximately 110 km) around the coastline to include rainfall from hurricanes which pass nearby but do not technically make landfall. The estimated hurricane total rainfall over each country was calculated by cross referencing the date of intersection to the nearest six-hourly track point with ERA5 hourly precipitation data. The rainfall data was then summed over the country area from the time of intersection minus six hours (to account for late track intersections) for a further 72 hours, any additional rainfall not associated with the hurricane during this period is assumed to be negligible compared to that of the storm. The event return period was then calculated as the reciprocal of the annual exceedance probability i.e. one over the sum of probabilities of events which exceed a certain rainfall amount. The annual probability of an event with rainfall x is the average yearly number of events multiplied by the ratio of total rain from all events size x and total rainfall from all events .

3.2.2 Simulating hurricane rainfall

The method used in this study is outlined in figure 7. Overall, this study implements a physics-based hurricane rainfall algorithm developed for risk analysis (Zhu et al. 2013; Lu et al. 2018) to estimate hurricane rainfall in the Caribbean region under three climate scenarios. The model generates rainfall estimates along hurricane tracks, accounting for major processes such as hurricane interaction with topography and wind shear. A return period statistic is then generated representing how often a rainfall event of a certain strength is likely to occur. The hurricane rainfall model is computationally cheap and has been shown to give good estimates of rainfall risk compared to gauge-based observations (Zhu et al. 2013; Lu et al. 2018) and to Weather and Research Forecasting-estimated rainfall (Lu et al. 2018).

The rain rates were estimated for 60,000 simulated hurricanes at two-hour intervals and a bias correction was applied to approximate observed rainfall return periods, described above, accounting for an underestimation in return period likely driven by a higher track density in the Caribbean and an overestimation in potential intensity (figure 8a). The rainfall bias correction factor was generated on a country by country basis in a subjective manner to fit the rainfall model output to observations (figure 9). Return period results were multiplied by a factor of 0.54 for Cuba, 0.32 for Jamaica, 0.64 for Puerto Rico, 0.73 for Haiti and 0.41 for the Dominican Republic. A bias-correction factor based solely on track density was explored and although estimations improved, the corrected results still differed substantially from observations indi-

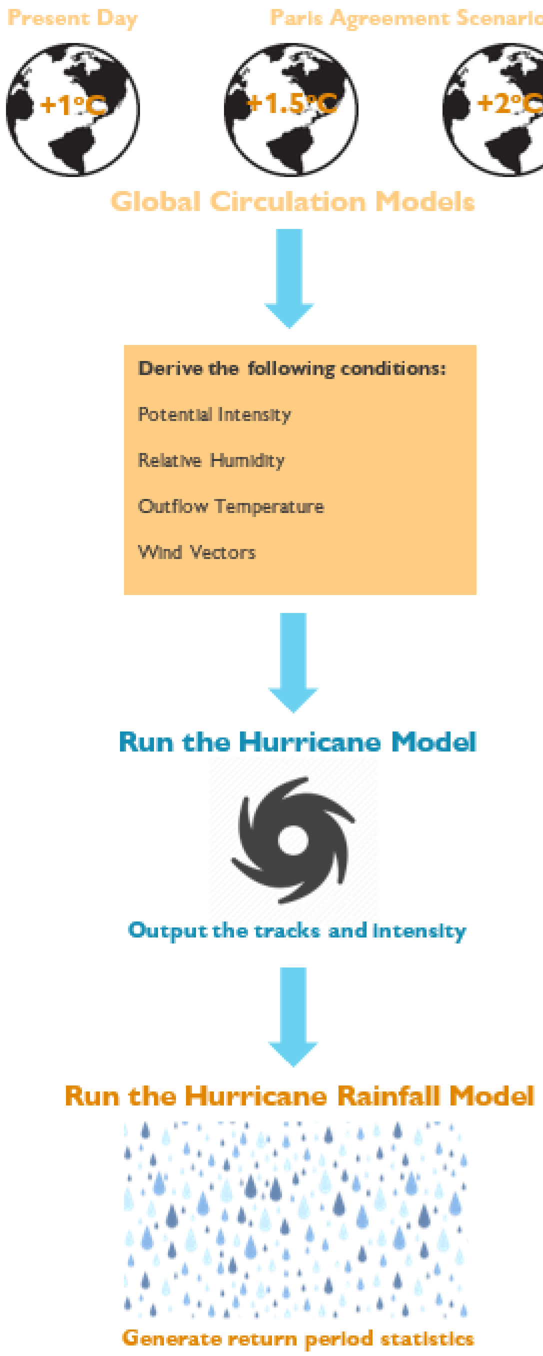

Figure 7: This flowchart gives an outline of the method used in this study.

cating further mechanisms were responsible for the detected bias. Lastly, in the absence of knowledge about how bias may change in warming scenarios, it is assumed to be constant with global temperature increase. The bias correction is limited by the scope of the ERA5 data, which is currently available for the period 1979 - 2019. As hurricane track data is available for a much longer period, it would be possible to collect rainfall data for a larger time slice, however the ERA5 data and timeline has been used here for consistency.

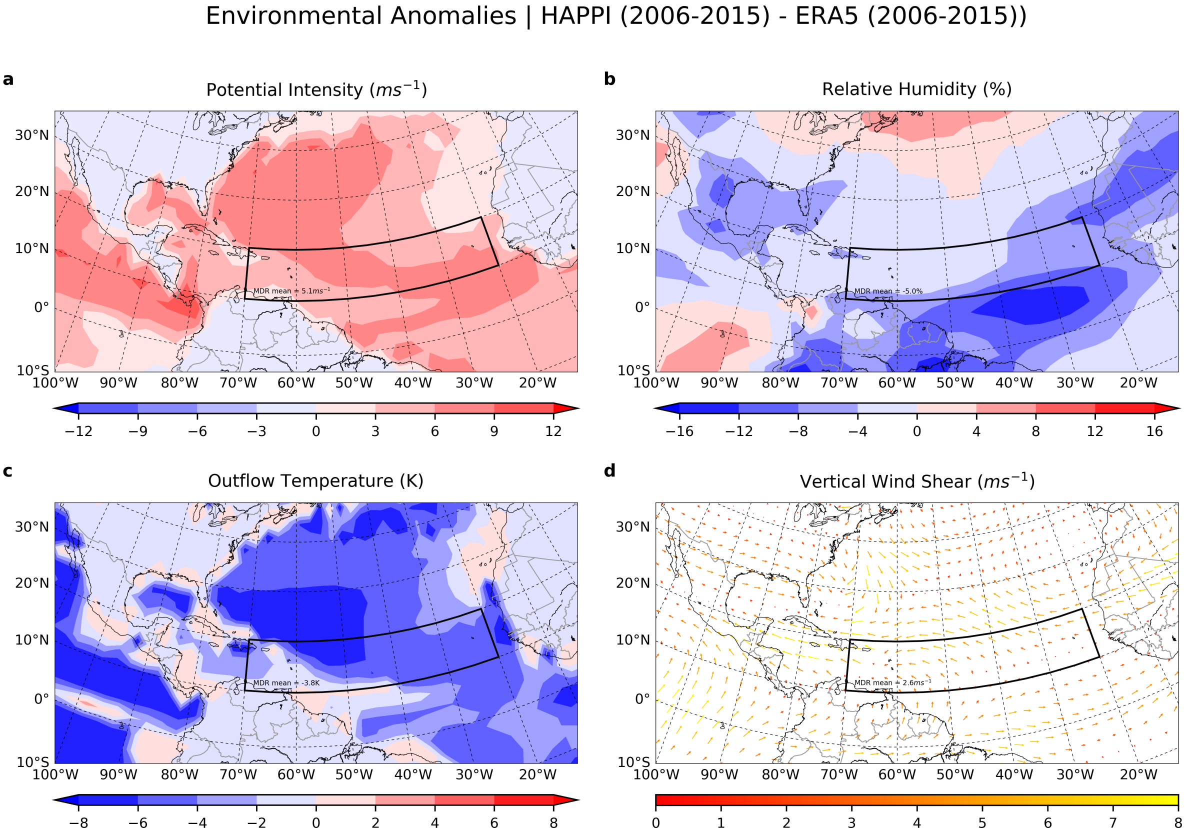

Figure 8: Seasonal (June-November) anomalies are depicted here between the simulated time period 2006-2015 and ERA5 reanalysis data for the same period for four variables, the box is the main development region (MDR) where most hurricanes tend to develop. The seasonal mean potential intensity (**a**) over the MDR is overestimated by 5.1ms^{-1} by the historical simulations. Mid-tropospheric relative humidity (**b**) differs by -5% between simulations and observations whereby the HAPPI ensemble has made a seasonal underestimate over the MDR. Seasonal mean outflow temperature (**c**) across the MDR is -3.8C lower in the HAPPI ensemble compared to ERA5 reanalysis. Lastly, the simulations overestimate the magnitude of mean seasonal wind shear (**d**) over the MDR by 2.6 ms^{-1} and over this region the HAPPI ensemble have a stronger westward component than the ERA5 reanalysis.

3.2.3 The hurricane model

The synthetic hurricanes were generated using the dynamical hurricane model described in detail in Emanuel et al. (2008) whereby output from four global climate models (GCMs; table 4) supplies the boundary and initial conditions. The hurricane model derives hurricane climatology using the three following steps: Firstly, genesis by random seeding — an alternative procedure to a genesis probability density function which relies on historical data. This process initiates warm-core “seed vortices” at points randomly distributed throughout space-time with peak wind speeds of 12ms^{-1} analogous to generating initial tropical wave perturbations which

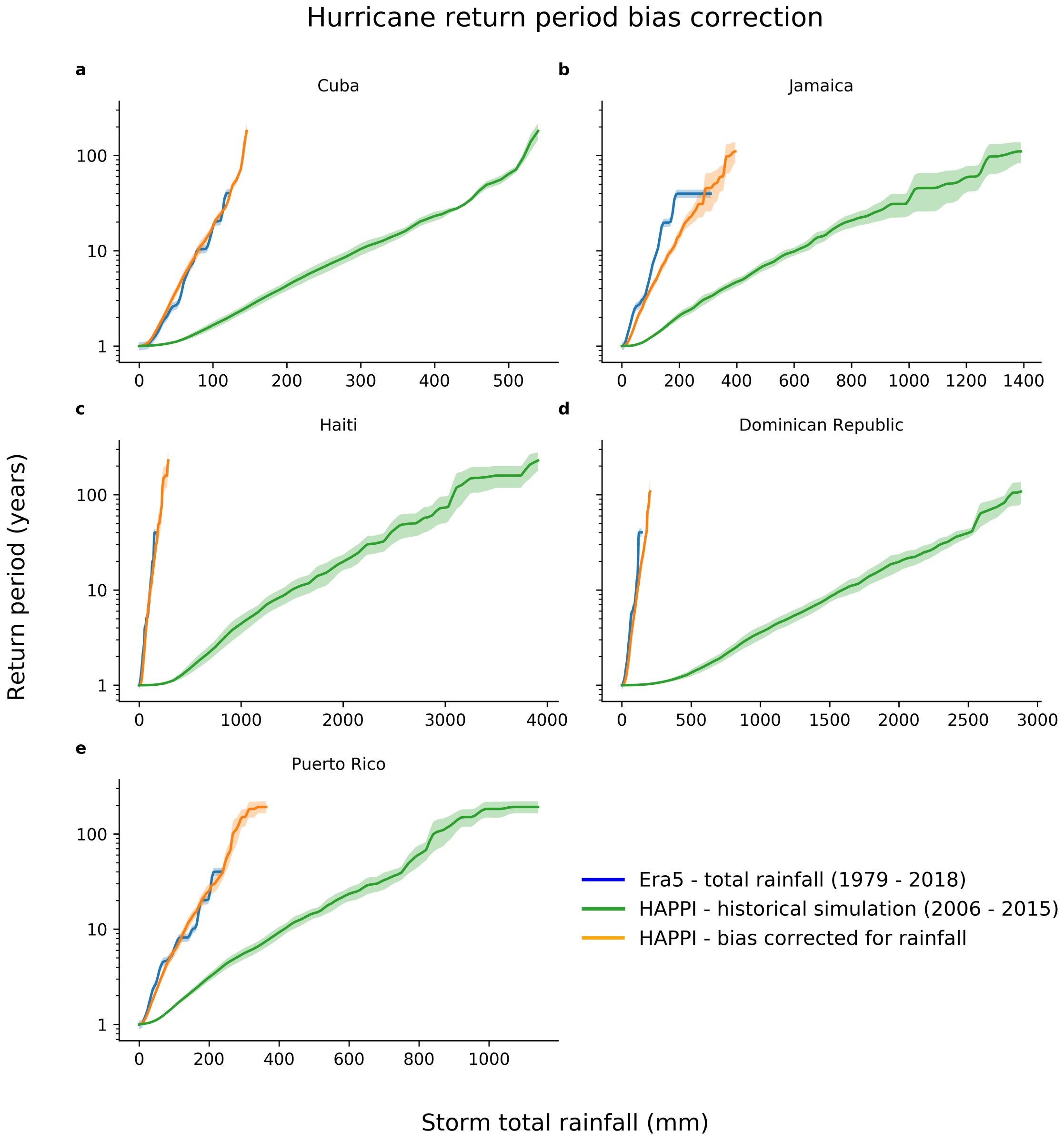

Figure 9: Bias correction of simulated hurricane rainfall. Lines represent the return period, the reciprocal of the annual exceedance probability, of a rainfall event associated with a storm producing total rainfall of amount x across the country in question. Raw estimations of hurricane return period is represented by the red line, the orange line is bias corrected data based on the ERA5 reanalysis return periods in blue. The line shading represents the confidence interval by a bootstrapping technique.

kick start hurricane formation (Frank and Roundy 2006). Tropical cyclones are considered to form when these seeds develop winds of at least 21ms^{-1}, so naturally many will fail as they do not have the right conditions to strengthen. Secondly, tracks are drawn via a beta-and-advection model described in Marks (1992) which uses large scale background wind fields and a beta drift correction adjusting for the Coriolis effect. The seed vortices and hurricanes are assumed to move with a weighting of the winds at 250 hPa and 850 hPa plus a correction for the Coriolis effect which ensure they move poleward and westward. Lastly, intensity is estimated by the Coupled Hurricane Intensity Prediction System (CHIPS) model (Emanuel et al. 2004), which is also used to forecast tropical cyclone intensity in real-time and consequently processing time is minimised.

The benefits of using this technique is that it is computationally cheap, and the intensity model allows for very high radial resolution of the inner-core region. The model has been shown to reproduce observed hurricane activity well in an array of metrics (Emanuel et al. 2006, 2008; Emanuel 2010). However, it should be noted that the model does not account for the hurricane-induced SST cooling which produces cold wakes behind passing hurricanes and has been shown to have a reductive effect on the intensity of subsequent hurricanes (Vincent et al. 2012). This must be taken into consideration when interpreting the results of this study.

3.2.4 The climate models

The GCM output is taken from the Half a degree of Additional warming, Prognosis and Projected Impacts project (HAPPI; Mitchell et al. (2017)). HAPPI aims to document the impacts of extreme weather events under stabilised 1.5°C and 2°C temperature increases above pre-industrial levels by providing a super-ensemble of bias-corrected climate model output. The high volume of model output allows for the risks associated with high-impact, low-probability events to be explored under the Paris Agreement scenarios and the present-day. 600 simulated years were used from the HAPPI protocol across three scenarios representing the historical world over the period 2006-2015 and stabilised 1.5°C (stabilised via RCP2.5) and 2°C (stabilised by a weighing of RCP2.5 and RCP4.5) worlds over the period 2106-2115. The selected models: CAM5 0.25-degree, NorESM1, CanAM4 and ECHAM6.3, were chosen due to the availability of the climate variables necessary to run the hurricane model (Table 3). Potential intensity relative humidity and outflow temperature were calculated from model output data for use in the hurricane model (table 4).

When calculating the risk for extreme events, stabilised climate scenarios are advantageous over transient simulations – which use 20-year periods centred on the attainment of a global mean temperature threshold. With transient simulations, output is only resonant with the global-mean temperature for a small amount of time and the period to be compared can range depending on the model and radiative concentration pathway (RCP) used (James et al. 2017). In this case, making direct comparisons of extreme events in different warming sce-

Table 4: Inputs to hurricane model. Specific humidity and atmospheric temperatures are sampled at 17 pressure levels including 600hPa, 100hPa and 70hPa

Variable	Temporal Averaging
Atmospheric Temperature	Monthly
Specific Humidity	Monthly
Sea Surface Temperature	Monthly
Wind Vectors (850hPa, 250hPa)	Daily

narios can be challenging. However, stabilised simulations represent the same time period at a different level of warming and therefore enable a direct comparison between climate scenarios at a given historical period. It should be noted that the HAPPI ensemble exhibits differences in the spatial distribution of aerosols between the RCPs used to generate the scenarios. Aerosol concentrations decrease in the 1.5°C and 2°C simulations compared to present day (Wehner et al. 2014; Mitchell et al. 2017) which is important to note as aerosols can have a reducing effect on potential intensity more so than greenhouse gas emissions have an increasing effect (Sobel et al. 2019; Wang et al. 2014). Additionally, it is likely that an increase in aerosols could increase rainfall rate and rainfall area of hurricanes (Zhao et al. 2018a). Readers should be aware that this study will not explore such mechanisms as aerosol concentrations are not considered in the hurricane model nor the rainfall model and so results could be somewhat conservative.

3.2.5 Hurricane model input fields

Upon comparing global circulation model data to ERA5 reanalysis data, the HAPPI ensemble demonstrates an overestimation in potential intensity (Figure 8a) over the main development region (MDR) which here is described as the region enclosed by 10-20°N and 20-70°W representing the rough area where most hurricanes form (Goldenberg et al. 2001; Kossin 2017; Balaguru et al. 2018).

Potential intensity is the maximum sustainable intensity a storm can achieve given by:

$$V^2 = \frac{C_k}{C_D}\frac{T_s - T_o}{T_o}(k_s - k_a) \tag{1}$$

where V is the maximum sustained wind speed, C_k and C_D are coefficients for the total heat content of the system and momentum, T_s and T_o are the absolute temperatures of the sea

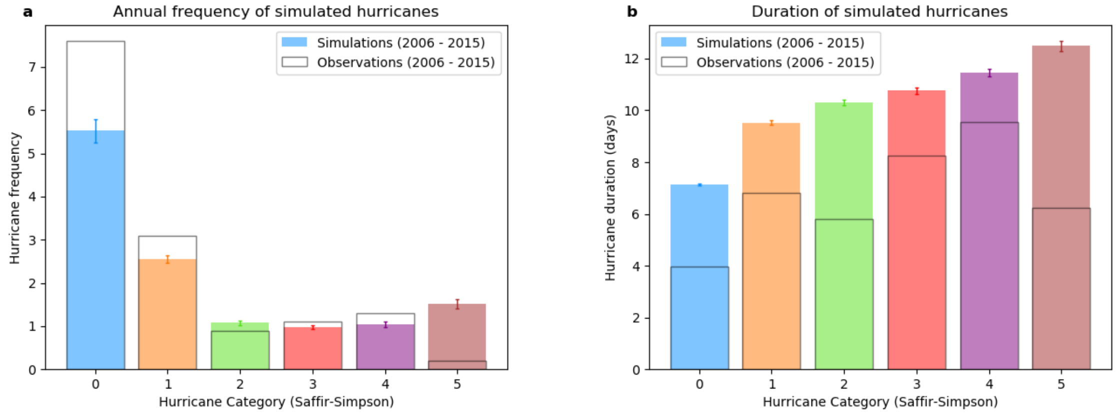

Figure 10: A comparison of hurricane annual frequency (**a**) and duration (**b**) for the period 2006-2015. (**a**) Hurricane frequency is separated by the Saffir-Simpson intensity scale (x-axis) and is measured in units of number of hurricanes occurring per year (y-axis). (**b**) Hurricane duration is the measure of how long a hurricane of category x remains at tropical storm strength or more. Filled bars represent simulated tracks while unfilled bars represent observed tracks from the best-tracks data set. It should be noted that due to the paucity of events in the observable period this does not represent fully the overall behaviour for the North Atlantic basin, only the decade in question.

surface and the outflow temperature respectively, and (k_s - k_a) represents the total heat content difference between saturated air at the ocean surface and ambient boundary layer air (Emaunel 1999). Potential intensity is therefore driven by sea surface temperature and the temperature difference of the air at different levels of the atmosphere.

The overestimated potential intensity (Figure 8a) stems from an underestimate of the outflow temperature (Figure 8c) rather than any SST related bias as the HAPPI ensemble is forced with prescribed SSTs from the observable period. Outflow temperature, or the temperature of neutral buoyancy, is the temperature at which a rising parcel of air reaches equilibrium with its surroundings and subsequently stops rising. In a hurricane, these parcels of air then move outward, creating the recognisable swirl pattern in the cloud formation of the hurricane. Outflow temperature is generated using the HAPPI simulated atmospheric temperature at various pressure levels from the lower troposphere (table 3) to the top of the tropopause. The underestimation of outflow temperature is due to a cooler atmospheric temperature bias present in the HAPPI ensemble.

3.2.6 Hurricane model output

For storms of hurricane strength, the annual frequency has been well captured (Figure 10a), however, category five storms occur more often in the simulations compared to observations and typically last six days longer (Figure 10b). This is likely due to a large area of the North At-

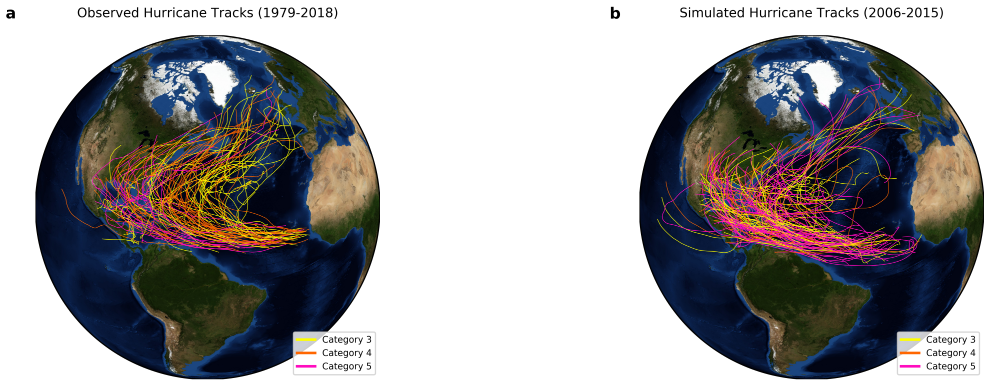

Figure 11: 620 observed (**a**) and a random selection of 600 simulated (**b**) hurricane tracks from the period (1979-2018) for major hurricanes (category 3-5). Category 3 hurricanes are mapped with yellow lines, category 4 with orange and category 5 with pink. An intensity stratification is visible in the observations, whereby more intense hurricanes have a stronger westward trajectory, but not in the simulations.

lantic basin experiencing higher potential intensity compared to observations (figure 8a) meaning simulated hurricanes are contained in a favourable environment for more of their track than they would in reality. Moreover, the hurricane tracks in figure 11a show a tendency for observed category 5 hurricanes to travel further west before veering north. A hurricane with this trajectory is likely to intersect land masses sooner and therefore lose its energy source and dissipate at an earlier point than a hurricane which travels further north over the ocean. This intensity stratification is not present in simulated hurricane trajectories for intense storms (figure 11b) which presents an explanation for the overestimated frequency of category 5 hurricanes as there is no distinction in behaviour to the weaker storms.

Figure 11b shows a track density bias towards the Caribbean region and Gulf of Mexico where tracks have a stronger westward component compared to observations. Longer time over the warm Caribbean ocean means hurricanes are fed more energy which allows them to further intensify, this points to an explanation for higher than observed category 5 hurricane frequency (figure 10a). Wind field anomalies at the 250 hPa level stray further from observations compared to the 850 hPa level, as seen in supplementary figure S.1. The 250 hPa winds exhibit a south westerly bias which is a likely cause for the simulated track pattern modelled by the equation:

$$\mathbf{V_{track}} = \alpha \mathbf{V_{850}} + (1-\alpha)\mathbf{V_{250}} + \mathbf{V}_{\beta} \tag{2}$$

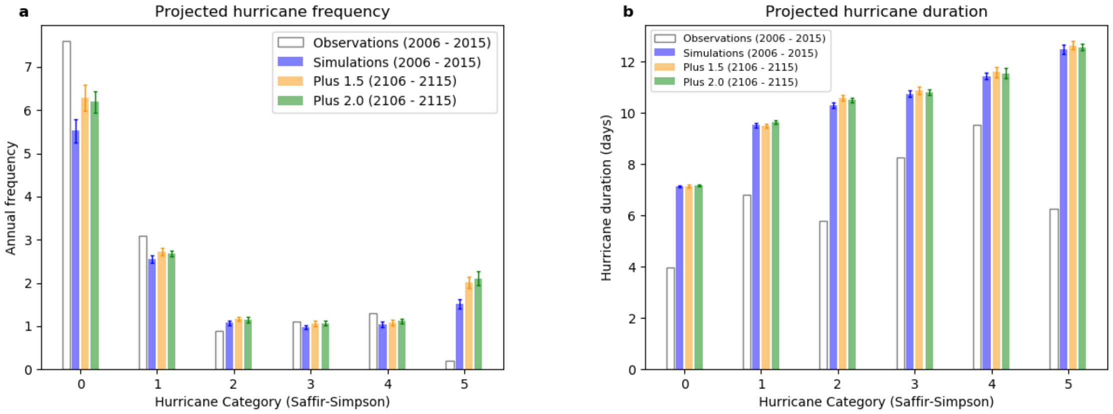

Figure 12: Projections of hurricane frequency (**a**) and duration (**b**) under the Paris Agreement scenarios. 95% confidence intervals are calculated via the Monte-Carlo method.

Where V_{track} is the track trajectory, V_{850} and V_{250} are the wind field vectors at 850hPa and 250hPa respectively, V_{β} is the beta correction vector, and lastly α is a weighting (Marks 1992; Emanuel 2006).

3.3 Results and Discussion

Figure 12a indicates there is an increased occurrence of both tropical storms and category 5 hurricanes under the Paris Agreement scenarios compared to the present climate. Under historical simulations, there are 12.5 hurricanes a year — scaled to match observed trends — this is seen to increase to 14.5 under the 1.5°C scenario and 14.2 in a 2 degree warmer world. This could be due to the higher potential intensity anomaly and a lower outflow temperature anomaly between the warmer scenarios and the present climate (figure 13a and 13c). On the other hand, there are no global warming reactions in the average projected duration of hurricanes, shown in figure 12b and supplementary figure S.3a.

There is a shift in the Accumulated Cyclone Energy (ACE) of the most extreme storms, with the 95^{th} percentile moving from $82.5 \text{x} 10^4$ Kn in the historical simulation to $92.1 \text{x} 10^4$ Kn in the 1.5°C warmer scenario and $93.8 \text{x} 10^4$ Kn in the 2°C scenario. This signifies that the most extreme hurricanes will become more intense under the Paris Agreement scenarios (see supplementary figure S.3d). This is in line with other studies which explored tropical cyclone intensity under the Paris Agreement scenarios (Burgess et al. 2018; Wehner et al. 2018; Muthige et al. 2018). This change is likely to have arisen from an increase in potential intensity in the 1.5°C and 2°C scenarios compared to the historical runs. For example, the potential intensity

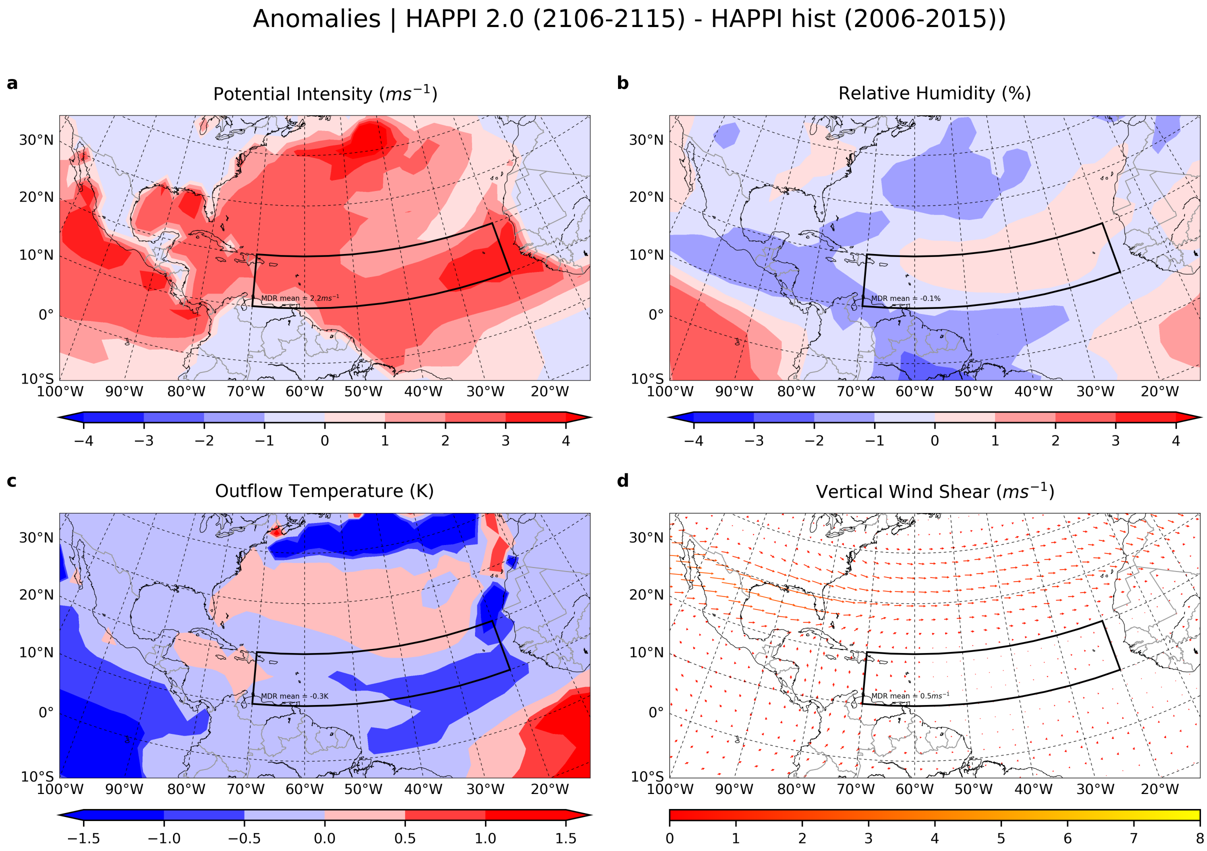

Figure 13: Anomalies of the plus 2.0 scenario compared to historical simulations looking as **a.** Potential intensity **b.** Relative humidity **c.** Outflow temperature and **d.** Vertical wind shear.

anomaly between 2°C and historical is 2.2 ms^{-1} in the Main development region (MDR) which indicates a shift towards a higher theoretical maximum intensity (figure 13a). These findings are consistent with the notion that the North Atlantic basin has shown an increasing trend in potential intensity (Wing et al. 2015). The shift is due to both an increase in SST under the warming scenarios and a cooling of the tropical tropopause layer which reduces the outflow temperature (Figure 13c). Per 1°C of tropical tropopause cooling, potential intensity increases at a rate of 1 ms^{-1}, while per 1°C of SST warming, the potential intensity increased by 2 ms^{-1} (Ramsay 2013).

Although there are no substantial global warming signals in the overall translation speed, duration or genesis date (see supplementary figure S.3), it is likely any global warming signals are masked by the basin-wide behaviour and a stronger signal could be detected by looking in certain regions or at different intensity levels. However, this has not been explored in the study for these parameters.

3.3.1 Hurricane rainfall

The study highlights five major hurricanes which have hit the Caribbean region in the last 40 years: Hurricane Irma, Maria, Georges, Ivan and Matthew which all brought substantial rainfall to Cuba, Puerto Rico, Dominican Republic, Jamaica and Haiti respectively. Using ERA5 reanalysis and the best-tracks dataset, hurricanes were tagged based on their intersection at time T with the chosen countries and the corresponding total storm rainfall was calculated for the period T – 6 hours to T + 72 hours that the hurricane was passing over the country. Figure 14 shows the observed rainfall of each of the five hurricanes. Hurricane Harvey shows a particularly concentrated signal as this hurricane stalled over Texas in 2017 bringing catastrophic amounts of rainfall to the region.

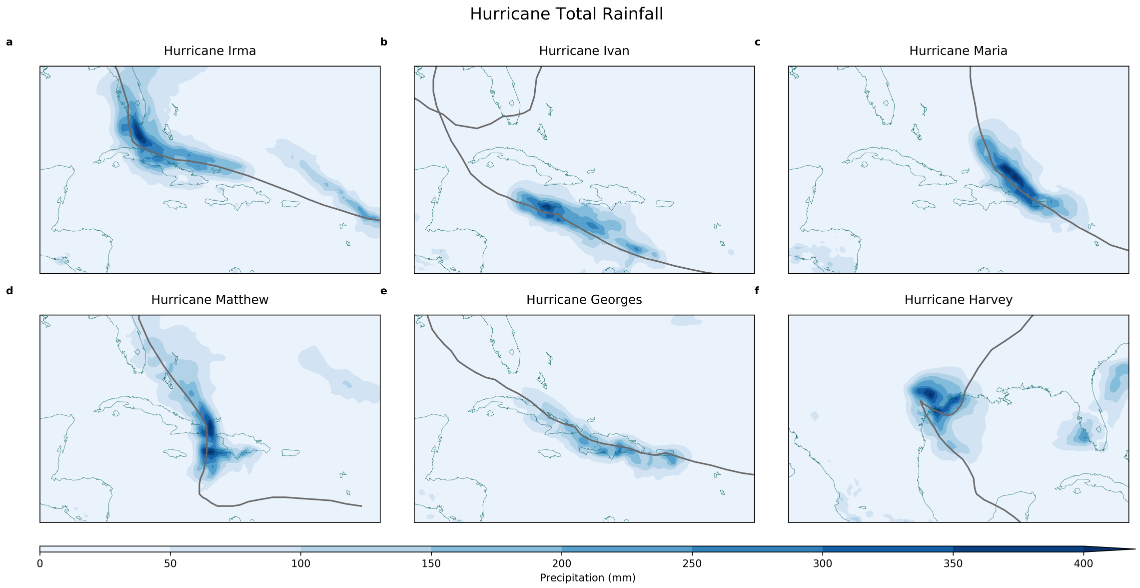

Figure 14: Hurricane tracks and associated rainfall for five major hurricanes affecting the Caribbean region and Hurricane Harvey (**f**), a hurricane which made history by stalling over Texas, bringing with it tumultuous amounts of rain.

Return periods were calculated as the reciprocal of the annual exceedance probability of a rainfall event whereby each event is unique to the country it affected (figure 15).

The difference between the Paris Agreement scenarios of 1.5°C and 2°C warming above pre-industrial levels is subtle overall but more pronounced in the Eastern Caribbean region, where the simulations exhibit a decrease in the return period with a global warming. A hurricane rainfall event like hurricane Maria, affecting Puerto Rico, would be 43% less likely in the Paris Agreement goal of a 1.5°C warming scenario compared to the more conservative target of 2°C. The difference between the current and 1.5°C simulations for Puerto Rico is small and although there is uncertainty in the results, it points towards a likely benefit in committing to the ambitious target of 1.5°C with rainfall events likely being similar to the present day. Similarly, hurricane Georges which hit the Dominican Republic in 1998, would become a one in 12-year event under the more extreme climate scenario of 2 degrees warming. Increasing mitigation efforts in order to halt global warming and stabilise temperature rise to 1.5°C above pre-industrial levels would mean an event resonant with hurricane Georges would be 42% less likely to occur than if warming was stabilised at 2°C. Overall, results suggest a visible global warming signal present in hurricane rainfall affecting Puerto Rico and the Dominican Republic.

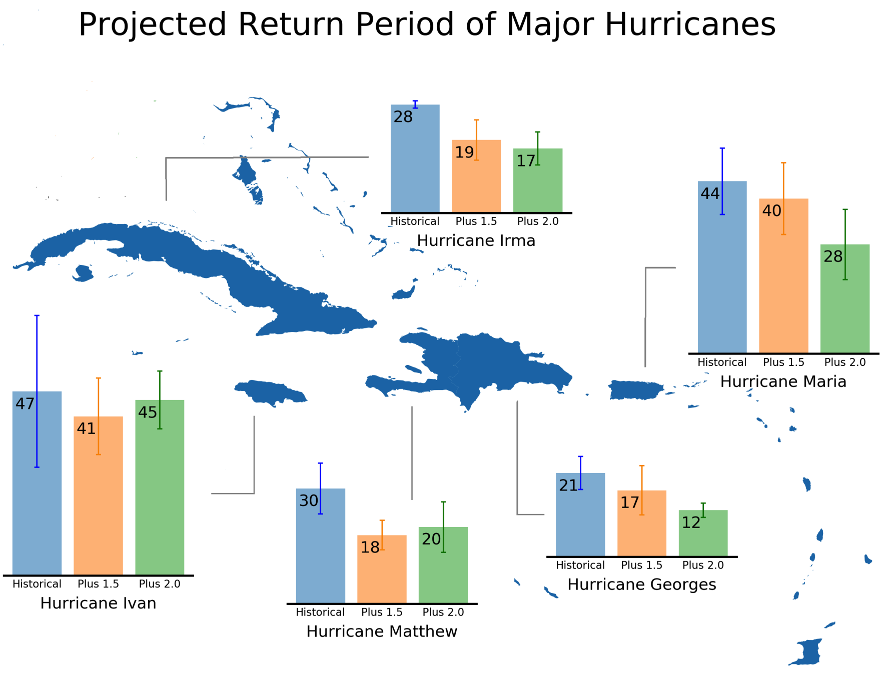

Figure 15: Hurricane-rainfall return period projections for Cuba, Haiti, the Dominican Republic, Puerto Rico and Jamaica. Confidence intervals are calculated by a bootstrapping technique applied to results from each model ensemble.

In the Central and West Caribbean regions, there is not a discernible difference between the Paris Agreement scenarios. In Cuba, a storm with rainfall matching or exceeding that of hurricane Irma could become a one in 19 year event in a 1.5°C warmer world compared to a one in 17 year event in the 2°C scenario. It is a similar story in Haiti, where a hurricane rainfall event such as Matthew is actually projected to be 10% more likely in the lower warming scenario compared to the higher. However, there is an overall global warming signal present in the simulations for these countries, with an Irma-scale rainfall event becoming 75% more likely in a 2°C warming scenario compared to the present climate, occurring once every 17 years compared to once every 28 years. A rainfall event matching or exceeding that of hurricane Matthew would be 50% more likely in a 2°C scenario compared to the present climate.

In Jamaica, there is little or no hurricane response to global warming in terms of rainfall events. Hurricane Ivan, a one in 47-year event under the current climatic conditions, would be just as likely to occur in either warming scenario compared to the present day.

It should be noted that these results represent a possible underestimate of projected hurricane rainfall as the Clausius-Clapeyron relationship, whereby the water holding capacity of the troposhpere increases by 7% for every 1°C of warming (Held and Soden 2006), is not taken into account in the rainfall model. Moreover a further underestimate could be likely as anthropogenic aerosols are not accounted for in the HAPPI 1.5 and 2.0 scenarios nor the rainfall model and aerosols have been shown to increase the rainfall rate and area of hurricanes (Zhao et al. 2018a).

The increase in accumulated cyclone energy (ACE), which is sum of the square of storm intensity along a track, in the Paris Agreement scenarios is a likely factor in the observed climate change signal. Tropical cyclone rain rate is known to increase with storm intensity and the maximum rain rate occurs closer to the storm centre for major tropical cyclones (category 3-5) compared to weaker storms (Lonfat et al. 2004; Yu et al. 2017). With the aforementioned shift towards more intense hurricanes in a warming world, it is therefore likely to have contributed to the higher probability of extreme rainfall events in the 1.5°C or 2°C warming scenarios compared to the present day.

Another possible influencer in the observed climate change signal could be hurricane stalling. Locally, the amount of rainfall that falls on a region also depends on hurricane translation speed i.e. the speed the hurricane moves along its track. A hurricane moving slowly over a region dumps its rainfall over the same area for longer — this is particularly evident in the recent case of hurricane Harvey — and with translation speed showing a decreasing trend globally, having decreased 10% since 1949 (Kossin 2018), this could be a factor in projected local rainfall resulting from hurricanes. Additionally, hurricane tracks can loop and while the translation speed might remain constant or indeed be quite rapid, the hurricane is still hovering over a local region for an extended period of time. Both looping and a slow translation speed are characteristics of stalling hurricanes. Hall and Kossin (2019) showed that the rainfall from stall events exhibit an increasing trend in both their frequency and associated rainfall over the coast of the USA. However no attribution to anthropogenic global warming was explored in the study. Hurricane stalling is further studied here to gauge the possible extent to which it could be a factor in hurricane rainfall projections.

There are limitations in the bias correction method which uses ERA5 data to estimate the return period of future hurricane rainfall events. Evaluation of the model has indicated large biases within the rainfall results which could in part be due to reanalysis products underestimating hurricane rainfall — results derived from satellite observations might only be measuring rainfall when the satellite is flying over the hurricane therefore not continuously taking measurements throughout its track. Other possible model evaluation methods could include data from multiple rainfall products, for example the TRMM rainfall dataset and rainfall gauge data. The latter is hard to obtain as there is no centralised rainfall dataset in the Caribbean region and rain gauges tend to get damaged during hurricane events making their readings unreliable. With this in mind, caution should be taken when interpreting the results and readers should be aware that, although corrected for, these biases are significant.

3.3.2 Stalling Hurricanes

In this study, a hurricane is defined as stalled if, for any six-hour track point $P_{t=n}$ at timestep n, the points P_{t-24}, P_{t-18}, P_{t-12}, P_{t-6}, P_{t+6}, P_{t+12}, P_{t+18} and P_{t+24} are contained within a 200km radius of point $P_{t=n}$ (i.e. a hurricane hovers over a region with 200 km radius for at least 48 hours). This method accounts for both translation speed and a possible change in direction which are both key indicators of stalling (Hall and Kossin 2019). Figure 16 shows a selection of stalled hurricanes, the red circles depicting the regions of stalling. It should be noted that selection of the stall region is arbitrary and there is a slight variation in results depending on its value.

When looking at hurricane intensity, figure 17 shows the category of the hurricane at the point of stalling, with a higher proportion of tropical storms and weak hurricanes more likely to stall. The most common stalling category is tropical storms, where roughly 30% of tropical storms stall, whilst overall the stalling rate decreases as intensity increases. Major hurricanes (category 3, 4 and 5) have a much lower stalling rate and no category 5 stalls were detected. This behaviour is reproduced similarly in the historical simulations, however weaker tropical

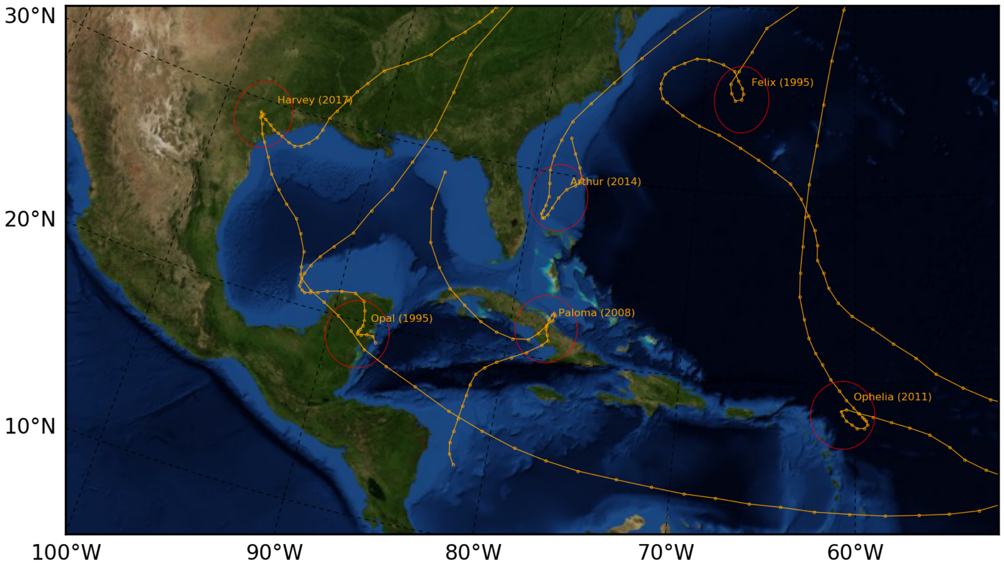

Figure 16: A selection of stalled hurricanes which occurred between 1979 - 2018. Orange lines denote hurricane tracks and points along the tracks are six hours apart. Lastly, the red circles highlight the points of stalling.

storms are much more likely to stall in simulations.

The trend of stalling hurricane frequency exhibits a moderate positive relationship with a Pearson r-value of 0.38 and is significant to the 0.05 level for the period 1900-2018 (figure 18). However a trend is not significant with results from 1852. Although a significant trend is not observed in the entire dataset, the result suggests the annual frequency of stalling hurricanes could be increasing over the period 1900-2019 which would be in line with Hall and Kossin (2019) who define a stalling event based on a reduction in translation speed and a trajectory angle change during a 48-hour period.

To calculate the annual frequency of stalling hurricanes in the Paris Agreement scenarios, a total of 100 storms were generated per year, per ensemble member. The number of stalling hurricanes is then multiplied by a scaling factor. This scaling factor is generated based on the annual frequency statistic for each model which ensures an equal weighting for each year of the simulation based on the total number of hurricanes generated for that year. In the comparable period 2006-2015 there is an average of 3.4 stalling hurricanes annually in the observational dataset and the simulated tracks in the historical simulation produced 3.5 stalling hurricanes a year when scaled in line with the total annual frequency of hurricanes.

According to the KolmogorovSmirnov test, there is a significant difference between the historical distribution and both the plus 1.5°C and plus 2°C distributions, however, the distri-

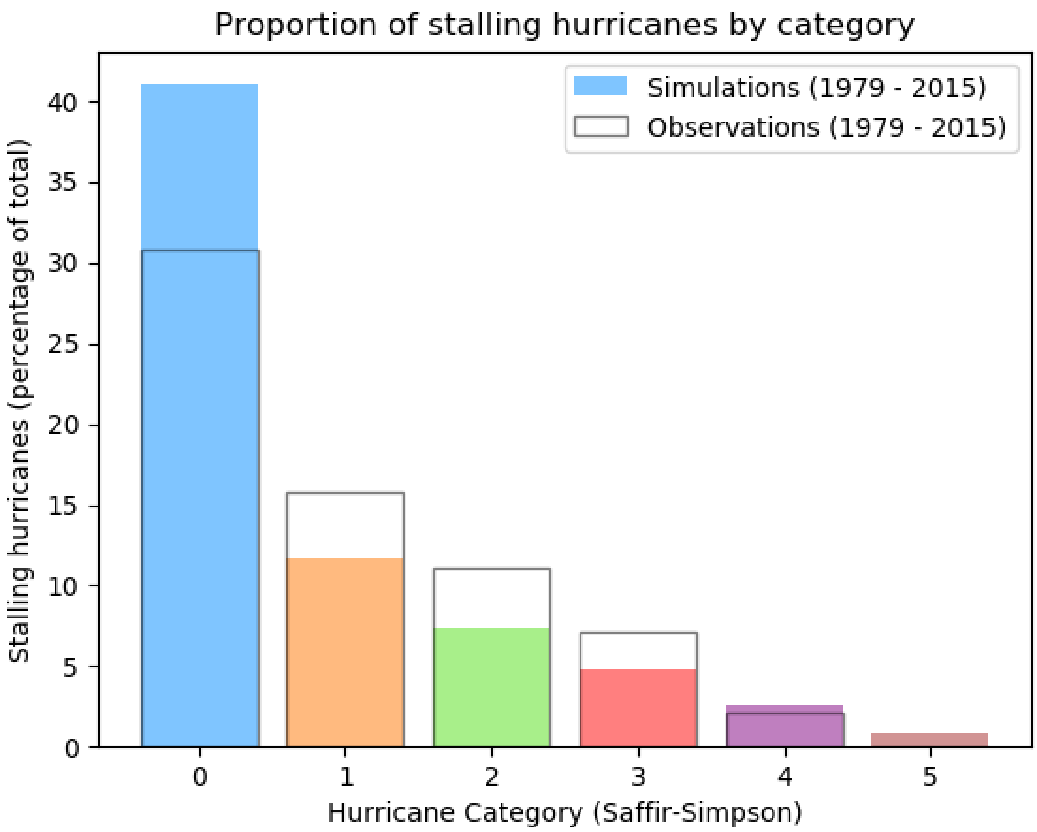

Figure 17: The proportion of hurricane stalls when at category x strength in the best-tracks dataset (unfilled bars) and historical simulations (filled bars).

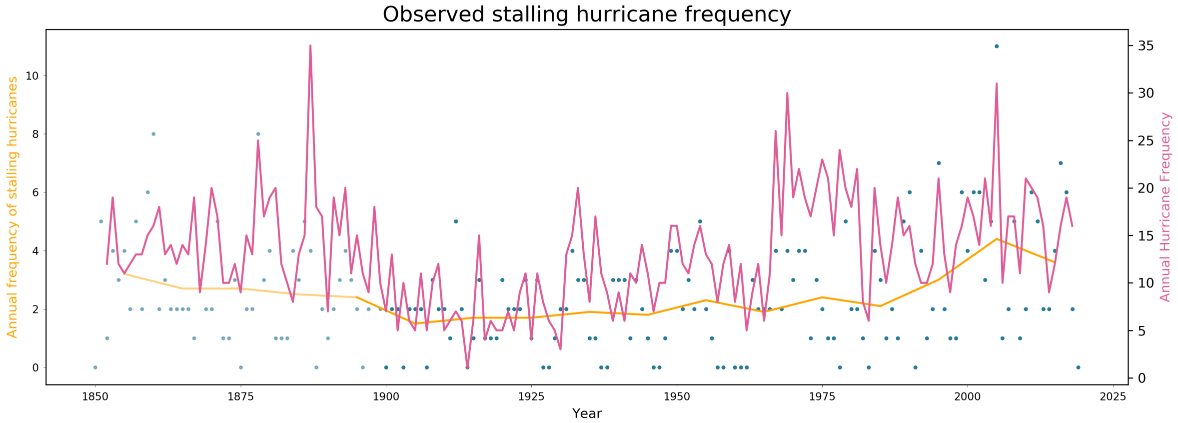

Figure 18: Annual frequency of stalling hurricanes between 1852 and 2018. The orange line represents the ten year moving average of stalling hurricane frequency and the red line represents the annual hurricane frequency overall. The period 1900 - 2019 shows a moderate increasing trend significant to the 0.05 level by the Pearson significance test. Significance is not present for the period 1852-2018.

butions of the warming scenarios do not differ significantly from each other (figure 19). The projected increase in the annual number of stalling hurricanes under the Paris Agreement scenarios is likely due to an increase in the overall frequency of hurricanes in the projections,

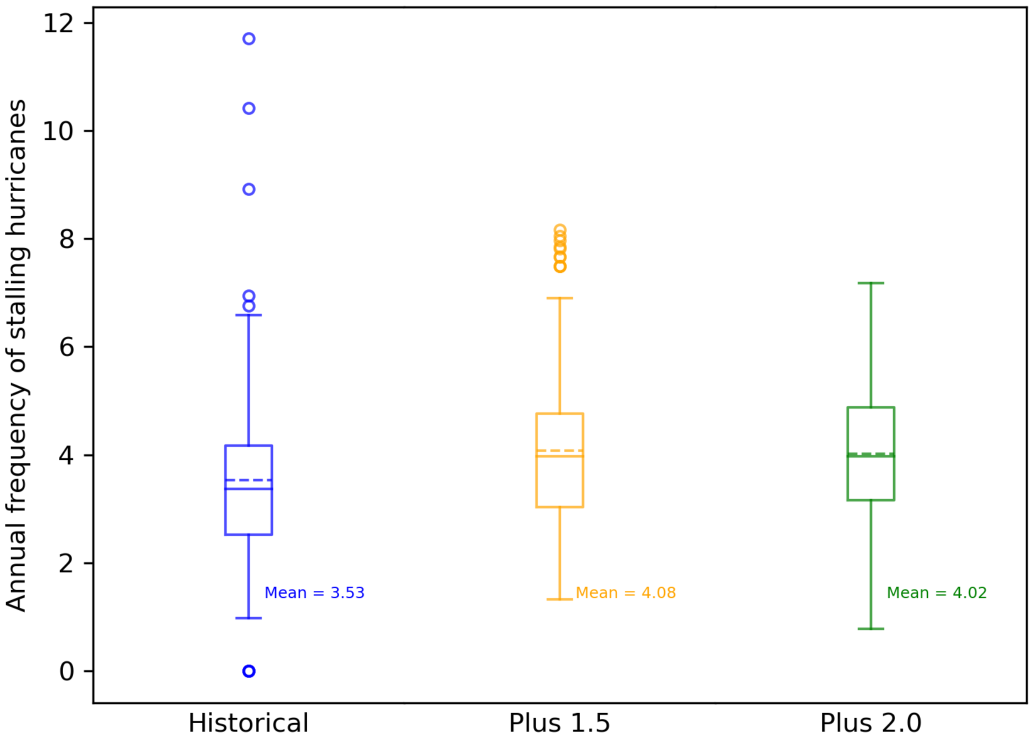

Figure 19: A box and whisker plot of the annual stalling frequency of hurricanes in historical simulations (2006-2015), and the 1.5°C and 2°C warming scenarios of the Paris Agreement. The dashed horizontal line denotes the mean of the data set while the full horizontal line is the median.

as the overall proportion of stalling hurricanes is not significantly different between each of the three scenarios by the Kolmogorov-Smirnov test (see supplementary figure S.4). Translational speed in each of the three scenarios show no significant difference which is in contrast to the observed trend in the North Atlantic where hurricane translation speed has decreased 16% since 1949 (Kossin 2018). This could be due to weaker summer tropical circulation caused by anthropogenic global warming (Vecchi and Soden 2007; He and Soden 2015; Kossin 2018). Vis-a-vis weaker tropical circulation, the wind fields at the 250 hPa and 850 hPa levels across the three scenarios do not display a large variation which could provide an explanation for the minimal change in the proportion of stalling hurricanes between these projections.

3.4 Conclusion

In summary, the results suggest that the Eastern Caribbean region in particular is likely to benefit from a reduction in hurricane precipitation as a result of increased efforts to stabilise global warming to the more ambitious Paris Agreement target of 1.5°C instead of 2°C. For example, hurricane rainfall events such as hurricane Maria, which caused devastation in Puerto Rico in 2017, would be 43% less likely in a 1.5°C warmer world compared a 2°C warming. With the exception of Jamaica, there is a global warming signal present in the rainfall results across the Caribbean which is likely due to a projected increase in accumulated cyclone energy in the Paris Agreement scenarios.

Stalling hurricanes have a notable impact on local hurricane rainfall (Hall and Kossin 2019) and have shown a significant increasing trend of occurrence over time (1900-2019) in this study and along the US coast this century (Hall and Kossin 2019). Projections of stalling hurricane frequency portray an increase under the Paris Agreement scenarios, however this is likely due to a general increase in hurricane frequency under warming conditions as there is not a significant change in the proportion of stalling hurricanes across the three regimes. Further investigation is needed to establish a relationship between projected hurricane rainfall and stalling events and explore whether a trend in stalled hurricanes can be attributed to anthropogenic global warming.

The study makes a direct comparison of hurricane rainfall between scenarios and therefore did not take into account the Clausius-Clapeyron relationship, nor are anthropogenic aerosols considered in the rainfall projections. As a result, it is likely that the projected rainfall pattern would be more pronounced in reality under the Paris Agreement scenarios. Rainfall results were found to contain a bias resulting from a higher track density in the Caribbean region and an overestimated potential intensity, therefore a bias-correction was applied based on ERA5 return period calculations.

For the most part, this study points towards an increased likelihood of extreme hurricane-rainfall events across the Caribbean under the Paris Agreement scenarios. Such a region stands to be disproportionately affected by this increase as well as many more aspects of climate change and is likely to benefit from further research into integrated climate risks.

4 Concluding remarks

Hurricanes have made up the majority of damages to the Caribbean since 1960 (Burgess et al. 2018) and are mainly responsible for the extreme rainfall events and extreme sea levels experienced in the region (Khouakhi et al. 2017; Walsh et al. 2015; Peterson et al. 2002). This, coupled with the recent adoption of the ambitious Paris Agreement climate targets, have highlighted the importance of research into climate-related risks over a range of timescales (Shuckburgh et al. 2017; Mitchell et al. 2016).

Planned adaptation and resilience efforts — such as retreat, accommodate and protect — vary substantially in the Caribbean (Mycoo 2018; Hoegh-Guldberg et al. 2018). Choosing an adaptation method relies heavily on the scale and longevity of the threat to infrastructure and life, thus it is necessary to build up robust evidence across the board to paint a reliable and detailed picture of the path ahead. Therefore, the overarching aim of this study was to identify any changes in future projections of hurricane rainfall in the context of the Caribbean and explore the relationship with hurricane stalling projections.

4.1 Projected hurricane rainfall

With the observed increase in mean and peak rain rates with intensity (Lonfat et al. 2004; Yu et al. 2017), the projected shift towards more intense tropical cyclones in a warming world (Wehner et al. 2018; Zhao et al. 2009; Walsh et al. 2016) indicates the possibility of more intense hurricane-rainfall events under the Paris Agreement scenarios.

This study employed a dynamical hurricane model, developed by Kerry Emanuel (Emanuel et al. 2008), embedded within four global climate models in the HAPPI ensemble. Hurricane activity was explored under three scenarios: historical, 1.5°C and 2°C warming above pre-industrial levels. Hurricane rainfall was estimated along tracks using a physics-based hurricane rainfall algorithm (Zhu et al. 2013) and return period data was generated for five Caribbean countries: Cuba, Jamaica, Puerto Rico, the Dominican Republic and Haiti. The results suggest that the Eastern Caribbean region, in particular, is likely to benefit from a reduction in hurricane precipitation as a result of increased efforts to stabilise global warming to the more ambitious Paris Agreement target of 1.5°C. For example, hurricane-rainfall events consistent with hurricane Georges, which hit the Dominican Republic in 1998, would be 42% less likely to occur if warming was stabilised at 1.5°C above pre-industrial levels instead of 2°C. The projected increase in accumulated cyclone energy under the Paris Agreement scenarios by the HAPPI ensemble provides a possible explanation for the greater likelihood of extreme hurricane-rainfall events in a warmer world.

Stalling hurricanes have a notable impact on local hurricane rainfall (Hall and Kossin 2019) and have shown a moderate increasing trend (1900-2019) which is significant along the US coast this century (Hall and Kossin 2019). Projections of stalling hurricane frequency portray an increase under the Paris Agreement scenarios, however this is likely due to a general increase in hurricane frequency under warming conditions as there is no significant change in the proportion of stalling hurricanes across the three setups. There are an average of 3.4 hurricane stalls a year, but stalling over land is rare with just 25 land stalls in the past 40 years. Even with a projected increase in stall events the probability of a hurricane stalling over land would remain low, however, even one stalling event over land — such as hurricane Harvey in 2017 — can have great impact to an area and cause extensive damage.

4.2 Key limitations

Rain rate has been shown to increase in warming scenarios by several related mechanisms, for example, Lin et al. (2015) showed that rain rate increases by $\sim 22.5\%$ with a 3°C warming of SSTs. Moreover, the Clausius-Clapeyron relationship, whereby the water holding capacity of the troposhpere increases by 7% for every 1°C of warming (Held and Soden 2006), would also infer hurricanes could hold more water under warming scenarios. As the study did not look at the Clausius-Clapeyron relationship it is likely that the projected rainfall pattern is less pronounced in the Paris Agreement scenarios. While this is definitely something that could be incorporated into the model, exploring the extent to which the Clausius-Clapeyron relationship proportionately affects hurricane rainfall is outside the scope of this study.

Zhao et al. (2018a) found an increase in rainfall rate and rainfall area of hurricanes resulting from higher aerosol concentrations. The rainfall model used in this study does not incorporate aerosols (Zhu et al. 2013; Lu et al. 2018) so results assume aerosol concentrations remain constant across all scenarios.

Rainfall results contained a bias which most likely result from a higher track density in the Caribbean region and an overestimated potential intensity, therefore a bias-correction was applied based on ERA5 return period calculations. The bias-correction method itself was relatively rudimentary, relying on subjectively matching simulations to observations under the assumption that the bias follows a linear trend. Observational data could be enhanced by including hurricane-rainfall estimates from a longer ERA5 dataset (when available) as well as incorporating more datasets such as The Tropical Rainfall Measuring Mission (TRMM) and Climatic Research Unit Timeseries (CRU TS) rainfall datasets. The impact of bias correction practices on results could be explored in detail in order to elect the best possible method.

There is a possibility for more ensemble members to be used in generating hurricane tracks. In this study, 200 simulated years of data were used to generate 20,000 hurricane tracks in each scenario, but many models in HAPPI have hundreds of ensemble members. The relative benefits of such an extension would require investigation as processing the data for use in the hurricane model is resource intensive. In this study, server space availability limited the number of ensemble members chosen as unprocessed data was of the order of 15-20 TB.

4.3 Next steps

It takes at least six years for even the richest of the Caribbean countries to rebuild after a major hurricane hits, preventing six years of growth in the process, and this can be substantially longer for the less economically developed countries with recovery costs often outstripping the countrys annual GDP. Building resilient infrastructure ubiquitously throughout the islands is not feasible due to financial and time constraints. Therefore, a multi-hazard, multi-scale approach is needed to identify the most at-risk islands, cities and communities to target resilience funding and strategies more effectively.

Hurricane damages are normally categorised over two phases, the impact phase of the hurricane (i.e. when it makes landfall, and the days immediately following it), and the post-impact phase, which comprises the weeks and months following landfall. Further focus on the impact phase is possible, where mortality and morbidity arise mainly due to coastal storm surges, inland flooding, intense winds, and landslides, directly affecting the health and well-being of local populations. An integrated climate risk approach is needed to fully understand the threat of future hurricanes to Caribbean populations. Studies to follow could therefore incorporate storm surge, flood and landslide modelling into the rainfall results to quantify such threats and to allow for informed adaptation and resilience planning.

In conclusion, this study contributes another piece of the climate change impacts puzzle. The findings further support the argument that the Caribbean is set to be disproportionately affected by the impacts of a global warming of 2°C above pre-industrial levels and that they also stand to benefit from increased mitigation efforts in order to stabilise warming to the 1.5°C level.

References

Anderson, M., L. Holcombe, R. Flory, and J. P. Renaud, 2008: Implementing low-cost landslide risk reduction: A pilot study in unplanned housing areas of the Caribbean. *Natural Hazards*, **47 (3)**, 297–315, doi:https://doi.org/10.1007/s11069-008-9220-z.

ARC Centre of Excellence in Coral Reef Studies, 2018: Coral reefs protect coasts from severe storms. Tech. rep., ARC Centre of Excellence in Coral Reef Studies. URL www.sciencedaily.com/releases/2018/04/180403111123.htm.

Balaguru, K., G. R. Foltz, and L. R. Leung, 2018: Increasing Magnitude of Hurricane Rapid Intensification in the Central and Eastern Tropical Atlantic. *Geophysical Research Letters*, **45 (9)**, 4238–4247, doi:10.1029/2018GL077597.

Balaguru, K., S. Taraphdar, L. R. Leung, G. R. Foltz, and J. A. Knaff, 2014: Cyclone-cyclone interactions through the ocean pathway. *Geophysical Research Letters*, **41 (19)**, 6855–6862, doi:10.1002/2014gl061489.

Barker, D., 2012: Caribbean agrictulture in a period of global change: vulnerabilities and opportunities. *Caribbean Studies*, **40 (2)**, 41–61, URL http://www.jstor.org/stable/41917603.

Bell, G. D., and Coauthors, 2000: Climate Assessment for 1999. *Bulletin of the American Meteorological Society*, **81 (6)**, S1–S50, doi:https://doi.org/10.1175/1520-0477(2000)81[s1:CAF]2.0.CO;2.

Bender, M. A., T. R. Knutson, R. E. Tuleya, J. J. Sirutis, G. A. Vecchi, S. T. Garner, and I. M. Held, 2010: Modeled Impact of Anthropogenic Warming on the Frequency of Intense Atlantic Hurricanes. *Science*, **327 (28)**, 454–458.

Benjamin, L., and A. Thomas, 2016: 1.5 To Stay Alive? AOSIS and the Long Term Temperature Goal in the Paris Agreement. *SSRN Electronic Journal*, **(January)**, doi:http://dx.doi.org/10.2139/ssrn.3392503.

Blake, E. S., and D. A. Zelinsky, 2017: Hurricane Harvey. Tech. Rep. 2005, 1–77 pp. URL https://www.nhc.noaa.gov/data/tcr/AL092017_Harvey.pdf.

Bove, M. C., J. B. Elsner, C. W. Landsea, X. Niu, and J. J. O'Brien, 1998: Effect of El Nino on U . S . Landfalling Hurricanes , Revisited. *Bulletin of the American Meteorological Society*, doi:https://doi.org/10.1175/1520-0477(1998)079⟨2477:EOENOO⟩2.0.CO;2.

Bryan, G. H., and R. Rotunno, 2008: The Maximum Intensity of Tropical Cyclones in Axisymmetric Numerical Model Simulations. *Monthly Weather Review*, **137 (6)**, 1770–1789, doi:10.1175/2008mwr2709.1.

Burgess, C. P., M. A. Taylor, N. Spencer, J. Jones, and T. S. Stephenson, 2018: Estimating damages from climate-related natural disasters for the Caribbean at 1.5 °C and 2 °C global warming above preindustrial levels. *Regional Environmental Change*, **18 (8)**, 2297–2312, doi:10.1007/s10113-018-1423-6.

Cai, W., and Coauthors, 2015: Increased frequency of extreme La Niña events under greenhouse warming. *Nature Climate Change*, **5 (2)**, 132–137, doi:10.1038/nclimate2492.

Camargo, S. J., 2013: Global and regional aspects of tropical cyclone activity in the CMIP5 models. *Journal of Climate*, **26 (24)**, 9880–9902, doi:10.1175/JCLI-D-12-00549.1.

Campbell, J., and J. Barnett, 2010: *Climate change and small island states: Power, knowledge and the South Pacific*. 1st ed., Taylor & Francis Group, London, 280 pp., doi:https://doi.org/10.4324/9781849774895.

Cangialosi, J. P., A. S. Latto, and R. Berg, 2018: National Hurricane Center Tropical Cyclone Report - Hurricane Irma. 111, URL https://www.nhc.noaa.gov/data/tcr/AL112017_Irma.pdf.

Cashman, A., and M. R. Nagdee, 2017: Impacts of Climate Change on Settlements and Infrastructure in the Coastal and Marine Environments of Caribbean Small Island Developing States (SIDS). *Science Review*, 155–173, URL https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/605066/11._Settlements_and_Infrastructure_combined.docx.pdf.

Copernicus Climate Change Service (C3S), 2017: ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. URL https://cds.climate.copernicus.eu/cdsapp#!/home.

Cruz, R., and Coauthors, 2007: *Climate Change 2007: impacts, adaptation and vulnerability: contribution of Working Group II to the fourth assessment report of the Intergovernmental Panel*. 976pp pp., doi:10.1256/004316502320517344.

Elsner, J. B., 2003: Tracking hurricanes. *Bulletin of the American Meteorological Society*, **84 (3)**, 353–356, doi:10.1175/BAMS-84-3-353.

Elsner, J. B., B. H. Bossak, and X. F. Niu, 2001: Secular changes to the ENSO-U.S. hurricane relationship. *Geophysical Research Letters*, **28 (21)**, 4123–4126, doi:10.1029/2001GL013669.

Elsner, J. B., and B. Kocher, 2000: Global tropical cyclone activity: A link to the North Atlantic Oscillation. *American Geophysical Union*, **27 (1)**, 129–132.

Emanuel, K., 2003: Tropical Cyclones. *Annual Review of Earth and Planetary Science*, 75–104, doi:10.1146/annurev.earth.31.100901.141259.

Emanuel, K., 2005a: *Divine Wind*. Oxford University Press, New York, 285 pp.

Emanuel, K., 2005b: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, **436 (7051)**, 686–688, doi:10.1038/nature03906.

Emanuel, K., 2006: Climate and tropical cyclone activity: A new model downscaling approach. *Journal of Climate*, **19 (19)**, 4797–4802, doi:10.1175/JCLI3908.1.

Emanuel, K., 2010: Tropical cyclone activity downscaled from NOAA-CIRES Reanalysis, 19081958. *Journal of Advances in Modeling Earth Systems*, **2**, 1–12, doi:10.3894/james.2010.2.1.

Emanuel, K., 2011: Self-Stratification of Tropical Cyclone Outflow. Part II: Implications for Storm Intensification. *Journal of the Atmospheric Sciences*, **69 (3)**, 988–996, doi:10.1175/jas-d-11-0177.1.

Emanuel, K., 2017: Assessing the present and future probability of Hurricane Harveys rainfall. *Proceedings of the National Academy of Sciences*, **114 (48)**, 12 681–12 684, doi:10.1073/pnas.1716222114.

Emanuel, K., C. DesAutels, C. Holloway, and R. Korty, 2004: Environmental Control of Tropical Cyclone Intensity. *Journal of the Atmospheric Sciences*, **61 (7)**, 843–858, doi: https://doi.org/10.1175/1520-0469(2004)061⟨0843:ECOTCI⟩2.0.CO;2.

Emanuel, K., S. Ravela, E. Vivant, and C. Risi, 2006: A statistical deterministic approach to hurricane risk assessment. *Bulletin of the American Meteorological Society*, **87 (3)**, 299–314, doi:10.1175/BAMS-87-3-299.

Emanuel, K., S. Solomon, D. Folini, S. Davis, and C. Cagnazzo, 2013: Influence of tropical tropopause layer cooling on atlantic hurricane activity. *Journal of Climate*, **26 (7)**, 2288–2301, doi:10.1175/JCLI-D-12-00242.1.

Emanuel, K., R. Sundararajan, and J. Williams, 2008: Hurricanes and Global Warming: Results from Downscaling IPCC AR4 Simulations. *Bulletin of the American Meteorological Society*, **(89)**, 347–368, doi:https://doi.org/10.1175/BAMS-89-3-347.

Emanuel, K. A., 2013: Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century. *Proceedings of the National Academy of Sciences*, **110 (30)**, 12 219–12 224, doi:10.1073/pnas.1301293110.

Emaunel, K. A., 1999: Thermodynamic control of hurricane intensity. *Nature*, **401 (6754)**, 665–669, doi:10.1038/44326.

Frank, W. M., and P. E. Roundy, 2006: The Role of Tropical Waves in Tropical Cyclogenesis. *Monthly Weather Review*, **134 (9)**, 2397–2417, doi:https://doi.org/10.1175/MWR3204.1.

Goldenberg, S. B., Christopher W. Landsea, Alberto M. Mestas-Nuñez, and William M. Gray, 2001: The recent increase in Atlantic hurricane activity: Causes and implications. *Science*, **293 (5529)**, 474–479, doi:10.1126/science.1060040.

Goldenberg, S. B., and L. J. Shapiro, 1996: Physical Mecahnisms for the Association of El Niño and West African Rainfall with Atlantic Major Hurricane Activity. *Journal of Climate*, **9 (June 1996)**, 1169 – 1187.

Gray, W. M., 1984: Atlantic Seasonal Hurricane Frequency. Part I: El Niño and 30 mb Quasi-Biennial Oscillation Influences. *Monthly Weather Review*, **112 (September)**, 1649–1668.

Guiney, J. L., 1999: Hurricane Georges. Tech. Rep. October 1998, 10 pp.

Hall, T. M., and J. P. Kossin, 2019: Hurricane stalling along the North American coast and implications for rainfall. *npj Climate and Atmospheric Science*, **2 (1)**, 1–9, doi:https://doi.org/10.1038/s41612-019-0074-8.

Hallam, S., R. Marsh, S. A. Josey, P. Hyder, B. Moat, and J. J. Hirschi, 2019: Ocean precursors to the extreme Atlantic 2017 hurricane season. *Nature Communications*, **10 (1)**, 1–10, doi:https://doi.org/10.1038/s41467-019-08496-4.

Halverson, J. B., 2018: The Costliest Hurricane Season in U.S. History. *Weatherwise*, **71 (2)**, 20–27, doi:https://doi.org/10.1080/00431672.2018.1416862.

Haustein, K., M. R. Allen, P. M. Forster, F. E. Otto, D. M. Mitchell, H. D. Matthews, and D. J. Frame, 2017: A real-time Global Warming Index. *Scientific Reports*, **7 (1)**, 1–6, doi:https://doi.org/10.1038/s41598-017-14828-5.

He, J., and B. J. Soden, 2015: Anthropogenic weakening of the tropical circulation: The relative roles of direct CO2forcing and sea surface temperature change. *Journal of Climate*, **28 (22)**, 8728–8742, doi:https://doi.org/10.1175/JCLI-D-15-0205.1.

Hebert, C. G., R. A. Weinzapfel, and M. A. Chambers, 2010: Hurricane Severity Index: A New Way of Estimating a Tropical Cyclones Destructive Potential. *ImpactWeather, Inc.*, 1–5.

Held, I. M., and B. J. Soden, 2006: Robust Responses of the Hydrological Cycle to Global Warming. *Journal of Climate*, **19**, 5686–5699, doi:10.5220/0001648603850388.

Heron, S., J. Morgan, M. Eakin, and W. Skirving, 2005: Hurricanes and their Effects on Coral Reefs. Tech. rep., 31–36 pp. URL https://www.coris.noaa.gov/activities/caribbean_rpt/SCRBH2005_03.pdf.

Hetzinger, S., M. Pfeiffer, W. C. Dullo, N. Keenlyside, M. Latif, and J. Zinke, 2008: Caribbean coral tracks Atlantic Multidecadal Oscillation and past hurricane activity. *Geology*, **36 (1)**, 11–14, doi:https://doi.org/10.1130/G24321A.1.

Hoegh-Guldberg, O., and Coauthors, 2018: Impacts of 1.5°C Global Warming on Natural and Human Systems. *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,*, 175–311, URL https://www.ipcc.ch/sr15.

Holcombe, E., S. Smith, E. Wright, and M. G. Anderson, 2012: *An integrated approach for evaluating the effectiveness of landslide risk reduction in unplanned communities in the Caribbean*, Vol. 61. 351–385 pp., doi:https://doi.org/10.1007/s11069-011-9920-7.

Hsiang, S., and T. Houser, 2017: Dont Let Puerto Rico Fall Into an Economic Abyss. URL www.nytimes.com/2017/09/29/opinion/puerto-rico-hurricane-maria.html%0A.

Hurrell, J. W., Y. Kushnir, and M. Visbeck, 2001: The North Atlantic Oscillation. *Science*, **291 (5504)**, 603 LP – 605, doi:10.1126/science.1058761.

International Trade Centre, 2010: Strategy Grenada Nutmeg Sector Development Strategy. Tech. rep., 106 pp.

James, R., R. Washington, C. F. Schleussner, J. Rogelj, and D. Conway, 2017: Characterizing half-a-degree difference: a review of methods for identifying regional climate responses to global warming targets. *Wiley Interdisciplinary Reviews: Climate Change*, **8 (2)**, doi: https://doi.org/10.1002/wcc.457.

Johnson, M., and C. Watson, 1999: Return Period Estimation of Hurricane Perils in the Caribbean. Tech. rep., 1–17 pp.

Karnauskas, K. B., C. F. Schleussner, J. P. Donnelly, and K. J. Anchukaitis, 2018: Freshwater stress on small island developing states: population projections and aridity changes at 1.5 and 2 °C. *Regional Environmental Change*, **18 (8)**, 2273–2282, doi:https://doi.org/10.1007/s10113-018-1331-9.

Khouakhi, A., G. Villarini, and G. A. Vecchi, 2017: Contribution of tropical cyclones to rainfall at the global scale. *Journal of Climate*, **30 (1)**, 359–372, doi:https://doi.org/10.1175/JCLI-D-16-0298.1.

Kishore, N., and Coauthors, 2018: Mortality in Puerto Rico after Hurricane Maria. *New England Journal of Medicine*, **379 (2)**, 162–170, doi:10.1056/nejmsa1803972.

Klotzbach, P. J., 2010: On the Madden-Julian oscillation-atlantic hurricane relationship. *Journal of Climate*, **23 (2)**, 282–293, doi:https://doi.org/10.1175/2009JCLI2978.1.

Knapp, K. R., M. C. Kruk, D. H. Levinson, H. J. Diamond, and C. J. Neumann, 2010: The international best track archive for climate stewardship (IBTrACS). *Bulletin of the American Meteorological Society*, **91 (3)**, 363–376, doi:https://doi.org/10.1175/2009BAMS2755.1.

Knight, J. R., C. K. Folland, and A. A. Scaife, 2006: Climate impacts of the Atlantic multidecadal oscillation. *Geophysical Research Letters*, **33 (17)**, 2–5, doi:10.1029/2006GL026242.

Knutson, T. R., J. J. Sirutis, S. T. Garner, G. A. Vecchi, and I. M. Held, 2008: Simulated reduction in Atlantic hurricane frequency under twenty-first-century warming conditions. *Nature Geoscience*, **1 (6)**, 359–364, doi:10.1038/ngeo202.

Knutson, T. R., J. J. Sirutis, M. Zhao, R. E. Tuleya, M. Bender, G. A. Vecchi, G. Villarini, and D. Chavas, 2015: Global projections of intense tropical cyclone activity for the late twenty-first century from dynamical downscaling of CMIP5/RCP4.5 scenarios. *Journal of Climate*, **28 (18)**, 7203–7224, doi:10.1175/JCLI-D-15-0129.1.

Knutson, T. R., and Coauthors, 2010: Tropical cyclones and climate change. *Nature Geoscience*, **3 (3)**, 157–163, doi:10.1038/ngeo779.

Knutson, T. R., and Coauthors, 2013: Dynamical downscaling projections of twenty-first-century atlantic hurricane activity: CMIP3 and CMIP5 model-based scenarios. *Journal of Climate*, **26 (17)**, 6591–6617, doi:https://doi.org/10.1175/JCLI-D-12-00539.1.

Kossin, J. P., 2017: Hurricane intensification along United States coast suppressed during active hurricane periods. *Nature*, **541 (7637)**, 390–393, doi:https://doi.org/10.1038/nature20783.

Kossin, J. P., 2018: A global slowdown of tropical-cyclone translation speed. *Nature*, **558 (7708)**, 104–107, doi:https://doi.org/10.1038/s41586-018-0158-3.

Kossin, J. P., S. J. Camargo, and M. Sitkowski, 2010: Climate modulation of north atlantic hurricane tracks. *Journal of Climate*, **23 (11)**, 3057–3076, doi:https://doi.org/10.1175/2010JCLI3497.1.

Lal, M., H. Harasawa, and K. Takahashi, 2002: Future climate change and its impacts over Small Island States. *Climate Research*, **19 (3)**, 179–192, doi:10.3354/cr019179.

Latif, M., N. Keenlyside, and J. Bader, 2007: Tropical sea surface temperature, vertical wind shear, and hurricane development. *Geophysical Research Letters*, **34 (1)**, 12–15, doi: 10.1029/2006GL027969.

Lewsey, C., G. Cid, and E. Kruse, 2004: Assessing climate change impacts on coastal infrastructure in the Eastern Caribbean. *Marine Policy*, **28 (5)**, 393–409, doi:https://doi.org/10.1016/j.marpol.2003.10.016.

Lim, Y. K., S. D. Schubert, R. Kovach, A. M. Molod, and S. Pawson, 2018: The Roles of Climate Change and Climate Variability in the 2017 Atlantic Hurricane Season. *Scientific Reports*, **8 (1)**, 1–10, doi:https://doi.org/10.1038/s41598-018-34343-5.

Lin, Y., M. Zhao, and M. Zhang, 2015: Tropical cyclone rainfall area controlled by relative sea surface temperature. *Nature Communications*, **6**, 1–7, doi:http://dx.doi.org/10.1038/ncomms7591.

Lonfat, M., F. Marks, and S. Chen, 2004: Precipitation Distribution in Tropical Cyclones Using the Tropical Rainfall Measuring Mission (TRMM) Microwave Imagery: A Global Perspective. *Monthly Weather Review*, **132**, 1645–1660, doi:https://doi.org/10.1175/1520-0493(2004)132⟨1645:PDITCU⟩2.0.CO;2.

Lu, P., N. Lin, K. Emanuel, D. Chavas, and J. Smith, 2018: Assessing Hurricane Rainfall Mechanisms Using a Physics-Based Model: Hurricanes Isabel (2003) and Irene (2011). *Journal of the Atmospheric Sciences*, **75 (7)**, 2337–2358, doi:https://doi.org/10.1175/JAS-D-17-0264.1.

Madden, R. A., and P. R. Julian, 1972: Description of Global-Scale Circulation Cells in the Tropics with a 4050 Day Period. *Journal of the Atmospheric Sciences*, **29 (September)**, 1109–1123.

Madden, R. A., and P. R. Julian, 1994: Observations of the 4050-Day Tropical Oscillation: A Review. *Monthly Weather Review*, **122 (May)**, 814–337, doi:https://doi.org/10.1175/1520-0493(1994)122⟨0814:OOTDTO⟩2.0.CO;2.

Maloney, E. D., and D. L. Hartmann, 2001: The MaddenJulian Oscillation, Barotropic Dynamics, and North Pacific Tropical Cyclone Formation. Part I: Observations. *Journal of the Atmospheric Sciences*, **58 (17)**, 2545–2558, doi:https://doi.org/10.1175/1520-0469(2001)058⟨2545:TMJOBD⟩2.0.CO;2.

Mann, M. E., and K. A. Emanuel, 2006: Atlantic Hurricane trends linked to climate change. *Eos*, **87 (24)**, 233–235, doi:https://doi.org/10.1029/2006EO240001.

Marks, D. G., 1992: The Beta and advection model for hurricane track forecasting. *NOAA technical memorandum NWS NMC*, **70**, 1–89.

Matthews, T., R. L. Wilby, and C. Murphy, 2019: An emerging tropical cyclonedeadly heat compound hazard. *Nature Climate Change*, **9 (August)**, doi:https://doi.org/10.1038/s41558-019-0525-6.

McNoldy, B., 2012: Sandy packed more energy than Katrina at landfall. URL https://www.washingtonpost.com/blogs/capital-weather-gang/post/sandy-packed-more-total-energy-than-katrina-at-landfall/2012/11/02/baa4e3c4-24f4-11e2-ac85-e669876c6a24_blog.html?noredirect=on.

Meléndez, E., and J. Hinojosa, 2017: Estimates of Post-Hurricane María Exodus from Puerto Rico. Research Brief. Tech. Rep. October 2017, 1–7 pp.

Metz, B., O. R. Davidson, P. R. Bosch, R. Dave, and L. A. E. Meyer, 2007: *Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007*. Cambridge University Press, Cambridge, URL http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm.

Mimura, N., L. Nurse, R. McLean, J. Agard, L. Briguglio, P. Lefale, R. Payet, and G. Sem, 2007: Small islands. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M. Parry, O. Canziani, J. Palutikof, P. v. d. Linden, and E. C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 687–716.

Mitchell, D., R. James, P. M. Forster, R. A. Betts, H. Shiogama, and M. Allen, 2016: Realizing the impacts of a 1.5 °C warmer world. *Nature Climate Change*, **6 (8)**, 735–737, doi:http://dx.doi.org/10.1038/nclimate3055.

Mitchell, D., and Coauthors, 2017: Half a degree additional warming, prognosis and projected impacts (HAPPI): Background and experimental design. *Geoscientific Model Development*, **10 (2)**, 571–583, doi:https://doi.org/10.5194/gmd-10-571-2017.

Muthige, M. S., J Malherbe, F A Englebrecht, S Grab, A Beraki, T R Maisha, and J Van der Merwe, 2018: Projected changes in tropical cyclones over the South West Indian Ocean under different extents of global warming. *Environmental Research Letters*, **13 (6)**, doi:10.1088/1748-9326/aabc60.

Mycoo, M. A., 2018: Beyond 1.5 °C: vulnerabilities and adaptation strategies for Caribbean Small Island Developing States. *Regional Environmental Change*, **18 (8)**, 2341–2353, doi: https://doi.org/10.1007/s10113-017-1248-8.

National Oceanic and Atmospheric Administration, ????: Saffir-Simpson Hurricane Wind Scale. URL https://www.nhc.noaa.gov/aboutsshws.php.

Neumann, B., A. T. Vafeidis, J. Zimmermann, and R. J. Nicholls, 2015: Future coastal population growth and exposure to sea-level rise and coastal flooding - A global assessment. *PLOS ONE*, **10 (6)**, 131 375, doi:https://doi.org/10.1371/journal.pone.0118571.

Nicholls, R., 1998: *Coastal Vulnerability Assessment for Sea Level Rise: Evaluation and Selection of Methodologies for Implementation*. TR˜98002.

Ourbak, T., and A. K. Magnan, 2018: The Paris Agreement and climate change negotiations: Small Islands, big players. *Regional Environmental Change*, **18 (8)**, 2201–2207, doi:https://doi.org/10.1007/s10113-017-1247-9.

Pasch, R. J., A. B. Penny, and R. Berg, 2019: Hurricane Maria. Tech. Rep. AL 152017, 1–36 pp. URL https://www.nhc.noaa.gov/data/tcr/AL152017_Maria.pdf.

Perkins, S. E., L. V. Alexander, and J. R. Nairn, 2012: Increasing frequency, intensity and duration of observed global heatwaves and warm spells. *Geophysical Research Letters*, **39 (20)**, 1–5, doi:https://doi.org/10.1029/2012GL053361.

Peterson, T. C., and Coauthors, 2002: Recent changes in climate extremes in the Caribbean region. *Journal of Geophysical Research Atmospheres*, **107 (21)**, 1–9, doi:https://doi.org/10.1029/2002JD002251.

Pielke, R. A., and C. N. Landsea, 1999: La Niña, El Niño, and Atlantic Hurricane Damages in the United States. *October*, **(1994)**, 2027–2033, doi:https://doi.org/10.1175/1520-0477(1999)080⟨2027:LNAENO⟩2.0.CO;2.

Pörtner, H.-O., D. M. Karl, P. Boyd, W. Cheung, S. Lluch-Cota, Y. Nojiri, D. Schmidt, and P. Zavialov, 2014: Ocean Systems. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, United Kingdom and New York, NY, USA,, 411–484, URL https://epic.awi.de/id/eprint/37501/1/WGIIAR5-Chap6_FINAL.pdf.

Powell, M. D., and T. A. Reinhold, 2007: Tropical Cyclone Destructive Potential by Integrated Kinetic Energy. *Bulletin of the American Meteorological Society*, **88**, 513–526, doi:https://doi.org/10.1175/BAMS-88-4-513.

Rahmstorf, S., 2017: Rising hazard of storm-surge flooding. *Proceedings of the National Academy of Sciences*, **114 (45)**, 11 806–11 808, doi:https://doi.org/10.1073/pnas.1715895114.

Ramsay, H. A., 2013: The effects of imposed stratospheric cooling on the maximum intensity of tropical cyclones in axisymmetric radiative-convective equilibrium. *Journal of Climate*, **26 (24)**, 9977–9985, doi:https://doi.org/10.1175/JCLI-D-13-00195.1.

Rasmussen, D. J., K. Bittermann, M. K. Buchanan, S. Kulp, and B. H. Strauss, 2018: Extreme sea level implications of 1.5 °C, 2.0 °C, and 2.5 °C temperature stabilization targets in the 21st and 22nd centuries. *Environmental Research Letters*, **13 (3)**.

Rogelj, J., and Coauthors, 2016: Paris Agreement climate proposals need a boost to keep warming well below 2 °c. *Nature*, **534 (7609)**, 631–639, doi:https://doi.org/10.1038/nature18307.

Rogoziński, J., 1999: *A Brief History of the Caribbean: From the Arawak and the Carib to the Present*. 2nd ed., Facts On File, 415 pp.

Santos-Lozada, A. R., and J. T. Howard, 2018: Use of Death Counts From Vital Statistics to Calculate Excess Deaths in Puerto Rico Following Hurricane Maria. *New England Journal of Medicine*, **320 (14)**, 1491–1493, doi:10.1001/jama.2018.10929.

Schleussner, C. F., and Coauthors, 2016: Differential climate impacts for policy-relevant limits to global warming: The case of 1.5 °C and 2 °C. *Earth System Dynamics*, **7 (2)**, 327–351, doi:10.5194/esd-7-327-2016.

Shaevitz, D. A., and Coauthors, 2014: Characteristics of tropical cyclones in highresolution models in the present climate. *Journal of Advances in Modeling Earth Systems*, **6 (4)**, 1154–1172, doi:https://doi.org/10.1002/2014MS000372.

Shapiro, L. J., and L. J. Shapiro, 1987: Month-to-Month Variability of the Atlantic Tropical Circulation and Its Relationship to Tropical Storm Formation. *Monthly Weather Review*, **115 (11)**, 2598–2614, doi:https://doi.org/10.1175/1520-0493(1987)115⟨2598:MTMVOT⟩2.0.CO;2.

Shuckburgh, E., D. Mitchell, and P. Stott, 2017: Hurricanes Harvey, Irma and Maria: how natural were these natural disasters? *Weather*, **72 (11)**, 353–354, doi:https://doi.org/10.1002/wea.3190.

Sobel, A. H., S. J. Camargo, and M. Previdi, 2019: Aerosol vs. Greenhouse Gas Effects on Tropical Cyclone Potential Intensity and the Hydrologic Cycle. *Journal of Climate*, 5511–5527, doi:https://doi.org/10.1175/JCLI-D-18-0357.1.

Stephenson, T. S., and Coauthors, 2014: Changes in extreme temperature and precipitation in the Caribbean region, 1961-2010. *International Journal of Climatology*, **34 (9)**, 2957–2971, doi:https://doi.org/10.1002/joc.3889.

Stewart, S. R., 2004: Hurricane Ivan. Tech. Rep. September 2004, 44 pp.

Stewart, S. R., 2017: Hurricane Matthew. Tech. Rep. April, 1–96 pp. URL http://www.nhc.noaa.gov/data/tcr/AL142016_Matthew.pdf.

Stocker, T., and Coauthors, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Strazzo, S., J. B. Elsner, J. C. Trepanier, and K. A. Emanuel, 2013: Frequency, intensity, and sensitivity to sea surface temperature of North Atlantic tropical cyclones in best-track and simulated data. *Journal of Advances in Modeling Earth Systems*, **5 (3)**, 500–509, doi:10.1002/jame.20036.

Tang, B., and K. Emanuel, 2012: A ventilation index for tropical cyclones. *Bulletin of the American Meteorological Society*, **93 (12)**, 1901–1912, doi:https://doi.org/10.1175/BAMS-D-11-00165.1.

Taylor, M. A., and Coauthors, 2018: Future Caribbean climates in a world of rising temperatures: The 1.5 vs 2.0 Dilemma. *Journal of Climate*, **31 (7)**, 2907–2926, doi:https://doi.org/10.1175/JCLI-D-17-0074.1.

Tory, K. J., and R. A. Dare, 2015: Sea surface temperature thresholds for tropical cyclone formation. *Journal of Climate*, **28 (20)**, 8171–8183, doi:https://doi.org/10.1175/JCLI-D-14-00637.1.

UNFCCC, 2005: Climate change: small island developing States. Tech. rep., 32 pp. URL http://unfccc.int/resource/docs/publications/cc_sids.pdf.

Vecchi, G. A., and B. J. Soden, 2007: Global warming and the weakening of the tropical circulation. *Journal of Climate*, **20 (17)**, 4316–4340, doi:https://doi.org/10.1175/JCLI4258.1.

Villarini, G., B. Luitel, G. A. Vecchi, and J. Ghosh, 2016: Multi-model ensemble forecasting of North Atlantic tropical cyclone activity. *Climate Dynamics*, 1–17, doi:10.1007/s00382-016-3369-z.

Villarini, G., and G. A. Vecchi, 2012: North Atlantic power dissipation index (PDI) and accumulated cyclone energy (ACE): Statistical modeling and sensitivity to sea surface temperature changes. *Journal of Climate*, **25 (2)**, 625–637, doi:https://doi.org/10.1175/JCLI-D-11-00146.1.

Villarini, G., and G. A. Vecchi, 2013: Projected increases in North Atlantic tropical cyclone intensity from CMIP5 models. *Journal of Climate*, **26 (10)**, 3231–3240, doi:https://doi.org/10.1175/JCLI-D-12-00441.1.

Vincent, E. M., M. Lengaigne, J. Vialard, G. Madec, N. C. Jourdain, and S. Masson, 2012: Assessing the oceanic control on the amplitude of sea surface cooling induced by tropical cyclones. *Journal of Geophysical Research: Oceans*, **117 (5)**, 1–18, doi:https://doi.org/10.1029/2011JC007705.

Walsh, K. J., and Coauthors, 2015: Hurricanes and climate: The U.S. Clivar working group on hurricanes. *Bulletin of the American Meteorological Society*, **96 (6)**, 997–1017, doi:https://doi.org/10.1175/BAMS-D-13-00242.1.

Walsh, K. J. E., and Coauthors, 2016: Tropical cyclones and climate change. *Wiley Interdisciplinary Reviews-Climate Change*, **7 (1)**, 65–89, doi:https://doi.org/10.1002/wcc.371.

Wang, C., S. K. Lee, and D. B. Enfield, 2008: Atlantic warm pool acting as a link between atlantic multidecadal oscillation and atlantic tropical cyclone activity. *Geochemistry, Geophysics, Geosystems*, **9 (5)**, doi:https://doi.org/10.1029/2007GC001809.

Wang, C., S. K. Lee, and C. R. Mechoso, 2010: Interhemispheric influence of the Atlantic warm pool on the Southeastern pacific. *Journal of Climate*, **23 (2)**, 404–418, doi:https://doi.org/10.1175/2009JCLI3127.1.

Wang, Y., K. H. Lee, Y. Lin, M. Levy, and R. Zhang, 2014: Distinct effects of anthropogenic aerosols on tropical cyclones. *Nature Climate Change*, **4 (5)**, 368–373, doi:https://doi.org/10.1038/nclimate2144.

Webster, P. J., G. J. Holland, J. A. Curry, and H.-R. Chang, 2005: Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science*, **309 (5742)**, 1844–1846, doi:10.1126/science.1116448.

Wehner, M. F., K. A. Reed, B. Loring, D. Stone, and H. Krishnan, 2018: Changes in tropical cyclones under stabilized 1.5 and 2.0 degrees C global warming scenarios as simulated by the Community Atmospheric Model under the HAPPI protocols. *Earth System Dynamics*, **9 (1)**, 187–195, doi:https://doi.org/10.5194/esd-9-187-2018.

Wehner, M. F., and Coauthors, 2014: The effect of horizontal resolution on simulation quality in the Community Atmospheric Model, CAM5.1. *Journal of Advances in Modeling Earth Systems*, **6 (4)**, 980–997, doi:https://doi.org/10.1002/2013MS000276.

Wen, S., and Coauthors, 2018: Estimation of economic losses from tropical cyclones in China at 1.5 °C and 2.0 °C warming using the regional climate model COSMO-CLM. *International Journal of Climatology*, **39 (2)**, 724–737, doi:https://doi.org/10.1002/joc.5838.

Wing, A. A., K. Emanuel, and S. Solomon, 2015: On the factors affecting trends and variability in tropical cyclone potential intensity. *Geophysical Research Letters*, **42 (20)**, 8669–8677, doi:https://doi.org/10.1002/2015GL066145.

World Bank, 2005: Grenada: A nation rebuilding - An assessment of reconstruction and economic recovery one year after Hurricane Ivan. Tech. rep., 70 pp. URL http://siteresources.worldbank.org/INTLACREGTOPHAZMAN/Resources/grenanda_rebuilding.pdf.

World Travel and Toursim Council, 2017: Caribbean Resilience and Recovery: Minimising the Impact of the 2017 Hurricane Season on the Caribbean's Tourism Sector. Tech. rep.

WRI, 2006: Value of Coral Reefs in Caribbean Islands. 27.

Xie, S., and J. A. Carton, 2004: Tropical Atlantic Variability: Patterns, Mechanisms, and Impacts. *Earth's Climate: The Ocean-Atmosphere Interaction*, C. Wang, S. Xie, and J. Carton, Eds., American Geophysical Union, doi:https://doi.org/10.1029/147GM07.

Yu, Z., Y. Wang, H. Xu, N. Davidson, Y. Chen, Y. Chen, and H. Yu, 2017: On the relationship between intensity and rainfall distribution in tropical cyclones making landfall over China. *Journal of Applied Meteorology and Climatology*, **56 (10)**, 2883–2901, doi:https://doi.org/10.1175/JAMC-D-16-0334.1.

Zappino, V., 2005: Caribbean tourism and development : an overview. Tech. Rep. 65, 1–36 pp.

Zehr, R. M., and J. A. Knaff, 2007: Atlantic major hurricanes, 1995-2005 - Characteristics based on best-track, aircraft and IR images. *Journal of Climate*, **20 (24)**, 5865–5888, doi:https://doi.org/10.1175/2007JCLI1652.1.

Zhang, L., K. B. Karnauskas, J. P. Donnelly, and K. Emanuel, 2017: Response of the North Pacific tropical cyclone climatology to global warming: Application of dynamical downscaling to CMIP5 models. *Journal of Climate*, **30 (4)**, 1233–1243, doi:https://doi.org/10.1175/JCLI-D-16-0496.1.

Zhang, R., and T. L. Delworth, 2006: Impact of Atlantic multidecadal oscillations on India/Sahel rainfall and Atlantic hurricanes. *Geophysical Research Letters*, **33 (17)**, 1–5, doi:https://doi.org/10.1029/2006GL026267.

Zhao, C., Y. Lin, F. Wu, Y. Wang, Z. Li, D. Rosenfeld, and Y. Wang, 2018a: Enlarging Rainfall Area of Tropical Cyclones by Atmospheric Aerosols. *Geophysical Research Letters*, **45 (16)**, 8604–8611, doi:https://doi.org/10.1029/2018GL079427.

Zhao, H., X. Duan, G. B. Raga, and F. Sun, 2018b: Potential large-scale forcing mechanisms driving enhanced North Atlantic tropical cyclone activity since the mid-1990s. *Journal of Climate*, **31 (4)**, 1377–1397, doi:https://doi.org/10.1175/JCLI-D-17-0016.1.

Zhao, M., and I. M. Held, 2010: An Analysis of the Effect of Global Warming on the Intensity of Atlantic Hurricanes Using a GCM with Statistical Refinement. *Journal of Climate*, **23 (23)**, 6382–6393, doi:https://doi.org/10.1175/2010JCLI3837.1.

Zhao, M., I. M. Held, S. J. Lin, and G. A. Vecchi, 2009: Simulations of global hurricane climatology, interannual variability, and response to global warming using a 50-km resolution GCM. *Journal of Climate*, **22 (24)**, 6653–6678, doi:10.1175/2009JCLI3049.1.

Zhu, L., S. M. Quiring, and K. A. Emanuel, 2013: Estimating tropical cyclone precipitation risk in Texas. *Geophysical Research Letters*, **40 (23)**, 6225–6230, doi:https://doi.org/10.1002/2013GL058284.

5 Supplementary material

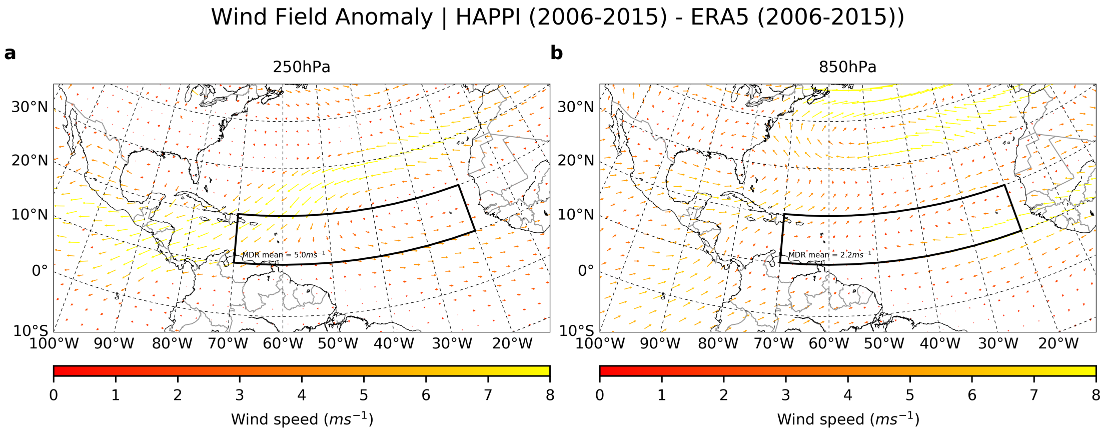

Figure 1: Wind field anomalies at 250 hPa (**a**) and 850 hPa (**b**) between the simulated period 2006-2015 and ERA5 reanalysis for the same time period.

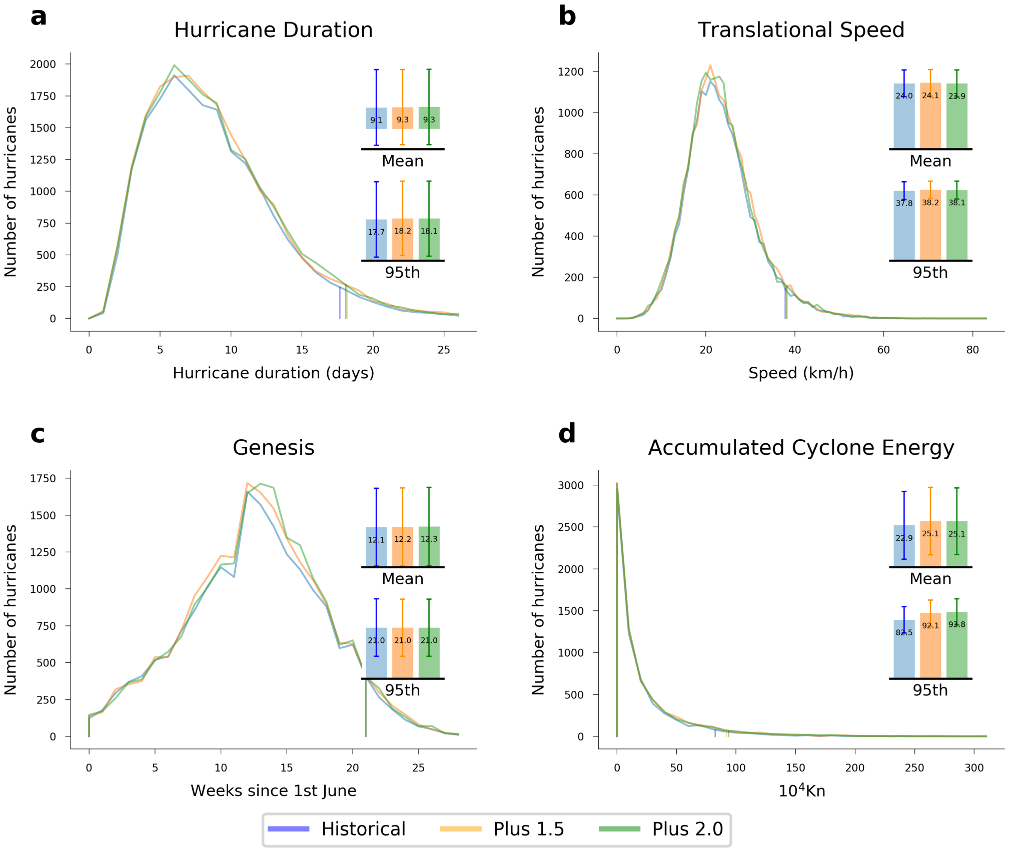

Figure 2: A comparison of hurricane duration (**a**), translation speed (**b**), genesis date (**c**) and acumulated cyclone energy (**d**) under the current and warming scenarios. Confidence intevals are calculated using the Monte-Carlo method

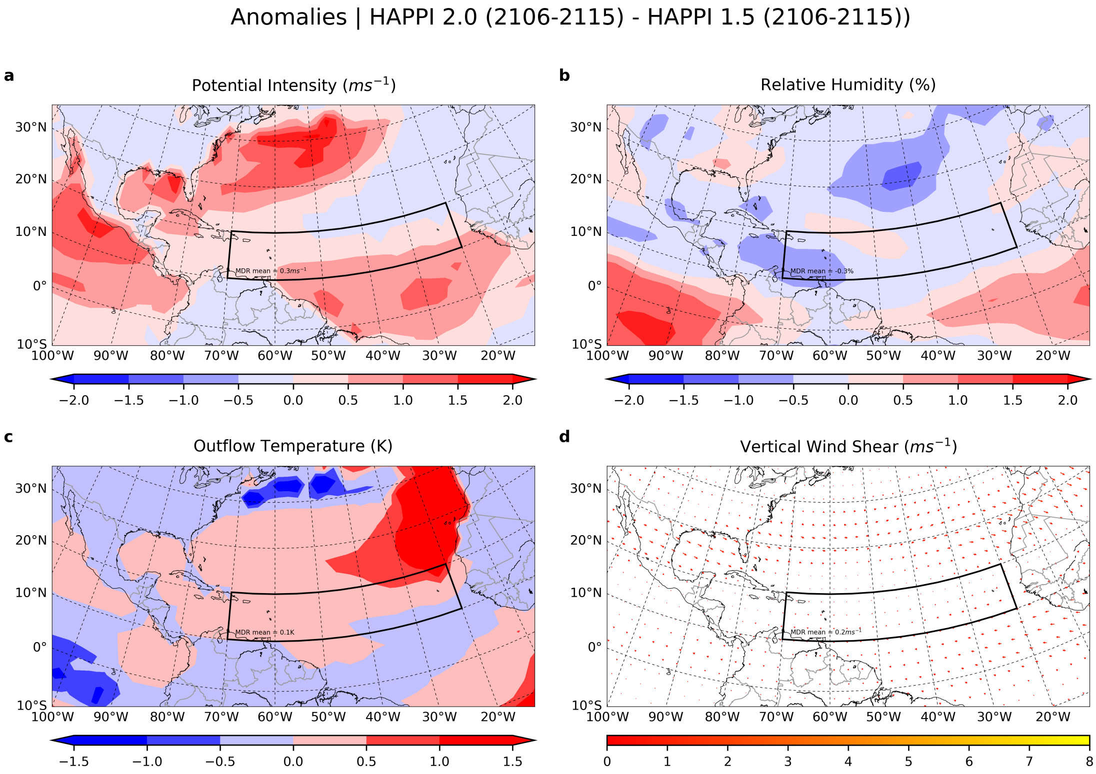

Figure 3: Seasonal anomalies between Paris Agreement scenarios in potential intensity (**a**), relative humidity (**b**), outflow temperature (**c**) and vertical wind shear (**d**).

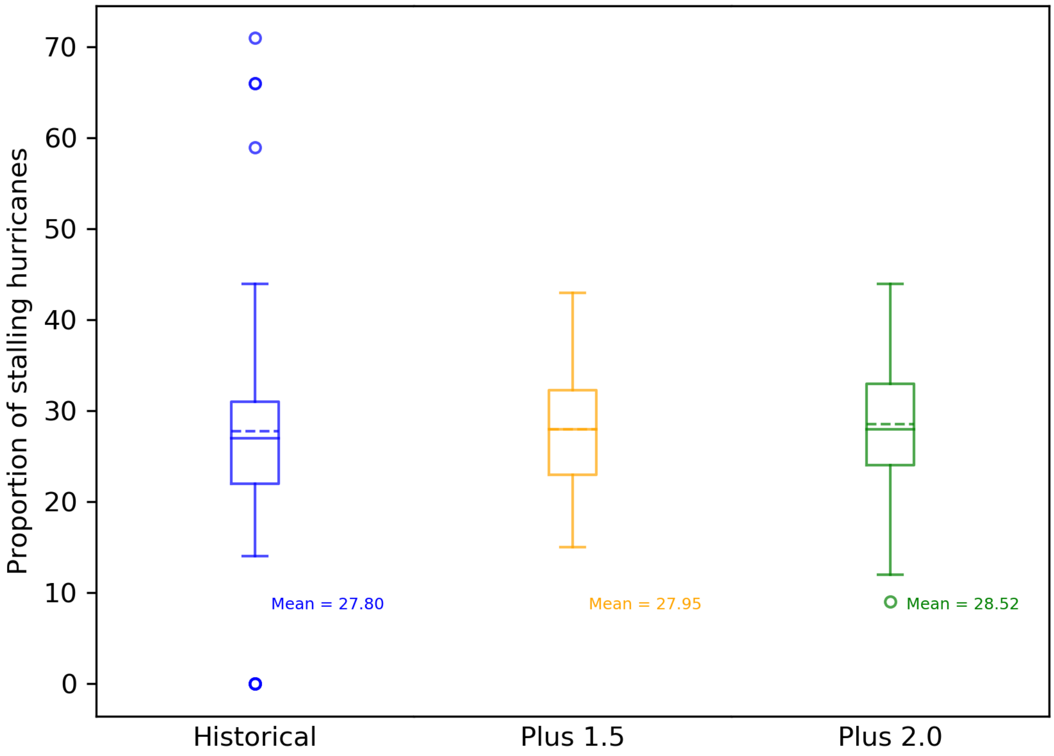

Figure 4: Proportion of stalling hurricanes under the Paris Agreement scenarios. The distributions do not differ significantly under the KolmogorovSmirnov test.