Photo: Killarney Provincial Park, Sept 2020

Climate Change: What we know and how we know it

Week 2: The First Climate Model

Steve Easterbrook, University of Toronto

Email: sme@cs.toronto.edu
Blog: www.easterbrook.ca/steve
Mastodon: @steve@fediscience.org

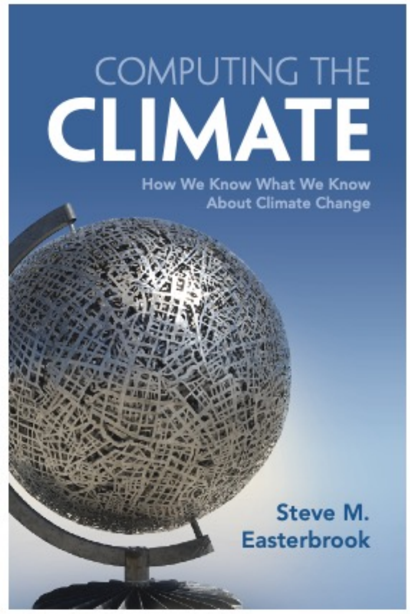
Reminder: You can read along

"This engaging, beautifully written book brings alive the scientists who created climate models, how they did it, and what the models can (and cannot) tell us - all in straightforward, nontechnical language and enlightening illustrations.

If you want to understand how modern climate science works, start here."

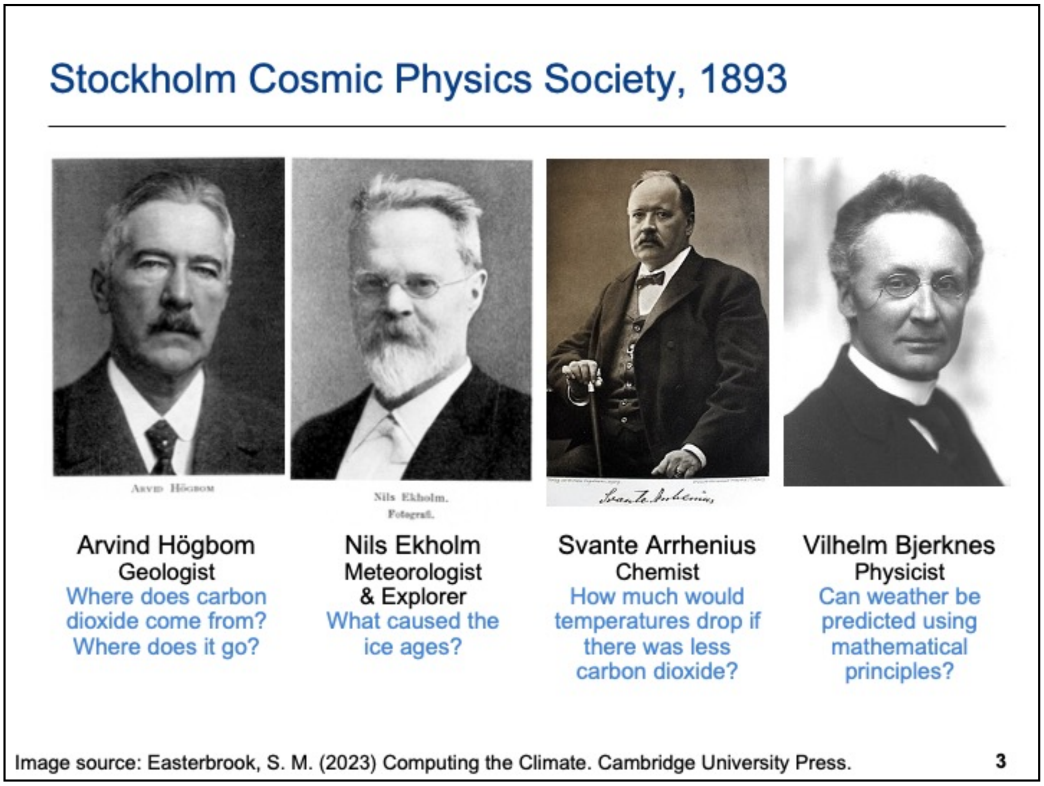
-- Paul N. Edwards, Stanford University. Author of *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming*

Order directly from Cambridge University Press and use the code **COMC2023** at checkout for a 20% discount (until Oct 31, 2025)



https://www.cambridge.org/9781107589926

2



Pronunciation: "Hergboom" "Arr-een-e-oos" "Be-yerk-ness"

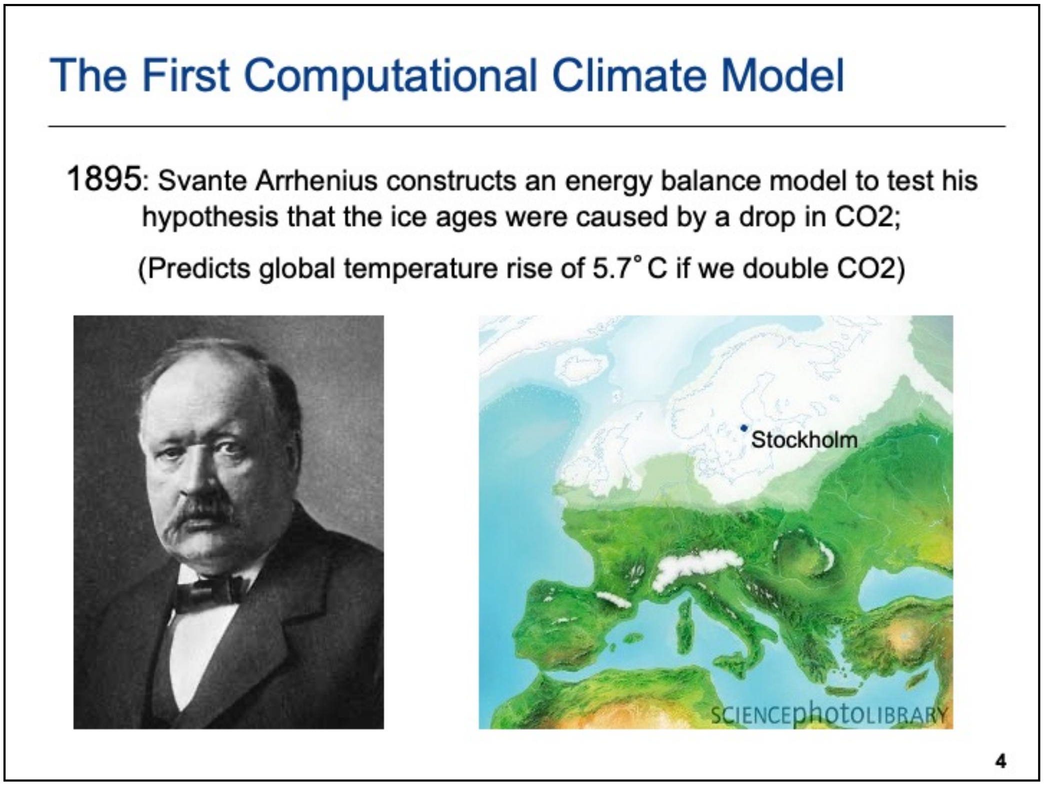
Chapter 2 in my book (this week's reading) tells the story of the first climate model, built in 1894 by Svante Arrhenius. He was inspired by a talk by Arvind Högbom to the Stockholm Cosmic Physics Society on the sources and sinks of "carbonic acid" (today we call it carbon dioxide) in the atmosphere

Hogbom's six sources of carbon dioxide in the atmosphere were: erupting volcanoes, meteorites, vegetation as it decomposes or burns (including burning of coal and oil), release of carbon trapped in rocks by chemical reactions, or by rock fracturing, and seawater as it warms under the sun.

Three sinks: rock weathering (in which carbon dioxide dissolves in rainwater and reacts with limestone to produce calcium bicarbonate), absorption by plants, and absorption by the oceans.

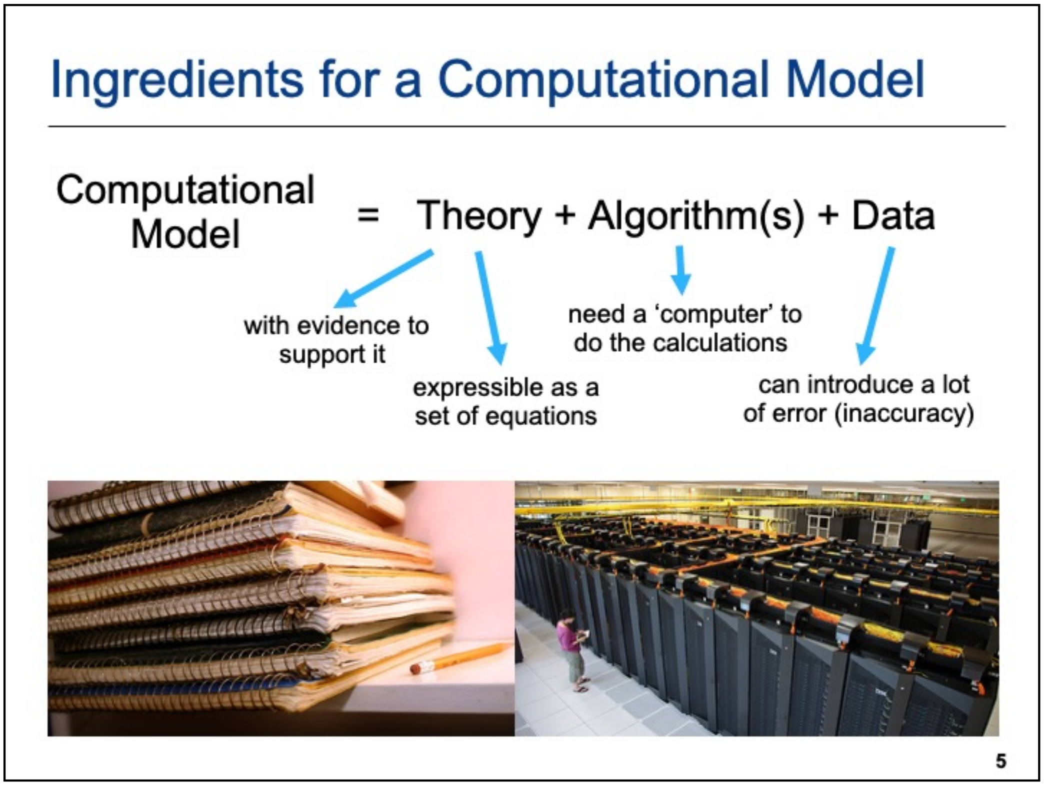
That same year, the explorer Nils Ekholm returned from an expedition to the island Spitzbergen, where he had been studying evidence of the ice ages. This was a big scientific mystery of the time: what had caused the ice ages?

Arrhenius thought that maybe they could be explained by a reduction in carbon dioxide in the atmosphere, and set out to prove his hypothesis…

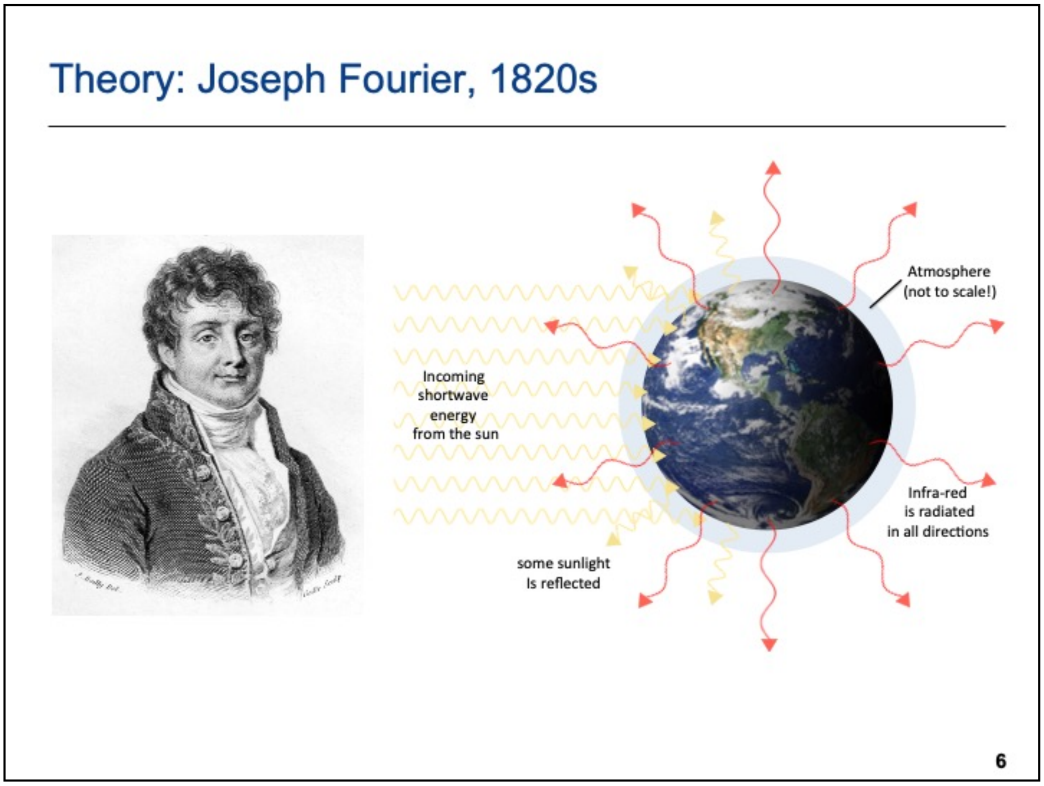


Arrhenius spent a year putting together a model to calculate what would happen to temperatures on Earth if you lowered or raised the amount of carbon dioxide in the atmosphere (he called it carbonic acid back in those days). As there were no electronic computers, he did all the calculations by hand.

Note: Arrhenius was Greta Thunberg's great grandmother's cousin!

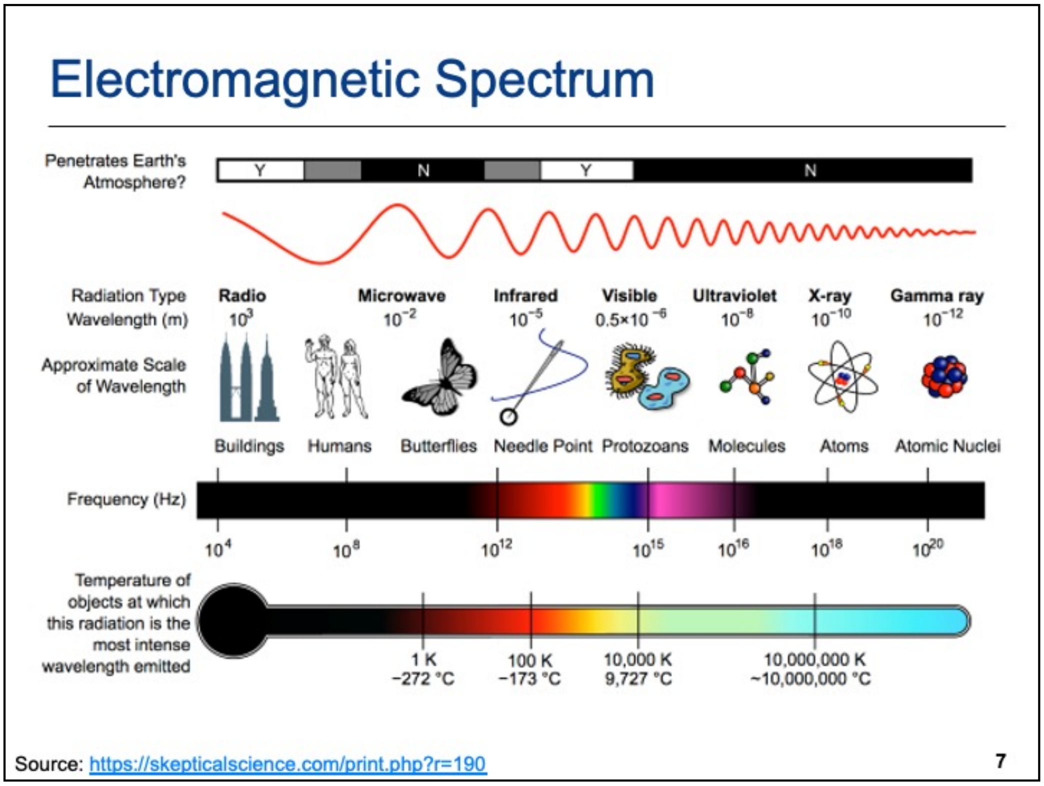


The left photo is The Yellowstone supercomputer at the NCAR Wyoming Supercomputing Center, Cheyenne, and is used for running today's massive climate simulation models.



Arrhenius was building on earlier scientists' work.

For example, the core theory comes from Fourier, who wondered why the earth doesn't lose all it's heat at night once the sun sets. He guessed there is something in the atmosphere that lets the sun's heat through, but traps that heat when it leaves the planet. He realized the two types of heat flow are different. Sunlight arrives mainly as visible light (plus some ultraviolet – the stuff that gives us sunburn). Heat leaving the earth is mainly infra-red, because the earth is not hot enough to radiate visible light. You can feel infra-red (e.g. if you put you hand near a fire or hot oven), but you can see visible light.



Visible light is just one part of the electromagnetic spectrum.

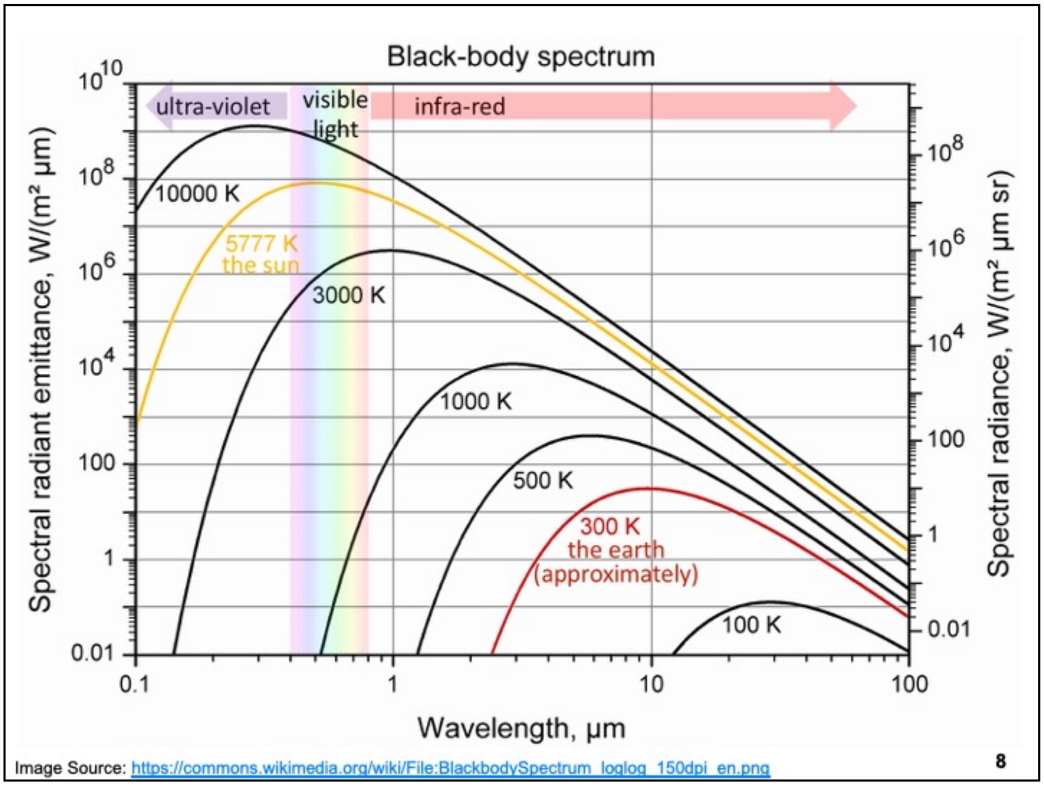
This form of radiation travels in straight lines (rays) at the speed of light. Our eyes can only see a small part of the broader spectrum, from red through to violet.

Some animals can see parts of the spectrum we cannot (e.g. part of the infrared, useful for predators that hunt at night).

The key thing you need to know is that the atmosphere blocks rays on some parts of the spectrum (e.g X-rays and gama rays), but lets other rays through (e.g. visible light, radio waves).

In the infrared, some gases (greenhouse gases) block parts of the spectrum, while other gases do not.

Source: https://skepticalscience.com/print.php?r=190



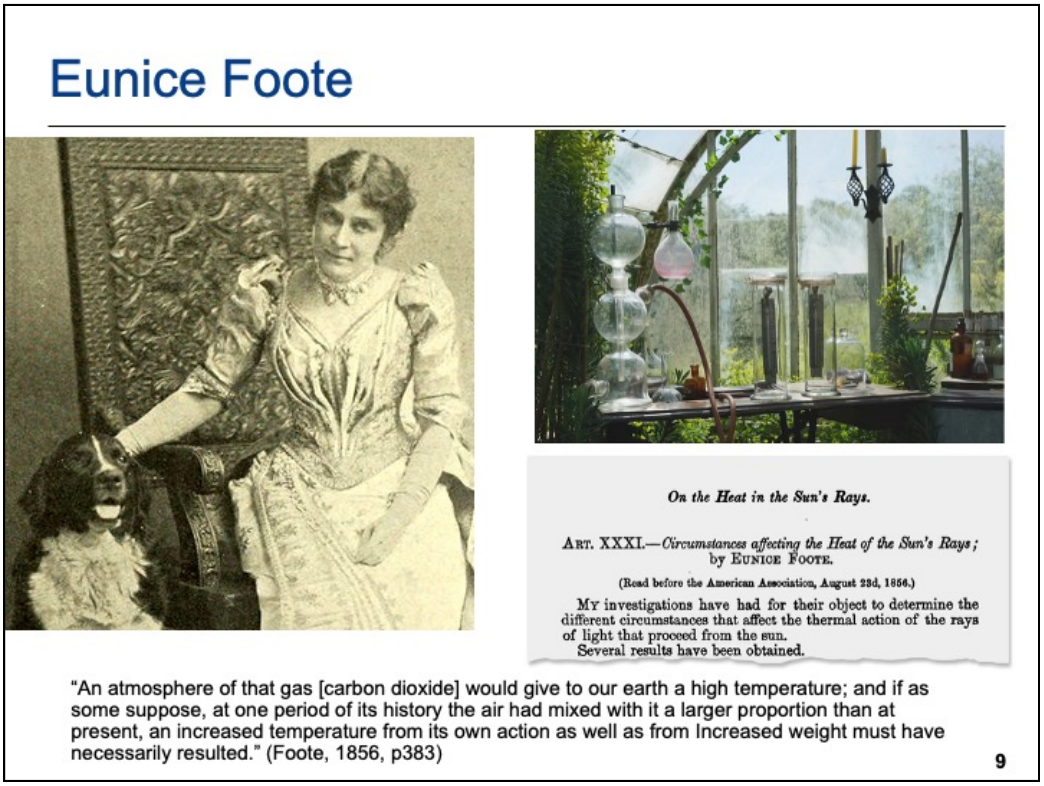
This chart shows how objects at different temperature give off electromagnetic radiation at different wavelengths (measured in micrometers, or microns, or **µ**m). A micrometer is a millionth of a meter. Very small!

The Earth is (very) approximately 300Kelvin (which is roughly 25 degrees Centigrade), so most of its radiation is longer waves, in the infrared

The Sun is thousands of degrees hotter, so most of its radiation is shortwave – in the visible part of the spectrum, and in the ultraviolet. But note that it also radiates some energy across the infrared part of the spectrum too.

The scale on the Y axis of this chart is in Watts per square meter per micron.

Watts is how we measure energy flow. We do this per square meter of the surface of the object that's radiating heat, as the heat comes from each part of its surface.



The first person to show experimentally that carbon dioxide acts as a heat-trapping gas was Eunice Foote in 1856. Her experiment used glass jars filled with different gases, left out in the sun to see which would heat faster/slower. She realized that her experiment showed that if the Earth had more CO2, the climate would be warmer.

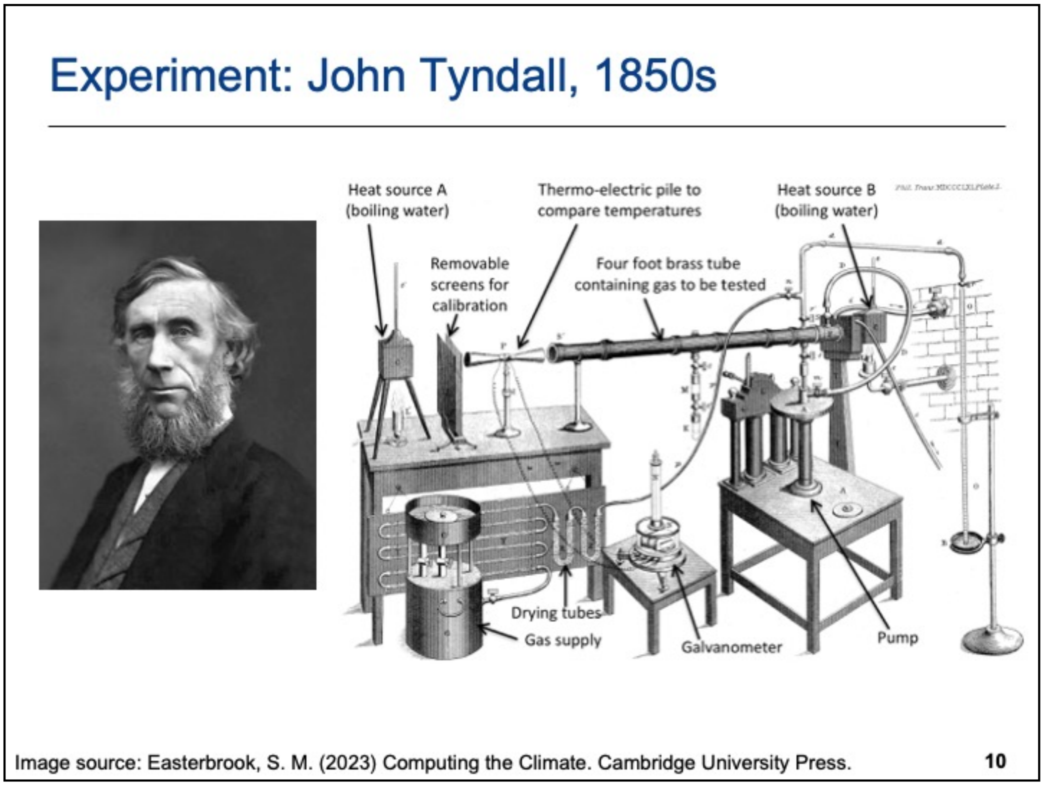
As a woman, she was not permitted to present her paper to the American Association for the Advancement of Science meeting, so another scientist had to present it for her.

And her work was forgotten entirely until a few years ago, when it was rediscovered.

She is certainly one of the "Hidden Figures" of climate science.

The film: https://www.youtube.com/watch?v=WxgAOKzOcBU

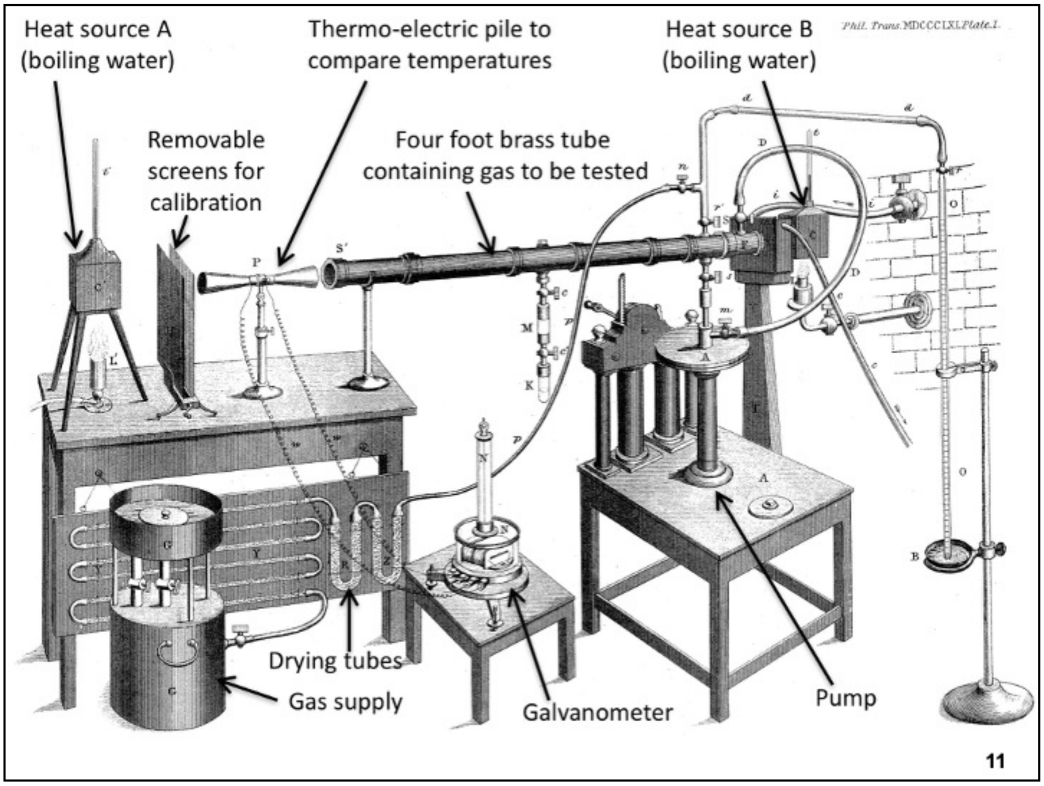
See also: https://www.nytimes.com/2020/04/21/obituaries/eunice-foote-overlooked.html



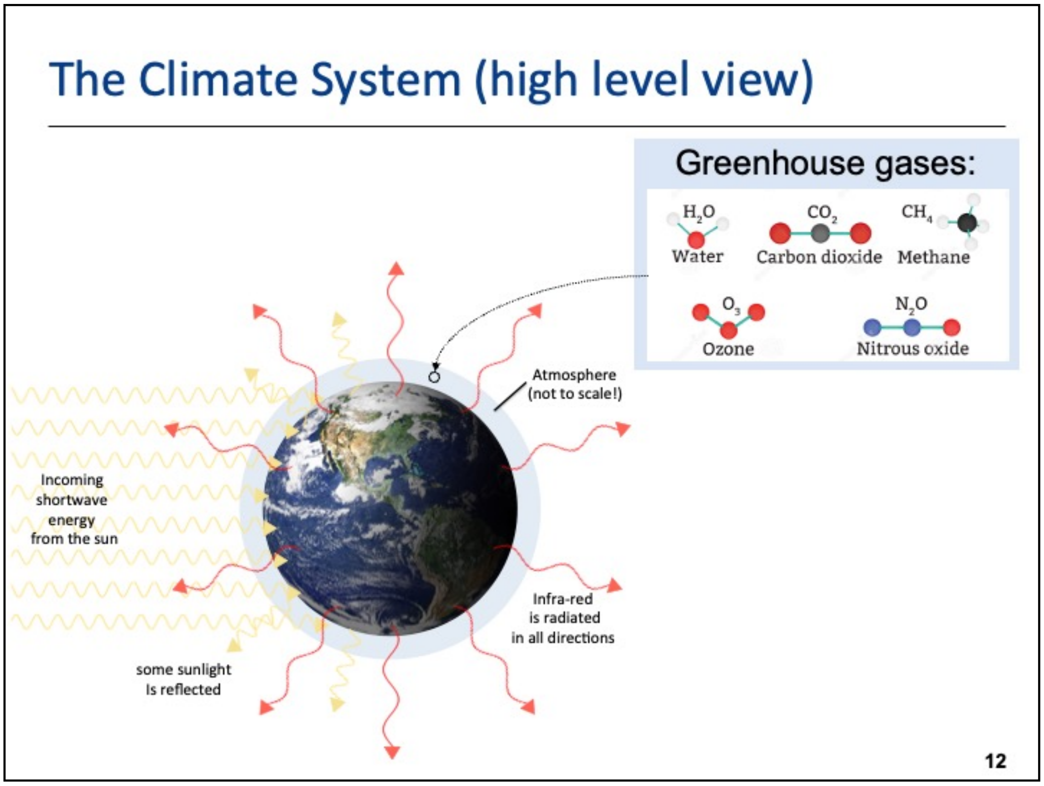
Tyndall's experiments, just a few years later, were the first to show the effect that Foote observed is because some gases block infra-red heat (his heat source in the experiments is a pot of boiling water).

He found that infra-red heat passes through oxygen and nitrogen easily, but that ethene, methane, and carbon dioxide all block the heat.

Note that at the ends of his brass tube, he used disks of polished salt crystals instead of glass, as infrared will not pass through glass.



Here's a closer look at his experimental set-up.



Any object that's warmer than its surroundings gives off rays, but the wavelength will depend on how hot the object is.

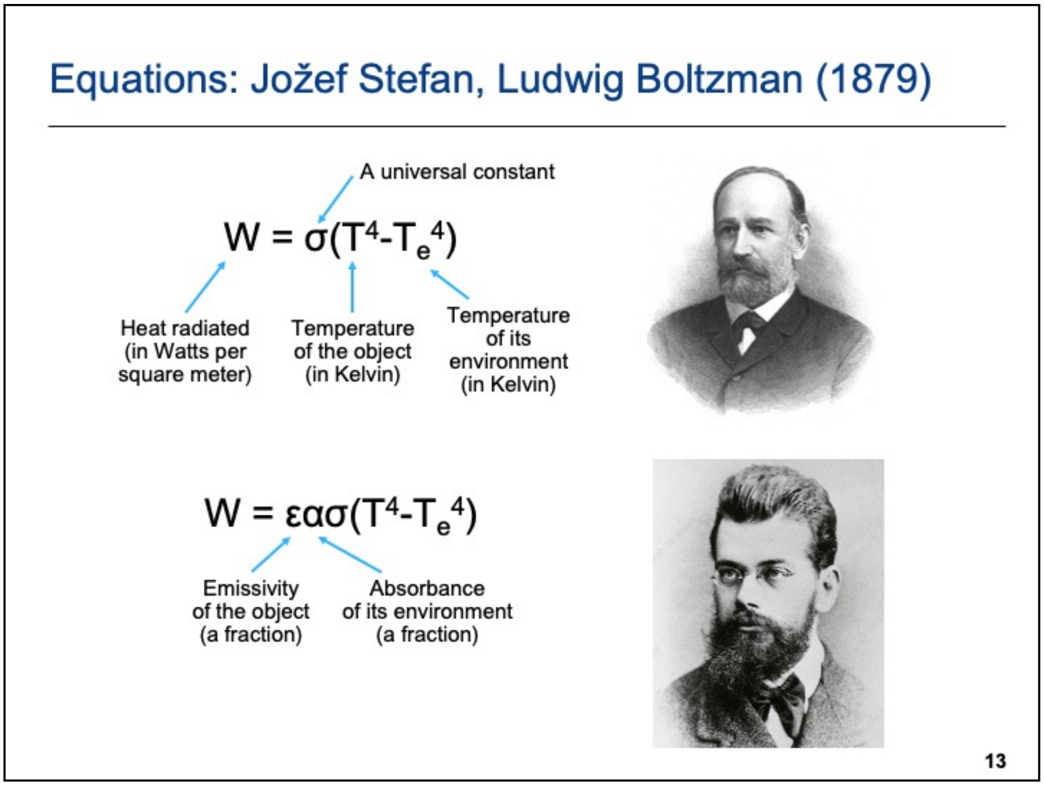
Very hot objects have a lot of energy, so when they radiate heat, it's at shorter wavelengths.

One way to think about it is to compare it with making waves in the water with a stick. If you put a lot of energy into it and jiggle the stick rapidly, the waves will be close together (shorter wave length). If you only put a little energy into it and move the stick slowly, the waves will be much further apart,

Because the sun is much hotter than the earth, the rays it gives off are much shorter wavelength.

The atmosphere is transparent to shortwave radiation from the sun, but opaque to (some parts of) the infrared rays emitted by the earth.

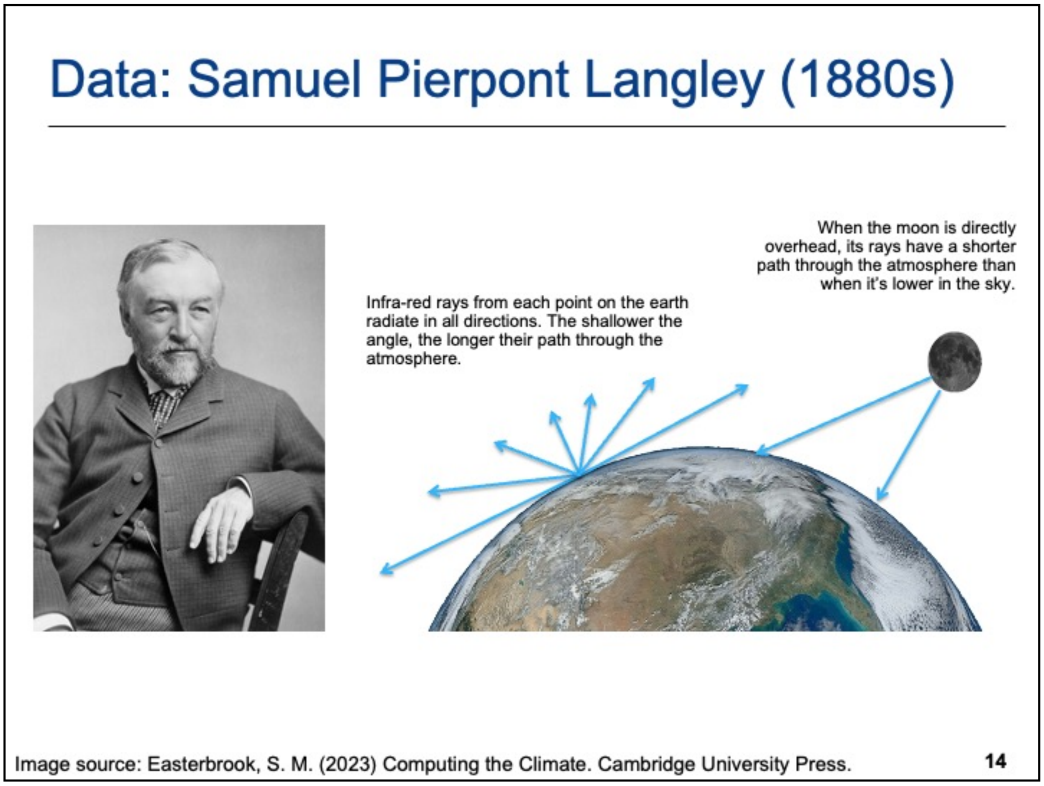
This means the earth's atmosphere acts as an insulator. The heat leaving the planet is slowed down by the greenhouse gases.



Another key ingredient for Arrhenius' model is a set of equations that describe how fast objects lose heat.

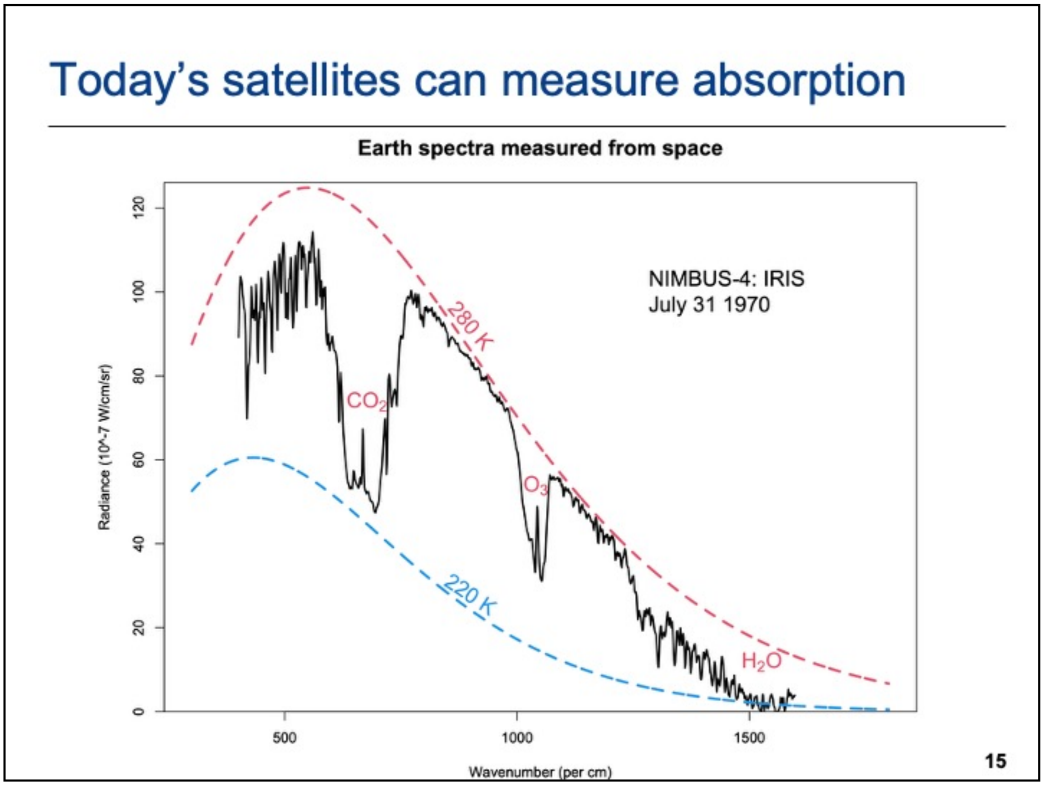
These were the key equations Arrhenius needed to calculate the relationship between the temperature of an object (in his case, planet Earth), and the rate at which it radiates heat to its environment. The equations say that you can work out how much heat (in Watts) will be given off from the surface of an object (per square meter) by looking at the difference in temperature between the object and its surroundings, and multiplying by a universal physical constant, known as the Stefan-Boltzman constant. Heat will always flow from a hotter object to a cooler one – the equations just tell you how fast this heat will flow.

Note: Don't worry if these equations don't make sense to you – just a bit of background to help explain how Arrhenius did his calculations.

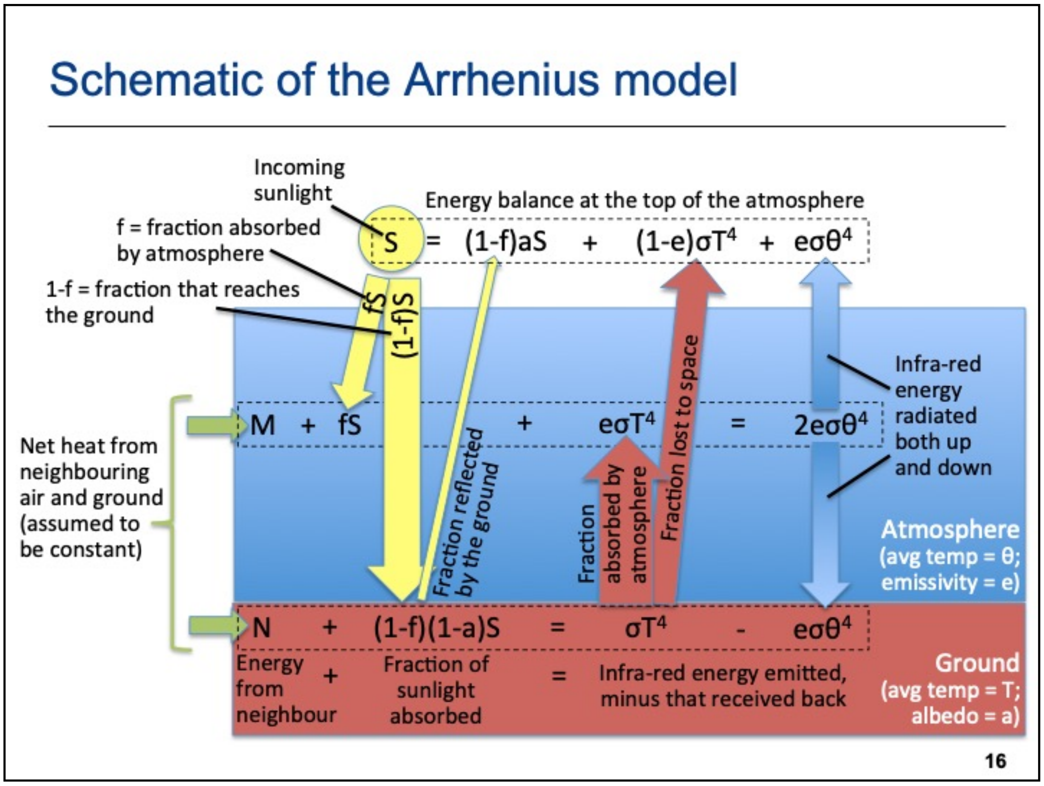


Finally, Arrhenius needed data about how much heat greenhouse gases actually absorb in the atmosphere. These he found in the observations from Samuel Pierpoint Langley.

Langley collected readings over several years of infra-red heat from the moon. As this has passed down through the atmosphere, some of it has been absorbed by the greenhouse gases. By looking at the readings when the moon is at different heights in the sky, Arrhenius was able to calculate the effect of different amounts of greenhouse gases – because longer paths through the atmosphere would be like the rays having passed through more of those gases.



This chart shows the fingerprint of greenhouse gases in our atmosphere. It was one of the first satellites to measure infra-red from the ground, in 1970. If the satellite is detecting IR waves from the ground, they would follow the red dotted curve – the emissions profile for 280Kelvin (about 7C, the temperature at ground level when these measurements were taken). But at some wavelengths, the amount of IR drops, closer to the 220K line in blue (aound -50C), the temperature of the upper atmosphere. At those wavelengths, greenhouse gases in the atmosphere have absorbed the infrared from the ground, so the satellite only sees the IR from the upper atmosphere, where it is much cooler.

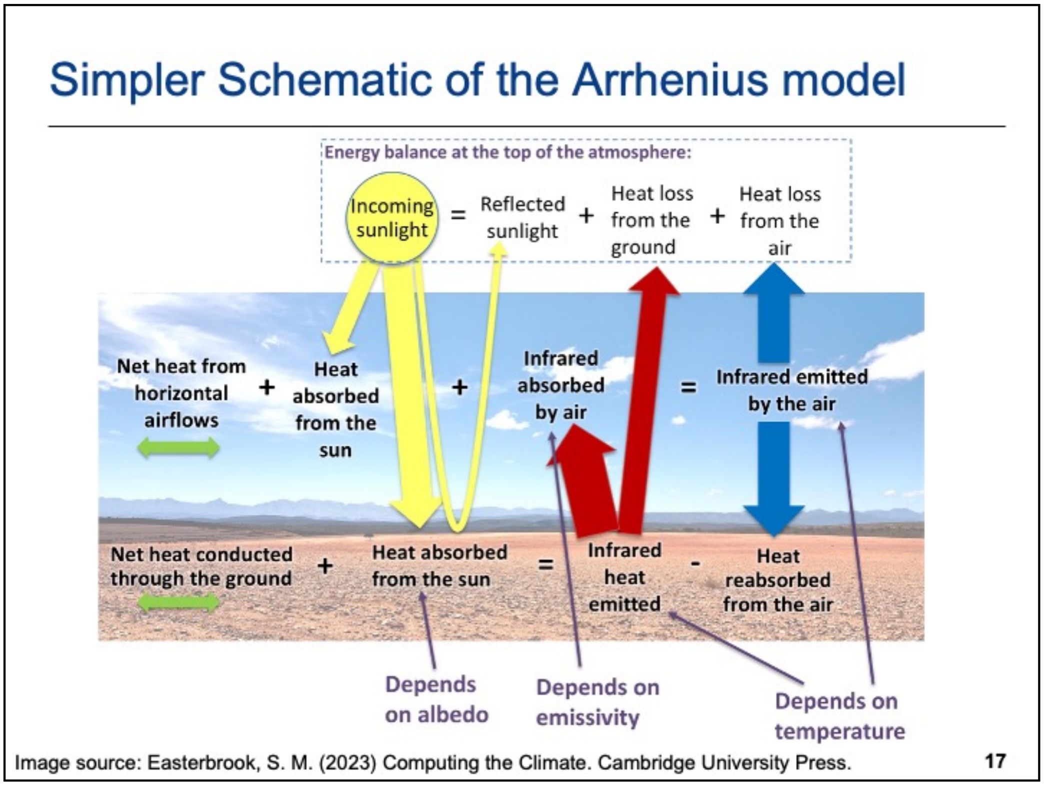


Here's how Arrhenius's model worked.

It's an equilibrium model: assume that over time (years) the planet must be in thermal equilibrium with its environment. In that state, inflows of energy must match outflows.

Note: No representation of time (how long does it take to change temperature in response to a change in the forcings?). Arrhenius included one feedback loop, water vapour, by repeating the calculations for adjusted humidity.

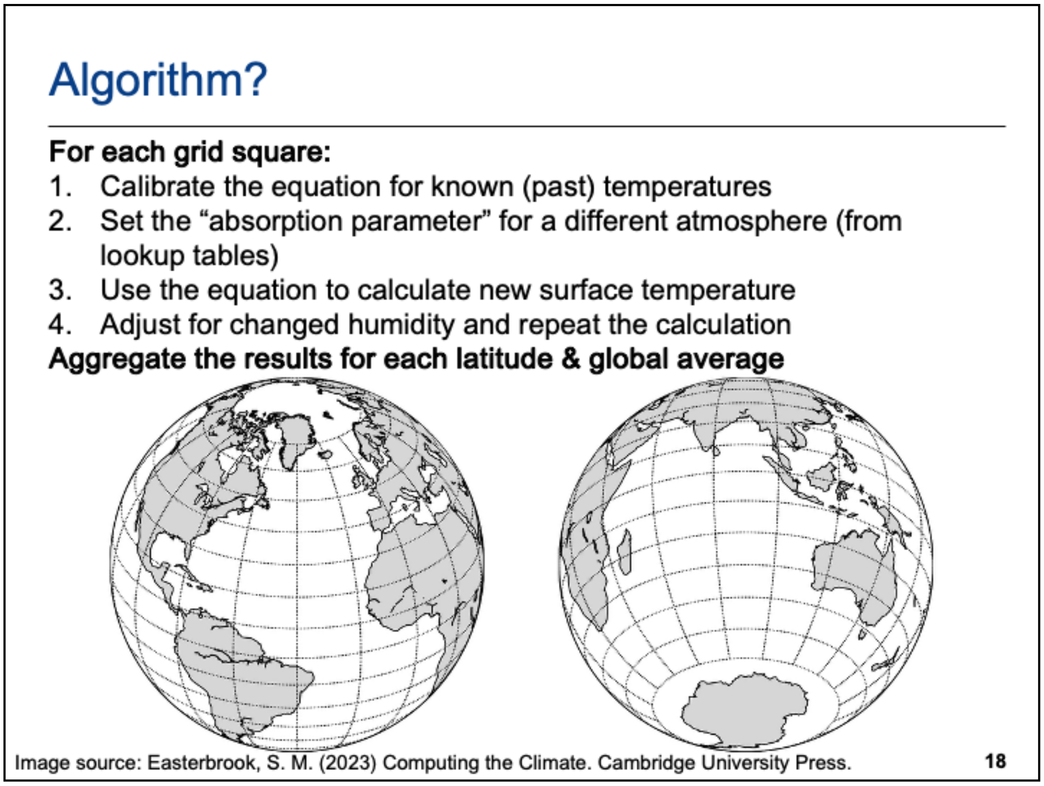
I originally drew this diagram to use in my book. Then I decided it was still to complicated, so I ended up using the diagram on the next slide…



Here's a closer look at how his model worked.

In each grid cell, he calculates the energy balance at the top of the atmosphere. In other words, he calculates what the temperature of the ground has to be, to balance incoming and outgoing energy at the top of the atmosphere. He treats the heat flows for horizontal transfer unknown constants, and rearranges the equations to turn these into a single unknown parameter. He then gets a value for this parameter by calibrating his model using existing weather data.

Once this is done, he re-computes the change if you alter the emissivity (e) of the atmosphere for different amounts of CO2 in the atmosphere.



So, his model tells him the relationship between the amount of greenhouse gases in the atmosphere, and the temperature of the ground.

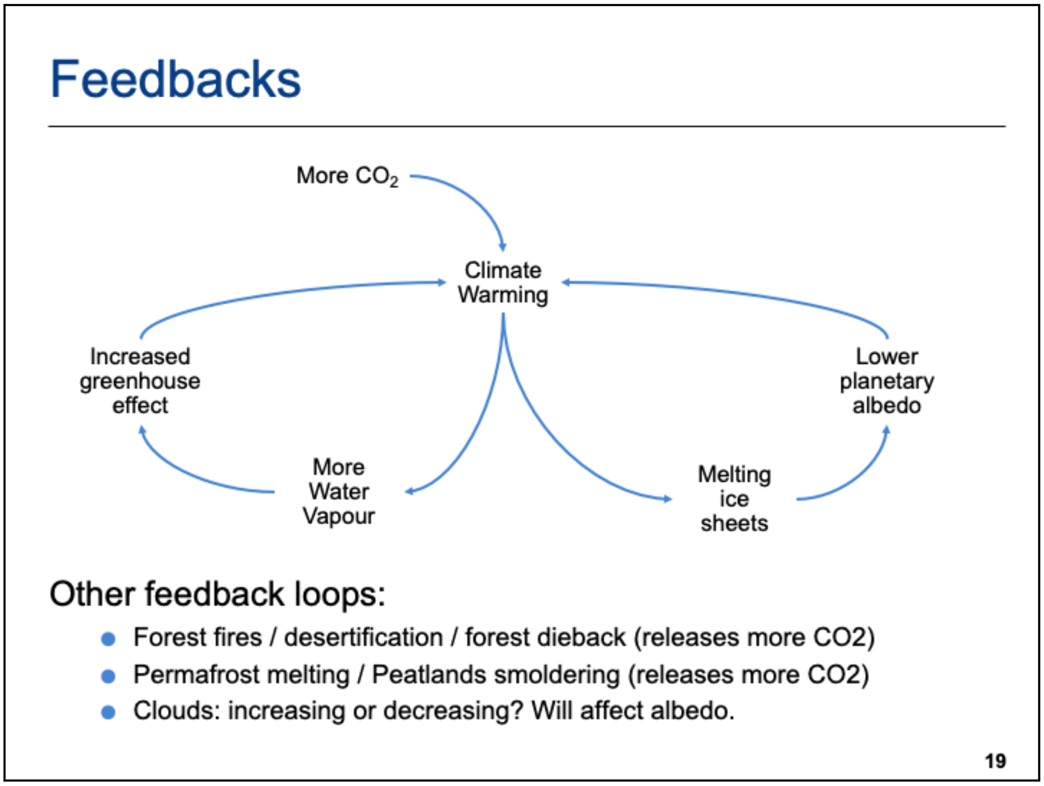
To do his calculations, he divided the earth up into grid cells, each 20 degrees of longitude by 10 degrees of latitude. He used published tables of average weather conditions for each grid cell. The published weather data omitted the polar regions, because scientists at the time didn’t have enough data from these parts of the world.

Arrhenius first calibrated his equation for typical conditions in each grid cell, for each season of the year.

He then re-calculated what the temperature would be if you changed the amount of carbon dioxide (again, for each grid cell, for each season of the year).

This gave him a number for the expected temperature increase (or decrease) for different amounts of carbon dioxide.

Some stats: about 3,000 data points, 3,120 separate calculations. Took him over a year, from December 1894 to January 1896.



Water Vapour and CO2 are the two most abundant greenhouse gases. There's about 100 times more water vapour in the atmosphere than CO2 (4% vs 0.04%). But water vapour stabilizes itself through evaporation and precipitation, so the amount depends only on the temperature of the air (warmer air will hold more moisture: about 7% more for each 1° C of temperature).

Arrhenius knew about these feedback effects. He included the water vapour feedback in his model by doing the calculations twice, the first time to calculate the warming from increased CO2, and the second time to calculate how much further warming you would get when the warmer air holds more moisture.

Arrhenius's Model "Outputs"

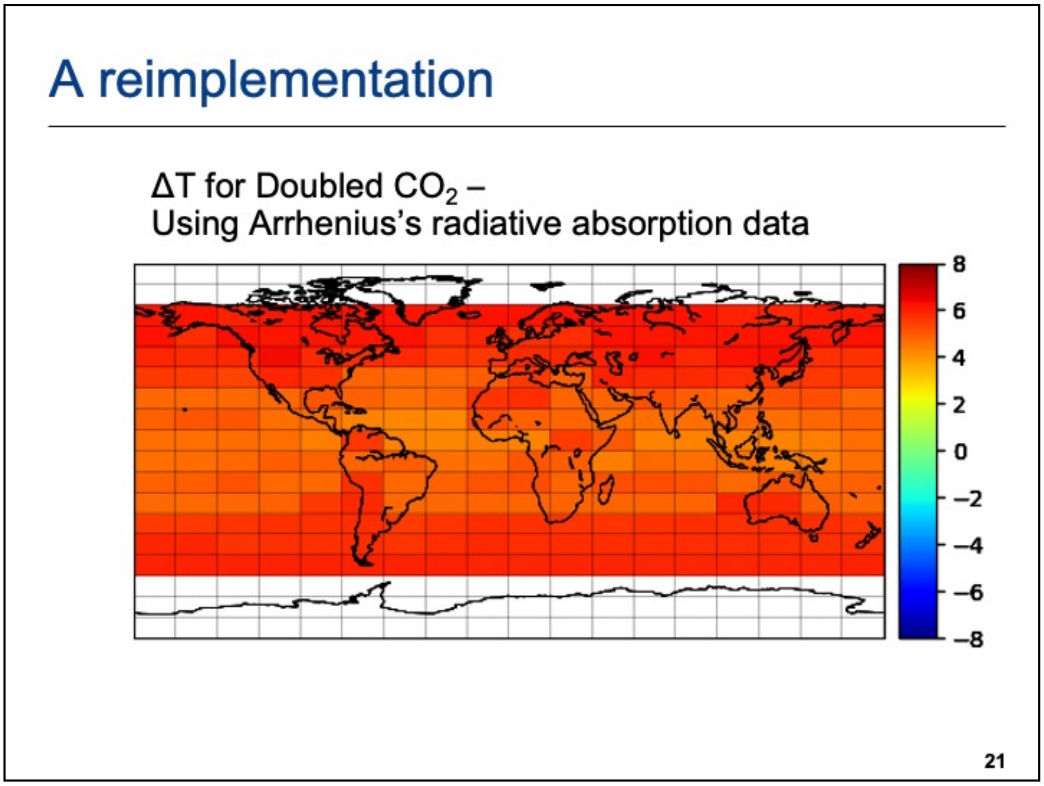
TABLE VII.—*Variation of Temperature caused by a given Variation of Carbonic Acid.*

Latitude.	Carbonic Acid=0·67.					Carbonic Acid=1·5.				
	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.
70–60	−2·9	−3·0	−3·4	−3·1	−3·1	3·3	3·4	3·8	3·6	3·52
60–50	−3·0	−3·2	−3·4	−3·3	−3·22	3·4	3·7	3·6	3·8	3·62
50–40	−3·2	−3·3	−3·3	−3·4	−3·3	3·7	3·8	3·4	3·7	3·65
40–30	−3·4	−3·4	−3·2	−3·3	−3·32	3·7	3·6	3·3	3·5	3·52
30–20	−3·3	−3·2	−3·1	−3·1	−3·17	3·5	3·3	3·2	3·5	3·47
20–10	−3·1	−3·1	−3·0	−3·1	−3·07	3·5	3·2	3·1	3·2	3·25
10–0	−3·1	−3·0	−3·0	−3·0	−3·02	3·2	3·2	3·1	3·1	3·15
0–−10	−3·0	−3·0	−3·1	−3·0	−3·02	3·1	3·1	3·2	3·2	3·15
−10–−20	−3·1	−3·1	−3·2	−3·1	−3·12	3·2	3·2	3·2	3·2	3·2
−20–−30	−3·1	−3·2	−3·3	−3·2	−3·2	3·2	3·2	3·4	3·3	3·27
−30–−40	−3·3	−3·3	−3·4	−3·4	−3·35	3·4	3·5	3·7	3·5	3·52
−40–−50	−3·4	−3·4	−3·3	−3·4	−3·37	3·6	3·7	3·8	3·7	3·7
−50–−60	−3·2	−3·3	—	—	—	3·8	3·7	—	—	—

Latitude.	Carbonic Acid=2·0.					Carbonic Acid=2·5.					Carbonic Acid=3·0.				
	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.
70–60	6·0	6·1	6·0	6·1	6·05	7·9	8·0	7·9	8·0	7·95	9·1	9·3	9·4	9·4	9·3
60–50	6·1	6·1	5·8	6·1	6·02	8·0	8·0	7·6	7·9	7·87	9·3	9·5	8·9	9·5	9·3
50–40	6·1	6·1	5·5	6·0	5·92	8·0	7·9	7·0	7·9	7·7	9·5	9·4	8·6	9·2	9·17
40–30	6·0	5·8	5·4	5·6	5·7	7·9	7·6	6·9	7·3	7·42	9·3	9·0	8·2	8·8	8·82
30–20	5·6	5·4	5·0	5·2	5·3	7·2	7·0	6·6	6·7	6·87	8·7	8·3	7·5	7·9	8·1
20–10	5·2	5·0	4·9	5·0	5·02	6·7	6·6	6·3	6·6	6·52	7·9	7·5	7·2	7·5	7·52
10–0	5·0	5·0	4·9	4·9	4·95	6·6	6·4	6·3	6·4	6·42	7·4	7·3	7·2	7·3	7·3
0–−10	4·9	4·9	5·0	5·0	4·95	6·4	6·4	6·6	6·6	6·5	7·3	7·3	7·4	7·4	7·35
−10–−20	5·0	5·0	5·2	5·1	5·07	6·6	6·6	6·7	6·7	6·65	7·4	7·5	8·0	7·6	7·62
−20–−30	5·2	5·3	5·5	5·4	5·35	6·7	6·8	7·0	7·0	6·87	7·9	8·1	8·6	8·3	8·22
−30–−40	5·5	5·6	5·8	5·6	5·62	7·0	7·2	7·7	7·4	7·32	8·6	8·7	9·1	8·8	8·8
−40–−50	5·8	6·0	6·0	6·0	5·95	7·7	7·9	7·9	7·9	7·85	9·1	9·2	9·4	9·3	9·25
−50–−60	6·0	6·1	—	—	—	7·9	8·0	—	—	—	9·4	9·5	—	—	—

Arrhenius, S. (1896). On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground. 20

Arrhenius did his calculations for each grid square, and then calculated an average for each latitude of the planet. This table shows the latitude averages. The middle row (0) represents the equator. The rows above this show the northern hemisphere – every ten degrees, while the lower half of the table shows the southern hemisphere. Note that he's missing results for the regions around the North and South poles, as he didn't have data at the time for these parts of the planet.



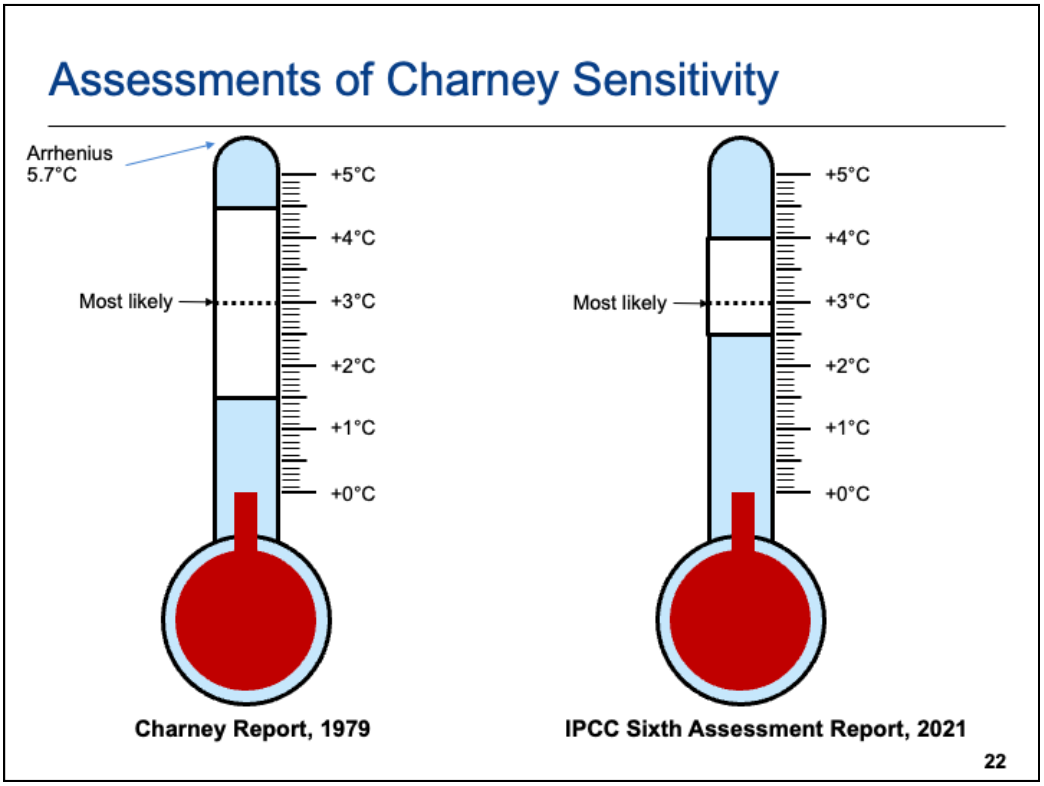
My students recently re-implemented Arrhenius's model in Python code, using all of Arrhenius's original data (he published all the data in his papers).

We got exactly the same results, shown here for doubled CO2.

If you look carefully, you can see that towards the poles you get more warming than near the equator.

You can also see that the land areas warm a little more than the oceans (see the darker grid cells over Africa and Australia, for example).

Both of these are correct predictions: both effects have been observed in recent global warming.



So how does Arrhenius' model (in 1894!) compare to modern assessments of Charney sensitivity? He's not out by much!

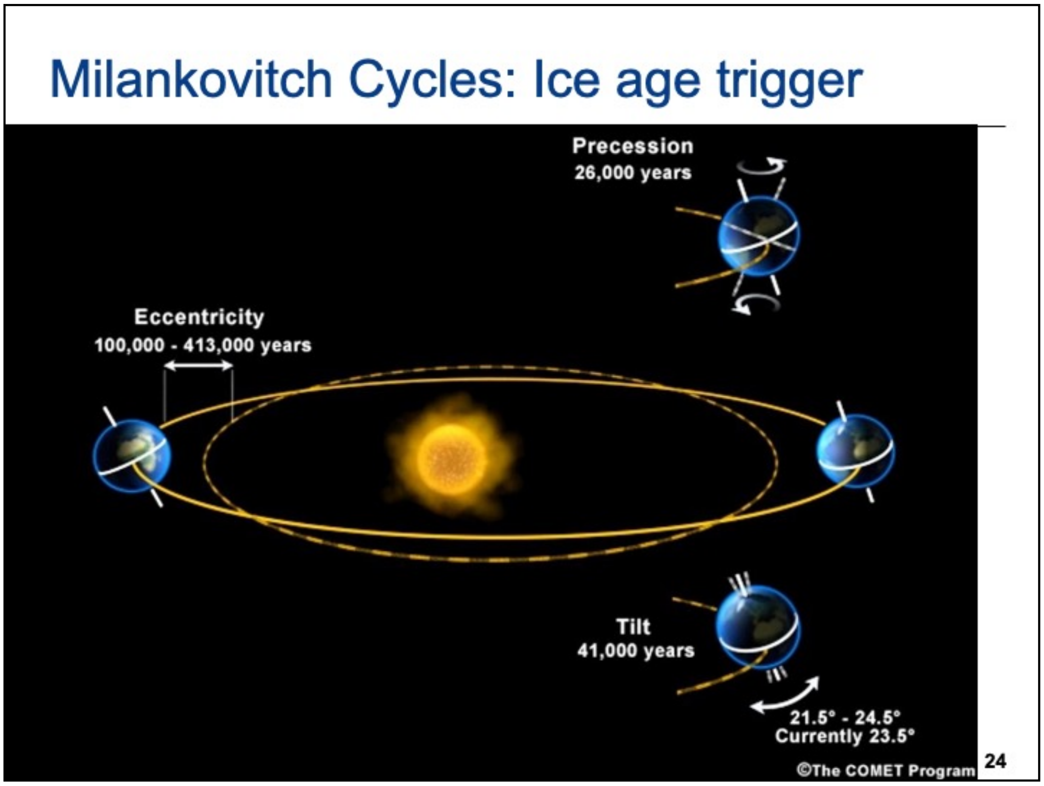
Arrhenius's predictions

- More warming over land than ocean
- More warming in the northern hemisphere
- More warming towards the poles
- More warming in the winter than summer
- More change in nighttime temperature than daytime

> "If carbonic acid content rises, temperature differences between land and sea, between summer and winter, between night and day, and between equator and temperate zones will be levelled out, at least for habitable parts of the Earth's surface. The reverse will be true if the carbonic acid content diminishes."
>
> **- Svante Arrhenius lecture, Feb 3, 1896**

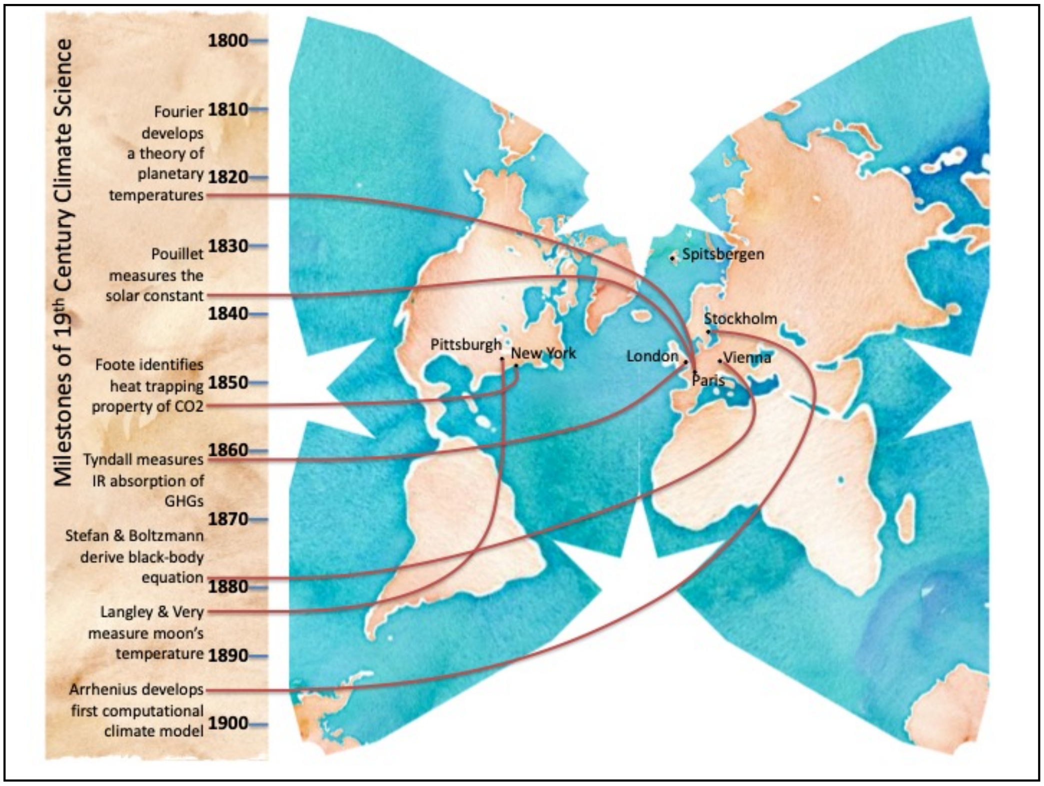
23

All of these predictions have come true.



For nearly a century, Arrhenius's theory about what caused the ice ages was ignored. In part because a few years later, Milankovitch showed that the icea ages are triggered by the interaction of three different cycles in the earth's orbit.

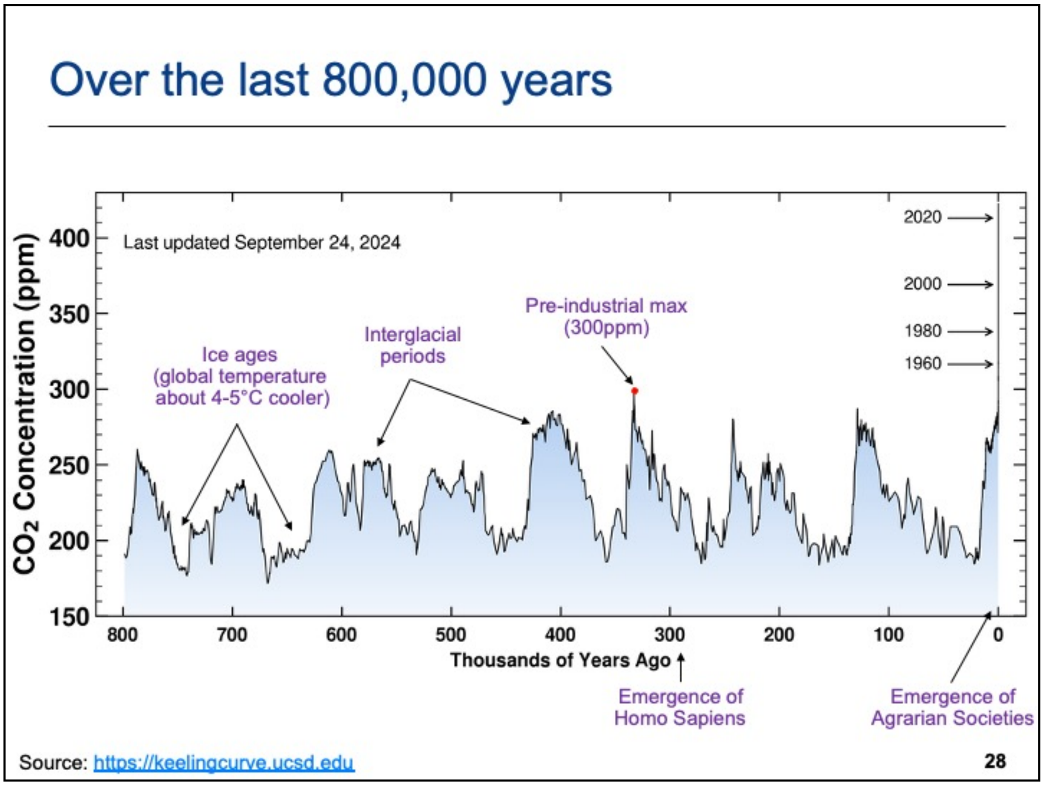
But in the 1990's, ice cores drilled down deep into the Antarctic ice showed Arrhenius was right. As you go deeper down into the ice sheets, the ice gets older and older. A 2km deep ice core goes back 800,000 years, far enough to cover several cycles of ice ages. And bubbles trapped in this old ice showed that there was about 2/3 of the amount of CO2 in the atmosphere as there is today, just as Arrhenius predicted.



Here's a summary of the key milestones we talked about today.

Photo: Killarney Provincial Park, Sept 2020

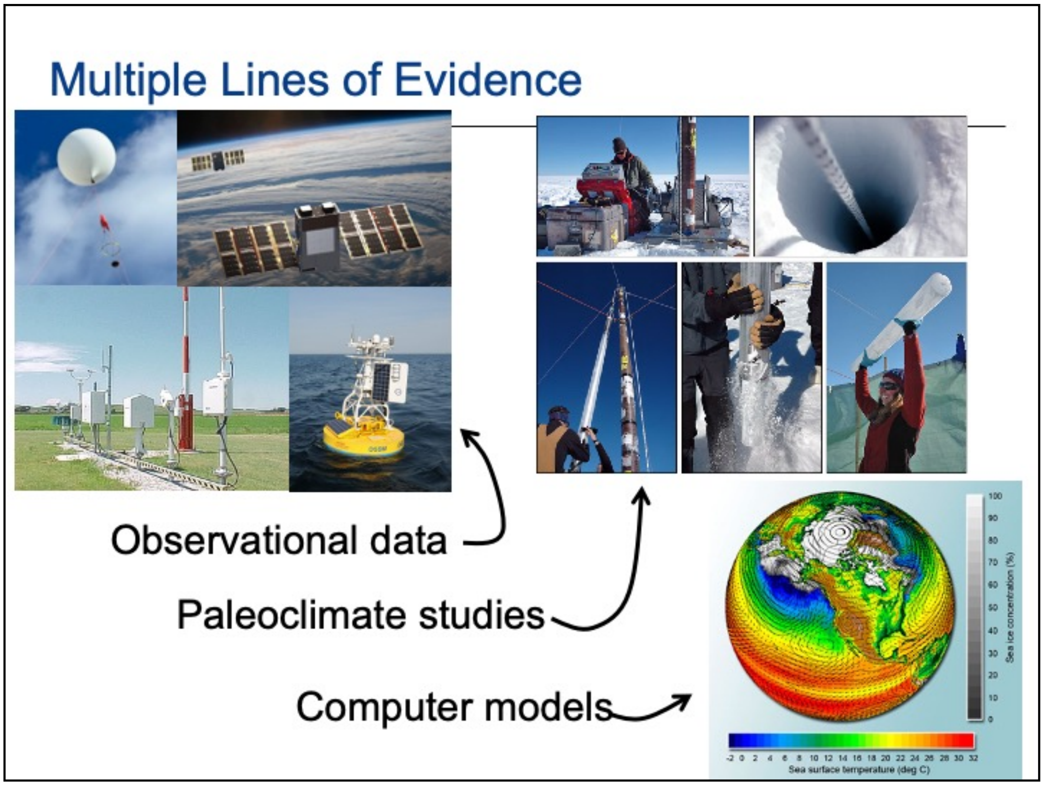
Bonus Slides (use as needed)



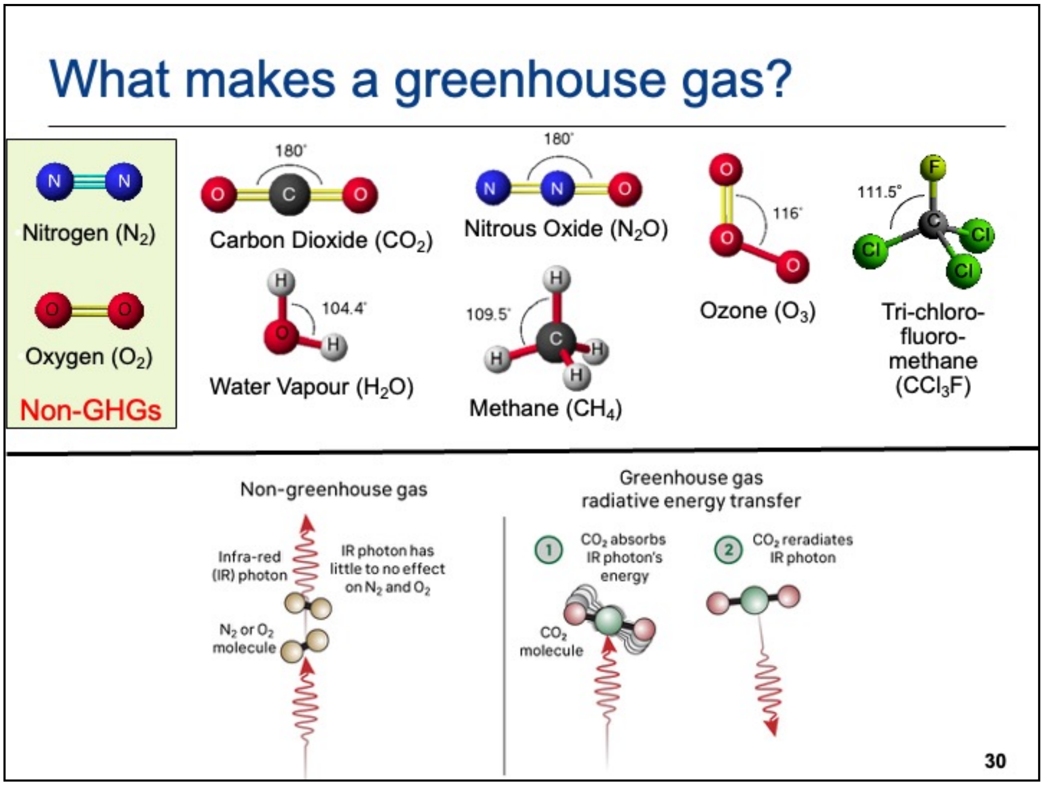
I showed this slide in week 1, but it adds nearly a million years to the previous slide.

If you go back over the last (nearly) 1 million years, the amount of CO2 was often much lower, and that caused the ice ages.

Think about how different the planet was in the ice ages to the interglacial periods. And then think about how the new climate we're creating might be different again from the climate in which human civilization grew up (the last 10,000 years)



We didn't know how good Arrenhius's model was until nearly 100 years later, with data from satellites that could measure the heat flows, and from bubbles trapped in the ice in the Antarctic, which showed that there was indeed less carbon dioxide in the atmosphere during the ice ages.

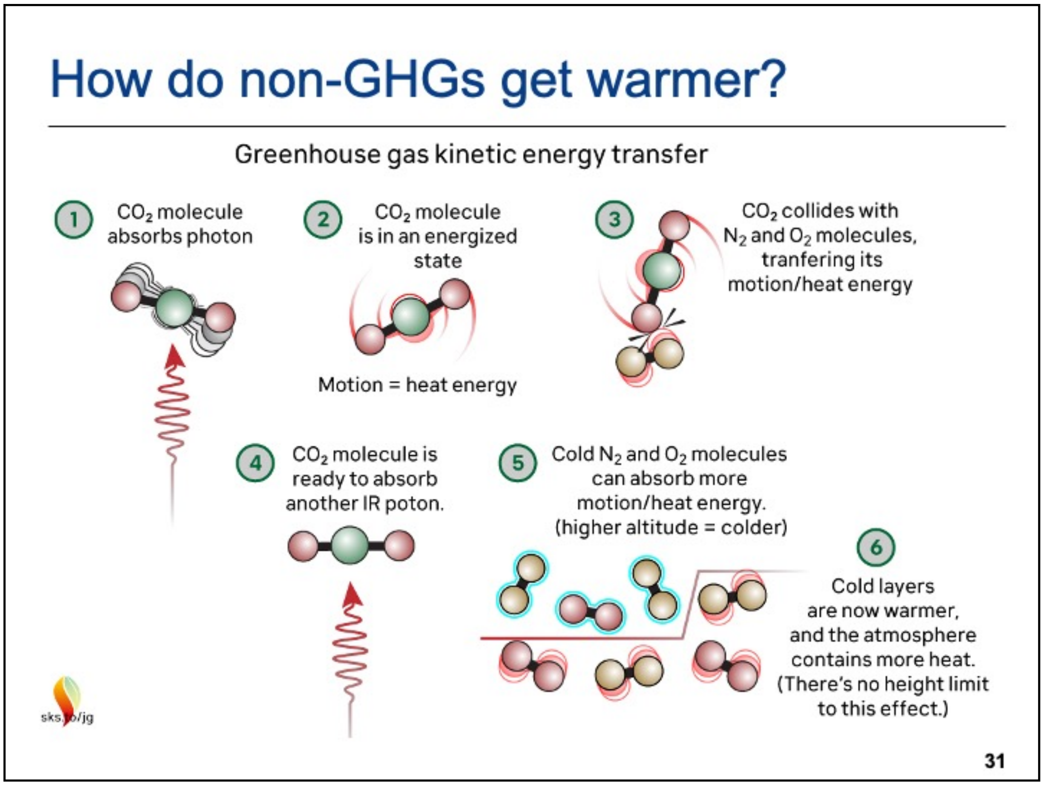


Most of the atmosphere (nearly 80%) is Nitrogen. Most of the rest (nearly 20%) is Oxygen.

Water vapour changes depending on how humid it is, but typically 2-3%.

All the others are trace gases, less than 1%. For example, CO2, at 425 parts per million is 0.04% of the atmosphere.

But these greenhouse gases have a big effect on how heat moves through the atmosphere



If only the greenhouse gas molecules absorb infrared, and then they emit it again, how come all of the atmosphere warms up, including the non-greenhouse gases?

The answer is that some of the heat absorbed by the CO2 molecules is transferred to other gas molecules when they collide.