The Science of Climate Change Explained: Facts, Evidence and Proof

Definitive answers to the big questions.

Photo Illustration by Andrea D'Aquino

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The science of climate change is more solid and widely agreed upon than you might think. But the scope of the topic, as well as rampant disinformation, can make it hard to separate fact from fiction. Here, we've done our best to present you with not only the most accurate scientific information, but also an explanation of how we know it.

- How do we know climate change is really happening?
- How much agreement is there among scientists about climate change?
- Do we really only have 150 years of climate data? How is that enough to tell us about centuries of change?
- How do we know climate change is caused by humans?
- Since greenhouse gases occur naturally, how do we know they're causing Earth's temperature to rise?
- Why should we be worried that the planet has warmed 2°F since the 1800s?
- Is climate change a part of the planet's natural warming and cooling cycles?
- How do we know global warming is not because of the sun or volcanoes?
- How can winters and certain places be getting colder if the planet is warming?
- Wildfires and bad weather have always happened. How do we know there's a connection to climate change?
- How bad are the effects of climate change going to be?
- What will it cost to do something about climate change, versus doing nothing?

1.

How do we know climate change is really happening?

Climate change is often cast as a prediction made by complicated computer models. But the scientific basis for climate change is much broader, and models are actually only one part of it (and, for what it's worth, they're surprisingly accurate).

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For more than a century, scientists have understood the basic physics behind why greenhouse gases like carbon dioxide cause warming. These gases make up just a small fraction of the atmosphere but exert outsized control on Earth's climate by trapping some of the planet's heat before it escapes into space. This greenhouse effect is important: It's why a planet so far from the sun has liquid water and life!

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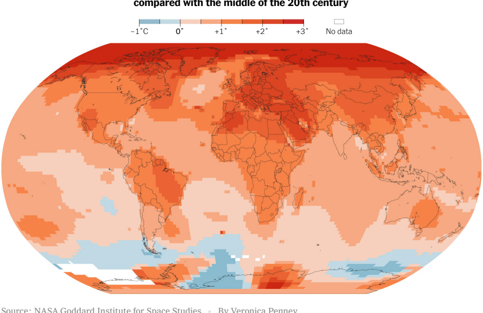
However, during the Industrial Revolution, people started burning coal and other fossil fuels to power factories, smelters and steam engines, which added more greenhouse gases to the atmosphere. Ever since, human activities have been heating the planet.

We know this is true thanks to an overwhelming body of evidence that begins with temperature measurements taken at weather stations and on ships starting in the mid-1800s. Later, scientists began tracking surface temperatures with satellites and looking for clues about climate change in geologic records. Together, these data all tell the same story: Earth is getting hotter.

Average global temperatures have increased by 2.2 degrees Fahrenheit, or 1.2 degrees Celsius, since 1880, with the greatest changes happening in the late 20th century. Land areas have warmed more than the sea surface and the Arctic has warmed the most — by more than 4 degrees Fahrenheit just since the 1960s. Temperature extremes have also shifted. In the United States, daily record highs now outnumber record lows two-to-one.

Where it was cooler or warmer in 2020 compared with the middle of the 20th century



Source: NASA Goddard Institute for Space Studies • By Veronica Penney

This warming is unprecedented in recent geologic history. A famous illustration, first published in 1998 and often called the hockey-stick graph, shows how temperatures remained fairly flat for centuries (the shaft of the stick) before turning sharply upward (the blade). It's based on data from tree rings, ice cores and other natural indicators. And the basic picture, which has withstood decades of scrutiny from climate scientists and contrarians alike, shows that Earth is hotter today than it's been in at least 1,000 years, and probably much longer.

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In fact, surface temperatures actually mask the true scale of climate change, because the ocean has absorbed 90 percent of the heat trapped by greenhouse gases. Measurements collected over the last six decades by oceanographic expeditions and networks of floating instruments show that every layer of the ocean is warming up. According to one study, the ocean has absorbed as much heat between 1997 and 2015 as it did in the previous 130 years.

We also know that climate change is happening because we see the effects everywhere. Ice sheets and glaciers are shrinking while sea levels are rising. Arctic sea ice is disappearing. In the spring, snow melts sooner and plants flower earlier. Animals are moving to higher elevations and latitudes to find cooler conditions. And droughts, floods and wildfires have all gotten more extreme. Models predicted many of these changes, but observations show they are now coming to pass.

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Where 2020's Record Heat Was Felt the Most
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2.

How much agreement is there among scientists about climate change?

There's no denying that scientists love a good, old-fashioned argument. But when it comes to climate change, there is virtually no debate: Numerous studies have found that more than 90 percent of scientists who study Earth's climate agree that the planet is warming and that humans are the primary cause. Most major scientific bodies, from NASA to the World Meteorological Organization, endorse this view. That's an astounding level of consensus given the contrarian, competitive nature of the scientific enterprise, where questions like what killed the dinosaurs remain bitterly contested.

Scientific agreement about climate change started to emerge in the late 1980s, when the influence of human-caused warming began to rise above natural climate variability. By 1991, two-thirds of earth and atmospheric scientists surveyed for an early consensus study said that they accepted the idea of anthropogenic global warming. And by 1995, the Intergovernmental Panel on Climate Change, a famously conservative body that periodically takes stock of the state of scientific knowledge, concluded that "the balance of evidence suggests that there is a discernible human influence on global climate." Currently, more than 97 percent of publishing climate scientists agree on the existence and cause of climate change (as does nearly 60 percent of the general population of the United States).

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So where did we get the idea that there's still debate about climate change? A lot of it came from coordinated messaging campaigns by companies and politicians that opposed climate action. Many pushed the narrative that scientists still hadn't made up their minds about climate change, even though that was misleading. Frank Luntz, a Republican consultant, explained the rationale in an infamous 2002 memo to conservative lawmakers: "Should the public come to believe that the scientific issues are settled, their views about global warming will change accordingly," he wrote. Questioning consensus remains a common talking point today, and the 97 percent figure has become something of a lightning rod.

To bolster the falsehood of lingering scientific doubt, some people have pointed to things like the Global Warming Petition Project, which urged the United States government to reject the Kyoto Protocol of 1997, an early international climate agreement. The petition proclaimed that climate change wasn't happening, and even if it were, it wouldn't be bad for humanity. Since 1998, more than 30,000 people with science degrees have signed it. However, nearly 90 percent of them studied something other than Earth, atmospheric or environmental science, and the signatories included just 39 climatologists. Most were engineers, doctors, and others whose training had little to do with the physics of the climate system.

A few well-known researchers remain opposed to the scientific consensus. Some, like Willie Soon, a researcher affiliated with the Harvard-Smithsonian Center for Astrophysics, have ties to the fossil fuel industry. Others do not, but their assertions have not held up under the weight of evidence. At least one prominent skeptic, the physicist Richard Muller, changed his mind after reassessing historical temperature data as part of the Berkeley Earth project. His team's findings essentially confirmed the results he had set out to investigate, and he came away firmly convinced that human activities were warming the planet. "Call me a converted skeptic," he wrote in an Op-Ed for the Times in 2012.

Mr. Luntz, the Republican pollster, has also reversed his position on climate change and now advises politicians on how to motivate climate action.

A final note on uncertainty: Denialists often use it as evidence that climate science isn't settled. However, in science, uncertainty doesn't imply a lack of knowledge. Rather, it's a measure of how well something is known. In the case of climate change, scientists have found a range of possible future changes in temperature, precipitation and other important variables — which will depend largely on how quickly we reduce emissions. But uncertainty does not undermine their confidence that climate change is real and that people are causing it.

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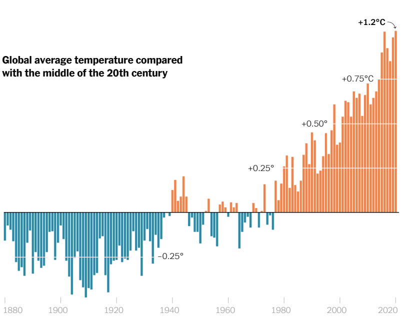
Do we really only have 150 years of climate data? How is that enough to tell us about centuries of change?

Earth's climate is inherently variable. Some years are hot and others are cold, some decades bring more hurricanes than others, some ancient droughts spanned the better part of centuries. Glacial cycles operate over many millenniums. So how can scientists look at data collected over a relatively short period of time and conclude that humans are warming the planet? The answer is that the instrumental temperature data that we have tells us a lot, but it's not all we have to go on.

Historical records stretch back to the 1880s (and often before), when people began to regularly measure temperatures at weather stations and on ships as they traversed the world's oceans. These data show a clear warming trend during the 20th century.



Source: NASA Goddard Institute for Space Studies • By Veronica Penney

Some have questioned whether these records could be skewed, for instance, by the fact that a disproportionate number of weather stations are near cities, which tend to be hotter than surrounding areas as a result of the so-called urban heat island effect. However, researchers regularly correct for these potential biases when reconstructing global temperatures. In addition, warming is corroborated by independent data like satellite observations, which cover the whole planet, and other ways of measuring temperature changes.

Much has also been made of the small dips and pauses that punctuate the rising temperature trend of the last 150 years. But these are just the result of natural climate variability or other human activities that temporarily counteract greenhouse warming. For instance, in the mid-1900s, internal climate dynamics and light-blocking pollution from coal-fired power plants halted global warming for a few decades. (Eventually, rising greenhouse gases and pollution-control laws caused the planet to start heating up again.) Likewise, the so-called warming hiatus of the 2000s was partly a result of natural climate variability that allowed more heat to enter the ocean rather than warm the atmosphere. The years since have been the hottest on record.

Still, could the entire 20th century just be one big natural climate wiggle? To address that question, we can look at other kinds of data that give a longer perspective. Researchers have used geologic records like tree rings, ice cores, corals and sediments that preserve information about prehistoric climates to extend the climate record. The resulting picture of global temperature change is basically flat for centuries, then turns sharply upward over the last 150 years. It has been a target of climate denialists for decades. However, study after study has confirmed the results, which show that the planet hasn't been this hot in at least 1,000 years, and probably longer.

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How do we know climate change is caused by humans?

Scientists have studied past climate changes to understand the factors that can cause the planet to warm or cool. The big ones are changes in solar energy, ocean circulation, volcanic activity and the amount of greenhouse gases in the atmosphere. And they have each played a role at times.

For example, 300 years ago, a combination of reduced solar output and increased volcanic activity cooled parts of the planet enough that Londoners regularly ice skated on the Thames. About 12,000 years ago, major changes in Atlantic circulation plunged the Northern Hemisphere into a frigid state. And 56 million years ago, a giant burst of greenhouse gases, from volcanic activity or vast deposits of methane (or both), abruptly warmed the planet by at least 9 degrees Fahrenheit, scrambling the climate, choking the oceans and triggering mass extinctions.

In trying to determine the cause of current climate changes, scientists have looked at all of these factors. The first three have varied a bit over the last few centuries and they have quite likely had modest effects on climate, particularly before 1950. But they cannot account for the planet's rapidly rising temperature, especially in the second half of the 20th century, when solar output actually declined and volcanic eruptions exerted a cooling effect.

That warming is best explained by rising greenhouse gas concentrations. Greenhouse gases have a powerful effect on climate (see the next question for why). And since the Industrial Revolution, humans have been adding more of them to the atmosphere, primarily by extracting and burning fossil fuels like coal, oil and gas, which releases carbon dioxide.

Bubbles of ancient air trapped in ice show that, before about 1750, the concentration of carbon dioxide in the atmosphere was roughly 280 parts per million. It began to rise slowly and crossed the 300 p.p.m. threshold around 1900. CO2 levels then accelerated as cars and electricity became big parts of modern life, recently topping 420 p.p.m. The concentration of methane, the second most important greenhouse gas, has more than doubled. We're now emitting carbon much faster than it was released 56 million years ago.

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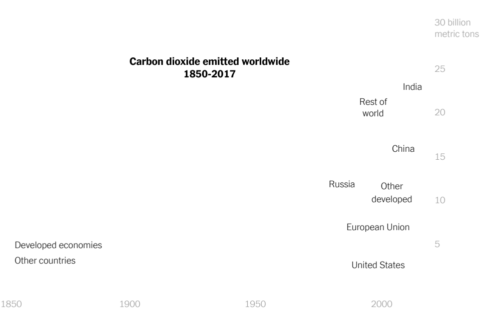

Note: Total carbon dioxide emissions are from fossil fuels and cement production and do not include land use and forestry-related emissions. Russia data includes the Soviet Union through 1991, but only the Russian Federation afterward. • Source: Research Institute for Environment, Energy and Economics at Appalachian State University • By Veronica Penney

These rapid increases in greenhouse gases have caused the climate to warm abruptly. In fact, climate models suggest that greenhouse warming can explain virtually all of the temperature change since 1950. According to the most recent report by the Intergovernmental Panel on Climate Change, which assesses published scientific literature, natural drivers and internal climate variability can only explain a small fraction of late-20th century warming.

Another study put it this way: The odds of current warming occurring without anthropogenic greenhouse gas emissions are less than 1 in 100,000.

But greenhouse gases aren't the only climate-altering compounds people put into the air. Burning fossil fuels also produces particulate pollution called soot particles and coals the planet. Scientists estimate that this pollution has resulted in one-half of the greenhouse warming we would have experienced.

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Since greenhouse gases occur naturally, how do we know they're causing Earth's temperature to rise?

Greenhouse gases like water vapor and carbon dioxide serve an important role in the climate. Without them, Earth would be far too cold to maintain liquid water and humans would not exist!

Here's how it works: the planet's temperature is basically a function of the energy the Earth absorbs from the sun (which heats it up) and the energy Earth emits to space as infrared radiation (which cools it down). Because of their molecular structures, greenhouse gases absorb and re-emit the Earth's outgoing infrared radiation and then re-emit it in all directions, sending some of that energy back toward the surface and heating the planet. Scientists have understood this process since the 1850s.

Greenhouse gas concentrations have varied naturally in the past. Ice core samples show that they have fluctuated over time, depending on how much of the gas volcanoes belched into the air and how much gas removed through geologic processes. On time scales of hundreds to thousands of years, concentrations have changed at surfaces has cycled between the ocean, soil and air.

Today, however, we are the ones causing CO2 levels to increase at an unprecedented pace by taking ancient carbon from geologic storage and putting it into the air. Atmospheric concentrations of CO2 have been. Since 1750, carbon dioxide concentrations have increased by almost 50 percent. Methane and nitrous oxide, other important anthropogenic greenhouse gases have also increased mainly by agricultural activities, but also spiked over the last 250 years.

We know based on ice cores and direct observations that this should cause the climate to warm. We also see certain telltale "fingerprints" of greenhouse warming. For example, nights are warming even faster than days because greenhouse gases don't go "to sleep" when the sun goes down. Nighttime temperatures have actually cooled, because heat energy is being trapped by greenhouse gases in the lower atmosphere.

We also know that we are the cause of rising greenhouse gas concentrations — and not just because we can measure the CO2 we put into the air from our tailpipes and smokestacks. We can see it in the chemical signature of the carbon in CO2.

Carbon comes in three different isotopes: 12, 13 and 14. Things made of carbon-containing fossil fuels(coal to have relatively less carbon-13. Volcanoes tend to produce CO2 with relatively more carbon-13. And over the last century, the carbon in atmospheric CO2 has gotten lighter, pointing to an organic source.

We can tell it's all organic matter by looking for carbon-14, which is radioactive and decays over time. Fossil fuels are too ancient to have any carbon-14 left in them. So when we burn fossil fuels to CO2 levels, you would expect the amount of carbon-14 in the atmosphere to drop, which is exactly what the data show.

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Why should we be worried that the planet has warmed 2°F since the 1850s?

Two degrees doesn't sound like much, but it comes to climate changes is the difference between weather and climate. Weather is the constantly changing set of meteorological conditions that we experience when we step outside, whereas climate is the long-term average of these conditions, usually calculated over a 30-year period, such as same-day. Weather is your mood and climate is your personality.

So while 2 degrees Fahrenheit doesn't represent a big change in the weather, it's a huge change in climate. As we've already seen, it's enough to melt ice and raise sea levels, to shift rainfall patterns and to make the world hotter and more humid, causing more extreme heat waves (and weather hazards and lethal times by the million.

Climate change also affects the ocean, causing it to become more global overall, and many parts of the world have already warmed by more than that. For example, land areas have warmed about twice as much as the sea surface. And the Arctic has warmed by about 5 degrees. That's because the loss of snow and ice at high latitudes exposes more land and ocean surface, thereby adding additional heating on top of greenhouse warming.

Relatively small long-term changes in climate averages also shift extremes in significant ways. For instance, most people are happy happened, but they have shattered records in recent years. In June of 2016, a record-breaking international temperature of 166 degrees. And in Australia, meteorologists have added a new color to their weather maps to accommodate temperatures hotter than 125 degrees. Rising sea levels have also increased the risk of flooding because of storm surges and high tides. These are the foreshocks of climate change.

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Is climate change a part of the planet's natural warming and cooling cycles?

Earth's climate has always changed. Hundreds of millions of years ago, the oceans shifted from. Fifty million years ago, alligators lived in what we now call the Arctic. And for the last 14 million years, the planet has cycled between ice ages when the planet was up to 5 degrees Celsius (9 degrees Fahrenheit) colder than today and Europe, and other unexplored periods like the one we're in now.

Climate denialists often point to these natural climate changes as a way to cast doubt on the idea that humans are causing climate to change. But there's a problem with this argument: it's like saying a house fire can't be caused by anything but people because sometimes the house burns down in the past, caused by a wide variety of natural causes." A case of social scientists wrote in The Debunking Handbook, which explains the misinformation strategies behind many climate myths.

Indeed, we know that different mechanisms caused the climate to change in the past. Ice ages, for instance, are caused by gradual periodic variations in Earth's orbit, which take place over tens of thousands of years and change how solar energy gets distributed around the globe and across the seasons.

These orbital variations don't affect the planet's temperature much on their own. But they set off a cascade of other changes in the climate system, for instance, growing or melting vast Northern Hemisphere ice sheets. These ice sheets themselves are big changes, in turn, affect climate by altering the amount of snow and ice, which reflect sunlight, and by changing greenhouse gas concentrations. The ice ages of the past show how tiny greenhouse gases have the ability to significantly affect Earth's temperature.

Put at least the last 800,000 years, atmospheric CO2 concentrations oscillated between about 180 parts per million during ice ages and about 280 p.p.m. during interglacial periods, as carbon moved between oceans, forests, soils and the atmosphere. These changes occurred at the pace of the planet's orbital cycles, and they amplified the entire planet warmed and cooled during glacial cycles, not just the tiny poles.

Today, however, CO2 levels have soared to 410 p.p.m. — the highest they've been in at least three million years. The concentration of CO2 in the atmosphere is now 47 percent higher than it was at the start of the last ice age. That degree something other is going on, and we know what it is. Since the Industrial Revolution, humans have been burning fossil fuels and releasing greenhouse gases that are heating the planet now over Decades.) for more details on how we know that the current warming is due to more than other natural factors and it's limited.

Over the next century or two, scientists and ecosystems will experience the consequences of this climate change. But our emissions will have even more lasting geologic impacts. According to a study in the Proceedings of the National Academy of Sciences, the planet enough to delay the onset of the next glacial cycle by at least an additional 50,000 years.

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How do we know global warming is not because of the sun or volcanoes?

The sun is the ultimate source of energy in Earth's climate system, so it's a natural candidate for causing climate change. And solar activity has been tracked by a variety of ways, including direct measurements and other astronomical observations that the sun's output changes on 11-year cycles. Geologic records and tomper markers, which astronomers have tracked for centuries, also show long-term variations in the sun's activity, including some exceptionally quiet periods in the late 1600s and early 1800s.

We know that, from 1890 until the 1950s, solar irradiance increased, and it contributed to the warming of the planet. But since 1950, the exact climate, continuing up to 50 percent of the warming that's occurred since the late 1800s. However, in the second half of the 20th century, the sun's output has been flat or even slightly declining. This disparity is one of the main reasons we know that the sun is not the driving force behind climate change.

Another reason we know that solar activity hasn't caused recent warming is that, if it had, all the layers of the atmosphere should be heating up. Instead, data show that the opposite atmosphere has actually cooled in recent decades — a hallmark of greenhouse warming.

So have about volcanoes? Eruptions cool the planet by injecting ash and particles into the air, which block incoming sunlight. We've observed this effect for years following large eruptions. There are also some notable historical examples, like when Iceland's Lakí volcano erupted in 1783, causing widespread crop failures in Europe and beyond, and the "Year Without a Summer" when a volcano in Indonesia blew in 1815 and caused global cooling.

Since volcanoes mainly act on climate centers, they can't really explain recent warming. However, scientists say that they may also have contributed slightly to rising temperatures in the early 20th century. That's because there were several large eruptions in the 1900s, which put enough particles into the air to cool the planet with no major volcanic events either warming caught up. During the second half of the 20th century, though, several big eruptions occurred in the planet warming kept on. Everything, they temporarily masked some amount of human-caused warming.

Climate change also affects volcanoes, and there's some concern that it may increase the frequency and intensity of certain eruptions. Ice melt, for instance, some studies suggest that climate change may be to blame. Ice melt possibility is that rapid Arctic warming has affected atmospheric circulation, including the Jet Stream, in ways that have made it more wavy. When the Jet Stream is wavy, it can trap weather patterns in place, which can lead to prolonged droughts and heavy rainfall. Some studies have suggested that these patterns have also increased the intensity of heavy rainfall events, which can stress volcanoes and trigger eruptions. The science is still in its infancy, however, and there's not yet a consensus.

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How can winters and certain places be getting colder if the planet is warming?

When a big snowstorm hits the United States, climate denialists can't ty it is a proof that climate change isn't happening. In 2015, Senator James Inhofe, an Oklahoma Republican, famously lobbed a snowball on the Senate as he denounced climate science. But these events don't actually disprove climate change.

While there have been some remarkable stories in recent years, winters are actually warming across the world. In the United States, for instance, average temperatures in December and February have increased by about 2.5 degrees 21st century.

On the flip side, record-cold days are becoming less common than record-warm days. In the United States, record-high-low outnumber record lows by two-to-one. And ever smaller areas of the planet experience record-cold temperatures. (The same trends are happening globally.)

So what's with the blizzards? Weather always varies, so it's no surprise that we still have extreme winter storms even as average temperatures rise. However, some studies suggest that climate change may be to blame. One possibility is that rapid Arctic warming has affected atmospheric circulation, including the Jet Stream, in ways that have made it more wavy. When the Jet Stream is wavy, it can trap weather patterns in place, which can lead to prolonged droughts and heavy rainfall. Some studies have suggested that these patterns have also increased the intensity of heavy rainfall events, which can stress and trigger eruptions. The science is still in its infancy, however, and there's not yet a consensus.

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Wildfires and bad weather have always happened. How do we know there's a connection to climate change?

Extreme weather and natural disasters are part of life on Earth — and they have been long before humans arrived on the scene. Climate models project that, by the 2050s, heat waves will be about 12 times more frequent. And that's concerning since extreme heat often causes increased hospitalizations and deaths, particularly among older people and those with underlying health conditions. Heat waves are the deadliest form of weather, almost 30 percent more severe because of climate change. It was the never drought the region had experienced in more than 1,000 years.

Rising temperatures have also increased the intensity of heavy precipitation events in many parts of the world. In 2017, for example, studies have found that, because warmer air holds more moisture, Hurricane Harvey, which struck Houston in 2017, dropped between 15 and 40 percent more rainfall than it would have without climate change.

It's still unclear whether climate change is changing the overall frequency of hurricanes, but it is making them stronger. And rising temperatures have also increased the intensity of storms like the "Derecho Series" of storms that caused devastating flooding across the Midwest in 2020.

Let's start with heat waves. Studies show that stretches of abnormally high temperatures now happen about five times more frequently than they would without climate change, and they last about two Chinese models project that, by the 2050s, heat waves will be about 12 times more frequent. And that's concerning since extreme heat often causes increased hospitalizations and deaths, particularly among older people and those with underlying health conditions. Heat waves are the deadliest form of weather, almost 30 percent more severe because of climate change. It was the never drought the region had experienced in more than 1,000 years.

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It's important to remember that in most natural disasters, there are multiple factors at play. For instance, the 2019 Midwest floods were caused by a combination of factors, including heavy precipitating the spring and heavy snowpack melting rapidly into the Missouri and Mississippi Rivers. These waterways have a long history of flooding, and there's no single cause of flooding.

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some of which failed in the floods.

Wildfires are another phenomenon with multiple causes. In many places, fire risk has increased because humans have aggressively fought natural fires and prevented Indigenous peoples from carrying out traditional burning practices. This has allowed fuel to accumulate that makes current fires worse.

However, climate change still plays a major role by heating and drying forests, turning them into tinderboxes. Studies show that warming is the driving factor behind the recent increases in wildfires; one analysis found that climate change is responsible for doubling the area burned across the American West between 1984 and 2015. And researchers say that warming will only make fires bigger and more dangerous in the future.

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How bad are the effects of climate change going to be?

It depends on how aggressively we act to address climate change. If we continue with business as usual, by the end of the century, it will be too hot to go outside during heat waves in the Middle East and South Asia. Droughts will grip Central America, the Mediterranean and southern Africa. And many island nations and low-lying areas, from Texas to Bangladesh, will be overtaken by rising seas. Conversely, climate change could bring welcome warming and extended growing seasons to the upper Midwest, Canada, the Nordic countries and Russia. Farther north, however, the loss of snow, ice and permafrost will upend the traditions of Indigenous peoples and threaten infrastructure.

It's complicated, but the underlying message is simple: unchecked climate change will likely exacerbate existing inequalities. At a national level, poorer countries will be hit hardest, even though they have historically emitted only a fraction of the greenhouse gases that cause warming. That's because many less developed countries tend to be in tropical regions where additional warming will make the climate increasingly intolerable for humans and crops. These nations also often have greater vulnerabilities, like large coastal populations and people living in improvised housing that is easily damaged in storms. And they have fewer resources to adapt, which will require expensive measures like redesigning cities, engineering coastlines and changing how people grow food.

Already, between 1961 and 2000, climate change appears to have harmed the economies of the poorest countries while boosting the fortunes of the wealthiest nations that have done the most to cause the problem, making the global wealth gap 25 percent bigger than it would otherwise have been. Similarly, the Global Climate Risk Index found that lower income countries — like Myanmar, Haiti and Nepal — rank high on the list of nations most affected by extreme weather between 1999 and 2018. Climate change has also contributed to increased human migration, which is expected to increase significantly.

Even within wealthy countries, the poor and marginalized will suffer the most. People with more resources have greater buffers, like air-conditioners to keep their houses cool during dangerous heat waves, and the means to pay the resulting energy bills. They also have an easier time evacuating their homes before disasters, and recovering afterward. Lower income people have fewer of these advantages, and they are also more likely to live in hotter neighborhoods and work outdoors, where they face the brunt of climate change.

These inequalities will play out on an individual, community, and regional level. A 2017 analysis of the U.S. found that, under business as usual, the poorest one-third of counties, which are concentrated in the South, will experience damages totaling as much as 20 percent of gross domestic product, while others, mostly in the northern part of the country, will see modest economic gains. Solomon Hsiang, an economist at University of California, Berkeley, and the lead author of the study, has said that climate change "may result in the largest transfer of wealth from the poor to the rich in the country's history."

Even the climate "winners" will not be immune from all climate impacts, though. Desirable locations will face an influx of migrants. And as the coronavirus pandemic has demonstrated, disasters in one place quickly ripple across our globalized economy. For instance, scientists expect climate change to increase the odds of multiple crop failures occurring at the same time in different places, throwing the world into a food crisis.

On top of that, warmer weather is aiding the spread of infectious diseases and the vectors that transmit them, like ticks and mosquitoes. Research has also identified troubling correlations between rising temperatures and increased interpersonal violence, and climate change is widely recognized as a "threat multiplier" that increases the odds of larger conflicts within and between countries. In other words, climate change will bring many changes that no amount of money can stop. What could help is taking action to limit warming.

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What will it cost to do something about climate change, versus doing nothing?

One of the most common arguments against taking aggressive action to combat climate change is that doing so will kill jobs and cripple the economy. But this implies that there's an alternative in which we pay nothing for climate change. And unfortunately, there isn't. In reality, not tackling climate change will cost a lot, and cause enormous human suffering and ecological damage, while transitioning to a greener economy would benefit many people and ecosystems around the world.

Let's start with how much it will cost to address climate change. To keep warming well below 2 degrees Celsius, the goal of the Paris Climate Agreement, society will have to reach net zero greenhouse gas emissions by the middle of this century. That will require significant investments in things like renewable energy, electric cars and charging infrastructure, not to mention efforts to adapt to hotter temperatures, rising sea-levels and other unavoidable effects of current climate changes. And we'll have to make changes fast.

Estimates of the cost vary widely. One recent study found that keeping warming to 2 degrees Celsius would require a total investment of between $4 trillion and $60 trillion, with a median estimate of $16 trillion, while keeping warming to 1.5 degrees Celsius could cost between $10 trillion and $100 trillion, with a median estimate of $30 trillion. (For reference, the entire world economy was about $88 trillion in 2019.) Other studies have found that reaching net zero will require annual investments ranging from less than 1.5 percent of global gross domestic product to as much as 4 percent. That's a lot, but within the range of historical energy investments in countries like the U.S.

Now, let's consider the costs of unchecked climate change, which will fall hardest on the most vulnerable. These include damage to property and infrastructure from sea-level rise and extreme weather, death and sickness linked to natural disasters, pollution and infectious disease, reduced agricultural yields and lost labor productivity because of rising temperatures, decreased water availability and increased energy costs, and species extinction and habitat destruction. Dr. Hsiang, the U.C. Berkeley economist, describes it as "death by a thousand cuts."

As a result, climate damages are hard to quantify. Moody's Analytics estimates that even 2 degrees Celsius of warming will cost the world $69 trillion by 2100, and economists expect the toll to keep rising with the temperature. In a recent survey, economists estimated the cost would equal 5 percent of global G.D.P. at 3 degrees Celsius of warming (our trajectory under current policies) and 10 percent for 5 degrees Celsius. Other research indicates that, if current warming trends continue, global G.D.P. per capita will decrease between 7 percent and 23 percent by the end of the century — an economic blow equivalent to multiple coronavirus pandemics every year. And some fear these are vast underestimates.

Already, studies suggest that climate change has slashed incomes in the poorest countries by as much as 30 percent and reduced global agricultural productivity by 21 percent since 1961. Extreme weather events have also racked up a large bill. In 2020, in the United States alone, climate-related disasters like hurricanes, droughts, and wildfires caused nearly $100 billion in damages to businesses, property and infrastructure, compared to an average of $18 billion per year in the 1980s.

Given the steep price of inaction, many economists say that addressing climate change is a better deal. It's like that old saying: an ounce of prevention is worth a pound of cure. In this case, limiting warming will greatly reduce future damage and inequality caused by climate change. It will also produce so-called co-benefits, like saving one million lives every year by reducing air pollution, and millions more from eating healthier, climate-friendly diets. Some studies even find that meeting the Paris Agreement goals could create jobs and increase global G.D.P. And, of course, reining in climate change will spare many species and ecosystems upon which humans depend — and which many people believe to have their own innate value.

The challenge is that we need to reduce emissions now to avoid damages later, which requires big investments over the next few decades. And the longer we delay, the more we will pay to meet the Paris goals. One recent analysis found that reaching net-zero by 2050 would cost the U.S. almost twice as much if we waited until 2030 instead of acting now. But even if we miss the Paris target, the economics still make a strong case for climate action, because every additional degree of warming will cost us more — in dollars, and in lives.

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