Anthropogenic climate change

Astronomy 101
Syracuse University, Fall 2021
Walter Freeman

November 30, 2021

"Since, now, warm ages have alternated with glacial periods, even after man appeared on the earth, we have to ask ourselves: Is it probable that we shall in the coming geological ages be visited by a new ice period that will drive us from [Europe] into the hotter climates of Africa? There does not appear to be much ground for such an apprehension. The enormous combustion of coal by our industrial establishments suffices to increase the percentage of carbon dioxide in the air to a perceptible degree...

We often hear lamentations that the coal stored up in the earth is wasted by the present generation without any thought of the future.... We may find a kind of consolation in the consideration that here, as in every other case, there is good mixed with the evil. By the influence of the increasing percentage of [CO_2] in the atmosphere, we may hope to enjoy ages with more equable and better climates, especially as regards the colder regions of the earth, ages when the earth will bring forth much more abundant crops than at present, for the benefit of rapidly propagating mankind."

–Svante Arrhenius, Swedish physicist, in *Worlds in the Making* (1906)

"Our climate has alternated between ice ages and warm periods. Should we Europeans fear a new ice age which will make Europe too cold for us to live in, and force us to move to Africa? We do not need to worry about this since we are burning enough coal to raise the amount of carbon dioxide in the atmosphere.

People sometimes complain that we are wasting coal and not saving any for the future. But the CO_2 released by burning coal will intensify the greenhouse effect, making Earth's climate warmer. This will especially benefit cold countries like Northern Europe, and we can grow more crops in the warmer climate to feed our growing population."

–Svante Arrhenius, *Worlds in the Making*, in simple modern English

"Our climate has alternated between ice ages and warm periods. Should we Europeans fear a new ice age which will make Europe too cold for us to live in, and force us to move to Africa? We do not need to worry about this since we are burning enough coal to raise the amount of carbon dioxide in the atmosphere.

People sometimes complain that we are wasting coal and not saving any for the future. But the CO_2 released by burning coal will intensify the greenhouse effect, making Earth's climate warmer. This will especially benefit cold countries like Northern Europe, and we can grow more crops in the warmer climate to feed our growing population."

–Svante Arrhenius, *Worlds in the Making*, in simple modern English

"The highest effect of the sun's rays I have found to be in [carbon dioxide] gas. ... An atmosphere of that gas would give to our earth a high temperature; and if, as some suppose, at one period of its history, the air had mixed with it a larger proportion than at present, an increased temperature from its own action... must have necessarily resulted."

–Eunice Foote, American botanist from Seneca Falls (40 miles west of Syracuse), for the *American Journal of Science and Arts*, 1856

Since today's topic is the most important of the semester, I will do announcements and logistical questions today by email.

Expect an email from me around 5pm with announcements. Send questions to Discord or email; I will answer them in another broadcast email tonight.

Summary

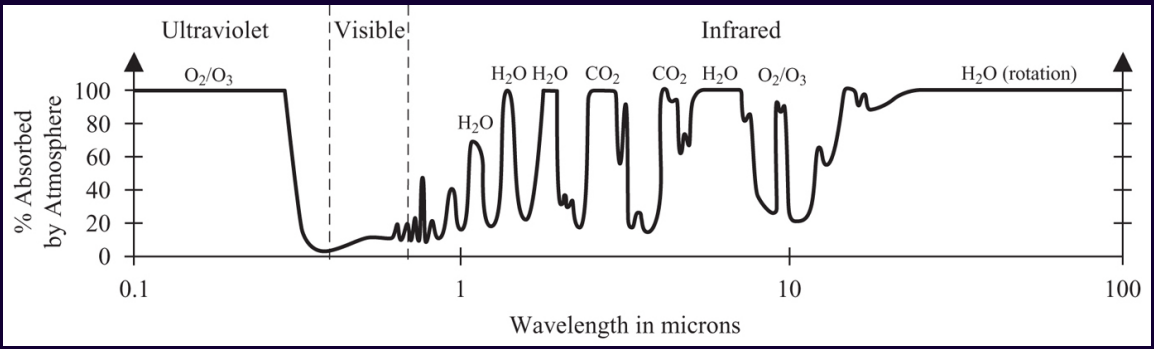
- Review: the greenhouse effect
- History
  - What is the history of the Earth's climate?
  - What processes caused it to vary?
  - How do they affect each other?
- The Anthropocene: the era of human influence on geology
  - In an eyeblink, a drastic jump in atmospheric CO_2:
  - Evidence that this is already causing warming
  - Evidence that this has the potential to cause far more warming

Summary, II

- Consequences
  - Exaggerated effect in the Arctic
  - Sea level rise
  - Disruption to society
  - Ecological shocks and extinctions
- What do we do about this?
  - What are the sources of CO_2 emissions?
  - *Who* are the sources of CO_2 emissions (spoiler: us)
  - Electricity generation
  - Transportation
  - Obstacles, legitimate and otherwise
  - Positive signs

Part 0: Review of the greenhouse effect

The greenhouse effect



Venus has a *tremendously thick* atmosphere and a powerful greenhouse effect.

- Its atmosphere contains a great deal of CO_2, which reflects IR strongly
- The thermal radiation that would carry heat away from Venus can't get out
- It is over 400 K hotter than was predicted by the calculation you did in lab

Earth has a *thinner* atmosphere.

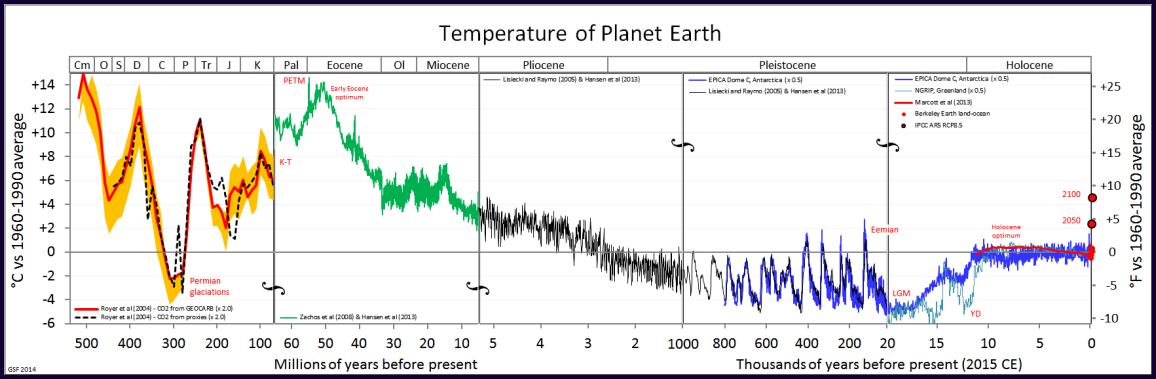
- Nitrogen doesn't absorb strongly at any relevant wavelengths
- H_2O and CO_2 are strong greenhouse gases, but they are only a bit of the atmosphere

The greenhouse effect

- The Sun is around 5500 K, and emits visible/short-wavelength IR; this goes through Earth's atmosphere and warms it
- The Earth is around 300 K, and emits longer-wavelength IR
- Some of that energy is absorbed by gases (water, carbon dioxide, methane) in the atmosphere
- When the atmosphere reradiates it, much of it falls back to Earth
- If the short-wavelength sunlight has an easier time getting in than the long-wavelength Earthlight has getting out, Earth's temperature will go up
- This is called the greenhouse effect.
- It raises our temperature by 20-30 K
- Its strength controls variations in Earth's temperature

Part 1: History of Earth's climate

Variation of Earth's climate



Earth has seen quite a lot in its lifetime...

The past state of Earth can help us study what the future may hold.

The climate spectrum

Temperature differences compared to 20th century average:

- -33C: complete lack of greenhouse effect
- -10C: “snowball Earth”; glaciers cover entire planet except for a small band at Equator
- -5C: ice age; Syracuse covered in glaciers
- 0C: our familiar climate
- +5C: ??? (but maybe our future)
- +10C: Like the time of the dinosaurs; inland seas common; much of America underwater

What process is most driving these recent fluctuations in climate?

A: Changes in the Sun's brightness affect the amount of energy reaching Earth

B: Changes in the rate that volcanoes discharge greenhouse gases into the atmosphere affect the strength of the greenhouse effect

C: Changes in the Earth's orbit affect the axial tilt and the distance from the Sun

D: All of the above

E: An increase in CO_2 in the atmosphere due to the burning of fossil fuels has increased the strength of the greenhouse effect

- Solar output: fluctuates in an 11-year cycle, but creates only an 0.2-degree change

- Solar output: fluctuates in an 11-year cycle, but creates only an 0.2-degree change
- Volcanism: variation in the amount of greenhouse gases discharged over this timescale is not that large

- Solar output: fluctuates in an 11-year cycle, but creates only an 0.2-degree change
- Volcanism: variation in the amount of greenhouse gases discharged over this timescale is not that large
- The ice ages come in cycles...
  - Cyclical changes in Earth's orbit and tilt, driven by gravity of Jupiter, caused the series of ice ages

- Solar output: fluctuates in an 11-year cycle, but creates only an 0.2-degree change
- Volcanism: variation in the amount of greenhouse gases discharged over this timescale is not that large
- The ice ages come in cycles...
  - Cyclical changes in Earth's orbit and tilt, driven by gravity of Jupiter, caused the series of ice ages
- Look at the time axis – the industrial revolution is just the last eyeblink of history

Positive and negative feedback

The Earth is quite complex. If the Earth warms, then...

- ... certain effects will cause even more warming: *positive feedback*
- ... other effects will slow that warming down: *negative feedback*

Positive feedback: snow

White snow absorbs less heat than dark soil
This is why snow piles take so long to melt!

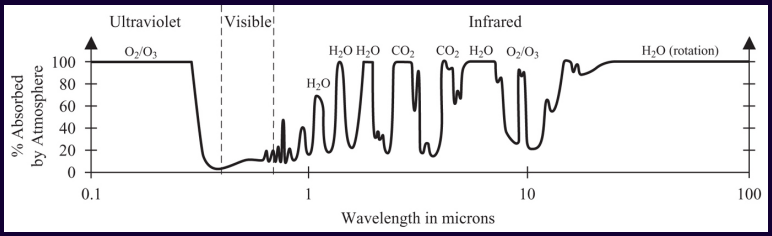
This feedback loop is *fast* – it doesn't take that long to melt snow (years)

Negative feedback: oceans

More CO_2 in the air $\rightarrow$ oceans absorb faster
This brings the CO_2 levels back down.

This feedback loop is *slow* – it takes a long time for CO_2 to be absorbed (hundreds/thousands of years)

The strongest feedback mechanism: evaporation

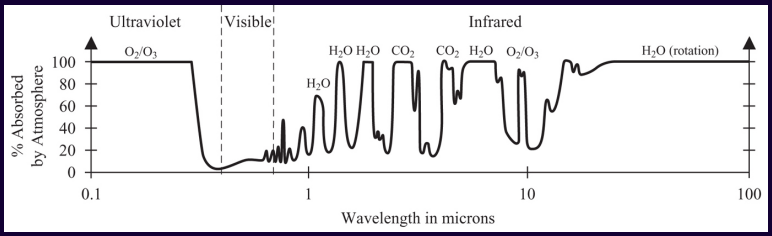


Two of the strongest greenhouse gases are H_2O (water) and CO_2.

However:

- Water is found as both liquid and vapor on Earth
- Water evaporates faster at higher temperatures
- Water is constantly evaporating and condensing all over Earth

The strongest feedback mechanism: evaporation

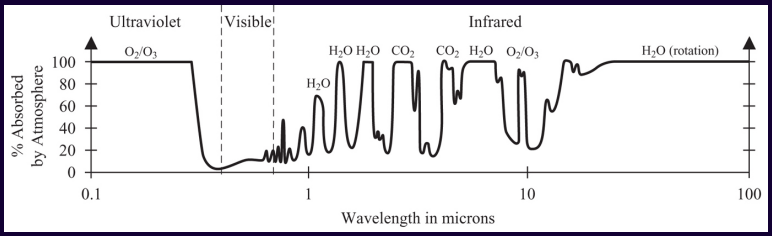


Two of the strongest greenhouse gases are H_2O (water) and CO_2.

However:

- Water is found as both liquid and vapor on Earth
- Water evaporates faster at higher temperatures
- Water is constantly evaporating and condensing all over Earth
- The concentration of water vapor in the atmosphere depends almost totally on temperature and changes fast

The strongest feedback mechanism: evaporation



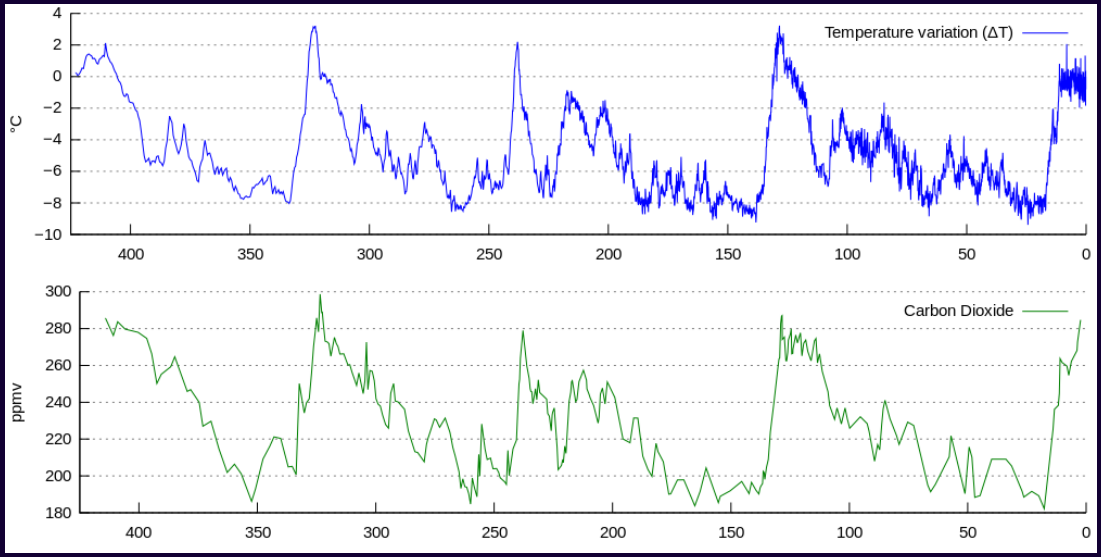
Two of the strongest greenhouse gases are H_2O (water) and CO_2.

However:

- Water is found as both liquid and vapor on Earth
- Water evaporates faster at higher temperatures
- Water is constantly evaporating and condensing all over Earth
- The concentration of water vapor in the atmosphere depends almost totally on temperature and changes fast
- ... so the positive feedback from evaporating more water greatly magnifies any small changes to our climate coming from something else (like CO_2)

This understanding is not new: its strength was calculated in detail by Arrhenius in 1896!

The strength of positive feedback mechanisms means that a small direct impact from CO_2 levels will be greatly magnified.



CO_2 is strongly correlated with temperature (positive feedback in both directions).

- More CO_2 in the atmosphere strengthens the greenhouse effect, raising the temperature
- Higher temperatures speed up chemical processes that release carbon stored in rocks
- Lower temperatures speed up chemical processes by which rocks *absorb* carbon

What if we change CO_2 on our own?

What if we change CO_2 on our own?

A: The climate will be altered for a few centuries

B: The climate will be altered for a few tens of thousands of years

C: The climate will be altered for a few million years

D: The climate will be altered forever

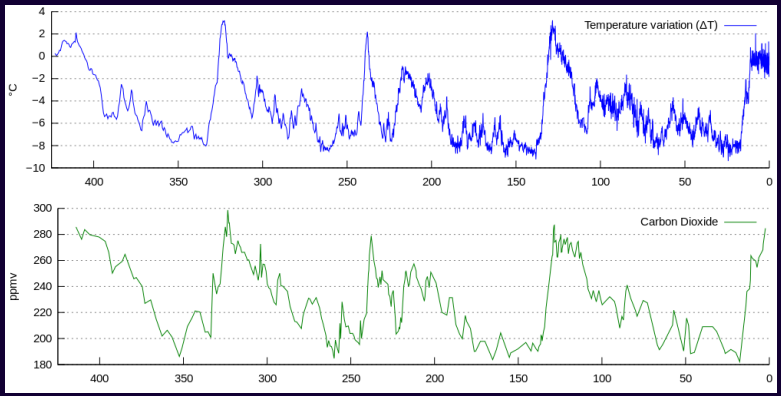
How high must atmospheric CO_2 levels get for the climate to be seriously changed compared to the past few hundred thousand years?

A: 275 ppm

B: 300 ppm

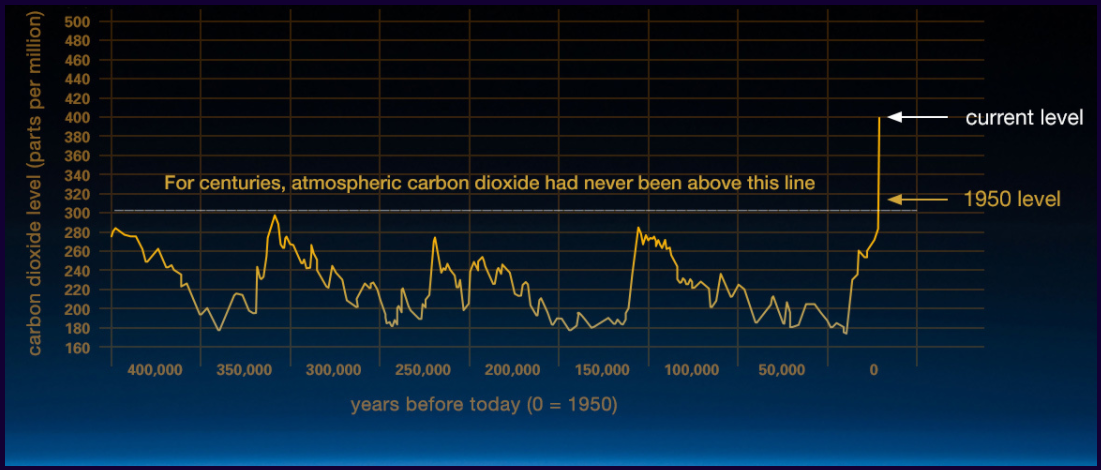
C: 325 ppm

D: 350 ppm



The current state

The 2020 average CO_2 level was 412 ppm.
The Industrial Revolution took us there in a geological blink of an eye.

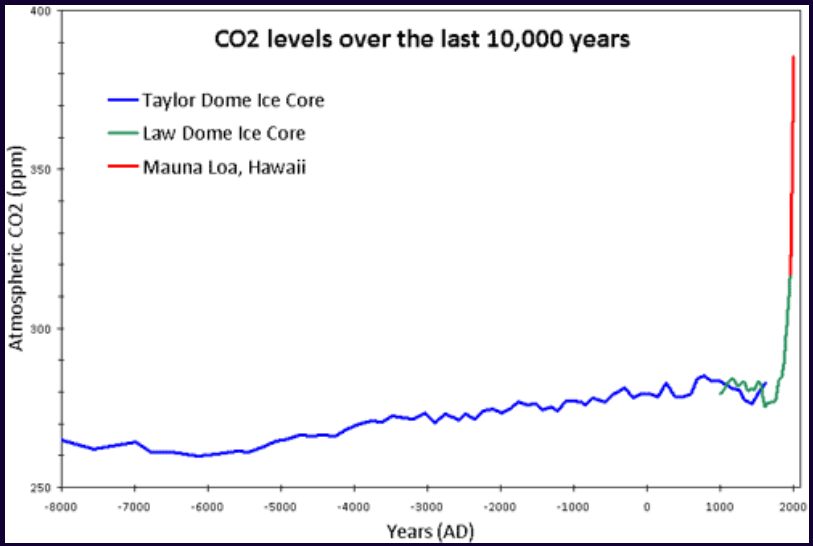


(NASA)

Let's zoom in on recent history:

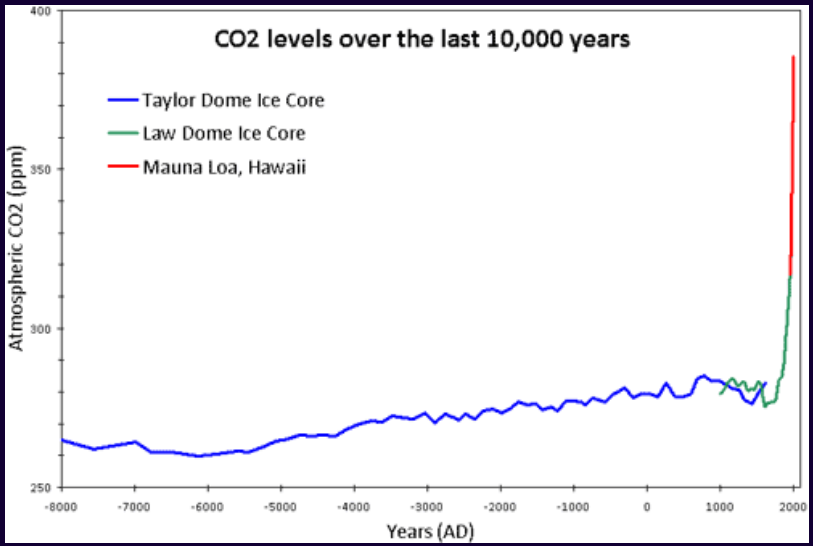
The current state

The 2020 average CO_2 level was 412 ppm.
The Industrial Revolution took us there in a geological blink of an eye.



The current state

The 2020 average CO_2 level was 412 ppm.
The Industrial Revolution took us there in a geological blink of an eye.



This graph is a few years old; note that we are now off the top of the chart.

Part 2: Learning from the past to understand the present

What will this do to Earth?

Geophysics is enormously complicated.

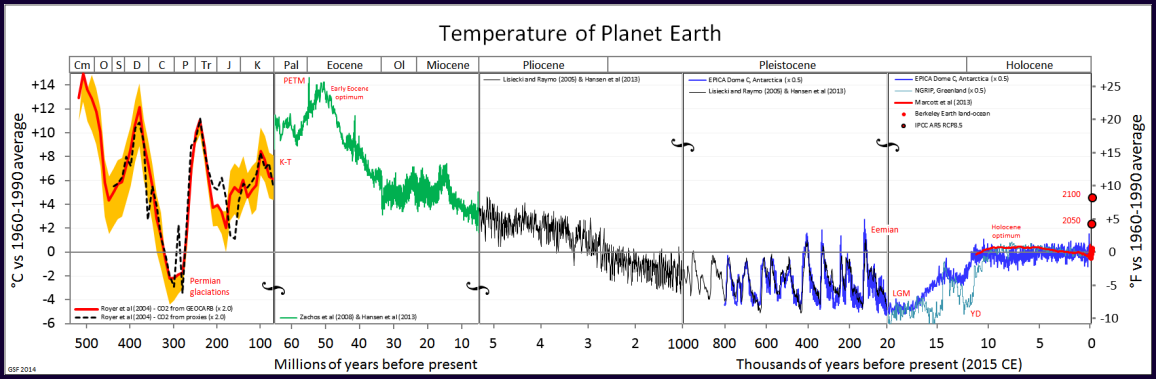
Models (from simple ones to enormous supercomputer simulations) tell us unequivocally: the CO_2 produced by humans will warm the planet.

But for how much, and for how long, and to what effect?

We'll talk about those models in a bit, but in the meantime, let's look at history to get an answer.

This happened once before...

The "Paleocene-Eocene Thermal Maximum" was a sudden release of carbon dioxide 56 Myr ago. (We're not sure from where, but we know it happened, by looking at isotope ratios in fossils.)



- Something caused a rapid release of CO_2 over two thousand years, at a peak rate of up to 6 billion tons/year.
- This caused a temperature spike of 5-8 C that lasted many thousands of years
- The oceans absorbed much of this carbon as carbonic acid, bleaching corals
- There was a mass extinction of deep-ocean life and large changes to surface life

Part 3: Effects of future climate change

A candid word on scientific rigor

As we've discussed, a crucial part of scientific integrity is honesty about the limitations of your knowledge.

In preparing for this class, I've used as source material:

- UN Intergovernmental Panel on Climate Change Fifth Assessment Report (2015)
- UN Intergovernmental Panel on Climate Change Sixth Assessment Report (2021)
- USA Fourth National Climate Assessment (2017-18)

These documents are *meticulous* about this. They make sure to describe:

- uncertainties in measurements and estimates
- how confident they are in conclusions, and where there is disagreement
- when important things are still unknown (some things are hard!)

These climate assessments are exemplary in their integrity and honesty in this regard – better than nearly any other scientific paper I have read.

What climate change is and is not

Climate change will cause an overall warming of the planet by 2-8 °C.

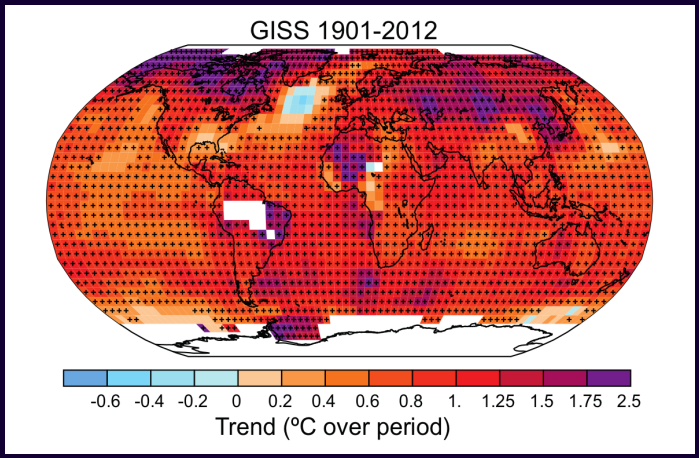
It does not mean an end to cold weather – and cold weather does not mean that climate change is not happening.

Most of the world will have more hot extremes and fewer cold ones, but there is a difference between weather and climate.

Arguments like "It is snowing and cold, thus climate change is a hoax" are classic examples of cherry-picking and "recency bias".

Effects on the Arctic

Observations show that the effects of current and future warming are magnified in the Arctic, because of the albedo effect from melting snow.



https://www.youtube.com/watch?v=VIxciS1B9eo

Sea level rise

All that water must go somewhere; heat also causes the oceans to expand. The Marshall Islands may simply cease to exist.

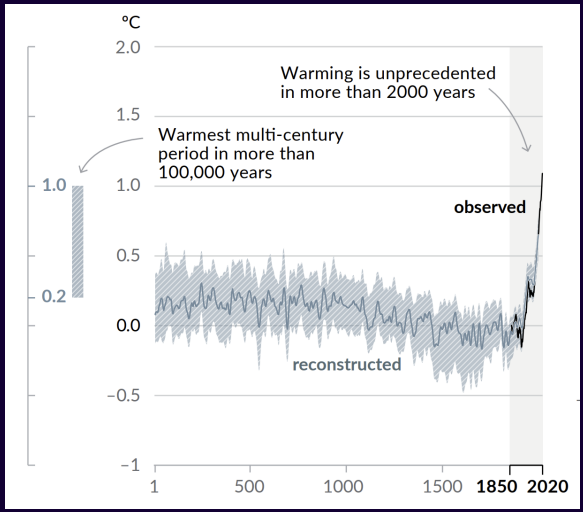
Miami, Manhattan, New Orleans, etc. are also threatened...

Validating computer models

We've gone from the simple calculations of Arrhenius to massive supercomputer simulations of the Earth's climate.

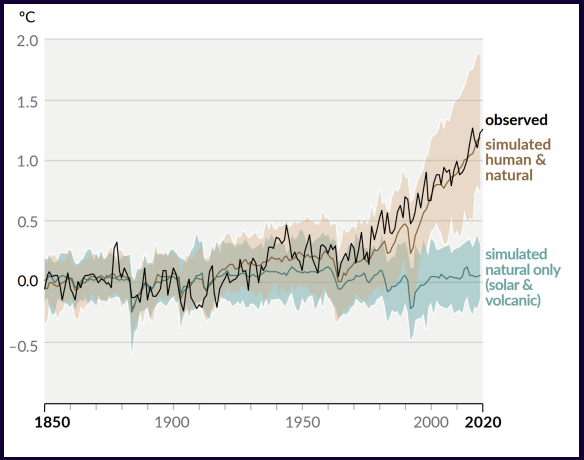
If we're going to trust them to predict details about the future, they ought to accurately capture the past.

Earth's climate has warmed by a little over 1° in the last 150 years.



Do computer simulations describe this accurately?

Validating computer models



We have done computer simulations of Earth's climate both with and without human influences included.

The observed climate trends *are not* consistent with simulations of natural influences on the climate, but are *very* consistent with simulations including human effects.

Climate simulations are accurate for broad trends like global temperature.

Effects on humans

Our societies are adapted for certain weather patterns and coastlines. If the earth warms:

- People may have to abandon coastal cities like Manhattan and Miami

Effects on humans

Our societies are adapted for certain weather patterns and coastlines. If the earth warms:

- People may have to abandon coastal cities like Manhattan and Miami
- Overall warming will render a lot of land unfarmable in Africa

Effects on humans

Our societies are adapted for certain weather patterns and coastlines. If the earth warms:

- People may have to abandon coastal cities like Manhattan and Miami
- Overall warming will render a lot of land unfarmable in Africa
- Seasonal rainfall patterns that equatorial farmers rely on may change

Effects on humans

Our societies are adapted for certain weather patterns and coastlines. If the earth warms:

- People may have to abandon coastal cities like Manhattan and Miami
- Overall warming will render a lot of land unfarmable in Africa
- Seasonal rainfall patterns that equatorial farmers rely on may change
- Extreme weather events may become more likely, including wildfires and storms

"Human-induced climate change is **already** *affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened [since 2016]."*

In wealthy nations like the US this will cause massive economic losses, as people are forced to adapt.

In poorer nations people may not have the resources to adapt...

It's definitely happening, and we did it

Global climate is changing rapidly compared to the pace of natural variations in climate that have occurred throughout Earth's history. Global average temperature has increased by about 1.8 °F *from 1901 to 2016, and observational evidence does not support any credible natural explanations for this amount of warming; instead, the evidence consistently points to human activities, especially emissions of greenhouse or heat-trapping gases, as the dominant cause.*

–The Fourth National Climate Assessment (US Government), 2018

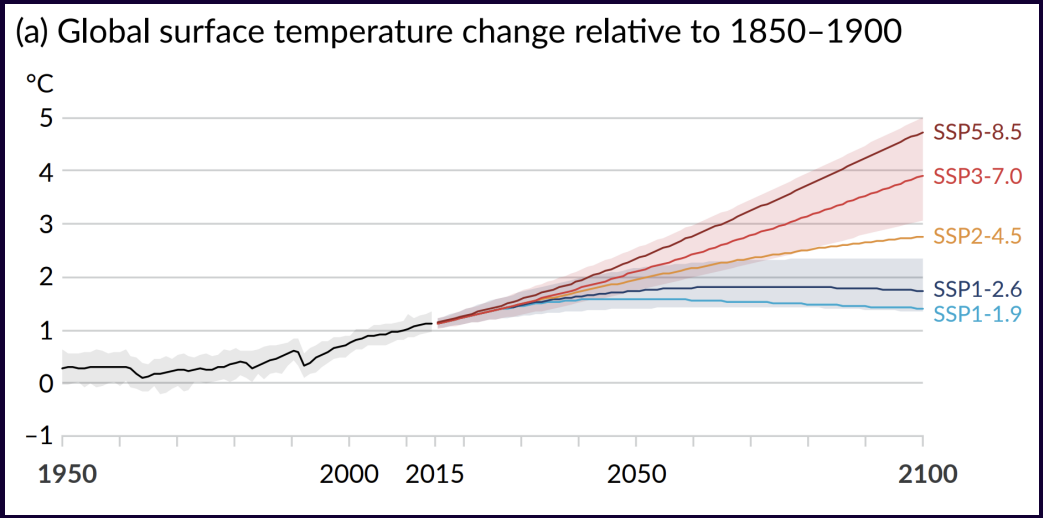
It's definitely happening, and we did it

Global climate is changing rapidly compared to the pace of natural variations in climate that have occurred throughout Earth's history. Global average temperature has increased by about 1.8 °F *from 1901 to 2016, and observational evidence does not support any credible natural explanations for this amount of warming; instead, the evidence consistently points to human activities, especially emissions of greenhouse or heat-trapping gases, as the dominant cause.*

–The Fourth National Climate Assessment (US Government), 2018

Part 4: Mitigating climate change

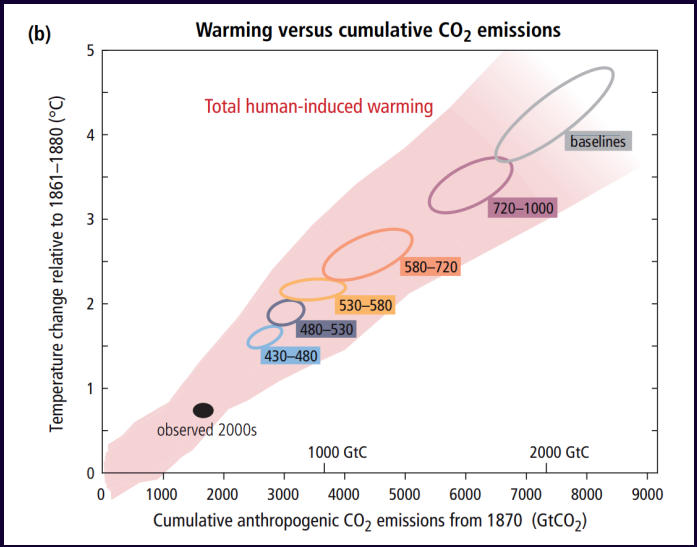
A crossroads



Warming is inevitable (it's already happened). How much more depends on our choices.

(Simulations from UN Sixth Assessment Report, 2021)

A crossroads



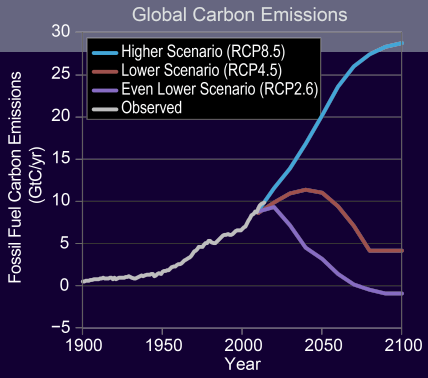
The future of the climate depends most strongly on the total amount of CO_2 produced by human activity.

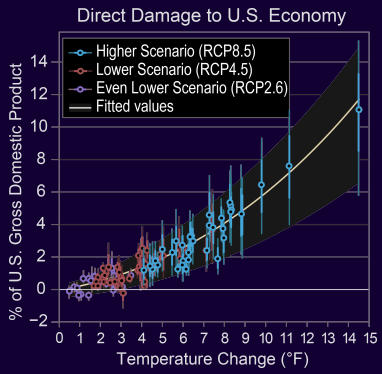
(Simulations from UN Fifth Assessment Report, 2016)

Climate change mitigation

The effect on global temperature – and on human society – will depend a great deal on how quickly and deeply we cut CO_2 emissions.

- Warming to date: 1° C (2° F)
- Depending on our choices: from $2 - 7^\circ$ C ($4 - 12^\circ$ F) likely.
- The next decade or two are crucial for what happens later
- Climate mitigation will be *good* for the US economy!





Sources of CO_2 emissions

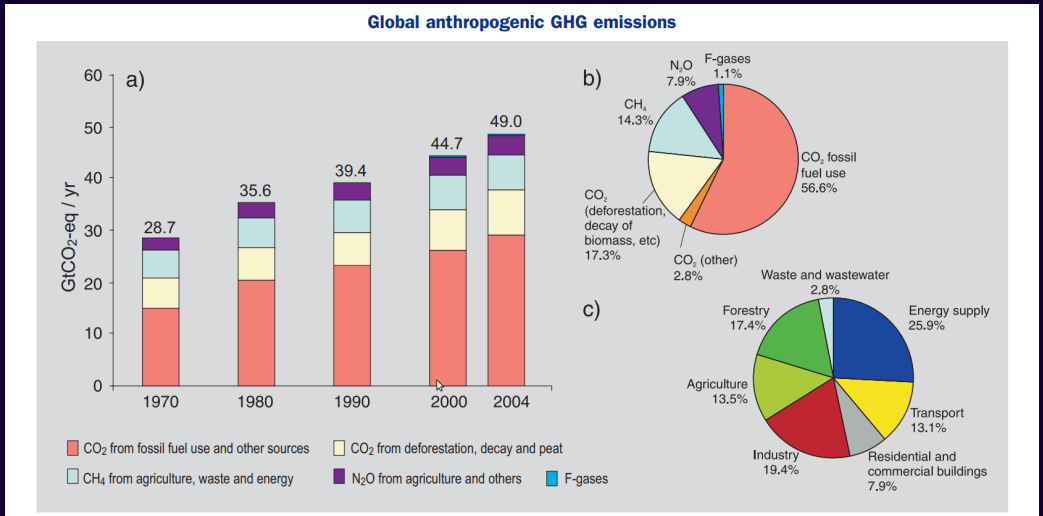


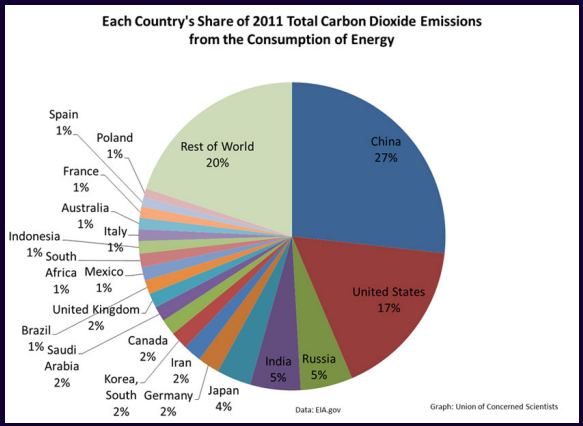
Figure SPM.3. *(a) Global annual emissions of anthropogenic GHGs from 1970 to 2004.[5] (b) Share of different anthropogenic GHGs in total emissions in 2004 in terms of carbon dioxide equivalents (CO_2-eq). (c) Share of different sectors in total anthropogenic GHG emissions in 2004 in terms of CO_2-eq. (Forestry includes deforestation.) {Figure 2.1}*

Most of our greenhouse gases come from burning fossil fuels.

These are mostly used to generate electricity, power vehicles, and in industry.

Who's doing most of this?

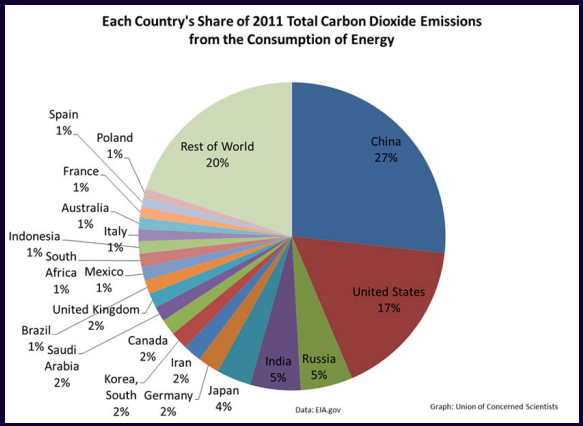
Us – the global wealthy.



(from the Union of Concerned Scientists)

Who's doing most of this?

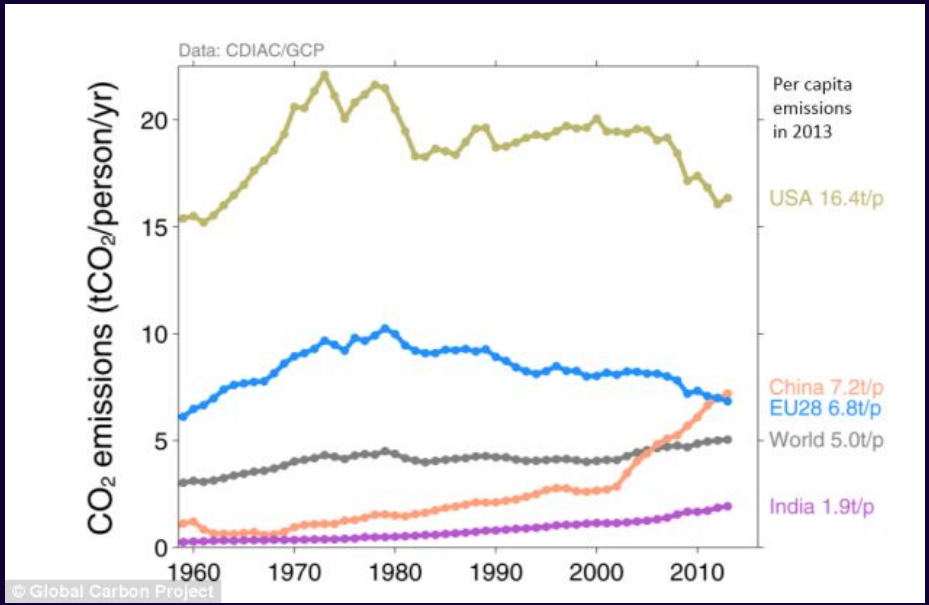
Us – the global wealthy.



(from the Union of Concerned Scientists)

Do these data tell the whole story?

Top CO_2 sources



What do you conclude from these data? Do *they* tell the whole story?

Pointing fingers

Globalization means that countries now specialize in different things:

- Many wealthy countries (USA, France) are moving away from industrial economies ("Rust Belt")
- Middle-income countries are industrializing, with many of their products exported

Pointing fingers

Globalization means that countries now specialize in different things:

- Many wealthy countries (USA, France) are moving away from industrial economies ("Rust Belt")
- Middle-income countries are industrializing, with many of their products exported
  - Many products are manufactured in China for the use of people in other places
  - Manufacturing requires a lot of energy
  - Food is often grown in one country and eaten in another
- In a global economy, this is a global problem!

Electricity generation

Electrical power is the largest source of CO_2 emissions.

- Coal: cheap and easy
- Natural gas: Very cheap in the USA and Russia (fracking)

Zero-emissions power sources:

- Hydropower: Cheap but limited, and can disrupt rivers

Electricity generation

Electrical power is the largest source of CO_2 emissions.

- Coal: cheap and easy
- Natural gas: Very cheap in the USA and Russia (fracking)

Zero-emissions power sources:

- Hydropower: Cheap but limited, and can disrupt rivers
- Nuclear: Large startup cost, more expensive than coal/gas, but reliable and clean (France, Canada)

Electricity generation

Electrical power is the largest source of CO_2 emissions.

- Coal: cheap and easy
- Natural gas: Very cheap in the USA and Russia (fracking)

Zero-emissions power sources:

- Hydropower: Cheap but limited, and can disrupt rivers
- Nuclear: Large startup cost, more expensive than coal/gas, but reliable and clean (France, Canada)
- Geothermal: Cheap where you've got it (Iceland); clean

Electricity generation

Electrical power is the largest source of CO_2 emissions.

- Coal: cheap and easy
- Natural gas: Very cheap in the USA and Russia (fracking)

Zero-emissions power sources:

- Hydropower: Cheap but limited, and can disrupt rivers
- Nuclear: Large startup cost, more expensive than coal/gas, but reliable and clean (France, Canada)
- Geothermal: Cheap where you've got it (Iceland); clean
- Wind: Decreasing in cost; intermittent supply

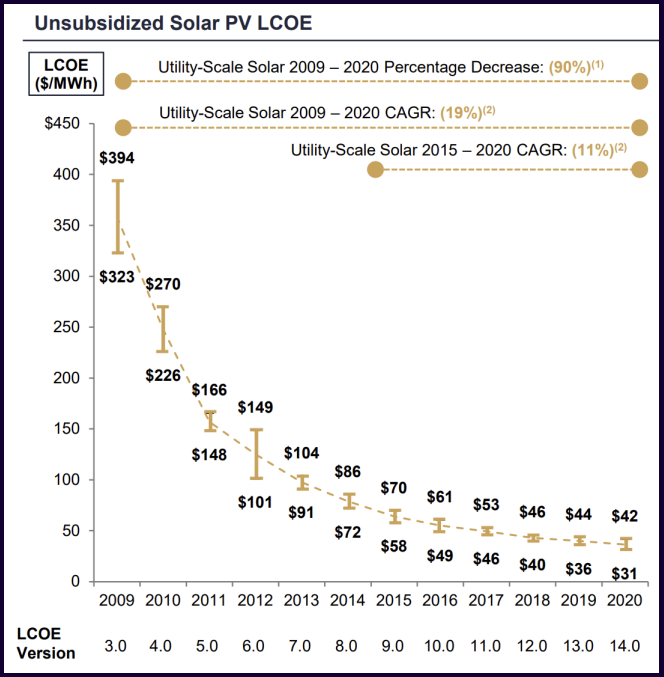
Electricity generation

Electrical power is the largest source of CO_2 emissions.

- Coal: cheap and easy
- Natural gas: Very cheap in the USA and Russia (fracking)

Zero-emissions power sources:

- Hydropower: Cheap but limited, and can disrupt rivers
- Nuclear: Large startup cost, more expensive than coal/gas, but reliable and clean (France, Canada)
- Geothermal: Cheap where you've got it (Iceland); clean
- Wind: Decreasing in cost; intermittent supply
- Solar: *Rapidly* decreasing in cost; variable like wind



Source: Lazard's Levelized Cost of Energy Analysis v. 14 (Data are for the USA)

The cost of solar power has dropped **dramatically** in the last decade thanks to manufacturing advances.

It is almost cheaper to *build and operate* solar farms than to operate natural gas plants already built and paid for.

The challenge with solar (and wind) power is storage: matching demand to fluctuating supply.

This is a solvable problem and there are many good ideas out there.

Transportation

- Cars – electric car prices dropping, charging infrastructure growing rapidly
- Buses – great in cities (see "bus rapid transit")
- Trains – great if you have the transport density
- Bicycles – most efficient transport in existence ("8 miles/banana")
- Airplanes – long-distance fast travel is very hard
- Ships – only real alternative to oil right now is nuclear (and that's hard)

Steps forward:

- Continual gains in efficiency: better cars and buses
- Electrification of everything we can: electric trains, electric cars/lorries
- Improve mass transit access and desirability
- Bike lanes in cities

Part 6: Politics and economics of climate mitigation

The "tragedy of the commons"

The problem:

- Carbon emissions consume a *shared resource* – the ability of Earth to absorb them without massive impact
- Our economic markets are based on *price signals*:
  - If a resource is precious or limited, its owner will charge more
  - People will buy less of it since it costs more
  - Demand gets matched to supply
- ... the atmosphere is shared by everyone, but it's hard to "own"
- There is currently no charge at *all* for using that resource!

On politics

Climate action in the USA is often framed as a partisan issue.

But it doesn't need to be a *politically divisive* issue!

There are liberal, conservative, socialist, and libertarian framings of both the problem of climate change and its solutions.

Avenues for climate change mitigation

- Ban things that yield little social benefit for the amount of CO_2: simple but crude

Avenues for climate change mitigation

- Ban things that yield little social benefit for the amount of CO_2: simple but crude
- "Cap and trade": need a permit to burn fossil fuels. Society decides to what extent to limit CO_2 and auctions that many permits; market forces determine how best to use them
- Carbon fee: Similar idea, where market incentives raise the cost and thus decrease the use of fossil fuels
- Subsidies: Government pays part of the cost to replace coal/gas plants with solar/wind/nuclear

Balance between rich and poor countries

India and China have built a lot of coal power plants.

Some arguments:

- "It's not fair for developed countries to have burned their coal already, but developing countries can't benefit in the same way, just because they were a little later"
- "Things are different now that we know what CO_2 does, so developing countries are going to have to leave their coal in the ground"

Balance between rich and poor countries

India and China have built a lot of coal power plants.

Some arguments:

- "It's not fair for developed countries to have burned their coal already, but developing countries can't benefit in the same way, just because they were a little later"
- "Things are different now that we know what CO_2 does, so developing countries are going to have to leave their coal in the ground"

- Idea of "climate debt": the West owes poor countries payment for their cumulative past emissions, and help with GDP growth in a low-carbon economy

Balance between rich and poor countries

India and China have built a lot of coal power plants.

Some arguments:

- "It's not fair for developed countries to have burned their coal already, but developing countries can't benefit in the same way, just because they were a little later"
- "Things are different now that we know what CO_2 does, so developing countries are going to have to leave their coal in the ground"

- Idea of "climate debt": the West owes poor countries payment for their cumulative past emissions, and help with GDP growth in a low-carbon economy

- We're all in this together – global problems demand global action

Obstacles

- "Regulatory capture" of government by fossil fuel industry
- Organized campaign of misinformation (compare to smoking/cancer link)
- Manufactured controversy:
  - The overwhelming scientific consensus agrees with what I've presented
  - ... but well-funded "skeptics" can speak with a loud voice
- Distraction:
  - Recent political and social crises can edge out long term issues
- International nature of the problem:
  - Addressing climate change requires cooperation between nations
  - Our species has never really done this before – except in war
  - Historical asymmetry between nations
  - Whatever happens wealthy nations are going to have to assist poorer ones

Summary

- Carbon dioxide level in the atmosphere acts as a “thermostat” for Earth
- CO_2 from human fossil fuel use is raising that level

Summary

- Carbon dioxide level in the atmosphere acts as a "thermostat" for Earth
- CO_2 from human fossil fuel use is raising that level

- The climate is getting warmer and will continue to get warmer:
  - 1°C warming already
  - $2 - 7$°C warming likely in a hundred years
  - Future CO_2 emissions will determine where in that range
- These changes are on the same level as natural variations of Earth's climate

Summary

- Carbon dioxide level in the atmosphere acts as a "thermostat" for Earth
- CO_2 from human fossil fuel use is raising that level

- The climate is getting warmer and will continue to get warmer:
  - 1°C warming already
  - $2 - 7$°C warming likely in a hundred years
  - Future CO_2 emissions will determine where in that range
- These changes are on the same level as natural variations of Earth's climate

- ... but they are happening far faster. This has already caused issues:
  - More / more intense hurricanes
  - More / more intense wildfires
  - Sea level rise
  - Altered rainfall patterns
- Future issues are likely to be a lot worse

Summary

- Carbon dioxide level in the atmosphere acts as a "thermostat" for Earth
- CO_2 from human fossil fuel use is raising that level

- The climate is getting warmer and will continue to get warmer:
  - 1°C warming already
  - $2 - 7$°C warming likely in a hundred years
  - Future CO_2 emissions will determine where in that range
- These changes are on the same level as natural variations of Earth's climate

- ... but they are happening far faster. This has already caused issues:
  - More / more intense hurricanes
  - More / more intense wildfires
  - Sea level rise
  - Altered rainfall patterns
- Future issues are likely to be a lot worse

- Solutions are technically well-understood
- ... the problem is just the cooperation needed to implement them