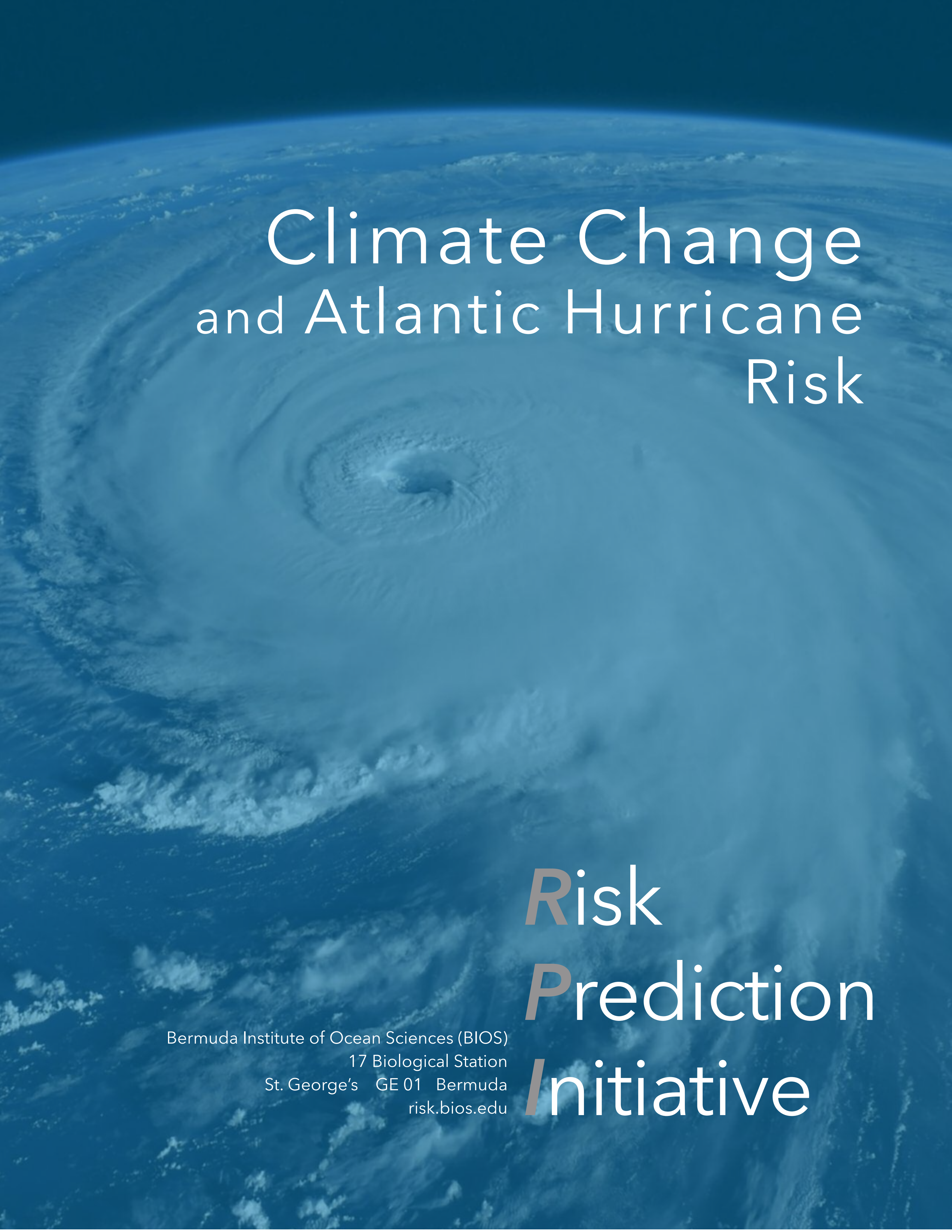

# Climate Change and Atlantic Hurricane Risk

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# contents




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Cover image: NASA satellite image of major Hurricane Florence in 2018.



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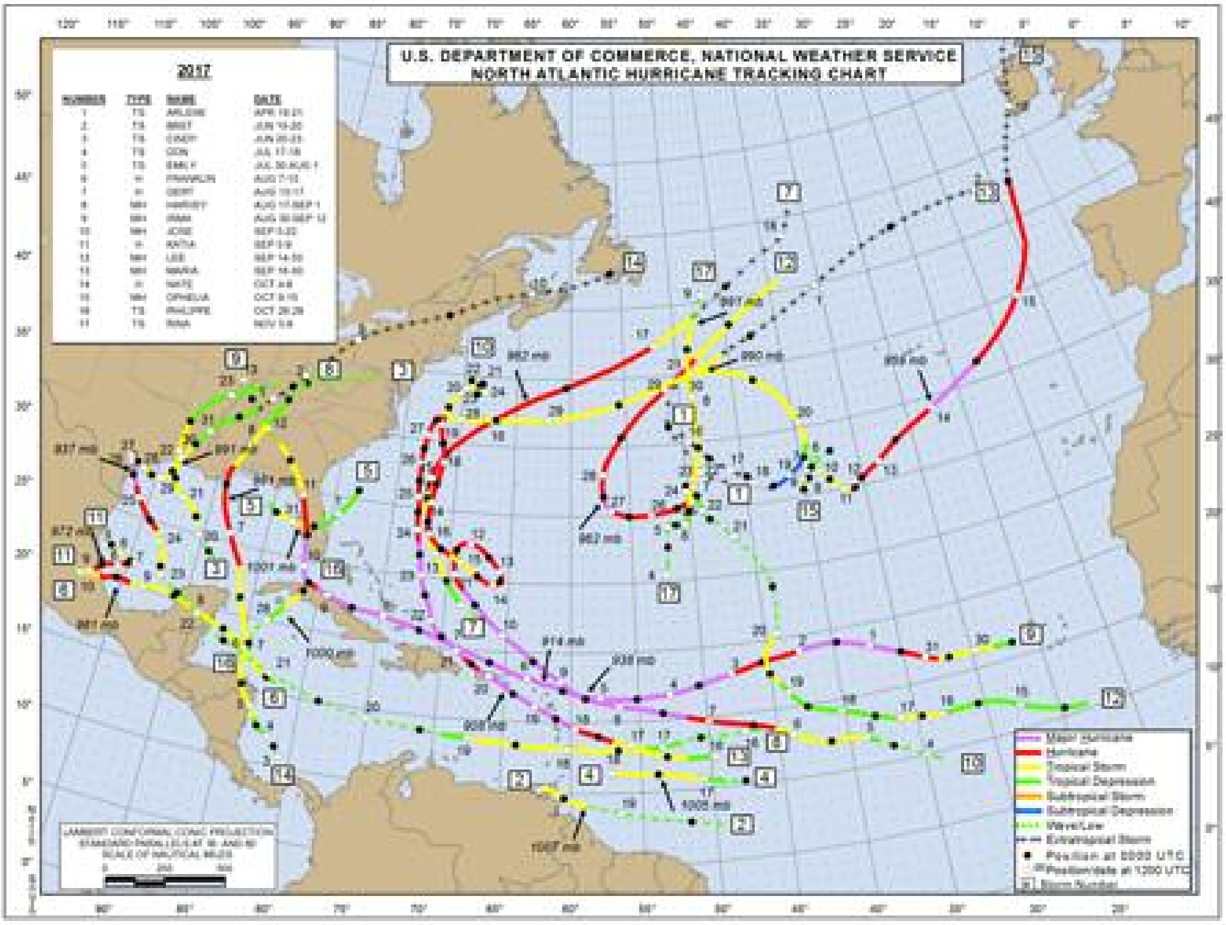



The 2017 hurricane season highlights most of the impacts suffered by countries with Atlantic, Caribbean or Gulf of Mexico coastlines. Storms in this season caused devastation from major hurricane wind speeds, storm surge and flood-induced flooding, tragic loss of life, disruption to livelihoods and destruction to property.

# Introduction

The 2017 and 2018 hurricane seasons have heralded the end of the period of no US major hurricane landfalls, caused devastating impacts across the Caribbean, Central and North America region, and sparked renewed questions about the impact of climate change on hurricane activity in the public and private sectors. In some cases, the damage inflicted by hurricanes in the last 2 seasons has been unprecedented in scale and impact, with record-breaking rainfall-induced flooding in some coastal communities and the highest wind speeds on record for some island nations.

This report will highlight scientific research that reveals recent findings with relevance to these issues, including trends detected in the long-term record, and future projections of changes of hurricane activity. It will not only focus on the wind or water hazards, but also impacts of some events that highlight the changing face of hurricane risk in the Atlantic, Caribbean Sea and Gulf of Mexico.

# Atlantic Hurricanes
## Landfall and Intensity

In 2015, the Risk Prediction Initiative (RPI) convened a workshop in London of academic hurricane researchers and insurance industry risk analysts to discuss the notion of a US hurricane landfall 'drought', in response to recent interest in the lack of Florida hurricanes since the major storm seasons of 2004 and 2005. Just prior to the meeting, a statistical analysis published by Hall and Hereid (2015) found that the return period of such a 'drought' (i.e. a decade of seasons with zero Florida landfalls) was within the bounds of statistical probability. A subsequent RPI-funded study (Hart et al. 2016) found that the notion of a US major hurricane landfall deficit is not to be trusted in the context of observational uncertainty bounds and different metrics of intensity (e.g. pressure). This is also true for storms that move close enough to the coastline to cause impacts, but that do not actually cross it – hurricanes that came within range of the coast did not see a change in their frequency during the period of supposed 'drought'. Given the sensitivity of landfall and the intensity metrics of 'major' storms, the study found that the period of the lack of US landfalls was somewhat arbitrarily defined, reinforcing the notion conclusion by Hall and Hereid that the 'drought' was a matter of luck.

Further to these conclusions, an examination of the historical hurricane database (HURDAT2) by Hart et al. (2016) also revealed an unphysical inflation of US hurricane landfalls with intensities at the 'major storm' wind speed threshold (Category 3). This was inferred to be a result of forecasting practices; a storm hovering near the Category 3 intensity threshold is perhaps better described in real-time as having reached major storm status, to motivate decision-making responses that better protect life and property. However, the maintained record of this (perhaps artificially-inflated) higher proportion of Category 3 storms is not useful in a historical dataset that is being used for risk analysis.

Hurricanes Katia, Irma, and Jose in the Atlantic during the 2017 hurricane season. Source NASA

Damage on the Gulf of Mexico coastline of Texas, following the impact of Category 2 Hurricane Ike's storm surge. Image by NOAA.

It is also worth noting that even if there has been a major hurricane landfall 'drought', it does not track with a deficit in impacts. Hurricane Ike in 2008 (Berg, 2009) and Hurricane Sandy (Blake et al., 2013) in 2012 highlight the immense damage and disruption that can be caused by hurricanes that are not officially major storms.

There is evidence demonstrated in a recent study (Kossin, 2017) to suggest a relationship between Atlantic hurricane seasons with high numbers of storms basin-wide, and wind shear near the US east coast. Wind shear is the change of environmental winds with height in the atmosphere, and generally, greater wind shear goes hand-in-hand with weaker hurricanes. In other words, Kossin's 2017 paper indicates that in seasons when there are large numbers of hurricanes, conditions are conducive to greater wind shear along the US east coast, possibly giving an element of protection to that region. In a follow up study, Ting et al (2019) found that this pattern of protection is likely to be eroded under climate warming. RPI is working with Kossin and colleagues to further explore this relationship.

The hurricane season in 2005 had the highest number of named storms (28) on record, and it leads to the question – is this the greatest possible number of storms we can expect? Thanks to research conducted by Lavender et al. (2018), we now know that the chances are very slim of a season with more tropical storms and hurricanes than 2005. The study undertaken demonstrated that from a climate perspective, there is little physical support for more hurricanes in Atlantic than were seen in 2005. However, it is worth noting that total numbers of storms do no correlate well with the rate of those that make landfall in a specific region. In fact, there were a lower number of hurricane landfalls in Florida during 2005 than during the preceding 2004 season.

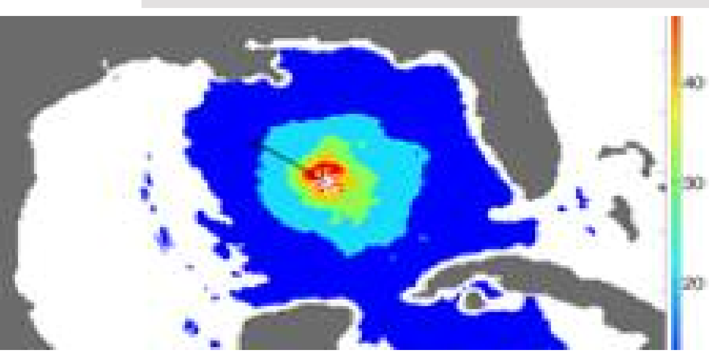
# Measuring Storm Strength

We know that hurricane counts alone do not account for impacts, so we can look to metrics of intensity to help us better understand the aspects of hurricanes that cause damage. The Saffir-Simpson Hurricane Wind Scale has been used for decades as a descriptive measure of a storm's potential for damage. The Saffir-Simpson scale indicates an estimate of the maximum sustained wind speed anywhere in a hurricane, and assigns a category to it as shown in the sidebar:

## Saffir-Simpson Hurricane Wind Scale

Categories are defined by maximum sustained wind speed anywhere in the circulation. Note: no storm surge, pressure, waves or rainfall are referred to in the scale (WMO, 2017).

| | | |
|---|---|---|
| Category | 1 | 64-82 kt |
| Category | 2 | 83-95 kt |
| Category | 3 (major) | 96-112 kt |
| Category | 4 (major) | 113-136 kt |
| Category | 5 (major) | 137+ kt |




Top left: This depiction of satellite-estimated wind speeds (knots) shows the large area covered by Hurricane Katrina's wind field on August 28, 2005. The maximum sustained wind speed, indicated in red shading in this case, is the basis for a Saffir-Simpson classification of a storm.

Bottom left : the color-enhanced visible satellite image of Hurricane Katrina at the same time frame shows the extent of clouds covering most of the Gulf of Mexico. Whether examining cloud imagery or an estimate of a hurricane's wind field, it is clear that the maximum sustained wind at one location omits information about the destructive potential of a hurricane. Wind estimates Courtesy of Dr. Dan Chavas, Purdue University. Satellite image courtesy of University Of Wisconsin – Madison

Previous representations of the Saffir-Simpson scale in public-facing documentation and online often added minimum central sea level pressure in the eye, and estimates of maximum storm surge to accompany the wind speed. On the face of it, this effort would have been useful information to the public, however, it was proven to be misleading – because there are various influences on the wind-pressure relationship (as demonstrated empirically by Holland, 1980), one cannot assign a wind strength to a minimum central sea level pressure. The maximum wind speed, while a response to the extreme low pressure, also depends on the gradient of pressure between the center and outer perimeter of the storm. Indeed, how and where one defines the 'outer perimeter' varies by storm, as not all cyclones have the same size (Chavas et al., 2016; Moyer et al. 2007).

Further, partly because of the variability of size and intensity of cyclones, one can also not assign a robust storm surge regime – other factors also include translation speed of the storm (and by association, its duration over an area of ocean), the incipient ocean conditions and local sea floor topography. A weak, large, long-duration storm impacting a coastline along a continental shelf (e.g. Hurricane Sandy making landfall on the US coast of New Jersey in 2012 – Blake et al., 2013) may have much greater impacts that an intense, smaller sized, major hurricane impacting a steeply sloped island platform at low tide (e.g. Hurricane Gonzalo impacting Bermuda in 2014 – Brown, 2015).

There are many pitfalls in using the Saffir-Simpson scale as a damage potential proxy, and solely using wind alone is insufficient to assess hurricane hazard. Many studies have noted the inadequacy of the Saffir-Simpson scale in describing the impact potential of hurricane winds, and have developed new metrics to assess the destructive potential associated with the maximum winds, such as power dissipation (Emanuel 2005) and accumulated cyclone energy (Bell et al., 1999). Other studies take this further to address cyclone damage potential (CDP - Done et al., 2018), and kinetic energy integrated around the cyclone (IKE - Kozar and Misra, 2014), incorporating cyclone size and forward motion. These newer metrics have the advantage of being more closely relatable to other parameters such as storm surge and wave action, however, do not explicitly involve ocean parameters; additionally, the more complex parameters are at a disadvantage as the historical datasets do not typically include a long record of the size parameters necessary to calculate IKE and CDP, whereas simpler metrics are derived directly from maximum sustained winds that have been recorded for several decades. None of the parameters mentioned here include rainfall or associated flooding hazards. In a follow-up study to Lavender et al. (2018), RPI is working to elucidate the maximum damage potential physically possible under a set of given climate conditions.

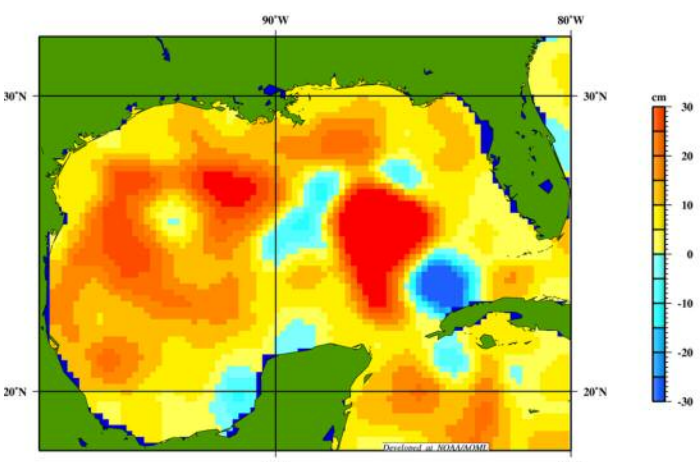

Extensive storm damage from Hurricane Irma to the island of Barbuda in 2017. Source: ABS TV Antigua.

# Hurricanes and Climate change

One of the questions that often arises when considering storm impacts is how climate change will affect hurricane activity. This section of the report will highlight some recent findings on trends in Atlantic hurricane activity in the context of climate trends.

## Warmer water → stronger storms

As a generally accepted theoretical principle, warm upper ocean temperatures serve as a necessary condition for hurricane development (Gray 1968, Emanuel, 1986). Whilst that is an insufficient condition on its own, it is instructive to note that around the world, tropical cyclones (called hurricanes in the Atlantic) form in warm tropical regions of the oceans. If wind shear acts as a 'brake' on hurricane intensity, then warm water is the 'fuel' to enable storms to develop. It is then intuitive to conclude that warmer water in greater abundance should provide more energy to the system that allows hurricanes to form. When researchers model future scenarios of hurricane activity, the near-surface ocean temperature is often one of the parameters they can change to help simulate hurricanes in a warmer world. The Intergovernmental Panel on Climate Change stated in their 2013 Assessment Report that upper ocean warming was of the scale of 0.11°C in the period 1971-2010 (IPCC, 2013)




Sea surface height anomalies in the Gulf of Mexico indicate the location of the warm loop current and warm anomalies (orange and red colors) south of the US coastline in August 2017, ahead of the development and impact of Hurricane Harvey.

Statistically, Elsner et al. (2013) found that hurricane at their highest intensities are on average 15 knots (18 mph or 28kph) stronger for every 1°C of warmer sea surface temperatures. The latitudes at which hurricanes attain their maximum intensities have also been shown to be progressing poleward on average (Kossin 2014). Combined, these conclusions suggest that for the Atlantic, regions in the northern tropics and subtropics are on balance more likely to be threatened by hurricanes reaching their lifetime maximum strength, and that with ocean warming steadily increasing, that strength is projected to be higher.

An aspect of regional warm water features, especially in the Gulf of Mexico, is the propensity for rapid intensification (RI) of hurricanes as they approach land. Warm water features such as the Loop Current in the Gulf of Mexico (Mainelli et al., 2008) provide a pool of greater heat from which storms can draw more energy, so there is a higher Maximum Potential Intensity (Emanuel, 1986) attainable by hurricanes over these features, all other factors being equal. It is notable that recent storms Hurricanes Harvey in 2017 (Blake and Zelinsky, 2018) and Michael in 2018 (Beven et al., 2019) passed over or near warm water anomalies in the Gulf of Mexico and underwent rapid intensification as they approached the coasts of Texas and Florida, respectively.

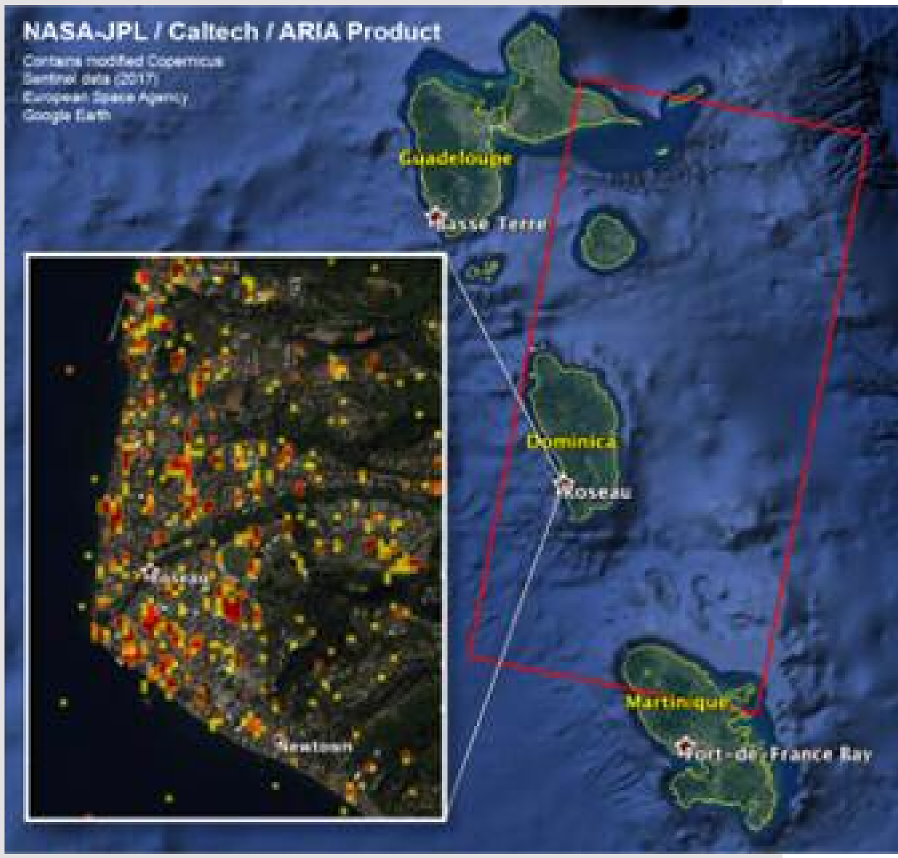
## Formation Locations and Maximum Intensity

A study presented by Kerry Emanuel in 2018 showed that in a modelled climate change scenario, Accumulated Cyclone Energy is increasing but not significantly, yet. Emanuel (2018) finds that there's a 10-fold increase in Hurricane Irma-magnitude event winds in the British Virgin Islands and Barbuda by the end of this century, and likewise a 10-fold increase in the probability of events of Hurricane Maria's scale in the northeast Caribbean. In similar simulation exercises, Wehner  et al. 2015 finds that tracks of tropical cyclones in modelled future climate scenarios are more frequent in the western North Atlantic, in the region of Bermuda. This is consistent with the projected formation of storms becoming more prevalent in the eastern tropical Atlantic (Colbert and Soden 2012).

### Impact of Hurricane Maria in Dominica

In 2017, Hurricane Maria devastated the Caribbean island nation of Dominica with Category 5 sustained winds, landslides induced by rainfall exceeding 20 inches (500mm) in some places, and the tragedy of 65 fatalities and presumed fatalities locally (Pasch et al. 2019). This was the first recorded Category 5 hurricane to have an impact on Dominica (WMO, 2018).

NASA rapid retrieval satellite imagery indicates the level of damage in Roseau, the capital city of Dominica. Warmer colors show "more significant ground surface change" from prior to the event, to just after Maria's impact. This damage proxy map was created by the Advanced Rapid Imaging and Analysis team at NASA's Jet Propulsion Laboratory and Caltech.



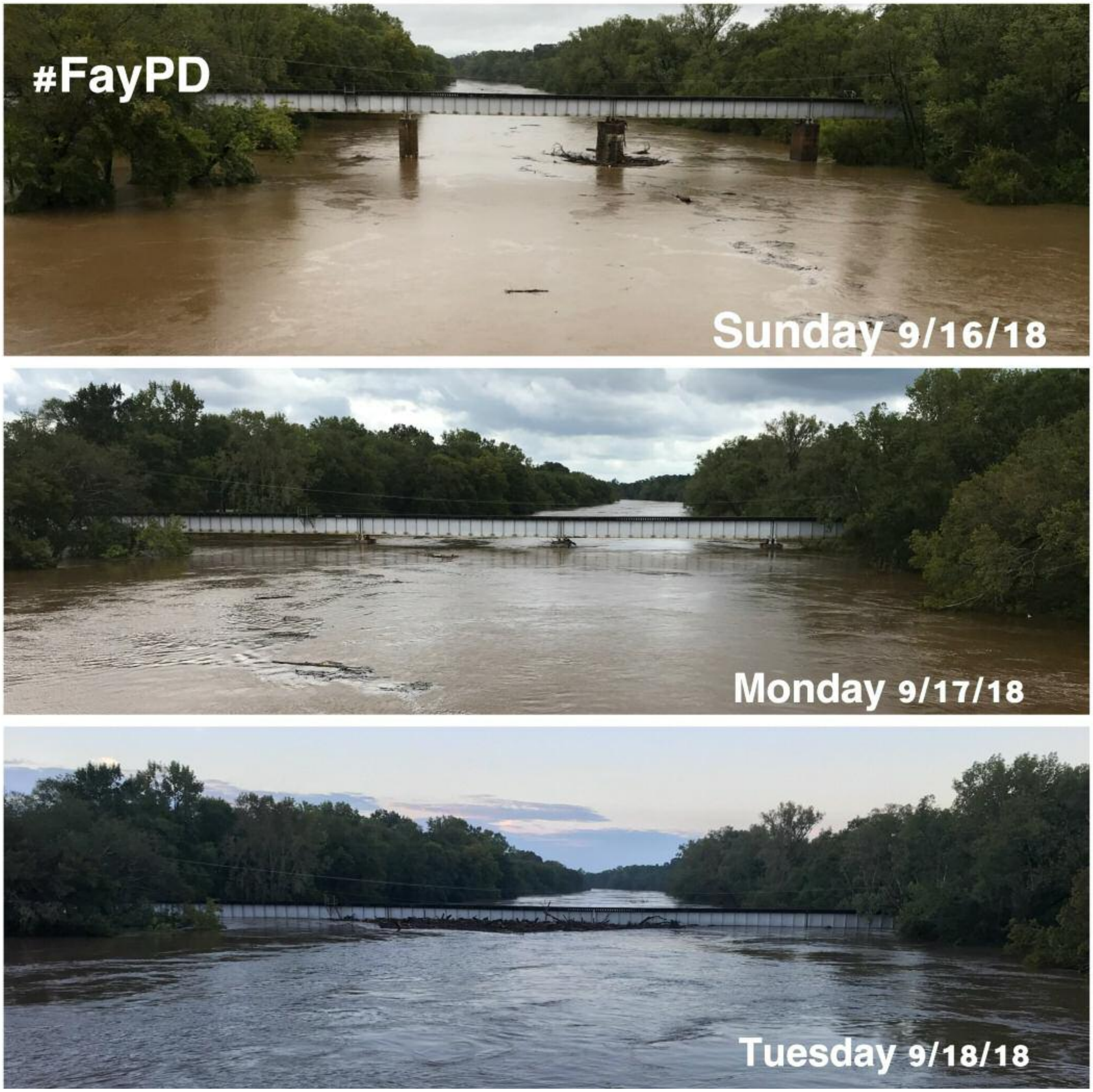
# Rainfall

Our understanding of atmospheric physics tells us that for every 1°C of average surface warming, there should be approximately 7% more atmospheric water vapor on average (Skliris et al., 2017; Held and Soden, 2006). Moist air is aggregated by tropical cyclones, so higher hurricane rainfall rates may also be expected in a warming world. Knutson et al. (2010) found in modelling studies that simulated hurricanes in the late 21st century should have up to 20% more rainfall within 100km of the center of the storm.

Kossin (2018) showed that there are average downward trends in the forward translation speed of tropical cyclones – approximately 10% globally in a 68-year period (1949-2016). A more specific examination of hurricanes landfalls in the Atlantic basin leads to the conclusion of a 20% slow-down of storms near or over coastlines. This means that over time, storm impacts are having a longer duration. The implications are that an estimated annual 10% increase in tropical cyclone rain rate per degree C warming (Knutson et al., 2015) would be potentially doubled by a 10% slowdown.

The relationship between hurricanes 'stalling' and local rainfall has now been demonstrated to be significant by Hall and Kossin (2019). This has been keenly felt by coastal communities in the US, with recent high profile flooding events caused by rainfall in Hurricanes Harvey (2017) in Texas and Hurricane Florence (2018) in the Carolinas. Given that these 2 trends both cause rainfall increases under climate warming and compound flooding impacts, there is much to be concerned about in terms of hurricane freshwater flood

Flooding in Texas following Hurricane Harvey. Source: NOAA




This sequence of photos posted on social media by the Fayetteville, North Carolina Police Department demonstrates the rapid rise of water levels following the passage of Hurricane Florence in September 2018. The rising flood waters were a direct result of widespread 10-inch rainfall accumulations across the Carolinas, including a maximum rainfall amount of 35.93 inches recorded near Elizabethtown NC (Stewart and Berg, 2019).


A car drives through a road flooded by king tides in southern Florida. Photo source: NOAA

# Exposure growth and Sea Level Rise

It has been noted by Willoughby and Hernandez (2018) that US hurricane damage tracks primarily with Gross Domestic Product, and not as much with wind speed parameters such as maximum wind speed or ACE. Weinkle et al. (2018) and Klotzbach et al (2018) likewise found no long term trend in normalized US economic losses reflected in hurricane landfalls. Each study points to the drivers of losses being primarily concentrations of wealth and populations at coastlines.

With this as context, it is interesting to note that a 2014 study by Climate Central (Kulp and Strauss, 2017), supported by RPI, tracks US trends of housing units and population within elevations of 10 feet of the coastline. The study further incorporates sea level rise into the analysis to reveal areas where both the population is growing, and the coastline is moving inland at a high rate. Not surprisingly, Florida features heavily as a state whose coastal exposure is greatly increasing. Miami-Dade County has a confluence of risk factors including:

i) One of the highest historical rates of major hurricane landfalls in the storm record (Jarrell et al., 1992);

ii) rapid historical increases in coastal housing density, projected out to continue through the next decades (Kulp and Strauss, 2017);

iii) increased numbers of 'sunny day' flooding events due to sea level rise (McNoldy, 2018).

# Summary

As we move into the next hurricane season, it is timely that this report should highlight some of the challenges we face under a changing regime of hurricane risk.

The Saffir-Simpson Hurricane Wind Scale has for decades been useful as a communications tool for forecasting. However, multiple studies indicate a need to augment the messaging that still heavily focuses on hurricanes' maximum wind speeds. The deadly water impacts such as storm surge and rainfall-induced flooding are often not accounted for in the measures currently being used as intensity metrics in public communications. Efforts have been afoot in academia and forecast communities to develop storm metrics that account for size, and duration of impacts over an area.

Recent research has found alarmingly that tropical cyclones have been slowing down in forward speed, thereby prolonging the duration of the storms' effects over coastlines. Indeed one of those major impacts that has gained a lot of attention is hurricane rainfall as demonstrated by storms like Hurricanes Harvey (2017 in Texas) and Florence (2018 in the Carolinas). Compounding this challenge of slower-moving storms is that a warming atmosphere can carry more moisture, enabling a greater availability of water for rain-bearing clouds to form and be collected into hurricanes' circulations. This one-two punch means potentially heavier rainfall, lasting longer as hurricanes make landfall.

As if that weren't enough, the gradually rising sea levels exacerbate this flooding hazard, and augment already dangerous seawater inundation from storm surge. Another challenge that is presented by climate change via the oceans is the warming of the near-surface temperatures. As warm water provides the fuel for hurricane development, the potential for more intense and rapidly intensifying storms increases, especially in regions where there are naturally localized extremes in upper-ocean temperature, like the Loop Current in the Gulf of Mexico. As storms move across this local area of warmer water, they are able to rapidly intensify close to coastlines, confounding the predictability of intensity forecasts.

Despite these gradually worsening aspects of hurricane impacts, perhaps the contributor that is both most relevant and preventable is the growth of coastal exposure – i.e. the increase in populations and infrastructure right near the water's edge. Studies show that some of the cities most vulnerable to sea level rise and hurricane frequency (even in the absence of changing hurricane characteristics) are those that are seeing continued rapid increases in coastal property. This has likely been contributed to (at least in the US) by the lack of hurricane landfall activity in 2005-2017, enabling complacency about coastal storm risk.

# References


Bell, G.D., M.S. Halpert, R.C. Schnell, R.W. Higgins, J. Lawrimore, V.E. Kousky, R. Tinker, W. Thiaw, M. Chelliah, and A. Artusa, 2000: Climate Assessment for 1999. Bull. Amer. Meteor. Soc., 81, S1–S50, doi.org/10.1175/1520-0477(2000)81[s1:CAF]2.0.CO;2

Berg, R. 2009. Tropical cyclone report Hurricane Ike (AL092008) 1- 14 September 2008, National Hurricane Center, 23 January 2009.

Beven, J.L., Berg, R., and Hagen, A.: Tropical Cyclone Report – Hurricane Michael (AL142018) 7–11 October 2018 , National Hurricane Center 17 May 2019.

Blake, E.S., Todd B. Kimberlain, Robert J. Berg, John P. Cangialosi and John L. Beven II: Tropical Cyclone Report - Hurricane Sandy (AL182012) 22 – 29 October 2012 National Hurricane Center, 12 February 2013

Blake E.S. and Zelinsky D.A.: Tropical Cyclone Report – Hurricane Harvey (AL092017) 17 August – 1 September 2017 National Hurricane Center 9 May 2018

Brown, D.: Tropical Cyclone Report, Hurricane Gonzalo (AL082014) 12 – 19 October 2014 National Hurricane Center, 4 March 2015

Chavas, D.R., N. Lin, W. Dong, and Y. Lin, 2016: Observed Tropical Cyclone Size Revisited. J. Climate, 29, 2923–2939, doi.org/10.1175/JCLI-D-15-0731.1

Colbert, A.J. and B.J. Soden, 2012: Climatological Variations in North Atlantic Tropical Cyclone Tracks. J. Climate, 25, 657–673, doi.org/10.1175/JCLI-D-11-00034.1

Done, J.M., PaiMazumder, D., Towler, E. et al. Climatic Change (2018) 146: 561. doi.org/10.1007/s10584-015-1513-0

Elsner, J.B., S.E. Strazzo, T.H. Jagger, T. LaRow, and M. Zhao, 2013: Sensitivity of Limiting Hurricane Intensity to SST in the Atlantic from Observations and GCMs. J. Climate, 26, 5949–5957, doi.org/10.1175/JCLI-D-12-00433.1

Emanuel, K. A., 1986: An air-sea interaction theory for tropical cyclones. Part I: Steady state maintenance. J. Atmos. Sci. 43, 585-604.

Emanuel, K., 2005: Increasing destructiveness of tropical cyclones over the past 30 years. Nature, 436, 686–688.

Emanuel, K., Assessing the present and future probability of Hurricane Harvey's rainfall, PNAS November 28, 2017. 114 (48) 12681-12684.

Emanuel, K., 2018, Climate Change and the Hurricanes of 2017, American Meteorological Society 33rd Conference on Hurricanes and Tropical Meteorology 6D.1, April 2018, Ponte Vedra, FL.

Gray, W. M., 1968: Global view of the origin of tropical disturbances and storms. Mon. Wea. Rev., 96, 669-700.

Hall, T.M., and K. Hereid, 2015: The frequency and duration of U.S. hurricane droughts. Geophys. Res. Lett., 42, no. 9, 3482-3485, doi:10.1002/2015GL063652.

Hall, T. M., and J. P. Kossin, 2019: Hurricane stalling along the North American coast and implications for rainfall. npj Clim. Atmos. Sci., 2, doi:10.1038/s41612-019-0074-8.

Hart, R.E., D.R. Chavas, and M.P. Guishard, 2016: The Arbitrary Definition of the Current Atlantic Major Hurricane Landfall Drought. Bull. Amer. Meteor. Soc., 97, 713–722, doi.org/10.1175/BAMS-D-15-00185.1

Held, I.M. and B.J. Soden, 2006: Robust Responses of the Hydrological Cycle to Global Warming. J. Climate, 19, 5686–5699, doi.org/10.1175/JCLI3990.1

Holland, G.J., 1980: An Analytic Model of the Wind and Pressure Profiles in Hurricanes. Mon. Wea. Rev., 108, 1212–1218, doi.org/10.1175/1520-0493(1980)108<1212:AAMOTW>2.0.CO;2

Jarrell, J.D., P.J. Hebert, and B.M. Mayfield, 1992: Hurricane Experience Levels of Coastal County Populations - Texas to Maine. NOAA, Technical Memorandum NWS-NHC-46, 152 pp. (updates through 2010 here: www.nhc.noaa.gov/climo/images/strikes_us_mjr.jpg )

Klotzbach, P.J., S.G. Bowen, R. Pielke, and M. Bell, 0: Continental United States Hurricane Landfall Frequency and Associated Damage: Observations and Future Risks. Bull. Amer. Meteor. Soc., 0, doi.org/10.1175/BAMS-D-17-0184.1

Kossin, J. P., 2017: Hurricane intensification along United States coast suppressed during active hurricane periods. Nature, 541, 390-393, doi:10.1038/nature20783

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

Kossin J.P., Emanuel K.A., Vecchi G.A., The poleward migration of the location of tropical cyclone maximum intensity. Nature. 2014 May 15;509(7500):349-52. doi: 10.1038/nature13278.

## References, continued


Kozar, M.E. and V. Misra, 2014: Statistical Prediction of Integrated Kinetic Energy in North Atlantic Tropical Cyclones. Mon. Wea. Rev., 142, 4646–4657, doi.org/10.1175/MWR-D-14-00117.1

Knutson, T. R., McBride, J. L., Chan, J., Emanuel, K., Holland, G., Landsea, C., ... & Sugi, M. (2010). Tropical cyclones and climate change. Nat Geosci 3: 157–163.

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. J. Climate, 28, 7203–7224, doi.org/10.1175/JCLI-D-15-0129.1

Klotzbach, P.J., S.G. Bowen, R. Pielke, and M. Bell, 2018: Continental U.S. Hurricane Landfall Frequency and Associated Damage: Observations and Future Risks. Bull. Amer. Meteor. Soc., 99, 1359–1376, doi.org/10.1175/BAMS-D-17-0184.1

Kulp, S. & Strauss, B.H. Rapid escalation of coastal flood exposure in US municipalities from sea level rise, Climatic Change (2017) 142: 477. doi.org/10.1007/s10584-017-1963-7

Lavender, S.L., K.J.E. Walsh, L-P. Caron, M. King, S. Monkiewicz, M. Guishard, Q. Zhang, and B. Hunt, 2018: Estimation of the maximum annual number of North Atlantic tropical cyclones using climate models. Science Advances, 4, doi: 10.1126/sciadv.aat6509.

Mainelli, M., M. DeMaria, L.K. Shay, and G. Goni, 2008: Application of Oceanic Heat Content Estimation to Operational Forecasting of Recent Atlantic Category 5 Hurricanes. Wea. Forecasting, 23, 3–16, doi.org/10.1175/2007WAF2006111.1

McNoldy, B., Hurricanes, Sea Level Rise, and South Florida's Challenging Future, CallisonRTKL SPARK Week Seminars: Designing for Resilience, July 2018

Moyer, A., Evans, J. & Powell, M. Meteorol. Atmos. Phys. (2007) 97: 41. doi.org/10.1007/s00703-006-0243-2

NASA Aria Damage Proxy Map: disasters.nasa.gov/hurricane-maria-2017/aria-damage-proxy-map-dominica-hurricane-maria
Pasch, R.J., Penny, A.B. and Berg, R.: Tropical cyclone report Hurricane Maria (AL152017) 16 - 30 September 2017, National Hurricane Center, 14 February 2019.

Skliris, N., Zika, J. D., Nurser, G., Josey, S. A., & Marsh, R. (2016). Global water cycle amplifying at less than the Clausius-Clapeyron rate. Scientific reports, 6, 38752.

Stewart, S. and Berg, R.: Tropical Cyclone Report – Hurricane Florence (AL062018) 31 August – 17 September 2018 National Hurricane Center 3 May

Ting, M., J. P. Kossin, S. J. Camargo, and C. Li, 2019: Past and future hurricane intensity change along the U.S. East Coast. Scientific Reports, 9:7795, 10.1038/s41598-019-44252-w.

Wehner, M., Prabhat, K.A. Reed, D. Stone, W.D. Collins, and J. Bacmeister, 2015: Resolution Dependence of Future Tropical Cyclone Projections of CAM5.1 in the U.S. CLIVAR Hurricane Working Group Idealized Configurations. J. Climate, 28, 3905–3925, doi.org/10.1175/JCLI-D-14-00311.1

Weinkle, J., C. Landsea, D. Collins, R. Masulin, R. P. Crompton, P. J. Klotzbach, and R. Pielke Jr., 2018: Normalized hurricane damage in the continental United States 1900-2017. Nature Sustainability, 1, 808-813, doi: 10.1038/s41893-018-0165-2.

Willoughby, H.E. and Hernandez, J.I., Synthesis of US and Caribbean Hurricane Impacts on a Warmer Globe, American Meteorological Society 33rd Conference on Hurricanes and Tropical Meteorology 6D.2, April 2018, Ponte Vedra, FL.

World Meteorological Organization Regional Association IV Hurricane Committee: Report from Dominica, April 2018
www.wmo.int/pages/prog/www/tcp/HC-40.html

World Meteorological Organization Technical Document WMO-TD No. 494, Tropical Cyclone Programme Report No. TCP-30, Regional Association IV (North America, Central America and the Caribbean), Hurricane Operational Plan 2017 Edition.

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