When It Rains, It Pours

Global Warming and the Rising Frequency of Extreme Precipitation in the United States

ENVIRONMENT OHIO
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Cover Photos: Main Image: A rainstorm descending on Miami; Nick Tzolov. Upper left: After 18 inches of rain fell in 36 hours, the Nisqually River in Mt. Rainier National Park flooded, tearing away more than 200 yards of the main park road and destroying most of Sunshine Point Campground; National Park Service, November 2006. Middle left: Heavy rain in January 2005 flooded the Saline River in Gallatin County, Illinois, which was declared a disaster area by state officials; Tracy Felty, c/o National Weather Service; Lower left: A driver and his vehicle stuck in floodwaters; Bart Sadowski.

Layout: Moebius Creative

Table of Contents

Executive Summary

Scientists expect that global warming will cause a variety of changes to precipitation patterns in the United States. Many areas will receive increased amounts of rain and snow over the course of a year; some areas will receive less. But scientists expect that, all across the country, the rainstorms and snowstorms that do occur will be more intense – increasing the risk of flooding and other impacts.

In this report, we evaluate trends in the frequency of storms with extreme levels of rainfall or snowfall across the contiguous United States over the last 60 years. We analyze daily precipitation records spanning from 1948 through 2006 at more than 3,000 weather stations in 48 states. We then examine patterns in the timing of heavy precipitation relative to the local climate at each weather station.

We find that storms with extreme amounts of rain or snowfall are happening more often across most of America, consistent with the predicted impact of global warming.

Scientists expect global warming to increase the frequency of heavy precipitation.

- As the earth warms, temperate regions of North America will face a growing risk of storms with extreme levels of rain or snowfall.
- Global warming increases the intensity of precipitation in two key ways. First, by increasing the temperature of the land and the oceans, global warming causes water to evaporate faster. Second, by increasing air temperature, global warming enables the atmosphere to hold more water vapor. These factors combine to make clouds richer with moisture, making heavy downpours or snowstorms more likely.
- The consequences of increasingly intense rainstorms may include flooding, crop damage, pollution of waterways with runoff, erosion, and other environmental and economic damage. During the 20th century, floods caused more property damage and loss of life than any other natural disaster in the United States.

An increase in the number of downpours does not necessarily mean more water will be available.

- Scientists expect that extreme downpours will punctuate longer periods of relative dryness, increasing the risk of drought. In the Southwest, for example, total annual precipitation is projected to decline – amplifying the impact of periods of little rainfall between heavy storms.

- Even in the rest of the country, where total annual precipitation is expected to increase, more of that precipitation will fall in heavy rainstorms or snowstorms, paradoxically increasing the potential for drought.

- As temperatures rise, precipitation will become increasingly likely to fall as rain rather than snow, increasing runoff and likely reducing water supplies in areas dependent on snowpack.

Weather records show that storms with extreme precipitation have become more frequent over the last 60 years.

- Consistent with the predicted impacts of global warming, we found that storms with extreme precipitation have increased in frequency by 24 percent across the continental United States since 1948. (According to a statistical analysis of the data, with 95 percent confidence, the increase has been between 22 and 26 percent.)

New England and the Mid-Atlantic experienced the largest increase in extreme precipitation frequency.

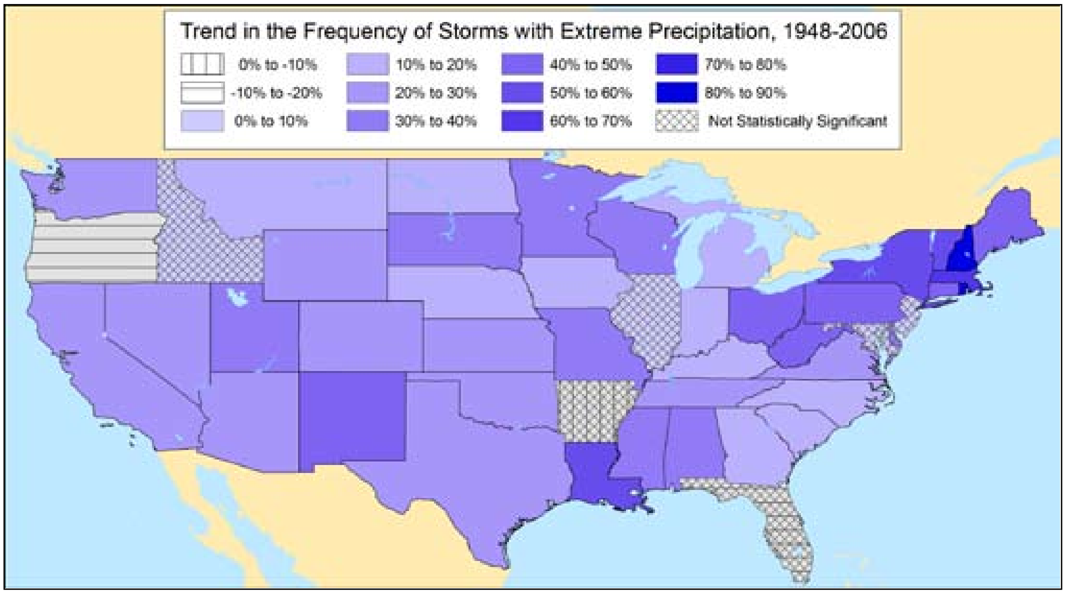
- New England and the Mid-Atlantic saw storms with extreme precipitation levels increase in frequency by 61 percent and 42 percent, respectively.

- At the state level, Rhode Island, New Hampshire, Massachusetts, Vermont, New York and Louisiana all saw extreme precipitation events increase in frequency by more than 50 percent.

- In the contiguous United States, 40 states experienced a statistically significant trend toward increasingly frequent storms with extreme precipitation. Only one state (Oregon) showed a statistically significant decline in frequency of storms with extreme precipitation. *(See Figure ES-1.)*

- See the report appendices on page 35 for a full list of results by region, state and metropolitan area.

Figure ES-1: Trend in the Frequency of Extreme Precipitation by State



Climate divisions covering more than half of the land area of the United States show a statistically significant trend toward more frequent storms with extreme precipitation.

- We also looked at the trend in frequency of storms with extreme precipitation within climate divisions, which are boundaries used by climatologists since the 1950s to aggregate weather observations. Figure ES-2 presents these trends, showing that the largest increases occurred across New England, New York, much of the Great Lakes area, the upper Midwest, plus Louisiana, New Mexico, northern Washington and southern California.
- Climate regions covering more than half of the surface area of the contiguous United States show a statistically significant increase in the frequency of storms with extreme precipitation levels.
- In contrast, the data show statistically significant decreases in extreme precipitation frequency for climate regions covering only 4 percent of the area of the United States. (Oregon, the northwestern corner of North Dakota, central Arkansas, the southern tip of Lake Michigan, and northern Florida.)

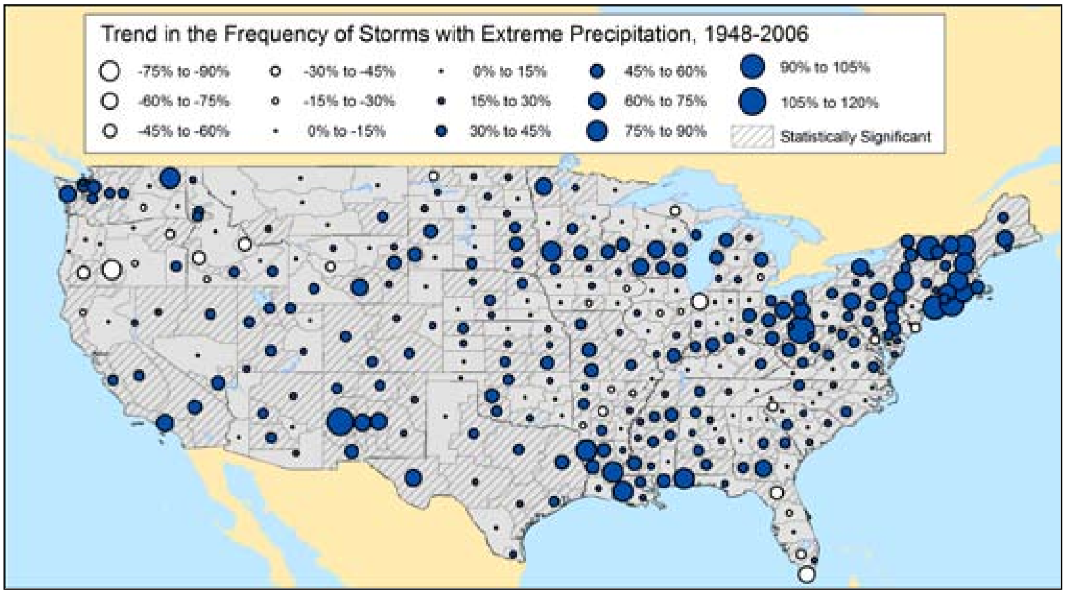
These findings are consistent with previous studies of extreme precipitation patterns, both in the United States and across the globe. For example:

- Scientists have observed warmer weather, higher atmospheric moisture content, increased formation of storm clouds, and an increase in thunderstorm activity over the contiguous United States in recent decades.
- In 1999, researchers at the Illinois State Water Survey and the National Climatic Data Center (NCDC) found that storms with extreme precipitation became more frequent by about 3 percent per decade from 1931 to 1996. Our findings are consistent with this result.
- In 2004, scientists at NCDC concluded that most of the observed increase in storms with heavy and very heavy precipitation levels since the early 1900s had occurred in the last three decades. In other words, they found that the change in extreme precipitation frequency is unusual and relatively recent.

How We Obtained Our Results

In this report, we examine trends in the frequency of extreme precipitation across the contiguous United States from 1948 through 2006. We analyze daily precipitation records obtained from the National Climatic Data Center for more than 3,000 weather stations, identifying storms with extreme 24-hour precipitation totals. We define extreme precipitation relative to the local climate, selecting storms with an average recurrence interval of 1 year or more. In practical terms, this means that we selected the 59 largest storms in terms of total precipitation at each weather station during the 59-year period of analysis, and labeled these “extreme.” We then examined trends in the frequency of these storms over time. For a more detailed explanation, see the “Methodology” section on page 32.

Figure ES-2: Trend in Frequency of Extreme Precipitation by Climate Division



- Moreover, NCDC found that extremely heavy storms are increasing in frequency more rapidly than very heavy storms – which in turn are increasing in frequency more rapidly than heavy storms.

The severity of the trend toward more intense downpours in the future depends upon our emissions of the pollution that drives global warming.

- Climate models predict that the trend toward increasingly frequent storms with heavy precipitation will intensify in the future. Some amount of change is inevitable given the global warming emissions humans have already created. However, we still have the ability to prevent the worst-case scenarios.

- By halting the increase in total U.S. global warming emissions now and reducing emissions by at least 80 percent by mid-century, we can limit the increase in major storm frequency — and thus reduce future risks of flooding and other serious consequences of extreme rainstorms.

To address global warming, America should limit emissions of global warming pollution, while improving energy efficiency and increasing the use of renewable energy.

- To protect future generations, the United States should adopt a mandatory cap on global warming pollution that reduces total U.S. emissions by at least 15 to 20 percent by 2020 and by at least 80 percent by 2050.

- If policymakers choose a cap-and-trade program to achieve this goal, it should include auctioning 100 percent of emission allowances, rather than giving allowances away to polluters. By auctioning allowances, we can reduce the cost of achieving emission reduction goals, making it more likely that America will succeed.

- The United States should also adopt complementary policies to improve energy efficiency and increase the use of clean, renewable energy.

National Park Service

November 6 and 7, 2006. After a massive rainstorm which dropped 18 inches of rain on Mt. Rainier National Park in Washington, the Nisqually River raged in flood. The rushing water destroyed more than 200 yards of the main park road and wiped out Sunshine Point Campground.

Introduction

"This is supposed to be a rainfall event that is a once-in-a-decade occurrence — we've had three in the past seven months. We've got a serious issue to worry about."

— New York Governor Eliot Spitzer, 8 August 2007[1]

That day, citizens of New York City woke up to a heavy thunderstorm. Rain waters flooded the streets and the subway tracks, disrupting transportation all across the city. Service was delayed or suspended on all 24 city subway lines during the morning rush hour, and nine lines were still disabled by evening – the third time such an event had happened since January.[2]

In late June 2006, communities from North Carolina to New York were drenched for four straight days by a storm that dropped as much as 13 inches of rain, breaking the one-day, two-day and one-week records for rainfall at Reagan National Airport outside Washington, D.C. The Delaware River at Callicoon, New York reached the 500-year flood level.[3] As many as 200,000 people were evacuated from their homes as a precaution, and the storm caused approximately $1 billion in damage across the region.[4]

On November 6, 2006, visitors to Mt. Rainier National Park in Washington State found themselves in the midst of a huge rainstorm, carried over the Pacific Northwest by Chinook winds. Over 36 hours, the storm dropped 18 inches of rain, washing out roads and trails; cutting sewer, water, and power lines; and destroying campgrounds. The entire park remained closed for six months.[5] According to the National Weather Service, the storm was "the fifth 10-year event in the last 16 years," (including storms in 1990, 1995, 1996, 2003 and 2006).[6]

On August 16, 2007, Tropical Storm Erin made landfall in Texas, dropping as much as 11 inches of rain over parts of the state. The storm came on the heels of 40 consecutive days of rain in Texas, where a thousand homes had been damaged or destroyed by flooding since late May.[7] The flooding killed 14 people from Texas to Oklahoma.[8]

During the third week of August 2007, heavy storms dropped up to 18 inches of rain across Illinois, Indiana, Iowa, Minnesota, Ohio, and Wisconsin. The resulting floods killed 18 people, and 21 counties across the region were declared federal disaster areas.[9] The Kishwaukee River in DeKalb, Illinois, rose above the severe flood stage, reaching the second-highest level ever recorded.[10] Firefighters rescued stranded people from flooded homes in Findlay and Ottawa, Ohio, where the Blanchard River crested more than 8 feet above flood level – the highest level the river had reached since 1913.[11]

These examples of extreme rainfall may seem like isolated incidents. But they are part of a larger story of increasingly intense downpours across the United States — a story likely tied to human-caused global warming.

In this report, we review the science behind the expectation that global warming will substantially increase the odds of extreme precipitation. We then analyze the precipitation records of thousands of weather stations across the country over the last 60 years.

Our conclusion is that, increasingly, across the United States, when it rains, it pours.

No single weather event can be conclusively blamed on global warming. However, the increase in heavy downpours and snowfalls that has taken place over the last 60 years is very consistent with scientists' projections of likely changes in a warming world. Moreover, scientists who have studied trends in the global water cycle have found strong fingerprints of human influence.

Given the changes that humanity has already made to the atmosphere, some increase in the risk of more intense downpours in the future is unavoidable. But how much worse it will get is largely within our control. If we continue to burn more fossil fuels each year, the planet will become much warmer and precipitation will become much more intense. But if we reduce our emissions of the pollution that drives global warming, we can limit the risk of increasingly extreme weather.

Achieving the cuts in emissions needed to prevent the most dangerous impacts of global warming won't be easy, but it can be done. By establishing aggressive goals for reducing pollution — and using energy efficiency and clean, renewable energy to meet them — we can stave off the worst effects of global warming.

Ivo Shandor

During the third week of August 2007, a heavy rainstorm descended on the Midwest, dropping as much as 18 inches of rain. In DeKalb, Illinois (pictured here), the Kishwaukee River reached a near-record flow level, flooding neighborhoods and causing extensive property damage.

How Scientists Expect Global Warming to Alter Precipitation Patterns

In 2007, the Intergovernmental Panel on Climate Change (IPCC), the world's most authoritative source of information on global warming, concluded that the evidence of global warming is "unequivocal" and that it is largely caused by human activity.[12]

Over the past several centuries, humans have changed the composition of the atmosphere, primarily by burning fossil fuels. As a result, the atmosphere is trapping more of the sun's energy and warming the earth. Over the last 100 years, the average temperature of the earth's surface has increased by 1.3° F, and the rate of increase is accelerating.[13]

Among the consequences of global warming, scientists predict that warming temperatures will increase the frequency of major storms with heavy rainfall or snowfall. Moreover, the amount of precipitation falling as rain rather than snow will increase.

The implications of this trend are clear. Heavy downpours are a frequent cause of flooding, which caused more property damage and loss of life in the United States than any other type of natural disaster during the 20th century.[14]

More Intense Precipitation

As the earth warms, scientists predict that precipitation will become more intense across temperate regions of North America, including most of the United States.[15] In other words, when it rains or snows, more rain or snow is likely to fall — making heavy precipitation more frequent. These storms will be characterized by higher moisture content and higher rates of precipitation. Moreover, heavy storms will tend to punctuate longer intervals of relatively dry weather.[16]

To examine the potential future impacts of global warming, scientists have developed sophisticated computer models of the climate. Starting with increasing levels of pollutants that drive global warming, the models forecast changes that could occur in precipitation patterns. Scientists judge the usefulness of these models by how well they are able to reproduce recent changes. And on this score, the models have become increasingly accurate.

Climate models show that the intensity of precipitation, or the amount of rain or snow falling during any given storm, is very likely to increase almost everywhere across the world. However, the increase will be most significant in areas, such as the middle and high latitudes, where overall precipitation also increases.[17] *(See Figure 1b.)*

Moreover, climate models predict that downpours and snowstorms will become increasingly intense as global warming progresses through the 21st century.[18] Some increase in precipitation intensity is inevitable given the pollution humanity has already added to the atmosphere. However, the trend will be more severe if global warming pollution continues unchecked. *(See Figure 1a.)* One paper estimates that storms with precipitation levels considered "extreme" could double in frequency by the end of the century.[19]

Models specifically focused on the contiguous United States also predict widespread increases in extreme precipitation as a result of global warming.[20]

Figure 1: Scientists Predict Global Warming Will Make Extreme Downpours More Frequent[21]

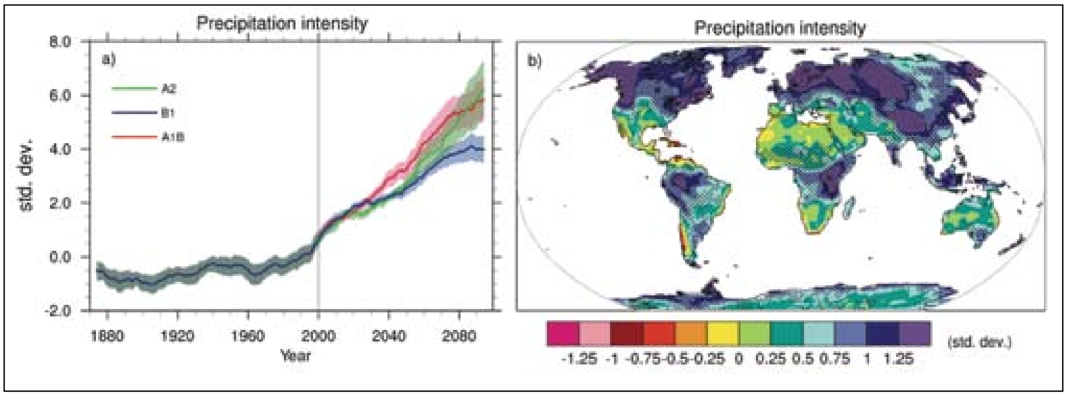


Figure 1a represents globally averaged changes in precipitation intensity (defined as the annual total precipitation divided by the number of wet days) from nine climate models. The figure presents projected future global warming impacts under three separate scenarios for future global development (and thus global warming emission levels) developed by the IPCC. The scenarios assume roughly these levels of global warming pollutant concentrations in the atmosphere by 2100 (in carbon dioxide equivalent): B1, 600 parts per million (ppm); A1B, 850 ppm; A2, 1,250 ppm. By contrast, pre-industrial concentrations of carbon dioxide are estimated at approximately 280 ppm and 2007 concentrations are at approximately 380 ppm. The solid line represents a 10-year rolling average across all the climate models, and the shaded area around the line represents the standard deviation of the mean. Precipitation intensity is presented in units of standard deviation, which represents the magnitude of the change in precipitation intensity compared to the 1980 to 1999 average. Figure 1b represents modeled changes in spatial patterns of precipitation intensity in 2080-2099 compared to 1980-1999 for the A1B scenario. Adapted from: Gerald Meehl, et al., "Global Climate Projections," Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007.

The Scientific Reasoning

Scientists predict that global warming will increase the frequency of major rainstorms and snowstorms for two primary reasons. First, warmer temperatures lead to greater evaporation. When land and ocean surface temperatures are warmer, liquid water more quickly becomes airborne. Second, warmer air can hold more water vapor.

Satellite data show that a 1° C increase in air temperature increases the amount of water in the atmosphere by 7 percent.[22] As the global average temperature has risen in recent decades, the amount of moisture in the atmosphere over the oceans has increased at a rate of about 1.2 percent per decade (plus or minus 0.3 percent).[23] A recent analysis led by Benjamin Santer at the Lawrence Livermore National Laboratory concludes that this trend is primarily due to human emissions of global warming pollution.[24]

These two factors, increased evaporation and increased ability of the air to hold water vapor, combine to increase how rich clouds can become with moisture. Clouds that are richer with moisture tend to produce storms with more rain or snow and higher rates of precipitation.

Warmer weather and higher atmospheric moisture content increase the frequency of formation of cumulonimbus clouds (sometimes called thunderclouds). Scientists have observed this change happening in the skies over both the United States and former Soviet republics.[25] Scientists have also observed a related increase in thunderstorm activity over the contiguous United States.[26]

Other, more complicated factors are also at play. For example, in humid regions, warmer minimum temperatures caused by global warming can increase the risk of severe weather.[27] Additionally, global warming will likely change air circulation patterns in the atmosphere, which can affect the distribution of water vapor from tropical to temperate parts of the globe.[28] In the Northern Hemisphere, this effect is predicted to play a role in increasing total precipitation in the northern latitudes, which will amplify the trend toward more intense storms.

Greater Annual Precipitation, Except in the Southwestern U.S.

In the United States, forecasts suggest that total annual precipitation will likely increase in most of the country but decline in the Southwest.[29]

This trend is already visible. A recent analysis led by Xuebin Zhang and Francis Zwiers at Environment Canada finds increased annual precipitation in temperate regions of the Northern Hemisphere from 1925 to 1999.[30] The authors conclude that this increase in average precipitation can only be explained by human emissions of global warming pollution.[31] Moreover, the observed changes are larger than climate models were able to predict — suggesting that predictions of the future impacts of global warming may also be underestimated.[32]

Seasonally, most scientific models predict that global warming will make summers drier and winters wetter in northern and temperate regions of North America.[33] For example, studies estimate that precipitation in the central and western parts of the United States may increase slightly overall, but may decline in the summer months.[34] The eastern U.S. likely will receive greater precipitation in every season, especially from December through May.[35]

Climate models predict that global warming will increase storm intensity more than it will affect total annual precipitation.[36] Downpours or heavy snowstorms will tend to be punctuated by extended periods of relatively dry weather, resulting in smaller overall changes in total precipitation.

However, changes in total precipitation, both annually and seasonally, will contribute to the trend toward more precipitation extremes. Areas with increasing total precipitation are likely to see greater trends toward heavy rainfall or snowfall events, while areas with decreasing total precipitation will be more vulnerable to drought.[37]

More Precipitation Falling as Rain Rather than Snow

Intense storms can bring large amounts of rainfall or snowfall. However, global warming will very likely increase the amount of precipitation that falls in the form of rain rather than as snow. This change is intuitive — warmer average temperatures caused by global warming will limit the conditions favorable to snowfall.

In fact, the trend is already measurable in the United States. In the western mountains of the U.S., 74 percent of weather stations showed an increase in the fraction of annual precipitation falling as rain rather than snow from 1949 to 2004.[38] The same trend is apparent in Canada.[39] Snow cover in the western U.S. is decreasing, primarily because of warming temperatures rather than changes in precipitation.[40]

As global warming progresses, rain will continue to become more likely than snow, relative to historical weather patterns at a given location.

Increased Drought

An increase in the frequency of storms delivering large amounts of rain or snow does not necessarily mean more water will be available. While it may seem like a paradox, scientists expect that extreme downpours will be punctuated by longer periods of relative dryness, increasing the risk of drought.

Overall, the science indicates that the number of dry days across the United States and most of the world will increase because of global warming.[41] *(See Figure 2.)* Under one scenario of intense warming (A2), scientists predict that the percent of land enduring severe drought globally could rise to 30 percent by the end of the century compared with 1 percent today.[42]

Areas projected to receive less total precipitation, such as the southwestern United States, will be particularly vulnerable.[44] The effect is also likely to be more pronounced in the summers, which likely will become drier in temperate regions of North America as a result of global warming.[45]

The increased temperatures brought by global warming will increase the rates of evaporation of moisture from the land and the ocean. This will tend to offset the effects of more rainfall, while magnifying the effect of less rainfall.[46] As a result, scientists predict that soils in parts of central North America may become drier overall, even as extreme precipitation events become more frequent.[47]

Another factor that may increase the risk of drought — especially in areas of the country dependent on winter snowpack for water supplies — is the fact that less precipitation is falling as snow.[48] Rain from extreme downpours may fall too quickly to be absorbed into the ground where it could recharge groundwater supplies. Moreover, snow is melting earlier, reducing the ability of snow to recharge aquifers.

Figure 2: Change in the Maximum Number of Consecutive Dry Days as a Result of Global Warming[43]

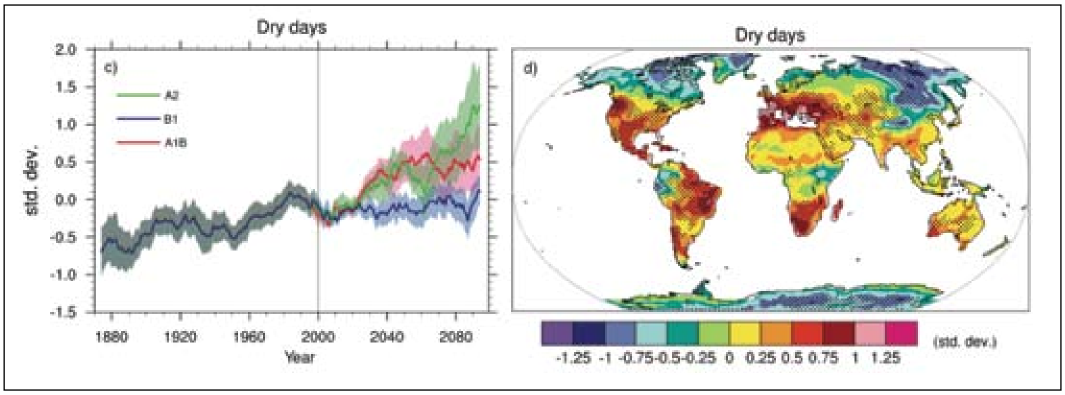
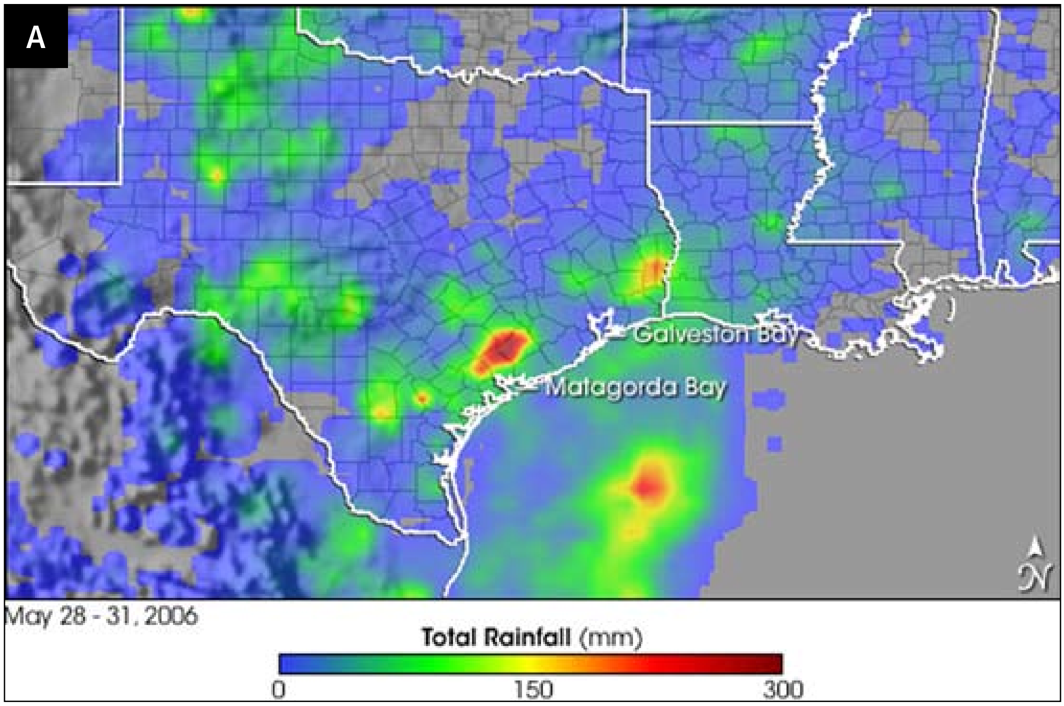


Figure 2a represents globally averaged changes in dry days (defined as the annual maximum number of consecutive dry days) from nine climate models. The figure presents projected future global warming impacts under three separate scenarios for future global development (and thus global warming emission levels) developed by the IPCC. The scenarios assume roughly these levels of global warming pollutant concentrations in the atmosphere by 2100 (in carbon dioxide equivalent): B1, 600 parts per million (ppm); A1B, 850 ppm; A2, 1,250 ppm. By contrast, pre-industrial concentrations of carbon dioxide are estimated at approximately 280 ppm and current concentrations are at approximately 380 ppm. The solid line represents a 10-year rolling average across all the climate models, and the shaded area around the line represents the standard deviation of the mean. Dry days are presented in units of standard deviation, which represents the magnitude of the change in dry days compared to the 1980 to 1999 average. Figure 2b represents modeled changes in spatial patterns of dry days in 2080-2099 compared to 1980-1999 for the A1B scenario. Adapted from: Gerald Meehl, et al., "Global Climate Projections," Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007.

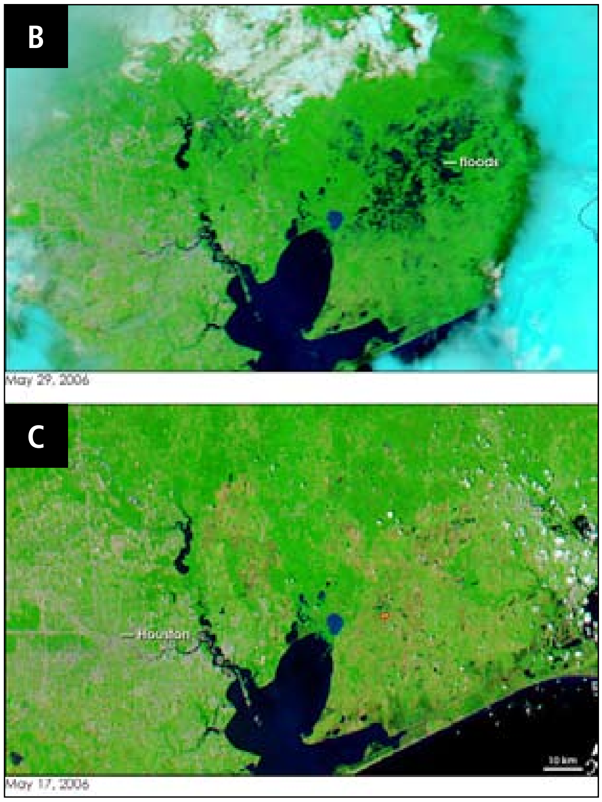
Summary

In summary, scientists expect global warming to alter general precipitation patterns over the contiguous United States in four key ways:

- Storms with extreme rates and amounts of rain or snowfall will become more frequent.
- Summers will tend to be drier while winters will be wetter. Total precipitation will increase over most of the country but not in the Southwest. The frequency of extreme events will increase much more than total precipitation.
- Precipitation will become increasingly likely to fall as rain rather than snow — a simple consequence of increased temperatures.
- Paradoxically, the number of dry days will also increase, because intense downpours will punctuate longer intervals of relatively dry weather.



NASA Earth Observatory



NASA Earth Observatory

In late May 2006, an extremely heavy rainstorm developed just east of Houston in southeastern Texas, dropping as much as 10 inches of rain (Photo A). The storm caused heavy flooding, visible in satellite images of the area taken after the clouds dissipated. Compare Photo B, which shows large areas of floodwater northeast of Galveston Bay, to Photo C, which is how the area looked before the storm.

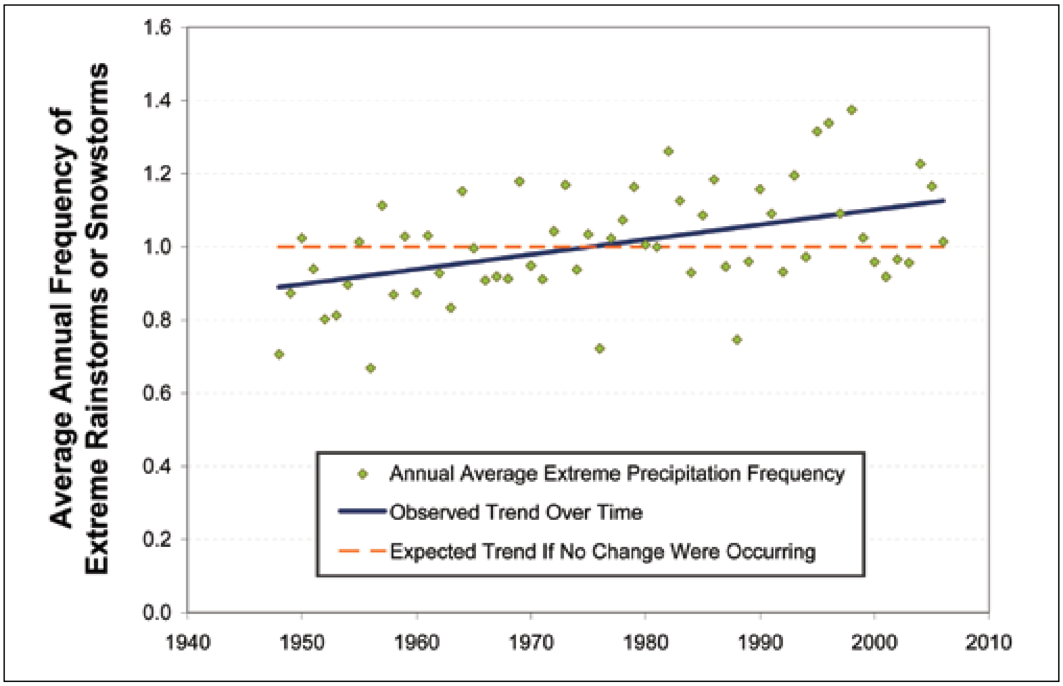
Storms with Extreme Precipitation are Becoming Increasingly Common Across Most of America

In this report, we evaluate trends in the frequency of storms with extreme levels of precipitation in the contiguous United States over the last 60 years.

We analyze daily precipitation records spanning from 1948 through 2006 at more than 3,000 weather stations across 48 states. At each individual weather station, we identify storm events with the largest 24-hour precipitation totals (including both rain and snow), selecting any storm of 1-year magnitude or larger. (In other words, we identified storms with precipitation totals that, on average, were exceeded no more than once per year at a given location during the period of analysis.) We then look for trends in the frequency of these storms over time. *(For a more detailed explanation of the methodology, see page 32.)*

Consistent with the predicted impacts of global warming, we find that extreme downpours and snowstorms have become more frequent over the last 60 years.

Figure 3: Annual Average Frequency of Storms with Extreme Precipitation in the United States from 1948–2006



Extreme Precipitation Has Become More Frequent Over the Last 60 Years

Our analysis finds that storms with extreme levels of precipitation have increased in frequency by 24 percent across the continental United States since 1948.

Figure 3 presents the average annual frequency of such storms across the U.S. from 1948 to 2006. The horizontal dashed line at "1" — representing an average of 1 storm per year at each weather station with a recurrence interval of 1-year or greater — shows what the trend would look like if no change were occurring. However, the actual trend — represented by the solid line with upward slope — is increasing.

This trend is highly statistically significant – meaning that it is very likely that the increase is a real phenomenon. With 95 percent confidence, the average increase in extreme precipitation frequency across the United States over the last 60 years lies between 22 and 26 percent.

On average across the whole country, 1995, 1996, and 1998 showed the greatest number of storms with extreme levels of precipitation. During these years, the annual average frequency of extreme downpours and snowstorms exceeded the 1948-2006 average frequency by almost 40 percent.

Regional Trends

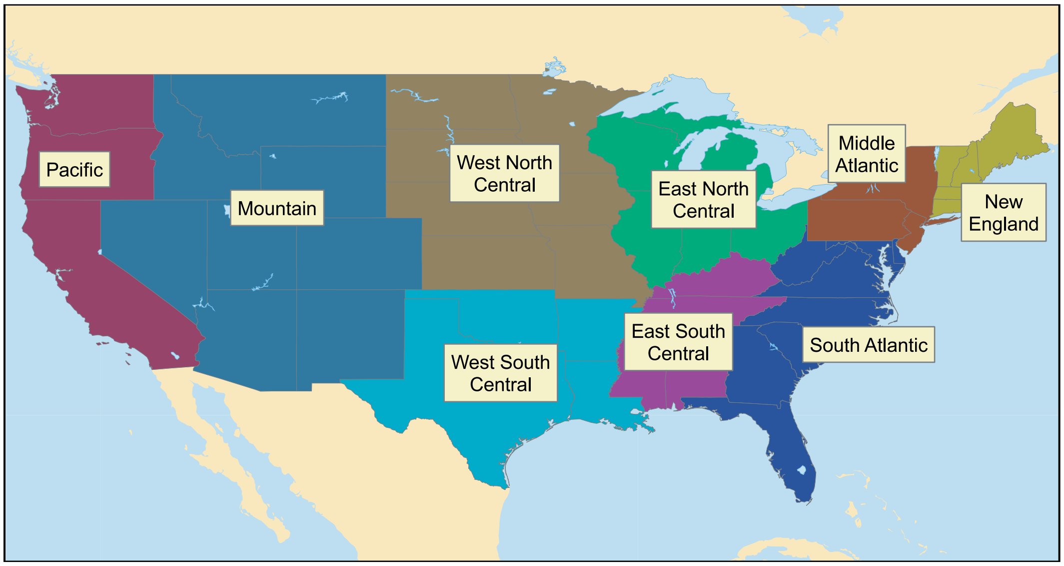
The nine regions of the contiguous United States, as defined by the U.S. Census Bureau, each show a statistically significant trend toward more frequent storms with extreme levels of rain or snowfall. *(See Table 1 and Figure 4.)*

New England and the Mid-Atlantic experienced the largest increase in extreme precipitation frequency — 61 percent and 42 percent, respectively. The remainder of the country showed increases ranging between 15 and 28 percent.

Table 1: Increased Frequency of Storms with Extreme Precipitation Levels by Region

Region	Percent Increase in Frequency of Extreme Precipitation	95 Percent Confidence Interval	Statistically Significant?
New England	61%	51%-71%	Yes
Mid-Atlantic	42%	34%-49%	Yes
East South Central	28%	22%-34%	Yes
Mountain	25%	21%-29%	Yes
West North Central	24%	20%-27%	Yes
West South Central	24%	19%-28%	Yes
East North Central	22%	18%-27%	Yes
Pacific	18%	13%-23%	Yes
South Atlantic	15%	10%-20%	Yes

Figure 4: Definition of Regions



Extreme precipitation events happened at least twice as frequently as the long-term average in the following regions and years:

- South Atlantic in 1964;
- East South Central in 1979;
- Pacific in 1995;
- Mid-Atlantic in 1996 and 2004; and
- New England in 1996 in 2005.

Table 2 lists, by region, years where heavy storm frequency was more than 50 percent greater than the regional average over the entire period of analysis.

Table 2: Years with Exceptionally Frequent Extreme Downpours and Snowstorms

Region	Years in Which Extreme Precipitation Frequency Was More Than 50 Percent Greater Than the Long-Term Average
New England	1955, 1954, 1969, 1973, 1990, 1991, 1996, 1998, 1999, 2005, 2006
Mid-Atlantic	1952, 1955, 1972, 1996, 1999, 2004, 2005
East South Central	1973, 1975, 1979, 1983, 1990, 1991
Mountain	1978
West North Central	1993
West South Central	1957, 1974
East North Central	1990
Pacific	1955, 1969, 1980, 1982, 1983, 1995, 1996, 1998
South Atlantic	1964, 1995, 1996, 2004

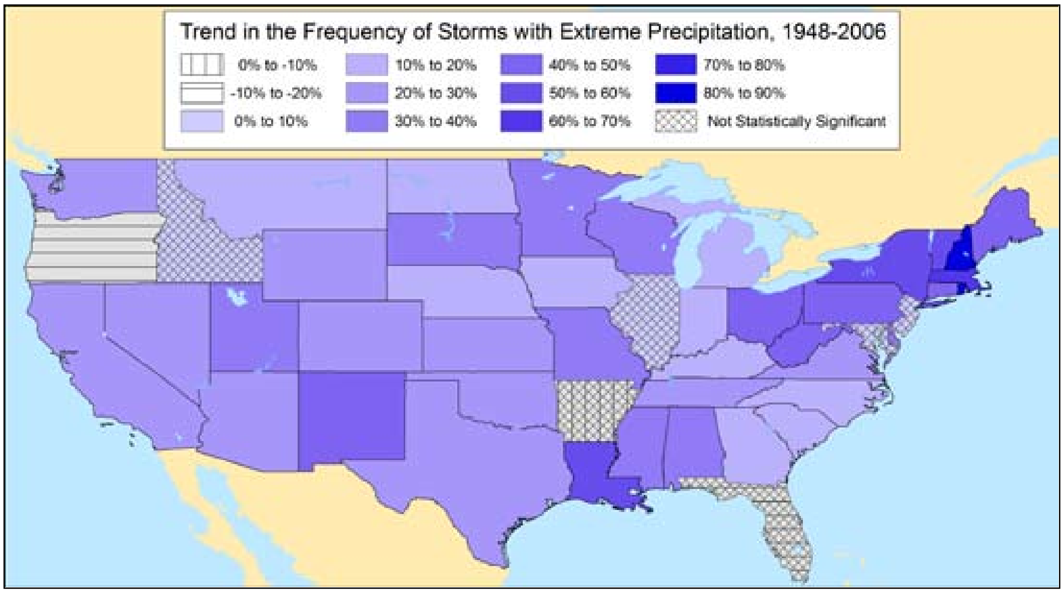
State Trends

At the state level, the trend toward increasingly frequent extreme downpours remains consistent.

In the contiguous United States, 45 states showed a trend toward more frequent storms with extreme levels of precipitation, reaching statistical significance in 40 of these states. Only three states (Oregon, Florida and Arkansas) showed a decline in frequency of such storms, and in only one of those states (Oregon) did the data reach statistical significance. *(See Figure 5.)*

Rhode Island, New Hampshire, Massachusetts, Vermont, New York and Louisiana all saw major rainstorms and/or snowstorms increase in frequency by more than 50 percent since 1948. See Appendix B on page 36 for a full list of results by state.

Figure 5: Trend in Extreme Precipitation Frequency by State



Local Trends

We also looked at the trend toward increased frequency of storms with heavy precipitation at finer levels of geography, including climate divisions and metropolitan areas.

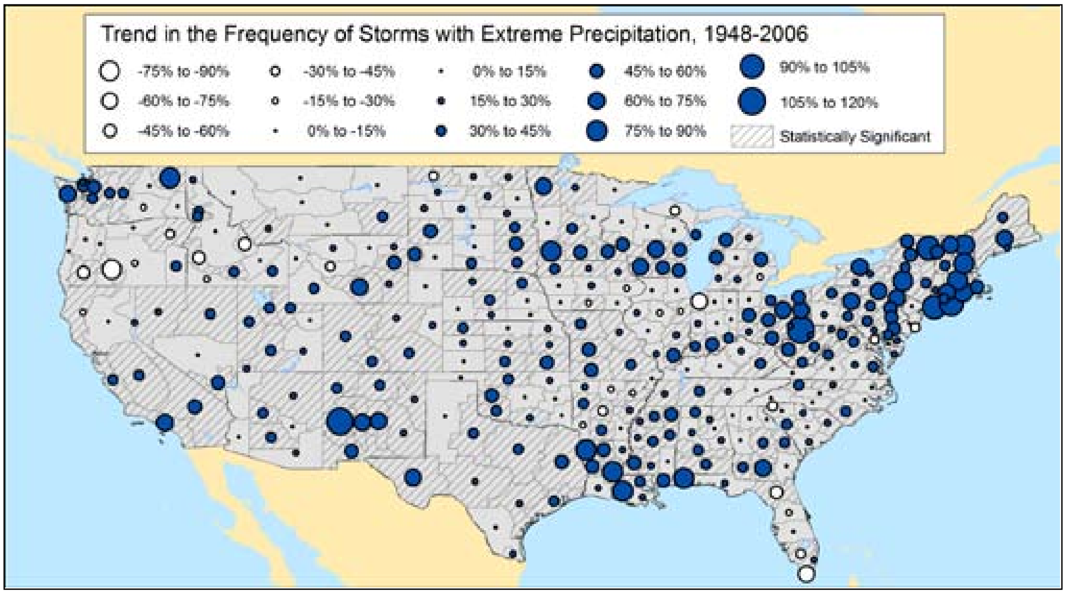
Climate Divisions

Since the 1950s, meteorologists have used climate divisions as a rough way to group weather measurements within states. Climate divisions group the country into 344 regions, with up to 10 divisions per state.[49] Figure 6 presents the trend in frequency of storms with heavy precipitation by climate division from 1948 through 2006. This map shows that the largest increases in major storm frequency occurred across New England, New York, much of the Great Lakes area, the upper Midwest, Louisiana, New Mexico, northern Washington and southern California.

Climate divisions covering 54 percent of the surface area of the contiguous

United States show a statistically significant increase in storms with extreme precipitation. (These areas appear with dark/blue circles and a crosshatched background in Figure 6.) In contrast, the data show statistically significant decreases in extreme storm frequency for climate divisions covering only 4 percent of the area of the United States. (These areas include parts of Oregon and Idaho, the northwestern corner of North Dakota, central Arkansas, the southern tip of Lake Michigan, and northern Florida — represented by areas with hollow circles and crosshatched background.)

Figure 6: Trend in Extreme Precipitation Frequency by Climate Division



Metropolitan Areas

The detection of trends in the frequency of major storms with extreme precipitation levels becomes more difficult at very small levels of resolution. With fewer weather stations able to contribute information, it is much harder to detect statistically significant trends at the metropolitan level. Results at this level tend to be much less precise than those covering larger areas and relying on larger numbers of weather stations.

However, many metropolitan areas across the United States show significant trends toward more frequent storms with extreme precipitation since 1948. Out of 248 metropolitan areas across the contiguous United States (as defined by the U.S. Census Bureau), 55 show a statistically significant increase in the frequency of major storms with heavy precipitation. These metropolitan areas include:

- New York (NY, NJ, CT, PA)
- Boston (MA, NH, ME, CT)
- Dayton and Columbus (OH)
- Grand Rapids (MI)
- Minneapolis / St. Paul (MN, WI)
- Memphis (TN, AR, MS)

- St. Louis and Kansas City (MO, KS, IL)
- New Orleans and Baton Rouge (LA)
- Houston, Dallas and Fort Worth (TX)
- Salt Lake City (UT)
- Phoenix (AZ)
- Los Angeles and San Diego (CA)
- Seattle (WA)

In contrast, only two areas show a statistically significant decrease — Little Rock, Arkansas and Medford/Ashland, Oregon.

Appendix C on page 38 lists trends in frequency of major storm events by metropolitan area.

These Results Are Consistent with Previous Research

Climate experts have published a number of studies that detect this same trend toward increased frequency of storms with extreme precipitation across the contiguous United States. Our results are consistent with this earlier research.

Since the first documentation of a trend toward more frequent major storms in 1993, several research teams have compiled more detailed evidence:[50]

- In 1995, Stanley Changnon and Kenneth Kunkel at the Illinois State Water Survey found that extreme precipitation frequency and flooding had increased across portions of the central United States over the period from 1921 to 1985.[51]
- Also in 1995, Thomas Karl, Richard Knight, David Easterling and Robert Quayle at the National Climatic Data Center published evidence that storms with extreme rainfall were becoming more frequent. They discovered that the area of the U.S. deriving a greater than normal amount of precipitation from extreme 1-day storms (defined as storms delivering more than 2 inches of rain) rose by about 2 percent during the 20th century. They calculated that the odds of such a result appearing by chance, given the natural year-to-year variability of the climate, were about 1 in 1,000.[52]
- In 1998, Thomas Karl and Richard Knight at the National Climatic Data Center found that total precipitation had increased by about 10 percent across the contiguous U.S. from 1910 to 1998, and that most of that increase was the result of more extreme precipitation events rather than an evenly distributed increase in precipitation.[53]
- In 1999, Kenneth Kunkel and Karen Andsager at the Illinois State Water Survey and David Easterling at the National Climatic Data Center found that the national trend toward more frequent extreme storms (defined as storms with a recurrence interval of 1 year or longer at each weather station) increased by 3 percent per decade from 1931 to 1996.[54]
- In 2003, Kenneth Kunkel and his colleagues found that weather stations across the contiguous United States showed that major storm frequency was relatively high around the turn of the 1890s and early 1900s, decreasing to a minimum in the 1920s and 30s, and then generally increasing through the 1990s.[55]

Are Observed Increases in Storm Intensity a Result of Global Warming?

Since the 1970s in the contiguous United States, an apparently unusual increase in precipitation intensity has occurred. At the same time, the annual number of days with rain or snowfall has decreased.

It is one thing to observe a change in weather patterns. It is another thing altogether to figure out why the change happened. As with any climate event that happens over a relatively short period of time (such as the last 100 years), there is always a chance that it could be simply a result of the natural variability that exists within the climate system.

However, scientists who have looked into the question of causation have found links to global warming.

To attempt to detect the fingerprints of human influence in recent precipitation trends, scientists have turned to climate models for evidence. Using models, scientists can conduct experiments to decipher the impact of changes humans have made in atmospheric levels of global warming pollution.

In 2002, Vladimir Semenov and Lennart Bengtsson at the Max Planck Institute for Meteorology in Germany compared actual observations of precipitation intensity with the results of two climate models over the contiguous United States during the 20th century. They found general agreement between the model and reality in terms of the trend toward more frequent extreme precipitation. They also observed that for the northeastern quadrant of the United States, the annual number of days with precipitation has been declining since the 1970s (simultaneously with an increase in the frequency of extreme downpours) – and the model generally reproduces the trend, albeit overestimating the absolute number of days with precipitation.[61]

A research team led by Pavel Groisman at the National Climatic Data Center reviewed the evidence in 2005, concluding that while more work is needed, "the evidence is growing that the observed historical trends of increasing very heavy precipitation are linked to global warming."[62]

In 2007, the Intergovernmental Panel on Climate Change concluded that it was more likely than not that human influence contributed to the trend toward more extreme precipitation events — and that future increases in extreme precipitation are very likely.[63]

The conclusion that global warming is tied to the observed increase in extreme rainstorm and snowstorm frequency is consistent with other measures of climate change that show evidence of human influence, including increasing concentration of global warming pollutants in the atmosphere; increases in global average air and ocean temperatures; changing temperature extremes; widespread melting of snow and ice; rising global sea level; altered wind patterns; increasing moisture content of the atmosphere over the oceans; and observed trends toward increasing annual precipitation totals across temperate regions of the Northern Hemisphere.[64]

- In 2004, Pavel Groisman, Richard Knight, Thomas Karl, David Easterling, Bomin Sun, and Jay Lawrimore at the National Climatic Data Center concluded that most of the observed increase in heavy and very heavy storm events since the early 1900s had occurred in the last three decades.[56] From 1970 to 1999, the frequency of heavy storms (the upper 5 percent of precipitation events) increased by 14 percent. The frequency of very heavy storms (the upper 1 percent) increased by 22 percent. And the frequency of extreme storms (the upper 0.1 percent) increased by more than 40 percent.[57] This was an important observation: that the change in heavy precipitation events is unusual and relatively recent.[58]

Additional studies reveal that similar trends are occurring in other regions of the world. For example:

- In 2002, Povl Frich at the Hadley Centre for Climate Prediction in the United Kingdom (and colleagues in Australia, the Netherlands and the United States) revealed that a significant trend toward more frequent extreme rainstorms existed globally for the period 1946-1999 (excluding major regions of Africa and South America, where data were inadequate to draw a conclusion).[59]

- In 2005, Pavel Groisman and his colleagues at the National Climatic Data Center, the University of North Carolina, Duke University, and the Russian Institute for Hydrometeorological Information compiled precipitation records from across the globe. They found increases in major storms (both for the top 5 percent and the top 0.3 percent of storm events in terms of total precipitation) during the 20th century for the western part of the former

Dr. David A. Robinson, New Jersey State Climatologist

A huge northeaster hit New Jersey in April 2007, bringing five to nine inches of rain, causing hundreds of millions of dollars in flood damage, and killing at least three people. Flooding submerged parts of Manville (pictured here) and Bound Brook. Manville was reachable only by boat for three days. More than 3,000 people were evacuated from their homes, and the flooding caused severe delays at local train lines and airports.

U.S.S.R, Siberia, northern Europe, the Pacific Coast of northwestern North America, Northern Canada, Quebec, the central United States, central Mexico, subtropical Brazil, Uruguay, South Africa, the eastern Mediterranean, India, eastern China, central and northern Japan, and southeast Australia. For the central U.S., central Mexico, and South Africa, they found that most of the increase in major storm frequency had happened since the 1970s. [60]

Implications of Increasingly Frequent Storms with Extreme Precipitation

The trend toward increasingly frequent heavy rainstorms and snowstorms over the last century has had significant consequences for communities across the United States. As this trend continues, with major storms becoming more intense and more frequent in the future, serious impacts are likely to occur. Among those impacts could be flooding (both flash flooding and longer-term flooding), pollution of waterways with runoff and sewage, the spread of infectious disease, and damage to agriculture.

Flooding

More frequent extreme downpours in the future will likely increase the risk of floods.

During the 20th century, flooding caused more property damage and loss of life in the United States than any other type of natural disaster.[65] Major floods can disrupt transportation, damage or destroy buildings, and cause severe injury to people unlucky enough to be caught in their path.

Floods are often caused by heavy rainfall — sometimes in short, intense storms and sometimes over longer periods of time. The last two decades provide numerous examples:

- From April through October 1993, widespread flooding occurred along the Mississippi and Missouri rivers and their tributaries, causing as much as $15 billion in damage across the Midwest.[66] It was the largest flood event ever to hit the United States, with some areas flooded for more than 200 days. The flood was caused by persistent rainfall over a period of months. From June through August, more than 24 inches of rain fell on central and northeastern Kansas, northern and central Missouri, most of Iowa, southern Minnesota and southeastern Nebraska — two to three times more than normal.[67]
- In January 1995, a major storm hit California. Many weather stations recorded record 24-hour rainfall totals. The Salinas River reached a record flood crest (exceeding the previous one by more than 4 feet). The flooding caused $1.8 billion in damage.[68]
- In January 1997, a series of major storms dropped up to 30 inches of rain on California, on top of one of the wettest Decembers on record. More than 23,000 structures were damaged by the flooding, which covered 300 square miles, causing more than $2 billion in damage.[69]
- The Red River Valley in Minnesota and North Dakota flooded in April and May 1997, causing floodwaters to extend up to 3 miles inland near Grand Forks. The storm was caused by a series of large snowstorms, followed by a rapid warming event causing extreme snowmelt in April. The flood caused as much as $2 billion in damages.[70]

- In July 1997, a series of heavy thunderstorms dropped up to 14 inches of rain on Fort Collins, Colorado. Spring Creek experienced heavy flooding, derailing a freight train and destroying two mobile home communities. Colorado State University lost much of its inventory of books and journals in the flood.[71]

- In September 1999, Hurricane Floyd dropped up to 19 inches of rain on North Carolina, causing record flooding in the eastern half of the state. Many town areas, including sections of Princeville and Greenville, were submerged under as much as 20 feet of water.[72]

- In June 2001, the remnants of tropical storm Alison dropped nearly 37 inches of rain near Houston, Texas — forcing more than 17,000 people from their homes, causing nearly $6 billion in flood damage and killing more than 40 people.[73]

- Between July 2004 and June 2006, four large storms struck the Delaware River Valley along the border of New Jersey and Pennsylvania, damaging or destroying 51 dams and flooding thousands of homes.[74] The June 2006 storm drenched communities from North Carolina to New York, causing approximately $1 billion in damage across the region.[75]

- In mid-April 2007, a huge Northeaster bore down on Connecticut, New York, New Jersey, and Philadelphia, dropping 9 inches of rain (and 17 inches of snow farther inland). In New Jersey, the Raritan River at Bound Brook exceeded flood stage by 10 feet. Overall damage exceeded $300 million.[76]

- In August 2007, storms dropped up to 18 inches of rain across Illinois, Indiana, Iowa, Minnesota, Ohio and Wisconsin — destroying hundreds of homes and causing hundreds of millions of dollars in property damage.[77]

During the 20th century, great floods (reaching 100-year water heights over large basins) increased in frequency.78 Moreover, climate models predict that great floods will continue to become more frequent as a result of the changes global warming is causing to the global water cycle.[79]

Runoff Pollution and Sewage Overflows

More frequent downpours in the future will likely increase the risk of water pollution from surface runoff and from sewage overflows.

Stormwater runoff is one of the primary factors behind water pollution.[80] After heavy rainfall, water flows down fields, lawns, rooftops, sidewalks, parking lots and streets, carrying everything from sediment to road grime into waterways. As a result, contaminated runoff makes streams, rivers and lakes less suitable for drinking and less able to support a diverse community of wildlife.[81]

To control runoff and downstream flooding, some municipalities may require new construction to be designed to rapidly absorb runoff from a 1-year rainstorm.[82] However, because the frequency of major storms is increasing, these developments may not function as designed in controlling runoff. Thresholds for what define 1-year rainstorms were lower 40 years ago than they are today — and those thresholds are likely to increase further in the future.

Heavy rainfall can also overwhelm sewage infrastructure, resulting in the release of raw or partially treated sewage into rivers and lakes. Sewage discharge can contaminate waterways with fecal bacteria, making rivers and lakes unsafe for swimming or drinking.[83]

For example, during May 2004, a series of rainstorms caused 4.6 billion gallons of wastewater to overflow from sewer systems in Milwaukee, Wisconsin, including more than 500 million gallons directly from sanitary sewer systems (which contain the highest concentration of waste).[84]

The U.S. EPA estimates that every year, such overflows discharge on the order of 1 trillion gallons of untreated stormwater containing human sewage.[85] This number could grow if major storms continue to become more frequent.

As a result, sewer system upgrades and construction — already expected to cost billions of dollars — are likely to be more expensive. In a March 2007 draft report, EPA estimated that increased precipitation severity in the Great Lakes region could make the design and construction of sewer systems cost at least 10 percent more.[86]

Spread of Disease

More frequent heavy rainfall could also increase the spread of disease.

Evidence links heavy rainfall and the resulting runoff with waterborne disease outbreaks.[87] For example, one study found that in the latter half of the 20th century, more than half of measured waterborne disease outbreaks in the United States were preceded by a major storm (defined as in the top 10 percent of events by total precipitation).[88]

Other research links the spread of Lyme disease with temperature and total precipitation. Lyme disease is a tick-borne disease in North America which causes fever and headaches and can spread to the heart and nervous system without treatment. Warmer temperatures and higher humidity levels help expand the range of tick populations.[89] Evidence indicates that Lyme disease infections are more frequent in seasons with above-average total precipitation.[90] Ticks are migrating north from north-central and northeastern states into Canada, where they have not been found often until recently.[91]

Agricultural Damage

In addition to flooding, extreme precipitation can cause direct economic damage — especially to farms.

Heavy precipitation can saturate soils with moisture, creating conditions low in oxygen that directly damage crops and increase the risk of disease and insect infestation. Heavy precipitation can also interfere with planting, harvesting or other production steps that require the operation of machinery.

The 1993 flooding along the Mississippi River caused $6 to $8 billion in damage to farmers.[92] 70 percent of total crop losses were due to super-saturated soils from heavy rains as opposed to floodwater submersion.[93] In Iowa in the 1980s and 1990s, damage from excess soil moisture was five times larger than direct damage from flooding.[94]

A research team led by Cynthia Rosenzweig at the NASA-Goddard Institute for Space Studies and Columbia University found that from 1951 to 1990, heavy precipitation caused an average of $3 billion per year in damage to the U.S. corn crop.[95] Moreover, the team estimated that the trend toward increasingly frequent extreme precipitation could double losses in U.S. corn production from heavy precipitation by 2030.[96]

Conclusions and Policy Recommendations

Our analysis finds that storms with extreme levels of precipitation have increased in frequency by 23 percent across the continental United States since 1948, with the greatest increases in New England and the Mid-Atlantic.

Previous research finds similar trends, with extremely heavy precipitation events increasing in frequency more rapidly than very heavy events — which in turn are increasing in frequency more rapidly than heavy events. Moreover, most of this change has occurred since 1970, indicating that it is unusual and relatively recent.

These trends are consistent with the expected impact of global warming.

Climate models predict that the trend toward increasingly frequent downpours will intensify in the future. At the same time, the number of dry days will also increase, making drought more likely. *(See Figures 1 and 2 on pages 12 and 15.)*

Some amount of change is inevitable given the level of global warming pollution already in the atmosphere. However, how serious the problem becomes is largely within our control. If we quickly and significantly reduce emissions of the pollutants that fuel global warming, we can still prevent the worst impacts.

To protect future generations, the United States should establish mandatory limits on emissions of global warming pollution and adopt complementary policies to increase energy efficiency and the use of clean, renewable energy.

Establish Mandatory Limits on Emissions of Global Warming Pollution

The United States has a disproportionate responsibility to reduce its emissions of global warming pollutants. The United States is responsible for 28 percent of all human-caused emissions of global warming pollutants cumulatively through 2005, while the next largest emitters, Russia and China, each account for only 8 percent of the world's total.[97]

America has the technology to dramatically reduce global warming pollution — everything from wind turbines to hybrid vehicles to more energy-efficient appliances. Many of these technologies benefit our economy, reducing our dependence on foreign oil and keeping American dollars — and jobs — here at home.

However, weak or half-hearted efforts won't be enough. It will take bold steps, starting immediately.

At minimum, the United States must:

- Start reducing emissions of global warming pollution now;
- Cut emissions by at least 15 to 20 percent below today's levels by 2020; and
- Reduce emissions by at least 80 percent by 2050.

These emission reductions must be real reductions, achieved within the United States. Developing nations, such as China and India, will need to act as well, but America must show the way.

Auction 100 Percent of Emission Allowances Under Any Cap-and Trade Program

America will be more successful in its efforts to reduce global warming pollution if emission reductions occur in the cleanest, least expensive and most equitable way possible.

Among the many proposals to limit U.S. emissions of global warming pollutants is a policy approach called "cap-and-trade." Under a cap-and-trade program, policy-makers establish a cap on global warming emissions from all or part of the economy. Polluters must hold permits, called "allowances," for every unit of pollution they emit, with the total number of allowances limited by the cap. Polluters are then free to buy, sell or trade allowances as they see fit, helping to drive emission reductions at the lowest aggregate cost to the economy.

One of the most important decisions policy-makers must make when designing a cap-and-trade system is how to distribute allowances. Allowances can be given away for free to polluters, or sold at an auction.

Academic research and practical experience show that giving away allowances to polluters for free allows many of those polluters to collect unjustified "windfall" profits — increasing the price of achieving global warming emission reductions and doing nothing to reduce the burden of the program on low- and middle-income people. [98]

A better approach is to auction 100 percent of emission allowances in any cap-and-trade program, with the revenue from those auctions used to encourage a transition to a clean energy economy and to compensate consumers for the cost of the program. Auctioning all allowances under a cap-and-trade program is fair, reduces the societal cost of achieving emission reductions compared to giving allowances to polluters for free, and promotes a transition to a clean energy economy.[99] By reducing global warming emissions in the cheapest, cleanest and fairest way possible, America can ensure that the public remains supportive of efforts to reduce global warming emissions even as those reductions become more difficult to achieve.

Adopt Policies to Improve Energy Efficiency and Increase the Use of Clean, Renewable Energy

To achieve meaningful reductions in global warming pollution, America must move quickly to reduce its use of fossil fuels. By improving the energy efficiency of our vehicles, buildings and appliances — while tapping America's immense potential for renewable energy from the sun, wind and crops — we can slash our emissions and demonstrate leadership for the rest of the world.


National Renewable Energy Laboratory

America has virtually limitless potential for the generation of power from renewable energy sources, such as wind power. Similarly vast potential exists for improving energy efficiency. Together, these resources can help America dramatically reduce its emissions of global warming pollution.

Obtain 20 Percent of Our Electricity from Renewable Energy Sources

America has virtually limitless potential for the generation of power from natural forces. By ramping up our use of wind power, solar photovoltaic and thermal power, geothermal heat pumps, and other renewable forms of energy — and using much of that energy to replace power production at dirty, coal-fired power plants — the United States could dramatically reduce global warming emissions from electric power production. Requiring that 20 percent of our electricity come from renewable sources by 2020 — when combined with a strong, mandatory cap on global warming pollution — would save more than 500 million metric tons of carbon dioxide equivalent relative to 2004 emissions levels. This is more than one-third of the emission reductions scientists say we need to achieve by 2020.[100]

Reduce Energy Consumption in our Homes and Businesses

Dramatic improvements in energy efficiency are possible in virtually every aspect of American life. Studies show that we could reduce our electricity consumption by as much as 20 percent at no net cost (and probably great savings) to the economy.[101] The U.S. can encourage the "greening" and weatherization of buildings, deployment of more efficient appliances and equipment, and efficiency improvements in industry. Using new technologies, such as those in zero-energy homes, we can transform the way we consume energy and achieve even larger improvements in efficiency.

Stabilize Vehicle Travel

Americans are driving more than ever, leading to increased emissions of global warming pollutants. Americans need more transportation choices to reduce and eventually halt this growth in vehicle travel. Policies to provide these choices include encouraging the development of compact neighborhoods with a mix of land uses, where more tasks can be completed on foot, or by bike or public transit; expanding the reach and improving the quality of transit service; and supporting programs to encourage carpooling, vanpooling, telecommuting, and other alternatives to single-passenger vehicle travel.

Make Cars and Trucks Go Farther on a Gallon of Gasoline

The creation of federal fuel economy standards for cars during the 1970s succeeded in reducing gasoline consumption and oil imports, as well as global warming pollution. But the corporate average fuel economy (CAFE) of new vehicles is now lower than it was during most of the Reagan administration. In 2002, the National Academy of Sciences concluded that automakers could use a combination of existing and emerging technologies to achieve 37 MPG within 10-15 years while improving safety and maintaining performance.[102] The Union of Concerned Scientists has shown that with more aggressive use of high-strength, lighter-weight materials, we could hit the 40 MPG mark in 10 years.[103] Similarly, major improvements in fuel economy are possible for heavy-duty trucks, which are currently exempt from fuel economy standards.[104]

Replace a Portion of Vehicle Fuel with Biofuels or Other Clean Alternatives

Ethanol and biodiesel that are produced cleanly and sustainably may have the potential to significantly reduce global warming emissions from transportation — especially if these biofuels are produced from plant wastes and cellulose. Other vehicle technologies — like “plug-in” hybrids, electric vehicles, and fuel cell vehicles – have the potential to dramatically reduce global warming emissions in the future.[105]

Methodology

The analysis of extreme precipitation frequency in this paper was based on a methodology developed by Kenneth Kunkel and Karen Andsager at the Illinois State Water Survey, with David Easterling at the National Climatic Data Center, published in: K. Kunkel et al., "Long-Term Trends in Extreme Precipitation Events over the Conterminous United States and Canada," Journal of Climate 12: 2515-2527, 1999.

Area of Study and Period of Analysis

We limited our area of study to the contiguous United States, excluding Alaska and Hawaii. We began our analysis in 1948, since weather observations in our digital weather record become increasingly scarce before this date. The period of analysis extends through the end of 2006, the most recent weather data available at the time the study was performed.

Data Source

We obtained weather data from the U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Climatic Data Center (NCDC), Cooperative Summary of the Day TD 3200 POR -2001 and NCDC, U.S. Summary of the Day Climate Data (DS 3200/3210) 2002-2006), August 2007. The data provide daily records of a variety of weather observations, including 24-hour precipitation totals, in addition to geographic coordinates for the weather stations.

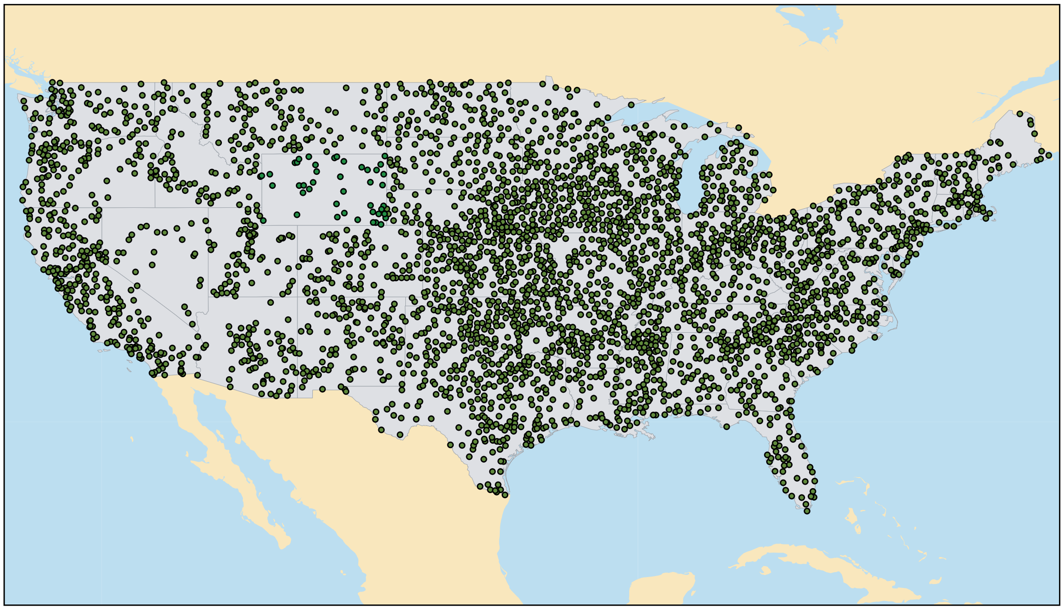
Per standard NCDC practice, for days where a precipitation measurement was missing, yet a measurement for snowfall was recorded (a miniscule percentage of total measurements), we filled in the missing precipitation information using the 10 to 1 ratio method (i.e. precipitation was estimated at 1/10th the amount of snowfall).

We discarded all observations that NCDC had flagged as invalid or as having failed a data consistency check. For values flagged as accumulated over a period of two days, we divided the measured value by 2 to ensure that 24-hour precipitation totals would not be overestimated.

Analysis of the Trend in Extreme Precipitation Frequency

We analyzed data from stations that were missing less than 5 percent of observations during the period of analysis, from 1948 to 2006. We were left with precipitation records from 3,445 weather stations in 48 states. Figure 7 shows the locations of these stations.

Figure 7: Location of Weather Stations Used in the Analysis



Definition of "Extreme Precipitation"

We identified storms with extreme levels of precipitation relative to the local climate at each individual weather station. We chose to examine the frequency of 24-hour precipitation events with total precipitation magnitude with a 1-year recurrence interval or larger. For example, for a given weather station, we identified the 59 largest 1-day precipitation totals during the 59 year period of analysis. The smallest of these values equaled the threshold for a precipitation event with a 1-year recurrence interval. We defined any storm with a 24-hour precipitation total equal to or larger than this threshold as extreme. Figure 8 graphically presents the minimum thresholds for extreme precipitation used in this analysis.

Analysis of Extreme Precipitation Frequency

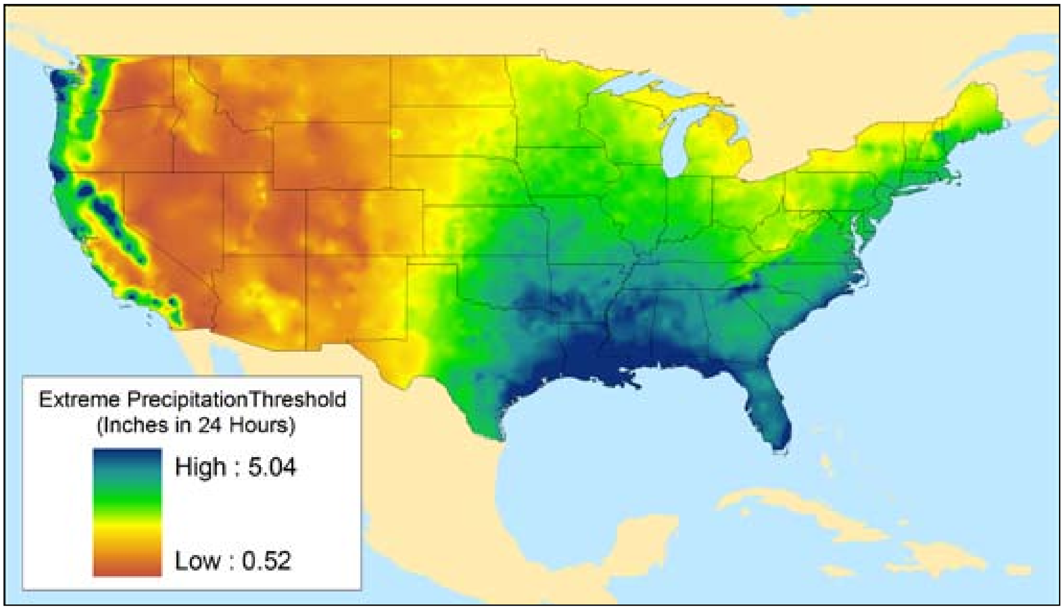
For each weather station, we calculated the annual frequency of storms with extreme levels of precipitation. The average for each weather station over the period of analysis was 1. If no change had occurred, we would expect the trend in annual major storm frequency over time to be close to zero. A significant positive or negative slope would indicate a change in the annual frequency of major storms over time or an increase or decrease in storm intensity.

To calculate the trend in major storm events over time, we aggregated data based on station location:

- for the United States as a whole;
- by the nine census divisions;[106]
- by state, or
- by census metropolitan division / consolidated metropolitan division.[107]

We then tested for the presence of a trend using standard least-squares regression, calculating both a slope and its standard error. To determine statistical significance of the resulting trend, we used a two-tailed t-test at the 95 percent confidence level.

Figure 8: Minimum Thresholds for Definition of Extreme Precipitation

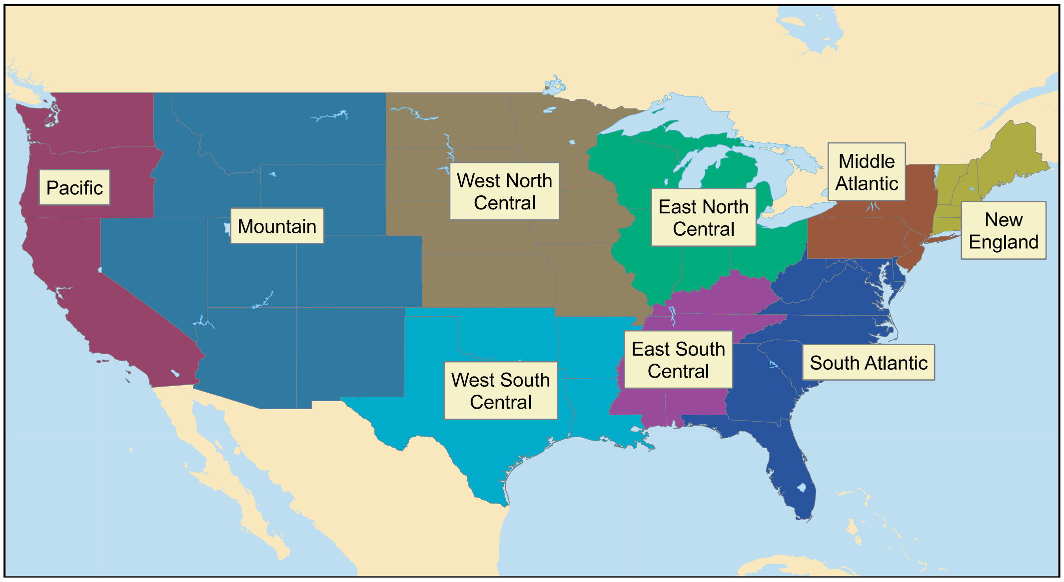


Appendices

A. Change in Extreme Precipitation Frequency by Region, 1948–2006

Region	Percent Increase in Frequency of Storms with Extreme Precipitation	95% Confidence Interval		Statistically Significant?
		Lower Bound	Upper Bound	
New England	61%	51%	71%	Yes
Mid-Atlantic	42%	34%	49%	Yes
East South Central	28%	22%	34%	Yes
Mountain	25%	21%	29%	Yes
West North Central	24%	20%	27%	Yes
West South Central	24%	19%	28%	Yes
East North Central	22%	18%	27%	Yes
Pacific	18%	13%	23%	Yes
South Atlantic	15%	10%	20%	Yes

Figure 4: Definition of Regions



B. Change in Extreme Precipitation Frequency by State, 1948–2006

State	Percent Increase in Frequency of Extreme Precipitation	95% Confidence Interval		Statistically Significant?
		Lower Bound	Upper Bound	
Alabama	35%	21%	49%	Yes
Arizona	26%	14%	38%	Yes
Arkansas	-1%	-11%	9%	No
California	26%	19%	33%	Yes
Colorado	30%	19%	41%	Yes
Connecticut	44%	9%	80%	Yes
Delaware	37%	-3%	77%	No
Florida	-12%	-25%	0%	No
Georgia	14%	3%	25%	YES
Idaho	1%	-12%	13%	No
Illinois	4%	-5%	13%	No
Indiana	18%	6%	30%	Yes
Iowa	14%	6%	23%	Yes
Kansas	25%	17%	33%	Yes
Kentucky	16%	1%	31%	Yes
Louisiana	52%	38%	66%	Yes
Maine	43%	22%	64%	Yes
Maryland	3%	-20%	26%	No
Massachusetts	67%	49%	85%	Yes
Michigan	18%	7%	29%	Yes
Minnesota	34%	24%	43%	Yes
Mississippi	34%	24%	45%	Yes
Missouri	37%	27%	48%	Yes
Montana	11%	2%	20%	Yes
Nebraska	16%	9%	24%	Yes

State	Percent Increase in Frequency of Extreme Precipitation	95% Confidence Interval		Statistically Significant?
		Lower Bound	Upper Bound	
Nevada	29%	10%	48%	Yes
New Hampshire	83%	58%	107%	Yes
New Jersey	4%	-16%	24%	No
New Mexico	44%	35%	54%	Yes
New York	56%	45%	67%	Yes
North Carolina	16%	6%	26%	Yes
North Dakota	13%	3%	23%	Yes
Ohio	43%	32%	53%	Yes
Oklahoma	22%	13%	30%	Yes
Oregon	-14%	-24%	-4%	Yes
Pennsylvania	41%	29%	52%	Yes
Rhode Island	88%	24%	152%	Yes
South Carolina	14%	1%	27%	Yes
South Dakota	32%	22%	42%	Yes
Tennessee	21%	8%	34%	Yes
Texas	28%	22%	33%	Yes
Utah	32%	21%	44%	Yes
Vermont	57%	33%	81%	Yes
Virginia	25%	13%	38%	Yes
Washington	30%	19%	41%	Yes
West Virginia	40%	25%	56%	Yes
Wisconsin	30%	21%	40%	Yes
Wyoming	22%	9%	36%	Yes

C. Statistically Significant Changes in Extreme Precipitation Frequency by Metropolitan Area, 1948-2006

Metropolitan areas without statistically significant trends are not presented here. The lack of statistical significance in these areas should not be interpreted as proof of the absence of a trend, however. The precise detection of trends in the frequency of extreme precipitation becomes more difficult at the metropolitan level, where fewer weather stations contribute information. For areas without statistically significant trends in extreme precipitation at the metropolitan level, please look at the results for larger areas — climate divisions, states, or regions – for an indication of probable change at the local level.

State	Metropolitan Area	Statistically Significant Change in Extreme Precipitation Frequency?	Mean	95% Confidence Interval	
				Lower Bound	Upper Bound
AL	Mobile	Yes	80%	31%	129%
AR	Little Rock – North Little Rock	Yes	-43%	-75%	-10%
AZ	Phoenix – Mesa	Yes	43%	17%	70%
AZ	Flagstaff (AZ, UT)	Yes	38%	3%	74%
CA	Bakersfield	Yes	93%	61%	125%
CA	Santa Barbara – Santa Maria – Lompoc	Yes	69%	21%	116%
CA	Los Angeles – Riverside – Orange County	Yes	58%	41%	75%
CA	San Diego	Yes	51%	14%	88%
CO	Grand Junction	Yes	53%	12%	94%
CT	Hartford	Yes	57%	3%	111%
CT	New York – Northern New Jersey – Long Island (NY, NJ, CT, PA)	Yes	37%	18%	55%
FL	Sarasota – Bradenton	Yes	95%	1%	189%
GA	Augusta – Aiken (GA, SC)	Yes	84%	30%	138%
IA	Sioux City (IA, NE)	Yes	53%	9%	97%
IL	St. Louis (MO, IL)	Yes	37%	7%	67%
IN	Bloomington	Yes	150%	47%	252%
IN	Elkhart – Goshen	Yes	103%	1%	205%
IN	Louisville (KY, IN)	Yes	52%	6%	98%
KS	Wichita	Yes	59%	16%	103%
KS	Kansas City (MO, KS)	Yes	44%	14%	75%
KY	Louisville (KY, IN)	Yes	52%	6%	98%
LA	Baton Rouge	Yes	110%	9%	212%
LA	Alexandria	Yes	98%	5%	190%

State	Metropolitan Area	Statistically Significant Change in Extreme Precipitation Frequency?	Mean	95% Confidence Interval	
				Lower Bound	Upper Bound
LA	Shreveport – Bossier City	Yes	77%	38%	116%
LA	Lafayette	Yes	58%	10%	107%
LA	New Orleans	Yes	51%	2%	100%
MA	Boston – Worcester – Lawrence (MA, NH, ME, CT)	Yes	72%	53%	92%
MA	Springfield	Yes	56%	7%	106%
ME	Portland	Yes	112%	12%	212%
MI	Grand Rapids – Muskegon – Holland	Yes	46%	2%	91%
MN	Grand Forks (ND, MN)	Yes	69%	23%	114%
MN	Minneapolis – St. Paul (MN, WI)	Yes	47%	18%	77%
MO	Kansas City (MO, KS)	Yes	44%	14%	75%
MO	St. Louis (MO, IL)	Yes	37%	7%	67%
MS	Jackson	Yes	187%	107%	267%
MS	Memphis (TN, AR, MS)	Yes	35%	0%	71%
ND	Grand Forks (ND, MN)	Yes	69%	23%	114%
NE	Sioux City (IA, NE)	Yes	53%	9%	97%
NH	Boston – Worcester – Lawrence (MA, NH, ME, CT)	Yes	72%	53%	92%
NJ	New York – Northern New Jersey – Long Island (NY, NJ, CT, PA)	Yes	37%	18%	55%
NY	Binghamton	Yes	105%	38%	171%
NY	Elmira	Yes	80%	13%	147%
NY	Rochester	Yes	59%	25%	93%
NY	Utica – Rome	Yes	57%	15%	99%
NY	Syracuse	Yes	45%	9%	81%
NY	New York – Northern New Jersey – Long Island (NY, NJ, CT, PA)	Yes	37%	18%	55%
OH	Youngstown – Warren	Yes	96%	49%	144%
OH	Columbus	Yes	71%	33%	109%
OH	Cleveland – Akron	Yes	59%	28%	90%
OH	Dayton – Springfield	Yes	46%	10%	82%
OR	Medford – Ashland	Yes	-60%	-107%	-14%
PA	Reading	Yes	116%	29%	202%

State	Metropolitan Area	Statistically Significant Change in Extreme Precipitation Frequency?	Mean	95% Confidence Interval	
				Lower Bound	Upper Bound
PA	Williamsport	Yes	103%	4%	202%
PA	Harrisburg – Lebanon – Carlisle	Yes	84%	30%	139%
PA	State College	Yes	69%	12%	125%
RI	Providence – Fall River – Warwick (RI, MA)	Yes	88%	23%	153%
SC	Augusta – Aiken (GA, SC)	Yes	84%	30%	138%
TN	Memphis (TN, AR, MS)	Yes	35%	0%	71%
TX	Longview – Marshall	Yes	65%	15%	115%
TX	El Paso	Yes	61%	3%	118%
TX	Houston – Galveston – Brazoria	Yes	49%	20%	78%
TX	Dallas – Fort Worth	Yes	42%	21%	62%
UT	Salt Lake City – Ogden	Yes	38%	2%	75%
UT	Flagstaff (AZ, UT)	Yes	38%	3%	74%
WA	Seattle – Tacoma – Bremerton	Yes	45%	22%	68%
WI	Milwaukee – Racine	Yes	63%	29%	97%
WI	Minneapolis – St. Paul (MN, WI)	Yes	47%	18%	77%
WI	Appleton – Oshkosh – Neenah	Yes	45%	8%	83%
WV	Charleston	Yes	66%	13%	119%

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