# Wetter Rainfall Hours in a Warming Climate

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**Climate change is supercharging the water cycle, leading to heavier rainfall extremes in many parts of the U.S. Heavy rains worsen the risk of flooding—which can injure people, take lives, destroy homes, and strain aging infrastructure.**

**More extreme rainfall isn't a distant future possibility; it's been increasing over much of America for more than three decades.**

**From 1988 to 2017, increases in rainfall accounted for one-third of U.S. flood damages (about $73 billion out of $210 billion in total) over that same period. Floods are complicated, but rain is an important factor. And the most intense downpours caused the largest damages.**

**This report focuses on these especially intense and risky rainfall extremes:**
**— how they're affected by climate change,**
**— how they've changed across the U.S.,**
**— and what we can expect in the coming decades.**

## Extreme rainfall is risky.

An extreme rainfall event brings an amount of rain that is well-above normal and is rare for a particular place and time of year. Extreme, heavy rainfall is about the intensity of rain events. A higher-than-normal amount of rain falling over a given period of time—whether a month, a day, or even several hours—can bring a range of risks, even in the driest places.

**Short, intense downpours bring risks such as:**

**Flood risks.** Heavy downpours bring more rain over a few hours or even a few minutes, which can lead to flash flooding and landslides. Flash floods are among the most hazardous weather-related events because their rapid onset limits time to issue early warnings and get people out of harm's way. Increases in extreme rainfall accounted for about a third of flood damages across the U.S. from 1988 to 2017 (equivalent to about $73 billion). It's important to note that many factors contribute to flood risk (see Box 1), but heavy rainfall is a key risk factor.

**Health risks.** Floodwaters can be fatal. They can also expose people to toxic contaminants, water-borne diseases, and injury from debris. Health risks aren't only physical; exposure to flooding has also been linked to post-traumatic stress.



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**Societal risk:** Downpours can displace families from their homes, compromise agricultural economies by drowning crops, and prevent access to public services like healthcare and education.

**Watershed risks:** Heavy downpours can damage or flood crops, cause soil erosion, or increase runoff of excess nutrients into freshwater and coastal ecosystems.

**Economic risks:** According to recent research, more extreme daily rainfall can also hinder economic growth, even in wealthy industrialized countries like the U.S.

## Rainfall extremes intensify in a warming climate.

**For every 1 °F of warming, the air can hold an extra 4% of moisture.**

This relationship between air temperature and water vapor pressure is governed by the laws of thermodynamics and represented in the Clausius-Clapeyron equation. 4% more moisture might not seem like much, but the U.S. has already warmed by 2.6 °F since 1970—meaning our atmosphere can already hold about 10% more moisture.

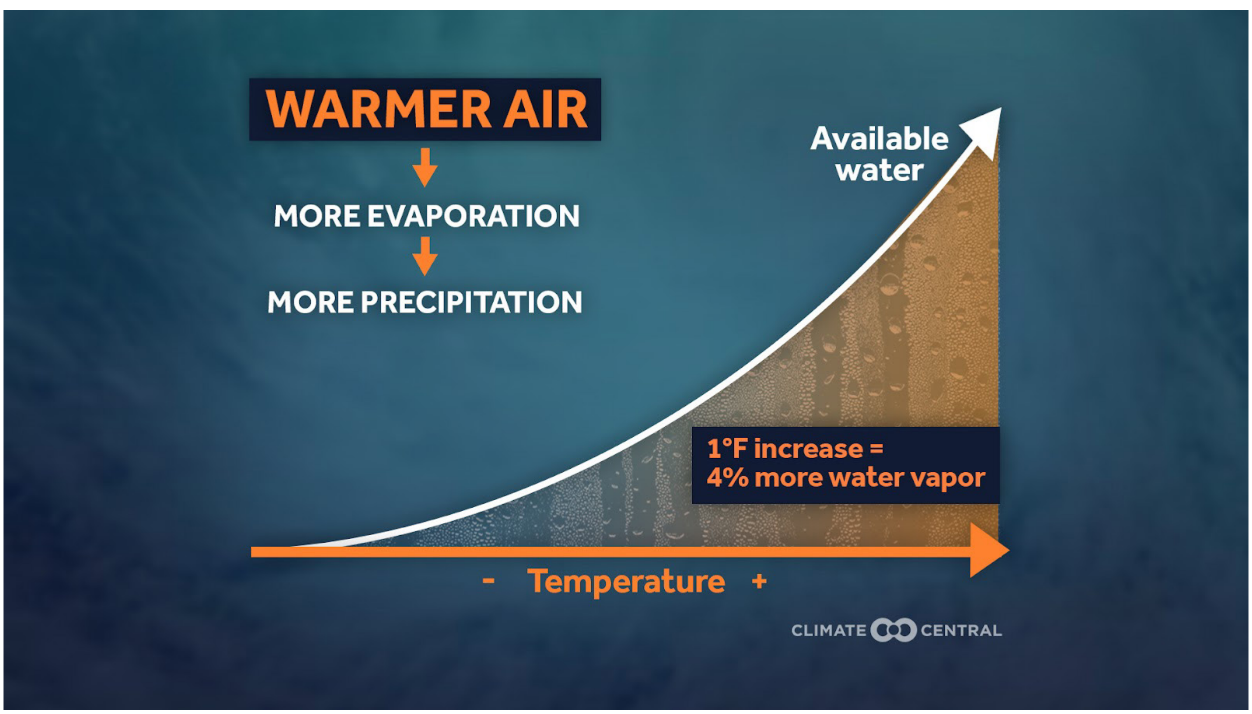
**More moisture in warmer air increases the chances that rain falls in heavier downpours.**

### Box 1: What is flash flooding, and how is it affected by rainfall extremes?

Flash flooding is defined by the American Meteorological Society as follows:

"Flooding caused by rapidly rising water level in streams, creeks, rivers, or other waterways, normally dry stream beds, or in urban areas, usually as a result of intense rainfall over a relatively small area or for moderate to intense rainfall over highly saturated or impervious land surfaces, and generally occurring within minutes to several hours of the rainfall event." (AMS definition here).

It is critical to note that, although extreme rainfall contributes to flash flood risk, there are many additional factors that also contribute. These factors include but are not limited to: land use, land cover (whether paved or vegetated), and water management. The complexity of flood generation limits our ability to directly relate intensifying rainfall extremes to increased flood risks.



Theory suggests that rainfall becomes more intense with warming. And both rain gauge data and modeling experiments support this theory. The latest reports from the Intergovernmental Panel on Climate Change states that there is high confidence that heavy rainfall frequency and intensity have increased globally since the 1950s, with human-caused climate change likely the main cause.

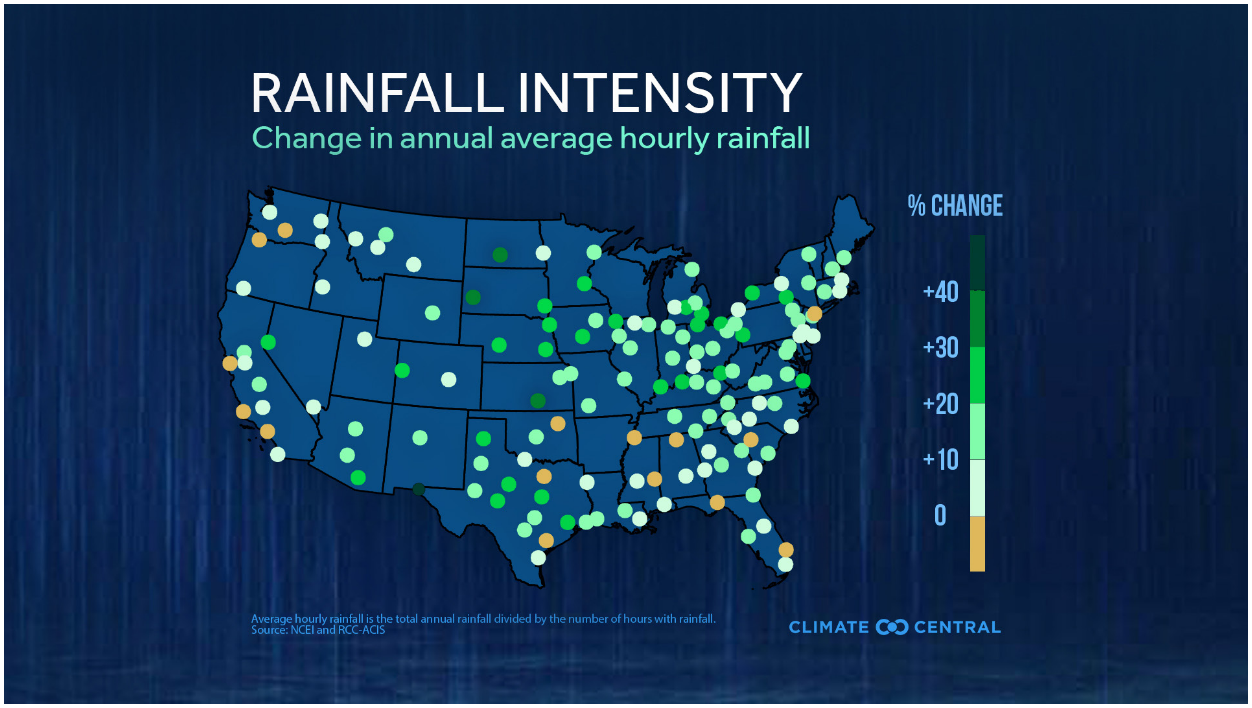
And in the U.S., extreme daily rainfall events have been on the rise since the 1980s. And from 1958 to 2016, the heaviest 1% of rainfall events became 55% and 42% wetter in the Northeast and Midwest, respectively—and 9-29% wetter for all other regions of the contiguous U.S. and Alaska.

**Faster intensification of shorter rainfall events.**

There is also evidence from locations with sufficient data available, such as Australia and the Netherlands, that ***hourly rainfall extremes*** have intensified at about double the rate that we would expect from the Clausius-Clapeyron equation. The more rapid intensification of *hourly* bursts of extreme rainfall (which can quickly lead to flash flooding or landslides) is likely related to the physics of convective clouds that lead to more intense storms.

## Changes in hourly rainfall intensity since 1970

**Hourly rainfall extremes** can be especially crucial for flash flood risk, but these shorter rainfall intervals are less-studied than longer (i.e., daily, 5-day, monthly) rainfall extremes. This is partly because few weather stations around the world have sufficient record length or resolution to robustly analyze hourly extremes. The U.S., however, is fortunate to have more long-duration rainfall data sets than most other countries.




**These hourly rainfall extremes are the focus of new analysis from Climate Central.**

To assess trends in hourly rainfall intensity, Climate Central calculated the Simple Hourly Rainfall Intensity Index (total inches of annual rainfall divided by the total annual hours of rainfall) for 150 U.S. weather stations with sufficient data quality over the 1970-2021 period.

An increase in the Simple Hourly Rainfall Intensity Index indicates an increase in hourly rainfall intensity—in other words, ***more rain falling per hour***.

The Simple Hourly Rainfall Intensity Index is the average rainfall intensity (inches per hour) but only for days when it rains. This means that it can show increasing intensity even if the total amount of rainfall in the year is decreasing. A decreasing Simple Hourly Rainfall Intensity Index could occur if a location has an increase in days with a little bit of rain, even if the maximum intensity is stable or increasing.

**More rain per hour in most places—even dry ones.**

Key findings from this Climate Central analysis include:

- 90% of the 150 stations analyzed had an increase in hourly rainfall intensity since 1970.
- Increases in hourly rainfall intensity since 1970 were widespread across the contiguous U.S. and prevalent throughout the Northeast, Ohio Valley, Upper Midwest, Northern Rockies and Plains, and Southwest.
- The change in the Simple Hourly Rainfall Intensity Index from 1970 to 2021 across all 150 stations ranged from -18% to +49%, with an overall average of +13%.
- 63% (95/150) of stations had an increase in hourly rainfall intensity of +10% or more.

The 10 locations with the greatest increase in hourly rainfall intensity spanned a wide range of mean annual precipitation, and all but one (Huntington, W.Va.) are below the national average (31.3 inches for the 1991-2020 normal).

| Location | Change in Simple Hourly Rainfall Intensity Index (1970-2021) | Mean Annual Precipitation (inches) |
|---|---|---|
| 1. Fairbanks, Alaska | 49% | 10.8” |
| 2. El Paso, Texas | 40% | 8.8” |
| 3. Wichita Area, Kan. | 38% | 27.0” |
| 4. Rapid City, S.D. | 32% | 16.6” |
| 5. Bismarck, N.D. | 31% | 16.5” |
| 6. Reno, Nev. | 30% | 7.4” |
| 7. San Angelo, Texas | 29% | 20.0” |
| 8. Sioux City, Iowa | 28% | 26.1” |
| 9. Huntington, W.Va. | 28% | 41.0” |
| 10. North Platte, Neb. | 28% | 19.1” |

This underscores that the change in hourly heavy rainfall intensity is widespread and that the risks posed by short bursts of extreme rainfall (see Section 1) are relevant for both wet and dry locations.

This finding is consistent with the latest reports from the Intergovernmental Panel on Climate Change (IPCC) indicating that precipitation extremes are likely to increase nearly everywhere, even in regions with decreasing average precipitation totals.

## How will extreme rainfall respond to additional warming in the future?

**Extreme rainfall intensification is likely to continue—globally and in the U.S.**

**Globally**, future intensification of extreme rainfall is expected to scale with the Clausius-Clapeyron equation (4% more moisture for every additional 1°F of warming), according to the latest IPCC reports. We can also expect the frequency of rarer events to accelerate even faster with additional warming, according to the same reports (see Chapter 11 of the Working Group I report). For example, very extreme rainfall events that used to occur on average *once* every 50 years are now expected to occur *three times* every 50 years, putting people, infrastructure, and ecosystems at more frequent risk.

**In most parts of the U.S.**, historical increases in the frequency and intensity of heavy rainfall are projected to continue, according to the latest National Climate Assessment. With additional warming, the Northeast and Midwest regions are expected to see the largest future increases in the extreme 1% of rainfall events (with ~40% increases projected by the end of the century).

**The U.S. is expected to see more flash floods with continued emissions.**

U.S. flash floods could intensify by about 8% by the year 2100 in a scenario with high future levels of heat-trapping emissions. The Southwest is projected to see the greatest increase in flash flooding, and the central U.S. could become a new flash flooding hotspot with future warming.

**The burdens of rising flood risk in the U.S. are not shared equally.**

A recent modeling study estimates a 26% increase in overall U.S. flood risk by 2050 in a scenario with moderate future levels of heat-trapping emissions. But according to the same study, flood risks aren't equally shared. Poorer, predominantly white populations bear the brunt of current flood risk, whereas future flood risks are expected to disproportionately impact Black communities along the Atlantic and Gulf coasts.

The likelihood of extreme rainfall intensification with additional warming indicates a need to adapt existing stormwater infrastructure to keep pace, as well as a need to enhance equitable flood resilience in current and future rainfall and flooding hotspots.

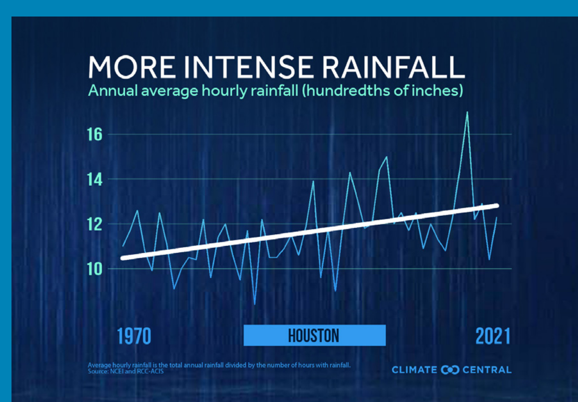
## Box 2: Hurricane Harvey and Hourly Rainfall Intensity

Hurricane Harvey, a Category 4 storm that made landfall in Texas in August 2017, was the second most costly weather and climate disaster in the country since tracking of such events began in 1980. According to the National Oceanic and Atmospheric Administration, Hurricane Harvey took 89 lives, cost an estimated $143.8 billion in damages, displaced over 30,000 people, and damaged over 200,000 homes and businesses.

The devastating impacts of Hurricane Harvey were due in large part to historic rainfall and extensive flooding. According to NOAA, 6.9 million people experienced over 30 inches of total rainfall, while 1.25 million had over 45 inches and 11,000 people had over 50 inches of rain during the week of Hurricane Harvey.

In Climate Central's analysis of long-term hourly rainfall intensity trends in Houston, Texas, 2017 had exceptionally high Simple Hourly Rainfall Intensity Index values, even relative to the long-term trend, reflecting the extreme rainfall during Hurricane Harvey.

A World Weather Attribution analysis indicated that the extreme rainfall from Hurricane Harvey over Texas was about three times more likely and 15% more intense due to human-caused climate change.



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## Methodology

The calculation of the Simple Hourly Rainfall Intensity Index is the total annual rainfall divided by the total number of hours with rainfall in a year. This is an extension of one of the core climate indices defined by the Expert Team on Climate Change Detection and Indices.

The trend in the Simple Hourly Rainfall Intensity at each site was computed using linear regression. The trends that we report are first and foremost a communications tool and we report them regardless of statistical significance. Not all stations usually in a Climate Matters analysis had available hourly data. After a series of data quality tests, 150 stations were included in the final analysis. The measurement of precipitation, which may include snowfall at some stations,  at times can be impacted by the changes to the instrumentation at the station. Over the past 50 years most stations in this subset have undergone changes in instrumentation These changes may impact the precise measurements derived from these gauges. The hourly component is dependent only on whether there was rain or was not rain, which should lessen the potential problems with exact hourly measurements. Despite these cautions, the datasets used remain the source for most research on hourly rainfall rates, and our results are consistent with prior studies. Hourly rainfall data was accessed from two separate sources NCEI and RCC-ACIS. Data accessed from NCEI was used for 1970 - 2011 and the RCC-ACIS tool was used 2012-2021. Among those stations in the final analysis, not all stations had data as far back as 1970. Those stations without data prior to 1990 were excluded.

To ensure that daily totals were within a reasonable range, the sum of the hourly data was compared to the record daily rainfall for that station as reported in ACIS. Those that exceeded this amount were removed. Another test of validity and to further compare the consistency of the two datasets, the annual total rainfall calculated from the hourly HPD data was compared to the annual rainfall from ACIS for the period 1970-2011. The same comparison was performed comparing the  annual total rainfall calculated from ACIS to the annual total rainfall from ACIS from 2012-2021. In those years where the annual totals were more than 25% different, all values for the year were excluded.