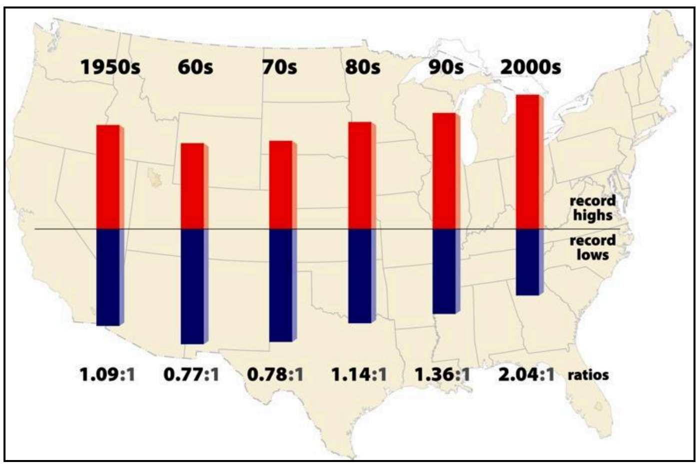
A primer on climate change

The Greenhouse Effect

- A lab demo of the heat-trapping properties of CO_2 (2:19) https://www.youtube.com/watch?v=Ge0jhYDcazY

Heat energy that has been reflected by Earth's surface is absorbed by gases in the atmosphere. This is known as the greenhouse effect. The greenhouse gases that absorb heat energy include water (H_2O), carbon dioxide (CO_2), methane, and a number of other less important ones. Together they make up about 1% of the atmosphere. Without these gases, Earth's average temperature would be around -18˚C, the same as on the moon. When the greenhouse gases stay at stable levels in our atmosphere, the global climate stays stable. When their levels drop enough, we get an ice age. For the past hundred years, human activity has been increasing the levels of greenhouse gases. As a result, the planet is warming.



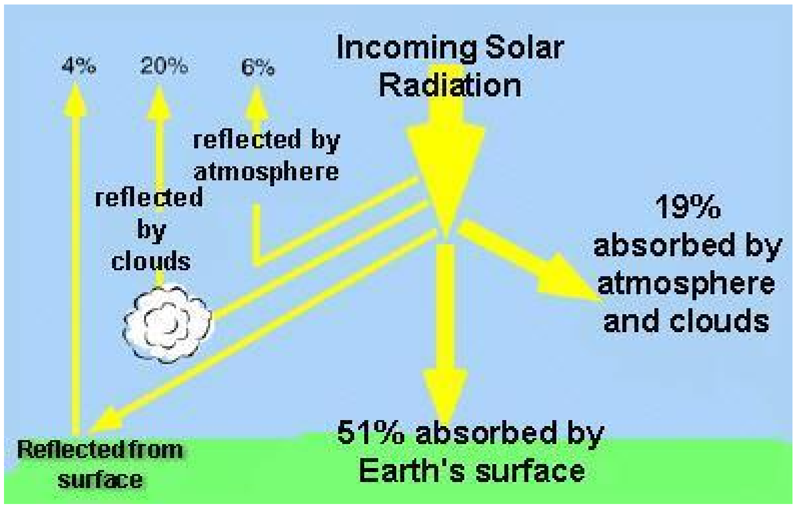
The ratio of record highs to record lows in the US each decade since the 1950s. What do these changes tell us?

The average global temperature has already risen by about 1.5˚F. That might seem like a small change, but it is actually a significant increase. In the past, a one- to two-degree drop was all it took to plunge the Earth into the Little Ice Age. A five-degree drop was enough to bury a large part of North America under a towering mass of ice 20,000 years ago.

Sunlight, or solar radiation, is one portion of the radiation given off by the sun. It mostly consists of infrared and visible light, and a small amount of ultraviolet light. When solar radiation reaches Earth's atmosphere, oceans and land, some of it is absorbed, and warms the surfaces it strikes. Some of it is re-radiated back into the air as infrared radiation (IR). You have probably seen a heat lamp warming food in a cafeteria. The heat lamp is using IR to heat the food.

Greenhouse gases don't block light, but they do absorb IR. They also re-emit it. When IR hits a greenhouse gas molecule, the molecule absorbs the energy. It becomes excited, vibrates, then re-emits or releases the energy in all directions. The higher the concentration of greenhouse gases, the higher the chances are that the heat energy released by one molecule will hit and be absorbed by another. This results in heat being trapped in the atmosphere. Eventually the heat energy escapes to space. However, not enough escapes to balance the amount that is being trapped by excess greenhouse gases.

Scientists have mapped Earth's "energy budget" to account for the greenhouse effect. Earth's land and ocean *surfaces receive almost twice as much energy from the greenhouse effect than they do directly from the Sun!*



Earth's energy inputs and outputs.
Image Source: solpass.org

In systems terms. Think of the atmosphere as a bathtub. The flow of energy from the faucet into the tub (solar radiation) has not changed. However, the water level in the tub is rising (because heat contained in the atmosphere is increasing. You can think of the bathtub "drain" being clogged by greenhouse gases. This means that the draining of heat from the bathtub through the drain (heat escaping back into space) cannot keep up with the rate of inflow from the faucet of the sun.

More information

To learn more about the **Greenhouse Effect**, check out these resources:

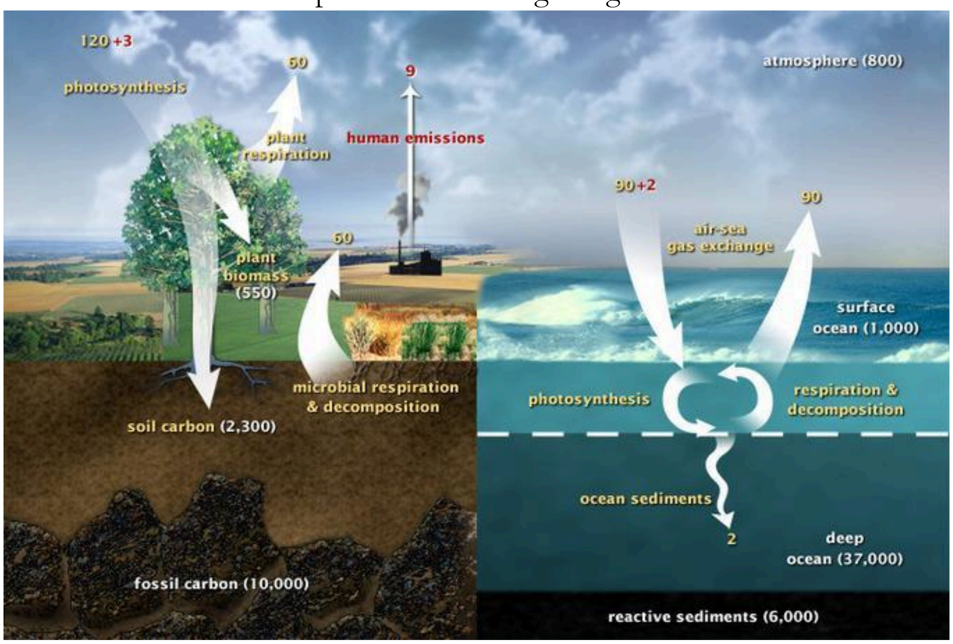
- Iain Stewart demonstrates how CO_2 can absorb and block heat using an IR camera and a candle (1:08)
  https://www.youtube.com/watch?v=Ot5n9m4whaw

- This interactive simulation uses a molecular model to show the impact of greenhouse gas concentration on temperature. It shows "sunlight photons" and "infrared photons" as the sources of solar energy in the system. A final interactive shows how different greenhouse gases react when hit by both types of photons (~10:00)
  https://phet.colorado.edu/en/simulation/legacy/greenhouse

The Carbon Cycle

- Play this game to follow a carbon atom through the carbon cycle:
https://www.windows2universe.org/earth/climate/carbon_cycle.html

Carbon moves through Earth's systems in various chemical forms. The carbon cycle describes how carbon flows through the living and non-living components of Earth systems. The **atmosphere** is an important carbon reservoir, even though CO_2 makes up a very small percent of its total volume. CO_2 and methane are two of the most important greenhouse gases in affecting changes in Earth's temperature. Carbon is the main component of all living things.



Carbon cycling. Numbers show amount of carbon cycled per year in billions of tons.
Image source: Adapted from US DOE.

We know that humans are adding CO_2 to the atmosphere through burning fossil fuels. How is CO_2 removed from the atmosphere? CO_2 is removed from the atmosphere through several different processes.

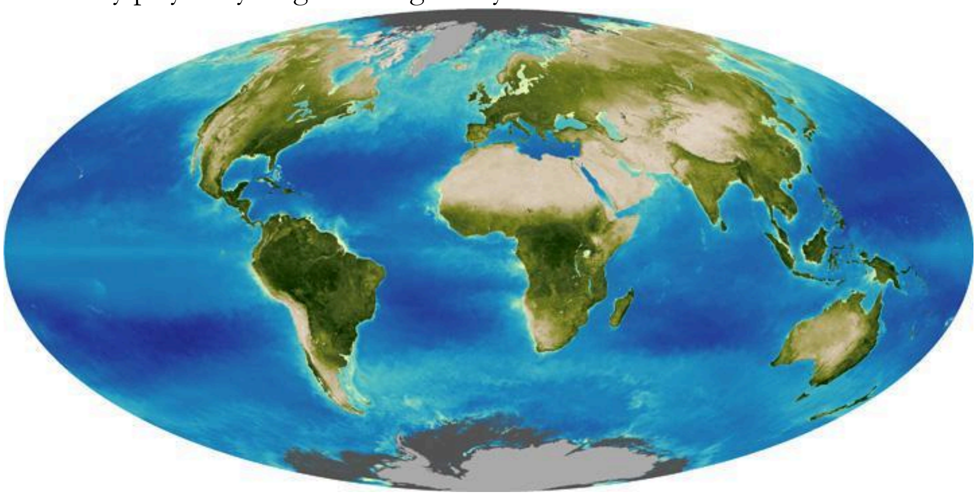
1) **Green plants** form the biggest carbon reservoir. Plants and algae take in CO_2 and emit oxygen during photosynthesis. During this process, sunlight provides the energy to combine carbon from the air and hydrogen from water to create glucose. The plant turns glucose into other molecules as it grows and uses them to build leaves, roots, trunk, and flowers. **Almost the entire mass of a huge oak tree comes entirely from the air!** The soil provides water and a few trace elements only.

What are trees made out of?

If you had asked me yesterday, I would have guessed that trees absorb raw materials from the ground through their roots, and use them to build new branches and roots as the tree grows. Or, perhaps trees are constructed by hardworking but underpaid gnomes and fairies during the night.

As it happens, that's not the case. Although roots take up a small amount of important nutrients, the majority of the mass of a tree is created from carbon dioxide absorbed from the air by the tree's leaves. That's right. It sounds crazy, but trees are mostly made out of air, and fairies aren't even involved.
©2017 Drew Olbrich (http://www.coolsciencefacts.com/2007/trees.html)

Look at the extent of plants across the globe in the image below. This will show you just how important a role they play in cycling carbon globally.



The distribution of terrestrial plants (green) and ocean algae (dark blue) indicated by satellite measurements of chlorophyll. NASA Earth Observatory.

Most of the organisms that don't photosynthesize get their carbon by eating organisms that do. This means that CO_2 from the air is the foundation of most food webs on the planet. Animals, like us, release a lot of CO_2 when we breathe out. In fact, by lunchtime, you are very likely exhaling a lot of the carbon that was contained in your breakfast! Besides releasing CO_2 through respiration, livestock also release carbon as methane (CH_4) by burping and farting.

2) Some CO_2 is also removed from the atmosphere through **dissolving in surface water**, forming carbonic acid. Since CO_2 also dissolves in water droplets in clouds, it is removed from the atmosphere when it rains.

3) Over time, carbonic acid in rain reacts with minerals in exposed rock. Called "weathering," this reaction forms various soil compounds, including new clay minerals. When calcium is dissolved in water with carbonic acid, and precipitated ocean or freshwater, limestone is formed by sedimentation and compression. **Limestone** is an important carbon reservoir. Though the process is slow, limestones store a significant amount of carbon, and do not give up the carbon again easily.

4) When organisms die and rot, they release CO_2 and methane. Much of the carbon in dead organisms either falls to the **bottom of the ocean**, or is stored in the **soil**. These are two significant carbon reservoirs. Wildfires also release some of the carbon in dead plant matter.

Before the rise of industry, carbon taken up by plants was generally balanced by natural emissions. Today photosynthesis removes about a quarter of our CO_2 emissions. About a quarter of our emissions are currently removed by dissolving in the ocean. This will not continue forever. There is a limit to how much more the oceans can hold.

In systems terms. Our emissions are moving carbon from the land component – fossil fuels – into another component – the atmosphere. In carbon cycle terms, fossil fuel and greenhouse gases both represent "reservoirs" of carbon. Emissions represent "flows" of carbon.

Evidence for human causes of climate change

- Dr. Richard Alley discusses how we know humans are causing the rise in CO_2 – because O_2 levels have decreased (2:41)
  https://www.youtube.com/watch?v=-PrrTk6DqzE

How do we know that humans are causing the rise in CO_2 levels by burning coal, gasoline, and other fossil fuels? There are several different lines of evidence; here are three.

1. When we burn fossil fuels, the carbon in them combines with oxygen to form CO_2 molecules. That oxygen comes from the atmosphere. This means that levels of oxygen in the atmosphere should be decreasing as we burn fossil fuels. Sure enough, oxygen levels over the past two decades have been dropping at a rate proportional to the increase in CO_2 levels. It's not nearly enough of a drop to cause breathing problems, but it is measurable.

2. There is an easy way to tell whether higher temperatures come from the increase in insulation from greenhouse gases, or from an external source of heat like the sun. Scientists have measured the temperature at different levels of the atmosphere, including the very outer layers. Temperatures are higher in the lowest layers, and lower in the upper layers. This is what we would expect from the extra insulation from greenhouse gases, rather than from extra incoming heat from the sun.

To understand, imagine you're wearing a jacket but are still feeling cold. If someone lights a bonfire near you, the outside of the jacket would warm up before your body feels the heat from the fire. Now imagine that instead of lighting a bonfire, you added a layer of long underwear underneath the jacket. It would trap more heat inside the jacket with you. What would happen to the outside layer of the jacket? Less of your body heat would reach the outer layers of the jacket. This means that the outer layers would be cooler.

3. There are three types of carbon molecules (called isotopes) with different atomic weights: carbon-12, carbon-13 and carbon-14. Carbon-14 is radioactive and dies away to undetectable levels in 50,000 years or so. Fossil fuels, being millions of years old, have no carbon-14 left. If burning fossil fuels is the cause of rising CO_2 levels in the atmosphere, the proportion of carbon-14 in the atmosphere should have decreased. Sure enough, it has. For the last 50 years, as the amount of CO_2 in the atmosphere has increased, its carbon-14 ratio has fallen steadily.

More information
For more information on how we know what's causing the climate to change, check out these links:

- This video from the Union of Concerned Scientists discusses the ways we know that humans are causing the climate to warm (3:14)
  https://www.youtube.com/watch?v=pbBb-SvRFjM

- This video from Earth the Operator's manual provides evidence from analysis of carbon isotopes that rising CO_2 levels are caused by burning fossil fuels (2:41)
  http://earththeoperatorsmanual.com/segment/6

Impacts of climate change

In this video DW English explains some of the impacts of climate change on animals (2:12)

- https://www.youtube.com/watch?v=9h7P8gWpolQ

What sorts of impacts are we likely to see from a rise in global temperatures?

Biotic impacts. Global warming has an impact on many living things. For example, it has affected the body size of some cold-blooded animal species. Higher temperatures increase the metabolism of cold-blooded animals in general. This means that they need more food to survive, which can be harder to find. This in turn increases the chances that smaller individuals of a species will survive better at higher temperatures than the larger ones. This can lead to a smaller average size of the species over time. The fossil record confirms this. It shows that populations of cold blooded animals of the same species included larger individuals in past cold periods, and smaller ones in past warm periods.

The Baltimore oriole.

Other biotic impacts include changes in seasonal behavior. For example, shrubs and trees flower earlier in spring. Birds migrate earlier than they used to. Scientists have also observed changes in where organisms can live. For example, birds such as the Baltimore oriole, usually found in Virginia, can now be seen in Connecticut and Massachusetts. Global warming will also likely cause some species to go extinct through changes in the physical environment.

Forest fires are increasing with global warming. So are insect infestations of trees, resulting from winters that are no longer cold enough to kill them. Both forest fires and dying trees are reinforcing feedbacks because they add more carbon to the atmosphere. This results in more warming, more fires and more insects.

Also, as soil warms, soil microbes become more active and decomposition speeds up. This emits more CO_2. As more vegetation dies from global warming, there is more dead plant matter to decompose. This is another reinforcing feedback.

Abiotic impacts. Abiotic effects of global warming include melting ice, which contributes to rising sea levels. Patterns of rainfall and snowfall are changing. Other abiotic impacts include heat waves and other extremes in weather such as floods and storms. Carbon dioxide is increasing the acidity of the ocean, since carbon dioxide forms carbonic acid when dissolved in water.

Some biotic effects can also trigger abiotic effects. For example, if a drought causes plants in an area to die off, this can result in a change to the water cycle in that area. This in turn can lead to more droughts in the future.

Sea level rise - What is happening and what should we expect?

- Peter Sinclair and Yale Climate Connections discuss what sea level rise looks like in real life (6:58)

https://www.youtube.com/watch?v=X1hJYLw7OlM

Sea levels have risen 8 inches globally since the start of the 1900s. This is the result of two factors. The first is the expansion of water. Liquid water expands very slightly as the water molecules vibrate more when it warms. The cumulative effect in a large body of water like the ocean is enough to cause a measurable change in sea level. This "thermal expansion" accounts for most of the sea level rise during the 20th century.

The other factor is the polar ice caps on land in Greenland and Antarctica. Each ice mass is over a mile thick in some places, five times taller than the Empire State Building. The ice caps extend for many, many square miles.

Ponds of meltwater form on top of the Greenland ice sheet.
Source: theguardian.com

However, the warmer the climate gets, the faster the ice will melt. If all the ice on Greenland were to melt into the sea, it would result in about six meters (20 feet) of sea level rise. If all of the ice on Antarctica were to melt, sea level would rise about ten times that amount, by 60 meters (200 feet). This level of melting will not happen in the span of one lifetime. There's a good chance that Antarctica wouldn't fully melt for thousands of years. However, expected melting and continued expansion of ocean waters could result in at least 3 feet of sea level rise in the next 80 years.

Sea level rise is already changing coastal ecosystems around the world. Rising seas mean that plants on the shoreline are exposed to more salt water than they can tolerate. Immediate effects of sea level rise include increased erosion of shorelines during storms.

Even a couple of centimeters of sea level rise can be enough to turn a storm surge - the water pushed towards the shore by a big storm - into a very destructive flood. If the water is even one or two millimeters above the top of a floodwall, you might as well have the entire ocean pouring in. Events such as the flooding from Superstorm Sandy in 2012 and Hurricane Irma in 2017 are more and more likely to happen for every inch of sea level rise. Gradual change can have very sudden and dramatic impacts.

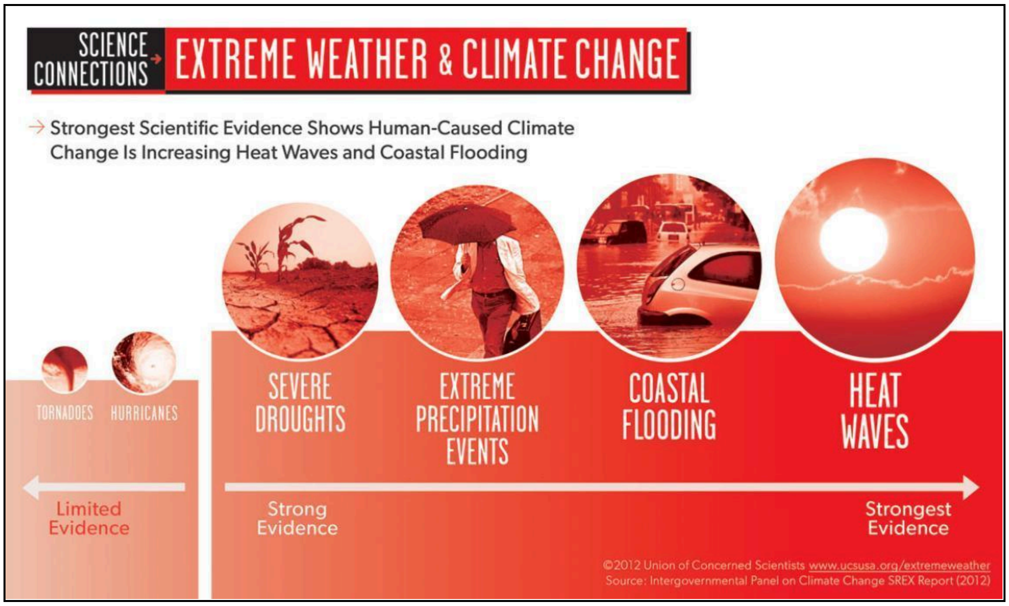
More information

- An interactive map lets you enter a location anywhere in the world to see what different amounts of sea level rise would look like:
  http://sealevel.climatecentral.org/

Extreme Weather

- Climate Central shows how the number of downpours in the U.S. is increasing http://www.climatecentral.org/gallery/graphics/more-us-downpours

Is there a link between extreme weather and climate change? Basic physics suggest that global warming should increase extreme weather since more energy is being added to the atmosphere. Cold weather events should decline, and heat waves should increase. As the atmosphere warms, it also holds more water vapor. This means there should also be changes in the strength and frequency of the dry and wet periods that cause droughts and floods.



Source: Union of Concerned Scientists
http://www.ucsusa.org/global_warming/science_and_impacts/impacts/extreme-weather-climate-change.html#share

However, the Earth's climate system is very complex and variable. For example, natural events like El Niño and La Niña make it difficult to tell if one extreme weather event is due to climate change or not. In addition, extreme weather is rare compared to average weather day-to-day. It can take a long time to see a meaningful trend.

Therefore, it is not possible to tie *individual* weather events to climate change. However, scientists are more and more sure that the *number* of extreme weather events is increasing. The Intergovernmental Panel on Climate Change recently studied all the scientific research on extreme weather. They found strong evidence that the number of extreme cold days around the world is decreasing. The number of extreme hot days is rising. Patterns of rainfall in many regions are changing as well. Surges created by storms are becoming higher. Rainfall and snowfall events are getting more intense.

There is still uncertainty about how much climate change affects hurricanes and tornadoes.

More information

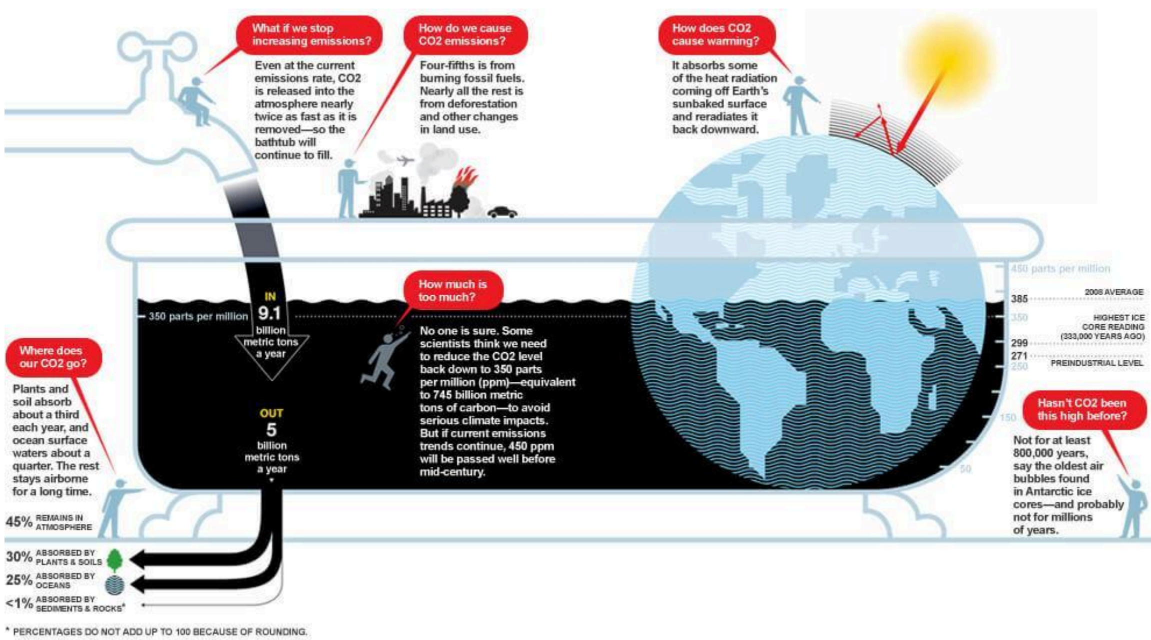
- Stanford scientists talking about extreme weather and climate change (2:55)
  https://www.youtube.com/watch?v=98VrLZFgGMY
- Climate Central shows how the number of very hot days is increasing
  http://www.climatecentral.org/gallery/graphics/number-of-extremely-hot-days-continues-to-rise

Human disruptions of the Carbon cycle

- A Very, Very Simple Climate Model that lets you explore how the rate of carbon emissions affects the level of CO_2 in the atmosphere and Earth's climate (~10:00): https://scied.ucar.edu/simple-climate-model

Clearing land. Growing populations over the last few hundred years have cleared away natural habitats faster and faster. We cut forests for construction material and firewood. We clear space for farming and cities. This has had two results.

First, deforestation from fires released the carbon trapped in the trees and in wood or brush left to rot. Second, land clearing reduces the natural world's capacity to absorb CO_2 by reducing the number of healthy ecosystems and plants that could do so. In addition, these changes in land use have changed the albedo, or reflectivity, of Earth's surface. For example, city surfaces such as tarmac roads and dark roofs reflect far less solar radiation than natural landscapes do. This means more heat is added to the atmosphere in urban areas.



© National Geographic Magazine, Dec 2009.

See http://ngm.nationalgeographic.com/big-idea/05/carbon-bath

Burning fossil fuels. Burning fossil fuels disrupts the carbon cycle in a much more serious way. It moves carbon from the natural reservoir of oil and gas into another reservoir, the atmosphere. We currently emit more than two million pounds of CO_2 per second. This means that we've tipped the carbon cycle out of equilibrium, or balance. CO_2 can remain in the atmosphere for hundreds of years before being removed by natural processes. Therefore, it will continue to contribute to global warming into the next century.

Global warming has caused many changes in physical and biological systems. Some of these changes have decreased biodiversity, and the ability of ecosystems to bounce back after being disturbed.

The rise in global average temperature dues to greenhouse gases will result in feedback loops like melting of arctic permafrost and melting of semi-solid methane deposits in the seafloor. These will cause the release of more CO_2 and methane, in turn.

Although this is a depressing topic, the fact is that the primary causes of global climate change are human. The good news is that this means that solutions are within our control also.

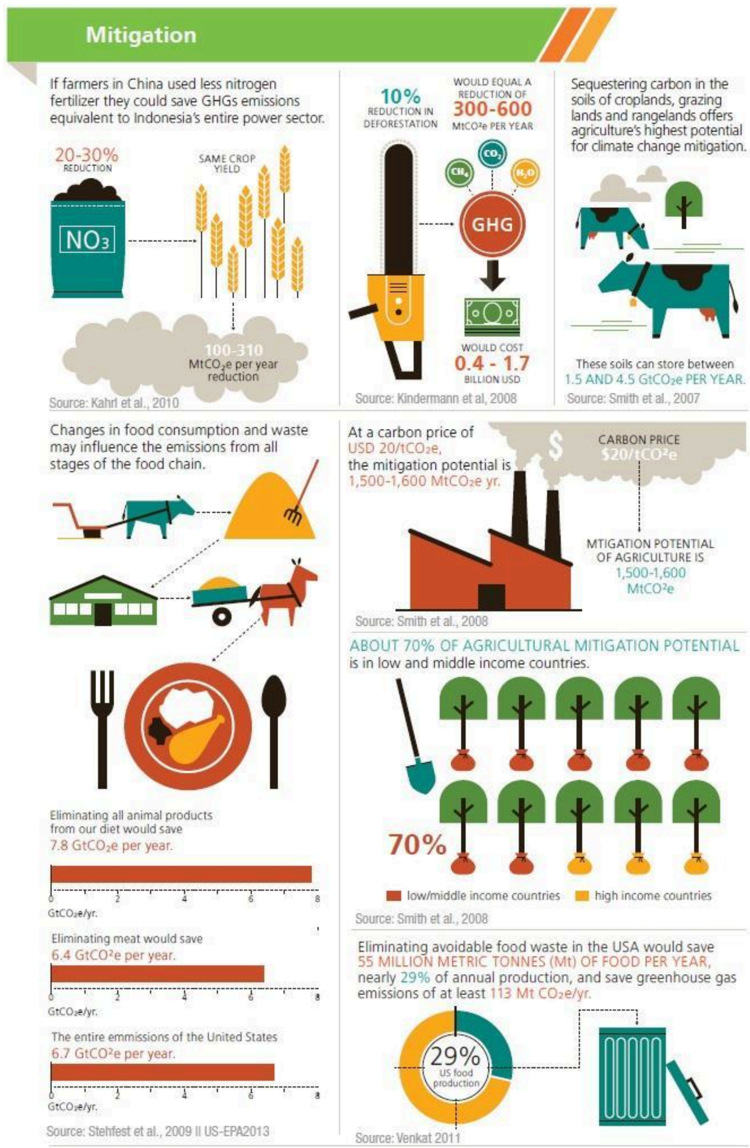
More information

- A complex simulation that shows how human industry affects the carbon cycle (scroll down to "The carbon cycle and climate change") (~10:00) http://mare.lawrencehallofscience.org/curriculum/ocean-science-sequence/oss68-overview/oss68-simulation-activities - carboncycle

Mitigation

Mitigation refers to ways of slowing global warming. We do not yet have approaches that could take enough greenhouse gases out of the atmosphere to reverse global warming. This means that we need to focus on reducing emissions for now.

The world's richest half-billion people (about 7% of the world population) are responsible for 50% of the world's CO_2 emissions. The poorest 50% are responsible for 7%. Since we are the cause of the increase, we can be the source of solutions! What are some of the solutions?



Source: cgiar.org

1. We can reduce **fossil fuel use** through:

- Increased efficiency (e.g., appliances, autos, buildings)

- Changing our habits (e.g., biking instead of using the car, reducing consumerism, reducing food waste)
- Switching to power sources that don't emit greenhouse gases (e.g., wind and solar).

2. We can reduce emissions related to our **food supply**. For example, cows emit CO_2 and huge amounts of methane. Manure from pigs and cows is stored in holding ponds, and these also produce methane. Methane is a powerful greenhouse gas. Each molecule has about 25x the heat-trapping power of a CO_2 molecule. Some of these emissions could be mitigated. For example, there are some farms that use the manure as a source of power. The best option is to greatly reduce meat in our diets.

3. **Trees** are important tools in mitigating climate change. They absorb and store CO_2 during photosynthesis, before it can reach the upper atmosphere and trap heat. While all living plants absorb CO_2, trees store significantly more CO_2 than smaller plants in their biomass due to their large size and extensive root structures. They are nature's most efficient carbon reservoir. This makes planting trees a form of mitigation. We have cut down a large percent of the world's forests. This has reduced the ability of the biosphere to pull CO_2 out of the atmosphere. We can remedy this by planting an enormous number of trees. We can also let farmed or developed areas grow wild. Between 2005 and 2014, deforestation accounted for around 30% of carbon emissions. During this period, reforestation helped to store 20% of emissions. However, reforestation will not do nearly enough to slow global warming.

4. Another solution is to **prevent deforestation** in the first place. Some organizations give payments to those who manage forests sustainably. In the US, the Department of Agriculture is encouraging an industry that makes wood panels by gluing smaller pieces of wood together. This gives forest managers a way to use diseased and dying trees before they burn in forest fires. The carbon from these forests is ultimately be stored inside of buildings rather than being released in fires.

5. We can also find other ways to use plants to take up CO_2. For example, some engineers are developing large systems that **use algae** to trap it. The carbon in these tiny plants can be stored away in a solid form as another carbon reservoir.

6. Some engineers are investigating methods for managing solar radiation. These include painting roofs white, or putting fleets of white reflectors out at sea. Both would increase the planet's albedo, and reflect more solar energy back into space.

More information on Mitigation

- The website of a youth organization that is suing the federal government to secure a healthy atmosphere:

http://ourchildrenstrust.org/

- The Princeton stabilization wedges are a way to plan a decrease in carbon emissions by combining multiple "green" power sources to replace fossil fuels:

http://cmi.princeton.edu/wedges/intro.php

- The Alliance for Climate Education gives presentations at high schools and helps high school students take action on climate change:

https://acespace.org/

- Renewable energy and energy conservation resources (7:24)
  https://www.youtube.com/watch?v=_JWxAAeQXe0

- A brief look at different kinds of renewable energy from Earth: The Operator's Manual (7:24)
  https://www.youtube.com/watch?v=_JWxAAeQXe0

- Yale Climate Connections on green roofs (1:30)
https://www.youtube.com/watch?v=1W64-Cl7Ir4

- Yale Climate Connections on insects for food (1:30)
https://www.youtube.com/watch?v=3bDcSM3JE5o

- Yale Climate Connections on urban solar power (1:30)
  https://www.youtube.com/watch?v=aFZmZJvsMc4