BACKGROUNDER

THE UNIVERSITY OF RHODE ISLAND
GRADUATE SCHOOL OF OCEANOGRAPHY

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# How Does Extreme Weather Relate to Climate Change

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*This backgrounder was developed to clarify the complex interactions between weather and climate, and to highlight some interactions that are active areas of research.*

Local weather anomalies are often conflated with longer-term climate trends, leading some to question or doubt the validity of climate change. Yet extreme weather events may be influenced by climate change, further complicating a clear understanding of the relationship between weather and climate.

When Hurricane Sandy hit the eastern U.S. in 2012, it left in its wake a devastating trail of destruction. The U.S. National Weather Service estimated that the hurricane caused $68 billion in damage, a total that is surpassed only by Hurricane Katrina.[1] The highly unusual aspects of Sandy, which was not even at hurricane strength when it made landfall, caused many people to wonder if it was a result of climate change.

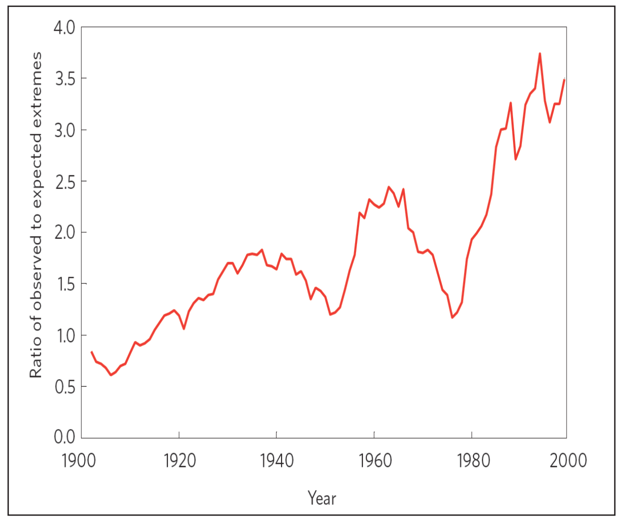


**Figure 1.** Average number of monthly high temperature records from 17 weather stations around the world. The "ratio of observed to expected extremes" on the y axis is the number of reported heat records divided by the number expected under "typical" conditions. One thing these events have in common? They all exhibit a close relationship with recent changes in Earth's climate. Source: Coumou and Rahmstorf, 2012.[6] Reprinted with permission.

It is common to hear the scientific caveat that no single extreme weather event can be attributed directly to climate change because these events occur both with and without climate change. Still, researchers are exploring whether and how weather events are affected by climate change: that is, are they strengthened, shifted, or happening more frequently than they would be in the absence of climate change? In fact, some types of extreme weather are becoming more frequent and intense, causing averages to gradually shift.

Americans have experienced marked overall increases in frequency and intensity of certain weather events in the past several decades:[2]

- The number of observed local monthly heat records worldwide is now more than three times higher than expected in a stable climate over the past century (Fig. 1).[3]
- Corresponding with this trend in high temperature records, there was a period of record drought in the southern U.S. during 2011 with rates of water loss double that of the long-term average.[4]

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- The U.S. Northeast, Midwest and Great Plains have experienced 30% more rainfall since the 1960s when compared to the first half of the 20th century.[4]
- Winter weather has also become more extreme. Cold snaps and winter storms have increased in frequency and intensity since the 1950s.[5]

**WHAT IS CLIMATE?**

Climate and weather are closely related but differ in significant ways. Weather reflects atmospheric conditions over short timescales, while climate represents long-term atmospheric trends.

When "greenhouse gases" like carbon dioxide ($CO_2$) and methane ($CH_4$) are released into the atmosphere through human activities such as coal and oil burning and fertilizer production, they act as a thermal blanket for the Earth. The continued production of greenhouse gases thickens this blanket, absorbing more heat from the sun and causing Earth's surface to warm (Fig. 2). This greenhouse effect leads to what is commonly known as global warming, an unusually accelerated increase in global average temperatures that scientists have observed since the 1950s. As a result of this increasing trend, the top ten warmest years between 1880 and 2014 have occurred since 1998. (Fig. 3).

Climate is the average of variations in temperature, precipitation, and seasonality within a geographic area–as small as a single city or region and as large as the whole globe–and over long time frames ranging from several decades to millions of years. Earth's regions are generally categorized by climate, representing polar, temperate, sub-tropical, or tropical conditions. Long-term climate change, measured in millennia to millions of years, is influenced by geologic activity and orbital cycles.[7]

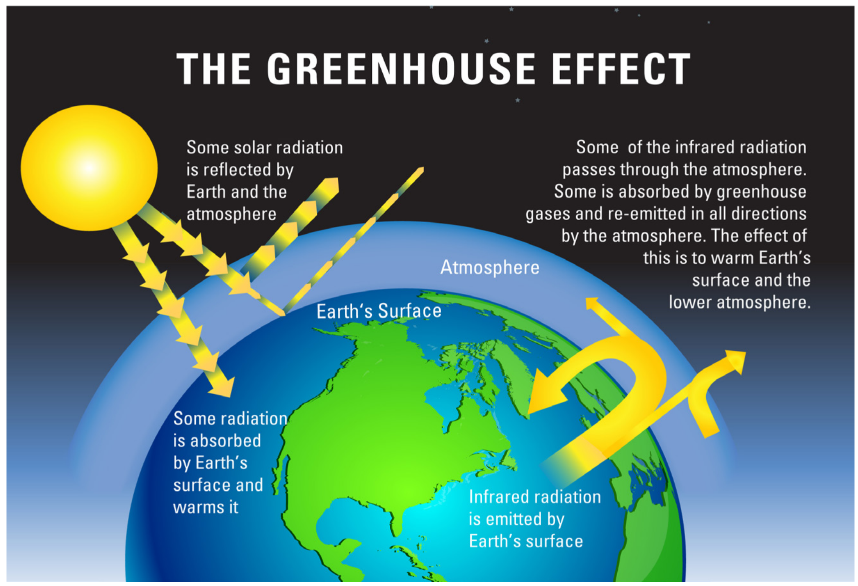


**Figure 2.** The greenhouse effect is a process by which greenhouse gases trap heat that would otherwise escape from Earth back into space. While some retention of solar radiation (heat) is essential to keep Earth habitable, $CO_2$ and other gases act as a greenhouse, further warming Earth's surface. The greater the concentration of greenhouse gases in the atmosphere, the more radiation will be absorbed, leading to further warming of the atmosphere. Source: Koshland Science Museum.[12] Reprinted with permission.

Climate change overall is a function of both natural cycles and anthropogenic forces. In the geological record, there have been periods of warming and cooling throughout Earth's history.[8,9] However, human activities have disrupted these changes and caused them to occur at a much more rapid pace over the past hundred years than in any similar time period over at least one thousand years.[10,41] The accelerated upward trend of global average temperature over the past century is sometimes referred to as "the hockey stick" by scientists, in reference to the fact that the acute upward angle of recent global temperatures looks similar to the wedge of a hockey stick, with the past 1,000 years of measured and reconstructed temperature data serving as the long, relatively straight portion of the hockey stick.

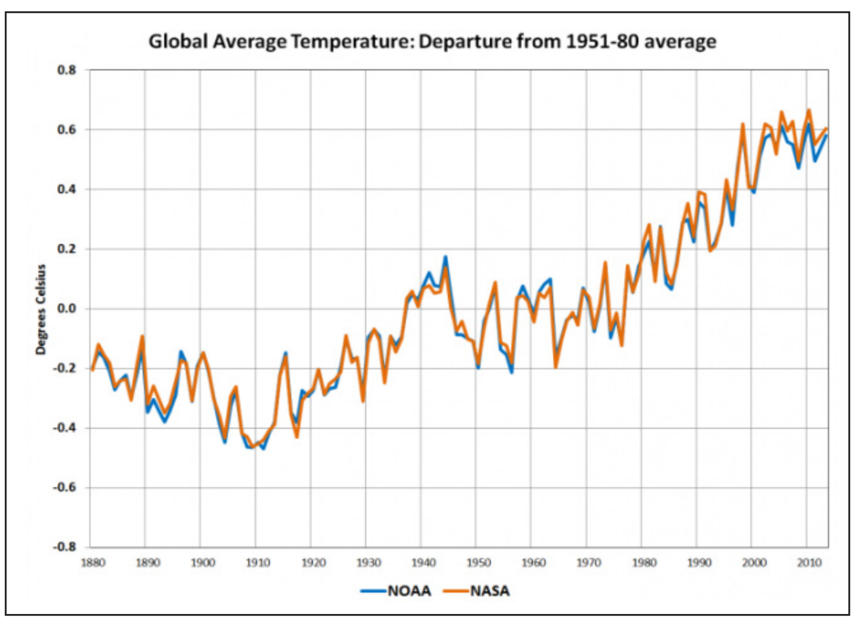


**Figure 3.** Measurements of temperature over a 134-year period show that global average temperatures have been increasing since the early 1900s. Additionally, the ten warmest years on record have occurred since 1998. Source: NOAA/NASA.[13]

## WHAT IS WEATHER?

Weather is the daily state of the atmosphere, which can change rapidly depending on factors like temperature, wind, precipitation and cloud cover.

J. Marshall Shepherd of the University of Georgia provided a useful analogy: "weather is your mood and climate is your personality."[14] Daily fluctuations in weather are influenced by many interacting factors, just as one's mood can change from day to day. The general state of the climate, however, is more consistent, like one's personality. Despite the relative constancy of the climate, fluctuations are still natural and occur on a daily to inter-decadal basis.

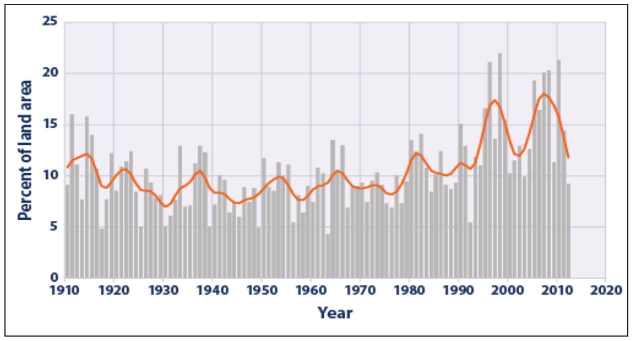


**Figure 4.** Extreme one-day precipitation events in the contiguous 48 United States, 1910-2012. The past two decades have witnessed an increase in the amount of land area with greater-than-normal precipitation from extreme precipitation events. In other words, intense rain and snow storms are affecting more of the contiguous U.S. and on a greater scale now than any time in the past century. The grey bars in this graph represent yearly averages, while the orange line is a nine-year running average. Source: US EPA.[15]

## HOW ARE CLIMATE AND WEATHER CONNECTED? TWO CASE STUDIES

### Frequency and Intensity of Precipitation Events

Over the past two decades, there has been a notable increase in extreme precipitation events (Fig. 4), spurring researchers to investigate the relationships between these extreme events and climate change. Warming temperatures near Earth's surface can cause increased evaporation from both land and sea. A warmer atmosphere can hold more water vapor than a cooler one, and this excess water vapor can add to the intensity of snow and rain storms. To complicate matters, water vapor is also a potent greenhouse gas, creating a feedback loop wherein warmer temperatures allow more water vapor to collect in the atmosphere, further warming Earth's surface.

The effect of atmospheric and sea-surface warming on hurricanes, or tropical cyclones, is a very active area of research. [39,40] Scientists studying these relationships generally agree that climate change increases the likelihood that hurricanes will be more intense, but disagree about whether warming air and ocean temperatures will lead to a greater number of hurricanes.[20,21,22]

Tropical cyclones are affected by warming sea-surface temperatures, although not as simply as one might expect. Tropical cyclones only form when

## WATER VAPOR AND CLIMATE CHANGE

Recent studies have shown that water vapor may have a stronger effect on climate change than previously thought. Additional water vapor in the stratosphere holds heat and causes further warming, creating an ongoing cycle of ever-increasing warming (Figure 5). A 2013 study suggested that this feedback loop is responsible for about 10% of global climate warming from greenhouse gases.[16] These findings came from models and satellite images, which researchers use to estimate future warming from the water vapor feedback loop. The large contribution of this effect on global warming makes it a useful signal for climate forecasting.

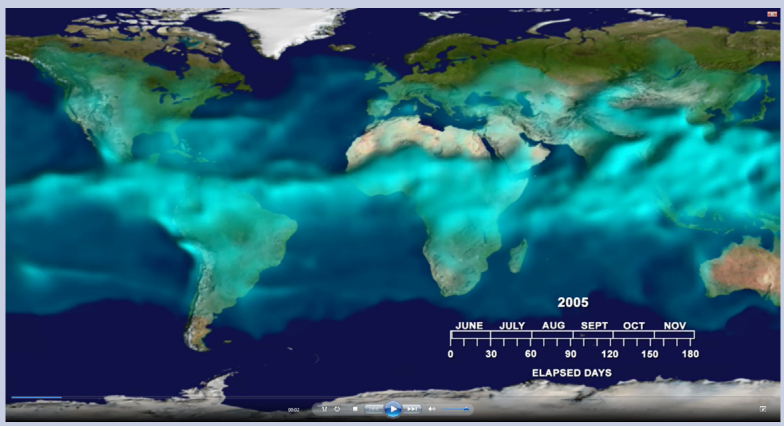


**Figure 5**. This snapshot from a NASA video shows the distribution of atmospheric water vapor during June 2005. Water vapor, the most abundant greenhouse gas, traps heat in the atmosphere and is particularly concentrated above tropical regions. Source: NASA.[17]

## SHIFTING SEASONS

Warming global temperatures have also led to shifts in regional seasonality, or phenology. Phenologic shifts can have significant ecological impacts. A study of Walden Woods, the New England forest made famous by naturalist Henry David Thoreau, found that the abundance of flowering species decreased in the 150 years since Thoreau's detailed observations, just as temperatures were gradually increasing.[24] These forest plants were unable to shift the timing of flowering, and study authors concluded that the plants became less abundant as a result of their inability to rapidly adapt to warming temperatures. Community shifts such as these lead to selective loss of species diversity and disruption of natural ecosystem processes in a wide variety of environments from the poles to the tropics, on land and at sea.

water temperatures are about 26.5°C (80°F) or more. It seems reasonable to assume, therefore, that a warmer ocean would result in more frequent tropical cyclone formation. But warmer temperatures may also cause stronger winds that mix ocean waters, bringing cooler water to the ocean surface. This cooler water decreases the potential for hurricanes to form.[18]

Tropical cyclones also require the proper level of "wind shear," a vertical gradient in wind speed and direction in the atmosphere. A weak wind shear allows storms to grow vertically and release heat into the air above the storm, while a strong wind shear causes the storms to become slanted and dispersed, thus weakening the tropical cyclone. As the globe continues to warm, recent research suggests that wind shear will increase in some regions where hurricanes typically form, which will tend to reduce storm formation.[19]

Sea-surface warming, therefore, can both increase and decrease the likelihood of hurricane formation, frequency, and intensity, further complicating the process of predicting and understanding these extreme events. Additionally, research suggests that warming sea surface temperatures are extending the North Atlantic hurricane season. The typical season peaks in September with quieter periods ranging from June to November, but in the past decade hurricane activity has increased in the beginning and end of the hurricane season.[23]

**The Polar Vortex.** The Polar Vortex is the circumpolar current, or band of wind, that circulates around the North Pole. It is also known as the jet stream, and is a natural and nearly ubiquitous phenomenon. In 2014, the jet stream took an unusually expansive dip toward the south, exposing wide swaths of the continental United States to sub-zero temperatures for extended periods of time. Researchers have

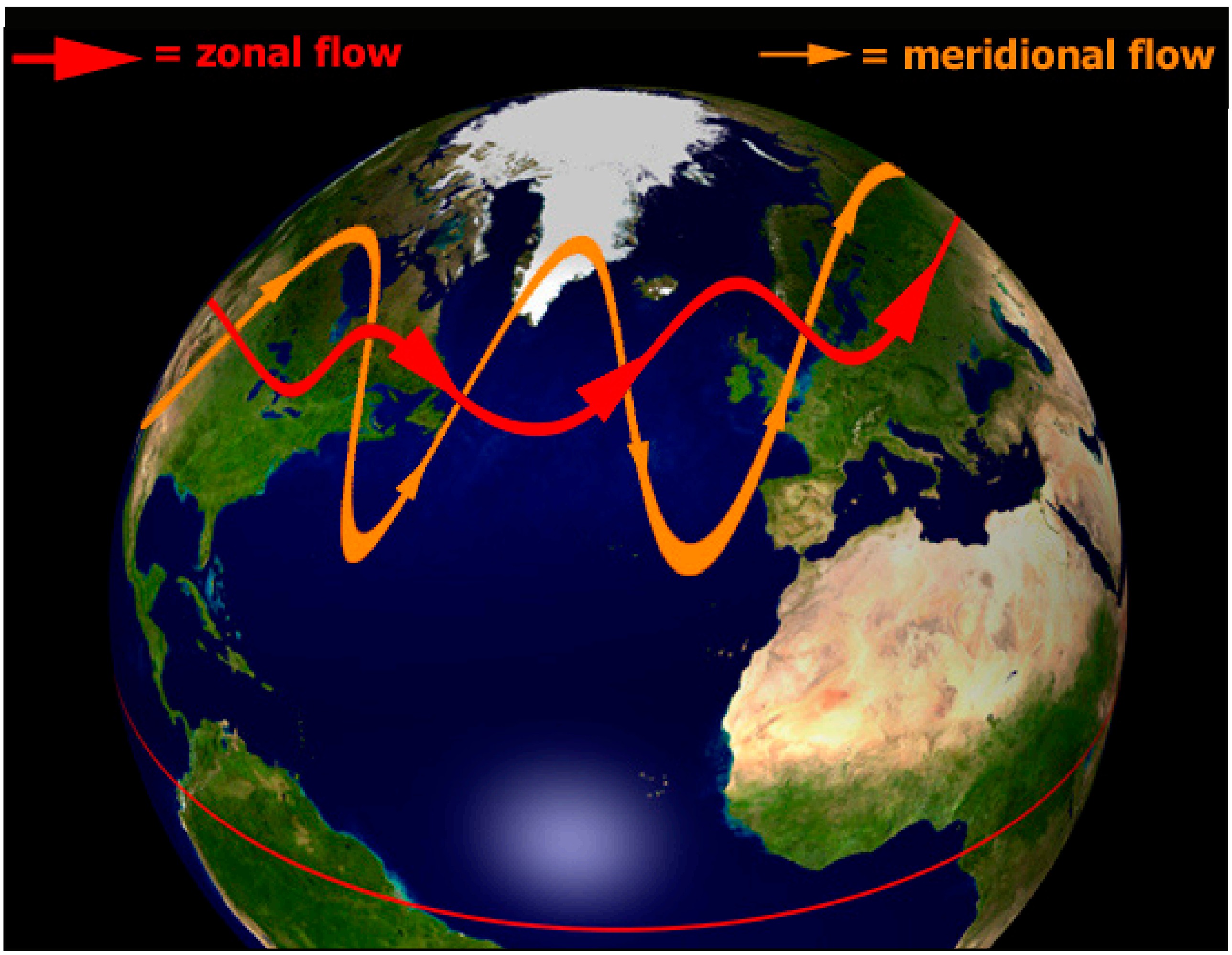


**Figure 6.** Typical flow of the jet stream is mainly zonal (red arrow), meaning it moves from west to east with low-amplitude waves, and it confines cold air to the Arctic. A weakening of the jet stream caused by reduced north/south pressure gradients can lead to a meridional flow (orange arrow), or increased amplitude waves that allow cold air from the Arctic to penetrate into temperate latitudes and warm, tropical air to travel farther north. During the winter of 2013/2014, this led to extremely cold temperatures in eastern North America along with abnormally warm temperatures in Alaska, Scandinavia, and the Arctic. Graphic by John Mason, used by permission. Source: https://skepticalscience.com/jetstream-guide.html.

suggested that unusual patterns like the one seen in the winter of 2013/2014 may become more frequent as a result of climate change. They argue that the jet stream, which normally separates cold Arctic air from warmer southern air, was weaker and slower during the winter of 2014, allowing it to meander farther north and south (Fig. 6).[25]

There is an ongoing scientific debate over the actual mechanism driving the jet stream to behave so unusually.[26,27,28] Jennifer Francis of Rutgers University's Institute of Marine and Coastal Sciences and colleague Stephen Vavrus of University of Wisconsin-Madison's Center for Climatic Research proposed a hypothesis to explain this phenomenon. They postulated that loss of Arctic sea ice and other factors warmed the Arctic faster than elsewhere in the northern hemisphere. This warming trend was strongly correlated with the slowing of the jet stream's eastward winds during autumn and winter, and these slower winds tend to result in a wavier jet stream. This wavier jet-stream, and the weather patterns it creates, tends to progress eastward more slowly, leading to persistent patterns.[29,30] When the jet stream dips southward into temperate latitudes, it causes frigid winters such as the one experienced during winter 2013 – 2014 in eastern North America, while northward swings bring abnormal warmth, such as that experienced in Alaska and the western U.S. during that same period. While plausible, this explanation stirred up debate among some climate scientists who thought the evidence was not strong enough to support Francis and Vavrus' conclusion. They offered the following arguments against the proposed climate change/jet-stream link:

- alternative analyses and models have not yet confirmed the hypothesis;
- there is a great deal of natural variability in atmospheric circulation;
- links between rapid Arctic warming and unusual weather in temperate climates are not observed in all seasons, and
- severe cold winters have occurred before, including before there was significant loss of sea ice.[31]

Ultimately, this debate centers on the common scientific flash point of correlation vs. causation. That is, even if two events, like slowing of the jet stream and Arctic sea ice melt, appear to occur at the same time, it is not certain whether one phenomenon causes the other. While Dr. Francis's hypothesis is feasible, some other climate scientists feel that more information is necessary to explain this mechanism. To fully understand the persistent 2014 jet-stream pattern and the mechanisms that cause or coincide with unusual atmospheric events, researchers must work together to unravel the intricate nature of the climate and weather relationship.

**COMPARING POSSIBLE EFFECTS OF SHORT-TERM WEATHER EVENTS AND LONG-TERM CLIMATE CHANGE**

| | **Weather** | **Climate Change** |
|---|---|---|
| **Infrastructure** | -Localized flooding damage to buildings, utilities, transportation; disrupts important services such as telecommunications | -Persistent sea level rise requires new approaches toward management of coastal zones, many of which contain major urban areas and expensive property |
| **Communities/economy** | -Damage due to intense storms requires state and/or federal government financial support<br>-Workers with weather-dependent jobs may be displaced, furloughed | -Increased variability leads to disruption in recreation and economic activities (e.g., winter sporting events)<br>-Community planners must adapt to more frequent coastal flooding, reduced water supplies, flooding, etc. |
| **Agriculture** | -Heavy precipitation and droughts reduce crop yield [32] | - Changing climate prompts shifts in viable crops, harvest timing [33] |
| **Ecosystems** | -Floods and droughts stress or even eliminate populations through drowning, heat exposure, starvation, or illness | -Changes in migration and hibernation patterns<br>-Permanent alteration of habitat (e.g., marine fish populations are generally shifting northward and deeper into the ocean with rising sea temperatures[34]) |

## PUBLIC OPINION ABOUT EXTREME WEATHER AND CLIMATE CHANGE

Although weather and climate are fundamentally different, the terms are sometimes misused in debates over climate change impacts. This confusion has the potential to drive American public opinion on climate change.

The Yale Project on Climate Change Communication and George Mason University conduct regular surveys to assess public opinion on climate change and related topics in the U.S. Their data indicate that over half of Americans (56%) feel "global warming is affecting weather in the United States" (Fig. 7).[35] Opinions on extreme weather are strongly tied to the respondents' positions on climate change, however. In a 2013 survey, fewer than 38% of those who were "doubtful" or "dismissive" of climate change reported that U.S. weather had been worse over the past several years, while 71-91% of those who were "concerned" or "alarmed" felt U.S. weather had worsened (Fig. 8).

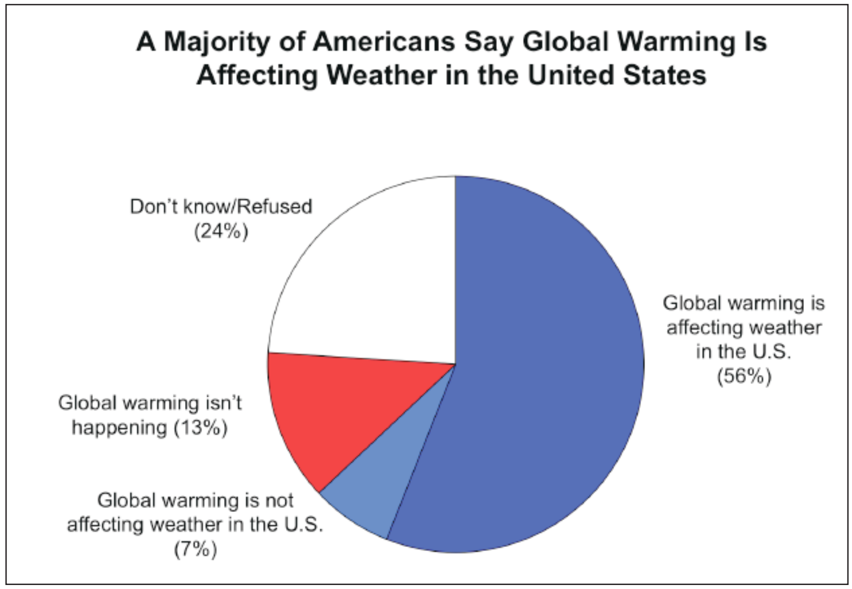


**Figure 7.** Over half of respondents to a 2013 survey on public opinion about extreme weather and climate change said that global warming is affecting weather in the United States. Source: "Extreme Weather and Climate Change in the American Mind in November 2013" by Yale Project on Climate Change Communication.[36] Reprinted with permission.

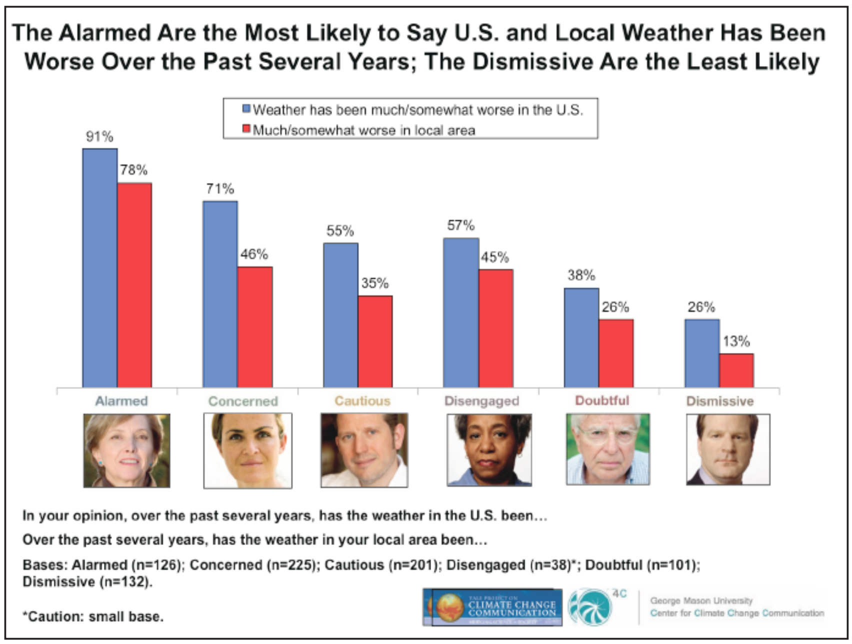


Figure 8 In a survey conducted by the Yale Project on Climate Change Communication, Americans were asked the question "In your opinion, over the past several years, has the weather in the U.S. been…" with two possible responses: "weather has been much/somewhat worse in the U.S." and "much/somewhat worse in local area." Those who are most concerned or alarmed about climate change were more likely to report worse weather over the past several years compared to those who are doubtful or dismissive. Source: "Extreme Weather and Climate Change in the American Mind in November 2013" by Yale Project on Climate Change Communication.[36] Reprinted with permission.

Public opinion on these topics may be strongly tied to personal ideologies and motivated reasoning. Motivated reasoning, i.e., "the unconscious tendency to fit information to conclusions that correspond with a preexisting belief or goal,"[37] leads people to selectively recall memories in a way that reinforces a personal opinion. Interestingly, research indicates that motivated reasoning may shape perception of temperature trends more than precipitation trends because of the strong mental ties between "global warming" and temperature,[38] making it even more important to clarify the distinctions and relationships between weather and climate.

The intricate relationship between climate and weather fosters a great deal of debate among scientists and confusion among the lay public. Although weather is influenced by many factors, we can better understand, anticipate, and plan for unusual weather events by tracking recent and long-term trends and by recognizing that climate change may have a large effect on these phenomena.

## SCIENTIFIC SOURCES

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Kerry Emanuel, Massachusetts Institute of Technology http://eaps4.mit.edu/faculty/Emanuel/
Isaac Ginis, University of Rhode Island Graduate School of Oceanography http://www.gso.uri.edu/users/iginis
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Gary Lackmann, North Carolina State University http://www4.ncsu.edu/~gary/
Kelly Lombardo, University of Connecticut http://www.marinesciences.uconn.edu/faculty/faculty.php?users=kel13009)
Peter Snyder, University of Minnesota http://www.tc.umn.edu/~pksnyder/

## OTHER RESOURCES

Global Climate Analysis, NOAA National Climatic Data Center, http://www.ncdc.noaa.gov/sotc/global/
Climate Change Indicators in the United States, U.S. Environmental Protection Agency, http://www.epa.gov/climatechange/science/indicators/weather-climate/index.html
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