



Current Extreme Weather and Climate Change

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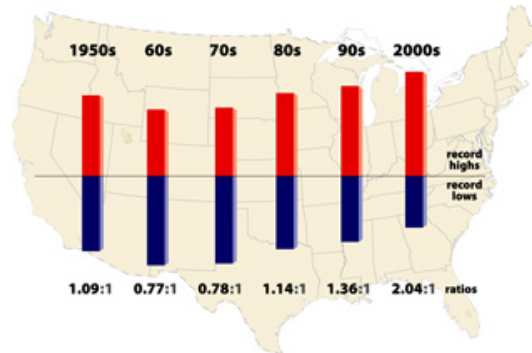
Overview

Recent weather events such as deadly heat waves and devastating floods have sparked popular interest in understanding the role of global warming in driving extreme weather. These events are part of a new pattern of more extreme weather across the globe, shaped in part by human-induced climate change.

As the climate has warmed, some types of extreme weather have become more frequent and severe in recent decades, with increases in extreme heat, intense precipitation, and drought.

Heat waves are longer and hotter. Heavy rains and flooding are more frequent. In a wide swing between extremes, drought, too, is more intense and more widespread.

Record Highs Now Outpace Record Lows by 2:1



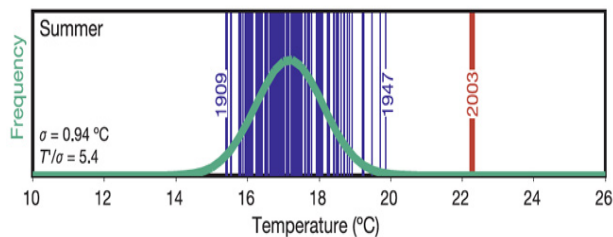
The ratio of record daily high temperatures to record daily lows observed at about 1,800 weather stations in the 48 contiguous United States from January 1950 through September 2009. Meehl et al. 2009

All weather events are now influenced by climate change because all weather now develops in a different environment than before. While natural variability continues to play a key role in extreme weather, climate change has shifted the odds and changed the natural limits, making certain types of extreme weather more frequent and more intense. The kinds of extreme weather events that would be expected to occur more often in a warming world are indeed increasing.

For example, 60 years ago in the continental United States, the number of new record high temperatures recorded around the country each year was roughly equal to the number of new record lows. Now, the number of new record highs recorded each year is twice the number of new record lows, a signature of a warming climate, and a clear example of its impact on extreme weather.¹

The increase in record highs extends outside the U.S. as well. A similar two to one ratio of record highs to record lows recently has been observed in Australia.² Over the past decade, 75 counties set all-time record highs but only 15 countries set all-time record lows. In 2010, 19 countries set new all-time record high temperatures, but not a single country set a new all-time record low (among those countries keeping these statistics).³

European 2003 Summer Temperatures Were Far Outside Normal Range



2003 European Heat Wave: The Hottest Summer in 140 Years (1864-2003). Each vertical line represents the average summer temperature for a single year from the average of four locations in Switzerland over the period

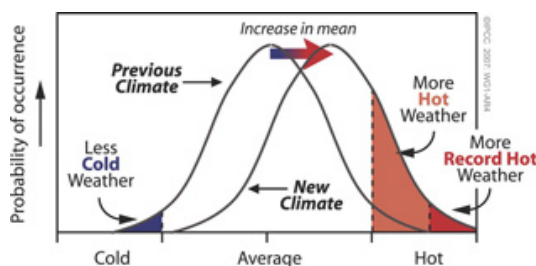
1864 through 2003. This illustrates how far outside the normal range the summer of 2003 was. Schär et al. 2004

One way in which climate change is connected to individual events such as heat waves and heavy rains is by increasing the odds they will occur. We witness that connection in the form of more frequent extreme events. Analyzing how global warming has changed the odds for a specific event has been done for standout moments such as the European heat wave of 2003 that killed tens of thousands. Based on temperature records from 1864 to 2002, the odds of such a heatwave occurring are about 1 in 10 million.⁴ An event like the 2003 heatwave becomes much more likely after factoring in the observed warming of 2°F over Europe and increased weather variability.⁵ In addition, comparing computer models of climate with and without human contribution shows that human influence has roughly quadrupled the odds of a European summer as hot as or hotter than the summer of 2003.⁶

A Small Increase in Average Temperature Leads to Big Changes in Extreme Weather

Small changes in the averages of many key climate variables can correspond to large changes in weather.⁷ Substantial changes in the frequency and intensity of extreme events can result from a relatively small shift in the average of a distribution of temperatures, precipitation, or other climate variables.⁸

Climate Change Shifts the Odds for Extreme Weather Events



Solomon et al. 2007

Weather variation on our planet can be described with a rough bell-shaped curve. So-called normal weather is very common while extreme weather is rare. While events close to normal occur frequently, in the broad center of the curve, there is a sharp fall-off in the frequency of events further away from normal, in the flatter ends of the curve. For instance, a small increase in temperature shifts the entire curve toward hotter high temperatures. The rarest and most extreme record heat events become even more severe and much more frequent. Precipitation does not follow quite the same pattern, but the same concept applies: fewer light and moderate rains are being replaced by more heavy rain events.

While our understanding of how climate change affects extreme weather is still developing, evidence suggests that extreme weather may be affected even more than anticipated. Changes in precipitation are quite complex,⁹ and current computer models of climate have only a limited

ability to predict the heaviest precipitation. Recent observed changes in precipitation have been even greater than the changes projected by climate models.¹⁰ Even with their limitations, current models still capture the physical processes associated with the observed increases in intense precipitation. Warmer air holds more moisture. That additional moisture fuels increases in precipitation intensity. This has been measured in real-world observations as well as simulated by climate models.¹¹

Humans Contribute to Extreme Weather – and Suffer its Consequences

Rigorous analyses have shown that natural variability alone cannot explain the observed long-term trends of changing extremes in temperature and precipitation.¹²

In contrast, the observed trends fit well with our understanding of how climate change drives changes in weather. Computer models of the climate that include both natural forces as well as human influences are consistent with observed global trends in heat waves, warm days and nights, and frost days over the last four decades.¹³ Human influence has also been shown to have contributed to the increase of heavy precipitation over the Northern Hemisphere.¹⁴

Extreme weather events do not have a single cause but instead have various possible contributing factors – and human-induced climate change is now one of those factors. Weather variability can be extremely costly. One estimate finds that the total U.S. economic output varies by up to \$485 billion/year owing to weather variability.¹⁵ From 1980 to 2010 there were 99 weather disasters in the U.S. in which damages exceeded \$1 billion. Altogether those disasters cost \$725 billion.¹⁶ In 2011, the costs of all weather-disaster damages so far has climbed past \$35 billion, according to NOAA estimates. As of August 30th, the U.S. has witnessed 10 weather disasters costing over \$1 billion each. This breaks the previous record for the number of such U.S. weather disasters in an entire year.¹⁷

Changes in extreme weather threaten human health as well as prosperity. Many societies have taken measures to cope with historical weather extremes, but new, more intense extremes have the potential to overwhelm existing human systems and structures.¹⁸ More frequent and more severe extreme weather events are more likely to destabilize ecosystems and cripple essential components of human livelihood, such as food production, transportation infrastructure, and water management. Death, disease, displacement, and economic hardship may follow, as we have seen with recent hurricanes, floods, heat waves, and droughts.

References for this section (see full references at end of report)

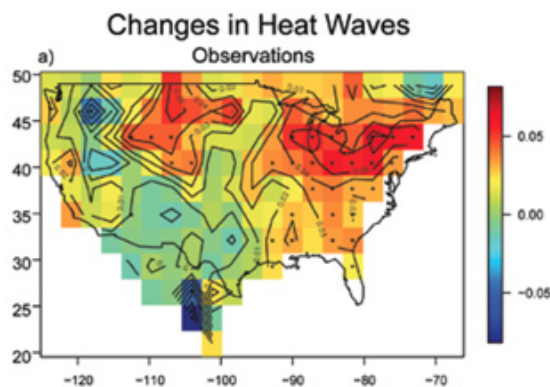
1. Meehl et al. 2009 [↩](#)
2. Trewin and Vermont, 2010 [↩](#)
3. Masters, 2010 [↩](#)
4. Schär et al. 2004 [↩](#)
5. Schär et al. 2004 [↩](#)

6. Stott et al. 2004 [↩](#)
7. Karl et al. 2008 [↩](#)
8. Trenberth 1999; Gutowski et al. 2008 [↩](#)
9. Trenberth 1998, 2011 [↩](#)
10. Gutowski et al. 2008, Allan and Soden 2008, and Min 2011 [↩](#)
11. Tebaldi et al. 2006 [↩](#)
12. Solomon et al. 2007, Stott et al. 2010, and Min et al. 2011 [↩](#)
13. Tebaldi et al. 2006 and Christidis 2011 [↩](#)
14. Min et al. 2011 [↩](#)
15. Lazo et al 2010 [↩](#)
16. Lott et al. 2011 [↩](#)
17. NOAA 2011 [↩](#)
18. Peterson et al. 2008 [↩](#)

Heat Waves

Across the globe in recent decades, there has been an increase in the number of hot extremes, particularly very warm nights.¹ Hot days have also been hotter and more frequent.² Since 1950 the number of heat waves has increased and heat waves have become longer.³

Heat Waves Are Increasing

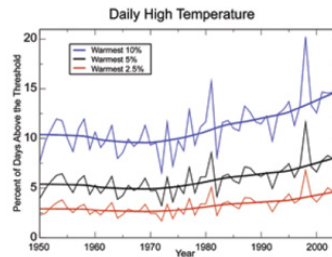


Trend from 1961-1990 in the Karl-Knight heatwave index, which tracks the warmest average minimum temperature over three consecutive nights in a year.

Gutowski et al. 2008

The effect of warming has been substantial. In the United States the record high temperature each year now outnumber the record lows by 2:1.⁴ The rise in heat-trapping gases in the atmosphere has increased the probability of U.S. temperatures breaking a record by 15 fold compared to pre-industrial times.⁵ In Europe, global warming is now responsible for an estimated 29% of the new record highs set each year.⁶ China has witnessed a remarkable increase of hot days across all regions.⁷ Globally, extremely warm nights that used to come once in 20 years now occur every 10 years.⁸

Change in the Frequency of Hot Days in North America



Changes in the annual percent of days in North America exceeding the temperature thresholds set by the historical average of warmest 10% of days, warmest 5% of days and the warmest 2.5% of days. Kunkel et al. 2008

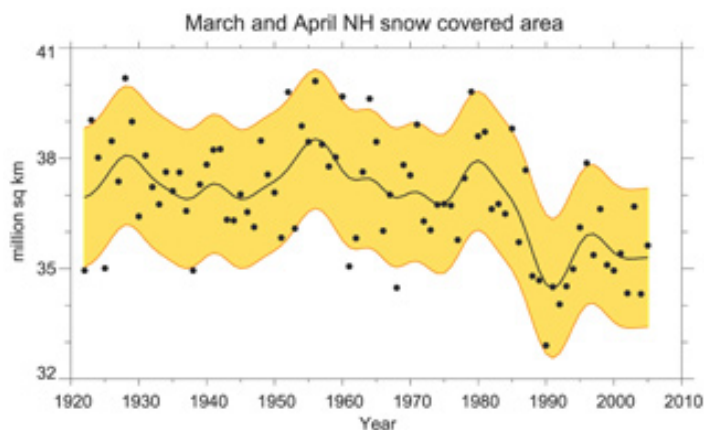
Natural variation alone cannot explain the increase in hot weather. Only with the inclusion of human influences can computer models of the climate reproduce the observed changes in frost days, growing season length, the number of warm nights in a year, warming on the warmest night of the year, warming on the coldest nights and days of the year, warming on the hottest day of the year, unusually hot days throughout the year, and heat waves.⁹ The increase in hot weather is a direct result of climate change, and human influence is estimated to have more than doubled the likelihood of the warming trends experienced recently in virtually every region of the globe.¹⁰

References for this section (see full references at end of report)

1. Gutowski et al. 2008 [↩](#)
2. Trenberth et al. 2007 [↩](#)
3. Trenberth et al. 2007] [↩](#)
4. Meehl et al. 2009 [↩](#)
5. Hoerling et al. 2007 [↩](#)
6. Wergen and Krug 2010 [↩](#)
7. Ding et al. 2009 [↩](#)
8. Zwiers et al. 2010 [↩](#)
9. Meehl et al 2007, Gutowski et al. 2008, Stott et al. 2010, and Christidis et al. 2011 [↩](#)
10. Christidis et al. 2009, and Stott et al. 2010 [↩](#)

Reduced Cold

Increasing hot weather has been accompanied by a decrease in cold weather. Across the globe in recent decades, there has been a reduction in the number of cold extremes, such as very cold nights, and a widespread reduction in the number of frost days in mid-latitude regions.¹ In the United States, there have been fewer unusually cold days. The 10-year period ending in 2007 witnessed fewer severe cold snaps than any other 10-year period since record keeping began in 1895.² These changes cannot be explained by natural variation, and correspond very well with computer simulations that include human influences on climate.³ Snow cover has decreased in most regions, especially in the spring, and mountain snowpack has also decreased in several regions.⁴



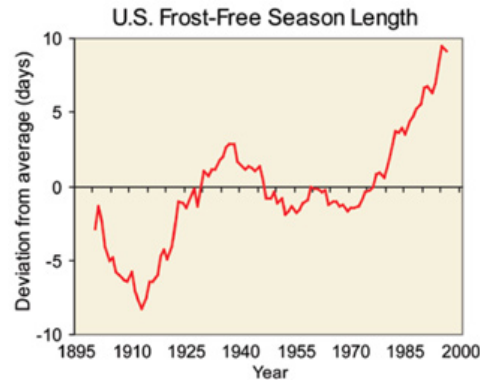
Northern Hemisphere March-April snow covered area from station-derived snow cover index before 1972 and from satellites during and after 1972 . Black dots represent data from individual years. Black line shows smoothed trend accounting for variation within a decade.
Trenberth et al. 2007

Snow Cover Decreasing Across the Northern Hemisphere

Snow cover has decreased in most regions, especially in the spring, and mountain snowpack has also decreased in several regions.⁵

Freezes Coming Later and Thawing Earlier

The freeze date for lakes and rivers in the Northern Hemisphere has moved later in the year, at an average rate of six days per 100 years, while the ice break-up date has moved up earlier in the year, at an average rate of a little more than six days over the last 100 years.⁶ Smaller lakes in North American show a uniform trend toward earlier ice break-up, up to 13 days early.⁷



Change in the length of the frost-free season averaged over the United States.
Kunkel 2008

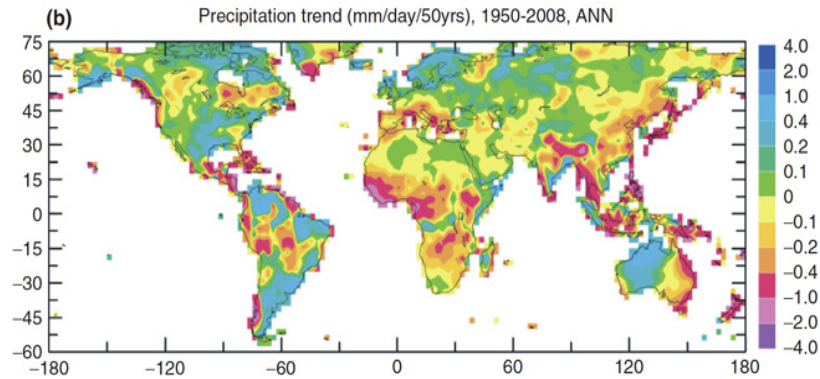
References for this section (see full references at end of report)

1. Gutowski et al. 2008 [↩](#)
2. Gutowski et al. 2008 [↩](#)
3. Stott et al. 2010 [↩](#)
4. Trenberth et al. 2007 [↩](#)
5. Solomon et al. 2007a [↩](#)
6. Trenberth et al. 2007 [↩](#)
7. Gutowski et al. 2008 [↩](#)

Precipitation, Floods and Drought

Precipitation has increased in many regions of the world and decreased in others, with little or no net change in the total amount of precipitation. Drought has increased in most places, consistent with expectations for a warming climate. Generally, wet areas have become wetter, and dry areas have become drier in the past 40 years. Precipitation has increased in the eastern parts of North and South America, Northern Europe, and northern and central Asia. Precipitation decreases have been observed in the subtropics and the tropics outside the monsoon trough, namely the Sahel, the Mediterranean, Southern Africa, and Southern Asia.¹

Some areas have experienced widening swings between the two precipitation extremes.² For instance, the summer of 2002 in Europe brought widespread floods, but was followed a year later in 2003 by record-breaking heat waves and drought. In the summer of 2007, widespread flooding in central England (the wettest since records began in 1766) was accompanied by drought and record-breaking heat waves in southeast Europe.³



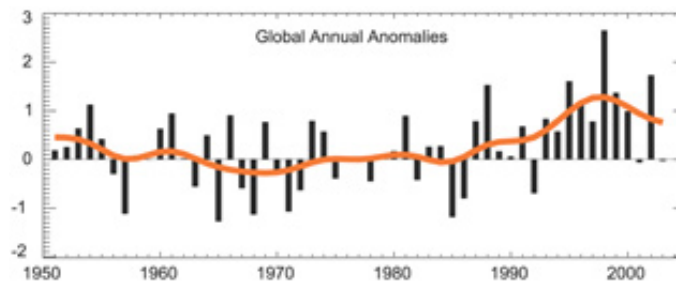
Trend map for observed annual precipitation.
Dai, 2010

Significantly, dramatic and widespread increases in heavy precipitation have also been observed, even in areas where the total precipitation has decreased. And the fingerprint of human influence has been found in these increases.⁴ This is of particular concern as heavy precipitation contributes to destructive and costly events such as floods.⁵

Natural variability cannot explain the observed changes in precipitation intensity or geographic distribution of precipitation. Rather, the observed changes follow from basic physical principles and are consistent with a combination of natural factors and human influence.⁶

Heavy Precipitation

The water holding capacity of the atmosphere increases in a warmer world. A 4% increase in atmospheric moisture has been observed and that is consistent with a warming climate.⁷ Natural variability cannot account for the changes, and the fingerprint of human influence has been identified in these changes.⁸

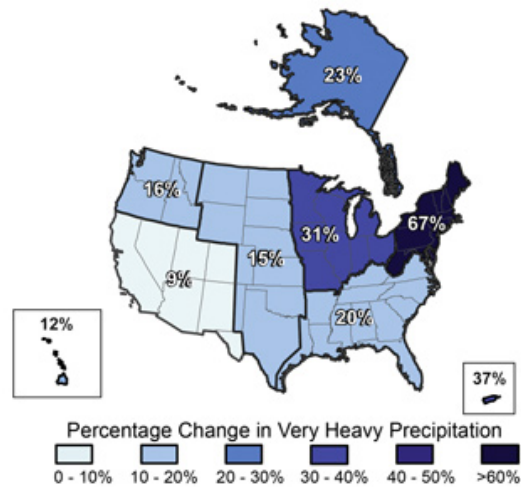


Changes in the proportion of precipitation falling on very wet days (wetter 5% of days). The vertical scale shows percent change from 22.5%, the average of the base period (1961-1990). The smooth red curve accounts for variation within a decade.

Trenberth et al. 2007

The increased moisture in the atmosphere is driving the shift to heavier but less frequent rains — “when it rains, it pours.” While an atmosphere that holds more moisture has greater potential to produce heavier precipitation, precipitation events also become less frequent and shorter, as

it takes longer to recharge the atmosphere with moisture.⁹ By analogy, a larger bucket holds and dumps more water, but takes longer to refill.



The map shows the percentage increases in very heavy precipitation (defined as the heaviest 1 percent of all events) from 1958 to 2007 for each region. There are clear trends toward more very heavy precipitation for the nation as a whole, and particularly in the Northeast and Midwest. Karl et al. 2009

Storms are producing more intense precipitation, even in areas where total precipitation is decreasing.¹⁰ Storms reach out to gather water vapor over regions that are 10-25 times as large as the precipitation area, multiplying the effect of increased atmospheric moisture. As water vapor condenses to form clouds and rain, it releases latent heat energy that adds buoyancy to the air and fuels the storm. This increases the gathering of moisture into storm clouds and further intensifies precipitation.¹¹

In the wettest areas of the tropical oceans, the most extreme rainfall events have increased by 60% per degree of warming.¹² While the geographic pattern and intensity of precipitation has changed dramatically, total global precipitation has changed little.¹³

The higher latitudes have become wetter in recent years, due mainly to the warmer air holding more moisture and in part to alterations in atmospheric circulation driven by climate change. At the same time, the subtropics and parts of the tropics have become drier as winds carry the moisture away to the monsoon rain areas or to mid-latitude storms.¹⁴

In the United States, total average precipitation has increased by about 7% in the past century, while the amount of precipitation falling in the heaviest 1% of rain events has increased 20%.¹⁵ Regions such as the Northeast and Midwest have seen considerably larger increases in the heaviest rains.

References for this section (see full references at end of report)

1. Trenberth et al. 2007, Trenberth 2011↩
2. Trenberth et al. 2007↩
3. Trenberth 2011↩
4. Min et al. 2011↩
5. Solomon et al. 2007↩
6. Stott et al. 2010, Trenberth 2011, Zhang et al. 2007↩
7. Trenberth et al 2007↩
8. Stott et al. 2010↩
9. Trenberth 2011↩
10. Trenberth 2011↩
11. Trenberth 2011↩
12. Allan et al 2010↩
13. Trenberth 2011↩
14. Trenberth 2011↩
15. Karl et al. 2009↩

Floods

Heavy precipitation contributes to increased flooding, a pattern that has already been observed around the world.¹ The frequency of great floods (100-year floods in large basins) increased substantially during the 20th century.² However, flooding is also affected by various other human activities. For example, deforestation may exacerbate flooding, while changes in land use can greatly influence runoff, which can either increase or reduce the risk of flooding.

Runoff, or the surface water left over when the land cannot soak up any more, has also increased in many parts of the world, consistent with changes in precipitation.³ Regional shifts in precipitation can also increase the risk of flooding by raising water table levels, as seen in the northeastern United States.⁴

The warming climate is increasing the risks of both flood and drought, but at different times or in different places. For instance, the summer of 2002 in Europe brought widespread floods, but was followed a year later in 2003 by record-breaking heat waves and drought. In the summer of 2007, widespread flooding in central England (the wettest since records began in 1766) was accompanied by drought and record-breaking heat waves in southeast Europe.⁵

Flooding in large river basins, such as the Mississippi, is not driven by brief, extreme precipitation episodes alone. Rather, extreme precipitation must be sustained for weeks to months to flood the Mississippi. In spring, heavy rains on top of snow can contribute to flooding

in northern regions. Such long-term, heavy precipitation episodes are becoming more common in some areas. In the U.S., 90-day periods of heavy rainfall were 20% more common from 1981 to 2006 than in any earlier 25-year period on record.⁶ Record breaking Mississippi flooding occurred in 2011 in association with very heavy rains, and was followed by extensive flooding further north in the Missouri River basin due to heavy rain and snowmelt.

Recent record floods, such as in Nashville, Tennessee in early 2010, in Pakistan in mid-2010, and in Australia in late 2010, were driven in part by the human-influenced trend toward heavy precipitation.⁷ Changes in large-scale patterns of atmospheric pressure also contributed to the Pakistan flooding.⁸

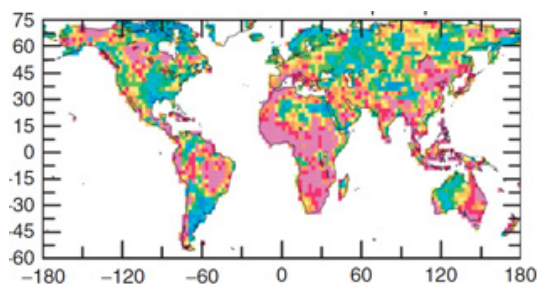
References for this section (see full references at end of report)

1. Parry et al. 2007 [↵](#)
2. Milly 2002 [↵](#)
3. Gutowski et al. 2008 [↵](#)
4. Weider and Boutt 2010 [↵](#)
5. Trenberth 2011 [↵](#)
6. Kunkel et al. 2008 [↵](#)
7. Ash 2011, Asrar 2010, and Trenberth 2010 [↵](#)
8. Stott 2010 [↵](#)

Drought

While climate change has increased precipitation in some areas, in other regions it has contributed to drought.¹ Though there are a number of factors that drive drought, such conditions are apt to develop in regions that lack rain; drought is also greatly intensified by increased evaporation from soil and vegetation associated with warming.² Very dry areas across the globe have doubled in extent since the 1970s.³ In particular, a long-term drying trend (from 1900 to 2008) persists in Africa, East and South Asia, eastern Australia, southern Europe, northern South America, most of Alaska, and western Canada.⁴

Long-term drying trends, 1900-2008



Warm-colored areas on the map represent drying trends. Cool-colored areas represent moistening trends. Dai, 2011

The global increase in drier, hotter areas and the trend in which dry areas are becoming drier can both be traced to the human influence.⁵ Drying trends have been observed in both the Northern and Southern hemispheres since the 1950s.⁶ These trends cannot be explained by natural variations but do fit well with climate model expectations for global warming.⁷ In particular, greenhouse gas emissions have contributed significantly to recent drying by driving warming over land and ocean.⁸

The increase in drought is caused by many factors: shortfalls in precipitation; earlier snow melt; a shift away from light and moderate rains towards short, heavy precipitation events; and increased evaporation from soil and vegetation due to higher atmospheric temperatures, all of which have been driven at least in part by climate change. Increased heating leads to greater evaporation of moisture from land, thereby increasing the intensity and duration of drought.⁹ Individual droughts have been linked to climate change, such as the drought that hit central India in 2008 when the north-south pattern of precipitation was disrupted by unusual weather driven by abnormally high sea surface temperatures due in part to global warming.¹⁰

Wet and Dry Extremes Both Increasing Across the Globe

The increase in drought is caused by many factors: shortfalls in precipitation, early snow melt, a shift away from light and moderate rains towards short, heavy precipitation events, and increased evaporation due to higher temperatures, all of which have been driven in part by climate change. Increased heating leads to greater evaporation of moisture from land, thereby increasing the intensity and duration of drought.¹¹

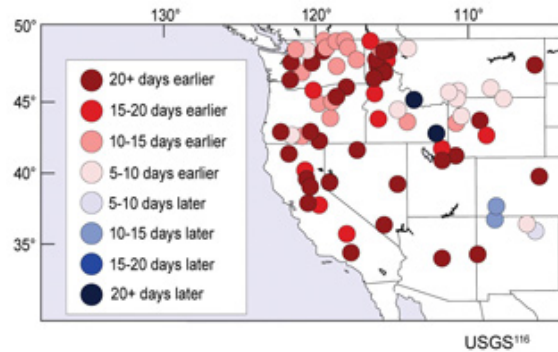
Alterations in atmospheric circulation have contributed to the distinctive pattern in global precipitation changes in recent years whereby the subtropics and much of the tropics (with the exception of the monsoon trough) have become drier.¹² Rapid warming since the late 1970s has both evaporated large amounts of moisture from the land into the atmosphere and altered atmospheric circulation patterns, contributing to the drying over land.¹³

Individual droughts have been linked to climate change, such as the drought that hit central India in 2008 when the north-south pattern of precipitation was disrupted by unusual weather driven by abnormally high sea surface temperatures linked to global warming.¹⁴

Spring Snowmelt Shifting to Earlier in the Year

Rising temperatures have also led to earlier melting of the snowpack in the western United States, more than 20 days earlier in some locations.¹⁵ Early snow melt, along with an increased tendency for precipitation to fall as rain rather than snow, can be an important contributor to drought in regions that count on snowpack to supply water, such as the western U.S. and Canada. A recent study of water cycle changes in the western U.S. attributes to human influence up to 60% of observed climate-related trends in river flow, winter air temperature, and snow pack in the region over the 1950–1999 period.¹⁶

Spring Snowmelt Shifting to Earlier in the Year



Date of onset of spring runoff pulse. Redish-brown circles indicate significant trends toward onsets more than 20 days earlier. Lighter circles indicate less advance of the onset. Blue circles indicate later onset. The changes depend on a number of factors in addition to temperature, including altitude and timing of snowfall. Karl et al. 2009

References for this section (see full references at end of report)

1. Trenberth et al. 2007, Solomon et al. 2007a [↩](#)
2. Dai 2011 [↩](#)
3. Dai 2011 [↩](#)
4. Dai 2011 [↩](#)
5. Stott 2010 [↩](#)
6. Gutowski et al. 2008 [↩](#)
7. Gutowski et al. 2008 [↩](#)
8. Dai, 2011 [↩](#)
9. Dai 2011 and Trenberth 2011 [↩](#)
10. Rao et al. 2010 [↩](#)
11. Dai 2011 and Trenberth 2011 [↩](#)
12. Trenberth 2011 [↩](#)
13. Dai 2011 [↩](#)
14. Rao et al. 2010 [↩](#)
15. Karl et al. 2009 [↩](#)
16. Stott et al. 2010 [↩](#)

Circulation Changes: El Niño and the Arctic Oscillation

Local weather, particularly extreme local weather, is often determined by fluctuations in large patterns of regional atmospheric pressure and sea surface temperatures, such as the Arctic Oscillation (and its close relative, the North Atlantic Oscillation) and other patterns associated with El Niño-Southern Oscillation (ENSO). These recognizable patterns come and go over a period of months to years. And these patterns may be altered by global warming.

Circulation variations, such as the ones associated with ENSO, largely determine where stormy, wet weather is favored and where dry weather prevails. In regions where the effects of these circulation variations are similar to global warming effects, new extremes are observed. While ENSO and other sources of natural variability can determine the location of extremes,¹ the intensity and duration of the associated extremes such as droughts, and the associated heat waves, have increased with climate change. Similarly, in the wet areas, the intensity of rains and risk of flooding is greater.

Regional circulation patterns have significantly changed in recent years.² For example, changes in the Arctic Oscillation cannot be explained by natural variation and it has been suggested that they are broadly consistent with the expected influence of human-induced climate change.³ The signature of global warming has also been identified in recent changes in the Pacific Decadal Oscillation, a pattern of variability in sea surface temperatures in the northern Pacific Ocean.⁴ El Niños have become more common and their intensity has nearly doubled in recent years, a statistically rare event. This recent shift towards more intense and frequent El Niños is related to the recent increase in dry areas around the world.⁵ However, past observations and reconstructions of El Niño events from non-instrumental records such as corals show that El Niño events naturally fluctuate in magnitude and frequency over time, and this has been demonstrated in long climate model simulations of past and future climate as well.⁶

El Niño's center of action appears to be shifting from the eastern to the central Pacific, which in turn is affecting the distribution and frequency of weather events.⁷ However, due to the wide natural fluctuations within circulation patterns, it is difficult to attribute recent changes solely to human activity. Further research is needed to determine how global warming impacts these circulation patterns.

Recent extreme weather events partially driven by circulation changes:

“Snowmageddon,” United States, 2010

A combination of changes in El Niño and the Arctic Oscillation (which is closely related to the North Atlantic Oscillation) has been identified as the immediate driver of the heavy snowfall experienced by the mid-Atlantic states in the United States during the winter of 2010.⁸ The warm tropical Atlantic contributed extra moisture to the record snows. Global warming may have contributed to the record negative phase of the Arctic Oscillation that helped to drive the extreme weather south to the U.S. (See Winter Storms section for more detail.)

Pakistan floods, 2010

The weather pattern over northern India, the Himalayas, and Pakistan is usually dominated by a circulation pattern that prevents mid-latitude weather systems from penetrating very far south. However, in 2010, active weather systems spread southward into Pakistan. Global warming had increased the amount of atmospheric moisture available to condense into rain, and La Niña, a circulation pattern that can produce heavy rains in Pakistan, was in progress. These systems combined with the monsoon to produce record rainfall. Record-breaking high temperatures in Moscow were another consequence of the mid-latitude weather moving southward, as was the excessive rain and flooding over China.⁹ Several studies are currently exploring how climate change may have contributed to these events, but scientists at the World Meteorological Organization are already convinced that higher Atlantic Ocean temperatures from global warming were a contributing factor.¹⁰

Southeastern U.S. floods and drought, early 2000s

The recent dramatic swings between drought and flooding in the southeastern United States have been found to be linked to changes in the North Atlantic Subtropical High (also known as the Bermuda High), and these changes may be linked to global warming.¹¹

The precise connections between global warming and circulation changes are still being investigated and our understanding will evolve accordingly. However, we now know that climate change is already affecting regional circulation patterns and by extension helping to shape local extreme weather.

References for this section (see full references at end of report)

1. Meehl and Teng, 2007 [↩](#)
2. Lee and McPhaden 2010, Stott 2010 [↩](#)
3. Stott 2010 [↩](#)
4. Bonfils and Santer 2010 [↩](#)
5. Dai 2011 [↩](#)
6. Meehl et al., 2006 [↩](#)
7. McPhaden 2010, Dai 2011 [↩](#)
8. Seager et al. 2010 [↩](#)

- 9. Stott 2010 ←
- 10. Gronewald 2010 ←
- 11. Li et al. 2010 ←

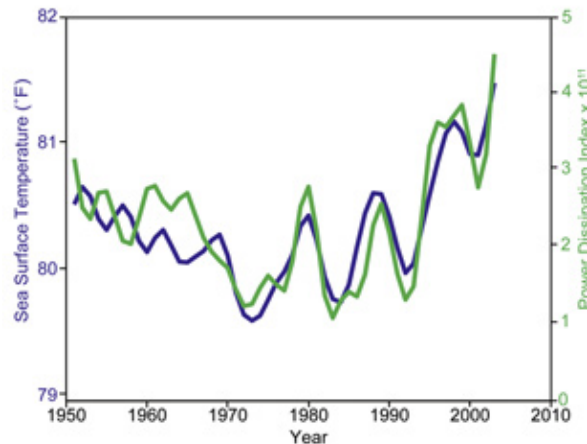
Hurricanes and Other Summer Storms

All storms, including thunderstorms, rain or snow storms, and tropical cyclones, are now developing in a warmer, moister environment. Consequently, storms are producing more heavy precipitation, even in areas where total precipitation is decreasing.¹ General storminess around the world, as measured by wind speeds and ocean wave heights, has increased in recent years, with the increase particularly pronounced in winter months. This pattern cannot be explained by natural variability alone, and is consistent with model simulations of a warming climate.²

Tropical Cyclones: Hurricanes, Typhoons, and Tropical Storms

The intensity of Atlantic hurricanes has increased in recent years, a pattern that is consistent with climate change. Warming oceans store increasing amounts of heat energy and fuel stronger storms.³

Hurricane Intensity Increases with Rising Sea Surface Temperatures



Observed sea surface temperature (blue) and the Power Dissipation Index (green), which combines frequency, intensity and duration for North Atlantic hurricane rainfall and wind speeds are likely to increase in response to human caused warming. Analyses of model simulations suggest that for each 1.8°F increase in tropical sea surface temperatures, rainfall rates will increase by 6 to 18 percent. Emanuel 2007

Globally, the strongest tropical cyclones have increased in intensity, with the most significant increases occurring in the Atlantic. The available evidence is that this has been due to a combination of natural variability and climate change. Gaps in records from the last century and other issues make it difficult to be precise about the relative influences at this stage, but climate

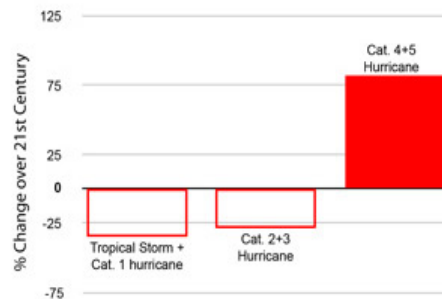
change is expected to dominate in the future.⁴

The Atlantic hurricane season is also getting longer, at a rate of 5 to 10 days per decade. The broadening of the season correlates with rising sea surface temperatures; each degree Celsius temperature change corresponds to a 20-day shift in both the beginning and end of hurricane season. Here too, however, due to the uneven state of record keeping, we cannot rule out the possibility of a role for natural variation in this trend.⁵

Atlantic Hurricane Intensity on the Rise

Looking forward, the trend is clearer. Over the coming decades, Atlantic hurricanes are likely to increase in strength as sea surface temperatures increase, fueling the intensity of storms in the Atlantic Ocean, and significantly increasing rainfall rates over those of present day storms.

Projected Changes in Atlantic Hurricane Frequency over the 21st Century



Adapted from NOAA Geophysical Fluid Dynamics Laboratory

Worldwide there will likely be an average increase in the maximum wind speed of tropical cyclones (hurricanes and typhoons) of 2 to 11%.⁶ Because of the way extremes respond to changes such as these, Category 4 and 5 hurricanes are expected to nearly double in number by the end of the century.⁷ The rate of rainfall associated with tropical cyclones, an important factor in flooding, is expected to increase approximately 20% within 100 km of the center of these storms.⁸

While the Atlantic basin is poised to see a dramatic increase in the number of very strong hurricanes, the global tropical cyclone count may decline slightly.⁹ The number of tropical cyclones is projected to decrease by 22% in the western North Pacific basin by the end of the 21st century.¹⁰

Thunderstorms and Tornadoes

Incomplete and inconsistent record keeping make it very difficult to assess how local thunderstorms and tornadoes in the United States have been affected by climate change to date. Looking forward, climate change creates a warmer, moister environment that may fuel additional thunderstorms. Computer models of a warming climate indicate that conditions may become more conducive to severe thunderstorms in some regions.¹¹ Thunderstorms provide a favorable

environment for tornado formation; but tornadoes also require wind shear, a highly uncertain element in climate models.

Extreme Winds

Average wind speed over a majority of the world's oceans has increased 5 to 10% over the past 20 years, and the speed of extreme winds (the strongest 1% of winds) has increased by at least 15% over the majority of oceans.¹² On the other hand, surface wind speed over land appears to be declining slightly in many mid-latitude locations, including the U.S.¹³ High-altitude circulation changes associated with climate change may affect wind speeds, but land use factors such as urban development and vegetation growth are also major contributors to slowing land surface winds.¹⁴

References for this section (see full references at end of report)

1. Trenberth 2011 [↩](#)
2. Stott et al. 2010 [↩](#)
3. Trenberth 2011 [↩](#)
4. Knutson et al. 2010 [↩](#)
5. Kossin 2008 [↩](#)
6. Knutson et al. 2010 [↩](#)
7. Knutson et al. 2010 and Bender et al. 2010 [↩](#)
8. Knutson et al. 2010 [↩](#)
9. Knutson et al. 2010 [↩](#)
10. Murakami et al. 2011 [↩](#)
11. Gutowski et al. 2008 and Trapp et al. 2007 [↩](#)
12. Young et al. 2011 [↩](#)
13. Vautard et al 2010, McVicar & Roderick 2010, Pryor et al 2009 [↩](#)
14. Vautard et al 2010 [↩](#)

Winter Storms

Climate change is fueling an increase in the intensity and snowfall of winter storms. The atmosphere now holds more moisture, and that in turns drives heavier than normal precipitation, including heavier snowfall in the appropriate conditions.¹

Heavy snowfall and snowstorm frequency have increased in many northern parts of the United States.² The heavier-than-normal snowfalls recently observed in the Midwest and Northeast United States are consistent with climate model projections. In contrast, the South and lower Midwest saw reduced snowstorm frequency during the last century.³ Overall snow cover has decreased in the Northern Hemisphere, due in part to higher temperatures that shorten the time snow spends on the ground.

Snowstorms Shift Northward in the Northern Hemisphere

The regional pattern of fewer snowstorms in the southern United States and more in the North corresponds to a similar northward shift of cold-season storms in the entire Northern Hemisphere over the past 50 years. Mid-latitude storms have decreased in frequency (e.g., in the United States overall) while high-latitude storm activity has increased (e.g., in Canada).⁴ It is likely that human influence contributed to these changes.⁵

Rapidly Warming Arctic Drives Recent Surprising Cold

In the past few years, unusually warm air in the Arctic has driven winter storm tracks south into the United States, reflecting the complex and sometimes counteracting ways that climate change may affect local weather extremes. In these events, cold-air usually penned in the Arctic by winds known as the polar vortex, broke out and reached the U.S. and Europe due to an erosion of the vortex, an erosion that may have been driven by an abnormally warm Arctic.⁶ Despite the outbreak of Arctic air, the winters of 2010 and 2011 experienced by the U.S. and Europe were only slightly colder than the average of the winters experienced from 1951-1980, many of which were much colder than the 2010 and 2011 winters. The remaining eight of the last 10 winters experienced by the U.S. were all warmer than the 1951-1980 average for the U.S.⁷

“Snowmageddon,” United States, February 2010

A combination of changes in El Niño and the Arctic Oscillation (which is closely related to the North Atlantic Oscillation) has been identified as the immediate driver of the famously heavy snowfall experienced by the mid-Atlantic states in the United States during the winter of 2010.⁸ Global warming may have played a part in this remarkable event by contributing in two ways to the record negative phase of Arctic Oscillation that helped to erode the polar vortex and permitted a cold-air outbreak south to the United States. Evidence suggests that the negative phase of the Arctic Oscillation was driven in part by warm air (air warmed by the dramatic seasonal loss of Arctic sea ice)⁹ as well as by changes in snow cover over Eurasia driven by climate change.¹⁰ This event is part of an emerging trend in which a warming climate may paradoxically bring colder, snowier winters to northern Europe and the eastern United States.¹¹

Lake-effect Snowfall near the Great Lakes, February 2007

In the Midwest, lake-effect snowfall has increased along and near the southern and eastern shores of the Great Lakes since 1950. Lake-effect snow is produced by the strong flow of cold air across large areas of relatively warmer ice-free water. As the climate has warmed, ice coverage on the Great Lakes has fallen. This has created conditions conducive to greater evaporation of moisture and thus heavier snowstorms. Among recent extreme lake-effect snow events was a February 2007 10-day storm total of over 10 feet of snow in western New York state.¹²

References for this section (see full references at end of report)

1. Trenberth 2011 [↵](#)
2. Karl et al. 2009 [↵](#)
3. Karl et al. 2009 [↵](#)
4. Karl et al. 2009 [↵](#)
5. Gutowski et al. 2008 [↵](#)
6. Overland 2010, NOAA 2010a, and NOAA 2010b [↵](#)
7. Hansen 2011 [↵](#)
8. Seager et al. 2010 [↵](#)
9. Overland 2010, NOAA 2010a, and NOAA 2010b [↵](#)
10. Cohen et al. 2010 [↵](#)
11. Overland 2010, NOAA 2010a, NOAA 2010b, Cohen et al. 2010, and Vavrus et al 2006. [↵](#)
12. Karl et al. 2009 [↵](#)

Conclusion

Human-induced climate change has contributed to changing patterns of extreme weather across the globe, from longer and hotter heat waves to heavier rains. From a broad perspective, all weather events are now connected to climate change. While natural variability continues to play a key role in extreme weather, climate change has shifted the odds and changed the natural limits, making certain types of extreme weather more frequent and more intense.

While our understanding of how climate change affects extreme weather is still developing, evidence suggests that extreme weather may be affected even more than anticipated. Extreme weather is on the rise, and the indications are that it will continue to increase, in both predictable and unpredictable ways.

References

Allan, R., 2011: Climate change: Human influence on rainfall. *Nature* 2011 Volume: 470, Pages: 344–345 doi:10.1038/470344a

Allan, R. and B. Soden, 2008: Atmospheric Warming and the Amplification of Precipitation Extremes. *Science* 2008: Vol. 321 no. 5895 pp. 1481-1484 DOI: 10.1126/science.1160787

Allan P., B. Soden, V. John, W. Ingram, and P. Good, 2010: Current changes in tropical precipitation. *Environ. Res. Lett.* 2010 doi: 10.1088/1748-9326/5/2/025205

Ash, Andrew, 2011: Coincidence or climate change? *Australian Broadcasting News*. February 3, 2011. <http://www.abc.net.au/unleashed/43560.html>

Bender, M., T. Knutson, R. Tuleya, J. Sirutis, G. Vecchi, S. Garner, and I. Held, 2010: Modeled Impact of Anthropogenic Warming on the Frequency of Intense Atlantic Hurricanes. *Science*. 22 January 2010: 327 (5964), 454-458. DOI:10.1126/science.1180568
<http://www.sciencemag.org/citmgr?gca=sci:327/5964/454>

Bonfils, C. and B. Santer, 2010: Investigating the possibility of a human component in various pacific decadal oscillation indices. *Climate Dynamics* 2010. DOI: 10.1007/s00382-010-0920-1. <http://dx.doi.org/10.1007/s00382-010-0920-1>.

Changnon, S., D. Changnon, T. Karl, 2006: Temporal and Spatial Characteristics of Snowstorms in the Contiguous United States. *J. Appl. Meteor. Climatol.*, 45, 1141–1155. doi: 10.1175/JAM2395.1

Christidis N, P.A. Stott, F.W. Zwiers, H. Shiogama, and T. Nozawa, 2009: Probabilistic estimates of recent changes in temperature: a multi-scale attributions analysis. *Climate Dynamics* 2009.

Christidis, N., P.A. Stott, and S. Brown, 2011: The role of human activity in the recent warming of extremely warm daytime temperatures. *Journal of Climate* doi:10.1175/2011JCLI4150.1 <http://journals.ametsoc.org/doi/abs/10.1175/2011JCLI4150.1>

Cohen, J., J. Foster, M. Barlow, K. Saito, and J. Jones, 2010: Winter 2009–2010: A case study of an extreme Arctic Oscillation event, *Geophys. Res. Lett.*, 37, L17707, doi:10.1029/2010GL044256.

Dai, A.: 2011: Drought under global warming: a review. *Wiley Interdisciplinary Reviews: Climate Change*, 2: 45–65. doi: 10.1002/wcc.81

Ding, T., Qian, W. and Yan, Z. (2010), Changes in hot days and heat waves in China during 1961–2007. *International Journal of Climatology*, 30: 1452–1462. doi: 10.1002/joc.1989

Emanuel, K., 2007: Environmental factors affecting tropical cyclone power dissipation. *Journal of Climate*, 20(22), 5497-5509.

Groisman, P., Knight, R., Karl, T., Easterling, D., Sun B., and Lawrimore, J. 2004: Contemporary Changes of the Hydrological Cycle over the Contiguous United States: Trends Derived from In Situ Observations. *J. Hydrometeor*, 5, 64–85. doi: 10.1175/1525-7541(2004)005<0064:CCOTHC>2.0.CO;2

Gronewald, Nathaniel, 2010: Is the Flooding in Pakistan a Climate Change Disaster? Devastating flooding in Pakistan may foreshadow extreme weather to come as a result of global warming. *Scientific American*. August 18, 2010.

<http://www.scientificamerican.com/article.cfm?id=is-the-flooding-in-pakistan>

Gutowski, W.J., G.C. Hegerl, G.J. Holland, T.R. Knutson, L.O. Mearns, R.J. Stouffer, P.J. Webster, M.F. Wehner, F.W. Zwiers, 2008: Causes of Observed Changes in Extremes and Projections of Future Changes in *Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands*. T.R. Karl, G.A. Meehl, C.D. Miller, S.J. Hassol, A.M. Waple, and W.L. Murray (eds.). A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC.

Hansen, J., 2011: *Perceptions of Climate Change*. March 27, 2011. <http://www.columbia.edu/~jeh1/mailings/>

Hoerling, M., J. Eischeid, X. Quan, and T. Xu, 2007: Explaining the record 2006 US warmth. *Geophys. Res. Letters*, 34, doi:10.1029/2007GL030643. <http://www.publicaffairs.noaa.gov/releases2007/aug07/noaa07-045.html>

Karl, T.R., G.A. Meehl, T.C. Peterson, K.E. Kunkel, W.J. Gutowski, Jr., D.R. Easterling, 2008: Executive Summary in *Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands*. T.R. Karl, G.A. Meehl, C.D. Miller, S.J. Hassol, A.M. Waple, and W.L. Murray (eds.). A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC.
Karl, T.R., G.A. Meehl, and T.C. Peterson, 2009: *Global Climate Change Impacts in the United States*. Cambridge University Press, 2009.

Knutson, T., J. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J. Kossin, A. Srivastava, and M. Sugi, 2010: Tropical cyclones and climate change. *Nature Geosci* 2010 <http://dx.doi.org/10.1038/ngeo779> http://www.nature.com/ngeo/journal/v3/n3/supinfo/ngeo779_S

[1.html](#)

Kossin, J. P., 2008: Is the North Atlantic hurricane season getting longer? *Geophys. Res. Lett.*, 35, L23705, doi:10.1029/2008GL036012

Kunkel, K.E., P.D. Bromirski, H.E. Brooks, T. Cavazos, A.V. Douglas, D.R. Easterling, K.A. Emanuel, P.Ya. Groisman, G.J. Holland, T.R. Knutson, J.P. Kossin, P.D. Komar, D.H. Levinson, and R.L. Smith, 2008: Observed changes in weather and climate extremes. In: *Weather and Climate Extremes in a Changing Climate: Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands*[Karl, T.R., G.A. Meehl, C.D. Miller, S.J. Hassol, A.M. Waple, and W.L. Murray (eds.)]. Synthesis and Assessment Product 3.3. U.S. Climate Change Science Program, Washington, DC, pp. 35-80.

Lazo, J., M. Lawson, P. Larsen, and D. Waldman, 2010: U.S. Economic Sensitivity to Weather Variability. *Bulletin of the American Meteorological Society*.
doi:10.1175/2011BAMS2928.1<http://journals.ametsoc.org/doi/abs/10.1175/2011BAMS2928.1>

Lee, T., and M. J. McPhaden, 2010: Increasing intensity of El Niño in the central-equatorial Pacific, *Geophys. Res. Lett.*, 37, L14603, doi:10.1029/2010GL044007.

Li, W., L. Li, R. Fu, Y. Deng, and H. Wang, 2010: Changes to the North Atlantic Subtropical High and Its Role in the Intensification of Summer Rainfall Variability in the Southeastern United States. *Journal of Climate* 2010
doi:10.1175/2010JCLI3829.1<http://journals.ametsoc.org/doi/abs/10.1175/2010JCLI3829.1>

Lott N., T. Ross, A. Smith, T. Houston and K. Shein, 2011: *Billion Dollar U.S. Weather Disasters, 1980-2010*. National Climatic Data Center. Jan. 18, 2011.
<http://www.ncdc.noaa.gov/oa/reports/billionz.html>

Masters J., 2010: Bolivia ties its all-time heat record. Dr. Jeff Masters *Wunderblog*. November 23, 2010. <http://www.wunderground.com/blog/JeffMasters/comment.html?entrynum=1701>

McPhaden, M., 2010 NASA/NOAA Study Finds El Niños Growing Stronger. *NOAA News August 25, 2010*. http://www.noaanews.noaa.gov/stories2010/20100825_elnino.html

McVicar, T. and Roderick, M. Atmospheric Science: Winds of Change. *Nature Geoscience* 3, 747–748 (2010) doi:10.1038/ngeo1002
<http://www.nature.com/ngeo/journal/v3/n11/full/ngeo1002.html>

Meehl, G.A., J.M. Arblaster and C. Tebaldi, 2007: Contributions of natural and anthropogenic forcing to changes in temperature extremes over the U.S. *Geophys. Res. Lett.*, 34, L19709, doi:10.1029/2007GL030948.

Meehl, G.A., and H. Teng, 2007: Multi-model changes in El Niño teleconnections over North America in a warmer climate. *Cli. Dyn.*, 29, 779-790, DOI 10.1007/s00382-007-0268-3.

Meehl, G. A., H. Teng, and G. W. Branstator, 2006: Future changes of El Niño in two global coupled climate models. *Climate Dynamics*, 26, 549-566, doi: 10.1007/s00382-005-0098-0.

Meehl, G. A., T. F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver, and Z. -C. Zhao, 2007: Global Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 747–845.

Meehl, G. A., C. Tebaldi, G. Walton, D. Easterling, and L. McDaniel, 2009: Relative increase of record high maximum temperatures compared to record low minimum temperatures in the U.S., *Geophys. Res. Lett.*, 36, L23701, doi:10.1029/2009GL040736.

Milly, P.C.D., R. T. Wetherald, K. A. Dunne, and T. L. Delworth, 2002: Increasing risk of great floods in a changing climate. *Nature* (31 January 2002) doi:10.1038/415514a

Min S., X. Zhang, F. Zwiers, and G. Hegerl, 2011: Human contribution to more-intense precipitation extremes. *Nature* 2011 Volume: 470, Pages: 378–381. doi:10.1038/nature09763

Murakami, H., B. Wang, and A. Kitoh, 2011: Future Change of Western North Pacific Typhoons: Projections by a 20-km-Mesh Global Atmospheric Model*. *J. Climate*, 24, 1154–1169. doi: 10.1175/2010JCLI3723.1

NOAA 2010a. NOAA Arctic Report Card 2010. Future of Arctic Sea Ice and Global Impacts. <http://www.arctic.noaa.gov/future/>

NOAA 2010b. NOAA Arctic Report Card 2010. Warm Arctic-Cold Continents Pattern. http://www.arctic.noaa.gov/future/warm_arctic_cold_continent.html and <http://www.arctic.noaa.gov/future/impacts-about.html>

NOAA 2011. National Climatic Data Center. Billion Dollar U.S. Weather Disasters. <http://www.ncdc.noaa.gov/oa/reports/billionz.html>

Overland, J., M. Wang, and J. Walsh, 2010: Arctic Report Card. NOAA, Pacific Marine Environmental Laboratory, Seattle, WA Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle, WA International Arctic Research Center, Fairbanks, AK October 14, 2010. <http://www.arctic.noaa.gov/reportcard/atmosphere.html>

Pall P., T. Aina, D. Stone, P. Stott, T. Nozawa, A. Hilberts, D. Lohmann, and M. Allen, 2011:

Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature* 2011 Volume: 470, Pages: 382–385 doi:10.1038/nature09762

Parry, M.L., O.F. Canziani, J.P. Palutikof and Co-authors, 2007: Technical Summary. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 23-78.

Peterson, T.C., D.M. Anderson, S.J. Cohen, M. Cortez-Vázquez, R.J. Murnane, C. Parmesan, D. Phillips, R.S. Pulwarty, J.M.R. Stone, 2008: Why Weather and Climate Extremes Matter in *Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands*. T.R. Karl, G.A. Meehl, C.D. Miller, S.J. Hassol, A.M. Waple, and W.L. Murray (eds.). A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC.

Pryor, S. C., R. J. Barthelmie, D. T. Young, E. S. Takle, R. W. Arritt, D. Flory, W. J. Gutowski Jr., A. Nunes, and J. Roads (2009), Wind speed trends over the contiguous United States, *J. Geophys. Res.*, 114, D14105, doi:10.1029/2008JD011416.
<http://www.agu.org/pubs/crossref/2009/2008JD011416.shtml>

Rao, Suryachandra A., Hemantkumar S. Chaudhari, Samir Pokhrel, B. N. Goswami, 2010: Unusual Central Indian Drought of Summer Monsoon 2008: Role of Southern Tropical Indian Ocean Warming. *J. Climate*, 23, 5163–5174. doi: 10.1175/2010JCLI3257.1

Schär, C., P. Vidale, D. Luthi, C. Frei, C. Haberli, M. A. Liniger, and C. Appenzeller, 2004: The role of increasing temperature variability in European summer heatwaves. *Nature* 2004.
<http://dx.doi.org/10.1038/nature02300>

Seager, R., Y. Kushnir, J. Nakamura, M. Ting, and N. Naik, 2010: Northern Hemisphere winter snow anomalies: ENSO, NAO and the winter of 2009/10, *Geophys. Res. Lett.*, 37, L14703, doi:10.1029/2010GL043830

Solomon, S., D. Qin, M. Manning, R.B. Alley, T. Berntsen, N.L. Bindoff, Z. Chen, A. Chidthaisong, J.M. Gregory, G.C. Hegerl, M. Heimann, B. Hewitson, B.J. Hoskins, F. Joos, J. Jouzel, V. Kattsov, U. Lohmann, T. Matsuno, M. Molina, N. Nicholls, J. Overpeck, G. Raga, V. Ramaswamy, J. Ren, M. Rusticucci, R. Somerville, T.F. Stocker, P. Whetton, R.A. Wood and D. Wratt, 2007: Technical Summary. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Stott, Peter, 2010: *Climate change: how to play our hand? There have always been extremes of weather around the world but evidence suggests human influence is changing the odds*. The Guardian. August 9, 2010.

<http://www.guardian.co.uk/environment/2010/aug/09/climate-change-flooding>

Stott, P.A. , D.A. Stone, and M.R. Allen, 2004: Human Contribution to the European heat wave of 2003. *Nature*, 432(7017), 610-614

Stott, P. A., Gillett, N. P., Hegerl, G. C., Karoly, D. J., Stone, D. A., Zhang, X. and Zwiers, F. , 2010: Detection and attribution of climate change: a regional perspective. *Wiley Interdisciplinary Reviews: Climate Change*, 1: 192–211. doi: 10.1002/wcc.34

Tebaldi, C., K. Hayhoe, J. M. Arblaster, and G. A. Meehl, 2006: Going to the Extremes – An Intercomparison of Model-Simulated Historical and Future Changes in Extreme Events. *Climatic Change*, 2006.

Trapp, R.J., N.S. Diffenbaugh, H.E. Brooks, M.E. Baldwin, E.D. Robinson, and J.S. Pal, 2007: Severe thunderstorm environment frequency during the 21st century caused by anthropogenically enhanced global radiative forcing, *PNAS* 104 no. 50, 19719-19723, Dec. 11, 2007.

Trenberth, K.E., P.D. Jones, P. Ambenje, R. Bojariu, D. Easterling, A. Klein Tank, D. Parker, F. Rahimzadeh, J.A. Renwick, M. Rusticucci, B. Soden and P. Zhai, 2007: Chapter 3, Observations: Surface and Atmospheric Climate Change. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Trenberth, K. E., 1999: The extreme weather events of 1997 and 1998. *Consequences*, 5, 1, 2–15. <http://www.gcrio.org/CONSEQUENCES/vol5no1/extreme.html>

Trenberth, K., 2010: *Tennessee Floods Demonstrate Potential Impacts of Climate Change*. Project on Climate Science. May 5, 2010. <http://theprojectonclimatescience.org/press-room/tennessee-floods-demonstrate-potential-impacts-of-climate-change/>

Trenberth, K. E., 2011: Changes in precipitation with climate change. *Climate Research*. doi:10.3354/cr00953, in press.

Trewin, B. and H. Vermont, 2010: Changes in the frequency of record temperatures in Australia, 1957-2009. *Australian Meteorological and Oceanographic Journal*, 60, 113-119.

Vautard, R., Cattiaux, J., Yiou, P, Thépaut, J., and Ciais, P. Northern Hemisphere atmospheric stilling partly attributed to an increase in surface roughness. *Nature Geoscience* 3, 756–761 (2010) doi:10.1038/ngeo979. <http://www.nature.com/ngeo/journal/v3/n11/full/ngeo979.html>

Vavrus, S., J. Walsh, W. Chapman, and D. Portis, 2006: The behavior of extreme cold air outbreaks under greenhouse warming. *Int. J. Climatol.* 26: 1133–1147 (2006) DOI: 10.1002/joc.1301

Weider, K., and D. F. Boutt (2010): Heterogeneous water table response to climate revealed by 60 years of ground water data, *Geophys. Res. Lett.*, 37, L24405, doi:10.1029/2010GL045561.

Wentz, F., L. Ricciardulli, K. Hilburn, and C. Mears, 2007: How Much More Rain Will Global Warming Bring? *Science* 13 July 2007: 317 (5835), 233-235. Published online 31 May 2007 [DOI:10.1126/science.1140746]

Wergen, G. and J. Krug, 2010: Record-breaking temperatures reveal a warming climate. *Europhysics Letters*, Volume 92, Issue 3, pp. 30008 (2010). DOI: 10.1209/0295-5075/92/30008
Young, I., S. Zieger, A. Babanin: Global Trends in Wind Speed and Wave Height. *Science*. 2011 Mar 24. DOI: 10.1126/science.1197219

Zhang, X., F.W. Zwiers, G.C. Hegerl, F.H. Lambert, N.P. Gillett, S. Solomon, P. Stott and T. Nozawa, 2007: Detection of human influence on 20th century precipitation trends. *Nature*. doi:10.1038/nature06025

Zwiers F., X. Zhang, and Y. Feng, 2010: Anthropogenic Influence on Long Return Period Daily Temperature Extremes at Regional Scales. *Journal of Climate* 2010 doi:10.1175/2010JCLI3908.1