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Abstract

Hurricanes are among the most impactful extreme weather events affecting small island states such as the Caribbean and require long-term planning for community and infrastructure resilience. By coupling an offline dynamical hurricane model to the output of a large ensemble of global climate model simulations from the Half a degree of Additional warming Prognosis and Projected Impacts (HAPPI) project, we assess how the impacts of hurricanes may change under the Paris Climate goals. Specifically, we concentrate on hurricane rainfall over particular regions, with both the mobility and intensity of a hurricane being key drivers of local level impacts. For example, Hurricane Dorian (2019) caused widespread devastation when it stalled over Bahamas as a category 5 storm. We show that since 1970 only one other hurricane stalled at this strength: Hurricane Mitch (1998). Due to a combination of increased stalling and precipitation yield under a warmer world, our analysis indicates a greater likelihood of extreme hurricane rainfall occurring in the Caribbean under both Paris Agreement scenarios of 1.5 °C and 2 °C Global Warming goals, compared to present climate projections. Focusing on specific hurricane events, we show that a rainfall event equal in magnitude to Hurricane Maria is around half as likely to occur under the 1.5 °C Paris Agreement goal compared to a 2 °C warmer climate. Our results highlight the need for more research into hurricanes in the Caribbean, an area which has traditionally received far less attention than mainland USA and requires more comprehensive infrastructure planning.

1. Introduction

Since 1960, the Caribbean has experienced 264 hurricanes which account for 95% 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). Hurricanes also present a significant threat to life in the Caribbean. For example while Hurricane Maria's (2017) official death toll in Puerto Rico was 64 (Kishore *et al* 2018), its actual mortality likely exceeded 1100 due to indirect impacts such as disease outbreaks (Santos-Lozada and Howard 2018).

With over half of the 44.2 million inhabitants of the Caribbean residing within 1.5 km of the coast, the region is particularly vulnerable to hurricane activity (Mimura *et al* 2007). For instance, critical

infrastructure such as major roads, air and seaports, utilities, and communication networks tend to be concentrated in low-elevation coastal zones and is therefore susceptible to severe damage from hurricanes (Cruz *et al* 2007, Mycoo 2018). Hurricane Dorian caused almost 2.5bn USD worth of damages when it stalled over the Bahamas as a category 5 storm in September 2019, rendering almost 3000 homes uninhabitable and causing widespread damage to hospitals, schools and fisheries (Panamerican Health Organisation 2019).

In the instance of a hurricane stalling event, such as Dorian, the hurricane hovers over a region for an extended period of time (usually between two to four days) leading to a significant accumulation of rainfall and wind damage (Emanuel 2017). Hall and Kossin (2019) showed that stall events in the North Atlantic exhibit an increasing trend in both their frequency

Table 1. The HAPPI models used in this study.

Dataset	Horizontal Resolution
CanAM4	$2.81^\circ \times 2.81^\circ$
CAM5-1-2-025degree	$0.31^\circ \times 0.23^\circ$
NorESM1-HAPPI	$1.25^\circ \times 0.94^\circ$
ECHAM6-3-LR	$1.88^\circ \times 1.88^\circ$

and associated rainfall over the coast of the USA—such an observation compels us to address the question: ‘will the number of stalling hurricanes increase under global warming scenarios?’

Not only does a storm’s trajectory affect rainfall, but so do its rain rates, which are projected to increase with global warming (Knutson *et al* 2010, 2013). In addition, both the mean and peak rain rates of hurricanes increase with storm intensity, but for major hurricanes (categories 3–5) the area covered by intense rain is smaller than for weaker hurricanes and tropical storms (Lonfat *et al* 2004, Yu *et al* 2017). With a projected shift towards more intense hurricanes in a warming world (Wehner *et al* 2018, Zhao *et al* 2009, Walsh *et al* 2016), it follows that a global warming could lead to more hurricane-related rainfall and potentially more flood damage.

2. Methods

Here we assess rainfall affecting six Caribbean countries under three global warming scenarios: the present day, 1.5 °C warming and 2 °C warming above pre-industrial levels, and calculate the projected return period of these events. To do this, synthetic hurricanes were generated using a dynamical hurricane model driven by data from four Global Climate Models (GCMs).

2.1. Simulating the Paris agreement scenarios

In order to assess hurricane activity under a range of climate scenarios, we used 600 simulated years of global climate data 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 (stabilised via Representative Concentration Pathway (RCP) 2.6) and 2 °C (stabilised by a weighting of RCP2.6 and RCP4.5) temperature increases above pre-industrial levels, by providing a super-ensemble of bias-corrected climate model output. Data consisted of five ensemble members from four global climate models, outlined in table 1. These models were chosen based on the availability of the required variables (see table 2) at the desired temporal resolution.

2.2. Simulating hurricane rainfall

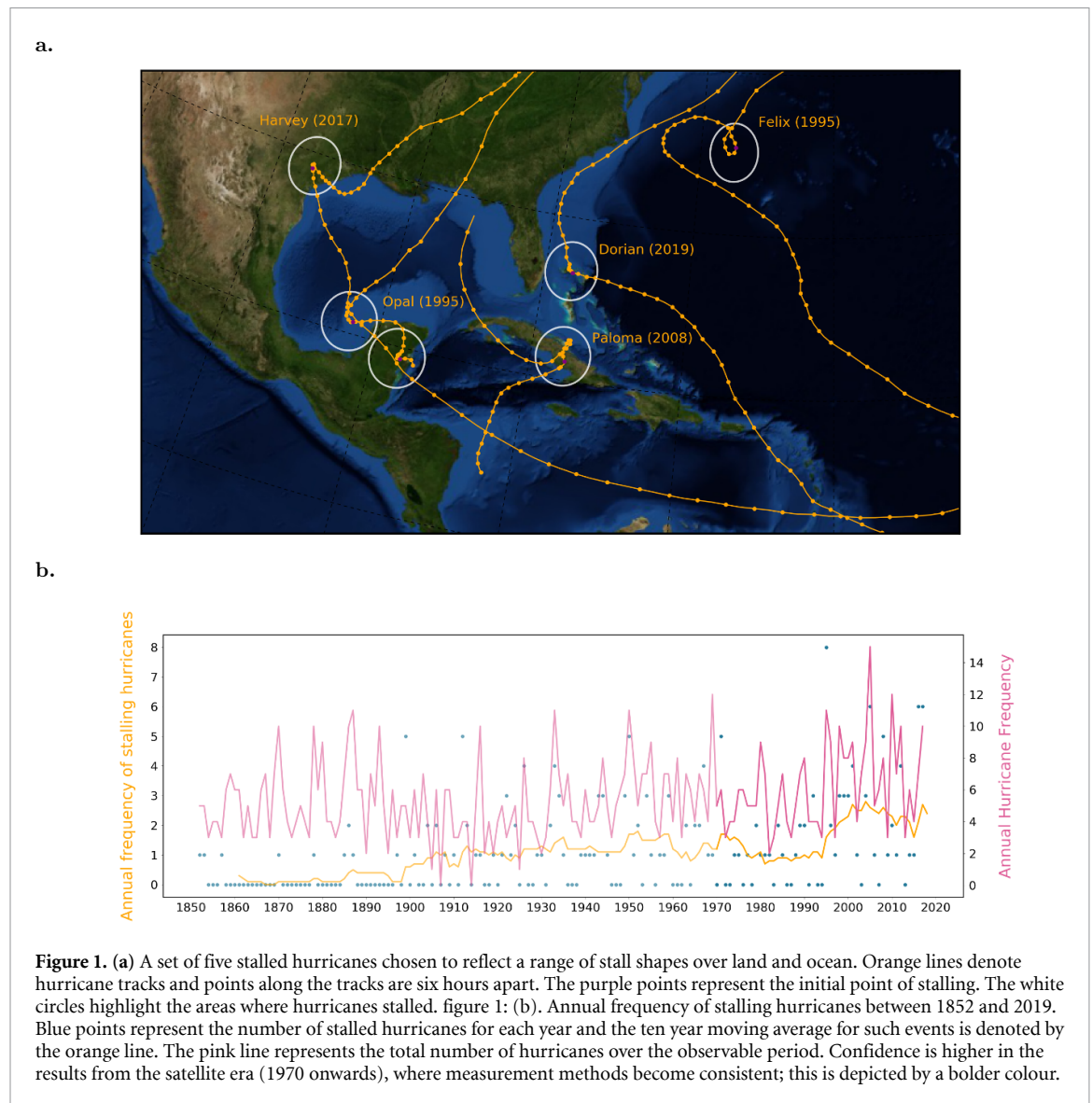
Although the monthly climatologies of observed North Atlantic storms have been reasonably well

Table 2. Inputs to hurricane model. Specific humidity and atmospheric temperature are sampled at 17 pressure levels including 600 hPa, 100 hPa and 70 hPa.

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

reproduced in some GCMs, for example the Community Atmospheric Model (CAM5) (Wehner *et al* 2014), GCMs struggle to consistently replicate observed annual frequency of the most intense hurricanes (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, we generate synthetic hurricanes using the dynamical hurricane model described in detail in Emanuel *et al* (2008) whereby output from four global climate models supplies the driving environmental conditions. This hurricane model is computationally cheap and has been shown to reproduce observed hurricane activity well in an array of metrics (Emanuel *et al* 2006, 2008, 2010).

We implement a physics-based hurricane rainfall model developed for risk analysis (Zhu *et al* 2013, Emanuel 2017, Lu *et al* 2018) to estimate hurricane rainfall in the Caribbean region under three climate scenarios. The model generates rainfall estimates along the synthetic hurricane tracks and a return period statistic is then generated which represents how often a rainfall event exceeding a certain magnitude is likely to occur. The model accounts for four major rainfall mechanisms: hurricane interaction with wind shear, the effect of topography, vortex stretching and surface frictional convergence. It has been shown to give good estimates of rainfall risk in the United States compared to gauge-based observations (Zhu *et al* 2013, Lu *et al* 2018, Feldmann *et al* 2019a), Weather and Research Forecasting-estimated rainfall (Lu *et al* 2018) and radar data (Feldmann *et al* 2019a), while allowing for thousands of rainfall events to be analysed. Moreover, the model output for San Juan (Puerto Rico) was compared to observational data by Feldmann *et al* (2019b) and, although rain gauge data was not available, the model performed within the 90% confidence intervals of the radar data, giving us high confidence in results from Puerto Rico. It should be noted that the model is sensitive to the drag coefficient (the roughness of the earth’s surface) and extensive improvements have been made to reduce uncertainty over the US coast as well as Puerto



Rico; the reader is referred to Feldmann *et al* (2019a) and (2019b) for details. Haiti and the Dominican Republic are considerably more mountainous than the East Coast of the USA and so confidence in the results for these countries is lower compared to flatter regions.

Obtaining rain gauge data for the Caribbean is challenging as there is no centralised rainfall dataset for the region and, moreover, rain gauges tend to be damaged or destroyed during hurricane events, making their readings unreliable in such instances. Satellite products such as IMERG mostly underestimate rainfall rate for extreme precipitation events (Mazzoglio *et al* 2019), this could have a compound effect when assessing total rainfall from a passing hurricane whereby the area of extreme rainfall is constantly changing. In this study, we therefore take estimates from the hurricane rainfall model as a best estimate of precipitation, with higher confidence in results from less mountainous countries.

3. Results and discussion

3.1. Stalling hurricanes

In this study, we define a hurricane to stall 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 200 km radius of point $P_{t=n}$ (i.e. a hurricane centre is contained within a region with 200 km radius for at least 48 hours). This method accounts for both translation speed and a possible change in direction, both key indicators of stalling (Hall and Kossin 2019). It should be noted that the radius of the stall region is in line with the definition established by Hall and Kossin (2019), but results are sensitive to the magnitude of the radius used. Figure 1(a) illustrates a subset of hurricanes selected under our stalling parameters; the white circles depict the regions of stalling. The figure highlights two types of stalls: looped stalls and translational stalls. Looped stalls, such as Hurricanes Harvey (2017) and Paloma (2008), are likely to occur due



to a change in prevailing direction of the large scale wind fields in the mid to upper troposphere, while translational stalls are due to a reduction in strength of the wind fields. It is also possible for a hurricane to stall more than once, such as the case of Hurricane Opal (2005). figure 1(b) depicts the annual frequency of stalled hurricanes between the years 1852 and 2019. Since 1970, there have been 89 hurricanes that have stalled in the Atlantic Basin and there is no visible trend in proportion of stalling hurricanes during this period.

Low intensity stalls are the most common, which is to be expected as weaker hurricanes dominate the historical record (figure 2). Stalls occurring when a hurricane is at category 5 strength are much rarer as such hurricanes are less common in general; only Hurricanes Mitch (1998) and Dorian (2019) are known to have stalled at category 5 strength in the past 50 years, with Dorian the most intense hurricane (at the point of stalling) to stall during this period. Since 1852, there have been three category 5 stalls in total; the most intense stall on record occurred in 1932 and that unnamed hurricane stalled with maximum wind speeds of 280 kmh^{-1} while Dorian reached wind speeds of 270 kmh^{-1} at the point of stalling.

The stalling algorithm was run on the simulated hurricane tracks to determine the annual frequencies under each of the Paris Agreement scenarios and results are shown in the box and whisker plot in figure 3(a). According to the Kolmogorov-Smirnov

test, there is a significant difference between the historical distribution and both the plus 1.5°C and plus 2°C distributions, however, the distributions of the warming scenarios do not differ significantly from each other (figure 3(b)). The mean number of stalling hurricanes in the historical climate simulation is 3.53 per year, this increases to around 4 per year under both warming scenarios.

Kossin (2018) found that tropical cyclone translation speed has decreased by 10% since 1949, although reported speeds over the North Atlantic showed minimal change during the satellite era (1970 onwards). Moreover, both the sensitivity of hurricane detection to latitude and the biases in pre-satellite era data could result in spurious trends within the hurricane dataset in turn putting the reported decrease in translation speed into question (Moon *et al* 2019, Lanzante 2019). This notion is supported through analysis of the synthetic hurricanes generated in this study: it is unlikely that the increase in stall frequency has been caused by a reduction of translation speed as there is no significant difference in translation speed between the present day and warming scenarios (see supplementary figure (stacks.iop.org/ERL/15/104053/mmedia)). The wind fields at the 250 hPa and 850 hPa levels across the three scenarios do not display a large variation between scenarios (figure not shown), which could provide an explanation for the minimal change in the translation speed and proportion of stalling hurricanes between these projections. Therefore, the projected

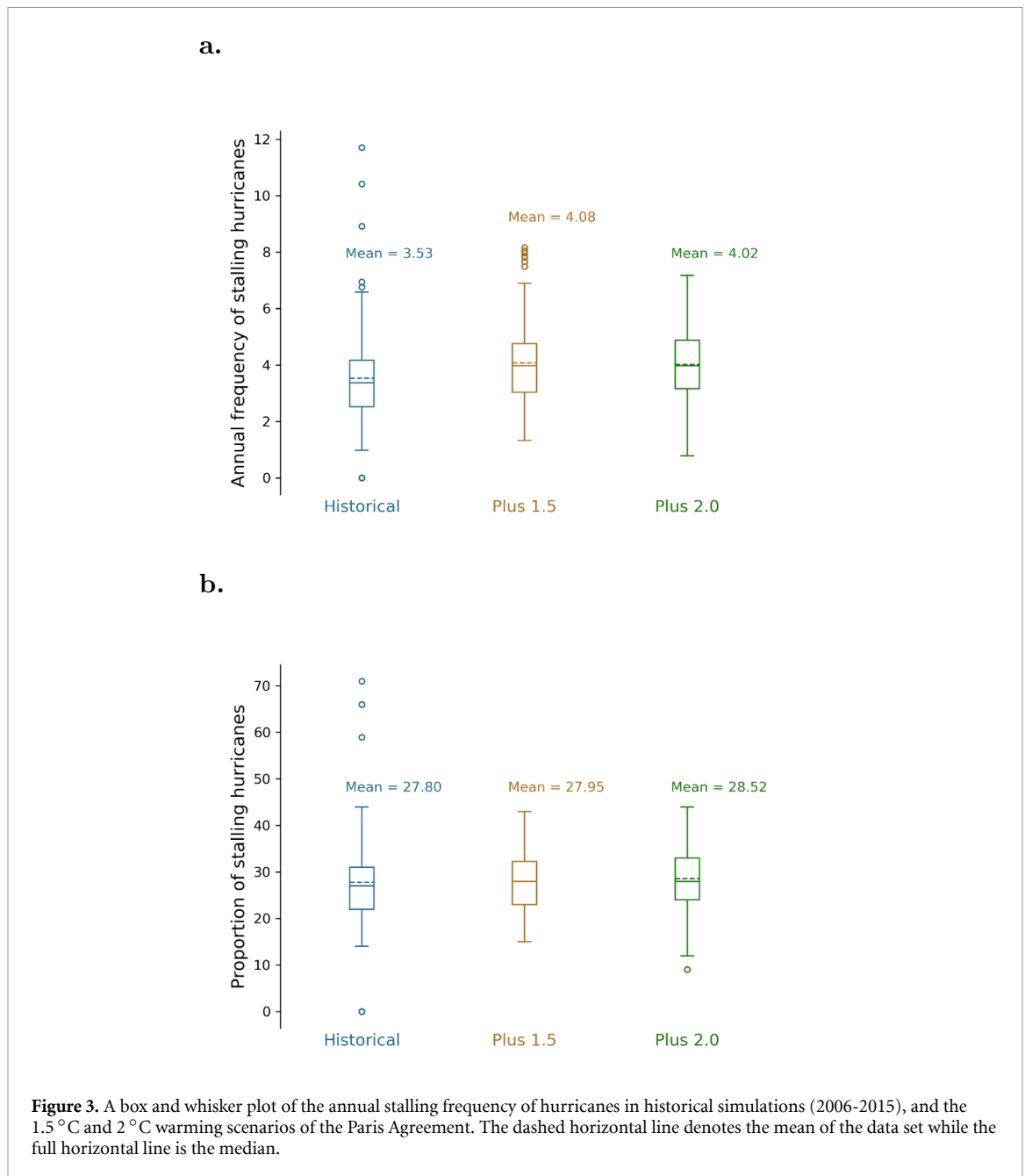
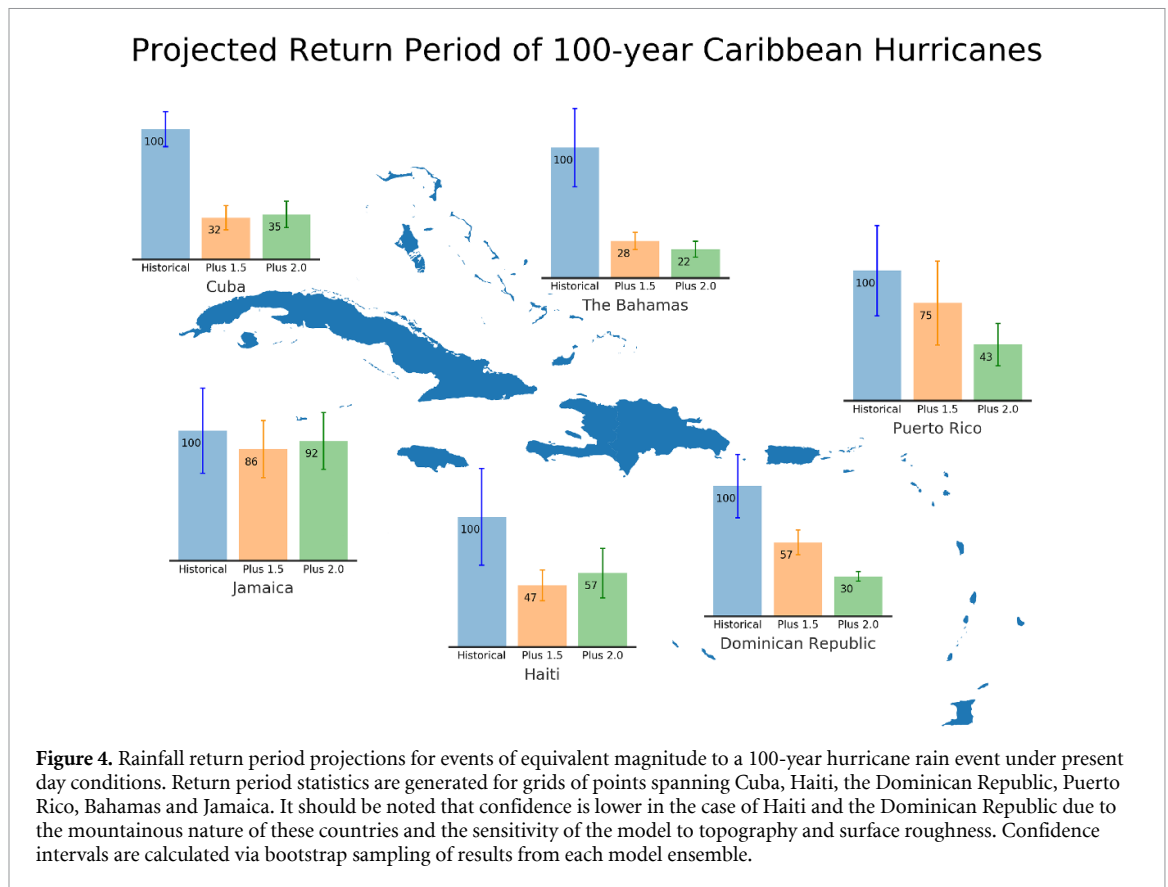


Figure 3. A box and whisker plot of the annual stalling frequency of hurricanes in historical simulations (2006–2015), and the 1.5 °C and 2 °C warming scenarios of the Paris Agreement. The dashed horizontal line denotes the mean of the data set while the full horizontal line is the median.

increase in stalling hurricane frequency under the Paris Agreement scenarios is likely due to the general rise in hurricane events in the projections, as the overall proportion of stalling hurricanes is not significantly different between each of the three scenarios by the Kolmogorov-Smirnov test (figure 3(b)). The rising hurricane frequency under the warming projections is consistent with Emanuel (2013), in which the increase was in turn consistent with increases in Genesis Potential Index developed by Emanuel (2010). More stalling hurricanes mean more extreme rainfall events, so the increase in frequency of stalling hurricanes—albeit not directly attributable to climate change—will likely make a moderate contribution to the higher likelihood of extreme rainfall events observed in the results under the warming scenarios.

3.2. Hurricane rainfall

Since the impacts of hurricane rainfall are felt at the island level rather than the Caribbean as a whole, we focus on six island states that have recently suffered significant hurricane impacts: Cuba, Puerto Rico, the Dominican Republic, Jamaica, Haiti and the Bahamas. For each country, return period statistics (calculated as the reciprocal of annual exceedance probability) are generated from a grid of latitude and longitude points approximately 30 km apart that span each country and range from 9 points for Puerto Rico to 111 for Cuba. The return periods are compared for equivalent magnitude storms across the warming scenarios using a baseline extreme rainfall event: one that would typically occur once every 100 years under present day conditions. Readers should be aware that



whilst an overall climate signal is present in the results, there is a large noise margin present due to inter-model spread which reduces the certainty when interpreting results.

Figure 4 shows the projected return periods of baseline 100-year Caribbean hurricane rain events under the Paris Agreement scenarios for each of the six Caribbean countries mentioned above. According to figure 4, the difference between the Paris Agreement scenarios of 1.5 °C and 2 °C warming above pre-industrial levels is more pronounced in the Eastern Caribbean region. In Puerto Rico, the return period of a hurricane rainfall event equivalent in magnitude to a 100-year storm in the present day, would be over twice as likely in a 2 °C world. However, increasing mitigation efforts in order to stabilise warming to 1.5 °C would result in such a storm's likelihood of occurrence being closer to the present day. Put into context, Hurricane Maria brought as much as a quarter of normal annual rainfall to some regions of Puerto Rico when it made landfall in 2017 (Keellings and Hernandez Ayala 2019). Analysing stations across the whole of Puerto Rico Keellings and Hernandez Ayala (2019) found that Hurricane Maria had a return period of 115 years, projecting this to a 1.5 °C warmer world a similar hurricane rainfall event would become a one in 75-year event and a one in 43-year event for the 2 °C scenario.

Similarly, results show that a 100-year event affecting the Dominican Republic would become a

one in 30-year event under the more extreme climate scenario of 2 °C warming. Under the 1.5 °C warming conditions the corresponding event would be a one in 57 year hurricane, which is half as likely compared to the 2 °C warming scenario.

Results for Jamaica show that global warming would have little or even no impact on extreme hurricane rainfall there. Small variance in the number of hurricane tracks, particularly category 5 hurricanes, passing through the country is a likely factor behind this result.

Where Cuba, Haiti and the Bahamas are concerned, there is no discernible difference between the two Paris Agreement goals. In Haiti, a 100-year hurricane rainfall event is projected to be 20% more likely under the 1.5 °C warming goal compared to the 2 °C. In Cuba, a hurricane with rainfall matching or exceeding that of a 100-year event could become a one in roughly 30-year event in both the 1.5 °C and 2 °C scenarios. In both Cuba and the Bahamas, extreme hurricane rainfall events become significantly more common under the warming conditions compared to the present day simulations. For example, a 100-year rainfall event in Bahamas would become about three times as likely in a 1.5 °C and 2 °C warmer world compared to the present day.

There are many mechanisms at play that contribute to the observed non-linearity in the hurricane response to global warming. Influences include wind shear and large-scale wind fields that have exhibited

non-linear increases in the HAPPI warming scenarios (figure not shown); such effects are likely to affect hurricane trajectories and intensification at a local level, which lead to non-linear responses for some of the Caribbean nations. While the dominant factor in the observed climate change signal is the increase in atmospheric water vapour capacity via the Clausius-Clapyron equation, a secondary factor could be the increase in accumulated cyclone energy (ACE) in the Paris Agreement simulations. Tropical cyclone rain rate is known to increase with storm intensity, with the maximum rain rate occurring closer to the storm centre for major tropical cyclones (categories 3–5) compared to weaker storms (Lonfat *et al* 2004, Yu *et al* 2017). **Supplementary figure** indicates a shift in the Accumulated Cyclone Energy (ACE) of the most extreme storms, with the 95th percentile moving from $82.5 \times 10^4 \text{ Kn}^2$ in the historical simulation to $92.1 \times 10^4 \text{ Kn}^2$ in the 1.5 °C warmer scenario and $93.8 \times 10^4 \text{ Kn}^2$ in the 2 °C scenario. This increase in intensity 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. The potential intensity 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 with global warming. 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: 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). The rainfall results are more strongly influenced by changes in hurricane tracks between the three scenarios. Regions where a climate change signal is present tend to experience a higher frequency of major hurricanes making landfall.

4. Conclusion

Small island developing states (SIDS) have already been feeling the effects of a 1 °C temperature rise, embodied in an increased occurrence of hot weather extremes, fewer cool temperature extremes and more intense precipitation (Stephenson *et al* 2014). The Paris Agreement directly addresses their concerns in seeking to mitigate future risks arising from climate change, but even with the more ambitious maximum warming goal of a 1.5 °C, SIDS stand to be disproportionately affected by the corresponding impacts that extreme weather phenomena inflict on human and natural systems, whilst being among those that have least contributed to anthropogenic climate change (UNFCCC 2005). The Caribbean region tends to receive far less attention when it comes to the analysis

of hurricane impacts, with most studies in the North Atlantic Basin typically focusing on the United States. As far as the authors are aware, this study is the first to use large ensemble GCMs coupled with a hurricane rainfall model to assess the future risk of hurricane rainfall in this region.

Stalling hurricanes have a notable influence on local precipitation levels (Hall and Kossin 2019, Emanuel 2017). Projections of stalling hurricane frequency indicate a rise under the Paris Agreement goals; however, this is most likely linked 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 regimes. Opinion is still divided over whether anthropogenic forcing is a significant factor in the increasing trend of hurricanes since the 1970 s (Knutson *et al* 2019); this leads us to conclude, at present, that any increase in stalling hurricane numbers cannot be directly attributed to climate change. However, a higher frequency in stalling hurricanes will still make a moderate contribution to rainfall statistics due to the significant precipitation associated with such events.

In terms of hurricane rainfall, the findings of this study point toward a significant global warming signal present in events affecting Puerto Rico, the Bahamas, Cuba, Haiti and the Dominican Republic. There is high confidence in results from Puerto Rico for which the rainfall model was well calibrated with radar data (Feldmann *et al* 2019b); Cuba and the Bahamas being relatively flat nations have topography similar to the East Coast of the United States—where the model has been more extensively calibrated—therefore confidence in results is high here too. Readers should be aware that the Dominican Republic, Haiti and to some extent Jamaica are considerably more mountainous and as the rainfall model is sensitive to topography (Lu *et al* 2018) rainfall results for these nations will likely be more uncertain. Overall, the results suggest that the Eastern Caribbean region in particular (Puerto Rico and the Dominican Republic) is likely to benefit from a reduction in extreme hurricane precipitation events resulting from increased efforts to stabilise global warming as part of the more ambitious Paris Agreement goal of 1.5 °C instead of 2 °C. With the exception of Jamaica, a rise in extreme hurricane rainfall events is projected to materialise across the Caribbean, as a result of a projected increase in both the storm tracks passing through or near each country and Accumulated Cyclone Energy linked to a greater rainfall incidence, as indicated in the Paris Agreement scenarios.

The Caribbean stands to experience more extreme hurricane-rainfall events under the Paris Agreement scenarios, with the Eastern Caribbean region, in particular, likely to benefit from increased mitigation efforts to stabilise the climate at 1.5 °C of warming. Further research into integrated climate risks is

needed in this area to support adaptation efforts and infrastructure planning.

Data Availability

The HAPPI stabilised data present day, 1.5 and 2 degrees GCM data can be found at:

www.happimip.org/happi_data/.

The synthetic hurricane tracks may be acquired by contacting the third author at emanuel@mit.edu.

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