STATEMENT TO THE
COMMITTEE ON OVERSIGHT AND REFORM
SUBCOMMITTEE ON ENVIRONMENT
OF THE UNITED STATES HOUSE OF REPRESENTATIVES

Hearing on
Recovery, Resilience and Readiness –
Contending with Natural Disasters in the Wake of Climate Change

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I thank the Chairman, Ranking Member and the Subcommittee for the opportunity to offer testimony on 'Recovery, Resilience and Readiness – Contending with Natural Disasters in the Wake of Climate Change.' I am President of Climate Forecast Applications Network (CFAN) and Professor Emerita and former Chair of the School of Earth and Atmospheric Sciences at the Georgia Institute of Technology. I have devoted four decades to conducting research on a variety of topics related to weather and climate. My company, Climate Forecast Applications Network (CFAN), provides predictions of extreme weather including hurricanes on time scales from days to decades.

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 decision makers 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 and particularly for predictions. I have found that the worst outcome for decision makers 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 U.S. weather disasters in context of historical events
- Projections of future Atlantic hurricane activity – seasonal, 2050, 2100
- Reducing vulnerability to extreme weather events in the face of a variable climate

Framework

The extreme damages from recent hurricanes, wildfires and floods emphasize that the U.S. 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 don't change the fundamental fact that many regions of the U.S. 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 issue of extreme weather events with manmade climate change can actually be counterproductive for understanding the variability of extreme weather events and reducing our vulnerability. Natural periods of low activity can cause complacency about extreme weather. Further, blaming the recent U.S. 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 build in response to the Great Mississippi Flood of 1927; and 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.

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.

Recent U.S. weather disasters in context

In the last few years, the U.S. 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 weather amnesia, consider the data for U.S. tornadoes for the last decade. From 2012 to 2018, U.S. tornadoes were well below average.[1] The above average tornadic activity so far in 2019 appears more extreme if 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 U.S. major hurricane landfalls since the end of 2005 - a major hurricane drought that is unprecedented in the historical record.

Looking further back into the 20th century, the 1930's hold records for many of the worst U.S. 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*[3] acknowledges that there is not yet evidence of changes in the global frequency or intensity of hurricanes, droughts, floods or wildfires.

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

- "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 U.S. 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 U.S. landfalling hurricanes and their causes is provided below.

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1 https://www.spc.noaa.gov/wcm/

2 Curry, JA 2014 Senate EPW testimony https://curryja.files.wordpress.com/2014/01/curry-senatetestimony-2014-final.pdf

3 IPCC Special Report on Extreme Events http://www.ipcc.ch/report/srex/

4 4th National Climate Assessment Vol 1 https://www.globalchange.gov/nca4

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 7 out of 10 western U.S. regions over the period 1984 to 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. (2009)[5] provide an analysis of the wildfire area burned in the western U.S. for the period 1916-2004 (Figure 1). Wildfires were elevated during the period 1916 through the 1930s. Wildfires during the 1950's through the 1970's 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.

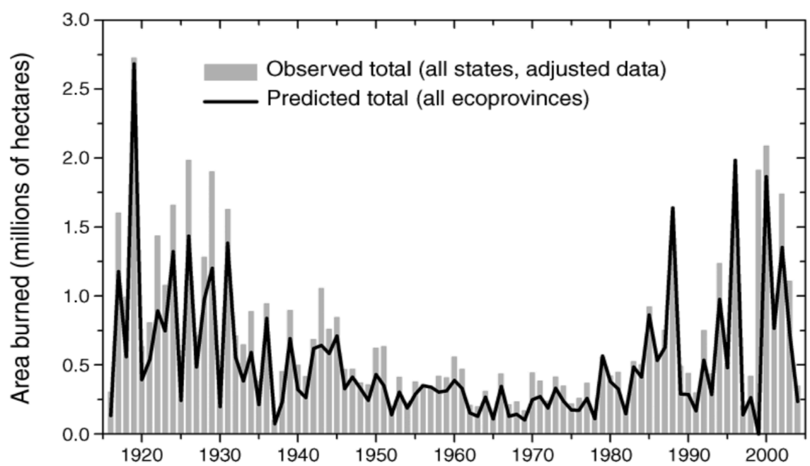

Figure 1. Time series of observed total wildfire area burned (WFAB) for 11 western U.S. states and reconstructed total WFAB for 16 ecoprovinces for the period 1916–2004. Source: Littell et al. (2009)

A longer perspective is provided by the Swetnam et al. (2016)[6] analysis of wildfire occurrence in the U.S. over the past 400 years (Figure 2). 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.

5 https://pdfs.semanticscholar.org/4af3/67682e73d0f2a2d45592baa571bf5332bfe3.pdf
6 https://royalsocietypublishing.org/doi/pdf/10.1098/rstb.2015.0168

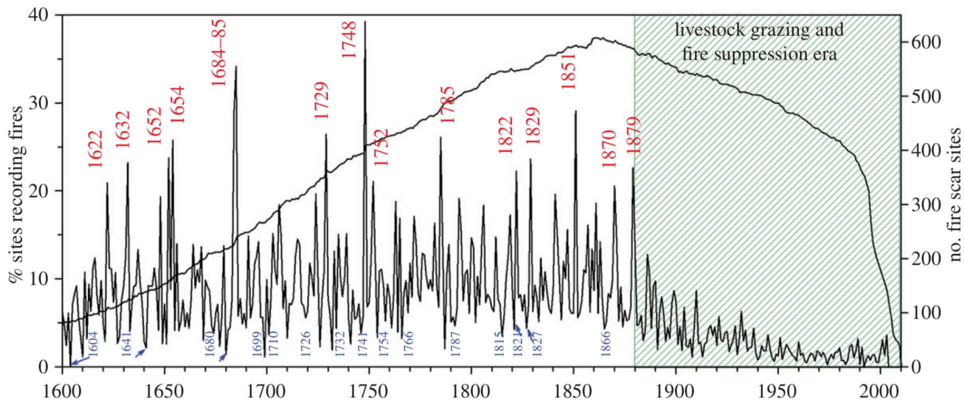

Figure 2. Combined record of fire occurrence from more than 800 sites in western North America. The 15 largest and smallest fire years are labelled.. From Swetnam et al. (2016)

To understand the climatic variations contributing to variations in wildfires, Kitzberger et al. (2007)[7] examined the relationships over the past 400 years between widespread wildfires and climate modes associated with ocean circulation variations: El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO). These climate modes influence the temperature and moisture patterns in the western U.S. 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 U.S. Rocky Mountains–Great Plains and in the Pacific Northwest. In contrast, southern California has above average moisture during warm AMO. During cool AMO, there is a reduced fire in the Southwest.

Coincident positive phases of the AMO and PDO result in drier conditions that persist for a decade or longer in the northern tier of western U.S. states and the Great Plains, which characterized the 1930's 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 is increased 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."

[7] https://www.researchgate.net/publication/6604237_Contigent_Pacific-Atlantic_Ocean_influence_on_multicentury_wildfire_synchrony_over_western_North_America

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 U.S. has suffered multi-billion dollar losses from several hurricanes, notably Sandy (2012), Harvey (2017), Irma (2017), Maria (2017) and Michael (2018). Earlier in the 21st century saw the devastating 2004 and 2005 hurricane seasons, when Florida suffered 5 major hurricane (Category 3+) 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 (invited by Democrats). [see my remarks regarding the content of this testimony, 9 years later].[13]

Since then, assessment of the role of manmade global warming on hurricane activity has been the subject of numerous assessment reports and reviews. Of the most 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."

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:

> "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* (Curry 2019)[15] that was published as a Technical Report by my company, Climate Forecast Applications Network (CFAN). The material in this section is drawn from this Report, which has been submitted as part of my written testimony (see the full Report for references, documentation and data sources).

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[8] https://www.hoover.org/research/californias-forest-fire-tragedy
[9] https://goldrushcam.com/sierrasuntimes/index.php/news/local-news/11451-addressing-the-resilient-federal-forests-act-congressman-tom-mcclintock-says-we-are-running-out-of-forests-to-save
[10] https://journals.ametsoc.org/doi/pdf/10.1175/BAMS-87-8-1025
[11] http://curry.eas.gatech.edu/climate/pdf/testimony-curry.pdf
[12] https://www.markey.senate.gov/GlobalWarming/tools/assets/files/0294.pdf
[13] https://judithcurry.com/2015/08/30/hurricanes-and-global-warming-10-years-post-katrina/
[14] https://www.sciencefriday.com/segments/hurricane-harvey-and-the-new-normal/
[15] https://docs.wixstatic.com/ugd/867d28_3de3fc17844d4725b0bd33961cefe4cd.pdf

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 U.S. landfalls is influenced by the climate modes associated with ocean circulation variations: El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO). These climate modes influence the atmospheric circulation patterns that are favorable (or not) for Atlantic hurricanes.

The Atlantic Multidecadal Oscillation (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, which 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 U.S. 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.

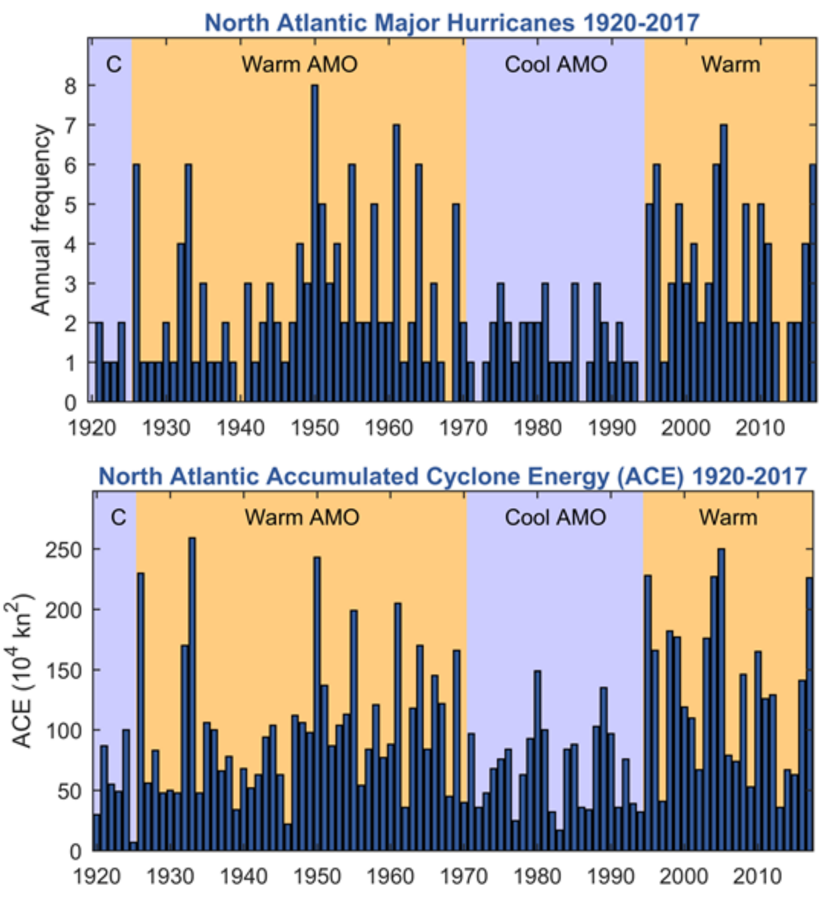

Figure 3 Observations of Atlantic hurricane activity since 1920. The warm phase of the Atlantic Multidecadal Oscillation is indicated by orange shading, with the cool phase indicated by purple shading. Top: Annual frequency of major hurricanes. Bottom: Annual frequency of Accumulated Cyclone Energy (ACE).

U.S. landfalling hurricanes

Figure 4 (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. Figure 4 (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.

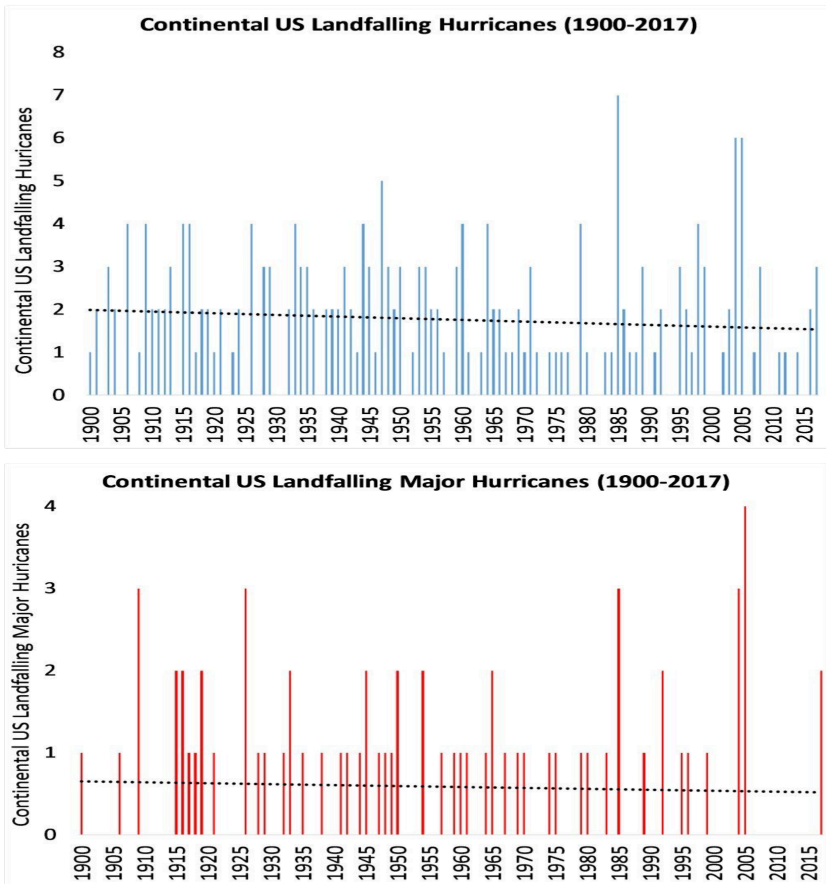

Figure 4: Time series from 1900 to 2017 for continental U.S. landfalling hurricanes (top) and major hurricanes (bottom). The dotted lines represent linear trends over the period, although neither of these trends is statistically significant. Source: Klotzbach et al. (2018).

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

Table 1 lists the 13 strongest U.S. landfalling hurricanes in the historical record. Of these storms, 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.

Table 1 Strongest continental U.S. landfalling hurricanes.

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

During the past decade, we have seen four exceptionally impactful continental U.S. 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 (Curry 2019, Chapter 6).

Sandy. There is no evidence of a global warming signal on impacts from Hurricane Sandy. Sandy's storm surge was relatively large for a Category 1 hurricane, owing to the large horizontal size of the storm that was caused by Sandy's 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, ten major hurricane Texas landfalls occurred with anomalously cool Gulf sea surface temperatures, while 11 occurred with 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 peak amount of 60 inches can be linked with manmade global warming.

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 U.S. 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 U.S. 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 and rainfall. Increases in storm surge and rainfall have been linked to manmade climate change (Curry 2019, section 5.6).

Since 1900, global mean sea level has risen 7-8 inches (see Curry 2018[16] for an overview). In many of the most vulnerable U.S. coastal locations (particularly Texas and Louisiana), more than half of the rate of sea level rise is caused by local sinking of the land (Curry 2018, section 6.3). 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 that can exceed 20 feet.

In any event, sea level rise is a small portion of the overall U.S. vulnerability to storm surge:[17]

- 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 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 has increased overall in landfalling hurricanes to date is disputed and remains an active area of research.

Vulnerability

Florida is the state that is most vulnerable to hurricanes, with 40% of the U.S. landfalls striking Florida. The history of Florida is intimately connected with hurricanes.

In the 1920's, the 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 storm surge in Lake Okeechobee breached a dike that killed over 2,000 people and destroyed two towns. The 1926 hurricane thrust Florida into an economic depression and the 1928 hurricane effectively ended the 1920's land boom.

From 1920 to 1940, Florida population increased by less than 1 million, and until the 1970's the Florida Keys were largely undeveloped. Between 1951 and until Hurricane Andrew in 1992, only 4 major hurricanes struck the state of Florida, and the population increased by 10 million between 1950

[16] https://docs.wixstatic.com/ugd/867d28_f535b847c8c749ad95f19cf28142256e.pdf
[17] https://www.nhc.noaa.gov/surge/

and 1990. A lull in hurricane landfalls during the 1970's and 1980's and rapid real estate development encouraged insurers to continue driving down the overall cost of the 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 was the focal point for 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 for Frederic's recovery with spurring development in hurricane prone regions.[18]

The landfall of Hurricane Andrew caused the largest catastrophic loss that the insurance industry had 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 U.S.

Projections of future Atlantic hurricane activity

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.

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[19] have recently been issued from the government, university and private sector forecasters. 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[20] is for an active 2019 Atlantic season (significantly above average activity). CFAN's forecast is based on an improved understanding of the climate dynamics of hurricanes that incorporates circulation patterns in the ocean, lower atmosphere and stratosphere. Once the atmospheric circulations have settled into their summer pattern, CFAN will issue another forecast in late June regarding U.S. landfall projections. At the time of submitting this testimony, I have warned CFAN's clients of substantial U.S. landfall risk in 2019.

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[18] https://en.wikipedia.org/wiki/Hurricane_Frederic
[19] http://seasonalhurricanepredictions.bsc.es/predictions
[20] https://docs.wixstatic.com/ugd/867d28_ca610d2d03ed42feab5263246985f310.pdf

2050 – decadal variability

On timescales at least to 2050, natural climate variability is expected to dominate future hurricane variations, rather than any warming trend. The biggest challenge is predicting shifts in the Atlantic and Pacific patterns of decadal variability. Climate models have minimal skill in predicting such shifts (see Curry 2019 Section 7.3).

A forthcoming shift to the cold phase of the Atlantic Multidecadal Oscillation (AMO) would result in fewer major hurricanes and fewer landfalls striking Florida, the U.S. 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 (Figures 3, 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 U.S. landfalls.

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

- 2020's: continued elevated hurricane activity, which could be exacerbated by a preponderance of La Nina events.
- 2030's: a shift to the cool phase of the AMO, associated with overall fewer major hurricanes and fewer landfalls striking Florida, the U.S. east coast and Puerto Rico.
- 2040's: 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[21] events. Severe landfall years may occur, associated with La Nina or Modoki events.

These scenarios of future decadal variability are also relevant for wildfires. A shift to the cool phase of the AMO would to contribute to reduced wildfire occurrence in the western U.S.[12]

2100 – manmade climate change

The IPCC AR5 (2013) made the following statement regarding 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."[22]

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

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[21] http://www.sciencemag.org/content/325/5936/77.abstract

[22] 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%

Apart from the challenges of simulating hurricanes in climate models, the amount of warming projected for the 21st century is associated with deep uncertainty. This deep uncertainty is associated with uncertainties in the sensitivity of the amount of warming to CO_2 concentrations, plus 21st century scenarios of solar variability, volcanic eruptions and ocean circulation patterns (IPCC AR5, Ch. 11,12). Hence, any projection of future hurricane activity associated with manmade climate change is contingent on the amount of predicted global warming being correct.

With regards to projections of 21st century North Atlantic hurricanes, GFDL (2018)[23] provides the following assessment:

> "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."

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.[24]

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), hurricane rainfall rates will likely increase due to manmade global warming and 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 projected sea level rise will cause higher storm surge levels, although expected values of sea level rise are a small fraction of significant hurricane-induced surges. As summarized by Curry (2018; Section 5.7), 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. Projections exceeding 5 feet require a cascade of poorly understood and extremely unlikely to impossible events. Further, these projections of sea level rise are contingent on the climate models predicting the correct magnitude of temperature increase.

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.

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[23] https://www.gfdl.noaa.gov/global-warming-and-hurricanes/
[24] https://www.nhc.noaa.gov/data/tcr/AL142018_Michael.pdf

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 multi-decadal to century time scales. Further, extreme weather events can occur in clusters, such as the large number of major hurricane landfalls in 2004/2005, which 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 don't change the fundamental fact that many regions of the U.S. 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 it was, without any updates or additional fortification.

Instead of 'bouncing back,' we can 'bounce forward' to reduce future vulnerability by evolving our infrastructures, institutions and practices. Nicholas Taleb's concept of antifragility[25] focuses on learning from adversity, and developing approaches that enable us to thrive from high levels of volatility, particularly unexpected extreme events. Anti-fragility goes beyond 'bouncing back' to becoming even better as a result of encountering and overcoming challenges. Anti-fragile 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:[26]

> "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.

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[25] Taleb, (2012) Antifragile: Things That Gain From Disorder. Random House.
[26] Russell (2013) https://www.amazon.com/Thrivability-Breaking-through-World-Works/dp/1909470287

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 U.S. 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 aren't 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) that were involved in both sides of what was an acrimonious debate over hurricanes and global warming. The statement is reproduced here in its entirety:[27]

> **Statement on the U.S. 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

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[27] http://wind.mit.edu/~emanuel/Hurricane_threat.htm

Electric power

Wild fires and hurricanes both cause substantial power outages. Electric power lines have been implicated in the causes of the recent California fires. In the aftermath of Hurricane Sandy (2012), many electric power providers[28] 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,[29] 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,[30] 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 process 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 1970's and they hadn't 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

[28] https://www.energy.gov/policy/initiatives/partnership-energy-secot-climate-resilience
[29] https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017GL073537
[30] https://rmi.org/solar-under-storm-designing-hurricane-resilient-pv-systems/

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. PG&E 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.[31]

Following the extensive electric power outages from Hurricane Sandy (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 that 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.

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 U.S. 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 manmade 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.

[31] https://cliffmass.blogspot.com/2018/11/why-did-catastrophic-camp-fire-start.html

Short Biography

Dr. Judith Curry is President of Climate Forecast Applications Network (CFAN) and Professor Emerita and former Chair of Earth and Atmospheric Sciences at the Georgia Institute of Technology. Dr. Curry received a Ph.D. in atmospheric science from the University of Chicago in 1982. Prior to joining the faculty at Georgia Tech, she held faculty positions at the University of Colorado, Penn State and Purdue University. She has authored over 190 scientific papers and is author of the textbooks *Thermodynamics of Atmospheres and Oceans* and *Thermodynamics, Kinetics and Microphysics of Clouds*. Dr. Curry has served on the NASA Advisory Council Earth Science Subcommittee, the DOE Biological and Environmental Research Advisory Committee, the National Academies Climate Research Committee and the Space Studies Board, and the NOAA Climate Working Group. Dr. Curry is a Fellow of the American Meteorological Society, the American Association for the Advancement of Science, and the American Geophysical Union.

Climate Forecast Applications Network

Climate Forecast Applications Network (CFAN; http://www.cfanclimate.net) develops innovative weather and climate forecast tools to help clients manage weather and climate risks. CFAN provides forecasts on timescales from days to decades. Forecast products include forecasts of temperature and renewables (wind, solar) for the energy sector, hurricanes and severe convective weather. CFAN's clients include other weather service providers, energy and power companies, insurance and asset management companies, government agencies, nongovernmental organizations and development banks. Recent government research grants to CFAN include a NOAA contract to improve subseasonal weather forecasts, a DOE contract to develop extended-range regional wind power forecasts, and a DOD contract to predict extreme weather/climate events having implications for regional stability.

Previous Congressional testimony

- House Committee on Natural Resources, "Climate Change: The Impacts and Need to Act," 2/6/19 https://curryja.files.wordpress.com/2019/02/curry-testimony-house-natural-resources.pdf
- House Committee on Science, Space & Technology, "Using Technology to Address Climate Change," 5/16/18 https://curryja.files.wordpress.com/2018/05/curry-house-science-testimony.pdf
- House Committee on Science Space & Technology, "Climate Science: Assumptions, Policy Implications and the Scientific Method," 3/29/17 https://curryja.files.wordpress.com/2017/03/curry-house-science-testimony-mar-17.pdf
- Senate Subcommittee on Space, Science & Competitiveness, "Data or Dogma? Promoting Open Inquiry in the Debate Over the Magnitude of Human Impact on Climate Change,"12/8/15 https://curryja.files.wordpress.com/2015/12/curry-senate- testimony-2015.pdf
- House Committee on Science, Space & Technology, "The President's U.N. Climate Pledge," 4/15/15, https://curryja.files.wordpress.com/2015/12/curry-senate-testimony-2015.pdf
- Senate Committee on Environment & Public Works, "President's Climate Action Plan," 1/16/14 https://curryja.files.wordpress.com/2014/01/curry-senatetestimony-2014-final.pdf
- House Subcommittee on Energy & Environment, "Policy Relevant Climate Issues in Context", 4/26/13 http://curryja.files.wordpress.com/2013/04/curry-testimony-2013-il.pdf
- House Subcommittee on Energy & Environment, "Rational Discussion of Climate Change: the Science, the Evidence, the Response," 11/17/10 http://curryja.files.wordpress.com/2013/02/curry-epw-testimony.pdf
- House Select Committee on Energy Independence and Global Warming, "Dangerous Climate Change," 4/26/07 http://curryja.files.wordpress.com/2013/02/energy-curry-testimony.pdf
- House Reform Committee, "Hurricanes and Global Warming," 7/20/06 http://curry.eas.gatech.edu/climate/pdf/testimony-curry.pdf