RECOVERY, RESILIENCE, READINESS
Contending with natural disasters

Judith Curry

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About the author

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This paper is based on Dr Curry's written testimony to the Subcommittee on Environment of the Committee on Oversight and Reform of the United States House of Representatives, as part of its hearing on 'Recovery, Resilience and Readiness – Contending with Natural Disasters in the Wake of Climate Change'.

1 Introduction

Since 2006, as President of Climate Forecast Applications Network LLC, I have been helping decision makers use weather and climate information to reduce vulnerability to extreme weather and climate events. By engaging with decisionmakers in both the private and public sectors on issues related to weather and climate, I have learned about the complexity of different decisions that depend, at least in part, on weather and climate information. I have learned the importance of careful determination and conveyance of the uncertainty associated with our scientific understanding, in particular for predictions. I have found that the worst outcome for decisionmakers is a scientific conclusion or forecast issued with a high level of confidence that turns out to be wrong.

With this perspective, my testimony focuses on the following issues of central relevance to contending with natural disasters in the wake of climate change, particularly with regards to hurricanes and wildfires:

- recent US weather disasters in context of historical events
- projections of future Atlantic hurricane activity – seasonal and for, say, 2050 or 2100
- reducing vulnerability to extreme weather events in the face of a variable climate.

2 Framework

The extreme damages from recent hurricanes, wildfires and floods emphasize that the US is highly vulnerable to weather disasters. A premise of this hearing is that manmade climate change is making extreme weather worse or more frequent. However, recent international and national climate assessment reports have reported low confidence in any link between manmade climate change and observations of wildfires, hurricanes, floods and droughts.

Possible scenarios of incremental worsening of weather and climate extremes over the course of the 21st century do not change the fundamental fact that many regions of the US are not well adapted to the current weather and climate variability or to the extremes that were seen earlier in the 20th century.

Our vulnerability to weather disasters is increasing as population and wealth continue to concentrate in susceptible locations. With our growing understanding of weather and climate variability and continued improvements in weather forecasting, we are able to be proactive in preparing for weather disasters.

However, conflating the extreme weather events with manmade climate change can actually be counterproductive for understanding their variability and reducing our vulnerability to them. Natural periods of low activity can cause complacency about extreme weather. Further, blaming the recent US wildfires and hurricane landfalls on manmade climate change deflects from understanding and amelioriating the real sources of the problems, which in part include federal policies.

As a practical matter, adaptation has been driven by local crises associated with extreme weather and climate events. Early examples of infrastructure designed to reduce vulnerability to extreme weather events include: the system and levees and floodways built in response to the Great Mississippi Flood of 1927, and the construction of the Herbert Hoover Dike in response to the Lake Okeechobee hurricane in 1928.

The Federal Relief Act of 1974, the Stafford Act of 1988 and subsequent amendments have resulted in reduced overall vulnerability to some types of weather disasters, including hurricanes. The Stafford Act requires destroyed buildings to be rebuilt the same way that they existed before the disaster occurred. This enables 'bouncing back' from weather disasters. However, rather than 'bouncing back' from extreme weather and climate events, we can aim to 'bounce forward', to reduce future vulnerability and increase thrivability by evolving our infrastructures, policies and practices.

By avoiding the conflation of weather disasters with manmade climate change, the acrimony associated with the political debate surrounding climate change can be avoided. Bipartisan support seems feasible for pragmatic efforts to reduce our vulnerability to extreme weather events and increase thrivability.

3 Recent US weather disasters in context

In the last few years, the US has suffered multiple devastating weather disasters. However, the sense that extreme weather events are now more frequent or intense, and attributable to manmade global warming, is symptomatic of 'weather amnesia.' As an example of this phenomenon, consider the data for US tornadoes for the last decade. From 2012 to 2018, US tornadoes were well below average.[1] The above-average tornadic activity so far in 2019 therefore appears more extreme; expectations are shaped mainly by recent history.

As another example, the devastating impacts in 2017 from Hurricanes Harvey, Irma and Maria invoked numerous alarming statements about hurricanes and global warming. However, it was rarely mentioned that 2017 broke a drought in US major hurricane landfalls that had persisted since the end of 2005. This was unprecedented in the historical record.

Looking further back into the 20th century, the 1930s hold records for many of the worst US weather disasters: [2]

- strongest landfalling hurricane (Labor Day Hurricane, 1935)
- longest and most extensive droughts, especially 1934
- largest number of severe heat waves, especially 1934.

Owing to the large natural variability in extreme weather events, it is very difficult to discern any trends in extreme weather events that can be attributed to manmade global warming. The Intergovernmental Panel on Climate Change (IPCC) Special Report on Extreme Events acknowledges that there is not yet evidence of changes in the global frequency or intensity of hurricanes, droughts, floods or wildfires.[3]

The recent Climate Science Special Report from the Fourth US National Climate Assessment (NCA4) reported the following conclusions about extreme events and climate change:[4]

> Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, the Dust Bowl era of the 1930s remains the benchmark drought and extreme heat event in the historical record. [Ch. 6]
>
> Detectable changes in some classes of flood frequency have occurred in parts of the US and are a mix of increases and decreases. Extreme precipitation is observed to have generally increased. However, formal attribution approaches have not established a significant connection of increased riverine flooding to human-induced climate change. [Ch. 8]
>
> State-level fire data over the 20th century indicates that area burned in the western United States decreased from 1916 to about 1940, was at low levels until the 1970s, then increased into the more recent period. [Ch. 8]
>
> [T]here is still low confidence that any reported long-term increases in [hurricane] activity are robust, after accounting for past changes in observing capabilities. [Ch. 9]

A summary of evidence for the variations of wildfires and US landfalling hurricanes and their causes is provided below.

Wildfires

As summarized by the National Climate Assessment Report (NCA4, Chapter 8), wildfires are influenced by a complex combination of natural and human factors. Natural factors include temperature, soil moisture, relative humidity, wind speed, and fuel density. Forest management and fire suppression practices have altered the relationship between fire and forest ecosystems.

The National Climate Assessment showed that the number of large fires increased in seven out of ten western US regions over the period 1984–2011. To understand what caused this increase, it is instructive to examine the historical record of wildfires in the 20th century and also the tree-ring record of fires back to 1600.

Littell *et al.* provide an analysis of the wildfire area burned in the western US for the period 1916–2004 (Figure 1).[5] Wildfires were elevated during the period from 1916 through to the 1930s. Wildfires during the 1950s through the 1970s were uniformly low. The current period of elevated fire activity started around 1985. Despite the influence of forest management and fire suppression practices, Littell *et al.* concluded that 39–64% of the variations in fire area burned is related directly to climate variability.

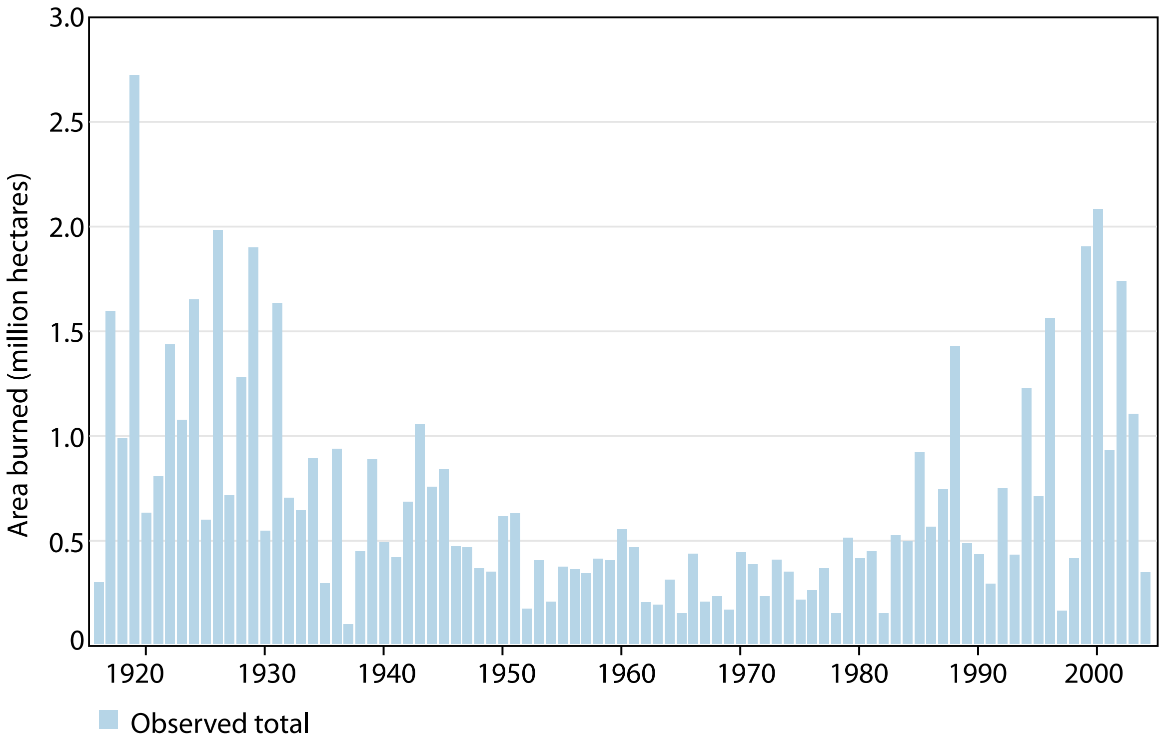


Figure 1: Wildfires in the USA.
Time series of observed total wildfire area burned (WFAB) for 11 western US states. Adapted from Littell *et al.* (2009).

A longer perspective is provided by the Swetnam *et al.* analysis of wildfire occurrence in the US over the past 400 years (Figure 2).[6] During the 18th and 19th centuries, wet/dry oscillations controlled widespread fire occurrence. In the late 19th century, intensive livestock grazing disrupted fuel continuity and fire spread, and then active fire suppression by government agencies maintained the absence of widespread surface fires during most of the 20th century. The abundance of fuels is the most important controlling variable in fire regimes of these semi-arid forests. Reduction of widespread fires over the last century reflects extensive human impacts on forests and fire regimes.

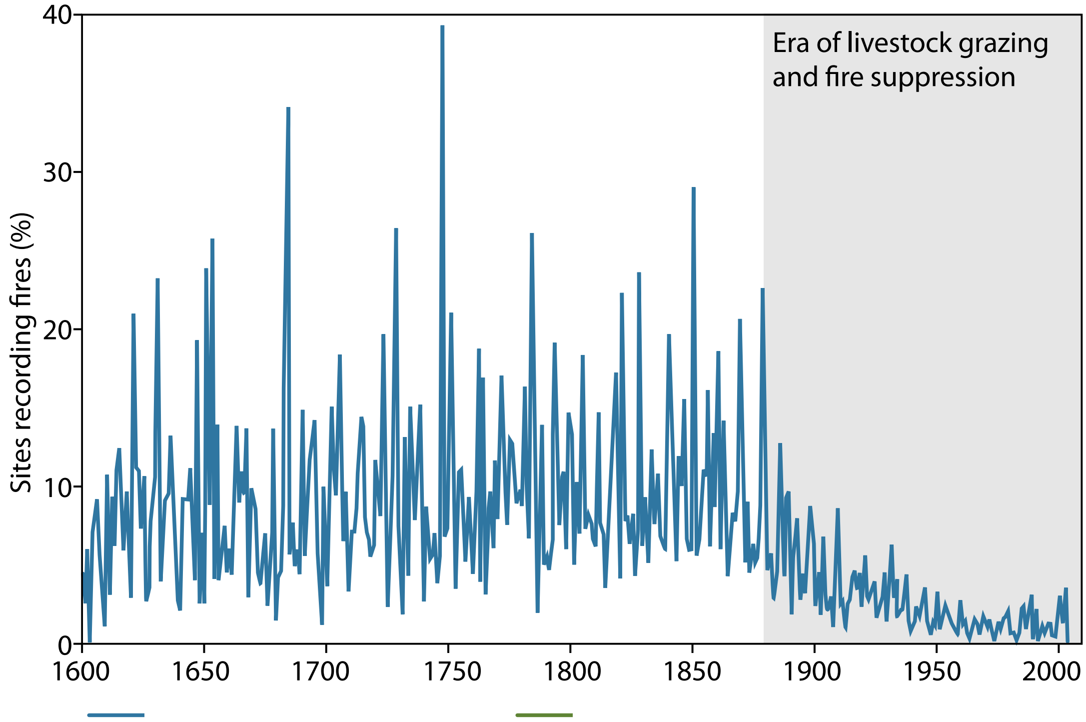


Figure 2: Fire occurrence in north America.
Combined record of fire occurrence from more than 800 sites in western North America.
Adapted from Swetnam *et al.* (2016).

To understand the climatic variations contributing to variations in wildfires, Kitzberger *et al.* examined the relationships over the past 400 years between widespread wildfires and climate modes associated with ocean circulation variations: El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Atlantic Multidecadal Oscillation (AMO).[7] These climate modes influence the temperature and moisture patterns in the western US that influence wild fires. ENSO and PDO are the main drivers of interannual-to-decadal variations in fire, whereas the AMO conditionally changes the wildfire occurrence at multidecadal scales. Periods of warm AMO are associated with drought from northern Mexico to the US Rocky Mountains–Great Plains and in the Pacific Northwest. In contrast, southern California has above-average moisture during warm AMO periods. During cool ones, there is a reduced fire risk in the southwest.

Coincident positive phases of the AMO and PDO result in drier conditions. These persist for a decade or longer in the northern tier of western US states and the Great Plains, as seen in the 1930s' droughts. In contrast, the coincidence of positive AMO and negative PDO phases are typically associated with dry and hot conditions across the southern tier of western states, as occurred during the 1950s droughts.

In the southwest and south-central Rocky Mountains, production of grass and needle litter increases during wet years, which are often associated with El Niño (warm ENSO) events. When these warm events are followed by La Niña (cold ENSO) events with their associated dry conditions, fires are synchronized across this region. In contrast to the influence of ENSO in the southwest, warmer/drier conditions in the Pacific northwest are associated with El Niño (warm ENSO) events, typically resulting in earlier melting of snowpack and hence a longer fire season.

Regarding the influence of manmade global warming on drought, the NCA4 (Ch. 11) concluded:

> Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s remains the benchmark drought and extreme heat event in the historical record. While by some measures drought has decreased over much of the continental United States in association with long-term increases in precipitation, neither the precipitation increases nor inferred drought decreases have been confidently attributed to [manmade] forcing.

The increase in wildfires since 1984 is attributable in part to state and federal policies.[8] California forest lands owned by the state and federal government have been far more vulnerable to forest fires than privately-owned lands. The National Environmental Policy Act of 1970 and the Endangered Species Act of 1973, along with state bureaucracy, contributed to an 80% reduction in the number of trees that were harvested and sold from public lands in California.[9] Drought and pestilence are catalysts, not causes, of fires in drastically overgrown forests.

Atlantic hurricanes

Over the past decade, the US has suffered multi-billion dollar losses from several hurricanes, notably Sandy (2012), Harvey (2017), Irma (2017), Maria (2017) and Michael (2018). During the devastating 2004 and 2005 hurricane seasons, Florida suffered five major (Category 3+) hurricane landfalls.

Following the devastation associated with Hurricane Katrina (2005), the debate about hurricanes and manmade global warming reached fever pitch.[10] During the period 2006–2007, I testified before the House Committee on Government Reform[11] and the Select Committee on Energy Independence and Global Warming[12] on this topic at the invitation of Democrat members.* Since then, assessment of the role of manmade global warming in hurricane activity has been the subject of numerous assessment reports and reviews. Of the more recent ones, the most thoroughly reviewed is the IPCC's 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.

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:

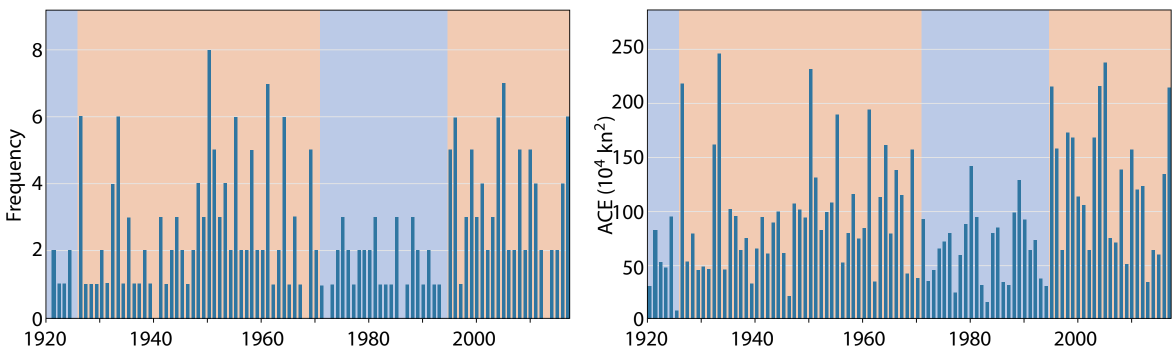
* My remarks regarding the content of this testimony, made nine years later, may also be worth reviewing.[13]

> 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[14]]

I recently prepared a comprehensive 84-page special report on hurricanes and climate change[15] that was published by my company. The material in this section is drawn from this report, which has been submitted as part of my written testimony.[†]

Atlantic hurricane activity shows strong variations on interannual, decadal and multi-decadal time scales. Similar to the climate variability of wildfires, the variability of Atlantic hurricanes and US landfalls is influenced by the climate modes associated with ocean circulation variations: ENSO, the PDO, and the AMO. These climate modes influence the atmospheric circulation patterns that are favorable (or not) for Atlantic hurricanes.

The AMO influences Atlantic hurricane activity primarily through sea surface temperatures in the Atlantic and also vertical wind shear – warm temperatures and reduced wind shear are favorable for Atlantic hurricanes. The impact of the AMO on historical Atlantic hurricane activity is illustrated in Figure 3. Accumulated cyclone energy (ACE) is an integral measure of seasonal hurricane activity that includes the number of hurricanes plus their duration and intensity. The current warm phase of the AMO began in 1995. It is associated with high ACE values and a large number of major hurricanes (Category 3+). The previous warm AMO period (1926–1970) was associated with comparably high values of ACE and major hurricanes. The cool phase of the AMO (1971–1994) was associated with lower values of ACE and substantially fewer major hurricanes. With regards to US landfalls, the frequency of Florida and east coast landfalls is substantially larger in the warm phase of the AMO, with twice as many major hurricane landfalls for warm phase versus cool phase.



(a) Frequency

(b) Accumulated cyclone energy

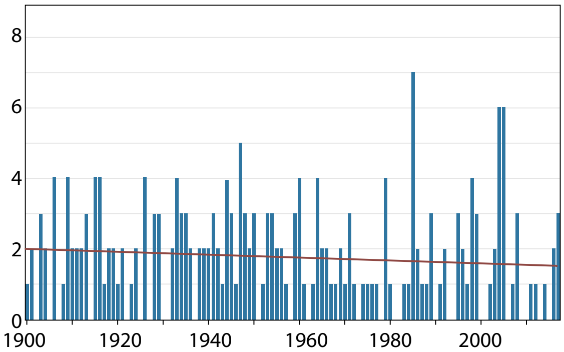
Figure 3: Observations of Atlantic hurricane activity since 1920.
The warm phase of the AMO is indicated by orange shading, with the cool phase indicated by blue shading.

US landfalling hurricanes

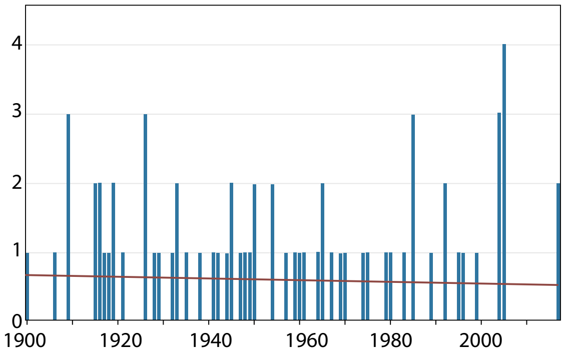
Figure 4a shows the time series of US landfalling hurricanes for the period 1900 to 2017. While the largest counts are from 1986, 2004 and 2005, there is a slight overall negative trend

† See the full report for references, documentation and data sources.

line since 1900. Figure 4b shows the time series for major hurricane landfalls (Category 3–5). The largest year in the record is 2005, with four major hurricane landfalls. However, during the period 2006 through 2016, there were no major hurricanes striking the US, which is the longest such period in the record.



(a) All hurricanes



(b) Major hurricanes

Figure 4: Continental US landfalling hurricanes 1900–2017.
The red lines represent linear trends over the period, although neither of these trends is statistically significant. Source: Klotzbach *et al.* (2018).

In addition to the multidecadal variability associated with the AMO, substantial year-to-year variability in US landfall activity is also seen in Figures 3 and 4. There are twice as many major hurricane landfalls in a La Niña year as in an El Niño year.

Table 1 lists the 13 strongest US landfalling hurricanes in the historical record. Of these, only three have occurred since 1970 (Andrew, Michael, Charley). Four of these strongest hurricanes occurred during the decade 1926 to 1935, when sea surface temperatures were substantially cooler than in recent decades.

During the past decade, we have seen four exceptionally impactful continental US landfalling hurricanes: Sandy (2012), Harvey (2017), Irma (2017) and Michael (2018). 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, and/or rainfall. A summary analysis is provided here of the role that manmade global warming might have played in exacerbating the impacts of these four storms.[‡]

Sandy There is no evidence of a global warming signal on impacts from Hurricane Sandy. The storm surge was relatively large for a Category 1 hurricane, owing to Sandy's large horizontal size of the storm, which was caused by transformation to an extratropical storm.

Harvey Examination of the number and intensity of historical Texas landfalling hurricanes shows no relationship with surface temperatures in the Gulf of Mexico. Since 1870, 10 major hurricane Texas landfalls occurred during periods with anomalously cool Gulf sea surface temperatures, while 11 occurred when there were anomalously warm Gulf sea surface temperatures. Harvey's extreme rainfall (60 inches) 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 total of 60 inches can be linked with manmade global warming.

‡ From Curry 2019, Ch. 6.

Table 1: The 13 strongest US landfalling hurricanes in the historical record.

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

Irma Hurricane Irma set several intensity records, although these have not been linked in any way to sea surface temperature or manmade global warming, owing to the fact that Irma intensified to a major hurricane over a relatively cool region of the ocean. Historical data of Florida landfalling major hurricanes indicate no trends in either frequency or intensity. During the period 1945–1950, Florida suffered from four Category 4/5 landfalls.

Michael 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. There is no obvious attribution of any of the features of Hurricane Michael to manmade global warming.

Of the recent major hurricane landfalls, only the rainfall in Hurricane Harvey passes a detection test for possible impact from manmade global warming, given that it is an event unprecedented in the historical record for a continental US landfalling hurricane.

Landfall impacts

While there is no observational evidence of increased frequency or intensity of landfalling Atlantic hurricanes, there is very clear evidence of increasing damage from landfalling hurricanes. Given that US landfalling hurricane frequency and intensity do not show significant trends, it has been argued that growth in coastal population and regional wealth are the overwhelming drivers of observed increases in hurricane-related damage.

Assessing whether there is an element of manmade global warming 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 factors contribute to damage:

- horizontal size of the hurricane

- forward speed of motion near the coast
- storm surge
- rainfall.

Increases in storm surge and rainfall have been linked to manmade climate change.[16]

Since 1900, global mean sea level has risen 7–8 inches.[17] In many of the most vulnerable US coastal locations (particularly Texas and Louisiana), more than half of the rate of sea level rise is caused by local sinking of the land.[18] Sea-level rise influences the height of storm surges, although this increase is a small fraction of the storm surge height in the strongest hurricanes, which can exceed 20 feet.

In any event, sea-level rise is a small portion of the overall US vulnerability to storm surge:[19]

- From 1990–2008, population density increased by 32% in Gulf coastal counties, 17% in Atlantic coastal counties, and 16% in Hawaii.
- Much of the densely populated Atlantic and Gulf Coast coastlines lie less than 10 feet above mean sea level.
- 72% of ports, 27% of major roads, and 9% of rail lines within the Gulf Coast region are at or below 4 feet elevation.

With regards to rainfall, warmer sea surface temperatures are expected to contribute to an overall increase in hurricane rainfall. However, whether rainfall in landfalling hurricanes has increased overall to date is disputed and remains an active area of research.

Vulnerability

Florida is the state that is most vulnerable to hurricanes, having 40% of US landfalls. The history of Florida is intimately connected with hurricanes. In the 1920s, Florida's new railroads spurred a land boom. Then the 1926 Miami hurricane nearly destroyed the city. In 1928, the Okeechobee hurricane made landfall near Palm Beach, severely damaging the local infrastructure. The storm surge at Lake Okeechobee breached a dike, killing over 2,000 people and destroying two towns. The 1926 hurricane thrust Florida into an economic depression and the 1928 hurricane effectively ended the 1920s land boom.

From 1920 to 1940, Florida's population increased by less than 1 million, and until the 1970s the Florida Keys were largely undeveloped. Between 1951 and the landfall of Hurricane Andrew in 1992, only four major hurricanes struck the state of Florida, and the population increased by 10 million between 1950 and 1990. A lull in hurricane landfalls during the 1970s and 1980s and rapid real estate development encouraged insurers to continue driving down the overall cost of homeowners' insurance, including wind damage.

The most politically important hurricane that you have probably never heard of is Hurricane Frederic, a Category 3 hurricane that struck Alabama and Mississippi in 1979. This landfall occurred shortly after FEMA was established, and led to nearly $250 million in federal aid for recovery. In 1992, following Hurricane Andrew, Robert Sheets (then Director of the National Hurricane Center) stated in Congressional testimony that he credited the aid given for recovery from Frederic with spurring development in hurricane-prone regions. [20]

The landfall of Hurricane Andrew caused the largest catastrophic loss that the insurance industry has ever experienced, and emphasized the increased exposure along Florida's coastline. Even following the catastrophic losses during 2004/2005, population and property development have continued to increase, with Florida's current population of more than 21 million people making it the third most populous state in the US.

4 Projections of future Atlantic hurricane activity

Quantitative projections of future changes in hurricane activity require:

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

While advances have been made, substantial uncertainties remain in climate model projections of future hurricane activity. Our understanding of how and why hurricanes change in a changing climate is incomplete.

Seasonal

While seasonal forecasts of Atlantic hurricane activity are of limited use for emergency managers, there is substantial interest from insurance companies, energy traders and electric power suppliers.

For the 2019 Atlantic hurricane season, a range of forecasts have recently been issued from the government, university and private sector forecasters.[21] The variation among these forecasts reflects different assumptions about the important factors that drive seasonal hurricane activity. The relatively low skill of seasonal hurricane forecasts reflects a combination of incomplete understanding and unpredictable weather variability.

CFAN's forecast is for an 2019 Atlantic season that is significantly above average activity.[22] This is based on an improved understanding of the climate dynamics of hurricanes, incorporating circulation patterns in the ocean, the lower atmosphere and the stratosphere. In late June, once the atmospheric circulations have settled into their summer pattern, CFAN will issue another forecast regarding US landfall projections. At the time of submitting this testimony, I have warned CFAN's clients of substantial US landfall risk in 2019.

2050 – decadal variability

On timescales at least to 2050, natural climate variability, rather than any warming trend, is expected to dominate hurricane variations. The biggest challenge is predicting shifts in the Atlantic and Pacific patterns of decadal variability. Climate models have minimal skill in predicting such shifts.[23]

A forthcoming shift to the cold phase of the AMO would result in fewer major hurricanes and fewer landfalls striking Florida, the US east coast and the Caribbean islands. An analogue for the cool phase of the AMO is the reduced level of hurricane activity observed between 1971 and 1994 (see Figures 3 and 4). 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 a transition to the cold phase within the next 15 years, with a 50% probability of the shift occurring in the next 7 years.

Atlantic hurricane outcomes out 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. The past decade has seen a preponderance of El Niño events (relative to La Niña). The Pacific Decadal Oscillation (PDO) has been weakly negative for the past year, following a period since 2014 of mostly positive values. At some point in the coming decades, we can anticipate a shift towards more frequent La Niña events, which would exacerbate Atlantic hurricane activity and US landfalls.

In summary, for the next three decades the following scenarios should be considered:

- 2020s: continued elevated hurricane activity, which could be exacerbated by a preponderance of La Niña events.
- 2030s: a shift to the cool phase of the AMO, associated with overall fewer major hurricanes and fewer landfalls striking Florida, the US east coast and Puerto Rico.
- 2040s: continued cool phase of the AMO, with overall reduced activity. Year-to-year variability depends on the distribution of El Niño, La Niña and Modoki[24] events. Severe landfall years may occur, associated with La Niña or Modoki events.

These scenarios of future decadal variability are also relevant for wildfires. A shift to the cool phase of the AMO would contribute to reduced wildfire occurrence in the western USA.

2100 – manmade climate change

The IPCC AR5 (2013) said of hurricanes and climate change:

> 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.[25]

A summary of relevant research since the IPCC AR5 is provided by the NCA4 report, in which some studies provided additional support for the AR5 conclusions, and others challenged aspects of it. In the end, the NCA4 conclusions were identical to those of IPCC AR5.

Apart from the challenges of simulating hurricanes in climate models, the amount of warming projected for the 21st century is associated with deep uncertainty, because of uncertainties in the sensitivity of the amount of warming to carbon dioxide concentrations, and also 21st-century scenarios of solar variability, volcanic eruptions and ocean circulation patterns.[26] Therefore, any projection of future hurricane activity associated with manmade climate change is contingent on the amount of predicted global warming being correct.

The National Oceanic and Atmospheric Administration's GFDL[§] unit provides the following assessment of 21st century North Atlantic hurricanes:[27]

> 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.

§ Geophysical Fluid Dynamics Laboratory.

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.[28]

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. As summarized by GFDL (2018),[29] hurricane rainfall rates will likely increase due to manmade global warming because of the accompanying increase in atmospheric moisture content. However, the magnitude of an increase in rainfall is uncertain. Improved analyses of the global satellite rainfall data is needed to better constrain and evaluate these numbers.

The most unambiguous signal for hurricane landfall impacts in a warmer climate is that sea-level rise will cause higher storm-surge levels, although expected values of sea-level rise are small by comparison with significant hurricane-induced surges. Relative to the 7 inches or so of sea level rise that occurred in the 20th century, projections of sea level rise for 2100 exceeding 2 feet are increasingly weakly justified.[30] Projections exceeding 5 feet require a cascade of poorly understood and extremely unlikely or even impossible events. Further, these projections of sea-level rise are contingent on the climate models predicting the correct magnitude of temperature increase.

In summary, recent assessment reports have concluded that there is low confidence in projected 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 from manmade global warming is expected to be small relative to the magnitude of natural interannual and decadal variability in hurricane activity, and is decades away from being detected.

5 Resilience, anti-fragility and thrivability

The paradox of weather disasters is that they are, at the same time, highly surprising as well as quite predictable. We should not be surprised by extreme weather events, when comparable events have occurred in the past century. With regards to the frequency of extreme weather events, return periods, such as a 1-in-100-year event, are relatively meaningless for rare events, particularly under conditions of climate variability and change on multidecadal-to-centennial timescales. Further, extreme weather events can occur in clusters, such as the large number of major hurricane landfalls in 2004/2005. These defy any statistical analysis of their return based on the historical record.

Possible scenarios of incremental worsening of weather and climate extremes over the course of the 21st century do not change the fundamental fact that many regions of the US are not well adapted to the current range of extreme weather events, or to the range of extreme weather events that has been experienced over the past century.

Extreme weather/climate events, such as landfalling major hurricanes and wildfires, become catastrophes through a combination of large populations, land-use practices and ecosystem degradation. Regions that find solutions to current problems of climate variability and extreme weather events will be well prepared to cope with any additional stresses from future climate change.

Advocates of adaptation to climate change are not arguing for simply responding to events and changes after they occur; they are arguing for anticipatory adaptation. However, in adapting to climate change, we need to acknowledge that we cannot know exactly how the climate will evolve in the 21st century, we are certain to be surprised, and we will make mistakes along the way.

'Resilience' is the ability to 'bounce back' in the face of unexpected events. Resilience carries a connotation of returning to the original state as quickly as possible. Resilience in this sense has been codified by the Stafford Act, whereby any buildings that are destroyed are to be rebuilt exactly how they were, without any updates or additional fortification.

Instead of 'bouncing back,' we can 'bounce forward', reducing future vulnerability by evolving our infrastructures, institutions and practices. Nassim Nicholas Taleb's concept of 'antifragility' [31] focuses on learning from adversity, and developing approaches that enable us to thrive during high levels of volatility, particularly unexpected extreme events. Antifragility goes beyond 'bouncing back' to becoming better as a result of encountering and overcoming challenges. Antifragile systems are dynamic rather than static, thriving and growing in new directions rather than simply maintaining the status quo.

Similar to anti-fragility, the concept of 'thrivability' has been articulated by Jean Russell:[32]

> It isn't enough to repair the damage our progress has brought. It is also not enough to manage our risks and be more shock-resistant. Now is not only the time to course correct and be more resilient. It is a time to imagine what we can generate for the world. Not only can we work to minimize our footprint but we can also create positive handprints. It is time to strive for a world that thrives.

A focus on policies that support resilience, anti-fragility and thrivability reduces our vulnerability to extreme weather events and doesn't rely on highly uncertain predictions of the future climate.

6 Ways forward – adaptation

Adaptation to extreme weather can take a variety of forms: development of advance warning systems, risk-management plans, 'hard' structures like sea walls, and ecosystem-based adaptation that seeks to use natural systems as a way to buffer against the worst impacts. Strategies that promote thrivability simultaneously protect against various aspects of extreme weather events while providing other benefits to human and/or natural systems.

With regards to wildfires, our forests are catastrophically overgrown and policy changes are needed. However, the US west will continue to burn if we blame the problem on climate change and focus only on what to do after lives and property have been destroyed. Proper management of forests includes tree thinning, controlled burns on public lands, and removal of dead trees. Dead trees that are not removed serve as kindling to feed the next fires. Further, replacing fully grown trees with young, growing trees helps increase the overall carbon sequestration by forests.

The need for adaptation strategies to deal with increased hurricane activity was emphasized in a statement made in 2006 by 10 scientists (including myself) who were involved in both sides of what was an acrimonious debate over hurricanes and global warming. The statement is reproduced here in its entirety. [33]

Statement on the US Hurricane Problem July 25th 2006

As the Atlantic hurricane season gets underway, the possible influence of climate change on hurricane activity is receiving renewed attention. While the debate on this issue is of considerable scientific and societal interest and concern, it should in no event detract from the main hurricane problem facing the United States: the ever-growing concentration of population and wealth in vulnerable coastal regions. These demographic trends are setting us up for rapidly increasing human and economic losses from hurricane disasters, especially in this era of heightened activity. Scores of scientists and engineers had warned of the threat to New Orleans long before climate change was seriously considered, and a Katrina-like storm or worse was (and is) inevitable even in a stable climate.

Rapidly escalating hurricane damage in recent decades owes much to government policies that serve to subsidize risk. State regulation of insurance is captive to political pressures that hold down premiums in risky coastal areas at the expense of higher premiums in less risky places. Federal flood insurance programs likewise undercharge property owners in vulnerable areas. Federal disaster policies, while providing obvious humanitarian benefits, also serve to promote risky behavior in the long run.

We are optimistic that continued research will eventually resolve much of the current controversy over the effect of climate change on hurricanes. But the more urgent problem of our lemming-like march to the sea requires immediate and sustained attention. We call upon leaders of government and industry to undertake a comprehensive evaluation of building practices, and insurance, land use, and disaster relief policies that currently serve to promote an ever-increasing vulnerability to hurricanes.

Kerry Emanuel, Richard Anthes, Judith Curry, James Elsner, Greg Holland, Phil Klotzbach, Tom Knutson, Chris Landsea, Max Mayfield, Peter Webster

Electric power Wildfires and hurricanes both cause substantial power outages. Electric power lines have been implicated as causes of the recent California fires. In the aftermath of Hurricane Sandy in 2012, many electric power providers[34] in hurricane prone regions have made efforts to harden their facilities and equipment. Upgrades include more resilient cables, poles that can withstand high winds, upgrading circuits to make them more resistant to tree and limb damage, adding redundancies to the power delivery system, installation of microgrids to power critical loads during grid outages, and burying high voltage networks. In flood-prone locations, companies have installed gates and floodwalls and raised critical equipment out of harm's way.

Hurricanes Irma and Maria hit Puerto Rico hard in 2017, knocking out power to nearly the entire island for extended periods. The Puerto Rico Power Authority is working to modernize their power system to include hardening of facilities to withstand hurricane-force winds and flooding and improving reliability for transmission, substation and distribution assets. This is an example of responding to a weather disaster by 'bouncing forward.'

Wind and solar power have a growing presence in wildfire and hurricane-prone regions. When wind speeds are high, wind turbines automatically turn off. However, most wind turbines are not built to withstand a direct hit from the strongest hurricanes,[35] and rapid changes in wind direction can also damage wind turbines. During Hurricane Florence's 2018 landfall in North Carolina, solar farms fared very well, with minimal wind damage, while the damage to rooftop solar was much greater. The stronger winds in Hurricane Maria caused greater damage to solar panels,[36] with some systems surviving unscathed and others sustaining extensive damage. The damage was associated primarily with failures in the racking supports. Most places in Florida require solar installations to withstand winds of 160 mph.

In principle, rooftop solar can provide on-site power supply during an outage. However, if utility power goes down as a result of the storm, home solar systems that are on the grid will shut down as well (a safety feature for line workers).

One of the challenges to making electric power systems more resilient is that state regulatory roadblocks often hinder implementation of resilience solutions (e.g. complex approval processes of regulators needed before making infrastructure investments).

One of my clients in the electric power sector recently contacted me regarding a proposed upgrade to a power plant. They contacted me because they were concerned about possible impacts of climate change on the siting of the power plant, particularly sea-level rise. The power plant was to be located right on the coast in a region that is prone to hurricanes. While the proposed plant would have some fortifications for hurricanes, my client wasn't too worried since the company had power plants in that location since the 1970s and they had not yet been hit by a hurricane. I provided my client with data that showed several major hurricane landfalls impacting their location back in the 19th and early 20th centuries, with large storm surges.

Worrying about climate change over the expected lifecycle of the power plant was not the issue that they should be concerned about; rather, they should be concerned about the prospect of a major hurricane landfall and storm surge, which has happened before. I told the client that if this were my power plant, I would be siting it inland, away from the storm surge footprint. However, a different site wasn't an option, since the regulatory requirements were much simpler for upgrading a plant in an existing location; a proposal for a new location would be much harder to get approved and would take years. Such regulatory roadblocks do not help electric power providers make sensible decisions regarding infrastructure siting.

Tactical adaptation practices can also play a large role in reducing the vulnerability of electric power systems prior to extreme weather events. Actions taken by electric power companies in the hours and days prior to the extreme weather event can substantially reduce vulnerability of the power system and lessen the duration and extent of power outages.

Following the catastrophic California wildfires in 2017, Pacific Gas and Electric instituted a policy of de-energizing the power lines during periods of high winds. It did not de-energize the lines prior to the Camp Fire in November 2018, in spite of high winds. The challenge is to effectively utilize a network of wind sensors along with high-resolution weather prediction models in managing electric power systems under conditions of high winds.[37]

Following the extensive electric power outages from Hurricane Sandy in 2012, I was contacted by an electric utility company in a hurricane-prone region. They wanted extended-range forecasts of landfalling hurricane winds at high spatial resolution. CFAN developed a forecast product for hurricane landfall winds that is being used to drive their outage model, which predicts the numbers and locations of downed power lines and transformer outages. The outage model provides an estimate of the number of emergency line workers that are needed and where to place them. The repair crews are then in place prior to the hurricane landfall. This strategy has helped this electric utility company rapidly restore power following recent landfalling hurricanes.

7 Conclusions

Possible scenarios of incremental worsening of weather and climate extremes over the course of the 21st century don't change the fundamental fact that many regions of the US are not well adapted to the current weather and climate variability or to the extremes that were seen earlier in the 20th century. Conflating the issue of extreme weather events with man-made climate change can actually be counterproductive for understanding the variability of extreme weather events and reducing our vulnerability.

We have an opportunity to be proactive in preparing for weather disasters. Rather than focusing on recovery from extreme weather events, we can aim to reduce future vulnerability and increase thrivability by evolving our infrastructures, policies and practices.

Apart from infrastructure improvements, improvements to federal and state policies can substantially reduce the occurrence and extent of wildfires, and can help mitigate the damage associated with landfalling hurricanes. Further, tactical adaptation practices incorporating tailored weather forecast products can help mitigate the damages associated with extreme weather events.

Bipartisan support seems feasible for pragmatic efforts that reduce our vulnerability to extreme weather events and increase thrivability.

Notes

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The Global Warming Policy Foundation is an all-party and non-party think tank and a registered educational charity which, while openminded on the contested science of global warming, is deeply concerned about the costs and other implications of many of the policies currently being advocated.

Our main focus is to analyse global warming policies and their economic and other implications. Our aim is to provide the most robust and reliable economic analysis and advice. Above all we seek to inform the media, politicians and the public, in a newsworthy way, on the subject in general and on the misinformation to which they are all too frequently being subjected at the present time.

The key to the success of the GWPF is the trust and credibility that we have earned in the eyes of a growing number of policy makers, journalists and the interested public. The GWPF is funded overwhelmingly by voluntary donations from a number of private individuals and charitable trusts. In order to make clear its complete independence, it does not accept gifts from either energy companies or anyone with a significant interest in an energy company.

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