Special Report:

Hurricanes and Climate Change

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Executive summary

This Report assesses the scientific basis for projections of future hurricane activity. The Report evaluates the assessments and projections from the Intergovernmental Panel on Climate Change (IPCC) and recent national assessments regarding hurricanes. The uncertainties and challenges at the knowledge frontier are assessed in the context of recent research, particularly with regards to natural variability. The following four questions frame this Report:

1. Is recent hurricane activity unusual?

In the North Atlantic, all measures of hurricane activity have increased since 1970, although comparably high levels of activity also occurred during the 1950's and 1960's. Geologic evidence indicates that the current heightened activity in the North Atlantic is not unusual, with a 'hyperactive period' apparently occurring from 3400 to 1000 years before present. Prior to the satellite era (1970's), there are no reliable statistics on global hurricane activity. Global hurricane activity since 1970 shows no significant trends in overall frequency, although there is some evidence of a small increase in the number of major hurricanes.

2. Have hurricanes been worsened by manmade global warming?

Any signal of increased hurricane activity has not risen above the background variability of natural climate variations. At this point, there is no convincing evidence that manmade global warming has caused a change in hurricane activity.

3. Have hurricane landfall impacts been worsened by manmade global warming?

Of recent impactful U.S. landfalling hurricanes, only the rainfall in Hurricane Harvey is unusual in context of the historical record. Warmer sea surface temperatures are expected to contribute to an overall increase in hurricane rainfall, although hurricane-induced rainfall and flooding is dominated by natural climate variability. Storm surge risk is increasing slightly owing to the slow creep of sea level rise. The extent to which the recent increase in ocean temperatures and sea level rise can be attributed to manmade global warming is disputed. The primary driver for increased economic losses from landfalling hurricanes is the massive population buildup along coastlines.

4. How will hurricane activity change during the 21st century?

Recent assessment reports have concluded that there is low confidence in projections of future changes to hurricane activity. Any projected change in hurricane activity is expected to be small relative to the magnitude of natural variability in hurricane activity.

1. Introduction

The concern over hurricanes is about the growing impact of landfalls in coastal regions where population and wealth are increasing. Numerous assessments and reviews have investigated the possible role of manmade global warming on global and regional hurricane activity. These include periodic assessment reports from the Intergovernmental Panel on Climate Change (IPCC), U.S. National Climate Assessment Reports (NCA) and periodic reports organized under the auspices of the World Meteorological Organization and CLIVAR.

Of the recent assessment reports, the most thoroughly reviewed is the IPCC AR5 (2013), which concluded:

- "Globally, there is low confidence in attribution of changes in tropical cyclone activity to human influence. This is due to insufficient observational evidence, lack of physical understanding of the links between anthropogenic drivers of climate and tropical cyclone activity, and the low level of agreement between studies as to the relative importance of internal variability, and anthropogenic and natural forcings."

- "Projections for the 21st century indicate that it is likely that the global frequency of tropical cyclones will either decrease or remain essentially unchanged, concurrent with a likely increase in both global mean tropical cyclone maximum wind speed and rain rates."

In spite of the low confidence in attributing changes in hurricane activity to human influence, the public discourse on the threat of hurricanes in a changing climate is often characterized by exaggerated alarm, fueled by statements from some climate scientists:

> "Florence is yet another poster child for the human-supercharged storms that are becoming more common and destructive as the planet warms." – Jonathan Overpeck, University of Michigan[1]
>
> "In other words, we get a Harvey-like event impacting the Gulf Coast, or a Sandy-like event impacting the New Jersey and New York City coast once every few years . . . We're talking about literally giving up on the major coastal cities of the world and moving inland." – Michael Mann, Penn State University[2]

CFAN's Special Report on Hurricanes and Climate Change addresses the following four issues:

1. Whether recent hurricane activity is unusual in context of the historical and geological record.
2. Whether recent hurricane activity has been exacerbated by manmade global warming.

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[1] https://www.chicagotribune.com/news/nationworld/ct-climate-change-hurricanes-20180914-story.html

[2] https://www.sciencefriday.com/segments/hurricane-harvey-and-the-new-normal/

3. Whether hurricane landfall impacts have been exacerbated by manmade global warming.
4. Projections of hurricane activity circa 2050 and 2100.

This Report is distinguished from recent assessments of hurricanes and climate change by the following:

- a focus on hurricane aspects that contribute to landfall impacts
- an emphasis on geologic evidence and interpretation of natural variability
- an approach to 'detection and attribution' that does not rely on global climate models
- a perspective on future projections that that accounts for uncertainties in climate models and also includes natural climate variability
- a longer format that allows for more in depth explanation suitable for a non-expert audience.

2. Hurricane terminology, structure and mechanisms

The term *hurricane* is one of three names for a rotating tropical storm, up to several hundred miles in diameter, with maximum wind speed of at least 74 mph. As a result of the Earth's rotation, tropical cyclones rotate in a counterclockwise direction in the Northern Hemisphere and in a clockwise direction in the Southern Hemisphere.

These storms are called *hurricanes* when they develop over the Atlantic or eastern Pacific Oceans. They are referred to as *cyclones* when they form over the Bay of Bengal and the northern Indian Ocean, and as *typhoons* when they develop in the western Pacific. For the sake of clarity, all further references in this Report will be to 'hurricanes.'

About 48 hurricanes form annually. Roughly two thirds of these storms form in the Northern Hemisphere from about June to November, while the remaining third form in the Southern Hemisphere, typically during the months of November to May. About 57% of total hurricanes occur in the Pacific, 31% in the Indian Ocean, and 12% in the Atlantic.

The International Best Track Archive for Climate Stewardship (IBTrACS; Knapp et al, 2010) provides a merged global dataset of hurricane frequency, location, and intensity, collected from all of the international hurricane forecast centers. Since 1970, global satellite observations have provided accurate information about the frequency of hurricanes. Hurricane intensity is inferred from satellite observations using a subjective pattern recognition technique (Dvorak, 1975). Meteorologists apply the technique in real time, based on available satellite imagery, and at the end of each season the intensity estimates are reassessed before being incorporated into the best track data.

Prior to the era of satellites, information on hurricanes comes from aircraft and ship observations and observations at landfall. Paleotempestology uses geological information from regions that have been impacted by landfalling hurricanes to infer hurricane occurrence prior to the historical record.

In developing hurricane climatologies, the following measures of global or regional hurricane activity are used:

- Total number (or frequency) of hurricanes
- Total number of major hurricanes (Category 3-5; wind speed exceeding 111 mph)
- Accumulated Cyclone Energy (ACE): a metric based on hurricane frequency, speed and duration that is calculated by summing the squares of the estimated 6-hourly maximum sustained wind speed over the lifetime of the storm
- Power Dissipation Index (PDI): like ACE, the PDI is also based on storm frequency, wind speed, and duration, but places more emphasis on storm intensity by using the cube of the wind speed.

2.1 Hurricane processes

A tropical cyclone may be divided into three regions (Figure 2.1). First is a ring-shaped outer region consisting of rain bands that spiral towards the center of the storm, having an outer radius of up to several hundred miles. In this region, the winds increase uniformly in speed toward the center. Wind speeds attain their maximum value at the second region, the *eyewall*, which is typically 10 to 20 miles from the center of the storm, and consists of a dense ring of clouds about 8 miles high. The eyewall is the region of strongest winds and heaviest rainfall. The eyewall surrounds the interior region, called the *eye*, where wind speeds decrease rapidly and the air is often calm.

Hurricanes can persist for many days and usually dissipate over land or colder oceans. Figure 2.2 shows the location of global hurricane tracks, the formation locations, and the underlying sea surface temperatures.

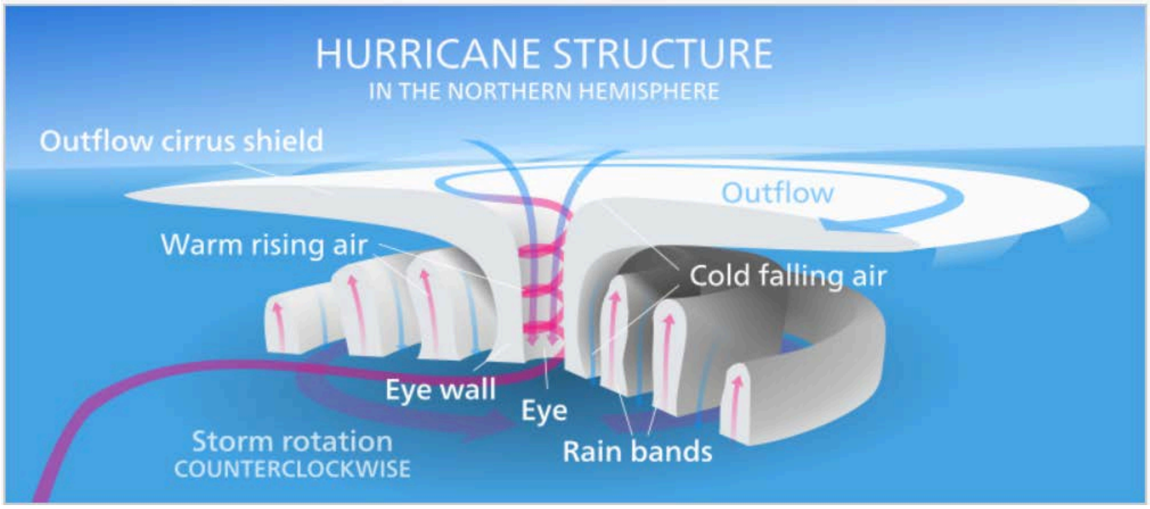


Figure 2.1. Cross-section diagram of a mature hurricane, with arrows indicating airflow in and around the eye. Source: Wikipedia

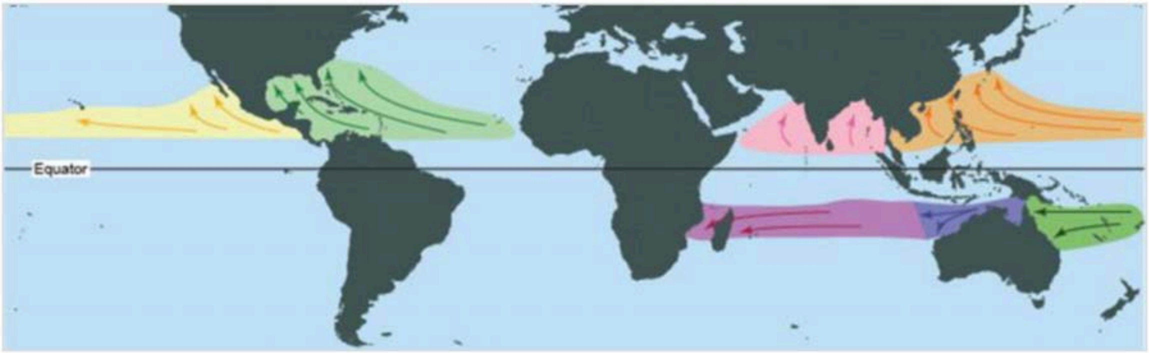


Figure 2.2 A map of hurricane basins around the globe. West Pacific (orange); North Indian Ocean (pink); North Atlantic (lt green); East Pacific (yellow); South Pacific (dark green); South Indian Ocean (purple). Source: NOAA

There are six general conditions that support the formation of a hurricane:

1. The temperature of the sea surface must be 80 °F [26.5 °C] or warmer, and the surface warm layer must be at least 150 feet deep.
2. A preexisting atmospheric circulation near the surface warm layer.
3. The atmospheric temperatures must decrease quickly enough with height to support the formation of deep convective clouds.
4. The atmosphere must be relatively humid at a height of about 3 miles above the surface.
5. The developing storm must be at least 300 miles away from the equator.
6. The wind speed must change slowly with height, i.e. little vertical wind shear.

Once formed, hurricanes are steered by the predominant atmospheric flow patterns and move generally from east to west during their early stages of life before drifting poleward and possibly recurving with the midlatitude westerly winds.

The intensification of a hurricane to a major hurricane is favored particularly by factors 1, 3, 4, and 6 above. Hurricanes dissipate when they can no longer extract sufficient energy from warm ocean water. A hurricane can actually contribute to its own demise by stirring up deeper, cooler ocean waters. A storm that moves over land will abruptly lose its fuel source and quickly lose intensity. A hurricane that remains over the ocean and moves into higher latitudes will become extratropical as it encounters cooler water, causing the storm to weaken and dissipate in a few days.

2.2 Factors contributing to landfall impacts

The largest landfall impacts from hurricanes are associated with high winds, storm surge, and heavy rainfall.

2.2.1 Wind damage

High winds cause some of the most dramatic and damaging effects associated with tropical cyclones.

Hurricane intensity is categorized based on the maximum sustained wind. The Saffir-Simpson Hurricane Wind Scale is a 1 to 5 rating based on a hurricane's sustained maximum wind speed. Hurricanes reaching Category 3 and higher are referred to as 'major hurricanes.' Table 2.1 summarizes the types of damage associated with the different category hurricanes.

Table 2.1. Saffir-Simpson scale of hurricane intensity.
https://www.nhc.noaa.gov/aboutsshws.php

Category	Sustained Winds	Types of Damage Due to Hurricane Winds
1	74-95 mph	**Very dangerous winds will produce some damage:** Well-constructed frame homes could have damage to roof, shingles, vinyl siding and gutters. Large branches of trees will snap and shallowly rooted trees may be toppled. Extensive damage to power lines and poles likely will result in power outages that could last a few to several days.
2	96-110 mph	**Extremely dangerous winds will cause extensive damage:** Well-constructed frame homes could sustain major roof and siding damage. Many shallowly rooted trees will be snapped or uprooted and block numerous roads. Near-total power loss is expected with outages that could last from several days to weeks
3 (major)	111-129 mph	**Devastating damage will occur:** Well-built framed homes may incur major damage or removal of roof decking and gable ends. trees will be snapped or uprooted, blocking numerous roads. Electricity and water will be unavailable for several days to weeks after the storm passes.
4 (major)	130-156 mph	**Catastrophic damage will occur:** Well-built framed homes can sustain severe damage with loss of most of the roof structure and/or some exterior walls. Most trees will be snapped or uprooted and power poles downed. Power outages will last weeks to possibly months. Most of the area will be uninhabitable for weeks or months.
5 (major)	157 mph or higher	**Catastrophic damage will occur:** A high percentage of framed homes will be destroyed, with total roof failure and wall Collapse. Power outages will last for weeks to possibly months. of the area will be uninhabitable for weeks or months.

In Category 5 hurricanes, sustained winds may exceed 160 mph and gusts can exceed 200 mph. The length of time that a given location is exposed to extreme winds depends on the size of the storm and the speed at which it is moving. During a direct hit, a location may endure high winds for several hours. In the Northern Hemisphere, the strongest winds are located in the right-forward quadrant of the storm, as measured in the direction of the overall storm motion. For example, the most damaging winds from a hurricane approaching the east coast of the U.S. are located to the northeast of the storm center.

The intense sustained winds near the center of the hurricane are not the only source of wind damage. Most hurricanes spawn tornadoes, although the majority of hurricanes spawn fewer than 10. Major hurricanes that have a large horizontal extent can spawn more than a hundred tornadoes, often at locations far inland from the landfall location. In the Northern Hemisphere, the preferred location for tornado formation is the right forward quadrant of the storm, relative to the storm motion.

2.2.2 Storm surge

Along the coast, storm surge is often the greatest threat to life and property from a hurricane. A storm surge is an abnormal rise of water near the coast that is generated by the onshore winds associated with the hurricane. The storm surge can cause extreme flooding in coastal areas, particularly when the surge coincides with high tide. In recent decades, the highest storm surge struck the Mississippi coast during Hurricane Katrina (2005), reaching almost 28 feet.

A storm surge is produced by water being pushed toward the shore by the force of the winds. Most of the surge is caused by friction between the strong winds and the ocean surface, which piles water up in the direction that the wind is blowing – in the Northern Hemisphere, this effect is largest in the right-forward quadrant of the storm. The magnitude of the storm surge depends on storm intensity, the size of the area covered by hurricane force winds, the rate of forward motion of the storm, and angle of approach to the coast.

Other factors impacting surge are the width and slope of the continental slope. A shallow slope produces a greater storm surge than a steep shelf. A Category 4 hurricane striking the Louisiana coast, which has a wide and shallow continental shelf, might produce a 20 foot storm surge. The same storm striking Miami Beach, where the continental shelf drops off quickly, might produce an 8 or 9 foot surge.

2.2.3 Rainfall

Hurricanes typically bring large amounts of rainfall, with heavy rainfall often occurring far inland from the landfall location. Much of the rainfall is associated with the deep convective clouds of the eyewall and with the rainbands of the outer edges of the storm. Rainfall rates are typically on the order of an inch per hour, with shorter bursts of much higher rates. It is not uncommon for total rainfall of 20 to 40 inches or more of rain to be reported over some regions.

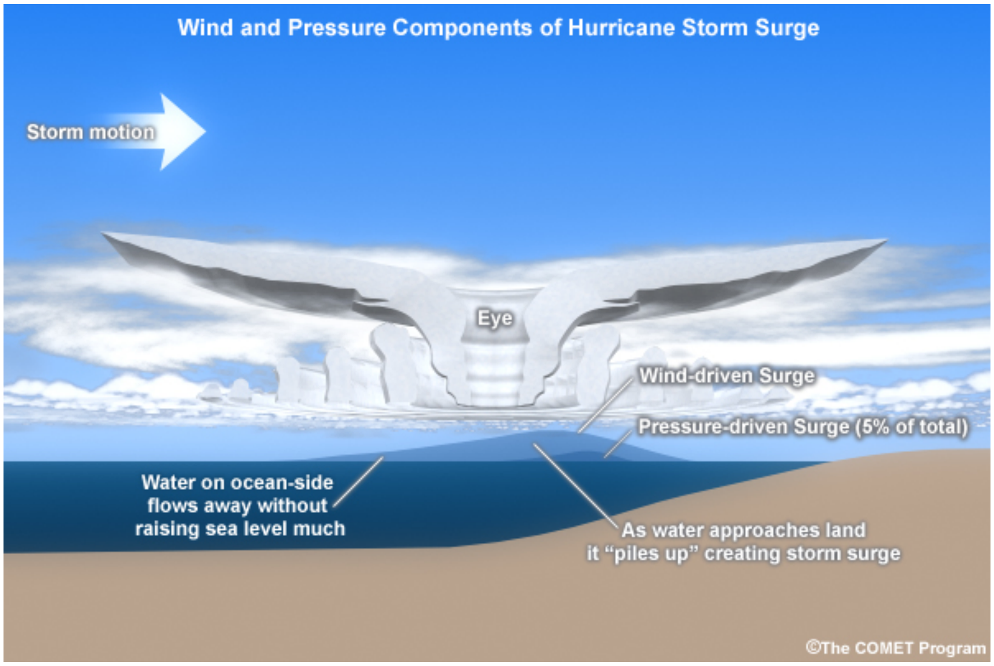


Figure 2.3 Schematic of a storm surge as a hurricane approaches the coast. http://surgebulge_COMET.jpg

Large, slow moving hurricanes produce the highest total rainfall. Hurricane intensity has little bearing on the amount of rainfall over land, The largest rainfall amounts fall in the right front quadrant in the Northern Hemisphere. The highest rainfall rates can occur in areas where mountains and canyons concentrate the rainfall.

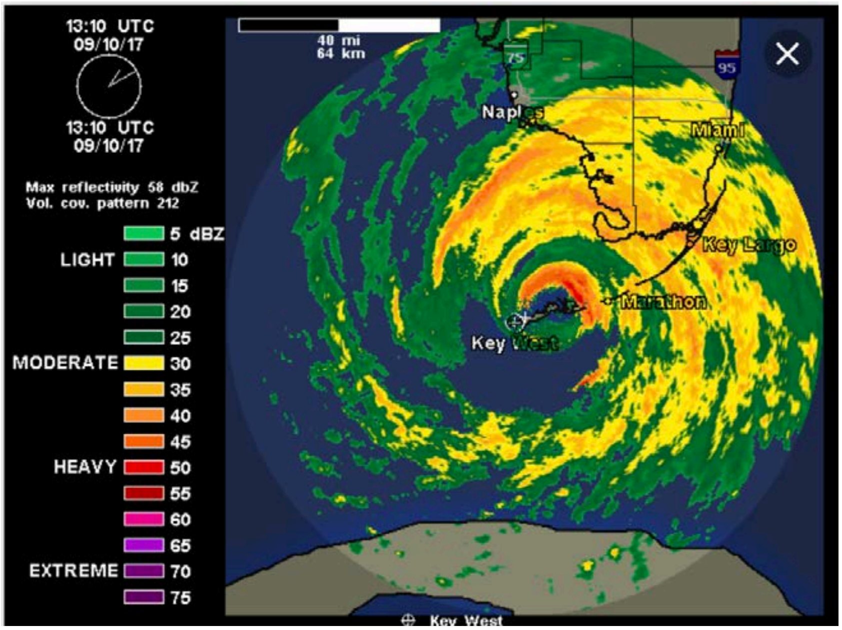


Figure 2.4 Radar depiction of rainfall from Hurricane Irma as it approaches Florida. Source: Weather Underground

3. Historical variability and trends

Documenting the variability and trends of hurricane activity requires long and accurate data records. Historical information on hurricane activity is obtained from the following sources:

- satellite observations (since ~1966)
- aircraft instrumental observations (since 1944)
- surface-based instrumental observations - landfalls, ships (since the 1800's)
- historical reports

Over the years, the way that hurricanes have been observed has changed radically. As a result, many hurricanes are now recorded that would have been missed in the past. Furthermore, satellites are now able to continually assess wind speeds, thus recording peak wind speeds that may have been missed in pre-satellite days. Unfortunately, temporally inconsistent and potentially unreliable global historical data hinder detection of trends in tropical cyclone activity.

This Chapter assesses the variability of global and regional hurricanes over the entire available database. An assessment is provided as to whether we can detect any global or regional trends in hurricane activity from the available data.

3.1 Global

Reliable global hurricane data from satellite has been available since 1970, although inference of hurricane intensity is not judged to be reliable prior to 1980 (and in some regions, prior to 1988). Hurricane intensity is estimated from satellite observations through cloud patterns and cloud top temperatures.

Figure 3.1 shows the time series since 1981 of total global hurricanes and major hurricanes. On average, each year there are about 47 hurricanes with about 20 reaching major hurricane status. Substantial year-to-year variability is seen, with a slight decreasing trend in the number of hurricanes and a slight but insignificant increasing trend in the number of major hurricanes.

Figure 3.2 shows the time series since 1971 of the global Accumulated Cyclone Energy (ACE) (see Chapter 2 for a definition of ACE). As an integral of global hurricane frequency, duration and intensity, ACE shows greater decadal variation than does the number of hurricanes in Figure 3.1. No trend in ACE is seen, and the recent period of 2009 to 20015 was characterized by particularly low values of ACE.

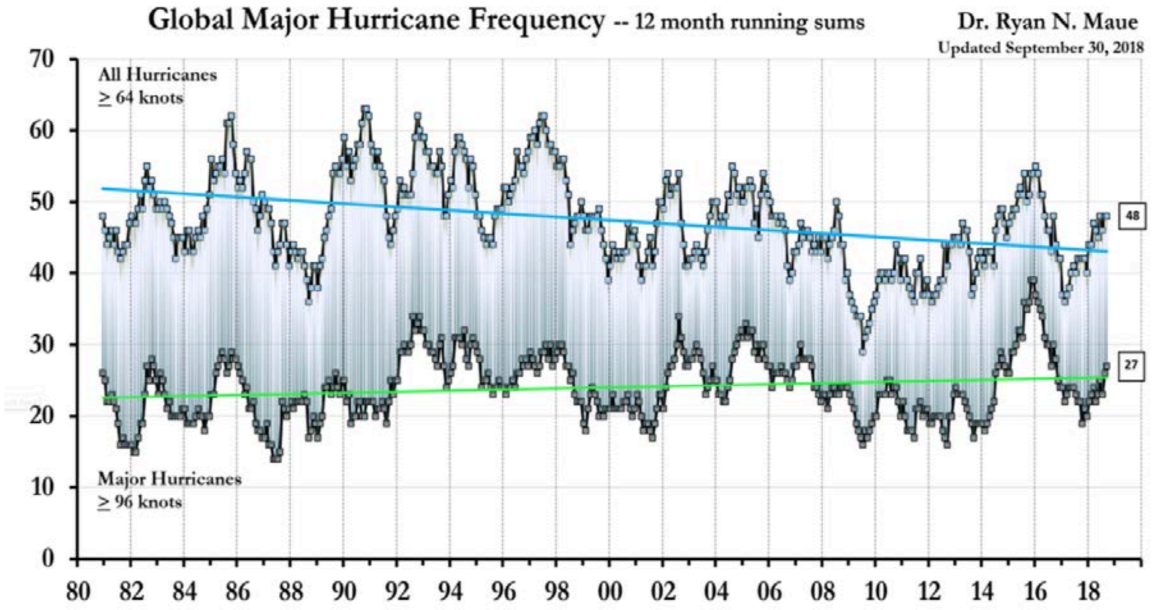


Figure 3.1: Global Hurricane Frequency (all & major) since 1981 – 12-month running means. The top time series is the number of global tropical cyclones that reached at least hurricane-force (maximum lifetime wind speed exceeds 64-knots). The bottom time series is the number of global tropical cyclones that reached major hurricane strength. Source: Maue (2018).

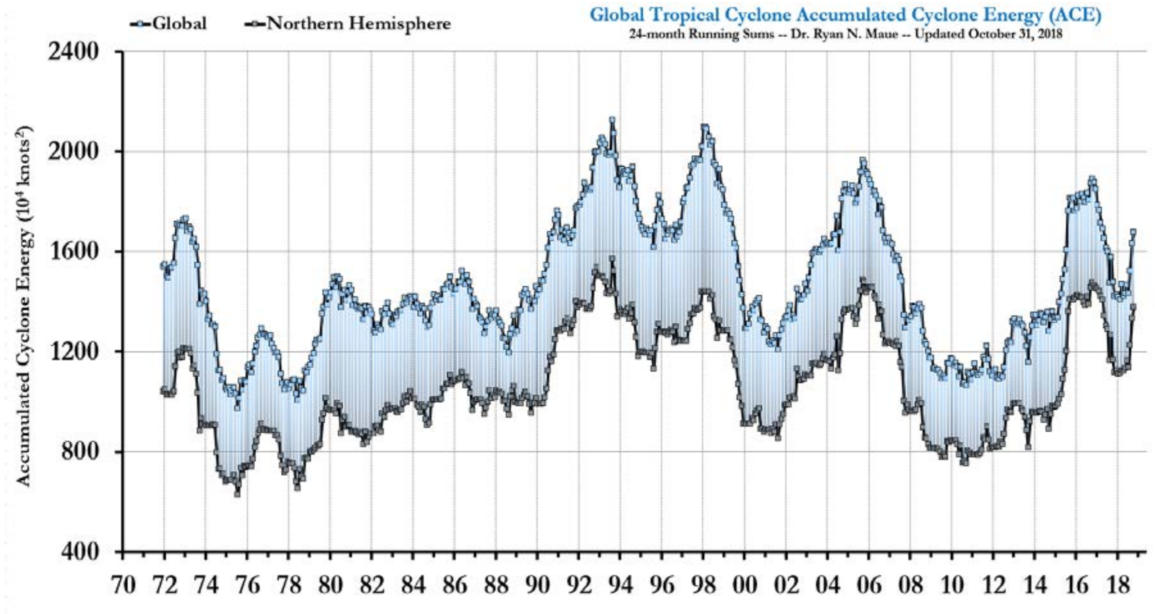


Figure 3.2: Global and Northern Hemisphere Accumulated Cyclone Energy: 24 month running means. Note that the year indicated represents the value of ACE through the previous 24-months for the Northern Hemisphere (bottom line/gray boxes) and the entire global (top line/blue boxes). The area in between represents the Southern Hemisphere total ACE. Source: Maue (2018)

3.1.1 Intensity

Figure 3.1 indicates that the number of major hurricanes shows a slight increasing trend globally, whereas the total number of hurricanes is decreasing. An increase in hurricane intensity has long been hypothesized to occur as global sea surface temperatures increase.

Emanuel (2005) identified a trend since 1950 of increasing maximum hurricane Power Dissipation Index (PDI), focusing on hurricanes in the North Atlantic and North Pacific. Shortly thereafter, Webster et al. (2005) showed that while the total number of hurricanes has not increased globally since 1970, the proportion (%) of Category 4 and 5 hurricanes had doubled, implying that the distribution of hurricane intensity has shifted towards more intense hurricanes.

Questions have been raised about the quality of the global data prior to 1988 used by Webster et al. Klotzbach and Landsea (2015) updated the Webster et al. (2005) analysis (Figure 3.3), with an additional 10 years of data and the availability of the International Best Tracks (IBTrACS) dataset, which reflects a cleaning up and homogenization of the data relative to what was used by Webster et al. Klotzbach and Landsea make a convincing argument that data prior to 1980 should not be used in trend analyses. The debate on the increase in % CAT4/5 hurricanes hinges on whether the data from 1985-1989 is of useful accuracy.

To address concerns about the validity of intensity data from the earlier periods, Kossin et al. (2013) developed a new homogeneous satellite-derived dataset of hurricane intensity for the period 1982-2009. The lifetime maximum intensity (LMI) achieved by each reported storm is calculated and the frequency distribution of LMI is tested for changes over this period. Kossin et al. found that globally, the stronger tropical cyclones have become more intense at a rate of about +1 m/s (2.2 mph) per decade during the period (Figure 3.4), but the statistical significance of this trend is marginal. Significant increases in the strongest hurricanes have occurred in the North Atlantic and decreases in the Western North Pacific, reflecting the influence of natural variability in the ocean circulations.

Summary. While an increase in hurricane intensity has long been hypothesized to occur as global sea surface temperatures increase, identification of any significant trend in the hurricane data is hampered by a short data record and substantial natural variability.

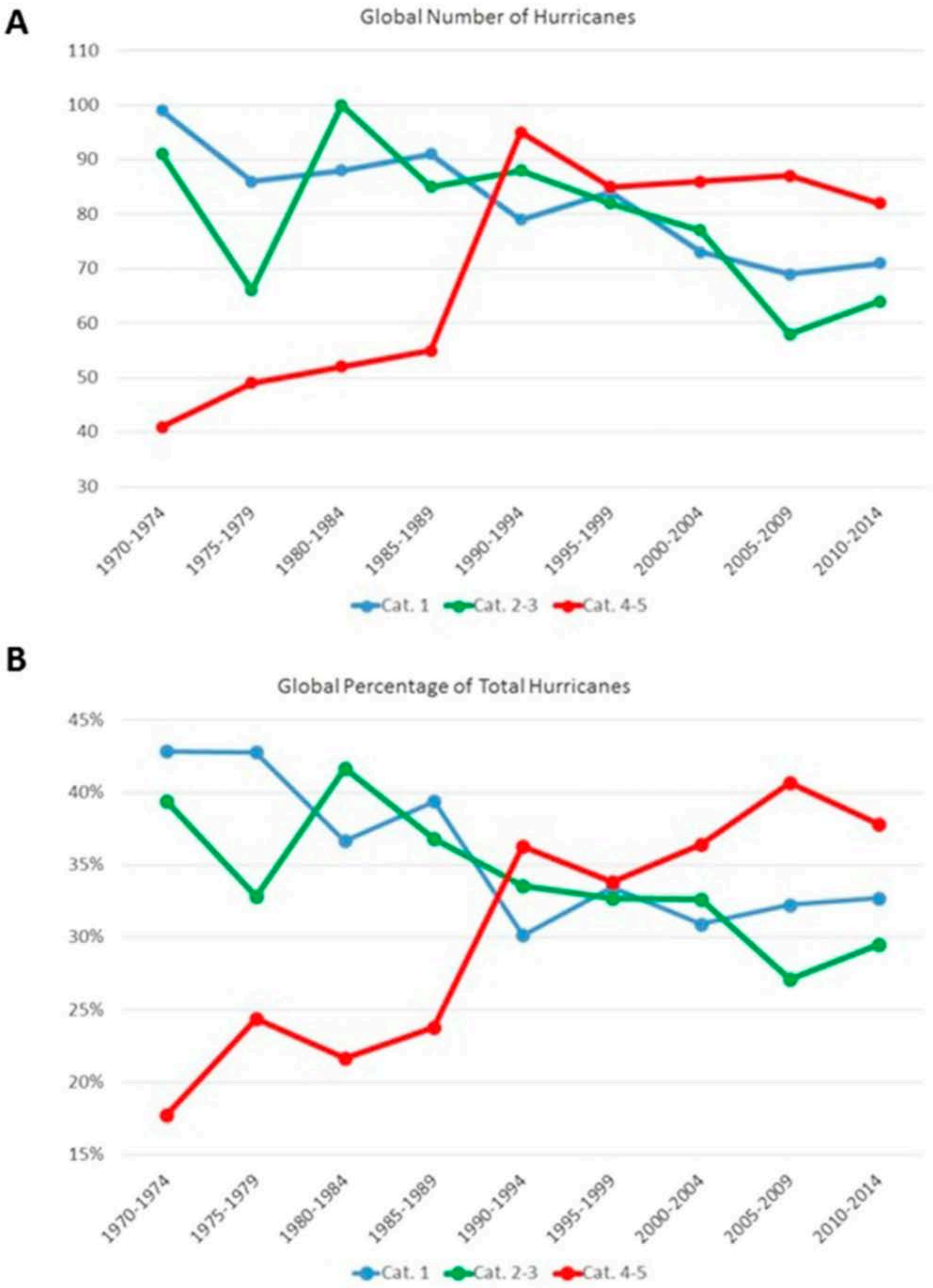


Figure 3.3. (a) Pentad total of the number of hurricanes that achieved a maximum intensity of each category grouping as delineated by the Saffir–Simpson scale. (b) As in (a), but for the percentage of total hurricanes achieving each category grouping. Klotzbach and Landsea (2015)

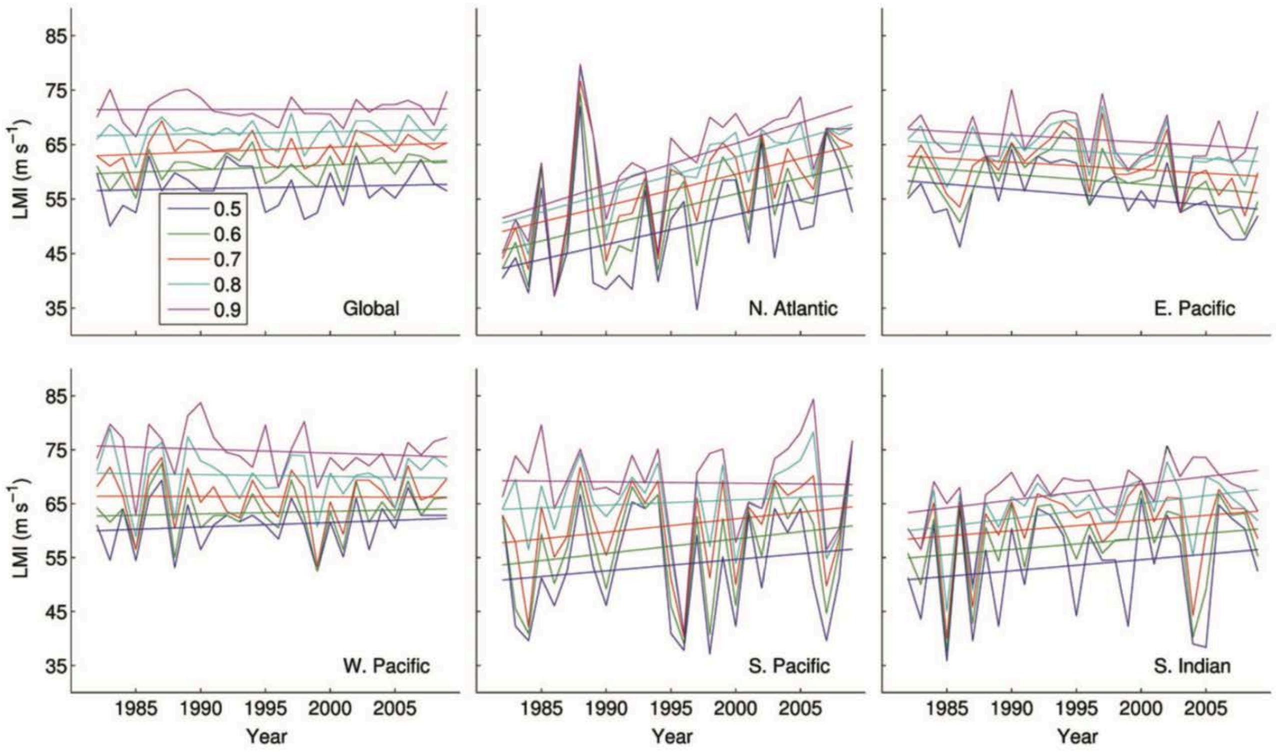


Figure 3.4. Plots of quantiles (mean to 0.9) of the lifetime maximum intensity (LMI) of storms in the various tropical cyclone formation basins, from a homogenized satellite-based analysis of tropical cyclone intensity (1982–2009). Kossin et al. (2013).

3.1.2 Intensification

Apart from the issue of maximum lifetime intensity achieved by a hurricane, the *rate* of intensification when a hurricane is developing is receiving increasing scrutiny.

A recent study showed the 95th percentile of 24-h intensity changes significantly increased in the central and eastern tropical Atlantic basin during the period 1986–2015 (Balaguru et al, 2018). The intensification rate also increased significantly between 1977 and 2013 in the West Pacific (Mei et al, 2016). In both the Atlantic and West Pacific, the areas with the largest increase in sea surface temperatures (SSTs) were collocated with the largest positive changes in intensification rates.

Bhatia et al. (2019) conducted a comprehensive analysis of global rates of hurricane intensification for the period 1982-2009 (Figure 3.5). Evaluation of the global data is hampered by intensity analysis uncertainties, although the intensity uncertainty is very low for the North Atlantic. The proportion of the highest 24-hour hurricane intensification significantly increased in the Atlantic between 1982 and 2009. Globally, a significant increase in hurricane intensification rates is seen in IBTrACS data but not in ADT-HURSAT (satellite-derived).

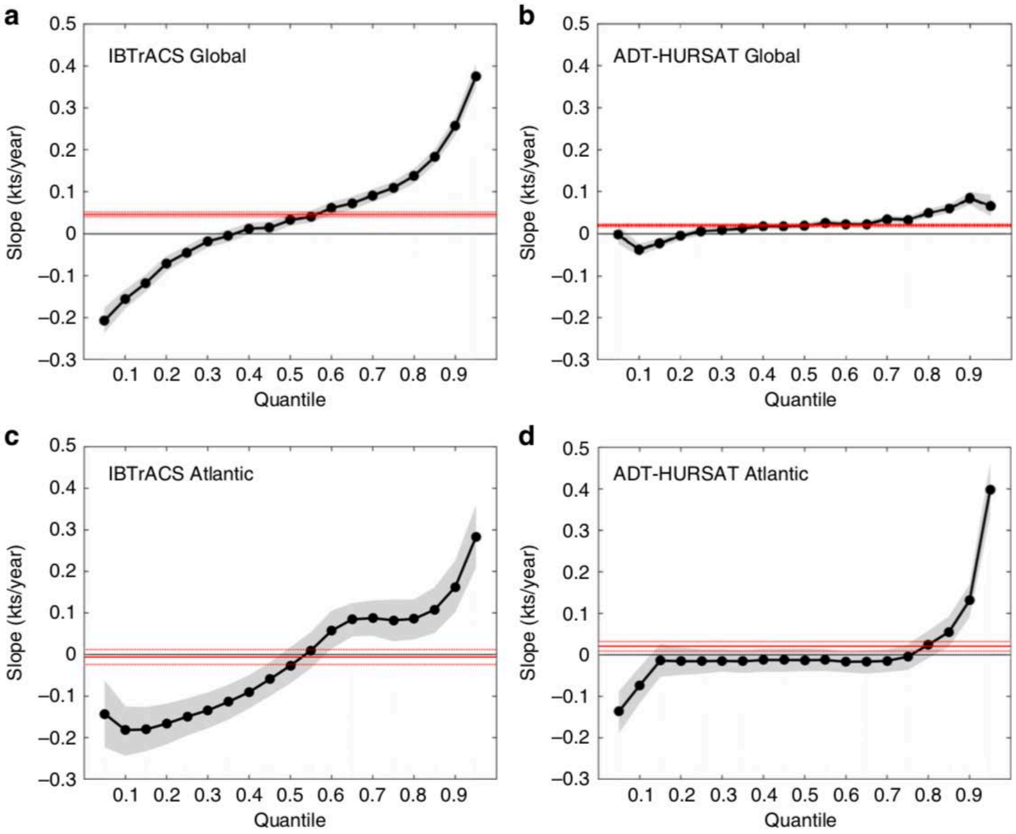


Figure 3.5 Quantile regression of 24-h intensity changes. Slope of the quantiles for 24-h intensity changes during the period 1982–2009. Slopes are shown for IBTrACS (a, c) and ADT-HURSAT (b, d) globally (a, b) and in the Atlantic basin (c, d). Source: Bhatia et al. (2019)

Summary. A positive rate of hurricane intensification has been identified in recent decades in the Atlantic. Whether this trend is associated with natural variability or warming is unknown. Global data on rates of hurricane intensification is ambiguous.

3.1.3 Tracks

Recent research has highlighted variation in the speed and location of hurricane tracks. These variations are associated with changing landfall locations and amounts of hurricane-induced rainfall.

Kossin (2018) showed that that tropical-cyclone translation speed (rate of forward motion) has decreased globally by 10% over the period 1949-2016 (Figure 3.6). The global distribution of translation speed exhibits a clear shift towards slower speeds in the second half of the period.

This slowdown is found in both the Northern and Southern Hemispheres but is stronger and more significant in the Northern Hemisphere, where the annual number of tropical cyclones is generally greater. The times series for the Southern Hemisphere exhibits a change-point around 1980 (Figure 3.6), but the reason for this is not clear. An overall slowdown while over water was found in every basin except the northern Indian Ocean. The largest slowdown was found in the western North Pacific Ocean and the region around Australia.

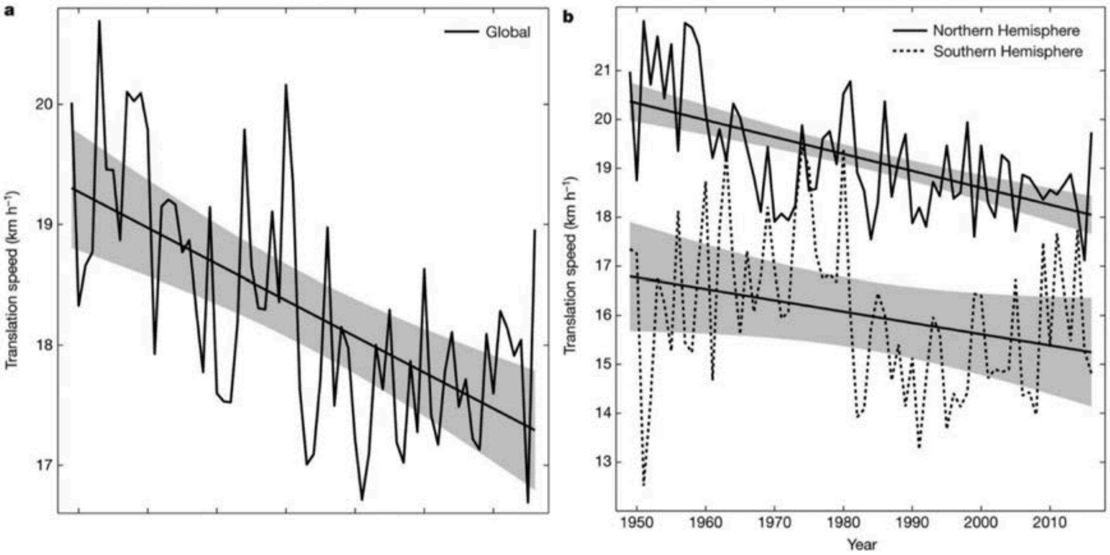


Figure 3.6 Global (a) and hemispheric (b) time series of annual-mean tropical-cyclone translation speed and their linear trends. Grey shading indicates 95 percent confidence bounds. Source: Kossin (2018).

In addition to the global slowing of hurricane translation speed, there is evidence that hurricanes have migrated poleward in several regions. Migration in the western North Pacific was found to be large, which has had a substantial effect on regional hurricane-related hazard exposure.

Kossin et al. (2014) identified a pronounced poleward migration in the average latitude where tropical cyclones have achieved their lifetime-maximum intensity (LMI) over the period 1982-2012. The poleward trends are evident in both the Northern and Southern Hemispheres, with an average migration of tropical cyclone activity away from the tropics at a rate of about 1° latitude per decade. In the Northern Hemisphere, the western North Pacific shows the largest migration, with the North Atlantic showing essentially no trend.

Moon et al. (2015) suggested that the poleward migration is greatly influenced by regional changes in hurricane frequency associated with natural multi-decadal variability of the ocean circulations. Moon et al. found 92% of the poleward trend is a result of the frequency changes associated with multi-decadal variability.

Daloz et al. (2018) examined whether the poleward migration of hurricane lifetime-maximum intensity is associated with a poleward migration of hurricane genesis (formation). They found a shift toward greater average number of genesis at higher latitudes over most regions of the Pacific Ocean, which is consistent with a migration of tropical cyclone genesis towards higher latitudes. They also found significant poleward shifts in mean genesis position over the Pacific Ocean basins.

Summary. In recent decades, the Northern Hemisphere Pacific Ocean has seen a poleward migration in hurricane track location and location of maximum intensity, and also a slowing of hurricane motion. This migration has been attributed primarily to natural variability of the ocean circulations.

3.1.4 Rainfall

Walsh et al. (2015) concluded that for the globe, a detectable change in hurricane-related rainfall has not been established by existing studies. However, satellite data is being increasingly used to assess tropical cyclone rainfall.

Kim and Ho (2018) examined the variation of hurricane rainfall area over the subtropical oceans using satellite radar precipitation data collected from 1998 to 2014. In the subtropics, higher translation speed and larger vertical wind shear significantly contribute to an increase in hurricane rainfall area by making horizontal rainfall distribution more asymmetric, while sea surface temperature rarely affects the fluctuation of hurricane rainfall area. They suggested that in the subtropics, unlike the tropics, atmospheric circulation conditions are likely more crucial to varying hurricane rainfall area than factors such as sea surface temperature.

Summary. It is hypothesized that as ocean surfaces warm, overall global rainfall will increase. The observational basis for evaluating this hypothesis in general, and specifically for hurricanes, is the global satellite data record. There have been relatively few studies to date that have investigated hurricane-induced precipitation using the satellite microwave data set that is available since 1979.

3.2 Regional summaries

Regional trends are of substantial interest in interpreting the causes of variations in tropical cyclone activity, as well as the regional impacts of hurricanes. A recent summary of the regional trends is provided by the review of Knutson et al. (2010). A detailed consideration of the North Atlantic is provided in Section 3.3.

3.2.1 Western North Pacific

There are four different best-track datasets that have been compiled for the Western North Pacific; unfortunately, they show substantial differences.

The datasets show an overall decreasing trend in tropical cyclone frequency since 1945, although the different datasets disagree regarding the magnitude and significance of the trend. All of the data sets agree on a decrease in late season hurricane frequency.

Regarding hurricane intensity, trends in Category 4 and 5 hurricanes show the greatest disparity among the different datasets, with some data sets showing an increase while others do not. Satellite based intensity datasets since 1982 show modest trends.

Despite the uncertainty in trends in basin-wide hurricanes, there is strong evidence of regional shifts, including a decreasing trend in the South China Sea and an increasing trend along the east coast of China during the past 40 years.

3.2.2 North East Pacific

Lupo et al. (2008) identified a slight decreasing trend in hurricane frequency over the period 1970 to 2007.

Walsh et al. (2016) conclude that for the northeast Pacific, no significant trends in intense hurricanes have been found.

3.2.3 North Indian Ocean

As summarized by Walsh et al. (2016), there are substantial concerns about inhomogeneity in the observation record to changes in analysis and observing methods in this region.

During the period 1961 – 2008, several studies find substantial decreasing trends in hurricane activity in the Bay of Bengal and Arabian Sea. However, several studies have identified a marked increase in the frequency of the most intense hurricanes in recent decades, although the satellite record is highly uncertain. Prior to the introduction of geostationary satellite imagery in 1998, viewing angles in the North Indian Ocean were quite oblique, making identification of hurricane intensity quite challenging.

Decadal variations in the translational speeds of hurricanes show that since 2000, the most probable speeds of hurricanes have increased over the Bay of Bengal, but have decreased over the Arabian Sea.

3.2.4 Southern Hemisphere

Kuleshov et al. (2010) analyzed a compiled Southern Hemisphere best track data archive from 1981. They found no trends either in the total numbers of hurricanes or in numbers of most intense hurricanes.

Malan et al. (2013) identified an increased occurrence of major hurricane days in the Southwest Indian Ocean since the 1990s, although total cyclone numbers decreased. In the Australian region, Kuleshov et al. found no significant trends in the total number of hurricanes, or in the proportion of the most intense hurricanes. Note that the South Indian Ocean has the same problem as the North Indian Ocean regarding the viewing angle, contributing to uncertainty in identification of hurricane intensity.

CSIRO (2015) provide a summary of the hurricanes in the Australian region since 1970. They concluded that the number of severe and non-severe hurricanes is dominated by natural variability, with periods of lower and higher frequencies of occurrence (Figure 3.7).

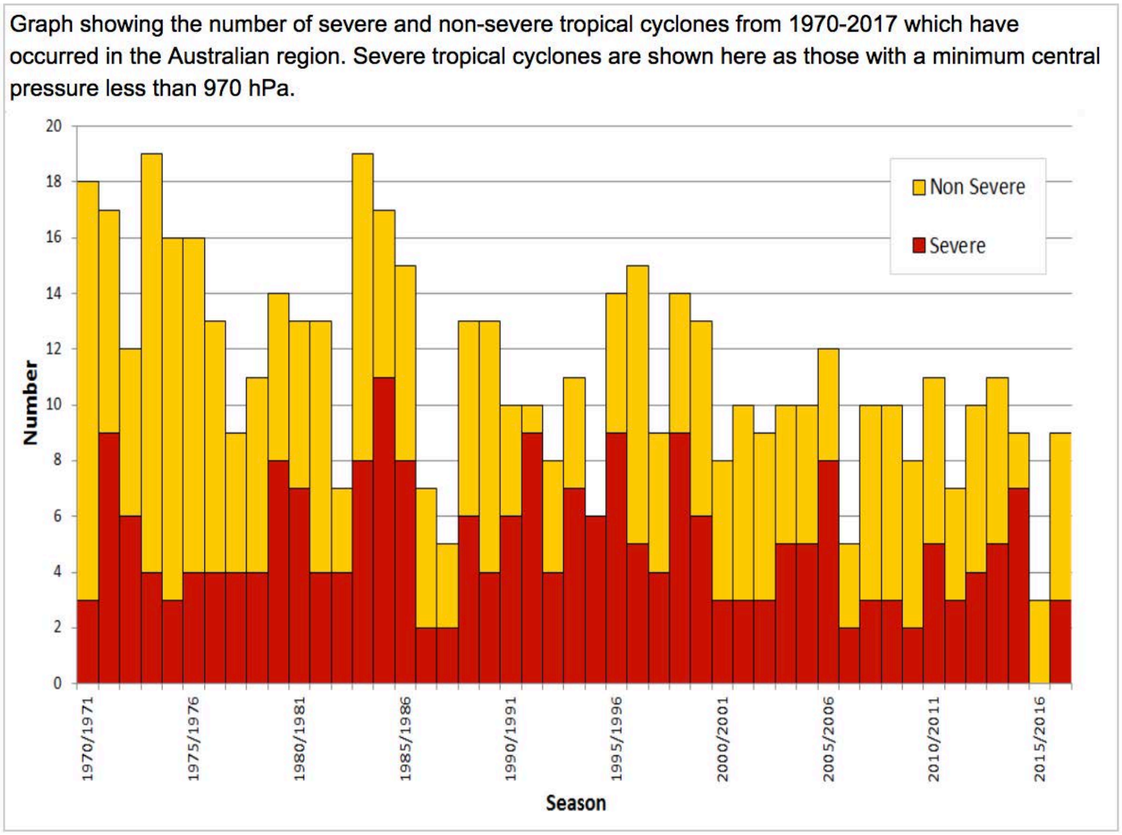

Graph showing the number of severe and non-severe tropical cyclones from 1970-2017 which have occurred in the Australian region. Severe tropical cyclones are shown here as those with a minimum central pressure less than 970 hPa.

Figure 3.7. Frequency of severe and non severe tropical cyclones from 1970-2017 in the Australian region (CSIRO, 2015).

Summary. Outside the North Atlantic, and particularly in the Southern Hemisphere, the historical data sets are fairly meager and of questionable quality, particularly with regards to intensity. There is no evidence of trends that exceeds natural variability.

3.3 North Atlantic

The North Atlantic has the best data quality of any of the regions. There is credible data on frequency and intensity since 1850, with the intensity data being most reliable since 1944, when aircraft reconnaissance flights began. Prior to the onset of satellite coverage in 1966, NOAA has adjusted total basin-wide counts upward based on historical records of ship track density. During years when fewer ships were making observations in a given region, hurricanes in that region were more likely to have been missed, or their intensity underestimated to be below hurricane strength, leading to a larger corresponding adjustment to the count for those years. These adjustment methods are described in Knutson et al. (2010).

The impact of undercounting is illustrated in Figure 3.8, which compares the raw hurricane counts (green) with adjusted counts (orange) for the period 1878-2015. The sign of the long-term trend depends critically on the adjustment.

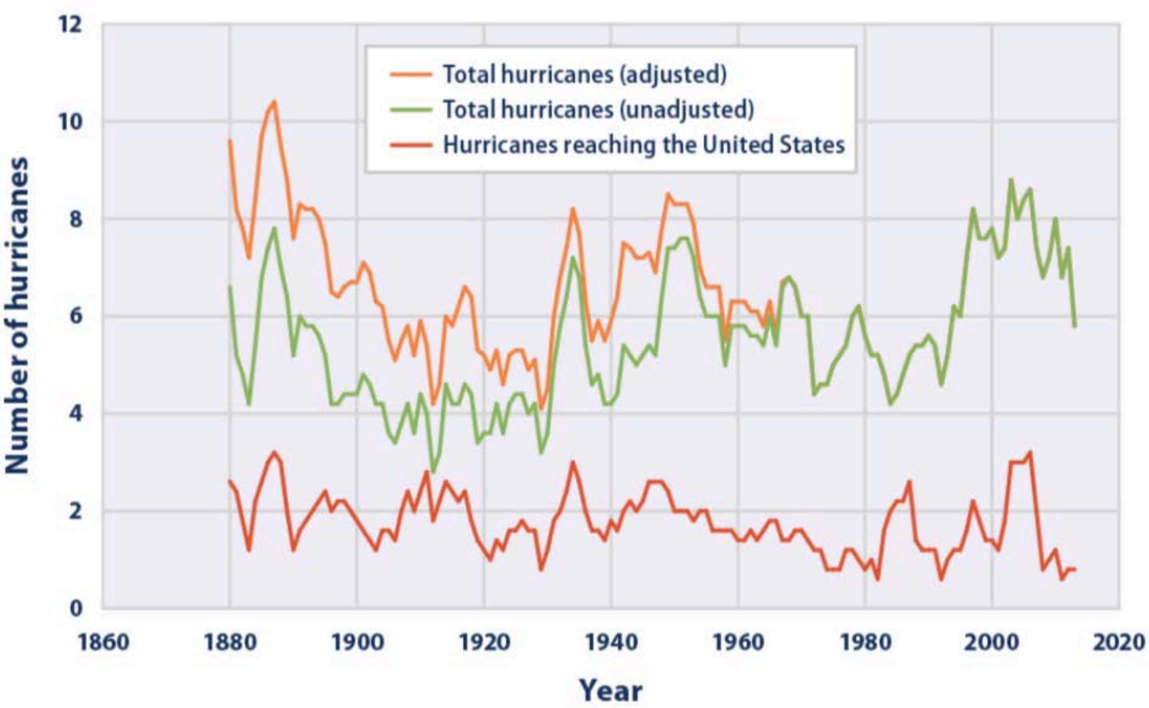


Figure 3.8. Time series for the period 1878-2015 of the total number North Atlantic hurricanes – unadjusted (green); adjusted (orange). The number of U.S. landfalling hurricanes is in red. Curves have been smoothed using a five-year average, plotted at the middle year. Source: https://www.epa.gov/climate-indicators/climate-change-indicators-tropical-cyclone-activity

Figure 3.9 shows the yearly values for the adjusted time series since 1850, for total North Atlantic hurricane counts and major hurricane counts. While the number of major hurricanes prior to 1944 is probably undercounted, it is noteworthy that the number of major hurricanes during the 1950's and 1960's was at least as large as the last two decades.

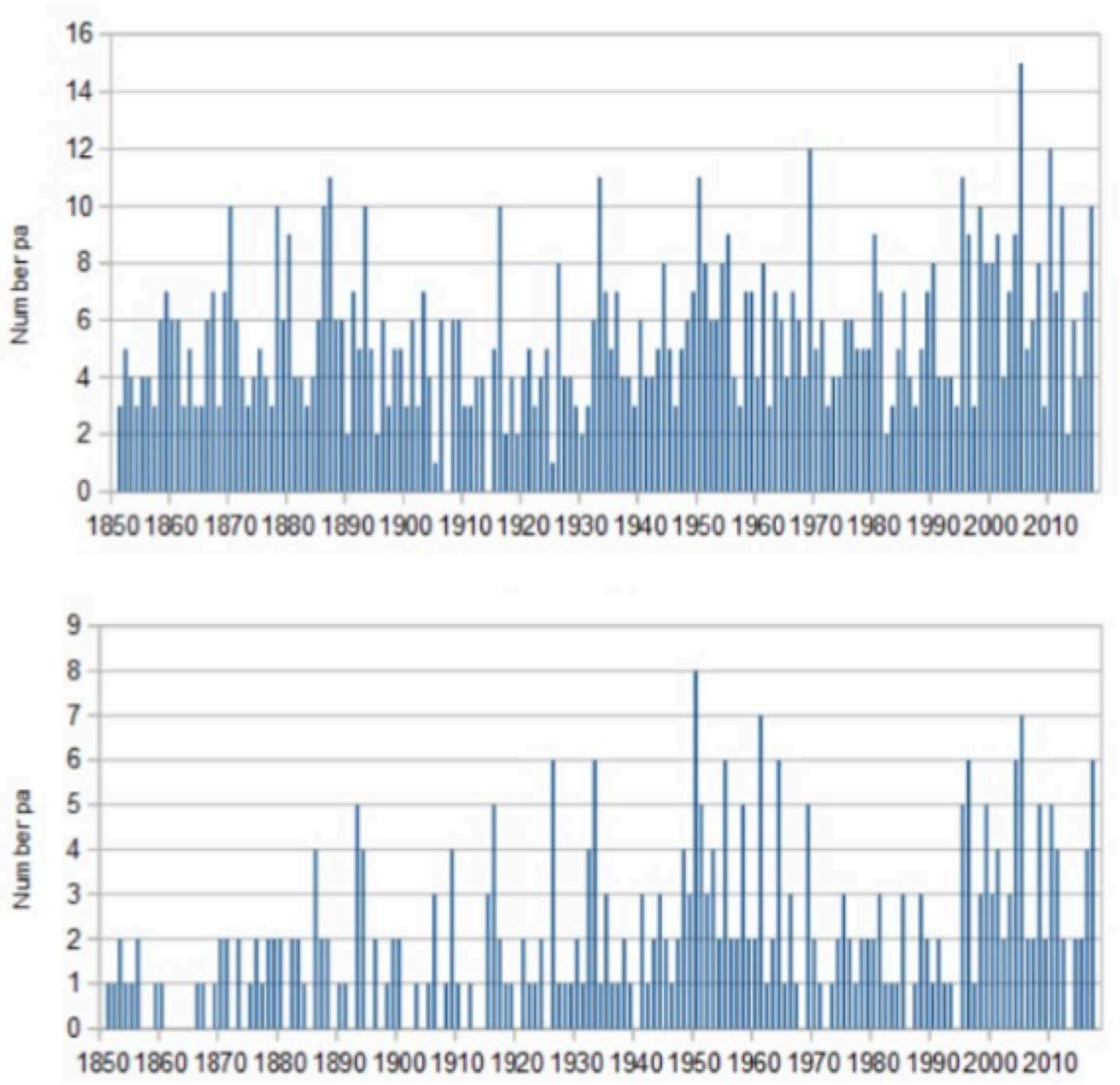


Figure 3.9 Adjusted numbers of total Atlantic hurricanes (top) and major hurricanes (bottom). Source: http://www.aoml.noaa.gov/hrd/hurdat/comparison_table.html

Accumulated Cyclone Energy (ACE) (Figure 3.10) and Power Dissipation Index (PDI) (Figure 3.11) provide integral measures of overall hurricane activity, with PDI providing greater weight to intensity. Values of ACE during the 1950's and 1960's are comparable to recent decades. Regarding PDI, the years 1926, 1934 and 1962 have PDI values as large as seen in 2004, 2005 and 2017, although prior to 1944 intensity data is less reliable.

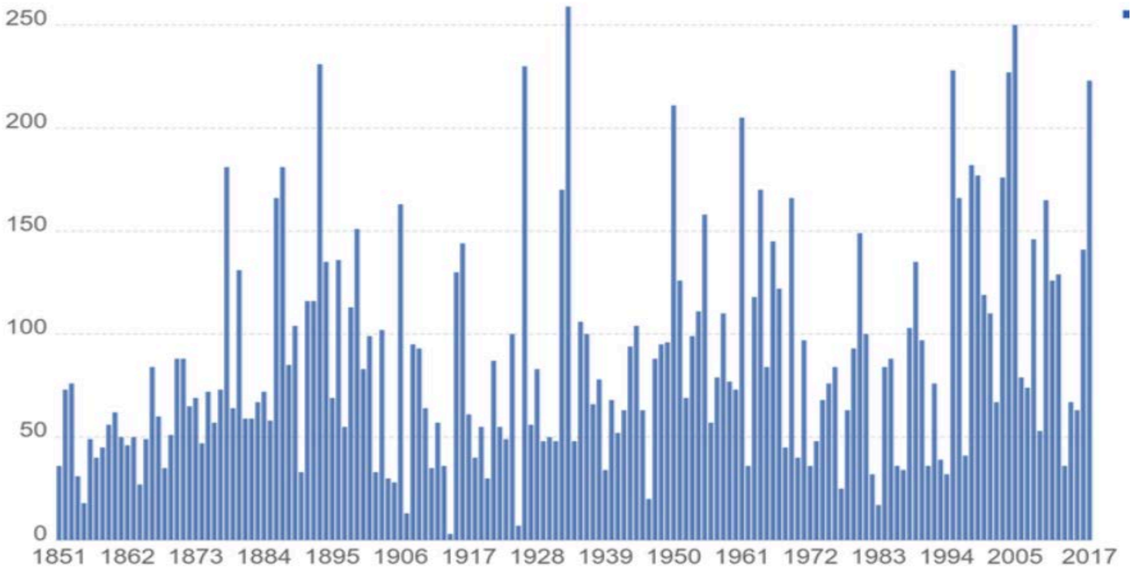


Figure 3.10 Accumulated Cyclone Energy Index for the Atlantic Ocean. Source: http://www.aoml.noaa.gov/hrd/hurdat/comparison_table.html. Ourworldindata.org

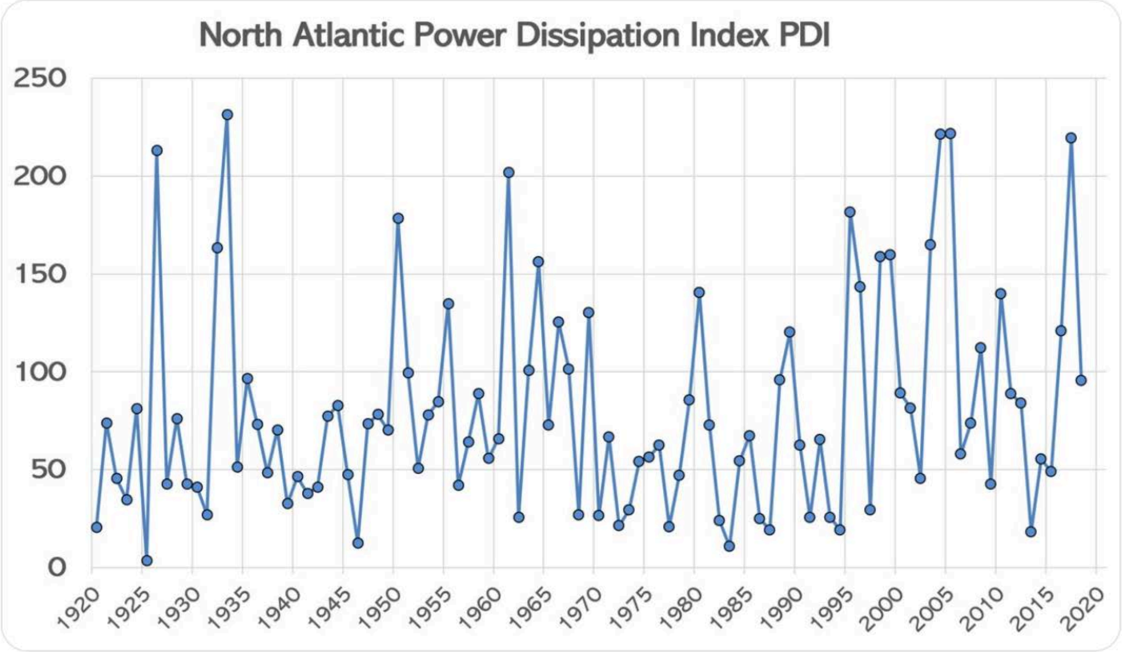


Figure 3.11 Power Dissipation Index (PDI) for the North Atlantic From 1920-2018. Source: Ryan Maue.

Summary. All measures of Atlantic hurricane activity show a significant increase since 1970. However, high values of hurricane activity (comparable to the past two decades) were also observed during the 1950's and 1960's, and by some measures also in the late 1920's and 1930's.

3.4 Paleotempestology

Hurricane data records for the past 40 years, or even the past 150 years, can present a misleading picture of range of variability of hurricane characteristics. Paleotempestology is the study of storm occurrence prior to the historical record, providing a way of establishing a longer climate baseline than the relatively short observational record.

Many types of geological proxies have been tested for reconstructing past hurricane activity, including hurricane-induced deposits of sediments in coastal lakes and marshes, stalagmites in caves, tree rings and corals. Since these studies typically focus on a specific geographic location, a caveat is that they cannot distinguish between regional trends and systematic changes in hurricane tracks.

In the Australian region, Haig et al. (2014) used stalagmite records to show that the present low levels of storm activity on the mid west and northeast coasts of Australia are unprecedented over the past 1,500 years. Their results reveal a multicentennial cycle of tropical cyclone activity, the most recent of which commenced around 1700. The present cycle includes a sharp decrease in activity after 1960 in Western Australia.

Nyberg et al. (2007) constructed a record of the frequency of major Atlantic hurricanes over the past 270 years using proxy records in the Caribbean from corals and a marine sediment core. The record indicates that the average frequency of major hurricanes decreased gradually from the 1760s until the early 1990s, reaching anomalously low values during the 1970s and 1980s.

Wallace et al. (2015) review paleo-trends in hurricane activity from sedimentary archives in the Gulf of Mexico, Caribbean and western North Atlantic margins. A site from Mattapoisett Marsh, Massachusetts shows that the total hurricane deposits remained relatively constant between 2200 and 1000 years B.P. (before present). However, the last 800 years B.P. appear to have been a time of relatively frequent total storm deposition. A site from Laguna Playa Grande, Puerto Rico has reconstructed intense hurricanes occurring over the past 5000 years B.P., with prominent increases in activity observed during 4400 - 3600, 2500 - 1000, and 250 – 0 years B.P. In the Gulf of Mexico, while the overall frequency of events remained relatively constant over the 4500 year record, the frequency of high threshold events has varied considerably – periods of frequent intense hurricane strikes occurred during 3950 - 3650, 3600 - 3500, 3350 - 3250, 2800 - 2300, 1250 - 1150, 925 -875, and 750 - 650 years B.P.

In the Big Bend region of Florida, Brandon et al. (2013) found a period of increased intense hurricane frequency between ~1700 and ~600 years B.P. and decreased intense storm frequency from ~2500 to ~1700 and ~600 years B.P. to the present.

Summary. There has not been a timeline or synthesis of the Atlantic hurricane paleotempestology results for the past five thousand years, either regionally or for the entire coastal region. However, it is clear from these analyses that significant variability of landfall probabilities occurs on century to millennial time scales. There appears to have been a broad hyperactive period from 3400 to 1000 years B.P. High activity persisted in the

Gulf of Mexico until 1400 AD, with a shift to more frequent severe hurricane strikes from the Bahamas to New England occurring between 1400 and 1675 AD. Since 1760, there was a gradual decline in activity until the 1990's.

3.5 Conclusions

Analyses of both global and regional variability and trends of hurricane activity provide the basis for detecting changes and understanding their causes.

The relatively short historical record of hurricane activity, and the even shorter record from the satellite era, is not sufficient to assess whether recent hurricane activity is unusual for the current interglacial period. Results from paleotempestology analyses in the North Atlantic at a limited number of locations indicate that the current heightened activity is not unusual, with a hyperactive period apparently occurring from 3400 to 1000 years before present.

Global hurricane activity since 1970 shows no significant trends in overall frequency. There is some evidence of increasing numbers of major hurricanes and of an increase in the percentage of Category 4 and 5 hurricanes, although the quality of intensity data in some regions prior to 1988 is disputed.

In the North Atlantic, all measures of hurricane activity have increased since 1970, although comparably high levels of activities also occurred during the 1950's and 1960's.

4. Detection and attribution of changes in hurricane activity

If oceans are getting warmer as a result of climate change, so the argument goes, surely hurricane activity must increase as a result, particularly hurricane intensity. However, most of the assessment reports cited in Chapter 1 have low confidence in attributing any recent changes in hurricane activity to manmade global warming.

What is the scientific basis for assessing whether or not manmade warming is causing a change in hurricane activity?

Detection and attribution of manmade signals in in the climate system is a new and rapidly developing field. Attributing an observed change or an event partly to a causal factor (such as manmade climate forcing) normally requires that the change first be detected. A *detected* change is one that is determined, based on observations to be very unlikely to occur (less than about a 10% chance) due to natural internal variability alone. An *attributable* change implies that the relative contribution of causal factors has been evaluated, along with an assignment of statistical confidence.

There are some situations whereby attribution without detection statements can be appropriate, although lower confidence is assigned when attribution is not supported by a detected change. For example, a trend analysis for an extremely rare event may not be meaningful. Including attribution without detection in the analysis of climate change impacts reduces the chance of a false negative – incorrectly concluding that climate change had no influence on a given extreme events. However, attribution without detection comes at the risk of increasing the rate of false positives – incorrectly concluding that manmade climate change had an influence when in fact it did not.

The conceptual framework for most detection and attribution analyses consists of four elements:

1) time history of relevant observations
2) the estimated time history of relevant climate forcings (such as greenhouse gas concentrations or volcanic activity)
3) an estimate of the impact of the climate forcings on the climate variables of interest
4) an estimate of the internal (unforced) variability of the climate variables of interest – e.g. natural unforced variations of the ocean, atmosphere, land, cryosphere, in the absence of external forcings.

Paleoclimate proxies from the geological record are useful for detection studies in providing a baseline against which to compare recent variability of the past century or so. *Time of emergence* is the time scale on which climate change signals will become detectable in various regions – an important issue, since natural variability can obscure forced climate signals for decades, particularly on regional scales.

4.1 Detection

There are three main challenges to detecting a signal of changed hurricane activity:

1) very long timescales in the oceans, resulting in substantial lag time between external forcing and the realization of climate change and its impacts
2) high-amplitude natural internal variability of ocean circulations ocean basins on time scales from the interannual to the millennial
3) strong regional variations, both in ocean circulation patterns and hurricane activity.

Based on the observations summarized in Chapter 3, the following summary is provided regarding the detection of changes in global or regional hurricane activity:

- *global hurricane activity*: small but insignificant trends of decreasing hurricane frequency and increasing number of major hurricanes;
- *global % of Category 4/5 hurricanes*: increasing trend since 1970, although the data quality for the period before 1988 is disputed.
- *rate of intensification*: hints of a global increase, although data sets disagree.
- *track migration*: poleward migration of the average latitude where hurricanes have achieved their lifetime-maximum intensity for 1982-2012.
- *Atlantic hurricanes*: increasing trends since 1970, but comparable activity was observed in the 1950's-1960's.
- *hurricanes in other regions*: observational record is too short, but no evidence of trends that exceed natural variability

Summary. The observational database (since 1970 or even 1850) is too short to assess the full impact of natural internal variability associated with large-scale ocean circulations.

Paleotempestology analyses indicate that recent hurricane activity is not unusual. Given the limited data record and its quality, there is no evidence of any changes in global or regional hurricane activity that exceeds natural variability.

4.2 Sources of variability and change

In the absence of detecting any significant change in global or regional hurricane activity, attribution methods without detection statements must be used. These methods require assessing the contributions to climate variability/change from external forcing (e.g. CO_2, volcanoes, solar) plus natural internal variability associated with the large-scale ocean circulations. In two-step attribution methods, changes in intermediate variables (such as sea surface temperature, wind shear, atmospheric humidity) are useful in identifying physical mechanisms whereby warming might contribute to a change in hurricane activity.

The focus in this section is on identifying sources of variability and change during the period since 1850, when historical data is available.

Many of the arguments surrounding an increase in hurricane activity are associated with increases in global sea surface temperature. Figure 4.1 shows the variability of globally-averaged sea surface temperature (SST) since 1850, along with external forcing from CO_2, volcanoes and the sun.

It is seen from Figure 4.1a that global mean sea surface temperature (SST) reached a global low point in 1910, and then increased rapidly until about 1945. The elevated Atlantic hurricane activity in the 1930's-1950's (Section 3.3) occurred when the global SSTs were ~0.8^{o}C cooler than present global average SSTs. This warming period was followed by a period of slight cooling until 1976, after which temperatures began increasing.

The global ocean warming during the period 35-year period from 1910 to 1945 of 0.6^{o}C was comparable to the 0.7^{o}C warming observed between the 42-year period between 1976 and 2018.

Regarding the recent warming, the IPCC AR5 made the following attribution statement:

> "It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. The best estimate of the human- induced contribution to warming is similar to the observed warming over this period."

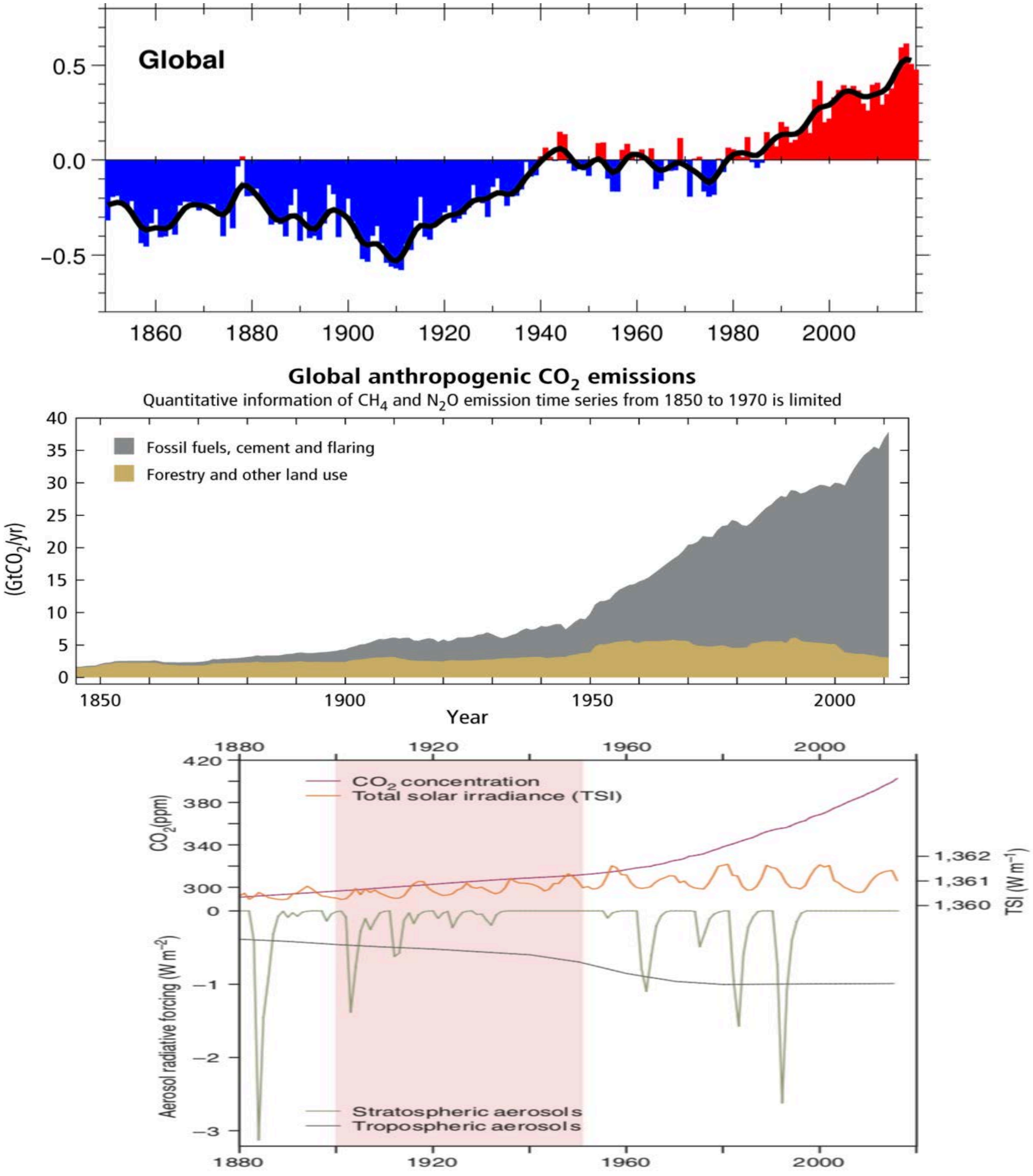


Figure 4.1 (top) Ocean surface temperature anomalies (°C) From HadSST. (middle) Human-caused carbon dioxide emissions Source: IPCC AR5. (bottom) Annual mean time series of climate forcing agents: atmospheric CO_2 concentration, stratospheric aerosols (volcanic eruptions), total solar irradiance, and tropospheric aerosols Source: Hegerl et al. (2018)

In other words, the IPCC AR5 best estimate is that *all* of the warming since 1951 has been caused by humans.

So, what caused the early 20th century global warming? This issue has received remarkably little attention from climate scientists. Lack of an explanation for the early 20th century global warming diminishes the credibility of the IPCC's attribution statement for warming since 1951.

The first substantive attribution analysis of the early 20th century warming was made in a recent paper by Hegerl et al. (2018), which came to the following conclusion:

> "Attribution studies estimate that about a half (40–54%) of the global warming from 1901 to 1950 was forced by a combination of increasing greenhouse gases and natural forcing, offset to some extent by aerosols. Natural variability also made a large contribution. The exact contribution of each factor to large-scale warming remains uncertain."

Hegerl et al. (2018) provides a summary of forcing from CO_2, volcanoes and solar (Figure 4.1). In 1910, the atmospheric CO_2 concentration is estimated to be 300.1 ppm; in 1950 it was 311.3 ppm; and in 2018 it is 408 ppm. So, the warming during the period 1910-1945 was associated with a CO_2 increase of 10 ppm, whereas a comparable amount of warming during the period 1950 to 2018 was associated with a 97 ppm increase in atmospheric CO_2 concentration - almost an order of magnitude greater CO_2 increase for a comparable amount of global ocean warming.

Clearly, there were other factors in play besides CO_2 emissions in the early 20th century global warming (Figure 4.1b). A period of relatively low volcanic activity during the period 1920-1960 would have a relative warming effect, although the period from 1945 to 1960 was a period of slight overall cooling. Solar forcing in the early 20th century is uncertain, with estimates of warming of varying magnitude, although the magnitudes are insufficient for solar to have been a major direct contributor to the early 20th century global warming.

Hegerl et al. (2018) analyzed the internal variability associated with ocean circulations during the period since 1900. They found that the unusual cold anomaly circa 1910 (Figure 4.1a) originated in the South Atlantic, and then spread globally in the subsequent decade, leading to cold anomalies in both Atlantic and Pacific.

This rarely-discussed cold period circa 1910 was followed by strong warming in the Northern Hemisphere, which was particularly pronounced in high latitudes. The Atlantic Multi-decadal Oscillation (AMO) is a coherent mode of natural variability of sea surface temperatures (SST) occurring in the North Atlantic Ocean, with an estimated period of 60-80 years. The Pacific Decadal Oscillation (PDO) is a recurring pattern of ocean-atmosphere climate variability of surface temperature centered over the northern hemisphere mid-latitude Pacific basin. Warm phases of the both the AMO and PDO contributed to warming particularly during the 1930's and 1940's.

Summary. With regards to the observed global warming of the oceans, it is clear that manmade contributions to atmospheric CO_2 do not provide a complete explanation of this warming. Solar variations, volcanic eruptions and the large-scale ocean circulation patterns also have a substantial influence on temperature variations in the global oceans.

4.3 Natural multi-decadal climate modes

Internal modes of climate variability are associated with regional-to-basin-scale oceanic circulation systems that define the dynamical memory of the climate system in the presence of fast, large-scale atmospheric processes. The faster atmospheric processes not only supply energy for the multi-decadal variability, but also provide the means for communication between the different ocean basins and synchronization of the multi-decadal climate modes (e.g. Wyatt and Curry, 2013; Kravtsov et al. 2018).

Multi-decadal modes (timescales of 30 to 80 years) are of the greatest relevance in attribution analyses of 20th and early 21st century climate change. Hurricane activity is also influenced by multidecadal variability in ways that do not directly rely on local changes in sea surface temperatures – such as changes in atmospheric circulation patterns and wind shear.

4.3.1 Atlantic modes and hurricane activity

Three modes of interannual to multi-decadal variability have been identified in the Atlantic: Atlantic Multidecadal Oscillation (AMO); North Atlantic Oscillation (NAO); and Atlantic Meridional Mode (AMM).

The most thoroughly studied of these modes with respect to Atlantic hurricanes is the AMO. The Atlantic Multidecadal Oscillation (AMO) is associated with basin-wide SST and sea level pressure (SLP) fluctuations. The positive (warm) AMO phase is associated with a pattern of horseshoe-shaped SST anomalies in the North Atlantic Figure 4.3), with pronounced warming in the tropical and parts of the eastern subtropical North Atlantic, an anomalously cool area off the U.S. East Coast, and warm anomalies surrounding the southern tip of Greenland.

The traditional AMO index (Figure 4.4) is calculated from the patterns of SST variability in the North Atlantic, once a linear trend has been removed. However, since the trend is significantly non-linear in time (Figure 4.1a), detrending aliases the AMO index. The nonlinearity is particularly pronounced during the period 1945-1975, when global sea surface temperatures showed a slight cooling trend.

To avoid the problems associated with detrending, Johnstone (2017) developed an Arc Index version of the AMO Index, which is the average SST in the Arc region (Figure 4.3). The Arc Index (Figure 4.5) shows abrupt shifts to the warm phase in 1926 and 1995, consistent with the conventional AMO analysis in Figure 4.5. Johnstone's analysis indicates a shift to the cold phase in 1971, which differs from the analysis shown in Figure 4.5 that indicates the shift to the cold phase in 1964. The revised AMO index of Klotzbach and Gray (2008) indicates a shift to the cold phase in 1970, consistent with the analysis of Johnstone.

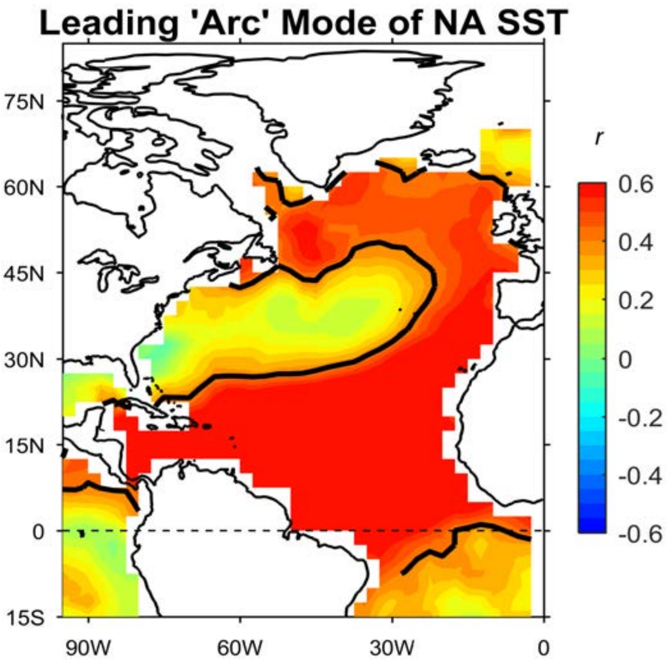


Figure 4.3 Horseshoe pattern of the AMO, where the ‘Arc’ Index corresponds to the average sea surface temperatures inside the black contours. Source: Johnstone (2017)

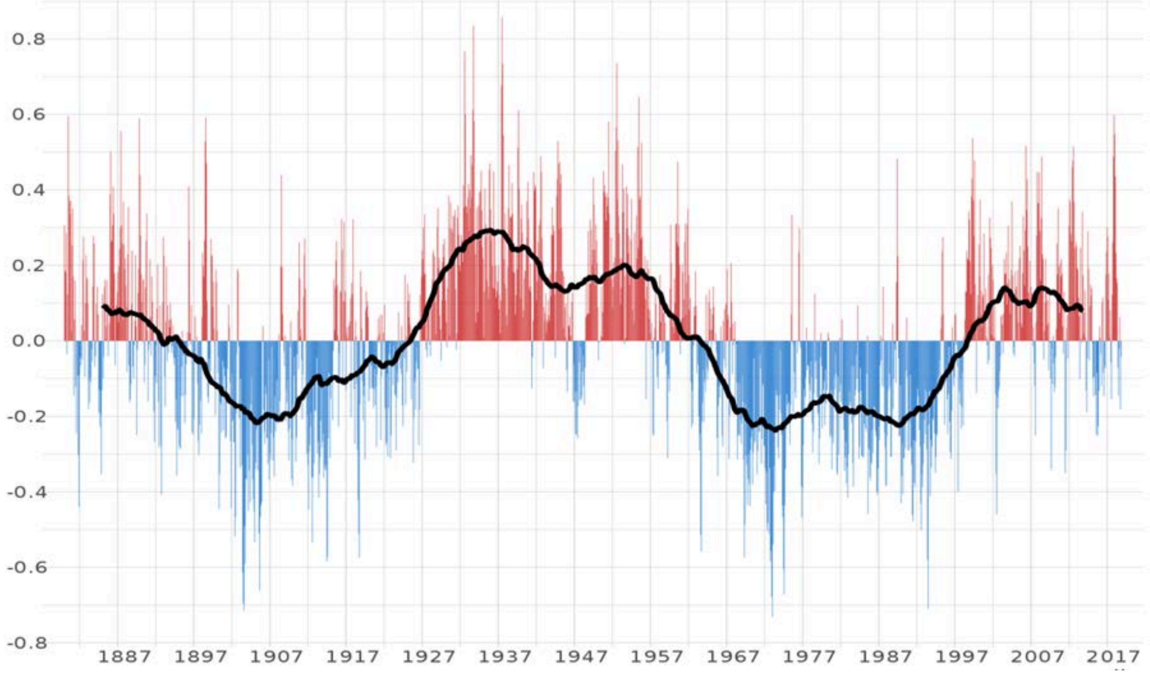


Figure 4.4. The Atlantic Multidecadal Oscillation (AMO) index showing positive (red) and negative (blue) phases. Source: https://commons.wikimedia.org/wiki/File:Atlantic_Multidecadal_Oscillation.svg

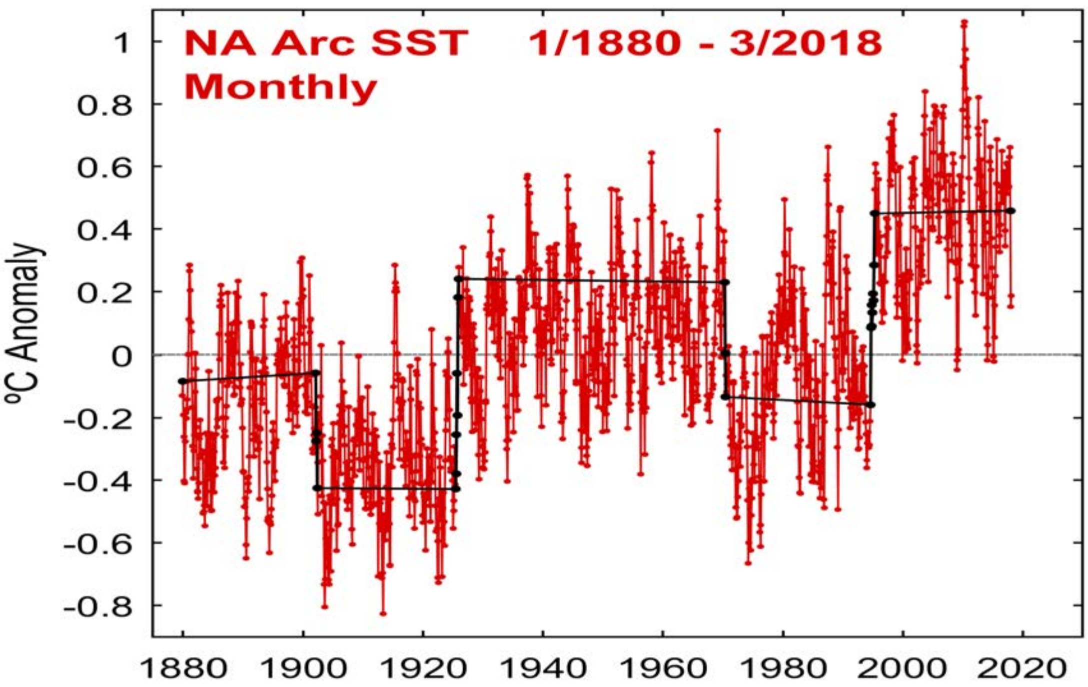


Figure 4.5 Arc Index version of the AMO. Source: updated from Johnstone (2017)

The main hurricane-relevant variables that change with the phase changes of the AMO, AMM and NAO are spatial patterns of SST (or oceanic heat content) and wind patterns. Hurricane genesis (formation) locations, tracks and intensification are temporally and spatially modulated by these large-scale climate modes.

Atlantic hurricanes show strong variations on decadal and multi-decadal time scales in the observed record (Figures 3.6 – 3.8). The greatest impact of the AMO is on the number of major hurricanes (Category 3+) and Accumulated Cyclone Energy, shown in Figure 4.6. The shift to the relatively inactive phase occurred around 1970/1971, in accord with the AMO analyses of Johnstone (2017) and Klotzbach and Gray (2008), with the late 1960's still characterized by a larger number of major hurricanes and high ACE values. The relationship of the AMO to major hurricane activity in the Atlantic was identified by Goldenberg et al. (2001) to be associated with above normal SSTs and decreased vertical shear associated with the warm AMO.

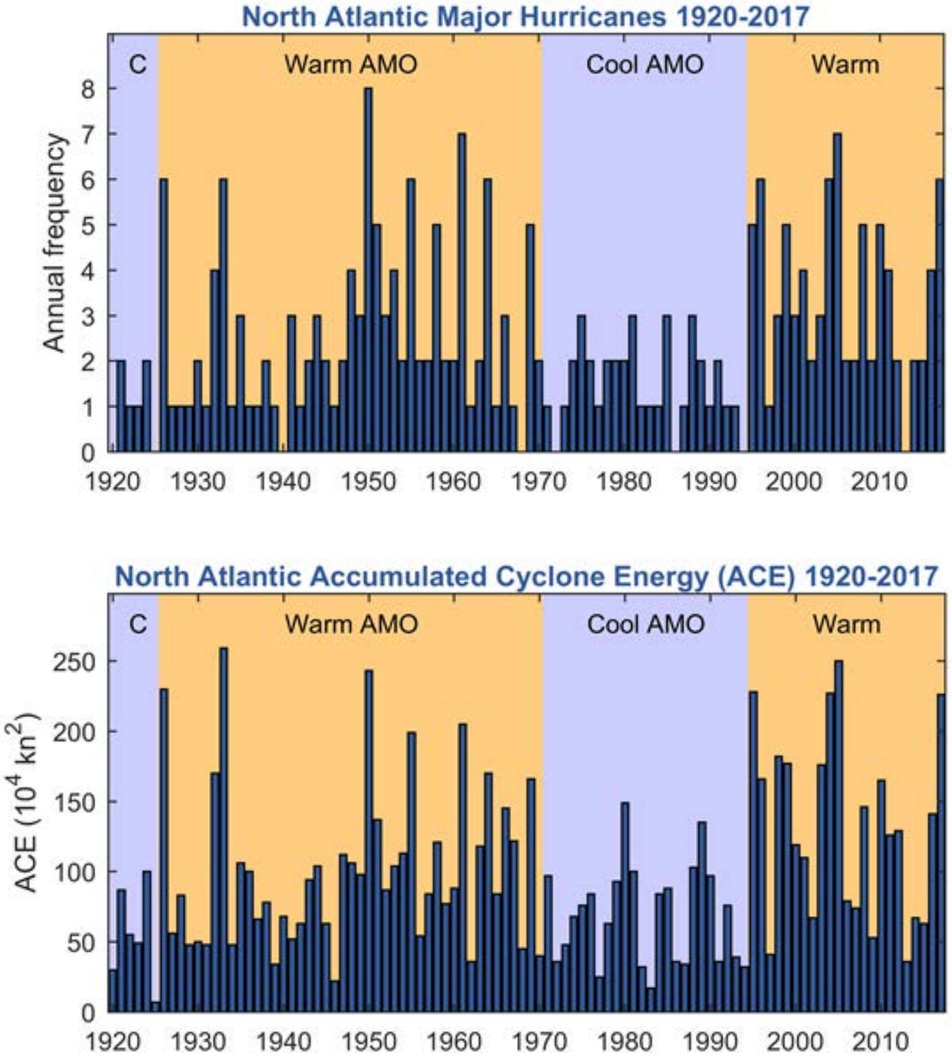


Figure 4.6 Observations of Atlantic hurricane activity since 1920. The warm phase of the Atlantic Multidecadal Oscillation is indicated by orange shading, with the cool phase indicated by purple shading. Top: Annual frequency of major hurricanes. Bottom: Annual frequency of Accumulated Cyclone Energy (ACE). Curry (2018c)

Bell and Chelliah (2006) related the interannual and multidecadal variability of hurricane activity in the Atlantic to two tropical multidecadal modes in the Atlantic. Comparing periods of high activity in the Atlantic, they showed that the most recent increase in hurricane activity is related to the exceptionally warm SSTs in the Atlantic, while the high activity period in the 1950s and 1960s was more closely associated with the West African monsoon.

Lin et al. (2019) argue that there are two regimes of the AMO, which appear to be consistent with the analysis of Bell and Chelliah. Lin et al. identify two separate AMO regimes: a 10-30 year regime (intrinsic to the Atlantic), and a 50-80 year regime (which is influenced by variability in the Pacific and the Greenland-Iceland-Norwegian Seas).

Vimont and Kossin (2007) related Atlantic hurricane activity to the Atlantic Meridional Mode (AMM). Hurricane genesis locations, SST and wind shear anomalies are influenced by the different phases of the AMM. During the positive AMM phase (above normal SSTs in the North Atlantic), there is an overall increase of hurricane activity in the Atlantic, with the mean genesis (formation) location shifting eastward and toward the equator. Also associated with a positive AMM is an increase in storm duration and the frequency of intense hurricanes (Kossin and Vimont 2007).

Grossman and Klotzbach (2009) provide the following summary of the relationships among the three Atlantic modes. The cross-equatorial pattern associated with the AMM and wind patterns associated with the AMO can be viewed as one overall phenomenon that stretches from the high latitudes to the tropics. The AMO and AMM are also closely related to the NAO on multidecadal time scales. Long-term positive (negative) phases of the NAO coincide with the negative (positive) phase of the AMO and AMM, generally with a lag of several years. The NAO depends on the North Atlantic meridional temperature and pressure gradient, which in turn lessens (increases) as the North Atlantic warms (cools) with the positive (negative) AMO.

Summary. Atlantic hurricane processes are influenced substantially by the natural modes of ocean circulation variability in the Atlantic, notably the Atlantic Multidecadal Oscillation and the Atlantic Meridional Mode.

4.3.2 Pacific modes and hurricane activity

The El Niño – Southern Oscillation (ENSO) is a major mode of natural climate variability. ENSO is associated with sea surface temperature (SST) changes in the tropical Pacific, which is associated with shifts in the seasonal temperature, circulation, and precipitation patterns in many parts of the world. El Niño and La Niña (warm and cold) events usually recur every 3 to 7 years and tend to last for approximately a year. ENSO has a strong impact on hurricanes, both in the Pacific and Atlantic Oceans.

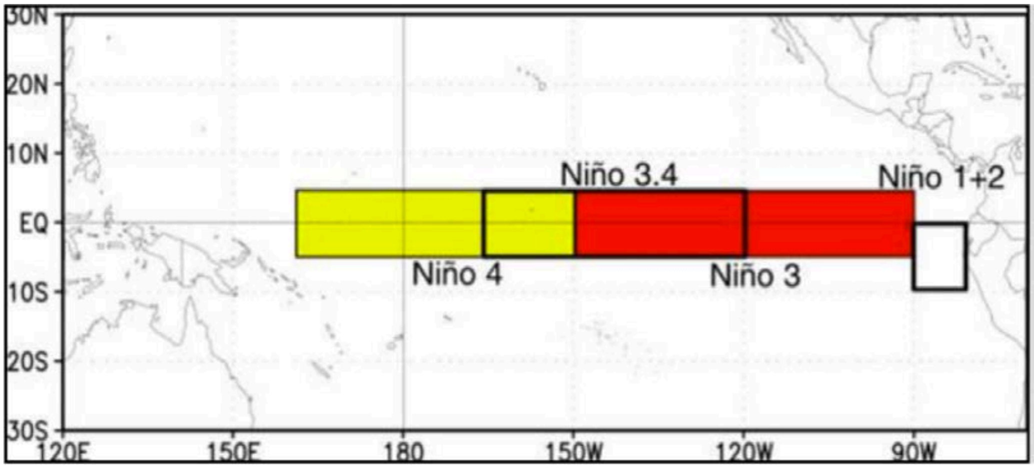


Figure 4.7 The various Niño regions where sea surface temperatures are monitored to determine the current ENSO phase (warm or cold) Source: Wikipedia

Kim et al. (2009, 2011) provide an overview of the impact of ENSO on tropical cyclones. In La Niña years, there are usually twice as many major hurricanes in the Atlantic as in El Niño years. ENSO influences Atlantic hurricane activity by altering the large-scale atmospheric circulation patterns for genesis (formation) and intensification. During an El Niño year, the vertical wind shear is larger than normal in most of the tropical Atlantic and especially in the Caribbean, which inhibits the formation of hurricanes.

The effect of ENSO on Pacific hurricanes is opposite to that in the Atlantic – El Nino years are associated with greater hurricane activity in the Pacific. As summarized by Kim et al. (2009), ENSO has an impact on the mean hurricane genesis location in the Pacific, with a displacement to the southeast (northwest) in El Niño (La Niña) years. Because of this shift to the southeast, further away from the Asian continent, hurricanes in El Niño years tend to last longer and be more intense than in other years. ENSO also affects the shapes of the tracks – in El Niño years, the hurricanes have a tendency to recurve northeastward and reach more northerly latitudes. Hence, hurricanes affect the southern South China Sea more frequently during La Niña years, but affect the Central Pacific more frequently in El Niño years.

Capotondi et al. (2015) address the issue of ENSO diversity, including the El Niño Modoki (a Japanese word that means 'similar but different'). By contrast to the traditional El Niño that is associated with warming in the eastern tropical Pacific (Niño 1,2,3 regions in Figure 4.7), the El Niño Modoki is associated with warming in the central tropical Pacific (Niño 4 region). Kim et al. (2011) found that the El Niño Modoki shifts hurricane activity to the western Pacific, providing more favorable conditions for Asian landfalls, while hurricane activity in the eastern Pacific is substantially reduced. In the Atlantic, the impacts of an El Niño Modoki on hurricane activity more closely resemble a La Nina season, with elevated hurricane activity (Figure 4.8).

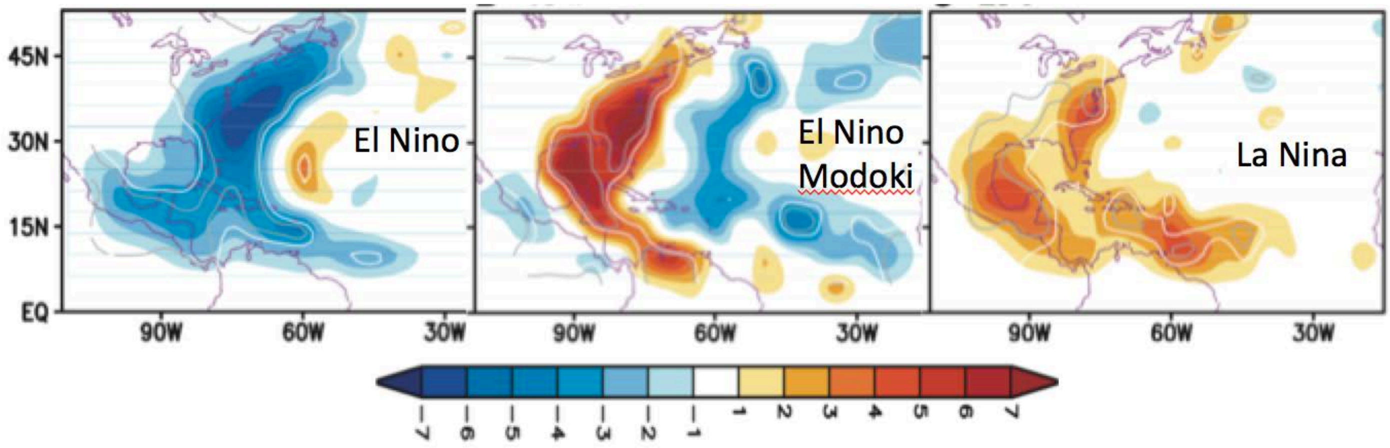


Figure 4.8 Composites of Atlantic track density anomaly (multiplied by 10) during the August to October period for (A) El Niño, (B) El Niño Modoki, and (C) La Niña. Source: Kim et al. (2009)

There is evidence of multidecadal variability in the relative frequency of El Niño, La Niña and Modoki events. In the Pacific, two decadal to multi-decadal modes have been identified:

- Pacific Decadal Oscillation (PDO) – an envelope for ENSO activity
- North Pacific Gyre Oscillation (NPGO) – an envelope for Modoki activity

The Pacific Decadal Oscillation (PDO) is a pattern of Pacific climate variability (poleward of 20°N), that can be interpreted as a decadal envelope of ENSO variability. During a warm (positive) phase, the west Pacific becomes cooler and part of the eastern ocean warms; during a cool (negative) phase, the opposite pattern occurs (Figure 4.9).

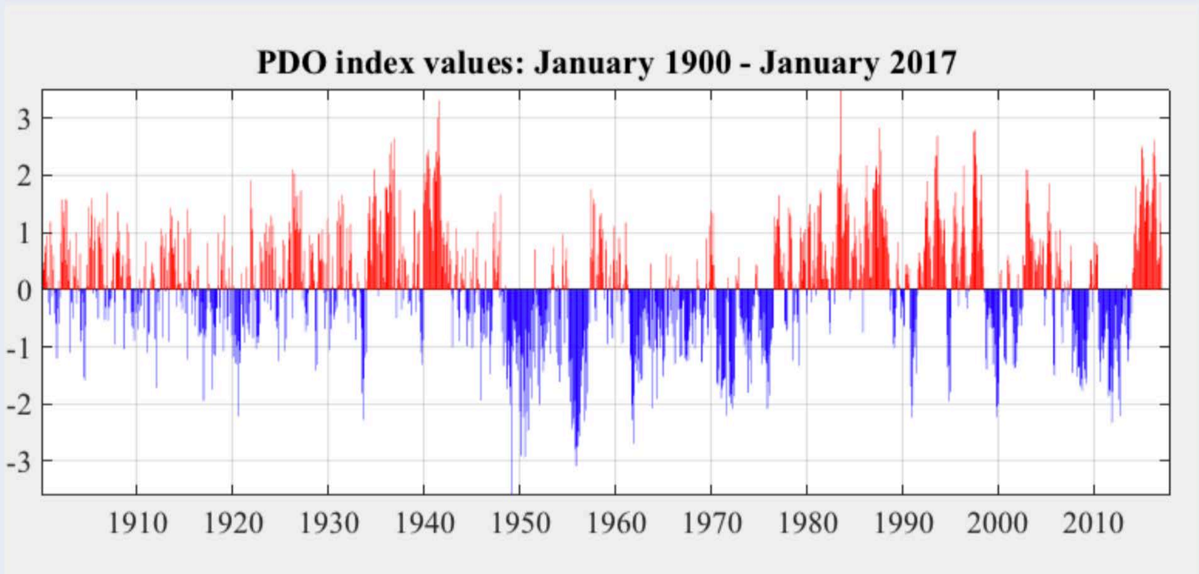


Figure 4.9 PDO Index values. Source: http://research.jisao.washington.edu/pdo/

The North Pacific Gyre Oscillation (NPGO; DiLorenzo et al. 2008) reflects variations in the strength of the central and eastern branches of the subpolar and subtropical ocean circulation patterns, and is driven by the atmosphere through the North Pacific Oscillation (NPO). The NPO spatial pattern consists of a dipole structure in which sea level pressure (SLP) variations in the central Pacific near 40°N oppose those over Alaska. Variations of the NPGO index are shown in Figure 4.10.

Maue (2011) interpreted the global Accumulated Cyclone Energy (Figure 3.2) in terms of the PDO and NPGO. The Pacific climate shifts of 1976–77 and 1988–89 have been related to the PDO and North Pacific Gyre Oscillation (NPGO), respectively, which are seen in the global ACE time series. Decadal variations in the NPGO, which has been enhanced since 1989, have been linked to SST anomaly patterns that resemble El Niño Modoki events.

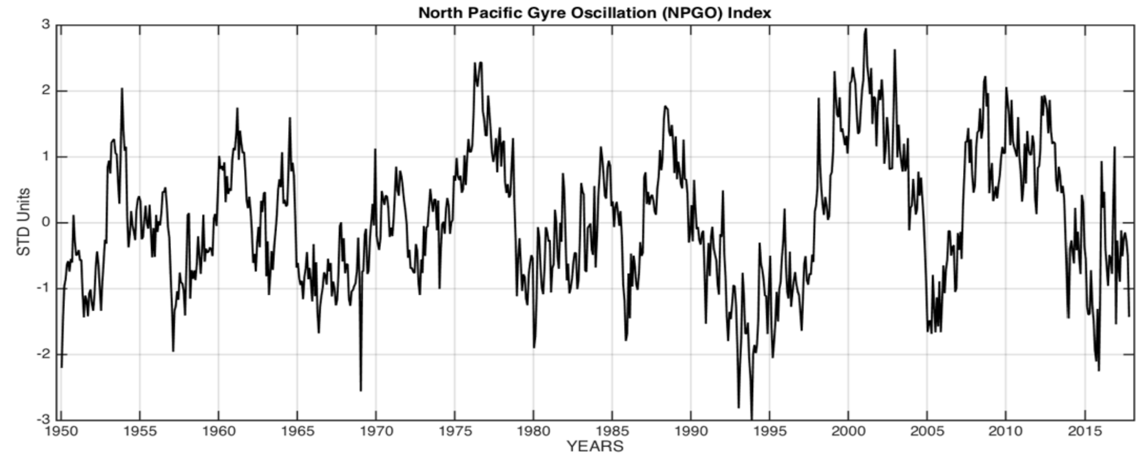


Figure 4.10 NPGO Index values. Source: https://asl.umbc.edu/hepplewhite/cindex/

Camargo et al. (2010) summarized several studies that have examined the decadal and multidecadal variability of hurricane activity in the western North Pacific. The observational record is unreliable before the 1950s, and perhaps even before the 1970s. The occurrence of major hurricanes is modulated by ENSO and the Pacific Decadal Oscillation. The decadal variability of hurricane tracks has been attributed to the Pacific Decadal Oscillation. Regions with greatest decadal changes are the East China Sea and the Philippine Sea.

Summary. Hurricanes in the Atlantic and Pacific are influenced substantially by the natural modes of ocean circulation variability in the Pacific. These modes include ENSO and Modoki, and also the Pacific Decadal Oscillation and the North Pacific Gyre Oscillation.

4.3.3 Does global warming change the internal modes of variability?

The internal modes of variability associated with the large-scale ocean circulations are often referred to as ‘oscillations.’ However, it is incorrect to view these oscillations as ‘cyclic,’ as their period and frequency tend to be somewhat irregular. In principle, because they are internal modes associated with the nonlinear dynamics of the coupled atmosphere-ocean system, a specific oscillation pattern can cease to exist or change its mode of variability. Because the historical record is relatively short, particularly outside of the Atlantic Ocean, it is useful to consider paleoclimatic evidence of these oscillations.

Knudsen et al. (2011) showed that distinct, 55- to 70-year oscillations have characterized the North Atlantic ocean-atmosphere variability over the past 8,000 years, consistent with the AMO. Cobb et al. (2013) analyzed fossil coral reconstructions of ENSO spanning the past 7000 years. The corals document highly variable ENSO activity, with no evidence for a systematic trend in ENSO variance. Twentieth-century ENSO variance is significantly higher than average fossil coral ENSO variance, but is not unprecedented.

The NCA4 (2017; Chapter 5) concluded that confidence is low regarding the impact of manmade global warming on changes to these internal modes associated with large-scale ocean circulation patterns.

4.4 Attribution – models

Extended integrations of global climate models in principle should allow for an assessment of the frequency, intensity, duration and tracks of hurricane-like features in the model simulations. Attribution of the impacts of manmade global warming on hurricane characteristics can then be assessed through comparing climate model simulations both with and without human impacts.

A prerequisite for using global climate models for attribution analyses or 21st century projections of hurricane activity is that historical climate model simulations accurately simulate hurricane characteristics and climate processes including interannual to decadal variability. However, simulation of realistic hurricane characteristics is hampered by the coarse resolution generally required of such global models and also the model treatment of tropical convection and clouds (e.g. Camargo et al 2008; Walsh et al. 2015). Further, climate models do not accurately simulate the timing and patterns of the multi-decadal ocean circulation patterns (e.g. Kravtsov et al. 2018).

More realistic maximum hurricane intensities have been simulated by downscaling individual storm cases from a coarse-grid global model into a regional high-resolution hurricane prediction system (see Walsh et al. 2016 for a summary). As a recent example, Patricola and Wehner (2018) used a high-resolution model to simulate 15 hurricane events from the global historical record. Simulations for each storm were conducted under current climate conditions versus the surface climate associated with pre-industrial conditions. They found that manmade climate change has enhanced the average and extreme rainfall of hurricanes Katrina, Irma and Maria by 4%–9% and increased the probability of extreme rainfall rates, suggesting that climate change to date has already begun to increase tropical cyclone rainfall.

However, the model used by Patricola and Wehner (2018) was driven by specified sea surface temperatures, and did not include coupling to the ocean. Lack of ocean coupling in the model leads to tropical cyclones that are more intense and frequent compared to coupled atmosphere–ocean simulations. Tropical cyclone winds typically induce a ‘cold wake’ of upper-ocean temperatures. The cold wake reduces the tropical cyclone intensity, depending on the tropical cyclone’s intensity and translation speed and the ocean heat content and salinity structure. Further, these simulations of individual storms only include the thermodynamic (temperature) related aspects of climate change, and do not include the impact of any atmospheric or ocean circulation changes that might be associated with global warming.

In one of the most sophisticated model-based attribution studies to date, Bhatia et al. (2019) investigated the issue of whether hurricane rates of intensification are increased by global warming. They compared the observed trends to natural variability in bias-corrected, high-resolution global coupled model experiments that accurately simulate the climatological distribution of tropical cyclone intensification. Their results suggest a detectable increase of Atlantic intensification rates with a positive contribution from manmade forcing and reveal a need for more reliable data before detecting a robust trend at the global scale. The paper concludes that the study is limited by the ability of a climate model to accurately represent natural variability as well as the uncertainty around the trends in relatively short observational records. Further analysis with additional high-resolution climate models and a longer and more reliable observational record are required to confirm these conclusions.

Summary. Global climate models are currently of limited use in hurricane attribution studies. High-resolution models used to simulate individual hurricanes are being used to perform controlled experiments that focus on specific events and the complexities of relevant physical processes. However, definitive conclusions regarding the impact of manmade warming on hurricanes cannot be determined from these simulations, given the current state of model development and technology.

4.5 Attribution – physical understanding

Our knowledge of the relationships between climate variability and hurricanes comes mainly from the analysis of historical data. Meaningful interpretation of these relationships requires understanding of the mechanisms that determine these relationships, but ultimately this understanding is limited by the same fundamental factors that limit our understanding of the mechanisms of the formation and intensification of individual hurricanes (see Emanuel 2018 for a review of current knowledge of hurricane processes).

4.5.1 Genesis

While there are some theories for hurricane genesis (formation), there is no quantitative theory that relates the probability of genesis to the large-scale environmental conditions. As summarized by Camargo et al. (2008), we have known for decades that sea surface temperature, vertical wind shear, and atmospheric humidity influence genesis, which gives us a basis for understanding how climate variations influence hurricane numbers.

As summarized by Walsh et al. (2015), the number of hurricanes appears to be related to changes in the mean vertical circulation of the atmosphere. Humidity in the lower atmosphere was shown to be the most important controlling parameter for formation in the Atlantic, with sea surface temperatures, cyclonic circulations patterns, wind shear and rising motion also being important.

The problem of understanding the impact of global warming on hurricane genesis is complicated by potentially compensating influences of a warming climate on hurricanes (e.g. Patricola and Wehner, 2018). Increasing sea-surface temperature (SST) are expected to intensify tropical cyclones. However, projected increases in vertical wind shear could work to suppress tropical cyclones regionally.

As summarized by IPCC AR5 (2013; Chapter 16), hurricanes can respond to manmade forcing via different and possibly unexpected pathways. Increasing emissions of black carbon and other aerosols in South Asia has been linked to a reduction of SST gradients in the Northern Indian Ocean, which has been linked to a weakening of the vertical wind shear in the region and an increase in the number of intense hurricanes in the Arabian Sea. In the North Atlantic, the reduction of pollution aerosols is linked to tropical SST increases, while in the northern Indian Ocean, increases in aerosol pollution have been linked to reduced vertical wind shear – both of these effects have been related to increased tropical cyclone activity.

4.5.2 Intensity

The causal chain for global warming to increase hurricane intensity has long been argued to occur via the increase in sea surface temperature (SST) (for a summary, see Curry et al. 2006). A nominal SST threshold of 26.5^{o}C [80 ^{o}F] has been used as a criterion for the formation of hurricanes, and a threshold of 28.5^{o}C [82.4 ^{o}F] for intensification to a major hurricane (Category 3+).

New insights into the relationship between warming and hurricane intensity are provided by Hoyos and Webster (2011). During the 20th century, tropical ocean SST increased by about 0.8°C, accompanied by a steady 70% expansion of the ocean warm pool area that encompasses the regions exceeding 28^{o}C [82.4 ^{o}F]. However, the region of hurricane formation has not expanded. Hoyos and Webster argue that the temperature threshold for hurricane formation increases as the average tropical ocean temperature increases. The increasing intensity of atmospheric convection with warmer temperatures seems to be the link between SST increase and hurricane intensity, rather than the absolute value of the SST itself. This idea received further confirmation by the analysis of Defforge and Merlis (2017). Vecchi et al. (2008) found that the location of the intense convection is related to the difference between the local SST and global tropical average SST, rather than to the absolute value of the SST itself.

The causal link between SST and hurricane plays a prominent role in theories to estimate the upper bounds on tropical cyclone intensity. Knutson and Tuleya (2004) estimated sensitivity of hurricane maximum intensity to be about 4% for 1 ^{o}C of SST warming. Such sensitivity estimates have considerable uncertainty, as shown by subsequent assessments.

4.5.3 Rainfall

As the ocean surface warm, more water evaporates and a warmer atmosphere has a greater capacity to hold water vapor. Simple thermodynamic calculations show that there is about 7% more water vapor in saturated air for every 1°C [2 ^{o}F] of ocean warming (e.g. Trenberth, 2007).

This increase in atmospheric water vapor can cause an even larger increase in hurricane rainfall, since water vapor retains the extra heat energy required to evaporate the water, and when the water vapor condenses into rain, this latent heat is released.

However, analysis of heavy rainfall events and flooding associated with U.S. landfalling hurricanes (Aryal et al. 2018) did not identify any significant changes in magnitude or frequency.

4.6 Conclusions

Models and theory suggest that hurricane intensity and rainfall should increase in a warming climate. There is no theory that predicts a change in the number of hurricanes or a change in hurricane tracks with warmer temperatures. Convincing attribution of any changes requires that a change in hurricane characteristics be identified from observations, with the change exceeding natural variability.

The global percent of Category 4/5 hurricanes has been observed to be increasing. Because of the short length of the data record and concerns about data quality, attribution of any portion of this increase to manmade global warming requires careful examination of the data and modes of natural variability in each of the regions where hurricanes occur.

While theory and models indicate that hurricane rainfall should increase in a warming climate, satellite-based observational analyses of hurricane rainfall have not addressed this issue on a meaningful spatial or temporal scale.

There is some evidence for a slowing of tropical cyclone propagation speeds globally over the past half century, but these observed changes have not yet been confidently linked to manmade climate change.

While substantial increases in Atlantic hurricane activity have occurred since 1970, these increases are likely driven by variations in the Atlantic Multidecadal Oscillation (AMO) and Atlantic Meridional Mode (AMM). However, climate model simulations suggest a recent increase in the rate of intensification of Atlantic hurricanes that exceeds what can be expected from natural internal variability.

If manmade global warming is causing an increase in some aspect of hurricane activity, this increase should be evident globally, and not just in a single ocean basin. One problem is that data is insufficient for detection on the global level. When considering a single ocean basin, correct interpretation and simulation of natural internal variability is of paramount importance; unfortunately our understanding and ability to correctly simulate natural internal variability with global climate models is limited.

In summary, there is no observed trend in hurricane activity that has risen above the background variability of natural processes. It is possible that manmade climate change may have caused changes in hurricane activity that are not yet detectable due to the small magnitude of these changes compared to estimated natural variability, or due to observational limitations. But at this point, there is no convincing evidence that manmade global warming has caused a change in hurricane activity.

5. Landfalling hurricanes

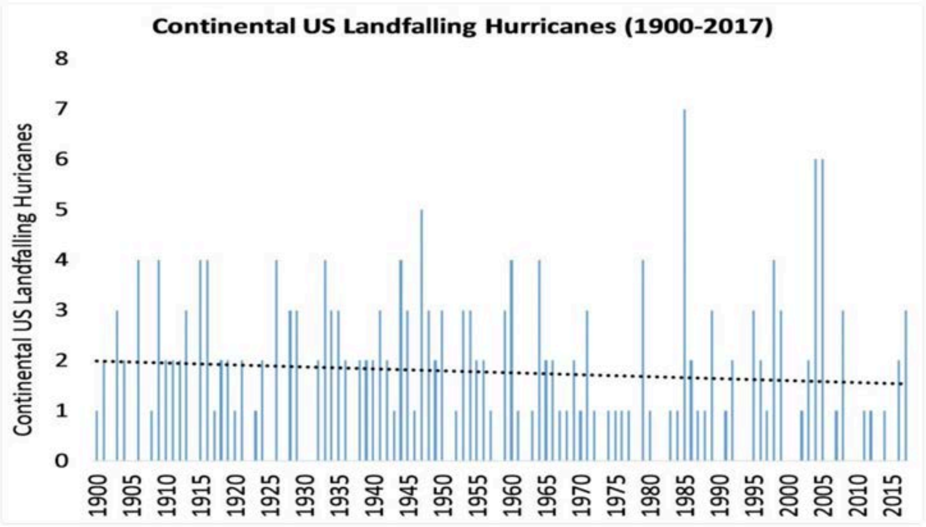
Total basin and global hurricane statistics are most easily related to global and regional climate variability and change. However, landfalling hurricanes are of particular interest owing to their socioeconomic impacts.

Economic losses from landfalling hurricanes have increased in recent decades, both in the U.S. and globally. Identifying a signal from manmade global warming in the increased losses requires identifying a trend that can be attributed to manmade global warming in any of the factors that contribute to economic losses from landfalling hurricanes. These factors include: hurricane frequency, intensity, horizontal size, storm surge, rate of motion near the coast, tornadoes and rainfall.

5.1 Continental U.S.

Klotzbach et al. (2018) have conducted a comprehensive evaluation of the landfalling hurricane data for the Continental U.S. (CONUS) since 1900.

Figure 5.1 (top) shows the time series of U.S. landfalling hurricanes for the period 1900 to 2017. While the largest counts are from 1986, 2004 and 2005, there is a slight overall negative trend line since 1900 that is not statistically significant. Figure 5.1 (bottom) shows the time series for major hurricane landfalls (Category 3-5). The largest year in the record is 2005, with 4 major hurricane landfalls. However, during the period 2006 through 2016, there were no major hurricanes striking the U.S., which is the longest such period in the record since 1900.



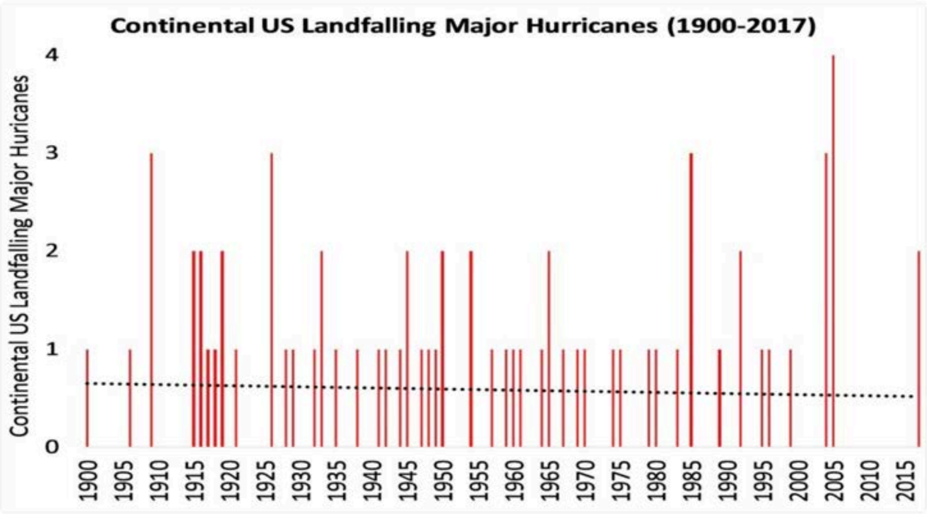


Figure 5.1 Time series from 1900 to 2017 for continental U.S. landfalling hurricanes (top) and major hurricanes (bottom). The dotted lines represent linear trends over the period, although neither of these trends is statistically significant. Source: Klotzbach et al. (2018).

Villarini et al. (2012) provide an analysis of U.S. landfalls back to 1878 (Figure 5.2). While it is possible that some landfalls were missed in the early decades owing to sparsely populated regions on the Gulf Coast, it is remarkable that the highest year in the entire record, with 7 landfalls, is 1886.

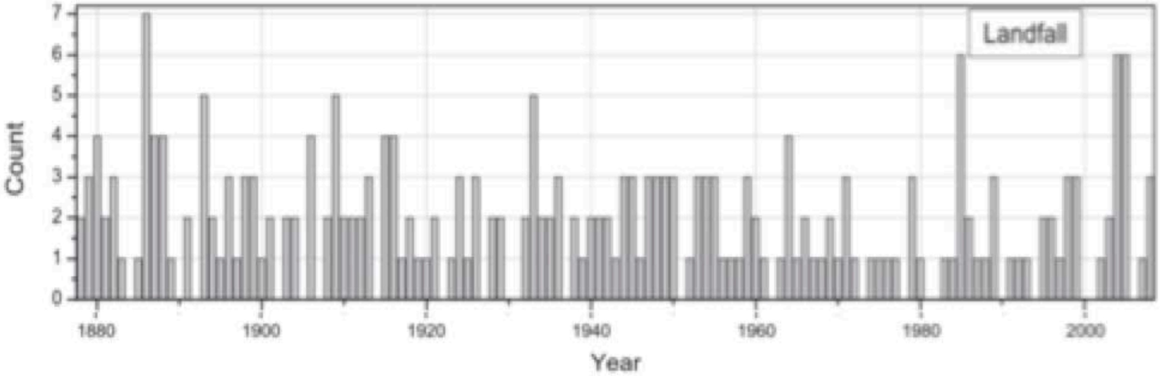


Figure 5.2 Time series of the count of U.S. landfalling hurricanes for the period 1878 - 2008. From Villarini et al. (2012).

An energetic perspective on U.S. landfalling hurricanes is provided by Truchelut and Staehling (2017). Figure 5.3 shows the time series of continental U.S. landfalling Accumulated Cyclone Energy (ACE), referred to as Integrated Storm Activity Annually Over the Continental U.S. (ISAAC). The 2006 - 2016 drought of U.S. major hurricane landfalls is associated with a landfall ACE value that was less than 60% of the 1900-2017 average.

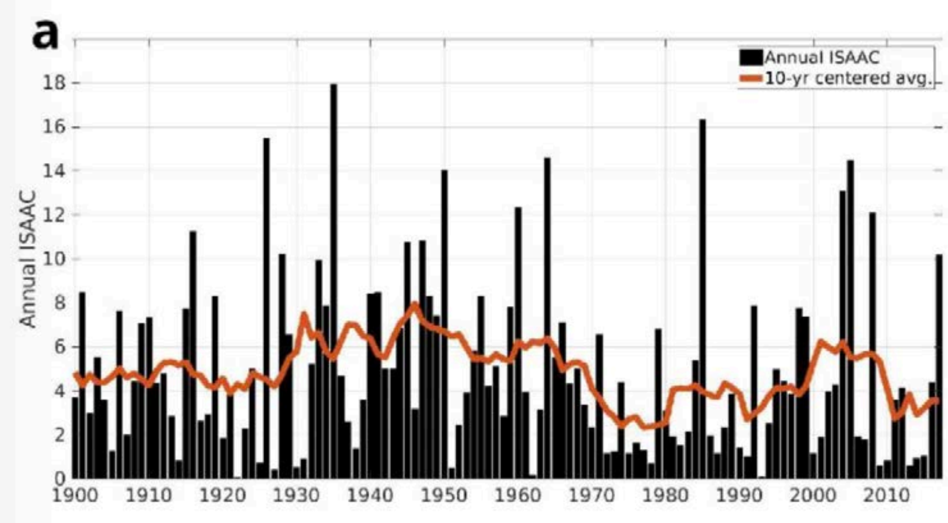


Figure 5.3. Timeseries of ISAAC for 1900-2017, with a ten-year centered average value (red**).** From Truchelut and Staehling (2017).

Truchelut and Staehling (2017) illustrate how the overall Atlantic basin hurricane activity does not directly relate to U.S. landfall activity in a consistent way. Figure 5.4 shows the landfalling ACE (ISAAC) as a percent of overall Atlantic basin Accumulated Cyclone Energy (ACE). The drought in major landfalling hurricane between 2006 and 2016 has the lowest decadal value of this ratio since 1950.

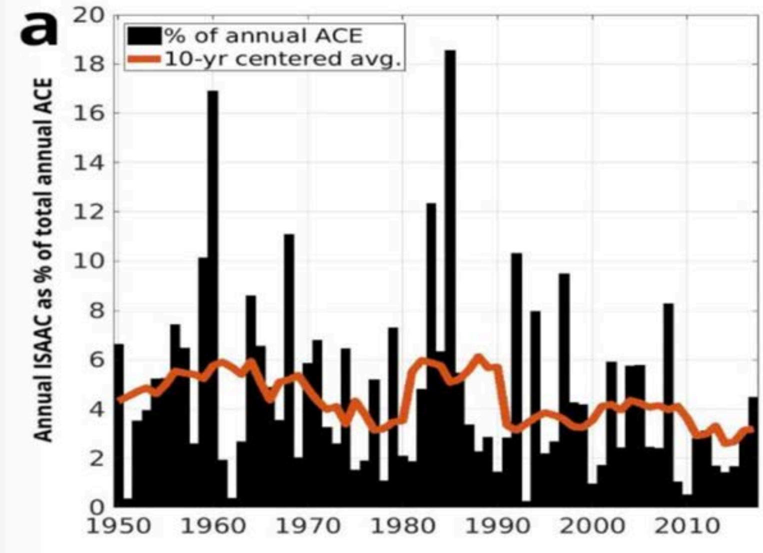


Figure 5.4: Time series of proportional ISAAC over 1950-2017, expressed as a percentage of the annual cumulative ACE occurring in the Atlantic Basin, with a ten-year centered average (red). From Truchelut and Staehling (2017).

Substantial interannual to multidecadal variability in U.S. landfall activity is seen in Figures 5.1 to 5.4. Klotzbach et al. (2018) examined how the landfall counts vary with ENSO (El Niño versus La Niña) and the warm versus cold phases of the Atlantic Multidecadal Oscillation (AMO).

Figure 5.5 compares U.S. landfall frequency during El Niño versus La Niña years. About 1.75 times as many hurricanes make U.S. landfall in La Niña seasons compared with El Niño seasons. Klotzbach et al. found similar ENSO-related modulation in both Florida and East Coast landfalls as well as Gulf Coast landfalls. The La Niña-to-El Niño ratio is slightly larger for major hurricane landfalls than for all hurricane landfalls, although the increase in hurricane landfalls observed in La Niña seasons from that observed in all seasons does not meet the 5% significance level.

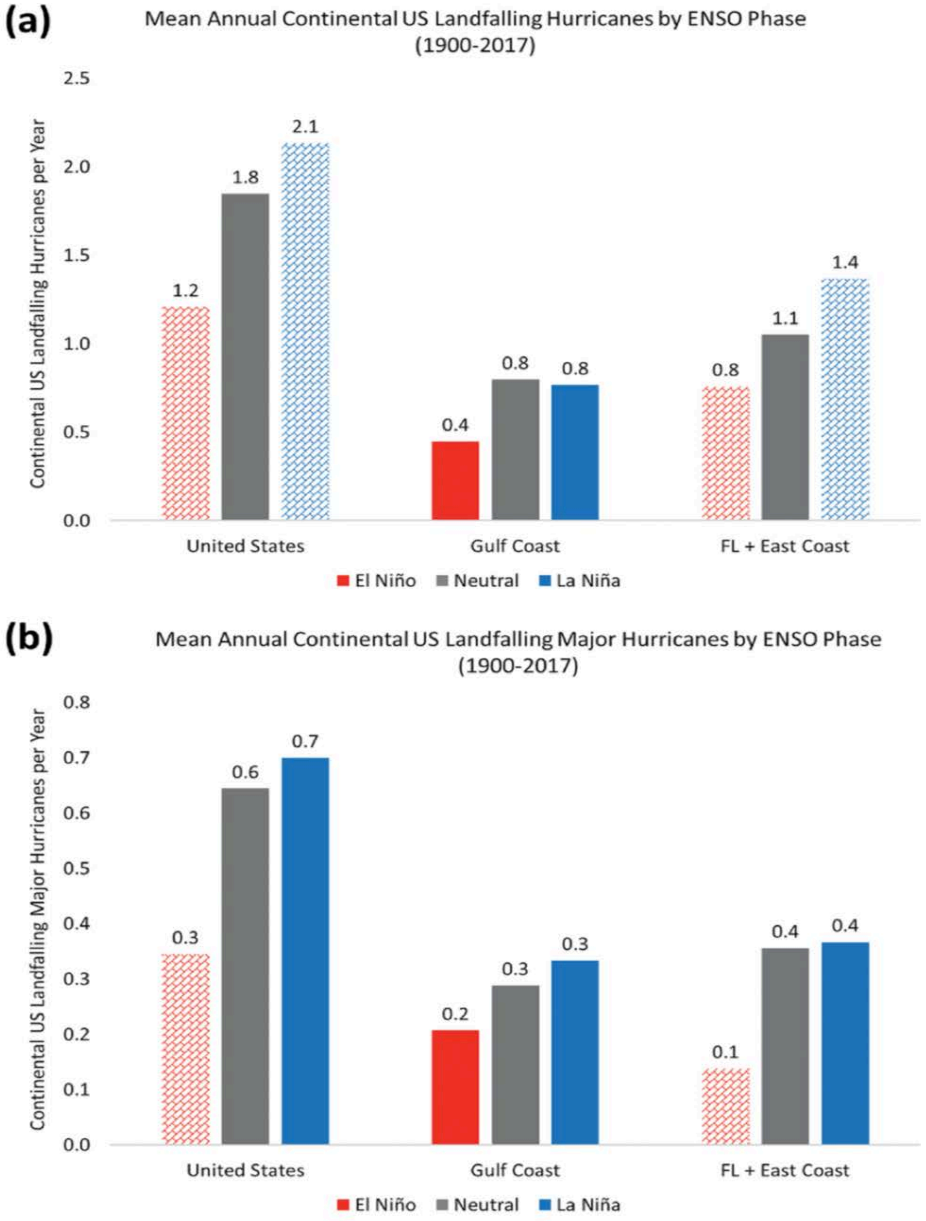


Figure 5.5: (a) Mean annual CONUS landfalling hurricanes by ENSO phase from 1900 to 2017, and (b) mean annual CONUS landfalling major hurricanes by ENSO phase from 1900 to 2017. Differences that are significant at the 5% level are plotted with diagonal hatching. Klotzbach et al. (2018).

Figure 5.6 compares U.S. landfall counts for the warm versus cold phase of the Atlantic Multidecadal Oscillation (AMO). There is a significant modulation between positive and negative AMO phases for Florida and East Coast landfalls.

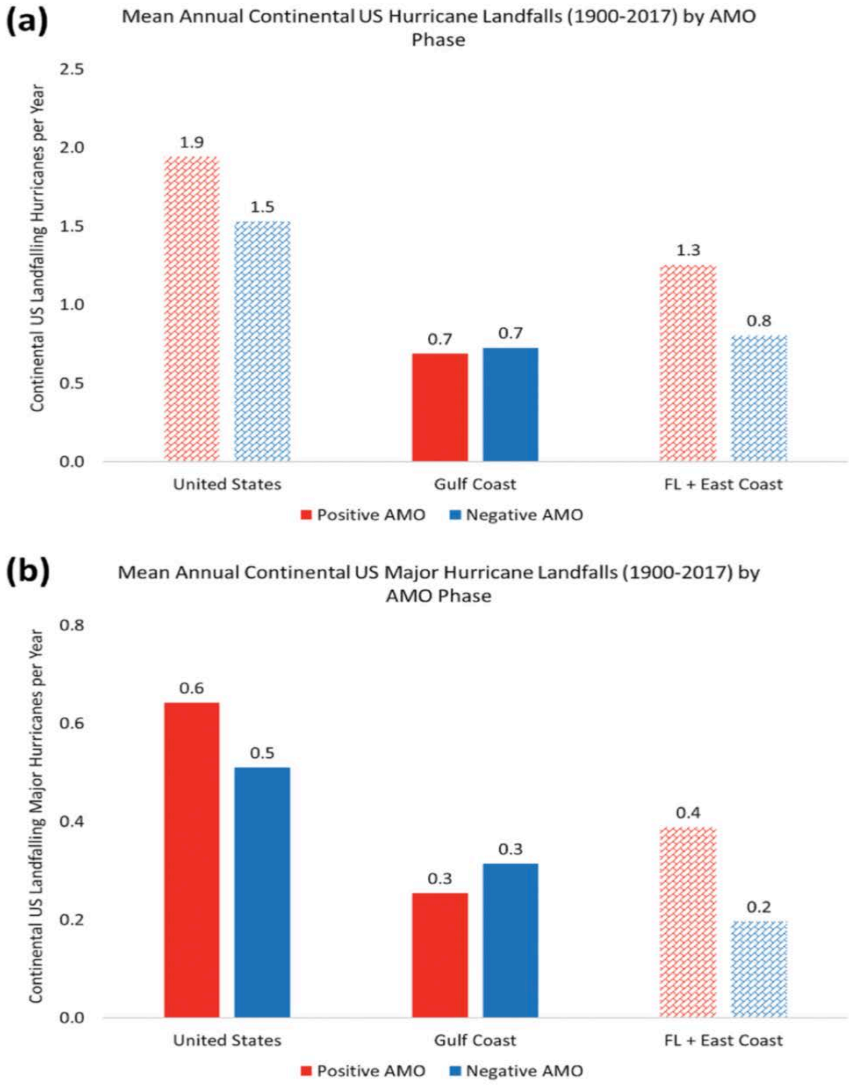


Figure 5.6: (a) Mean annual continental U.S. landfalling hurricanes by AMO phase; (b) mean annual CONUS landfalling major hurricanes by AMO phase. Differences that are significant at the 5% level are plotted with diagonal hatching. Klotzbach et al. (2018)

Figure 5.7 shows the number of continental U.S. landfalling major hurricanes by decade. Why were there fewer landfalling major hurricanes in the decade 2001 to 2010 versus 1941 to 1950, both decades at the peak of the warm phase of the Atlantic Multidecadal Oscillation (AMO)? Figure 5.7 shows that there arguably were more major hurricanes in the Atlantic basin during the earlier, mid-century AMO. The explanation probably lies in the relative frequencies of El Niño versus La Niña years during these two warm periods, with the current warm phase of the AMO being dominated by a relatively large number of El Niño years that are associated with low Atlantic hurricane activity.

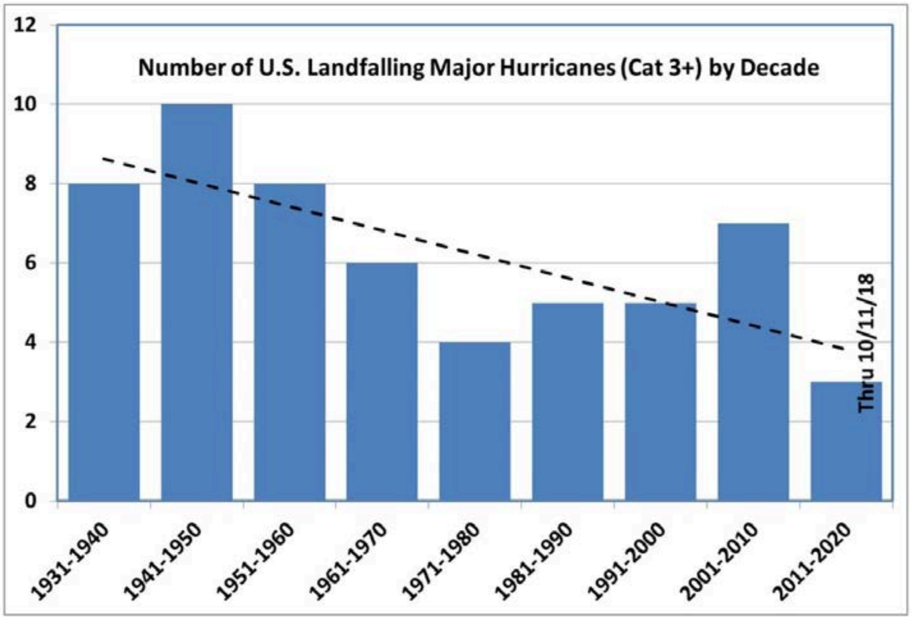


Figure 5.7 Plot of major (category 3 or higher) hurricanes striking the continental U.S. Source: Roy Spencer.

Kossin (2017) identified an increased tendency for enhanced vertical wind shear near the continental U.S. in the warm phase of the Atlantic Meridional Mode (AMM) as a potential contributor to diminished landfall efficiency in active seasons. During periods of greater Atlantic hurricane activity, a protective barrier of vertical wind shear and cooler ocean temperatures forms along the U.S. east coast, weakening storms as they approach land. Likewise, during periods of low activity, the sea surface temperatures are cooler and the wind shear is stronger there. When conditions in the tropical Atlantic are good for hurricane intensification, they are bad for it near the coast and vice versa.

The Arc horseshoe temperature pattern in the Atlantic (Figure 4.3) illustrates the spatial pattern of Atlantic surface temperatures associated with AMO. The east-west pattern of warm-cool temperatures influences the ratio of landfall ACE to total basin ACE (Figure 5.4), resulting in the opposing tendencies of hurricane intensification near the Atlantic coast versus in the Atlantic basin.

Summary. U.S. landfalling hurricanes show substantial year-to-year and decadal variability, associated primarily with ENSO and the Atlantic Multi-decadal Oscillation. Over the last century, there is a slight overall negative trend in the total number of hurricanes and major hurricanes striking the U.S. The number of major hurricanes striking the U.S. in recent decades is lower than the 1930's, 1940's and 1950's. During the period 2006-2016, no major hurricanes struck the continental U.S.

5.2 Caribbean

Klotzbach (2011) shows that there is no significant long-term trend Caribbean landfalling hurricanes (Figure 5.8). The primary interannual driver of variability in the Caribbean is ENSO, whereby much more activity occurs in the Caribbean with La Niña conditions than with El Niño conditions. On the multidecadal time scale, the AMO plays a significant role in Caribbean hurricane activity. When ENSO and the AMO are examined in combination, even stronger relationships are found. For example, 29 hurricanes tracked into the Caribbean in the 10 strongest La Niña years during a positive (warm) AMO period, compared with only two hurricanes tracking through the Caribbean in the 10 strongest El Niño years during a negative (cool) AMO period.

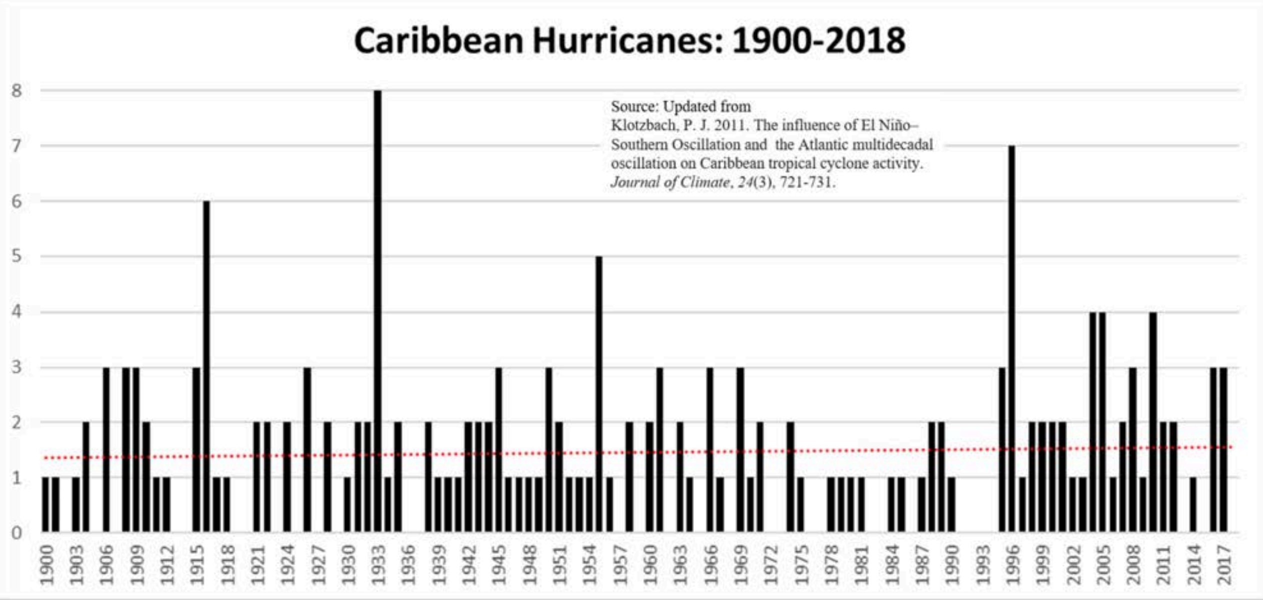


Figure 5.8: Caribbean landfalling hurricanes, for the period 1900-2018. Updated from Klotzbach (2011).

Chenoweth and Divine (2008) provide a longer-term perspective on Caribbean landfalling hurricanes by assembling a historical document-based 318 year record of tropical cylcones impacting the Lesser Antilles, for the period 1690-2007. Newspaper accounts, ships' logbooks, meteorological journals and other document sources were used to create this data set. This compilation estimates the position and intensity of each tropical cyclone that passes through the 61.5°W meridian from the coast of South America northward through 25.0°N. The numbers of tropical cyclones show no significant trends (Figure 5.9). The period with the largest number of landfalls was in the early 19th century. The time span 1968–1977 was probably the most inactive period since the islands were settled in the 1620s and 1630s.

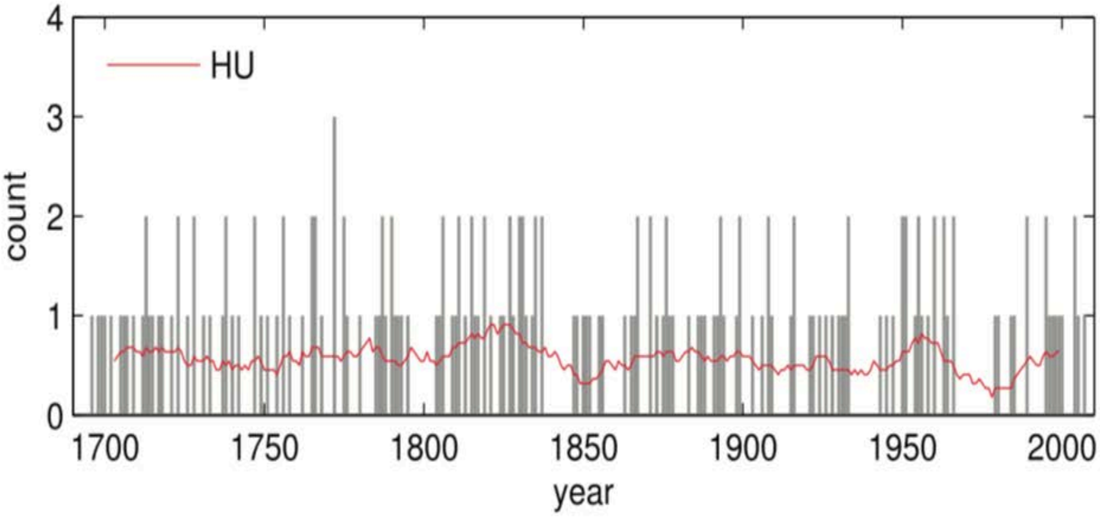


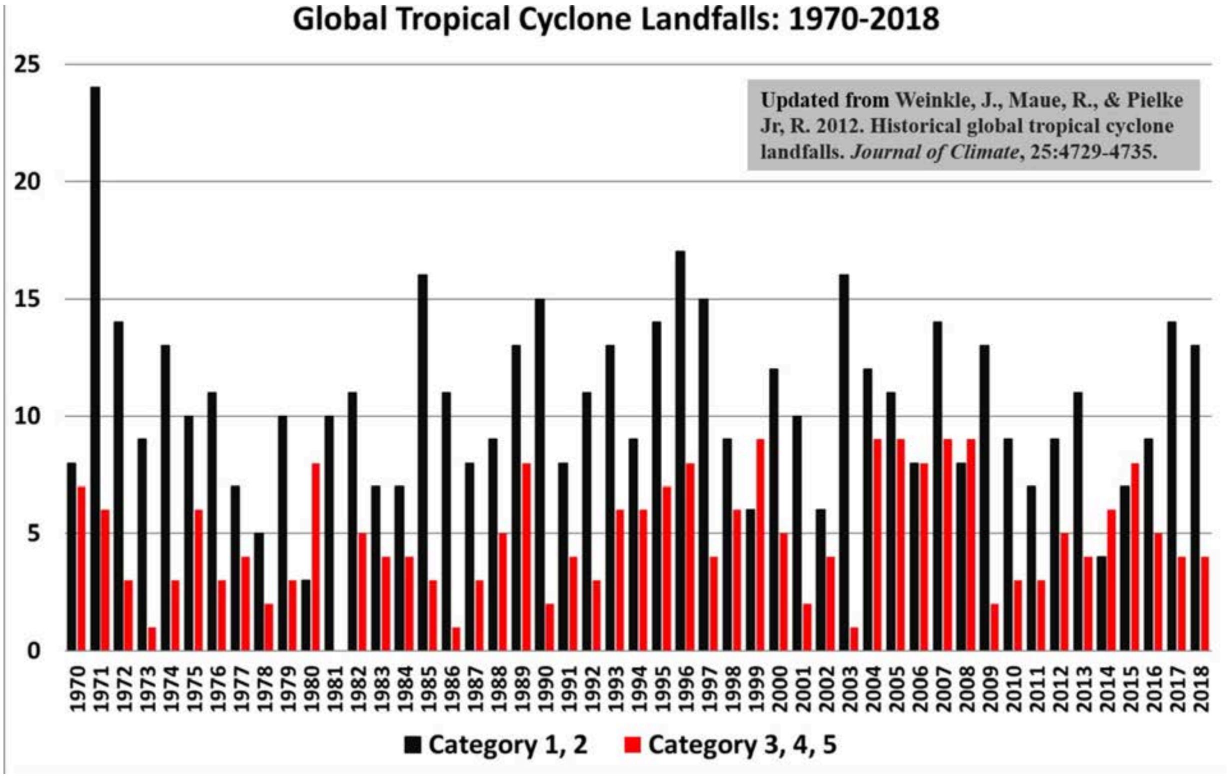
Figure 5.9. The number of hurricanes passing through 10–20°N 61.5°W from 1690 to 2007. Red curve is a 21-year moving mean.

Summary. No trend in Caribbean landfalls has been observed. ENSO and Atlantic Multidecadal Oscillation dominate the variability of Caribbean landfalls. Historical recrods show that the time span 1968–1977 was probably the most inactive period since the islands were settled in the 1620s and 1630s.

5.3 Global

Weinkle et al. (2012) summarizes the challenges in constructing a homogeneous global hurricane landfall data set. Uncertainty in tropical cyclone location and intensity data is a function of the evolving observation network throughout the past century, ranging from ship traffic, aerial reconnaissance, to satellite remote sensing. Weinkle et al. (2012) examined landfalls in the North Atlantic, northeastern Pacific, western North Pacific, northern Indian Ocean, and the Southern Hemisphere, using the International Best Track Archive for Climate Stewardship (IBTrACS).

The global frequencies of total and major hurricane landfalls show considerable interannual variability, but no significant linear trend (Figure 5.10). Furthermore, when considering each basin individually, there is no significant trend except in the Southern Hemisphere. This result is not unexpected considering the known multidecadal signals in tropical cyclone activity, which cannot be adequately resolved by the short historical record.


Global Tropical Cyclone Landfalls: 1970-2018

Updated from Weinkle, J., Maue, R., & Pielke Jr, R. 2012. Historical global tropical cyclone landfalls. *Journal of Climate*, 25:4729-4735.

Figure 5.10: Frequency of global hurricane, for the period 1970-2018. Updated from Weinkle et al. (2012).

Mei et al. (2015) investigated the intensity of landfalling hurricanes over the northwest Pacific since the late 1970s. Over the past 37 years, hurricanes that strike East and Southeast Asia have intensified by 12-15%, with the proportion Categories 4/5 storms more than doubling. In contrast, typhoons that stay over the open ocean do not reflect such an increase. They found that the increase in intensity of landfalling hurricanes is tied to locally enhanced surface warming on the rim of East and Southeast Asia.

As summarized by Camargo et al. (2010), ENSO's influence on western North Pacific hurricane tracks is reflected in the landfall rates throughout the region, with different landfall patterns associated with ENSO phase. There is a significant relationship between late season landfalls over China and ENSO. There is also an increase in landfalls in the Korean Peninsula and Japan during the early monsoon months and in the Indochinese peninsula during the peak monsoon months in El Niño years.

Summary. There are substantial challenges in constructing a homogeneous global hurricane landfall data set. Since 1970, the global frequency of total and major hurricane landfalls shows considerable interannual variability, but no significant linear trend. There is substantial regional variability in hurricane landfalls, primarily associated with ENSO phase.

5.4 Water – rainfall and storm surge

Historically, the most deadly and damaging impacts of hurricanes have been storm surge and inland flooding (e.g. Blake et al. 2011). This section assesses whether there has been any increase in storm surge and rainfall associated with landfalling hurricanes.

5.4.1 Rainfall

It has been estimated that tropical cyclones of at least tropical depression strength contribute about a quarter of the annual rainfall in the southeast U.S. Soule et al. (2012) found that tropical cyclones in the Southeast U.S. frequently 'bust' droughts. Between 1950 and 2008, the majority of counties in Florida, Georgia, South Carolina and North Carolina saw at least 20% of their droughts ended by a tropical cyclone. Hurricanes also account for approximately 20% of the observed monthly rainfall from June to November across the eastern U.S. Corn Belt (Wisconsin, Michigan, Illinois, Indiana, Ohio and Kentucky) (Kellner et al. 2016).

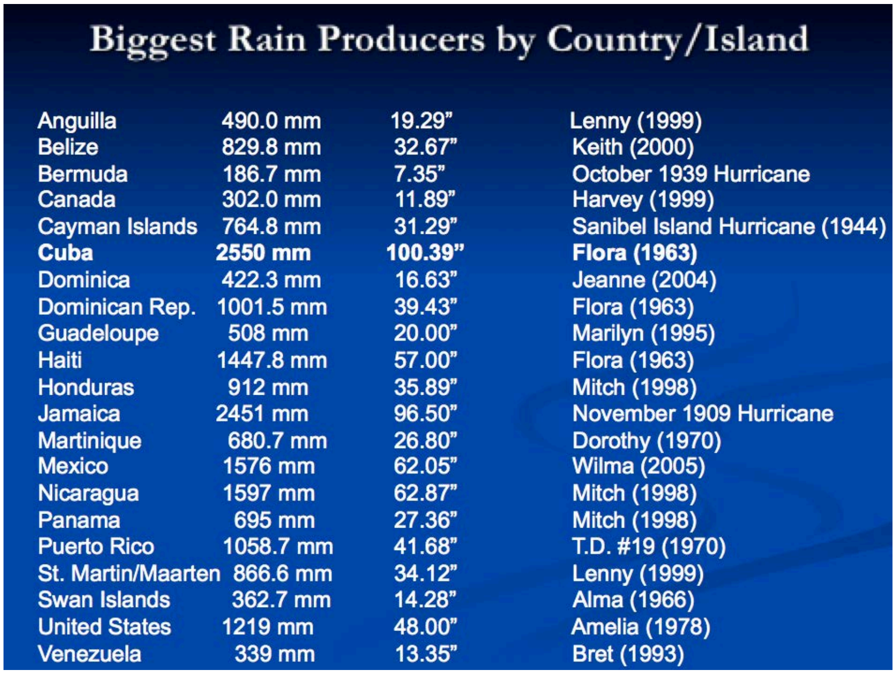
While inland flooding typically occurs with a landfalling hurricane, several factors lead to excessive rainfall. Slow motion of the hurricane near landfall can lead to high amounts of local rainfall (e.g. Danny – 1997; Wilma – 2005; Harvey – 2017; Florence – 2018). Mountains/hills near the coast magnify rainfall potential due to forced upslope flow (e.g. Mitch – 1998). Upper level troughs and cold fronts can lead to excessive rainfall (e.g. Floyd – 1999). Larger tropical cyclones have larger rain footprints, which can lead to excessive rainfall owing to the longer time frame over which rainfall falls at any one location.

Roth (2017) provides a list of the hurricanes that were the biggest rain producers for each country/island in the North Atlantic (Table 5.2). The table does not include Hurricane Harvey's (2017) rainfall of 60 inches, which occurred after this table was prepared. It is seen that Hurricane Mitch (1998), Hurricane Wilma (2005), Hurricane Flora (1963) and the November 1909 Hurricane each had peak landfall rainfall amounts exceeding that for Hurricane Harvey.

Knight and Davis (2007) examined tropical cyclone rainfall in the Southeast U.S. between 1980 and 2004. They found that 11 of the 84 stations analyzed showed statistically significant increases in tropical cyclone rainfall, and no stations had significant decreases. Over this period, they found that the increase in frequency of landfalling storms was a more important factor in the increase in hurricane rainfall, rather than the fact that individual storms have tended to be wetter.

Aryal et al. (2018) examined the contribution of North Atlantic hurricanes to flooding and heavy rainfall across the continental U.S. Their analysis does not point to any significant changes in the magnitude or frequency of floods. The found that the North Atlantic Oscillation (NAO) plays a significant role in hurricane-related extreme rainfall along the U.S. East Coast, while ENSO is most strongly linked to the hurricane-related precipitation in Texas.

Table 5.2. List of hurricanes that were the biggest rain producers in the North Atlantic. Source: Roth (2017).



Biggest Rain Producers by Country/Island

Anguilla	490.0 mm	19.29"	Lenny (1999)
Belize	829.8 mm	32.67"	Keith (2000)
Bermuda	186.7 mm	7.35"	October 1939 Hurricane
Canada	302.0 mm	11.89"	Harvey (1999)
Cayman Islands	764.8 mm	31.29"	Sanibel Island Hurricane (1944)
Cuba	**2550 mm**	**100.39"**	**Flora (1963)**
Dominica	422.3 mm	16.63"	Jeanne (2004)
Dominican Rep.	1001.5 mm	39.43"	Flora (1963)
Guadeloupe	508 mm	20.00"	Marilyn (1995)
Haiti	1447.8 mm	57.00"	Flora (1963)
Honduras	912 mm	35.89"	Mitch (1998)
Jamaica	2451 mm	96.50"	November 1909 Hurricane
Martinique	680.7 mm	26.80"	Dorothy (1970)
Mexico	1576 mm	62.05"	Wilma (2005)
Nicaragua	1597 mm	62.87"	Mitch (1998)
Panama	695 mm	27.36"	Mitch (1998)
Puerto Rico	1058.7 mm	41.68"	T.D. #19 (1970)
St. Martin/Maarten	866.6 mm	34.12"	Lenny (1999)
Swan Islands	362.7 mm	14.28"	Alma (1966)
United States	1219 mm	48.00"	Amelia (1978)
Venezuela	339 mm	13.35"	Bret (1993)

5.4.2 Storm surge

The magnitude of a storm surge depends on storm intensity, forward speed, size (radius of maximum winds), angle of approach to the coast, central pressure, high tide versus low tide, and the shape and characteristic of coastal features.

Sea level rise also influences the height of storm surges. Since 1900, global mean sea level has risen 7-8 inches (see Curry 2018a for an overview). Depending on local topography, a small change in sea level can translate into an increase in the inland reach of the storm surge.

Table 5.3 lists notable U.S. hurricane-induced storm surge events. The highest documented storm surge in the U.S. occurred in 2005 during Hurricane Katrina, when Pass Christian, MS, recorded a 27.8 foot storm surge.

5.4.3 Summary

The slow creep of sea level rise has contributed a small amount to the magnitude of hurricane-induced storm surges. With regards to the rainfall associated with landfalling hurricanes, there is no clear signal of increasing rainfall owing to the complexity of the factors contributing to hurricane-induced rainfall. In the U.S., the record hurricane rainfall is from Hurricane Harvey (2017), which was caused by stalling of the hurricane on the coast.

Table 5.3. Notable U.S. hurricane surge events since 1900. https://www.nhc.noaa.gov/surge/

Hurricane	Year	Location	Category	Surge (ft)
Ike	2008	Galveston, TX	2	15-20
Katrina	2005	New Orleans, LA	3	28
Dennis	2005	Camden, AL	3	7-9
Isabel	2003	Chesapeake Bay	2	8
Opal	1995	Pensacola Beach, FL	3	24
Hugo	1989	Charleston, SC	4	24
Camille	1969	Mississippi	5	24
Audrey	1957	Louisiana	4	12
New England	1938	Long Island, NY	3	10-12
Galveston	1900	Galveston, TX	4	8-15
Sandy	2012	New York City	(1)	14
Michael	2018	FL panhandle	4	9-14

5.5 Hurricane size

Hurricane size impacts storm surge, the number of tornadoes, and the amount of rainfall. Horizontal size was particularly important in the impacts of Hurricanes Katrina and Sandy. Relatively little research has been done on climatic variations of hurricane size.

A satellite-based hurricane size climatology was developed by Knaff (2014). Some limited information on the variability of Atlantic hurricane size is provided by Fritz (2009). Figure 4.10 shows the Atlantic season average of the maximum radial extent of 34 knot [39 mph] wind speeds (R34), for the period 1970-2005. While substantial year-to-year variability is seen, a large jump occurs in 1995, associated with the transition to the warm phase of the Atlantic Multidecadal Oscillation (AMO) (Section 4.3.1).

Given the importance of hurricane size in landfall impacts (storm surge, rainfall amount, tornadoes), increased attention should be given to documenting and understanding the variability of tropical cyclone size.

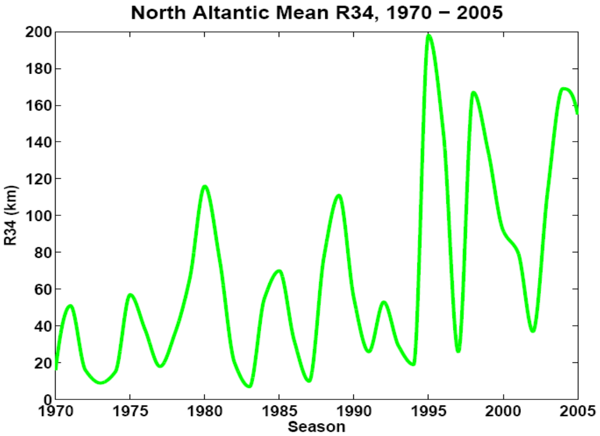


Figure 5.11. Time series of seasonal average of the radius of R34 for the North Atlantic, for the period 1970-2005. Unpublished diagram from A. Fritz, using the data set described by Fritz (2009).

5.6 Damage and losses

Data collected by MunichRe (2018) show that worldwide economic losses from landfalling tropical cyclones have increased over the past decades. Historically, the greatest amount of damage from landfalling hurricanes has been from winds and storm surge. Recently, we have seen several storms where the greatest damage occurred from inland rainfall, particularly for slow moving storms (e.g. Hurricane Harvey in 2017 and Hurricane Florence in 2018).

While there is no observational evidence of increased frequency or intensity of landfalling hurricanes either in the Atlantic or globally, there is very clear evidence of increasing damage from landfalling hurricanes. Is this increase in damage solely attributed to increasing population and wealth in vulnerable coastal locations, or is there an element of climate change that is contributing to the increase in damage?

Assessing whether there is an element of climate change that is contributing to the increase in damage from landfalling hurricanes requires the correct identification of the relevant variables driving the damage. In addition to the frequency and intensity of landfalling hurricanes, the following variables contribute to damage: horizontal size of the hurricane, forward speed of motion near the coast, storm surge and rainfall.

Klotzbach et al. (2018) and Weinkle et al. (2018) addressed the question as to whether Continental United States (CONUS) hurricane-related inflation-adjusted damage has increased significantly since 1900. Since 1900, neither observed U.S. landfalling hurricane frequency nor intensity shows significant trends, including the devastating 2017 season. Growth in coastal population and regional wealth are the overwhelming drivers of observed increases in hurricane-related damage. This trend has led to the growth in exposure and vulnerability of coastal property along the U.S. Gulf and East Coasts.

Klotzbach et al. and Weinkle et al. argue that since there are no significant trends in the frequency or intensity of landfalling U.S. hurricanes since 1900, we would expect an unbiased normalization to also exhibit no trend over this time period. Estrada et al. (2015) argue that the damage normalization approach used by Weinkle et al. and Klotzbach et al. is ambiguous owing to unobserved variables and spatial variability, such as changing adaptation practices and local vulnerability. Further, exposure to hurricane damage is not uniquely determined by landfall frequency and intensity: horizontal size, storm surge and precipitation amount are influenced by factors other than storm intensity.

Warmer sea surface temperatures, whatever the cause, are expected to contribute to an overall increase in hurricane rainfall; the extent to which rainfall has increased in landfalling hurricanes remains an active area of research.

Storm surge risk is increasing owing to the slow creep of sea level rise, although the extent to which this increase in sea level rise can be attributed to manmade global warming is disputed (e.g. Curry 2018a). Sea level rise is actually a small portion of the vulnerability to storm surge:[3]

- From 1990-2008, population density increased by 32% in Gulf coastal counties, 17% in Atlantic coastal counties, and 16% in Hawaii
- Much of the United States' densely populated Atlantic and Gulf Coast coastlines lie less than 10 feet above mean sea level
- Over half of the Nation's economic productivity is located within coastal zones
- 72% of ports, 27% of major roads, and 9% of rail lines within the Gulf Coast region are at or below 4 ft elevation
- A storm surge of 23 ft has the ability to inundate 67% of interstates, 57% of arterials, almost half of rail miles, 29 airports, and virtually all ports in the Gulf Coast area

5.7 Conclusions

Economic losses from landfalling hurricanes have increased in recent decades, both in the U.S. and globally. Growth in coastal population and regional wealth are the overwhelming drivers of observed increases in hurricane-related damage.

U.S. landfalling hurricanes show substantial year-to-year and decadal variability, associated primarily with ENSO and the Atlantic Multi-decadal Oscillation. Over the last century, there is a slight overall negative trend in the total number of hurricanes and major hurricanes striking the U.S. The number of major hurricanes striking the U.S. in recent decades is lower than the 1930’s, 1940’s and 1950’s. During the period 2006-2016, no major hurricanes struck the continental U.S. There is no evidence of a meaningful trend in global landfalling hurricanes, owing to the short data record and substantial regional and natural variability.

The slow creep of sea level rise has contributed a small amount to the magnitude of hurricane-induced storm surges. With regards to the rainfall associated with landfalling hurricanes, there is no clear signal of increasing rainfall owing to the complexity of the factors contributing to hurricane-induced rainfall.

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[3] https://www.nhc.noaa.gov/surge/

6. Attribution: Recent U.S. landfalling hurricanes

During the past decade, the following continental U.S. landfalling hurricanes rank in the top 5 historical hurricanes in terms of damage[4]:

- Hurricane Harvey (2017)
- Hurricane Sandy (2012)
- Hurricane Irma (2017)

Hurricane Michael (2018) ranks in the top 5 strongest continental U.S. landfalling hurricanes (Table 6.1). Note that only two hurricanes in the list – Michael and Charley – occurred since 1970.

Table 6.1 Strongest U.S. landfalling hurricanes. Source: HURDAT Version 2 https://www.aoml.noaa.gov/hrd/tcfaq/E23.html

Storm Name	Year	Landfall winds (mph)
Labor Day	1935	184
Camille	1969	173
Andrew	1992	167
Michael	2018	160
Last Island	1856	150
Indianola	1886	150
Florida Keys	1919	150
Freeport	1932	150
Charley	2004	150
Great Miami	1926	144
Lake Okeechobee	1928	144
Donna	1960	144
Carla	1961	144

Scientists have argued (in journal publications and media interviews) that at least some aspect of each of these four hurricanes was made worse by human-caused global warming: track, intensity, size, rainfall. Here we assess the arguments for claiming a contribution from global warming for each of these four impactful hurricanes.

6.1 Detection and attribution of extreme weather events

Given the challenges to actually detecting a change in extreme weather events owing to the large impact of natural variability, the detection step is often skipped and attribution arguments are made, independent of detection. There are two general types of extreme event attribution methods that do not rely on detection: physical reasoning and fraction of attributable risk (NCA4, 2017).

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[4] https://www.nhc.noaa.gov/news/UpdatedCostliest.pdf

The fraction of attributable risk approach examines whether the odds of occurrence of a type of extreme event have changed. A conditional approach employs a climate model to estimate the probability of occurrence of a weather or climate event within two climate states: one state with anthropogenic influence and the other state without anthropogenic influence (pre-industrial conditions). The fraction of attributable risk framework examines whether the odds of an event occurring have been increased due to manmade climate change.

Participants at the 2012 Workshop on Attribution of Climate-related Events at Oxford University questioned whether extreme event attribution was possible at all, given the inadequacies of the current generation of climate models (Nature, 2012):

> "One critic argued that, given the insufficient observational data and the coarse and mathematically far-from-perfect climate models used to generate attribution claims, they are unjustifiably speculative, basically unverifiable and better not made at all."

Given the inadequacies of climate models particularly for simulating hurricanes, attribution arguments related to individual hurricanes typically rely on the physical reasoning approach. The physical reasoning approach, often referred to as the conditional or ingredients-based approach, looks for changes in occurrence of atmospheric circulation and weather patterns relevant to the extreme event, or considers the impact of certain environmental changes (e.g. greater atmospheric moisture) on the character of an extreme event.

6.2 Hurricane Sandy

Hurricane Sandy made landfall on 10/22/12 near Atlantic City, NJ. Hurricane Sandy's most substantial impact was a storm surge. The highest measured storm surge from Sandy was 9.4 feet (at The Battery)[5]. The argument is that human-caused global warming worsened the storm surge because of sea level rise.

Curry (2018a) summarized sea level rise at The Battery. Sea level has risen 11 inches over the past century (Figure 6.1), with almost half of this sea level rise caused by subsidence (sinking of the land). Kemp et al. (2017) found that relative sea level in New York City rose by ~1.70 meters [5.5 feet] since ~575 A.D. A recent acceleration in sea level rise between 2000 and 2014 has been attributed to an increase in the Atlantic Multidecadal Oscillation and southward migration of the Gulf Stream North Wall Index. The extent to which manmade warming is accelerating sea level rise remains disputed (as summarized by Curry, 2018a).

When Hurricane Sandy made landfall on the mid-Atlantic coast, it was no longer classified as a tropical cyclone, but its maximum wind speed at landfall was equivalent to a Category 1 hurricane. As a result of its transition from a tropical cyclone, Sandy became a hybrid storm, which greatly increased its horizontal size and contributed to large storm surge.

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[5] https://www.weather.gov/okx/HurricaneSandy

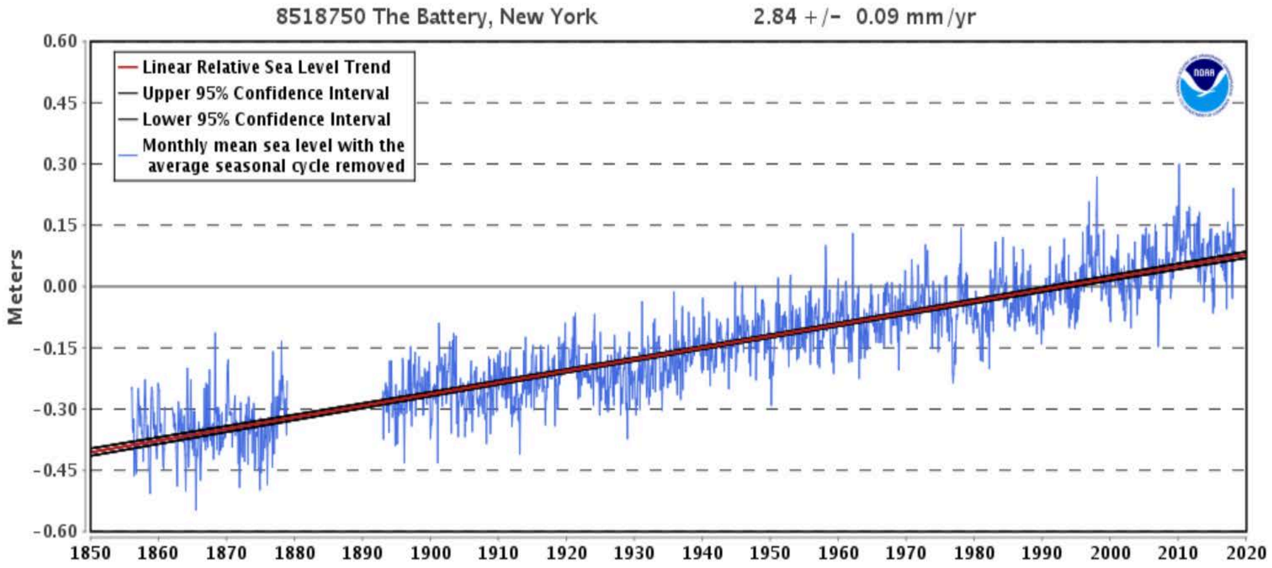

Figure 6.1. Tide gauge measurements at The Battery, New York, obtained from NOAA (downloaded 8/2/18).https://tidesandcurrents.noaa.gov/sltrends/.

The National Climate Assessment (NCA4, 2017) evaluated published analyses seeking to attribute aspects related to Hurricane Sandy to manmade global warming: e.g. sea surface temperatures, atmospheric temperatures, atmospheric moisture, and hurricane size.

> "In summary, while there is agreement that sea level rise alone has caused greater storm surge risk in the New York City area, there is low confidence on whether a number of other important determinants of storm surge climate risk, such as the frequency, size, or intensity of Sandy-like storms in the New York region, have increased or decreased due to anthropogenic warming to date."

Summary. There is no evidence of a global warming signal on impacts from Hurricane Sandy. Recent sea level rise is only a small fraction of the overall storm surge magnitude. Sandy's storm surge was relatively large for a Category 1 hurricane, owing to its large horizontal size that was caused by Sandy's transformation to an extratropical storm.

6.3 Hurricane Harvey

Hurricane Harvey made landfall in southern Texas on August 24, 2017 as a Category 4 hurricane. The primary damage from Harvey occurred after the storm had been downgraded to a tropical storm and stalled near the coastline, dropping torrential and unprecedented amounts of rainfall over Texas.

As summarized by Landsea (2017), Harvey set the record for most amount of rainfall from a continental U.S. hurricane (60 inches), going back at least to the 1880's when comprehensive records begin. The previous top four rainfall producers were: Tropical Storm Amelia (1978) with 48 inches in Texas, Hurricane Easy (1950) with 45 inches in Florida, Tropical Storm Claudette (1979) with 45 inches in Florida, and Tropical Storm

Allison (2001) with 40 inches in Texas. Harvey's stalled, meandering track was similar to Tropical Storms Claudette and Allison. But the peak amount of rainfall from Harvey, as well as Harvey's areal extent of extreme rainfall, substantially surpassed either of these earlier storms.

Several publications based on model simulations have concluded that as much as 40% of the rainfall from Hurricane Harvey was caused by human-caused global warming (Emanuel 2017; Risser and Wehner 2017).

The rationale for these assessments was that prior to the beginning of summer of 2017, sea surface temperatures in the western Gulf of Mexico exceeded 30 ^{o}C [86 ^{o}F] and ocean heat content was the highest on record in the Gulf of Mexico (Trenberth et al. 2017). However, El Niño–Southern Oscillation (ENSO) and Atlantic circulation patterns contributed to this heat content, and hence it is very difficult to separate out any contribution from human-caused global warming.

Landsea (2017) summarizes the arguments for more rainfall from tropical cyclones traveling over a warmer ocean. Intuitively, rainfall from hurricanes might be expected to increase with a warmer ocean, as a warmer atmosphere can hold more moisture. Simple thermodynamic calculations suggest that the amount of rainfall in the tropical latitudes would go up about 4% per ^{o}F [7% per ^{o}C] sea surface temperature increase. Examining a 300 mile radius circle for nearly all of the rain implies that about 10% more total hurricane rainfall for a warming of 2-2.5 ^{o}F [1-1.5 ^{o}C]. The Gulf of Mexico has warmed about 0.7 ^{o}F [0.4 ^{o}C] in the last few decades (Figure 6.2). Even if it is assumed that all of this warming is due to manmade global warming suggests that roughly 3% of hurricane rainfall today can be reasonably attributed to manmade global warming. Hence, only about 2 inches of Hurricane Harvey's peak amount of 60 inches can be linked to manmade global warming.

Figure 6.3 illustrates the role of sea surface temperature in the western Gulf on Texas major hurricane landfalls. Ten major hurricane Texas landfalls were observed to occur with anomalously cool Gulf sea surface temperatures, while 11 occurred with anomalously warm Gulf sea surface temperatures.

Summary. Examination of the number and intensity of historical Texas landfalling hurricanes shows no relationship with surface temperatures in the Gulf of Mexico. Harvey's extreme rainfall has been linked to unusually high temperatures in the Gulf of Mexico that were associated primarily with local ocean circulation patterns. It has been estimated that at most about 2 inches of Hurricane Harvey's peak amount of 60 inches can be linked with manmade global warming.

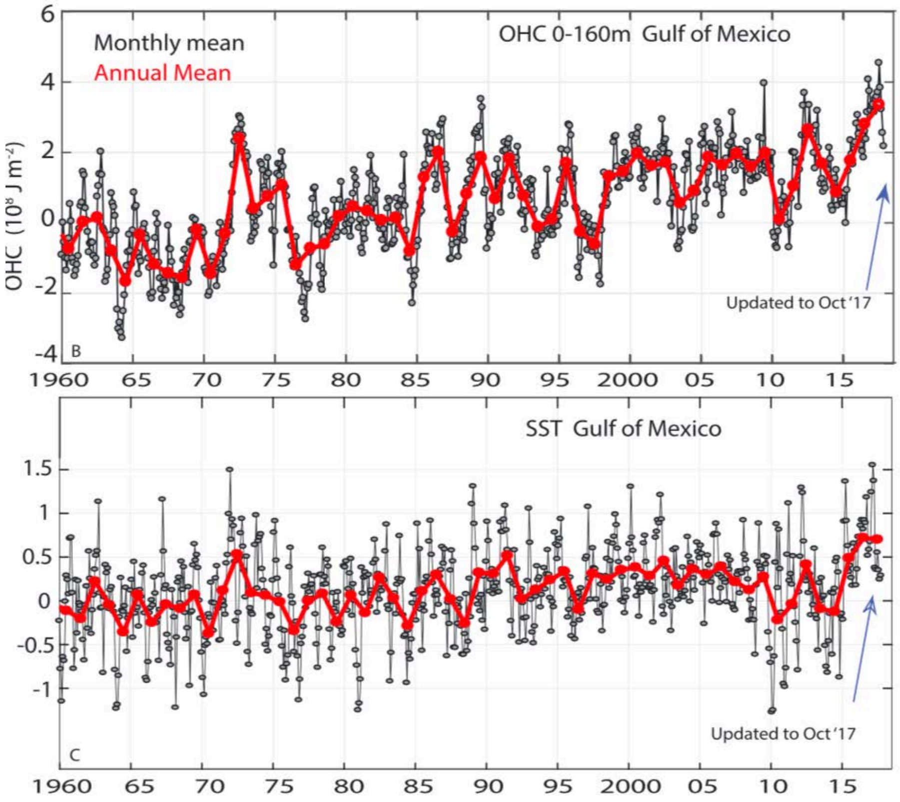

Figure 6.2. Ocean heat content anomalies (top) for the monthly (black) and annual (red) for the upper160 m in the Gulf of Mexico and sea surface temperature anomalies (bottom) in the Gulf of Mexico (^{o}C). The baseline is 1961–1990. Source: Trenberth et al. (2018)

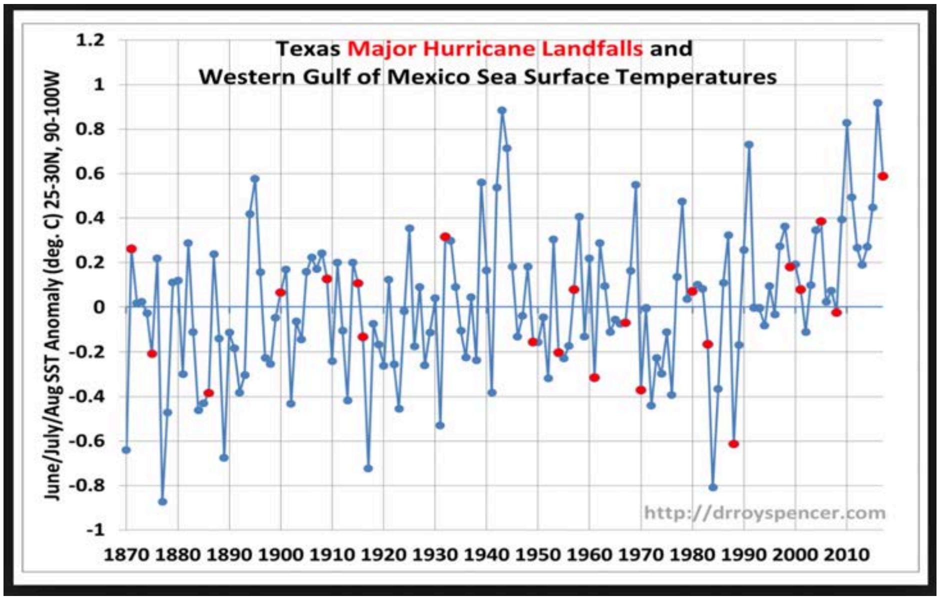

Figure 6.3. Texas major hurricane landfalls and Western Gulf of Mexico sea surface temperatures. Source: Roy Spencer

6.4 Hurricane Irma

Hurricane Irma made landfall on September 10, 2017 as a Category 4 hurricane. Hurricane Irma set several records. Irma was the 5th strongest Atlantic hurricane on record. Irma was the 2nd strongest Atlantic storm in recorded history in terms of its accumulated cyclone energy – a function both of intensity (wind speed) and duration of the storm. Irma is tied with the 1932 Cuba Hurricane for the longest time spent as a Category 5 hurricane. Hurricane Irma maintained 185-mph winds for 37 hours — longer than any storm on record globally.[6]

Irma formed and rapidly intensified to a major hurricane in the eastern Atlantic, where sea surface temperatures were 26.5 ^oC (80 ^oF). The rule of thumb for a major hurricane to develop is 28.5 ^oC. Clearly, simple thermodynamics associated with SST were not driving this intensification, but rather favorable atmospheric dynamics. In particular, wind shear was very weak. Further, the atmospheric circulation field (e.g. stretching deformation) was very favorable for spinning up this hurricane (Curry, 2017).

While the media made much ado about a global warming link to Irma's intensity, there have been no published journal articles to date that have examined this issue. This is presumably because the sea surface temperatures during Irma's development and intensification were relatively cool.

Since 1900, 14 Category 4 or 5 hurricanes have struck Florida (Table 6.2). Only two of these extremely strong hurricanes have struck Florida since 1965 – Andrew and Michael. During the period 1945-1950, 4 of these extremely strong hurricanes struck Florida.

Table 6.2 Category 4 and 5 hurricanes that have struck Florida. Source: HURDAT

Hurricane	**Wind (mph)**
Labor Day 1935	184
Andrew1992	167
Michael 2018	160
Florida Keys 1919	150
Charley 2004	150
Lake Okeechobee 1928	144
Donna 1960	144
Great Miami 1926	144
Fort Lauderdale 1947	132
Homestead 1945	132
Florida 1949	132
King 1950	132

Figure 6.4 analyzes the time series of major (Cat 3+) landfalling hurricanes in Florida since 1900. There is no significant trend in either frequency or intensity.

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[6] https://webcms.colostate.edu/tropical/media/sites/111/2017/09/Hurricane-Irma-Records.pdf

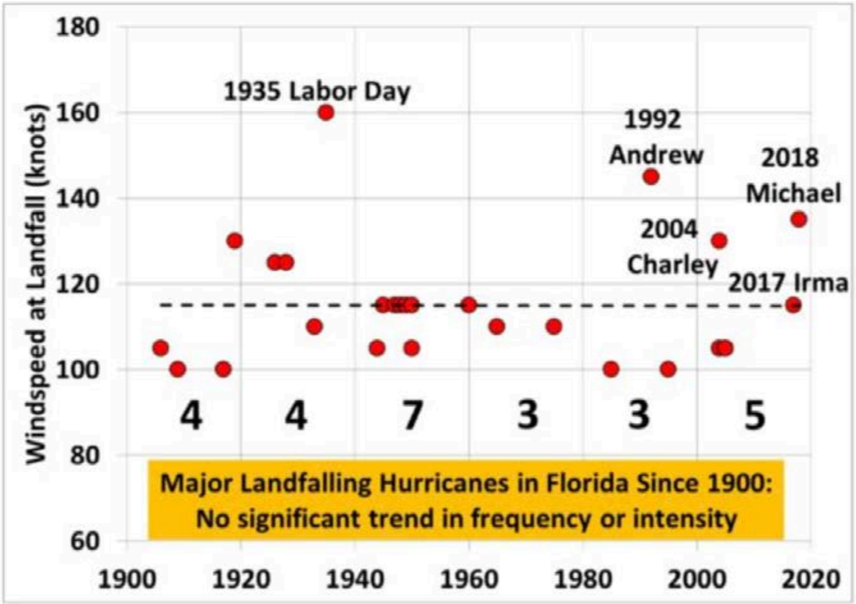

Figure 6.4 Florida major hurricane landfalls. Source: Roy Spencer

Summary. Hurricane Irma set several intensity records, although these have not been linked in any way to sea surface temperature or manmade global warming. Historical data of Florida landfalling major hurricanes indicate no trends in either frequency or intensity.

6.5 Hurricane Michael

Hurricane Michael made landfall on the Florida Panhandle on October 10, 2018 as a Category 5 hurricane. Michael was one of the strongest hurricanes in recorded Atlantic history, and ranks #4 in terms of landfall winds (Table 6.1). The National Hurricane Center estimated peak storm surge inundation of 9-14 feet on the Florida Panhandle (Table 5.2).

During late summer, Gulf of Mexico sea surface temperatures typically exceed 80 ^{o}F, which is more than sufficiently warm to sustain a major hurricane. The water in Michael's path was 2 to 4 ^{o}F warmer than usual. Since 1985, average sea surface temperatures in the Eastern Gulf of Mexico have increased by about 1 ^{o}F (Kennedy et al. 2007).

The most striking aspect of Hurricane Michael was its rapid intensification, from a Category 1 to Category 4 in 24 hours, as it traveled over a very warm patch of water off the coast of Florida. Near Florida, there are deep warm pools of water that move around (the Gulf Loop Current) in the Gulf of Mexico. If a hurricane travels over one of these deep warm pools, it will rapidly intensify if the atmospheric circulation patterns are favorable. Hurricanes Katrina and Rita in 2005 are examples of similar intensification.

For a tropical storm or hurricane to rapidly intensify, it needs three key ingredients: low wind shear, warm ocean water and high humidity. All of these ingredients were in place for Michael, which is somewhat unusual for October. Rather than the typical cold fronts bringing higher wind shear and dry air, circulation patterns were relatively stagnant, providing favorable conditions for Michael to intensify.

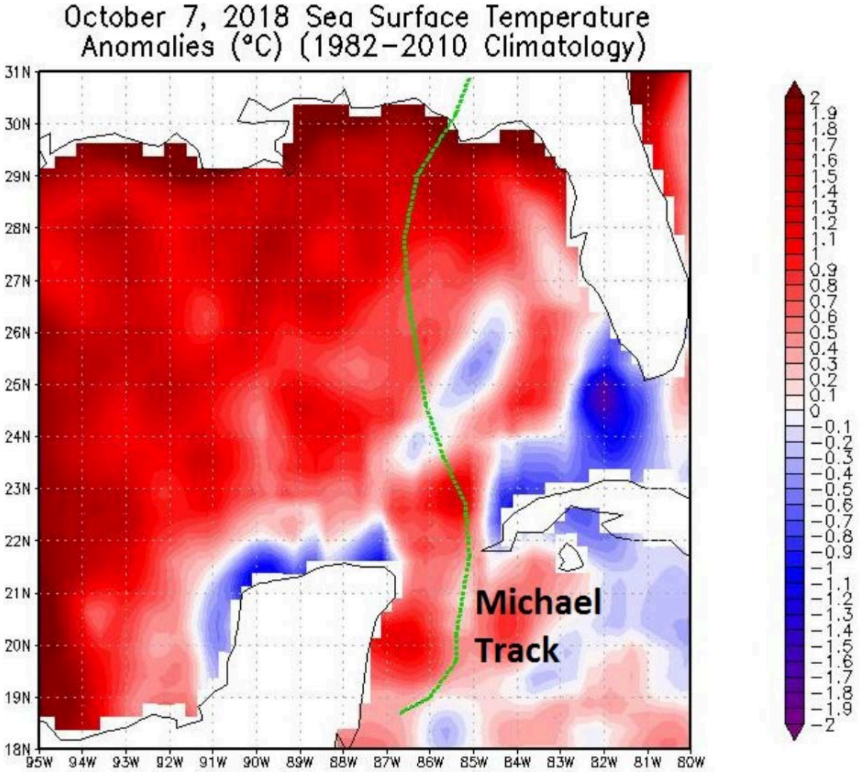

Figure 6.5 Sea surface temperature anomalies during Hurricane Michael. Source: Phil Klotzbach

A Category 4 or 5 hurricane striking the Gulf coast of Florida is nothing new (Table 6.2). The most notable of these storms in context of a manmade global warming argument is the 1848 Great Gale hurricane that struck Tampa Bay,[7] with a measured barometric pressure and storm surge that are consistent with a Category 4 hurricane. Global temperatures (and presumably the sea surface temperatures in the Gulf of Mexico) were substantially cooler in the mid 19th century.

Summary. Hurricane Michael is the third most intense hurricane in the historical record to have struck Florida. The most notable aspect of Michael was its rapid rate of intensification, which occurred as it passed over the very warm Gulf Loop Current and under exceptionally favorable atmospheric circulation patterns for October.

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[7] https://en.wikipedia.org/wiki/1848_Tampa_Bay_hurricane

6.6 Conclusions

Convincing detection and attribution of individual extreme weather events such as hurricanes requires:

- a very long time series of high-quality observations of the extreme event
- an understanding of the variability of extreme weather events associatedwith multi-decadal ocean oscillations, which requires at least a century of observations
- climate models that accurately simulate both natural internal variability on timescales of years to centuries and the extreme weather events

Of the four hurricanes considered here, only the rainfall in Hurricane Harvey passes the detection test, given that it is an event unprecedented in the historical record for a continental U.S. landfalling hurricane. Arguments attributing the high levels of rainfall to near record ocean heat content in the western Gulf of Mexico are physically plausible. The extent to which the high value of ocean heat content in the western Gulf of Mexico can be attributed to manmade global warming is debated. Owing to the large interannual and decadal variability in the Gulf of Mexico (e.g. ENSO), it is not clear that a dominant contribution from manmade warming can be identified against the background internal climate variability (Chapter 4).

7. 21st century projections

The effect of climate change on hurricanes has been a controversial scientific issue for the past several decades. While substantial uncertainties remain, improvements in the capabilities of climate models, the main tool used to predict future climate, have enabled more credible simulation of the present-day climatology of hurricanes (Walsh et al 2016). The increasing ability of climate models to predict the interannual variability of hurricanes in various regions of the globe indicates that they are capturing some of the essential physical relationships governing the links between climate and hurricanes.

This Chapter addresses climate model projections of hurricane activity out to 2100, in response to manmade global warming. Also addressed is the role of natural modes of climate variability in influencing hurricane activity out to 2050.

7.1 Climate model projections

Apart from the difficulty of simulating hurricane activity in climate models, there is substantial uncertainty associated with climate model projections of 21st century climate change, including the changes in sea surface temperatures and ocean and atmospheric circulation patterns that would cause any changes in hurricane activity. Curry (2018a; Sections 5.1, 5.6) provides an analysis of these uncertainties; a summary of that analysis is provided here.

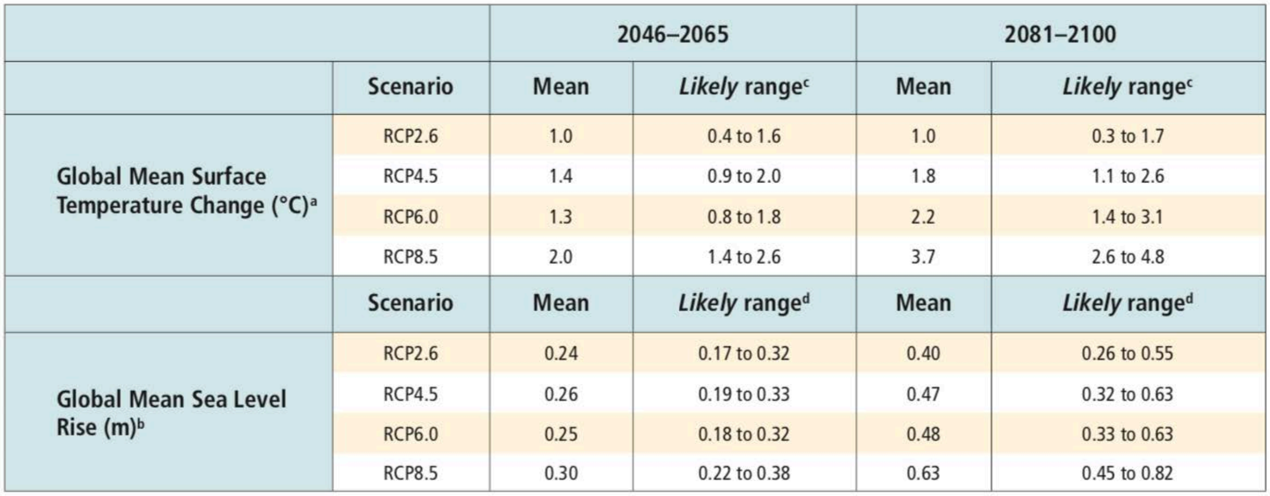
The climate model simulations of 21st century climate referenced in the IPCC AR5 (2013) are based on more than 30 different global climate models from international climate modeling groups. The climate models simulate changes based on a set of scenarios of manmade forcings from changing atmospheric composition, primarily from fossil fuel emissions. ‘Radiative forcing’ is the difference between insolation (sunlight) absorbed by the Earth and the energy radiated by the Earth and its atmosphere back to space. Radiative forcings are influences that cause changes to Earth’s climate system by altering the Earth’s radiative equilibrium, forcing temperatures to rise or fall.

A new set of emissions scenarios, the Representative Concentration Pathways (RCPs), was used for the climate model simulations in the IPCC AR5. In all RCPs, atmospheric CO_2 concentrations are higher in 2100 relative to present day as a result of a further increase of cumulative emissions of CO_2 to the atmosphere during the 21st century. The four RCPs are named according to radiative forcing target level for 2100. The radiative forcing estimates are based on the forcing of greenhouse gases and other forcing agents. The four selected RCPs include one mitigation scenario that leads to a very low forcing level (RCP2.6), two medium stabilization scenarios (RCP4.5/RCP6) and one very high emission scenario (RCP8.5).

RCP8.5 is sometimes referred to as a ‘business as usual’ scenario. It is not. Rather, it is an extreme scenario that may be impossible. Ritchie and Dowlatabadi (2017) recommend that RCP8.5 should not be used as a benchmark for future scientific research or policy studies.

Table 7.1 summarizes the IPCC AR5 temperature and sea level rise projections for 2046-2065 and 2081-2100. Eliminating RCP8.5 from further consideration here, the likely range of temperature increase by the end of the 21st century is 0.3 to 3.1°C [0.5 to 5.5°F].

Table 7.1 Projected change in global mean surface air temperature and global mean sea level rise for the mid- and late 21st century relative to the reference period of 1986-2005. [IPCC AR5 WGI]



		2046–2065		2081–2100	
	Scenario	**Mean**	***Likely* range[c]**	**Mean**	***Likely* range[c]**
Global Mean Surface Temperature Change (°C)[a]	RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8
	Scenario	**Mean**	***Likely* range[d]**	**Mean**	***Likely* range[d]**
Global Mean Sea Level Rise (m)[b]	RCP2.6	0.24	0.17 to 0.32	0.40	0.26 to 0.55
	RCP4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.63
	RCP6.0	0.25	0.18 to 0.32	0.48	0.33 to 0.63
	RCP8.5	0.30	0.22 to 0.38	0.63	0.45 to 0.82

Climate change projections for the 21st century are only as valid as the climate model simulations upon which they are based. Chapters 11 and 12 of the IPCC AR5 describes uncertainties in the climate model-based projections:

> “Projections of future states of the global climate are subject to several sources of uncertainty. The first source of uncertainty arises from natural internal variability, and includes phenomena such as variability in the mid-latitude storm tracks and the ENSO. The existence of internal variability places fundamental limits on the precision with which future climate variables can be projected. The second is uncertainty concerning the past, present and future forcing of the climate system by natural and anthropogenic forcing agents such as greenhouse gases, aerosols, solar forcing and land use change. The third is uncertainty related to the response of the climate system to the specified forcing agents, which is referred to as the ‘climate sensitivity.”
>
> “Simplifications and the interactions between parameterized and resolved processes induce ‘errors’ in models, which can have a leading-order impact on projections. Also, current models may exclude some processes that could turn out to be important for projections) or produce a common error in the representation of a particular process.”

The IPCC AR4 (2007) made the following projection for near-term warming:

> “For the next two decades, a warming of about 0.2°C per decade is projected.”

Figure 7.2 provides an update of Figure 11.25 from the IPCC AR5. It is seen that the observed temperatures between 2000-2012 are at the bottom of the envelope of climate model simulations (this period is often referred to as the ‘warming hiatus’). The red hatching in Fig. 11.25 (Figure 5.2) reflects the judgment by the AR5 authors that lowers the projected warming out to 2035 relative to the climate model simulations.

The large El Niño of 2016 returned the observed temperature curve to near the middle of the envelope of climate model simulations; however the previous large El Niño of 1998 was at the top of the envelope of climate model simulations. The recent data since 2012 continues to indicate that the sensitivity of at least some of the climate models to CO_2 forcing is too high.

A key issue is the uncertainty of sensitivity of climate models to CO_2. The equilibrium climate sensitivity (ECS) is a measure of the climate system response to sustained radiative forcing, defined as the amount of warming in response to a doubling of atmospheric CO_2.

For the past 40 years, climate scientists have presented a *likely* range for ECS that has hardly changed – the ECS range of 1.5−4.5 ^{o}C in 1979 (Charney et al. 1979) is unchanged in the 2013 IPCC AR5. While previous assessments have provided a ‘best estimate’ of 3.0 ^{o}C, the AR5 did not provide a best estimate value for ECS, stating:

> ″No best estimate for equilibrium climate sensitivity can now be given because of a lack of agreement on values across assessed lines of evidence."

At the heart of the uncertainty surrounding the values of ECS is the substantial difference between values derived from global climate models versus values derived from changes over the historical instrumental data record using global energy budget analyses. The median ECS given in IPCC AR5 for global climate models was 3.2 ^{o}C, versus 2.0 ^{o}C for the median values from historical-period energy budget based studies.

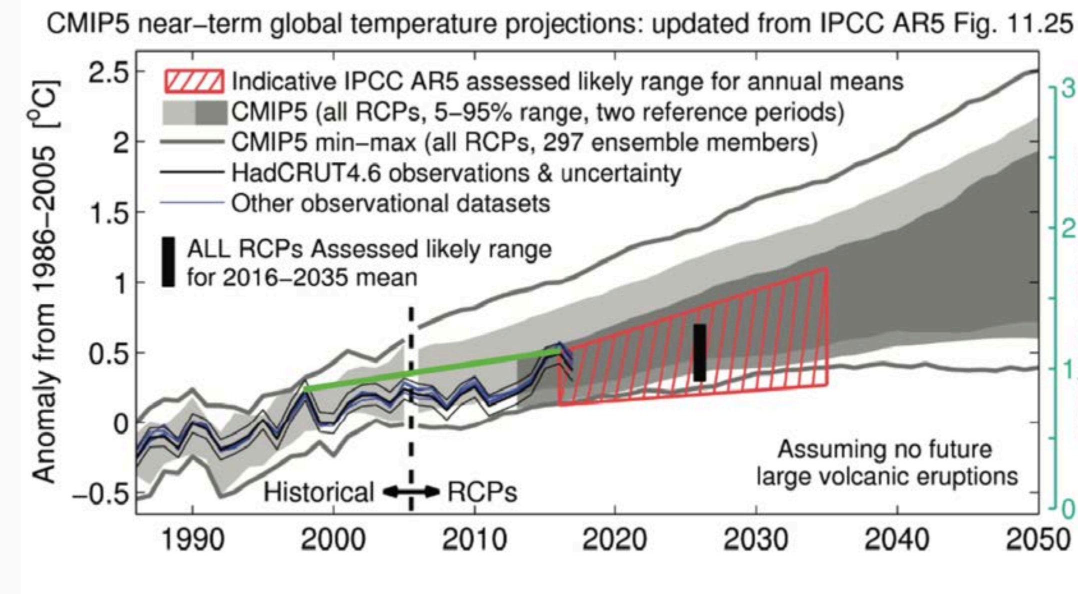


Figure 7.2 Synthesis of near-term projections of global mean surface air temperature anomalies. Projections from climate models showing the 5 to 95% range using a reference period of 1986–2005 (light grey shade). The maximum and minimum values from climate models using all ensemble members and the 1986–2005 reference period are shown by the grey lines. Black lines show annual mean observational estimates. The red-hatched region shows the indicative likely range for annual mean GMST during the period 2016–2035. [following IPCC AR5 WG I Figure 11.25; updated by Hawkins 2018]. Added green line between 1998 and 2016 reflects the trend between two strong El Niño years.

Subsequent to the IPCC AR5, Lewis and Curry (2015) used an observationally-based energy budget methodology with the AR5's global forcing and heat content estimate time series to derive a median ECS estimate of 1.6 °C, which makes the discrepancy with global climate models even larger. A recent update by Lewis and Curry (2018) concluded that high estimates of ECS derived from a majority of global climate models are statistically inconsistent with observed warming during the historical period. Lewis and Curry further concluded that the observationally-constrained values of ECS imply 21st century warming under increased CO_2 forcing of only 55-70% of the mean warming simulated by global climate models.

Apart from the uncertainties in the climate models described above, there are two overarching problems with climate model projections of 21st century climate (Curry, 2018b):

- The scenarios of future climate are incomplete, focusing only on emissions.
- The ensemble of climate models do not sample the full range of possible values of ECS, neglecting values between 1 and 2.1 °C, with values between 1.5 and 2.1 °C being within the IPCC AR5 *likely* range.

The IPCC AR5 acknowledges the constraints, assumptions, contingencies and uncertainties of their projections of future climate change:

> "With regard to solar forcing, the 1985–2005 solar cycle is repeated. Neither projections of future deviations from this solar cycle, nor future volcanic radiative forcing and their uncertainties are considered."
>
> "Any climate projection is subject to sampling uncertainties that arise because of internal variability. [P]rediction of the amplitude or phase of some mode of variability that may be important on long time scales is not addressed."

Summary. The climate model projections of 21st century surface temperature and sea level rise are contingent on the following assumptions [IPCC AR5 WG1 Section12.2.3]:

1. Emissions follow the specified concentration pathways (RCP).
2. Climate models accurately predict the amount of warming in 21st century.
3. Solar variability follows that of the late 20th century, which coincided with a Grand Solar Maximum.
4. Natural internal variability of ocean circulations does not impact temperature or sea level rise on these timescales.
5. Major volcanic eruptions are not considered.

Each of these contingent assumptions, with the possible exception of natural internal variability, likely contributes to a warm bias in the 21st century climate model projections.

7.2 2100 – manmade climate change

As summarized in Section 4.5, our basic physical understanding of hurricane processes leads us to expect the following in a warmer climate:

- increased hurricane intensity
- hurricanes are expected to produce more rainfall
- no particular rationale for an increase or decrease in the number of hurricanes.

Quantitative projections of future changes in hurricane activity require:

- projections of 21st century climate from both manmade and natural climate change
- an understanding of how and why hurricanes change with a changing climate.

As summarized in Chapter 4, our understanding of how and why hurricanes change in a changing climate is incomplete, with qualitative understanding based on analysis of limited observations and theoretical understanding. At best, climate model-based projections of future hurricane activity are contingent on the predicted amount of warming.

The IPCC AR5 (2013) provided a synthesis of global and regional model-based projections of future hurricane climatology by 2081-2100 relative to 2000-2019. Globally, their consensus projection is for decreases in hurricane numbers by approximately 5-30%, increases in the frequency of categories 4 and 5 storms by 0-25%, an increase of 0-5% in typical lifetime maximum intensity, and increases in rainfall rate by 5-20%.

Here are the conclusions from the IPCC AR5 (2013):

> "Based on process understanding and agreement in 21st century projections, it is *likely* that the global frequency of occurrence of tropical cyclones will either decrease or remain essentially unchanged, concurrent with a *likely* increase in both global mean tropical cyclone maximum wind speed and precipitation rates." [8]

A summary of research since the IPCC AR5 is provided by the NCA4 (2017), whereby some studies have provided additional support for the AR5 conclusions, and some have challenged aspects of it. In the end, the NCA4 conclusions were identical to the IPCC AR5 conclusions cited above.

7.2.1 Hurricane formation and frequency

As summarized by Walsh et al. (2016), at present there is no climate theory that can predict the formation rate of tropical cyclones from the mean climate state. It has been known for many years that there are certain atmospheric conditions that either promote or inhibit the formation of tropical cyclones, but so far an ability to relate these quantitatively to mean rates of tropical cyclone formation has not been achieved, other than by statistical means through the use of empirically-based genesis potential indices (e.g. Menkes et al. 2012).

An important test of climate model predictions of future hurricane frequency is whether the climate models can simulate the present hurricane climatology. Simulation of the climatological number of Atlantic hurricanes is particularly difficult.

Most climate models predict a decrease of the global number of hurricanes by 2100. Explanations of this decrease are linked to reduced relative humidity in the mid-levels of the atmosphere and reduced upward rising motion in hurricane formation regions. Not all methods for determining hurricane numbers identify a decrease in future numbers, however. Emanuel (2013) uses a downscaling method in which incipient tropical vortices are 'seeded' into large-scale climate conditions provided from a number of different climate models for current and future climate conditions. Emanuel's approach generates more hurricanes in a warmer world when forced with the output of climate models.

While most models predict fewer tropical cyclones globally in a warmer world, the difference in the predictions among different climate models becomes more significant when smaller regions of the globe are considered. This appears to be a particular issue in the Atlantic basin, where climate model performance has been poorer than in other oceanic regions. The issue as to whether the number of hurricanes will change in a warmer climate remains unresolved.

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[8] The terminology here for likelihood statements generally follows the conventions used in the IPCC assessments, i.e., for the assessed likelihood of an outcome or result: Very Likely: > 90%; Likely: > 66%; More Likely Than Not (or Better Than Even): >50%

Using millennia-long climate model simulations, Lavender et al. (2018) examined whether the record number of tropical cyclones in the 2005 Atlantic season is close to the maximum possible number for the present climate of that basin. They found that the likelihood that the maximum number of storms in the Atlantic could be greater than the number of events observed during the 2005 season is less than 3.5%. Hence, the 2005 season can be used as a risk management benchmark for the maximum possible number of tropical cyclones in the Atlantic.

7.2.2 Hurricane intensity

GFDL (2018) provides an analysis of the predictions of hurricane changes by 2100:

> "Hurricane intensities globally will *likely* increase on average by 1 to 10%, according to model projections for a 2 ^{o}C [4 ^{o}F] global warming. The global proportion of tropical cyclones that reach Category 4 and 5 levels will *likely* increase due to anthropogenic warming over the 21st century. There is less confidence in future projections of the global number of Category 4 and 5 storms."

With regards to the North Atlantic, GFDL (2018) provides the following assessment:

> "Current climate models suggest that tropical Atlantic SSTs will warm dramatically during the 21st century, and that upper tropospheric temperatures will warm even more than SSTs. Furthermore, most of the climate models project increasing levels of vertical wind shear over parts of the western tropical Atlantic. Both the increased warming of the upper troposphere relative to the surface and the increased vertical wind shear are detrimental factors for hurricane development and intensification, while warmer SSTs favor development and intensification."
>
> "The GFDL hurricane model supports the notion of a substantial *decrease* (~25%) in the overall number of Atlantic hurricanes and tropical storms with projected 21st century climate warming. However, the hurricane model also projects that the lifetime maximum intensity of Atlantic hurricanes will increase by about 5% during the 21st century. At present we have only low confidence for an increase in category 4 and 5 storms in the Atlantic; confidence in an increase in category 4 and 5 storms is higher at the global scale."

The tradeoff between a 25% decrease in the overall number of hurricanes versus a 5% increase in intensity in terms of damage from hurricane landfalls is not clear. To put a 5% increase in intensity into perspective, consider Hurricane Michael's (2017) maximum intensity at landfall of 160 mph. A 5% increase in 2100 would result in an intensity of 168 mph. A 5% increase is smaller than the 10% uncertainty in landfall intensity for Hurricane Michael cited by the National Hurricane Center.[9]

Using the GFDL hurricane modeling system, Knutson et al. (2015) found that projected median hurricane size is found to remain nearly constant globally, with increases in most basins offset by decreases in the northwest Pacific.

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[9] https://www.nhc.noaa.gov/data/tcr/AL142018_Michael.pdf

Changes in surface and subsurface ocean conditions can both influence a hurricane's intensification. Huang et al. (2014) suggest a suppressive effect of subsurface oceans on the intensification of future hurricanes. Under global warming, the subsurface vertical temperature profile may contribute to a stronger ocean cooling effect during the intensification of future hurricanes. Emanuel (2015) estimated that the effect of such increased upper ocean stratification is relatively small, reducing the projected intensification of hurricanes by only about 10%–15%.

The largest increase in Category 4-5 Atlantic hurricanes is predicted by Bender et al. (2010). Owing to the large interannual to decadal variability of SST and hurricane activity in the basin, Bender et al. estimate that detection of an anthropogenic influence on intense hurricanes would not be expected for a number of decades, even assuming a large underlying increasing trend (+10% per decade).

7.2.3 Rainfall

An increase in rainfall from hurricanes in a warmer climate is a consistent finding from climate model simulations and is supported by basic theoretical considerations. Hurricane rainfall rates will likely increase in the future due to manmade global warming and the accompanying increase in atmospheric moisture content (GFDL, 2018). Modeling studies on average project an increase on the order of 10-15% for rainfall rates averaged within about 100 km of the storm for a 2^{o}C [4^{o}F] global warming scenario. Improved analyses of the global satellite rainfall data is needed to better constrain these numbers.

7.3 2050 – decadal variability

Climate-model based projections of future hurricane activity have focused on the impacts of manmade climate change. It is of substantial interest to understand how hurricane activity might vary on timescales out to 2050, associated with the known modes of interannual and decadal variability in specific ocean basins.

The evolution of climate on decadal time scales is the combined result of A decadal climate prediction attempts to simultaneously forecast the evolution of an externally forced component – due to greenhouse gases, aerosols and the sun – and natural internal variability of the climate system over the next few decades.

The Decadal Climate Prediction Project (DCPP) is a coordinated investigation into decadal climate prediction and variability. The IPCC AR5 [WGI; Chapter 11] concluded that: "There is limited agreement and medium evidence that the Atlantic and Pacific patterns of climate variation exhibit predictability on timescales up to a decade."

The next generation of the DCPP simulations is described by Boer et al. (2016), for the CMIP6 and the forthcoming IPCC AR6 Report. At this point, the climate models, even when the oceans are initialized with current observations, do not have any prediction skill beyond a decade at most. The biggest challenge is predicting shifts in the Atlantic and Pacific patterns of decadal variability (e.g. AMO, PDO).

7.3.1 Scenarios of decadal variability

Given the challenges associated with climate model predictions on decadal scales, an alternative approach is to consider possible future scenarios of the indices of decadal climate variability and shifts in the multidecadal indices such as the AMO and PDO. Section 4.3 described the natural internal modes of variability, including the Atlantic Multidecadal Oscillation (AMO), North Atlantic Oscillation (NAO), Atlantic Multidecadal Mode (AMM), Pacific Decadal Oscillation (PDO) and the North Pacific Gyre Oscillation (NPGO).

Among these modes, a forthcoming shift in the phase of the AMO (away from the current warm phase to the cool phase) would have the greatest impact on Atlantic hurricanes Frajka-Williams et al. (2017) report a decline in the AMO index since 2013.

The timing of a shift to the AMO cold phase is not predictable; it depends to some extent on unpredictable weather variability. However, analysis of historical and paleoclimatic records suggest that a transition to the cold phase is expected prior to 2050. Enfield and Cid-Serrano (2006) used paleoclimate reconstructions of the AMO to develop a probabilistic projection of the next AMO shift. Figure 7.3 shows the probability of an AMO shift relative to the number of years since the last regime shift. The previous regime shift occurred in 1995; hence in 2019, it has been 24 years since the previous shift. Figure 7.3 indicates that a shift to the cold phase should occur within the next 15 years, with a 50% probability of the shift occurring in the next 7 years.

The implications of a shift to the cool phase of the AMO on Atlantic hurricanes include:

- fewer major hurricanes and lower values of Accumulated Cyclone Energy (ACE)
- fewer landfalls striking Florida, the U.S. east coast and the Caribbean

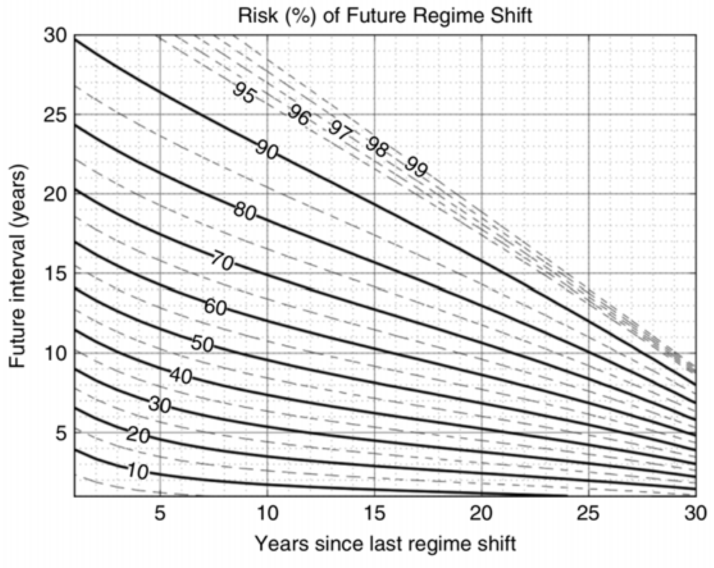

Figure 7.3 Probability of an AMO regime shift relative the number of years since the last regime shift. Source: Enfield and Cid-Serrano (2006)

7.3.2 Scenarios of interannual variability

Atlantic hurricane statistics for the period to 2050 depend not only on the timing of a shift of the AMO to the cool phase, but also on the variability of the other climate indices.

Caron et al. (2014) found that while some influences, such as ENSO, remain present regardless of the AMO phase, other climate factors show an influence during only one of the two phases. During the negative AMO phase, Sahel precipitation and the NAO play a role, while during the positive AMO phase, the 11-year solar cycle and dust concentration over the Atlantic appear to be more important.

Lim et al. (2016) showed that the NAO and AMM can strongly modify and even oppose the well-known ENSO impacts. Patricola et al. (2014) investigated the possible effects of combinations of extreme phases of the AMM and ENSO. Individually, the negative AMM phase and El Niño each inhibit Atlantic hurricanes, and vice versa. Simultaneous strong El Nino and strongly positive AMM, as well as strong concurrent La Niña and negative AMM, produce near-average Atlantic ACE, suggesting compensation between the two influences. Strong La Niña and strongly positive AMM together produce extremely intense Atlantic hurricane activity, while strong El Nino and negative AMM together are not necessary conditions for significantly reduced Atlantic tropical cyclone activity.

The past decade or so has seen a preponderance of El Niño events (relative to La Niña). The PDO has been weakly negative for the past year, following a period since 2014 of mostly positive values.[10] Presumably, at some point in the next 30 years, we can expect a period when La Niña events dominate.

The general probabilistic approach used by Enfield and Cid-Serrano (2006) seems promising for developing probabilities of regime combinations, which can then be related to Atlantic hurricane activity via historical relationships with these regime indices. However, the possibility of data-driven climate dynamics-based probabilistic predictions and scenarios of decadal scale hurricane activity is largely untapped.

7.3.3 Summary

On timescales at least to 2050, variations in hurricane activity are expected to be dominated by natural variability, relative to any secular warming trends. A forthcoming shift to the cold phase of the Atlantic Multidecadal Oscillation – on a time scale of a decade or so – would result in fewer major hurricanes, lower values of Accumulated Cyclone Energy and fewer landfalls striking Florida, the U.S. east coast and the Caribbean. At some point in the coming decades, we can also anticipate a shift in the Pacific Decadal Oscillation towards more frequent La Niña events, which are associated with more activity in the Atlantic but suppressed activity in the Pacific.

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[10] https://www.ncdc.noaa.gov/teleconnections/pdo/

7.4 Landfall impacts

The most unambiguous signal for hurricane landfall impacts in a warmer climate – whatever its cause – is that projected sea level rise should be causing higher storm surge levels for hurricanes that do occur, all else being equal. As summarized by Curry (2018; Section 5.7):

> "Emissions scenario choice exerts a great deal of influence on predicted sea level rise after 2050. If RCP8.5 is rejected as an extremely unlikely scenario, then the appropriate range of sea level rise scenarios to consider for 2100 is 0.2–1.6 m [8 inches to 5 feet]; however, values exceeding 2 feet are increasingly weakly justified. Values exceeding 5 feet require a cascade of poorly understood and extremely unlikely to impossible events. Further, these values of sea level rise are contingent on the climate models predicting the correct amount of temperature increase."

Increased rainfall rates can also be expected in a warmer climate (Section 7.2.3). There is no evidence of increasing hurricane size, which influences storm surge, rainfall amounts and the number of tornadoes (Section 4.5).

If climate model projections of fewer hurricanes but a greater percentage of Category 4 and 5 storms are correct, the tradeoff between these two competing effects on overall landfall impacts is not straightforward. The statistics of rare Category 4 and 5 landfalling events are much more volatile than basin-wide hurricane metrics.

Emanuel (2011) estimated the time of emergence of global warming effects on U.S. hurricane damage. Using a hurricane synthesizer driven by outputs from global climate models, 1000 artificial 100-yr time series of Atlantic hurricanes that make landfall along the U.S. Gulf and East Coasts were generated for four climate models and for current climate conditions as well as for the warmer climate circa 2100. These synthetic hurricanes produce damage to a portfolio of insured property according to an aggregate wind-damage function. Three of the four climate models used produced increasing damage with time, with the global warming signal emerging on time scales of 40, 113, and 170 years. For the fourth climate model, damages decreased with time, but the signal was weak.

7.5 Conclusions

Substantial advances have been made in recent years in the ability of climate models to simulate the variability of hurricanes. However, inconsistent hurricane projections emerge from modeling studies due to different down-scaling methodologies and warming scenarios, inconsistencies in projected changes of large-scale conditions, and differences in model physics and tracking algorithms. Systematic numerical modeling experiments organized under the auspices of the Hurricane Working Group of the U.S. CLIVAR Program (Walsh et al. 2015) were designed to coordinate efforts to improve understanding of the variability of tropical cyclone formation in climate models. Progress continues to be made, particularly with models that are coupled to the ocean.

Apart from the challenges of simulating hurricanes in climate models, the amount of warming projected for the 21st century is associated with deep uncertainty. Hence, any projection of future hurricane activity is contingent on the amount of predicted global warming being correct.

Recent assessment reports have concluded that there is low confidence in future changes to hurricane activity, with the greatest confidence associated with an increase in hurricane induced rainfall and sea level rise that will impact the magnitude of future storm surges. Any projected change in hurricane activity is expected to be small relative to the magnitude of interannual and decadal variability in hurricane activity, and is at least several decades away from being detected.

Decadal variability of hurricane activity is expected to provide much greater variability than the signal from global warming. In particular, a shift to the cold phase of Atlantic Multidecadal Oscillation (AMO) is anticipated within the next 15 years. All other things being equal (such as the frequency of El Niño and La Niña events), the cold phase of AMO harkens reduced Atlantic hurricane activity and fewer landfalls for Florida, the east coast and the Caribbean.

8. Conclusions

Numerous assessments and reviews have been conducted of the possible role of manmade global warming on global and regional hurricane activity. This Special Report on Hurricanes and Climate Change is distinguished from recent assessments by a focus on hurricane aspects that contribute to landfall impacts, and an increased emphasis on paleotempestology and interpretation of natural variability. Arguments have been presented supporting the important and even dominant role that natural processes play in global and regional hurricane variations and change.

1. Is recent hurricane activity unusual?

In the North Atlantic, all measures of hurricane activity have increased since 1970, although comparably high levels of activity also occurred during the 1950's and 1960's. Geologic evidence indicates that the current heightened activity in the North Atlantic is not unusual, with a hyperactive period apparently occurring from 3400 to 1000 years before present. Prior to the satellite era (1970's), there are no reliable statistics on global hurricane activity. Global hurricane activity since 1970 shows no significant trends in overall frequency, although there is some evidence of increasing numbers of major hurricanes.

2. Have hurricanes worsened from manmade global warming?

Models and theory suggest that hurricane intensity and rainfall should increase in a warming climate. Convincing attribution of any changes to manmade global warming requires that a change in hurricane characteristics be identified from observations, with the change exceeding natural variability.

Any signal of increased hurricane activity has not risen above the background variability of natural climate variations. At this point, there is no convincing evidence that manmade global warming has caused a change in hurricane activity.

3. Have hurricane landfall impacts been worsened by manmade global warming?

Worldwide economic losses from landfalling tropical cyclones have increased in recent decades. In addition to the frequency and intensity of landfalling hurricanes, the following variables contribute to damage: horizontal size of the hurricane, forward speed of motion near the coast, storm surge and rainfall.

Of the recent impactful U.S. landfalling hurricanes, only the rainfall in Hurricane Harvey is unusual in context of the historical record of U.S. landfalling hurricanes. Warmer sea surface temperatures are expected to contribute to an overall increase in hurricane rainfall, although hurricane-induced rainfall and flooding is dominated by natural climate variability. Storm surge risk is increasing owing to the slow creep of sea level rise. The extent to which the recent increase in ocean temperatures and sea level rise can be attributed to manmade global warming is disputed. The primary driver for increased economic losses from landfalling hurricanes is the massive population buildup along the coasts.

4. How will hurricane activity change during the 21st century?

Recent assessment reports have concluded that there is low confidence in projections of future changes to hurricane activity. Any projected change in hurricane activity is expected to be small relative to the magnitude of natural variability in hurricane activity.

Decadal variability of hurricane activity is expected to provide much greater variability than the signal from global warming. In particular, a shift to the cold phase of Atlantic Multidecadal Oscillation (AMO) is anticipated within the next 15 years. All other things being equal (such as the frequency of El Niño and La Niña events), the cold phase of AMO harkens reduced Atlantic hurricane activity and fewer landfalls for Florida, the east coast and the Caribbean.

Attribution of the causes of change in hurricane activity and projections of future hurricane activity depends on climate models. Substantial advances have been made in recent years in the ability of climate models to simulate the variability of hurricanes. However, inconsistent hurricane projections have emerged from modeling studies. Progress continues to be made, particularly with models that are coupled to the ocean. Apart from the challenges of simulating hurricanes in climate models, the amount of warming projected by climate models for the 21st century is associated with deep uncertainty. Hence, projections of future hurricane activity are contingent on the amount of predicted global warming being correct.

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