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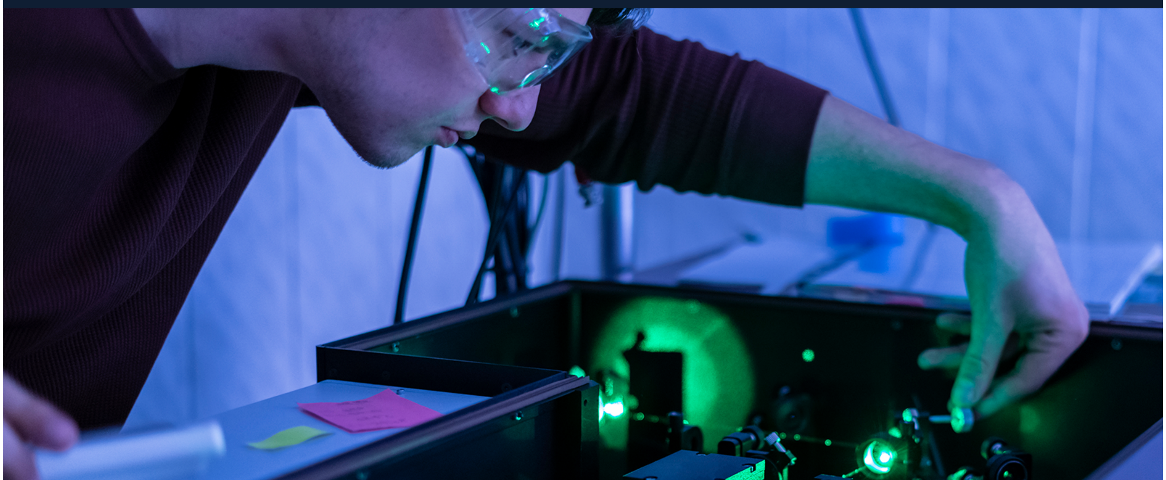

CONNECTING EXTREME WEATHER EVENTS TO CLIMATE CHANGE

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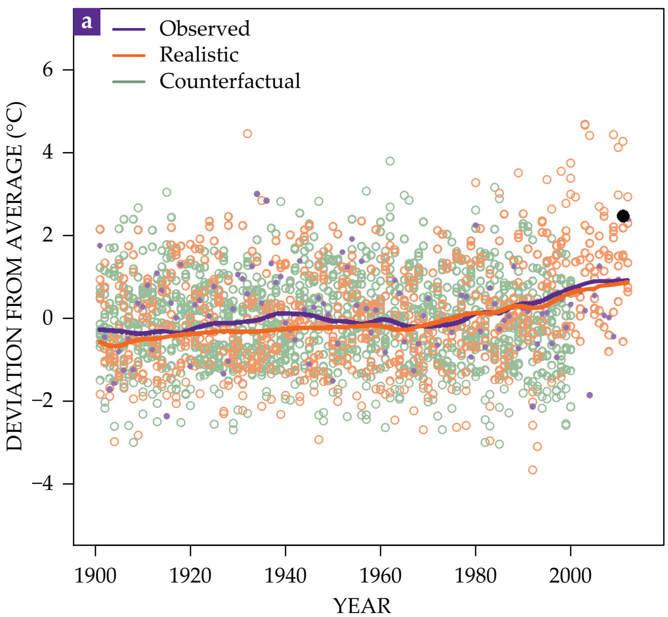
After his house in Oxford, UK, was flooded by an exceptionally rainy storm in January 2003, Myles Allen proposed that the anthropogenic influence on severe weather events could be quantified.[1] Before that, most climate scientists avoided discussing how human activity affected individual extreme weather events. Rather, they would deflect, saying, for example, "While no individual event can be tied to climate change, whatever happened is consistent with expectations." That statement is no longer true. Using extreme-event attribution techniques, it is now possible to make quantitative statements about the human influence on many classes of individual weather and climate events.



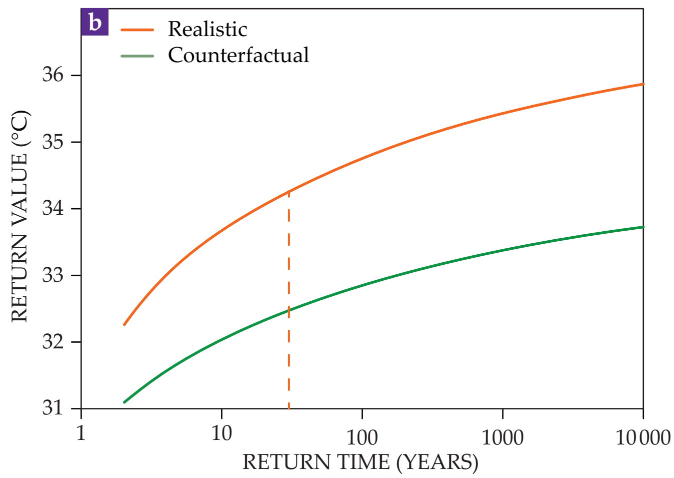


FIGURE 1. DEPARTURE FROM AVERAGE summer temperatures in Texas. **(a)** A realistic historical simulation (orange) and a cooler counterfactual climate without anthropogenic climate change (green) are compared with the observations (purple). The black dot represents the observed value of 2.467 °C for 2011. The solid lines represent the smoothed temperature anomalies. (Adapted from ref. 6.) **(b)** Simulations show the likelihood of Texas summer surface air temperature in a realistic climate (orange) and the cooler counterfactual climate (green). A return value (maximum temperature) has a 1/(return time) chance of being met or exceeded in a given year. The dashed line indicates that the observed temperature was a 1-in-30-year event in 2011, and it was 1.5 °C warmer than it would've been without climate change.

In 2003, shortly after Allen's proposal, central Europe experienced a disastrous heat wave that caused more than 70 000 excess deaths. At the time, using a high-quality record of European temperatures and a single climate model, Allen and colleagues estimated that climate change at least doubled the chances of the measured high daytime temperatures.[2] Since then, the field of extreme-weather-event attribution has expanded to include not just heat waves but also floods, droughts, heavy precipitation, and certain extreme storms, such as hurricanes (reference 3, chapter 11).

There is extensive literature on the detection and attribution of long-term changes in various climatic properties. Those studies provided the basis for the Intergovernmental Panel on Climate Change to assert in its sixth assessment report that "it is unequivocal that human influence has warmed the atmosphere, ocean, and land" (reference 3, page 4). While traditional attribution statements about climate change have focused on long-term observed changes in the climate system, extreme-event attribution statements are generally about the human influence on a single event. Although scientists are often asked if climate change caused a particular weather event, such inquiries invite a more general investigation into causality (see the box on page 43). Complex events, such as a storm or a heat wave, result from multiple complex causal factors—and not just ones related to climate change.

One motivation for performing extreme-event attribution studies is to satisfy the public's curiosity about how climate change affects them. But an equally important motivation is gaining insight into the physical mechanisms behind the changes in extreme weather events. Borrowing concepts from epidemiology, scientists hope to untangle and quantify the different causal factors. The ongoing work focuses on answering two questions: "Did climate change affect the *magnitude of an event* of a given estimated rarity?" and "Did climate change cause the *chances of an event* of an observed high magnitude to change?"

Extreme heat

Those two questions are two sides of the same coin, as illustrated by the abnormally hot temperatures in Texas during the summer of 2011. Figure 1a shows observed Texas summer temperature departures (purple) from the average of the 1961–90 temperatures. Two simulations are shown, one with realistic human changes to the atmospheric composition (orange)—mainly well-mixed greenhouse gas increases, stratospheric ozone decreases, and aerosol pollution—and the other counterfactual (green), in which temperatures are cooler because it doesn't include the effect of human changes. Both the observations and the predicted data in the realistic model trend upward. The absence of such a trend in the counterfactual simulation reveals that there is an attributable human influence on Texas summer temperatures. Increasingly hot summers are expected. Yet the 2011 temperature, shown by the black dot, was about 2.5 °C warmer than the average summer and was considered a rare, 1-in-30-year event at the time.

To answer the two event-attribution questions about changes in event magnitude and frequency, one needs to turn to the climate-model data. Figure 1b shows the return values of average summer temperatures in Texas as a function of time. The return value is the highest average temperature expected to be reached once in a given period of time, known as the return time. The solid orange line, representing the realistic simulation, reveals that an average temperature of 34 °C would occur once in 30 years. In the counterfactual simulation, shown by the green line, the average temperature occurring once every 30 years would be just over 32 °C. Thus the answer to the

Causality

Attribution is an exercise in causal inference. Causality can be a deeply philosophical and often confusing topic. But complex events have complex causes, and statistical techniques—particularly those developed in epidemiology—can be useful to quantify the role of climate change and other causal factors in individual extreme weather events. Broadly speaking, causal-inference techniques can be divided into two classes.

The first, known as Pearl causality, after Judea Pearl, a computer scientist at UCLA, involves a direct interference in the experiment. In medicine, that familiar exercise provides one group of patients with the treatment in question and the other with a placebo. But with only one real world, scientists have to use climate models where they can control the inclusion or exclusion of the external forcing agents of interest, such as greenhouse gases or land usage.

A second technique, known as Granger causality, after the econometrician Clive Granger, can be useful when direct interference in the experiment is undesirable or impossible. In epidemiology, for instance, a study of heart disease in a selected population might consider obesity, smoking habits, family history, and other relevant causal factors. A statistical model that involves those factors as variables can provide information on their possible influence. For climate, scientists have developed extreme-value statistical models using greenhouse gas concentrations, air pollution, urbanization, El Niño, and other natural modes of variability as covariates to isolate their relative influence on extreme weather.

Both Pearl and Granger causal-inference techniques have their strengths and limitations. Granger causal inference may lead to the *post hoc, ergo propter hoc* fallacy—that correlation does not necessarily imply causality. Additionally, the influence of unspecified covariates must be considered. Because Pearl causal inference relies on models, one must first ascertain whether the model is fit for the purpose at hand. Many extreme weather events are poorly simulated when available public climate model data sets are used, and thus those data sets are unsuitable for attribution studies.

Confidence in attribution statements is increased when both Granger and Pearl causal-inference techniques can be invoked and produce similar results. Confidence is further increased when multiple independent research groups use different models, observations, and methods and arrive at similar conclusions.

Port Arthur, Texas, was devastated by the overwhelming amount of precipitation from Hurricane Harvey in 2017. (Courtesy of US Air National Guard/Staff Sgt. Daniel J. Martinez.)

first question is that climate change increased the average temperature of a 1-in-30-year event by about 2 °C.

To answer the second question about the change in rarity, one needs to estimate chances of an average temperature of 34.2 °C without any climate change. The observed temperature is near the upper bound of the counterfactual distribution, and the return time is estimated to be 66 million years. Publishing an attribution statement based on that estimate would be unwise, however, because the uncertainties from extrapolating out that far are extreme. Best practice is to put uncertainty bounds on the ratio of those return times. Using a likelihood ratio test, scientists can place a 95% confidence interval of 16 to infinity on the ratio of counterfactual to observed return times. In plain language, climate change increased the chances of the observed 2011 Texas summer temperature by at least a factor of 16.

The current global warming level of about 1.2 °C above preindustrial levels means that any rare heat wave that now occurs has an attributable human influence (reference 3, chapter 11). Most areas of the world are significantly warmer, but highly polluted urban areas may actually be cooler because of the reflective properties of aerosol pollutants. That is not to say that quantifying the human influence on heat waves is always easy. As the climatologist Geert Jan van Oldenborgh pointed out, we must do better in observational, modeling, and statistical analysis tools to increase confidence in attribution statements.[4] Indeed, summer daily high temperatures throughout the Pacific Northwest in 2021 were such far outliers that some researchers concluded that they were "virtually impossible" without climate change.[5] Confidence in that statement is limited, however, because the models used fail to adequately describe the 100-year observational record.[6]

In general, the climate change influence on the best estimate of changes in extreme-event magnitudes is relatively insensitive to estimates of event rarity. That often inspires confidence in such attribution statements even when the observational period is relatively short. Conversely, the climate change influence on best estimates of changes in an event probability—for example, the chance of exceeding 34.2 °C in Texas—is more uncertain because of both the statistical model and event characterization, although the lower bound on probability changes has been found to be independent of estimates of event magnitude.[7,8]

Precipitation

Estimating the human influence on heavy precipitation events

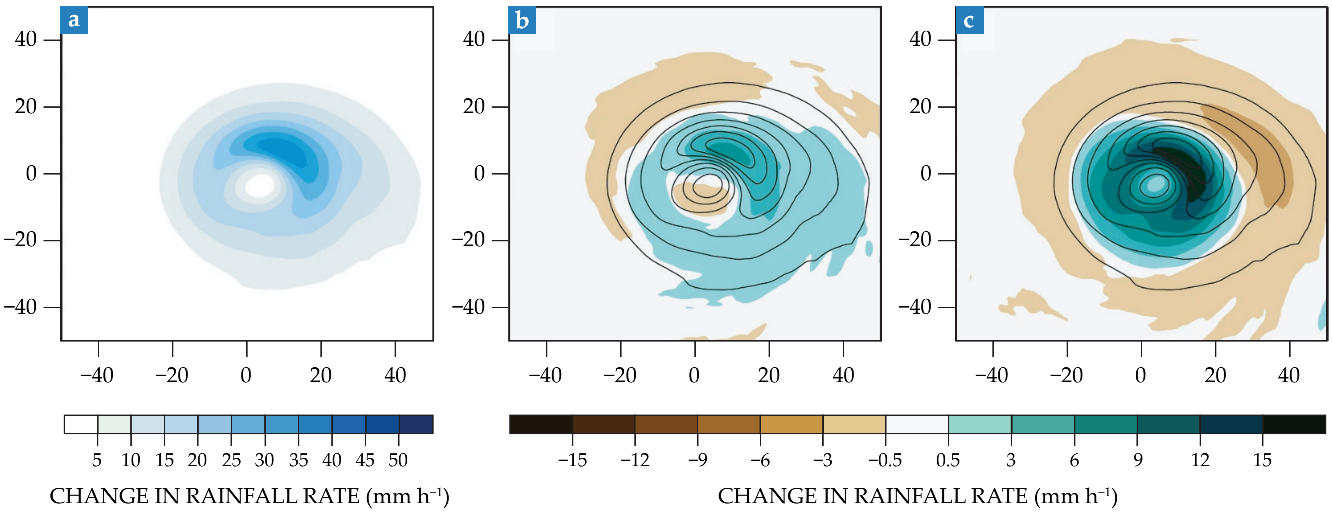


FIGURE 2. CHANGES IN PRECIPITATION during Hurricane Maria in 2017 relative to the cyclone center throughout its lifetime. **(a)** Composite simulated precipitation across multiple simulations under realistic climate conditions. **(b)** Attributable change in precipitation calculated from realistic simulations and a cooler, counterfactual simulation approximating preindustrial conditions. **(c)** Projected change in precipitation calculated from realistic simulations and counterfactual conditions at 3.5 °C warmer than preindustrial conditions, or how much worse it could've been. Contours indicate the rainfall rate from the historical simulation. The plots are in units of the grid resolution, 4.5 km. (Adapted from ref. 13.)

is more complicated than for heat waves for several reasons. The first is that precipitation is a sporadic event, and extreme precipitation even more so. (To learn about human influences on monsoons, see page 32 in this issue.) Well-established theory (the Clausius–Clapeyron relation) and traditional trend analysis reveal that saturation specific humidity increases by about 7% per 1 °C of local warming. Because extreme precipitation usually occurs in fully saturated atmospheric conditions, one might expect the likelihood of such an event to also increase at the same rate. The more likely a local area is to be fully saturated, the more likely it is to rain. Analyses that used the 100 km climate models on extreme precipitation trends confirm that rate of increase (reference 3, chapter 11). But the realism of simulated extreme storms in those coarse models is questionable. More-specialized high-resolution simulations suggest both that the Clausius–Clapeyron rate of increases in specific humidity is a lower bound for precipitation increases in certain types of extreme storms and that best estimates can exceed that lower bound by factors of two or more because of changes in localized storm dynamics.[9,10] Increases in computational resources are aiding understanding in that rapidly developing subject.

While some classes of extreme precipitation, such as wet winters, are amenable to lengthy but coarsely resolved climate model simulations because of their large spatial scales, simulations at high enough resolutions to permit tropical cyclones (less than 25 km) or convective storms (less than 4 km) are so computationally expensive that only a few data sets are available. Alternatively, one can use shorter, high-resolution hindcast or "storyline" simulations. Hindcasts simulate recent weather events for which various external factors are known or can be turned on and off. Hindcast simulations with imposed climate change permit attribution of the change in magnitude of severe storms. In many storyline event-attribution studies, two sets of hindcast simulations of the event are made: A set of the "event that was" under realistic conditions is compared with a set of the "event that might have been" had humans not interfered with the climate system. Because of their short duration, those weather-prediction-like simulations by design do not directly inform any changes in frequency. While storyline attribution studies can be made in the absence of attribution of the human influence on the local, long-term trends, confidence in an attribution is increased if multiple lines of evidence by independent research teams are available.

Much progress has recently been made in understanding the human-induced increases in tropical cyclone precipitation through storyline event-attribution analyses. For instance, three independent attribution studies were performed on data from Hurricane Harvey, a stalled tropical cyclone that dumped copious amounts of precipitation on Texas's greater Houston and Gulf Coast regions in 2017.[8,11,12] A best estimate distilled from those papers is that climate change increased Harvey's rainfall by 19%, or about 2.5 times as much as what might be expected

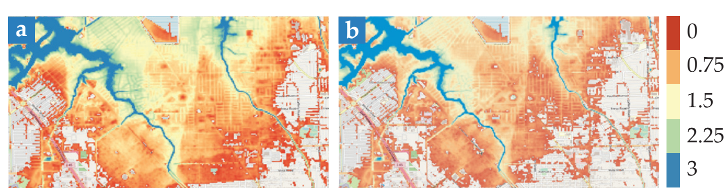


FIGURE 3. ACTUAL AND COUNTERFACTUAL FLOOD simulations in Texas's South Houston and Pasadena neighborhoods during Hurricane Harvey. **(a)** The flood that was. (Adapted from ref. 15.) **(b)** The flood that might have been in the absence of anthropogenic climate change. The difference between the models is the assumption that human activities increased Harvey storm total precipitation by 19%. Colors denote the depth of flood water in meters.

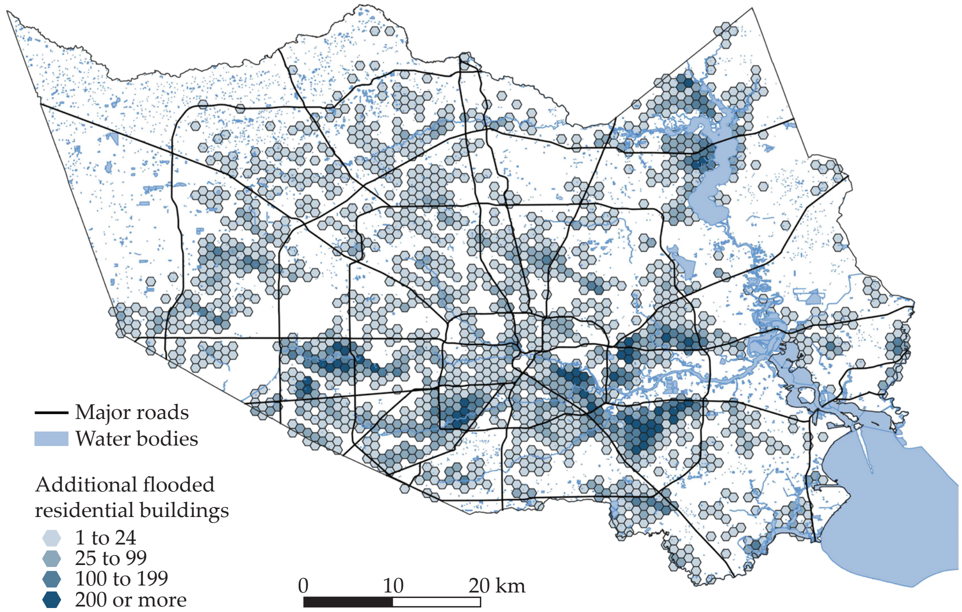


FIGURE 4. ADDITIONAL ANTHROPOGENIC FLOODING. Each hexagonal bin symbolizes the upper limit of the number of residential buildings that would not have flooded without the added impact of climate change in Harris County, Texas, during Hurricane Harvey in 2017. (Adapted from ref. 16.)

from Clausius–Clapeyron scaling of the increased available moisture from the 1 °C of attributable warming in the Gulf of Mexico. Since Harvey, numerous other tropical storms have been analyzed and have revealed similar scaling of precipitation statistics.[10,13]

The mechanism for the super Clausius–Clapeyron scaling is simple. Figure 2a shows the composite simulated precipitation from Hurricane Maria, which devastated Puerto Rico in 2017. Figure 2b shows the attributable precipitation changes at the time it occurred, and figure 2c shows the hypothetical precipitation changes in a much warmer world. The first thing to notice is that the increases, either in an absolute or relative sense, are the largest in the rainiest parts of the storm. The second is that there are decreases in the outer precipitation bands. What is happening is that warmer conditions are likely increasing the storm's wind speeds. While the changes in instantaneous maximum wind speeds are thought to be slight at present, they will become more robust in a much warmer world. That increase in tropical cyclone intensity causes the storm structure to change and become more efficient at precipitating available moisture.

Hurricanes receive much of the attention in the attribution community, but other storm types are worth studying. A recent storyline analysis found that precipitation from a selected group of strong atmospheric-river storms affecting the San Francisco Bay Area coincidentally also increased at about twice the Clausius–Clapeyron rate.[9] Analysis suggests that those physical mechanisms of change are very different than inferred for tropical cyclones. Although few additional studies have been made of atmospheric rivers that impact coastal zones, the information has been alarming enough for decision makers to act on it.

Although interest is high, little is known with confidence about anthropogenic increases in the intense summer mesoscale convective systems that can occur in continental interiors, partly because of computational constraints. Limited studies have analyzed the human influence on environmental conditions that support tornadoes, but there is no consensus regarding how climate change has influenced tornados.[14]

Drought

Assessing the impact of climate change on drought can be complicated. One must consider the different types of droughts. NOAA classifies drought as a hierarchy of four related conditions. Meteorological drought is characterized by a deficit of precipitation; agricultural or ecological drought, of soil moisture; and hydrological drought, of water supply. Socioeconomic drought occurs when demand for water exceeds the supply.

Agricultural drought depends on both the precipitation that falls on the ground and the evapotranspiration of moisture from plants and soils. Evaporation from bare ground depends strongly on air temperature. As the temperature increases from climate change, evaporation increases lead to drier soils. Transpiration from plants depends even more strongly on air temperature. Plants cool themselves by opening their stomata and evaporating water. In hot conditions, they can draw moisture from their root system until little soil moisture is left. Decreased soil moisture may in turn limit evapotranspiration, which means the relationship between temperature and soil moisture isn't linear. Recent literature shows that human-induced climate change has contributed to increases in agricultural droughts in some regions because of evapotranspiration increases (reference 3, chapter 11).

On the other hand, consensus has not been reached on changes in meteorological drought occurrences in most regions. At this time, only studies in the Mediterranean show a consistent human influence on precipitation deficits. Still, uncertainty levels are high (reference 3, chapter 11). Likewise, meteorological drought conditions in Mexico and the Southwest US are projected to be more common as the climate warms, but a robust signal has yet to be detected.

Hurricane Harvey flooding

It should be clear from the previous sections that scientists understand the human influence on certain types of extreme weather. Methods to comprehend the connection between the anthropogenic influences on weather and the socioeconomic outcomes are just now starting to be developed. For example, consider again Hurricane Harvey, which inundated much of the greater Houston area in 2017.

A counterfactual "flood that might have been" was constructed by decreasing Harvey's observed precipitation uniformly according to published precipitation-attribution statements and using that as the input to a credible flood model.[15]

Figure 3 compares the actual flood depth and the best estimate of the counterfactual one in two Houston neighborhoods, where almost 9 000 homes were flooded. The 19% precipitation increase attributable to human-influenced climate change translated to an additional 1 m of flood waters and a 14% increase in flood area. Equivalently, as a best estimate, the probability of a $90 billion hurricane loss (the amount of estimated insured losses) in Texas was quadrupled because of climate change.

The Harvey flood model has a resolution of 30 m—about the size of a suburban property—and its results have been made publicly available at https://portal.nersc.gov/cascade/Harvey. The maps permit individuals to understand whether their home would have flooded without human-influenced climate change. Individuals can select different estimates of the human influence on precipitation and locate their home on both the realistic and counterfactual flood maps. That level of detail also permits a more refined damage estimate by combining it with socioeconomic data sets. Projecting real-estate maps onto the flood maps results in a best estimate that approximately 32% of flooded homes in Harris County, where Houston is located, would not have been flooded without climate change. Furthermore, in the actual flood, 75% of the county's flooded homes were outside the federal 100-year flood plain—likely uninsured against flood damage—adding to the $90 billion insured loss.[16] Figure 4 shows an upper bound on the distribution of homes that were flooded in Harris County because of climate change.

Census data further reveal that Hurricane Harvey's flood damages were not equally distributed across socioeconomic groups. Hispanic households are about 36% of the population of Harris County, but they owned or rented roughly 50% of the flooded homes. Additional analysis reveals that in wealthy neighborhoods, damages increased for households with more wealth. In low-income neighborhoods, the opposite trend was found: that damages increased for households with less wealth. Given the relative contribution to increases in greenhouse gases from people who are wealthy compared with people who are economically marginalized, such analyses quantify environmental and other social injustices.[16]

More than just a weather forecast

Other human impacts of extreme weather can also be quantified. Of particular interest is whether climate change increases the number of deaths from heat waves. They are among the deadliest of all extreme weather events, and epidemiology studies have developed relationships between mortality risk and temperature.[17] At high temperatures, the relationship becomes more sensitive: In already hot weather, a small increase in temperature can cause large increases in mortality. Scientists can use the relationship when estimating the attributable human temperature increase to understand the change in mortality risk during a heat wave.

Another method maps mortality and temperature curves onto temperature-change plots, like those in figure 1, to estimate the number of people who have died because of the influence of climate change on a heat wave and to determine how the probability of death has changed.[18] The models are not perfect. Incorporating adaptive measures—for example, cooling centers and other outreach that can reduce the heat wave mortality risk—into attribution statements is currently challenging. There are many additional factors to consider when extending attribution statements about the human influence on extreme weather events to attribution statements about the human influence on the events' outcomes.

The sixth assessment report of the Intergovernmental Panel on Climate Change declares that "human-induced climate change is already affecting many weather and climate extremes in every region across the globe" (reference 3, page 8). Developments in attribution science over the past two decades reinforce that statement by extending attribution statements about observed long-term climate change to encompass robust statements about the human influence on many types of individual extreme weather events. That includes heat waves, heavy precipitation events, and floods. Attribution methods for some classes of events have matured to the point where they could be operationalized to regularly inform the public about the current dangers of climate change. That would also greatly increase the number of events analyzed in that way and further understanding.

Extreme weather happens everywhere, but most event-attribution studies have focused on events in nations that have the requisite human and computational resources. Groups like World Weather Attribution (https://www.worldweatherattribution.org) have begun to apply attribution science to significant weather events in low-income countries. Such organizations' credibility is increased when they involve experts from those nations who better understand the details of local climate and associated impacts.

The extension of attribution science to connect human increases to the socioeconomic damages and inequalities of extreme weather events is now underway. That work has the potential to inform low-income nations about their loss and damages, giving them the knowledge to negotiate for more assistance from recovery funds.

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