FINGERPRINTS EVERYWHERE

Review and Analysis of Detection and Attribution Studies Identifying the Fingerprint of Climate Change in US and Global Trends and Events

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SUMMARY

This report presents the results of a comprehensive literature review and meta-analysis of studies that positively identify the fingerprint of human-caused climate change on observed trends and events. The review is limited to detection and attribution studies on climate impacts in the United States and studies of global significance. It does not assess the robustness of the statements or methods used by individual studies.

The review identified 216 detection and attribution studies that documented the fingerprint of anthropogenic climate change, published between December 1995 and August 2018. Among these studies, human-caused climate change due to greenhouse gas emissions was found to have a direct hand in 88 distinct climate change trends or events.[1] Among 93 studies with findings specific to the United States, climate change was found to have a direct hand in 48 trends or events. Among 128 global studies, climate change had a direct hand in 40 distinct trends and events.[2]

In the US, human-caused climate change is directly implicated in rising and extreme temperatures, coastal flooding, extreme precipitation events, reduced snowpack and hydrological changes in the West, increased average precipitation in the Northeast and North Central US, increased drought risk, extreme hurricane seasons in the central Pacific, changing atmospheric patterns, and heightened wildfire risk.

Globally, climate change due to human activity is directly implicated in long-term warming of the atmosphere and ocean, record-breaking and extreme heat events, changes in average precipitation and atmospheric moisture content, extreme precipitation, sea level rise, extreme Arctic warmth and sea ice loss, tropical cyclone activity, acidification, biological systems, and large scale circulation.

1. A single study may identify multiple fingerprints, while several studies may support the same fingerprint.

2. The balance of global versus US trends and events reflects a well-known sampling bias in the literature. The distance between the lead author's home and the trend or event being studied is not a random variable. Researchers tend to investigate things in their own country.

Tech. Sgt. Keith Berry looks down into flooded streets searching for survivors post-Hurricane Katrina.

INTRODUCTION

Climate Signals conducted a detection and attribution literature review of climate change studies since the 1990s that show human-caused climate change has had a significant influence on observed trends—such as surface warming or atmospheric moisture increase—and events—such as heat waves or storms.

The report does not include detection and attribution studies unable to find evidence of climate change. The failure of those studies to find a fingerprint does not necessarily mean there isn't one, rather only that this particular direction of research was unable to find evidence indicating a link.[3] The report also does not assess the robustness of the statements or methods used by individual studies. See Appendix A for information about detection and attribution methods.

This literature review is a response to the need to better understand the breadth, depth and character of the existing research identifying the influence of human-caused global warming on observable trends and events. By identifying and quantifying the influence of climate change on distinct trends and events, detection and attribution studies close the gap between greenhouse gas emissions and consequences for humans. And as the collection of studies grows, the opportunity for deeper understanding of the consequences of climate change widens.

The review is limited to studies of local significance in the United States and studies of global significance. Studies of global significance include those attributing global warming to changes in large-scale dynamic and thermodynamic processes that have complex and far-reaching impacts, such as long-term global temperature rise and atmospheric moisture increase. It also includes studies on changes with global implications, such as ice sheet melt and Arctic sea ice decline. Finally, studies of global significance include those on topics of general concern, such as coral bleaching in the Great Barrier Reef, a world heritage site. It does not include studies of primarily local significance outside of the United States. See Appendix B for more details.

There is a complete list of studies included in this report available at www.climatesignals.org/reports/attribution-report.

Climate Signals has also established an independent database of attribution studies that will be updated regularly as new studies are published at www.climatesignals.org/reports/attribution.

3. The 2016 National Academy of Sciences report on extreme weather and climate change is dispositive about the treatment of such studies (National Academies of Sciences, 2016). The report states that the failure to find the fingerprint of climate change "should not be regarded as evidence...of...no effect," and further that it does not "necessarily mean that the effect is small." According to the Academy report, the blanket statement that we cannot attribute any single event to climate change "is no longer true."

BACKGROUND

Human greenhouse gas emissions have profoundly impacted the global climate, natural systems and human infrastructure.

Decades of research now documents the impacts of climate change. These impacts are clear, costly and widespread. The direct, causal link between increasing concentrations of heat-trapping gases in the air and rising global temperature is undisputed in the peer-reviewed literature. As the the science has become stronger, it has become clear that human activities are primarily, if not exclusively, responsible for the global warming trend (USGCRP, 2017).

Temperature plays a major role in the global climate system, and in an exceptionally short time span (from a geological perspective), the Earth's average surface temperature has warmed 1.8°F. Like a fever in the human body, increasing Earth's temperature by a few degrees has major consequences. An increase of only 4-8° C is enough to push Earth out of an ice age or into hot-house conditions with crocodiles and palm trees living above the Arctic Circle.

Because human activities—primarily the burning of fossil fuels—are responsible for the increase in global average temperature, it follows that human activities are also responsible for the consequences of global warming. Some of the consequences are intuitive: it makes sense that Arctic sea ice extent has rapidly declined in recent decades in large part because warmer temperatures have a direct impact on ice melt. Other consequences, however, are several steps removed from the increase in global average temperature. For example, some studies report that higher temperatures in the Arctic affect air circulation patterns that have weather impacts in the United States.

CLIMATE CHANGE IMPACTS ARE COMPLEX

The impacts of human-caused climate change are often the result of a long chain of cascading consequences, sometimes with multiple threads. In addition, global warming is often only one of many factors that shape a particular trend or event. For example, a complex combination of natural and human factors affect the frequency of large wildfires in the western US. Changes in firefighting practices over time—such as more frequent use of intentional burning to clear fuels as a fire suppression tactic—can impact the boundaries of burn areas, but generally, the effects of human development vary regionally, in some cases increasing fire activity and in others decreasing it (Dennison et al., 2014). In addition, short-term natural variability in precipitation can affect recent trends. However, regardless of these changes in the landscape, hotter and drier conditions due to human-caused climate change make it easier for fires to spread. Studies in this report document that climate change has already had a hand in shaping fire seasons, especially in California and the western United States.

DETECTION AND ATTRIBUTION OF HUMAN-CAUSED CLIMATE CHANGE

The field known as climate change detection and attribution began in the 1990s when scientists demonstrated that the increase in global average temperature during the 20th century could not be explained without accounting for human emissions of heat-trapping gases (Santer et al., 1996a). This process is often called "climate change fingerprinting," or just "fingerprinting." When studies identify the fingerprint of climate change, this means scientists have determined that human-caused global warming plays a role in whatever trend or event is under investigation.

Fingerprinting: Climate change fingerprinting studies positively identify, through detection or attribution analysis, the influence of human-caused global warming on observed trends or events.

Detection and attribution: Climate change detection and attribution studies demonstrate that the climate or a system affected by climate has changed, and this change cannot be explained by internal variability alone (Hegerl et al., 2010). For example, early studies detected observed warming during the 20th century that could not be explained in the absence of human-caused climate change. Attribution studies identify the factors affecting a detected climate change and evaluate the relative contributions of these factors. For example, Hegerl et al. (2007) attribute about a third of the warming in the first half of the twentieth century to human caused greenhouse gas emissions.

Since the initial days of detecting the fingerprint of human activities in 20th century warming, scientists are now able to attribute the specific influence of climate change on many events, disasters, and trends.

Presently, scientists can do rapid climate change attribution analysis to determine in a matter of days the extent to which climate change worsened a particular event, or made an event more likely to occur. For example, according to one such study, human-caused climate change made Hurricane Harvey's precipitation about 15 percent more intense, or equivalently made such an event three times more likely to occur (Van Oldenborgh et al., 2017b). In September 2018, for the first time, Reed et al., (2018) conducted an advance rapid attribution analysis finding that climate change made Hurricane Florence's most intense rains over North Carolina more than 50% greater in magnitude than they would have been otherwise.

For more information on the evolution of attribution science, see Appendix C.

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Smoke Stacks by Alfred T. Palmer, 1944

METHODOLOGY

Four primary sources were reviewed for attribution studies that positively identify the fingerprint of climate change in the US and globally: the IPCC Assessment Reports (IPCC ARs), the US National Climate Assessments (US NCAs), the American Meteorology Society (AMS) annual "Explaining Extreme Events" bulletins, and World Weather Attribution project analyses.

In addition to reviewing the detection and attribution sections of the IPCC ARs and US NCAs, the complete citation lists of these reports were reviewed using topic searches for 'attribution', 'fingerprint', 'signal', 'human', and 'anthropogenic'. The citation lists of studies pulled during the review of the four primary sources included additional detection and attribution studies. Informal methods such as expert consultation were also used to identify further studies. This discovery process identified the majority of studies cited in the present report.

Finally, the research team identified the journals in which the existing collection of detection and attribution studies were published and reviewed the journal databases using the same topic searches used for the citation lists — 'attribution', 'fingerprint', 'signal', 'human', and 'anthropogenic'. For a list of journal databases reviewed, see Appendix D.

Once the studies were gathered, each study was reviewed to confirm and document the detection or attribution statement. A chronological list of qualifying studies was then compiled, and the main detection and attribution statements were summarized and categorized by region and impact.

The literature review is limited to cataloguing detection and attribution studies and analyzing the state of science. It does not assess the robustness of the statements or methods used by individual studies. See Appendix A for information about detection and attribution methods.

FINDINGS

Literature review identified 216 detection and attribution studies published between December 1995 and August 2018 that found the fingerprint of human-caused climate change on US and globally significant trends and events. The studies collectively identified 88 distinct trends and events in which human-caused climate change had a direct hand. (Note: A single study may identify multiple fingerprints, while several studies may support the same fingerprint.)

Ninety-three of the 216 studies found the fingerprint of climate change on events and trends specific to the United States. Among these 93 studies, 48 distinct detection and attribution statements were identified.

One hundred and twenty-eight of the 216 studies had findings of global significance. These identified 40 distinct trends and events influenced by human-caused climate change.

HIGHLIGHTS

HUMANITY HAS ALREADY PUSHED THE GLOBAL CLIMATE INTO A NEW REGIME.

- Human-caused climate change has influenced almost all indices of temperature extremes during 1961–2010 and led to more prominent changes in the frequency of extremes on a nearly global scale (Christidis and Stott, 2016; Van Oldenborgh, 2018).
- There is a significant global-scale increase in surface specific humidity that is attributable mainly to human influence (Willett et al., 2007).
- There is a distinct intensification of heavy precipitation events at local scales. Observed local trends across the globe for the period 1960–2010 are clearly different to what would be expected from internal variability (Fischer and Knutti, 2014).
- In a database of 29,000 data series pertaining to observed impacts on Earth's natural systems, about 90% are linked to global warming (Rosenzweig et al., 2008). Human-caused climate change has had a significant impact on physical systems, such as glaciers shrinking, permafrost melting, and lakes and rivers warming. Climate change also affected biological systems, such as leaves unfolding and flowers blooming earlier in the spring, birds arriving earlier during migration periods, and plant and animal species moving toward Earth's poles and higher in elevation. In aquatic environments such as oceans, lakes, and rivers, plankton and fish are shifting from cold-adapted to warm-adapted communities.

HUMAN-CAUSED CLIMATE CHANGE DUE TO GREENHOUSE GAS EMISSIONS MAY BE RESPONSIBLE FOR OVER 100 PERCENT OF AT LEAST TWO OBSERVED TRENDS.

- The likely range of the human contribution to the global mean temperature increase over the period 1951–2010 is 1.1° to 1.4°F. This translates to a likely human contribution of 92 to 123% of the observed 1951–2010 change (USGCRP, 2017; Wigley and Santer, 2012). A contribution of greater than 100% indicates that some natural forces, such as volcanoes, are working to cool Earth, but are being overwhelmed by the effects of greenhouse gases. According to the 4th US National Climate Assessment, there are no convincing alternative explanations supported by the observational evidence (USGCRP, 2017).
- Slangen et al., (2016) find that human-caused climate change explains 15 ± 55% of sea level rise observations before 1950. This increases to become the dominant contribution after 1970 (69 ± 31%), and by 2000, the human contribution to sea level rise reaches 72 ± 39%, or up to 111% (Slangen et al., 2016).

HUMAN-CAUSED CLIMATE CHANGE HAS CAUSED EXTREME EVENTS.

- 2016's record global January–December warmth would not have been possible under climate conditions of the early 1900s. Human-caused climate change was a necessary condition for the event (Knutson et al., 2018).

- The warmth of the Bering Sea in 2016 was unprecedented in the historical record, and the warmth of the Gulf of Alaska nearly so. The 2016 warm ocean anomalies cannot be explained without anthropogenic climate warming (Walsh et al., 2018; Kam et al., 2018).

THERE IS EVIDENCE OF GLOBAL WARMING AS EARLY AS THE 1930S.

- There was a significant human contribution to the probability of record-breaking global temperature events as early as the 1930s. Since then, human-caused greenhouse gas emissions have contributed to the probability of occurrence of all 18 record-breaking hot years globally. Without human-induced climate change, recent hot summers and years would be very unlikely to have occurred (King et al., 2016).
- The effect of climate change on global record-breaking temperatures can be detected back to the 1930s. Human influence on the increased occurrence of hot record-breaking temperatures is clearer than it is for the decreased occurrence of cold records (King, 2017). In a stable climate, the ratio of new record highs to new record lows is approximately even. However, as the climate warms, record highs outpace record lows, with the imbalance growing as global average temperature increases.

REGIONAL WARMING IN THE UNITED STATES WAS FIRST TIED TO HUMAN-CAUSED CLIMATE CHANGE AS EARLY AS 2003.

- Stott (2003) detects the warming effects of increasing greenhouse gas concentrations in all the regions examined, including in large parts of North America.

REAL WORLD IMPACTS ARE LARGER AND HAPPENING SOONER THAN THE SCIENCE PROJECTED.

- Persistent changes to temperature extremes have already occurred over large parts of the Earth. These changes have emerged in observations earlier and over a larger spatial extent than models predicted. Simulations with and without anthropogenic forcings provide evidence that the observed changes are likely to be human-caused (Li et al., 2018).

EXISTING INFRASTRUCTURE IS FAILING IN THE CURRENT REGIME OF RECORD-BREAKING EXTREMES.

- Huang et al., (2018) found the fingerprint of global warming in the flooding that damaged the Oroville dam in California in February 2017. The overflow cost $870 million (Vartabedian, 2018) and is an example of how climate change is amplifying the threat that extreme weather poses to American infrastructure.

HUMAN-CAUSED CLIMATE CHANGE HAS WORSENED MANY EXTREME EVENTS IN THE UNITED STATES.

- Hurricane Harvey—which caused $125 billion in damages (Smith, 2018)—could not have produced so much rain—over 60 inches (Belles, 2017)—without human-induced climate change (Emanuel, 2017; Van Oldenborgh et al., 2017b; Risser and Wehner, 2017). Record high ocean heat values increased the fuel available to sustain and intensify the storm (Trenberth et al., 2017; Wang et al., 2018).
- Elevated temperatures due to climate change played an important role in exacerbating drought severity during the 2011-2016 California drought (Seager et al., 2015; Park et al., 2015; Mann and Gleick, 2015; Shukla et al., 2015; Diffenbaugh et al., 2015; AghaKouchak et al., 2014). Several studies also identify the fingerprint of climate change in the extreme geopotential height values in the California region linked to heightened drought risk (Seager et al., 2017; Wang et al., 2017; Swain et al., 2014; Wang et al., 2014). In 2014, California's driest and warmest year since records began in 1895, the total statewide economic cost of the drought was $2.2 billion, with a total loss of 17,100 seasonal and part-time jobs (Howitt et al., 2014).
- See Table 1 for the complete list.

DETECTION AND ATTRIBUTION STUDY CATEGORIZATION

The 216 climate change detection and attribution studies are broken down into two broad groups: US and global. Within the two groups, the studies are categorized by the subject of each study's detection or attribution finding.

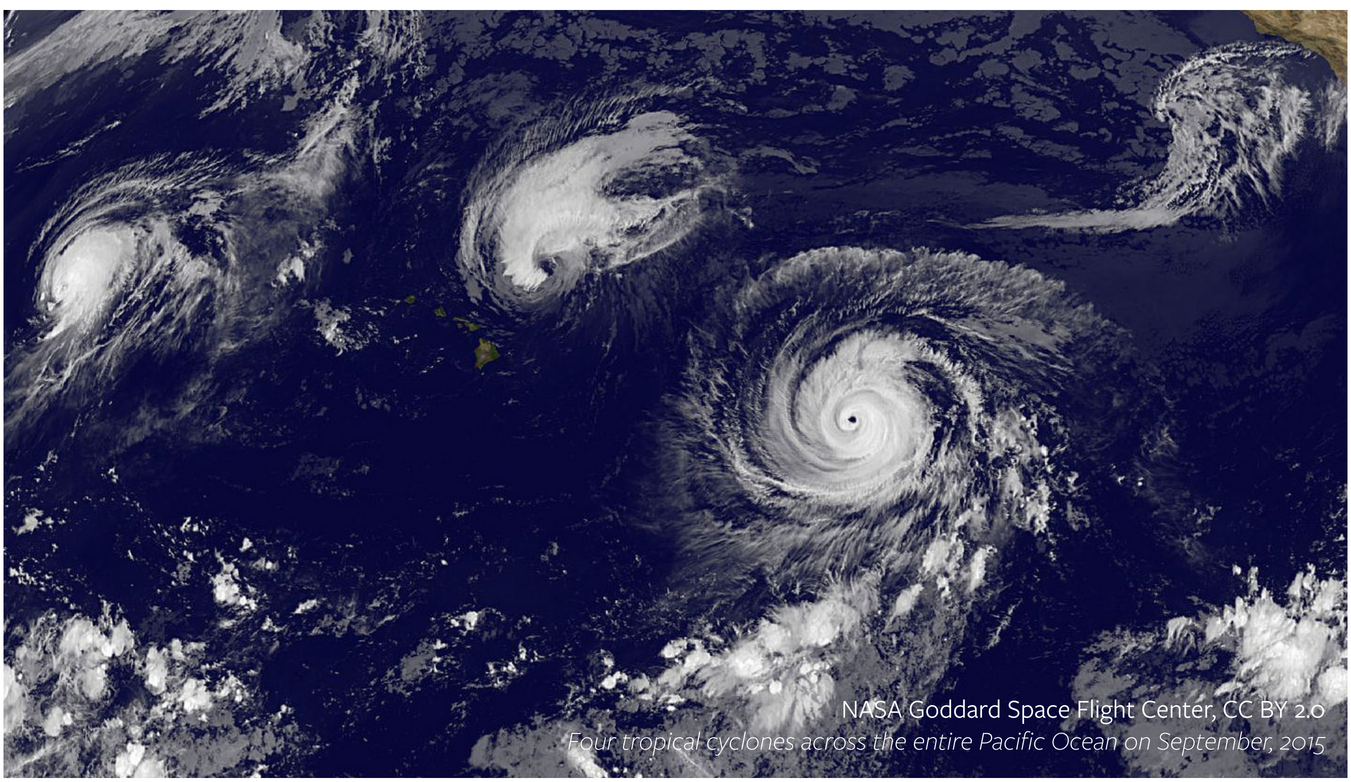
For example, in the US specific studies group, "Attribution of extreme rainfall from Hurricane Harvey, August 2017" is listed under the "Extreme Precipitation" category, while "Hurricane Harvey links to Ocean Heat Content and Climate Change Adaptation" is listed under the "Sea Surface Temperature and Extreme Precipitation Risk" category. In the first case, the study authors identified the fingerprint of climate change in Hurricane Harvey's extreme precipitation. In the second case, the authors identified the fingerprint in the record high ocean temperatures that helped to fuel, sustain, and intensify the storm. So, although the studies look at the same climate event—Hurricane Harvey—they analyze two unique ways that climate change affected the storm.

Finally, studies within each category are grouped together by impact. The impact can be an observed trend — reduced Colorado River Basin streamflow—or a climate event—storm surge during Superstorm Sandy.

For example, in the "global" studies group, in the "warming" category, there are 21 studies listed under the sub-category "long-term warming trend" because they all identify the fingerprint of climate change on long-term global warming. These 21 studies support one unique climate change impact statement: human-caused climate change is responsible for most, if not all, the observed warming during the 20th century.

The identification of unique climate change detection and attribution statements is among the major findings of the present literature review. Among the 93 US specific studies included in the review, the fingerprint of climate change is implicated in 48 unique impacts. Among the 128 global studies, 40 unique impacts were identified.

This means, climate change has had a direct hand in 48 impacts in the United States and 40 impacts in the larger climate system.



Four tropical cyclones across the entire Pacific Ocean on September, 2015

TABLE 1: IN THE US, CLIMATE CHANGE HAD A DIRECT HAND IN

IMPACT	STUDIES
WARMING	
US long-term temperature change	(Christidis and Stott, 2014; Christidis et al., 2011b; Jones et al., 2008; Karoly et al., 2003; Stott, 2003)
US winter warming	(Van Oldenborgh et al., 2018; Wolter et al., 2016)
Western US warming	(Lehner et al., 2018; Abatzoglou et al., 2014; Morak et al., 2011; Bonfils et al., 2007)
EXTREME HEAT	
US extreme temperatures in February 2017	(Van Oldenborgh et al., 2017a)
Southeastern US extreme heat and drought in the fall of 2016	(Williams et al., 2017)
Southwestern US heat in the summer of 2013	(Shiogama et al., 2014)
US extreme temperatures in July 2012	(Diffenbaugh and Scherer, 2013)
Western US extreme heat events	(Diffenbaugh et al., 2017)
Eastern US extreme spring heat in 2012	(Knutson et al., 2013)
Texas extreme heat and drought in the summer of 2011	(Jeon et al., 2018; Paciorek et al., 2016; Rupp et al., 2012a; Hoerling et al., 2012; Rupp et al., 2012b)
AVERAGE PRECIPITATION	
North-central and eastern US average precipitation increase	(Knutson and Zeng, 2018; Knutson et al., 2014)
EXTREME PRECIPITATION	
Hurricane Harvey and extreme precipitation in August 2017	(Wang et al., 2018; Lehner et al., 2018; Abatzoglou et al., 2014; Morak et al., 2011; Bonfils et al., 2007)
California extreme precipitation that led to the Oroville Dam breach in January 2017	(Huang et al., 2018)
Southern Louisiana extreme precipitation in August 2016	(Van Der Wiel et al., 2016; Wang et al., 2016)
Missouri extreme precipitation in December 2015	(Fosu et al., 2018)
Southern Great Plains El Niño precipitation anomaly in May 2015	(Wang et al., 2015)
Boulder floods and extreme precipitation in September 2013	(Pall et al., 2017; Eden et al., 2016)
Hurricane Katrina and extreme precipitation in August 2005	(Trenberth et al., 2007)

FLOOD RISK	
Northeastern US flood magnitude and frequency	(Armstrong et al., 2014)
SEA SURFACE TEMPERATURE	
Eastern Pacific extreme marine heat wave and mortality in 2016	(Jacox et al., 2018; Walsh et al., 2018; Oliver et al., 2018)
Northeast Pacific extreme marine heat wave and mortality	(Weller et al., 2016b)
SEA SURFACE TEMPERATURE & EXTREME PRECIPITATION RISK	
Hurricane Harvey and high sea surface temperatures in August 2017	(Trenberth et al., 2018; Wang et al., 2018)
Boulder floods and high sea surface temperatures in August 2013	(Trenberth et al., 2015)
Hurricane Sandy and high sea surface temperatures in October 2012	(Trenberth et al., 2015)
Snowmageddon and high sea surface temperatures in February 2010	(Trenberth et al., 2015)
Hurricane Katrina and high sea surface temperatures in August 2005	(Trenberth et al., 2007)
SEA LEVEL RISE & COASTAL FLOODING	
US sea level rise and flood days	(Strauss et al., 2016)
US cities and sea level rise	(Becker et al., 2014)
Miami tidal flood risk	(Sweet et al., 2017)
Hurricane Sandy storm surge in October 2012	(Garner et al., 2017; Lin et al., 2016; Reed et al., 2015; Toumi and Restell, 2014; Miller et al., 2013; Sweet et al., 2013; Kemp and Horton, 2013)
Hurricane Katrina storm surge in August 2005	(Irish et al., 2013)
Chesapeake Bay and Delaware Estuary salinity increase	(Hilton et al., 2008; Ross et al., 2005)
HURRICANE ACTIVITY	
Central and Eastern Pacific active hurricane seasons	(Murakami et al., 2016a; Murakami et al., 2016b)
Hurricane Sandy intensity in October 2012	(Reed et al., 2015; Trenberth et al., 2015)
Hurricane Katrina intensity in August 2005	(Grinsted et al., 2013)

DROUGHT RISK	
California warmth and drought from 2011 to 2016	(Seager et al., 2015; Park et al., 2015; Mann and Gleick, 2015; Shukla et al., 2015; Diffenbaugh et al., 2015; AghaKouchak et al., 2014)
Central US precipitation deficit in the summer of 2012	(Rupp et al., 2017)
Texas precipitation deficit during March-August 2011	(Paciorek et al., 2018)
HYDROLOGICAL CHANGE	
Western US temperature driven snow drought, river flow change, etc.	(Huang et al., 2018; Berg et al., 2017; Fosu et al., 2017; Mote et al., 2016; Hidalgo et al., 2009; Das et al., 2009; Pierce et al., 2008; Bonfils et al., 2008; Barnett et al., 2008)
Colorado River reduced streamflow	(McCabe, 2017; Udall and Overpeck, 2017)
Southwestern US decreased flood magnitude	(Hirsch and Ryberg, 2011)
WILDFIRE ACTIVITY	
Alaska increased wildfire severity	(Partain, Jr., 2017)
Western US moisture loss and wildfire risk	(Williams et al., 2018; Tett et al., 2018; Abatzoglou and Williams, 2016)
California increased wildfire severity	(Mann et al., 2016; Yoon et al., 2016)
CIRCULATION CHANGE	
Eastern US cold spells and temperature dipoles	(Bellprat et al., 2017; Singh et al., 2016; Lee et al., 2015)
California wet and dry weather whiplash	(Swain et al., 2018; Wang and Schubert, 2014)
California drought and the "Ridiculously Resilient Ridge"	(Seager et al., 2017; Wang et al., 2017; Swain et al., 2014; Wang et al., 2014)
CARBON SINKING	
US forests and carbon sinking	(Zhang et al., 2012)

TABLE 2: GLOBALLY, CLIMATE CHANGE HAD A DIRECT HAND IN

IMPACT	STUDIES
WARMING	
Long-term temperature change	(Ribe et al., 2017; Lott et al., 2013; Jones et al., 2013; Zhou and Tung, 2013; Wigley and Santer, 2012; Santer et al., 2013b; Kemp and Horton, 2013; Christidis et al., 2010; Allen et al., 2006; Zhang et al., 2006; Gillett et al., 2003; Stott, 2003; Jones et al., 2003; Zwiers and Zhang, 2003; Tett et al., 2002; Stott et al., 2001; Tett et al., 1999; North and Stevens, 1998; Hegerl et al., 1997; Hegerl et al., 1996; Santer et al., 1996; Santer et al., 1995)
Hot and cold extremes	(Van Oldenborgh, 2018; Dittus and Karoly, 2016; Christidis and Stott, 2016; Kim et al., 2015; Fischer and Knutti, 2014; Min et al., 2013; Morak et al., 2013; Zwiers et al., 2011; Christidis et al., 2005)
Seasonal changes	(Knutson and Ploshay, 2016; Kamae et al., 2014; Christidis and Stott, 2014; Stott et al., 2011; Jones et al., 2008)
Record hot years	(Knutson et al., 2018; King, 2017; Mann et al., 2017a; Kam et al., 2017; King et al., 2016; Record Hot Year, 2015; Rahmstorf and Coumou, 2011)
Daily temperature extremes	(Wehner et al., 2018; Van Oldenborgh, 2018; Li et al., 2018; Christidis et al., 2011a)
AVERAGE PRECIPITATION	
Average precipitation change	(Wan et al., 2014; Polson and Hegerl, 2013; Min et al., 2008a; Zhang et al., 2007)
ATMOSPHERIC MOISTURE CONTENT	
Atmospheric moisture content increase	(Sarojini et al., 2012; Santer et al., 2009; Willett et al., 2007; Santer et al., 2007)
EXTREME PRECIPITATION	
Record-breaking precipitation	(Lehner et al., 2018; Abatzoglou et al., 2014; Morak et al., 2011; Bonfils et al., 2007)
Moderate precipitation extremes	(Huang et al., 2018)
Heavy precipitation extremes	(Van Der Wiel et al., 2016; Wang et al., 2016)
SEA SURFACE TEMPERATURE	
Marine heatwave increase	(Frölicher et al., 2018)
Global oceans and sea surface temperature increase	(Newman et al., 2018; Kam et al., 2016; Weller et al., 2016b; Ting et al., 2009; Gillett et al., 2008b; Santer et al., 2006; Weller et al., 2016c)

Upper ocean warming	(Gleckler et al., 2012)
CORAL BLEACHING	
Great Barrier Reef coral bleaching in March 2016	(King, 2016)
OCEAN HEAT CONTENT	
Global ocean heat content increase	(Balmaseda et al., 2013; Pierce and Barnett, 2006; Barnett et al., 2005; Reichert et al., 2002; Levitus et al., 2001; Barnett et al., 2001)
Arctic ocean heat content increase	(Lind et al., 2018)
Southern Ocean heat content increase	(Fyfe, 2006; Banks et al., 2000)
Indo-Pacific warm pool expansion	(Weller et al., 2016a)
SEA LEVEL RISE	
Global long-term sea level rise	(Marcos et al., 2017; Slangen et al., 2016; Dangendorf et al., 2015; Slangen et al., 2014; Marcos and Amores, 2014; Jevrejeva et al., 2009)
ARCTIC WARMING	
Arctic warmth in 2016	(Kam et al., 2018; Sun et al., 2017; Van Oldenborgh et al., 2016)
Arctic long-term temperature change	(Najafi et al., 2015; Chylek et al., 2014; Fyfe et al., 2013; Gillett et al., 2008a)
ARCTIC SEA ICE	
Arctic sea ice loss	(Notz and Stroeve, 2016; Notz and Marotzke, 2012; Min et al., 2008b)
Sea of Okhotsk record low minimum sea ice extent in 2015	(Paik et al., 2017)
Northern hemisphere record low winter sea ice maximum in 2015	(Fučkar et al., 2017)
Northern Hemisphere record low summer sea ice minimum in 2012	(Kirchmeier-Young, 2016; Zhang and Knutson, 2013; Guemas et al., 2013)
Arctic sea ice loss and the "warm Arctic, cold Siberia" pattern	(Zhang et al., 2018)
SNOW COVER EXTENT	
Northern hemisphere spring snow cover extent	(Najafi et al., 2016; Rupp and Mote, 2013)
GLACIER MELT	
Glacier mass loss	(Marzeion et al., 2014)

DRYING	
Warmer and drier land areas	(Chan and Wu, 2015)
ATMOSPHERIC STRUCTURE	
Tropospheric warming and expansion	(Christidis and Stott, 2015; Santer et al., 2013a; Santer et al., 2003)
Sea level pressure change	(Gillett et al., 2013; Gillett and Stott, 2009; Gillett et al., 2003)
LARGE-SCALE CIRCULATION	
Planetary wave stalling	(Mann et al., 2017b)
Hadley cell widening	(Kim et al., 2017)
Atmospheric storminess	(Wang et al., 2008)
TROPICAL CYCLONE ACITIVITY	
Tropical cyclone activity	(Zhang et al., 2017; Holland and Bruyère, 2014; Mann and Emanuel, 2011)
OCEAN CHEMISTRY	
Acidification increase	(Sutton et al., 2016; Friedrich et al., 2012)
Oxygen content decrease	(Andrews et al., 2013)
Salinity changes	(Pierce et al., 2012; Terray and Corre, 2012; Stott et al., 2008; Banks et al., 2000)
BIOLOGICAL SYSTEMS	
Biological systems change	(Mao et al., 2016; Rosenzweig et al., 2008; Christidis et al., 2007)
FLOOD RISK	
Major flood frequency increase	(Milly et al., 2002)

Tables 1 and 2: *Climate change detection and attribution studies are broken down into two broad groups: US and global. Within the two groups, the studies are categorized by the subject of each study's detection or attribution finding. Finally, studies within each category are grouped together by impact. Impacts are trends or events affected by climate change.*

CONCLUSION

This report provides a meta-analysis of a literature review of detection and attribution studies that identify the fingerprint of human-caused climate change on events and trends in the United States and globally. It shows the connections between climate change and observed trends and events in the United States and globally. These climate impacts are numerous, strong and well-documented.

Among 93 studies with findings specific to the United States, climate change was found to have a direct hand in 48 trends or events. Among 128 global studies, climate change had a direct hand in 40 distinct trends and events. In total, the studies presented in this report find that human-caused climate change has had a direct hand in 88 observed trends and events.

The report is a response to the need to better understand the breadth, depth and character of the research identifying the influence of human-caused global warming on observable impacts. The report does not assess the robustness of the statements and scientific methods of individual studies included in the review. For recent analyses on the state of detection and attribution science and methods, see Stott et al., (2015), Easterling et al., (2016), Angélil et al., (2016), National Academies of Sciences (2016), Otto (2017), and Lloyd and Oreskes, (2018).

Mississippi National Guard Special Forces rescue residents post-Hurricane Isaac

APPENDICES

APPENDIX A: CLIMATE CHANGE DETECTION AND ATTRIBUTION METHODS

A common approach to event attribution uses climate models run under factual (real-world) conditions and counterfactual scenarios (the world that might have been without human-caused greenhouse gas emissions) to estimate the probabilities of the event occurring under each of the two situations (Jeon et al., 2016). This approach has had considerable success with extremes that are strongly governed by thermodynamic aspects of climate change, especially those related to temperature. This approach relies on many model runs with and without climate change present to determine how unusual an observed event is and how climate change affected the odds. Unfortunately, this approach is not well-suited for identifying climate extremes driven by atmospheric circulation, in part because these models are not well-suited for modeling dynamic circulation changes. As a result, these studies often underestimate or fail to find the fingerprint of climate change.

In 2012, Trenberth (2012) outlined a new "storyline" approach to climate change attribution that is better able to capture the fingerprints of human-caused climate change on atmospheric circulation. Trenberth (2012) states, "The answer to the oft-asked question of whether an event is caused by climate change is that it is the wrong question. All weather events are affected by climate change because the environment in which they occur is warmer and moister than it used to be."

In 2015, Trenberth and others expand on the storyline approach suggesting that "it is more useful to regard the extreme circulation regime or weather event [under investigation] as being largely unaffected by climate change, and question whether known changes in the climate system's thermodynamic state affected the impact of the particular event" (Trenberth et al., 2015). These scientists proposed a series of questions to be answered, such as: "Given a weather pattern, how were temperatures, precipitation and associated impacts influenced by climate change?" or "Given a flood, where did the moisture come from? Was it enhanced by high ocean temperatures that might have had a climate change component?" (Trenberth et al., 2015).

In March 2016, the National Academy of Sciences validated the storyline approach, stating that the traditional approach is limited by the available modeling tools and that the storyline approach has much to recommend it (National Academies of Sciences, 2016). An analysis by Lloyd and Oreskes (2018) concludes that "the risk-based and storyline approaches are complementary and compatible, and should be treated as useful and available tools in the toolkit of detection and attribution scientists."

APPENDIX B: LITERATURE REVIEW SCOPE

CATEGORIES			EXAMPLES
INCLUDED IN THE REPORT	Local (US specific)		"Attribution of Climate Effects on Hurricane Harvey's Extreme Rainfall in Texas" OR "Seasonal Climate Variability and Change in the Pacific Northwest of the United States"
	Global (non-US specific)	Large-scale change	"Attributing the increase in Northern Hemisphere hot summers since the late 20th century" OR "Influence of Anthropogenic Climate Change on Planetary Wave Resonance and Extreme Weather Events"
		Changes with large-scale implications	"Attributing Causes of 2015 Record Minimum Sea-Ice Extent in the Sea of Okhotsk" OR "The Extreme 2015/16 El Niño, in the Context of Historical Climate Variability and Change"
		General concern	"Great Barrier Reef Bleaching, March 2016" OR "Anthropogenic and Natural Influences on Record 2016 Marine Heat Waves"
NOT INCLUDED	Local (non-US specific)		"Climate extremes and climate change: The Russian heat wave and other climate extremes of 2010" OR "Detectable Anthropogenic Shift toward Heavy Precipitation over Eastern China"

Table 3: *The literature review is limited to studies of local significance in the United States and studies of global significance. Studies of global significance include those attributing global warming to changes in large-scale dynamic and thermodynamic processes that have complex and far-reaching impacts, such as long-term global temperature rise and atmospheric moisture increase. It also includes studies on changes with global implications, such as ice sheet melt and Arctic sea ice decline. Finally, studies of global significance include those on topics of general concern, such as coral bleaching in the Great Barrier Reef, a world heritage site. It does not include studies of primarily local significance outside of the United States.*

APPENDIX C: THE EVOLUTION OF ATTRIBUTION SCIENCE

Attribution science has advanced rapidly. In the mid to late 1990s, scientists identified the fingerprint of human-caused climate change in global surface temperature and distinguished it from other forcings, including solar radiation and volcanic aerosols. In the early 2000s, the evidence for human influence on surface air temperature strengthened (Hegerl et al., 1997; Tett et al., 1999; Zhang et al., 2006), and the signal of climate change was found for continental-scale temperature (Stott, 2003).

Also in the early 2000s, anthropogenic climate change signals emerged for many other variables, such as sea level pressure (Gillett et al., 2003), ocean heat content (Barnett et al., 2001; Levitus et al., 2001; Reichert et al., 2002), ocean salinity (Banks et al., 2000), free atmospheric temperature (Jones et al., 2003), and tropopause height (Santer et al., 2003). Changes in these variables have a significant effect on climate. They affect circulation in the air and ocean, and influence how moisture moves. These changes can alter rainfall, temperature, winds and storm intensity.

In 2004, a study analyzing the extreme European heat wave of 2003 became the first attribution study to quantify human influence on a distinct weather event (Stott et al., 2004). The study's innovation was asking how much climate change affects the risk, or probability, that an extreme event might occur (Harvey, 2018). Before this point, climate change attribution science existed in a different form; scientists investigated the relationship between human activity and changes in long-term trends like temperature. The 2004 study opened the door to a whole new era of attribution science.

By 2007, new evidence detected the fingerprint of climate change in global precipitation (Zhang et al., 2007), surface humidity (Willett et al., 2007), and the moisture content of the Earth's atmosphere (Santer et al., 2007). In 2008, the fingerprint of global warming was found in tropical cyclone activity in the cyclogenesis regions of the North Atlantic and Western North Pacific during the June–November hurricane season over the 20th century (Gillett et al., 2008b).

2012 marked the first year the American Meteorological Society (AMS) published its annual Bulletin, "Explaining Extreme Events From a Climate Perspective". The report analyzed the role of human factors for six specific extreme weather or climate events of 2011. Included in the report, was one of the first US-based event attribution studies, on the 2011 Texas drought (Rupp et al., 2012b).

In 2014, attribution analyses began quantifying the anthropogenic influence on trends such as sea level rise (Marcos and Amores, 2014 and Becker et al., 2014), glacier mass loss (Marzeion et al., 2014), and Arctic warming (Chylek et al., 2014).

In 2016, the direct influence of anthropogenic climate change was clearly identified in connection to increased cyclone intensity (Zhang et al., 2017).

In recent years, there has been an increase in the number of attribution studies on extreme events in the United States. Following the record rainfall during Hurricane Harvey, of up to 60.58 inches (Belles, 2017), a series of four attribution studies in 2017 identified the fingerprint of climate change in Harvey's extreme precipitation (Wang et al., 2018; Risser and Wehner, 2017; Van Oldenborgh et al., 2017; Emanuel, 2017), and two studies in 2018 attributed the record high sea surface temperatures that sustained and intensified Harvey's rainfall to climate change (Trenberth et al., 2018; Wang et al., 2018).

In September 2018, Reed et al., (2018) published a first-of-its-kind experimental "pre-attribution" study done as Hurricane Florence was approaching landfall. The study found that Florence's most intense rains over North Carolina were more than 50% greater in magnitude and Florence's areal size 8 to 9% greater due to climate change.

For further reading, see Stott et al., (2015), Easterling et al., (2016), Angélil et al., (2016), National Academies of Sciences (2016), Otto (2017), and Lloyd and Oreskes, (2018).

APPENDIX D: JOURNAL DATABASES REVIEWED

AMS Earth Interactions
AMS Journal of Climate
AMS Journal of the Atmospheric Sciences
Annual Review of Environment and Resources
Atmospheric Science Letters
Biogeosciences
Bulletin of the American Meteorological Society
Climate Dynamics
Climatic Change
Earth's Future
Environmental Research Letters
Geophysical Research Letters
Geophysics
Hydrological Sciences Journal
Hydrology and Earth Systems Science
Journal of Geophysical Research
Journal of Geophysical Research: Atmospheres
Journal of Geophysical Research: Oceans
Meteorological Society of Japan
Nature
Nature Climate Change
Nature Communications
Nature Geoscience
Plos One
Proceedings of the National Academy of Sciences
Science
Science Advances
Scientific Reports
Surveys in Geophysics
Transactions American Geophysical Union
Water
Water Resources Research
Weather and Climate Extremes
Wiley Interdisciplinary Reviews: Climate Change

Scientists sample from melt ponds on sea ice in the Chukchi Sea

APPENDIX E: DETECTION AND ATTRIBUTION MILESTONES

- **DECEMBER 1995:** Santer et al. (1995) provide first evidence that observed near-surface air temperature data reflect a temperature response to human-caused CO_2 and sulfate aerosol emissions.

- **JUNE 1996:** Chapter 8 of the Second Assessment Report of the Intergovernmental Panel on Climate Change presented a summary of work aimed at detecting the fingerprint of human-caused climate change on global surface warming (Santer et al., 1996a). The chapter concludes stating: "The body of statistical evidence . . . now points towards a discernible human influence on global climate."

- **JULY 1996:** Hegerl et al. (1996) find the probability that 20-year and 30-year near-surface warming was due to natural variability was less than 2.5 to 5 percent.

- **SEPTEMBER 2000:** The fingerprint of anthropogenic climate change is found in observed changes in ocean salinity and temperature (Banks et al., 2000). The signal is especially strong in the Southern Ocean.

- **MARCH 2003:** Scientists strengthened the case for an anthropogenic influence on climate when they detected the specific temperature response of anthropogenic emissions and stratospheric volcanic aerosols as well as the temperature response to change in solar irradiance (Jones et al., 2003).

- **JULY 2003:** Long-term warming due to human greenhouse gas emissions was identified specifically in the United States (Stott, 2003).

- **DECEMBER 2004:** Stott et al. (2004) make a quantitative attribution statement for a single weather event. They find that human influence at least doubled the risk of a heatwave exceeding the threshold passed during the extreme European heat wave of 2003 which killed as many as 70,000 people (Robine et al., 2008). Their best estimate is that climate change made such an extreme heat event 4 times as likely.

- **JULY 2007:** Human-induced changes in precipitation, surface humidity, and atmospheric moisture content were detected at the global scale (Zhang et al., 2007; Willett et al., 2007; Santer et al., 2007).

- **MAY 2008:** In an iconic study, Rosenzweig et al. (2008) identified over 29,000 different signals in observed changes of physical and biological systems.

- **OCTOBER 2009:** Scientists quantify the amount of global sea level rise attributable to anthropogenic climate change (Jevrejeva et al., 2009). They find that only 4 cm (25% of total sea level rise) during the 20th century is attributed to natural forcings, and the remaining 14 cm are due to a rapid increase in CO_2 and other greenhouse gases.

- **FEBRUARY 2011:** Human-induced increases in greenhouse gases were found to have contributed to the observed intensification of heavy precipitation events over approximately two-thirds of Northern Hemisphere land areas (Min et al., 2011).

- **JULY 2012:** The American Meteorological Society published its first annual bulletin on "Explaining Extreme Events From a Climate Perspective". These reports present attribution studies on extreme events from the previous year.

- **JULY 2012:** Two of the first US-based event attribution studies found that climate change increased the probability of the 2011 Texas heat wave and drought (Rupp et al., 2012b and Hoerling et al., 2012).

- **JUNE 2014:** The World Weather Attribution project began providing rapid, science-based assessments of the extent to which global warming caused by greenhouse gas emissions played a role in a weather or climate event's probability (Cullen and Wiles, 2014).

- **DECEMBER 2016:** In the Northwest Pacific in 2015, accumulated cyclone energy (ACE) was extreme, and scientists found that human-caused climate change largely increased the odds of the occurrence of such an extreme ACE value (Zhang et al., 2017). This is the first study to identify a direct link between climate change and increased cyclone intensity.

- **MARCH 2017:** Scientists identified the fingerprint of anthropogenic climate change in the temperature pattern favoring planetary wave stalling (Mann et al., 2017b). This pattern leaves whole regions under the same weather for extended periods, which can turn hot spells into heat waves and wet weather into floods.

- **April 2017:** Diffenbaugh et al. (2017) find that human-caused climate change has contributed to the severity and probability of 82 percent of record-hot days globally.

- **DECEMBER 2017:** For the first time, three studies in the annual AMS bulletin "Explaining Extreme Events From a Climate Perspective" found that three extreme heat events would not have been possible without human-caused climate change, including: global record heat in 2016 (Knutson et al., 2018), marine warming in the Gulf of Alaska and the Bering Sea from 2014–16 (Walsh et al., 2018), and heatwaves in Asia in 2016 (Imada et al., 2018).

- **DECEMBER 2017:** Two independent studies examining the rainfall under Hurricane Harvey find increases larger in tropical cyclone precipitation totals than predicted by the standard Clausius-Clapeyron (CC) process, indicating that rainfall totals for some events can increase exponentially as the climate warms, in a process known as super CC scaling (Risser and Wehner, 2017; Van Oldenborgh et al., 2017).

- **SEPTEMBER 2018:** A scientific analysis from Stony Brook University became the first advanced forecast attribution statement about climate change influence on a tropical cyclone (Reed et al., 2018). The authors calculate that the reach and volume of Hurricane Florence's rain was 50 percent greater than it would have been without man-made climate change.

California Department of Water Resources, Public Domain
Oroville Dam spillway damage February 2017

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