Photo: Killarney Provincial Park, Sept 2020

Climate Change:
What we know and how we know it
Week 1: Introduction

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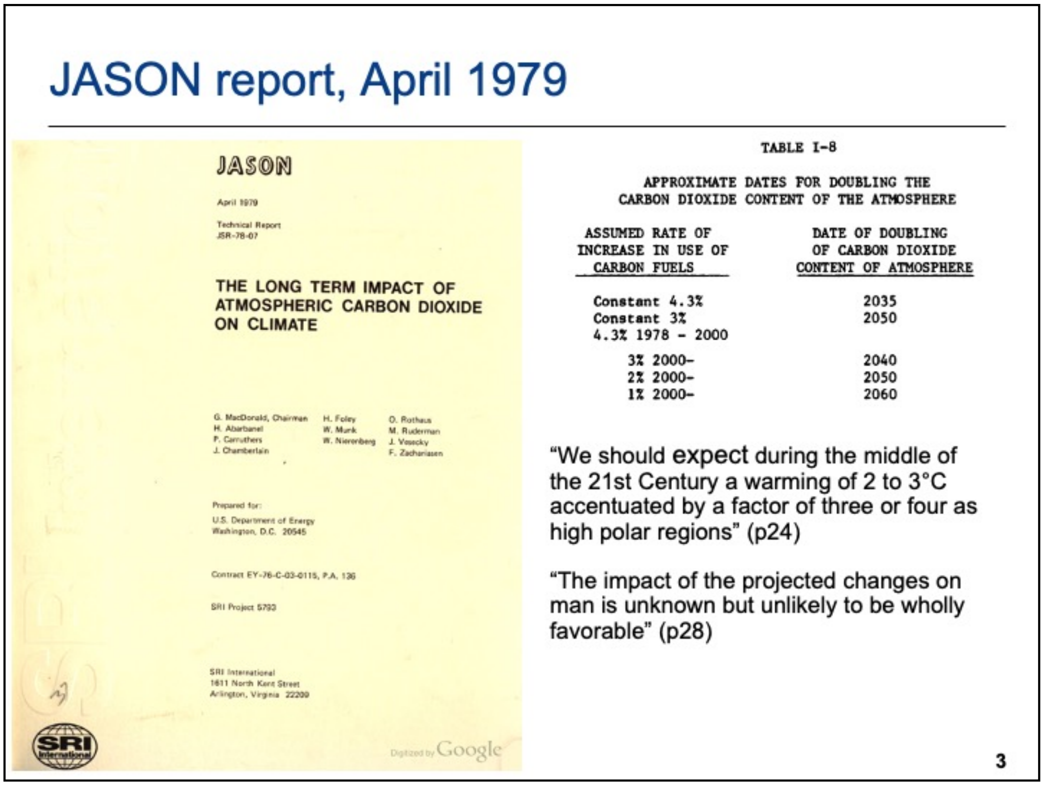
President Jimmy Carter, and Science Advisor Frank Press (White House Photograph, courtesy of AIP)

I want to begin with a teaser. In 1979, US President Jimmy Carter posed a question to the scientific community: how precise are the predictions about future climate change?

Here he is pictured in the White House with his science advisor, Frank Press, reviewing Press's textbook "Earth", which was published in 1978. I haven't dated this photo, but I wonder if this is a later photo, as Carter looks older here than when he was president. Anyway, I digress.

The reason Carter was asking the question was because an alarming report has landed on his desk, and the implications were serious: within 50-100 years, the US could be facing devastating dustbowl conditions again, as a result of rising greenhouse gases.

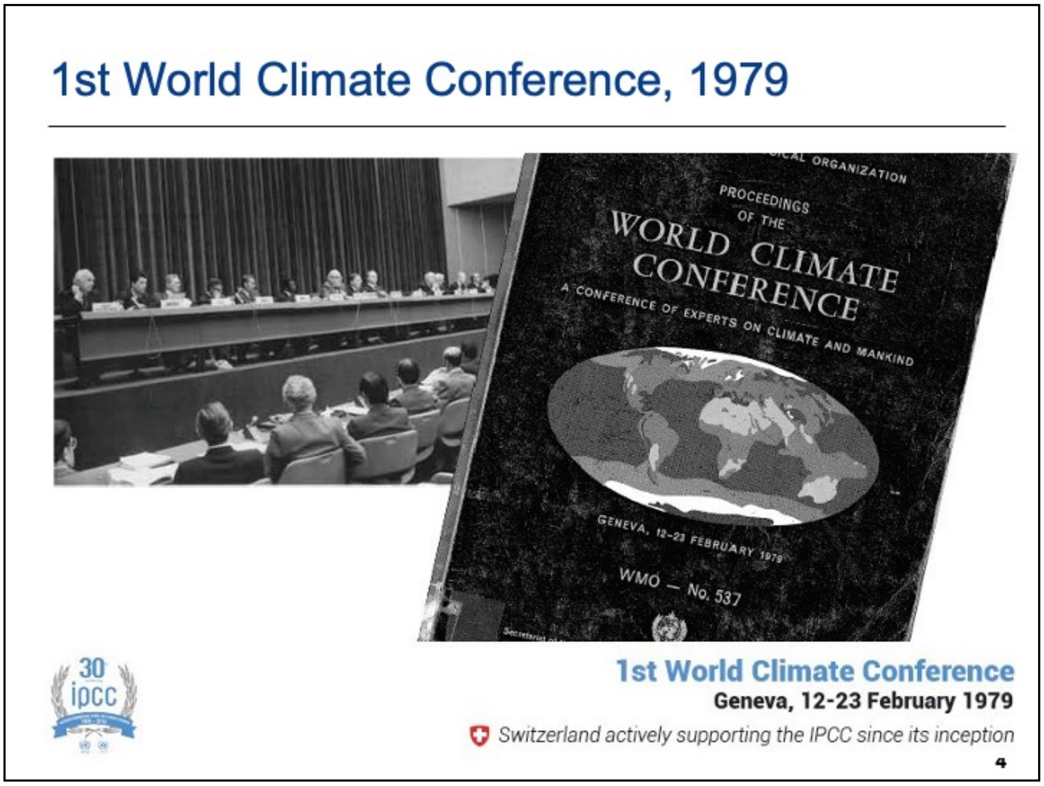
Notice the question he's asking isn't "is climate change real". There really wasn't any doubt in the scientific community, even in the 1970s. The question he's asking is about how to quantify the uncertainty.



The report President Carter was reacting to is this one: A study by the JASON group, an advisory panel of 40 of the most distinguished scientists in the US, set up to advice the Pentagon on science and technology matters in 1960 in the aftermath of Sputnik.

Named after the mythological character Jason. Most of their work is still classified, and much of it concerned the threat of nuclear weapons in the cold war.

The group has built its own climate model, and reported on the outcome. They anticipated that by the middle of the 21st century, the amount of CO_2 in the atmosphere could double, and would cause global temperatures to rise by 2 to 3 degrees. Their report is very light what this would mean, although it speculates on some of the consequences – especially the impact on agriculture.



1979 was an auspicious year anyway for the study of climate change. The World Meteorological Organization (WMO) held the first international conference on climate change in Geneva, and proposed a massive worldwide effort, the World Climate Program – designed to be a 20 year collaborative effort to study the causes and consequences of climate change. It's still running today.

US President Jimmy Carter speaking in front of solar panels placed on the West Wing Roof of the White House, June 20, 1979 (photo: Universal History Archive)

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Carter originally trained as an engineer, and didn’t shy away from scientific and environmental issues. He was the first president to install solar panels on the roof of the White House, partly in reaction to the energy crisis of the 1970s, and partly because of growing concerns about pollution from fossil fuels. Here he is posing in front of the panel on the West Wing in 1970. Notice that the panels a white – they were specially designed to fit in with the overall aesthetic of the White House. Despite an anticipated life of 30+ years, they were torn down by President Reagan in the mid-1980s. Several of them are now in museums around the world.

For background on the solar panels, see: https://www.scientificamerican.com/article/carter-white-house-solar-panel-array/

National Academies Summer Retreat

Photos: Steve Easterbrook 2013

1) “What is the basis for our scientific understanding of climate change?”
2) “Can the adequacy and uncertainty of this knowledge be quantified?”
3) “What are the key issues that policymakers need to be aware of?”

- Presidential Science Advisor Frank Press, 1979

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So, to answer the President’s question, the National Academy of Sciences convened a summer working group in August 1979, to address these questions. It met at the Jonsson Centre, a grand Victorian house in Cape Cod, not far from the Woods Hole Oceanographic institute. Overlooks Quisset Harbor.

We’ll come back to the working group later in this talk, and look at how they answered these questions.

About me

- U of T Professor in Computer Science (since 1999)
- Director of the School of the Environment (since 2018)
- I study how climate models are built and used
- Originally from the UK
  - Undergrad at the U. of York;
  - PhD at Imperial College London
- In my spare time:
  - Canoeing, kayaking, camping, gardening, cooking, making tie-dye, playing board games

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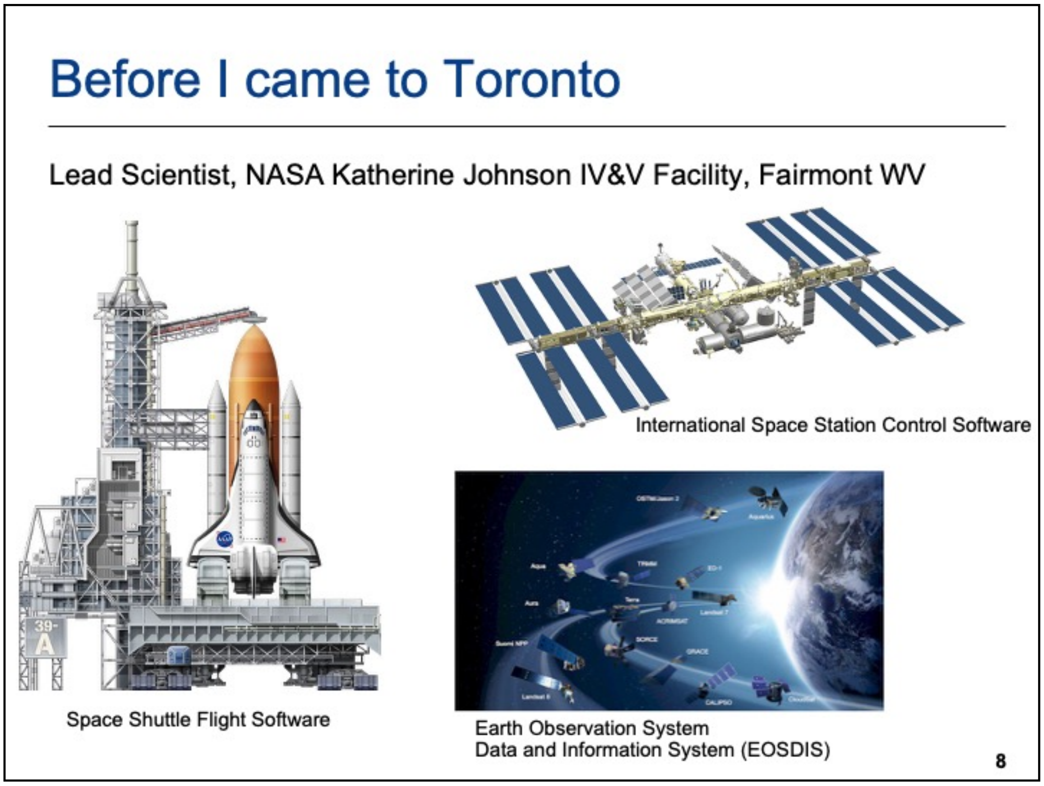
That’s a photo of me, kayaking on the Bay of Fundy.



The Katherine Johnson facility is named after one of the heroes of the Apollo missions to the moon. Katherine Johnson led the team that did the calculations for Apollo trajectories and orbits, and her story is the subject of the movie Hidden Figures.

Venice, during Acqua Alta, October 2010 (Photo: Steve Easterbrook)

So how did I get interested in climate modeling? I was looking for a new challenge after moving to Toronto to take up a position as a professor at U of T. In Toronto, we started a family, and I began to think about my kids' future. Here they are, in Venice, in 2010, during Acqua Alta, when the high fall tides flood the city. Venice is sinking (slowly), and the seas are rising due to climate change. Many more cities will look like this in the future. It got me thinking about how we know what this climate changed future will look like.

Golden, Colorado in the aftermath of the Four Mile Canyon Fire, October 29, 2010 (Photo: Steve Easterbrook)

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That same year, we witnessed another impact of climate change. I spent a few months in Colorado, visiting the National Centre for Atmospheric Research, in Boulder, and we rented a house up in the mountains, near a small town called Golden. A week before we were due to arrive, a forest fire ripped through the entire area, and for a few days we didn't know if the house we had arranged to rent would still be there. Luckily for us it was, although the neighbour's houses on both sides had burnt to the ground. We learnt a lot about forest fires that year.

I began my work with climate modeling via a series of ethnographic studies of how climate scientists build climate models. I started these studies expecting to be able to help the climate modelers with better software engineering techniques. While some of the software engineering is very ad hoc, for the bigger models, the labs have developed a very disciplined software development process. I published a few papers analyzing the software, but then wondered what to do with everything else I had learned.

My initial research questions

- How do scientists assess "correctness" of the code?
- How do they ensure experiments can be reproduced?
- How do they maintain a shared understanding?
- How do they prioritize model developments?
- How do they detect/prevent errors in the software?

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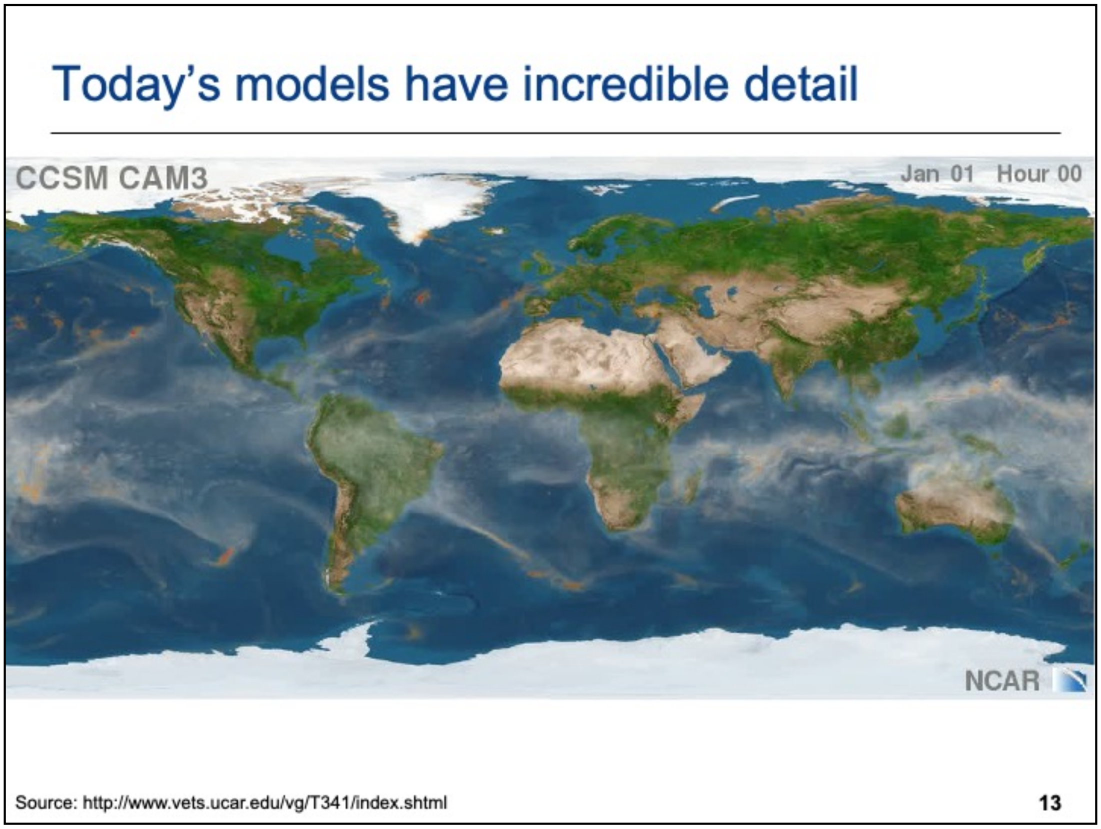
Especially interested in how they establish correctness of the code, repeatability of experiments, modularity of large software, and how the teams develop shared understanding.



The result is detailed simulations of the dynamics of weather and climate. For example, this simulation shows precipitation (heavy rain is orange, light rain is white) for a typical August month. Note: it doesn't represent an actual August – it shows typical conditions under current climate. The model can then be used to study how these patterns might change as the climate changes.

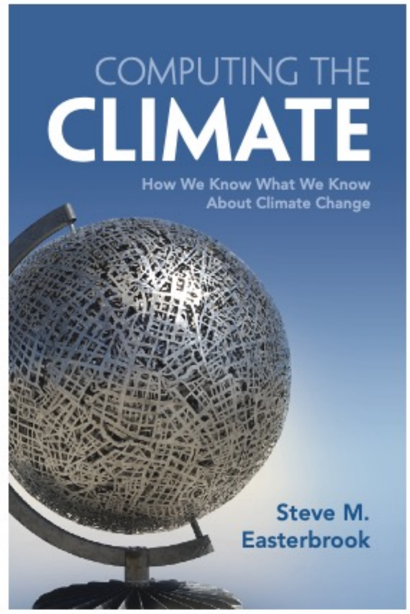
Read the book!

"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

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Themes

- Modern climate models are an incredible accomplishment
  - Tell the story of climate science's long history
  - Show how it connects (in a deep way) with many other branches of science
  - Show how climate modeling intertwines with the history of modern computing
- Computational models enable inter-disciplinary collaboration
  - Show how scientists from many different fields contribute
  - Bring alive the scientists who build and work with these models
- All models are wrong, but some are useful
  - Climate models not necessary to prove anthropogenic climate change…
    …but they allow us to test and deepen our understanding
  - Explain how we get valid knowledge from incomplete models
  - Explore how scientists know when to trust (and when to mistrust) their models

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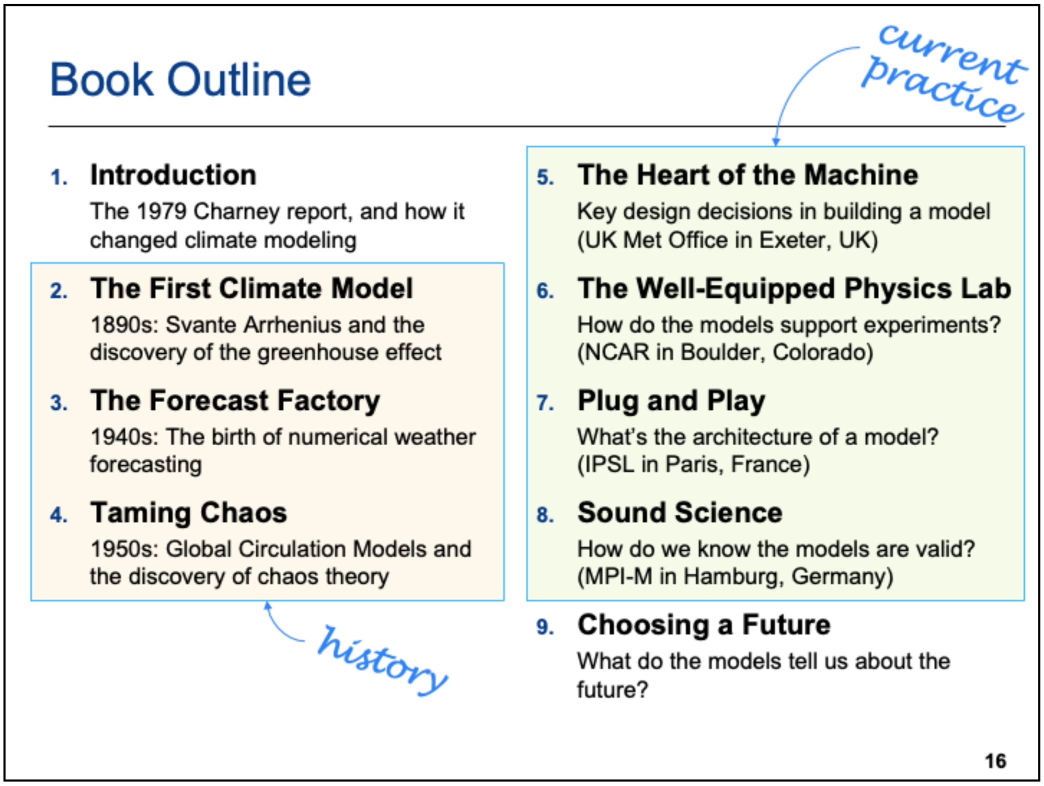
Book Outline
current practice
1. Introduction
The 1979 Charney report, and how it changed climate modeling
2. The First Climate Model
1890s: Svante Arrhenius and the discovery of the greenhouse effect
3. The Forecast Factory
1940s: The birth of numerical weather forecasting
4. Taming Chaos
1950s: Global Circulation Models and the discovery of chaos theory
history
5. The Heart of the Machine
Key design decisions in building a model (UK Met Office in Exeter, UK)
6. The Well-Equipped Physics Lab
How do the models support experiments? (NCAR in Boulder, Colorado)
7. Plug and Play
What's the architecture of a model? (IPSL in Paris, France)
8. Sound Science
How do we know the models are valid? (MPI-M in Hamburg, Germany)
9. Choosing a Future
What do the models tell us about the future?
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Recap: A Question from the White House

President Jimmy Carter, and Science Advisor Frank Press (White House Photograph, courtesy of AIP)

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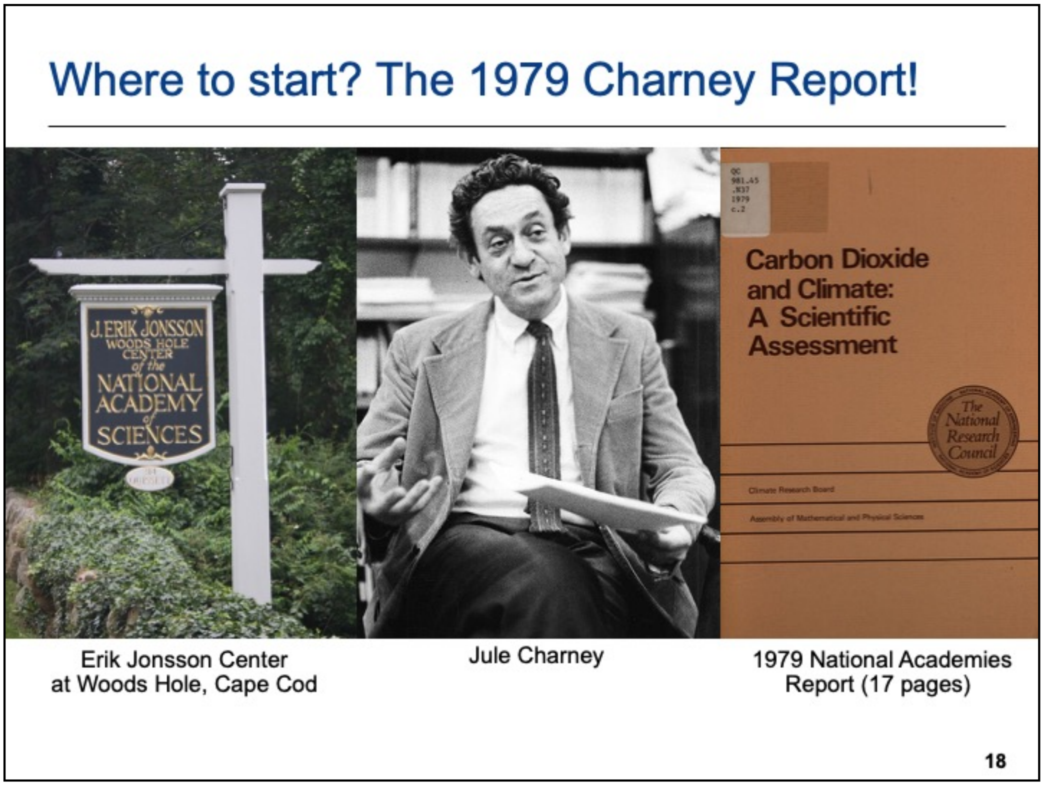
So, back to that question from Jimmy Carter in 1979. How do we assess the uncertainty in climate model projections?



I picked this question as the starting point for my book, and for this lecture series because the answer to it marked a major turning point in the science of climate modeling. In response to President Carter's question, the National Academies assembled a working group under the leadership of Jule Charney, regarded at the time as the "*father of modern dynamical meteorology*". We'll study his work in more detail in a couple of week's time.

Charney's committee met for a week in the summer of 1979 at the Erik Jonsson Centre, a beautiful Victorian house overlooking the Quisset harbour, just up the road from the Woods Hole Oceanographic Institute on Cape Cod.

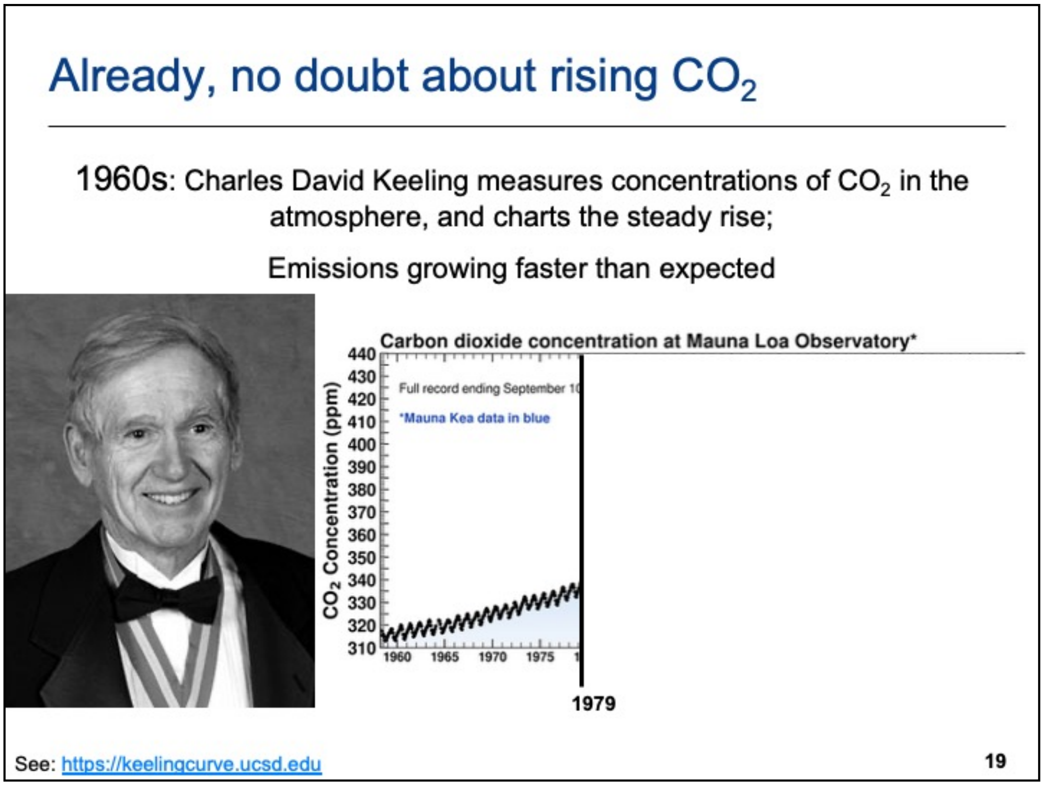
Jule Gregory Charney (1917-1981)

Known as the *"father of modern dynamical meteorology"*

1946 PhD at UCLA

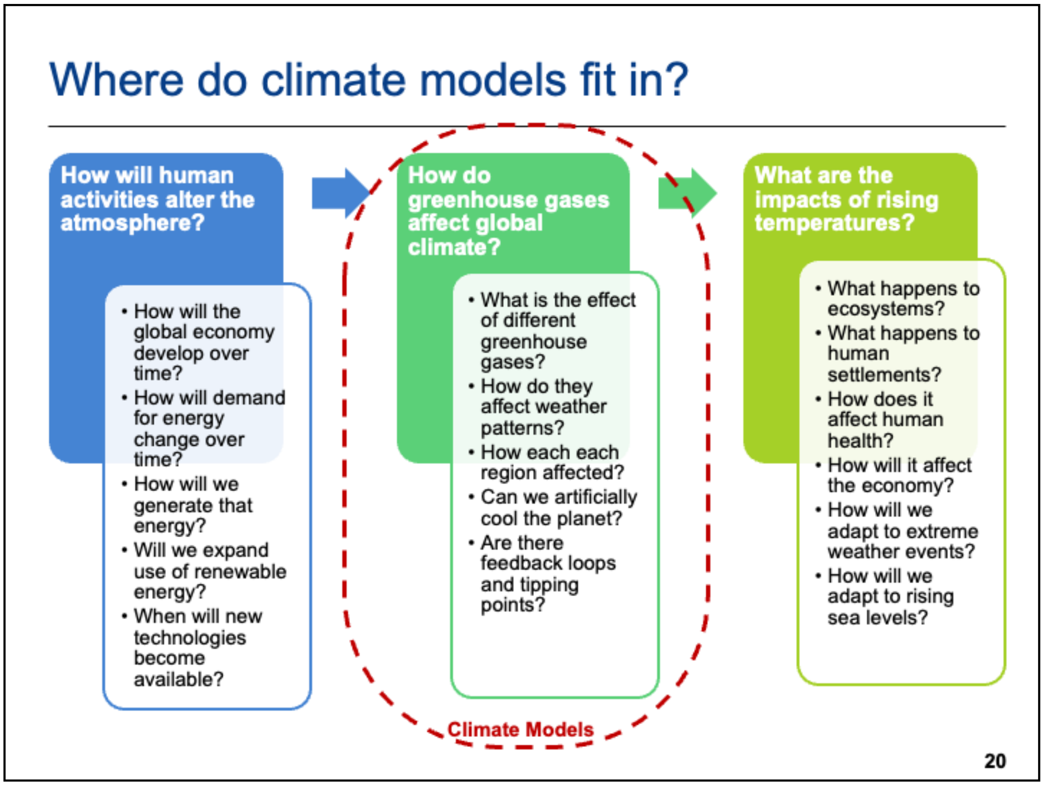
1948-1956 Institute for Advanced Study, Princeton

1956-1981 Dept of Meteorology, MIT

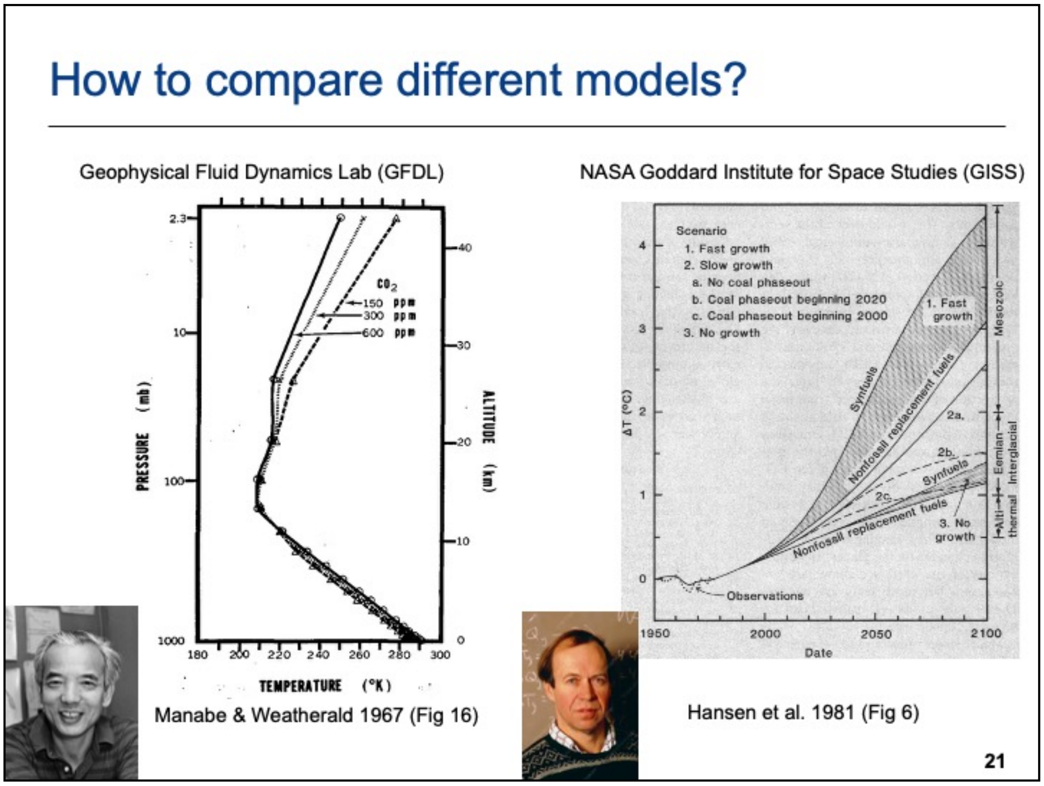


By the 1950s, scientists were worried enough about global warming that they began regular measurements of CO2 in the atmosphere. The longest running set of measurements were taken at the Mauna Loa observatory in Hawaii (far from most industrial sources of CO2). The measurements started by Charles Keeling in 1958 are sill being taken today – this chart shows the full temperature record.

See: https://keelingcurve.ucsd.edu



Charney’s team divided the question into three parts.

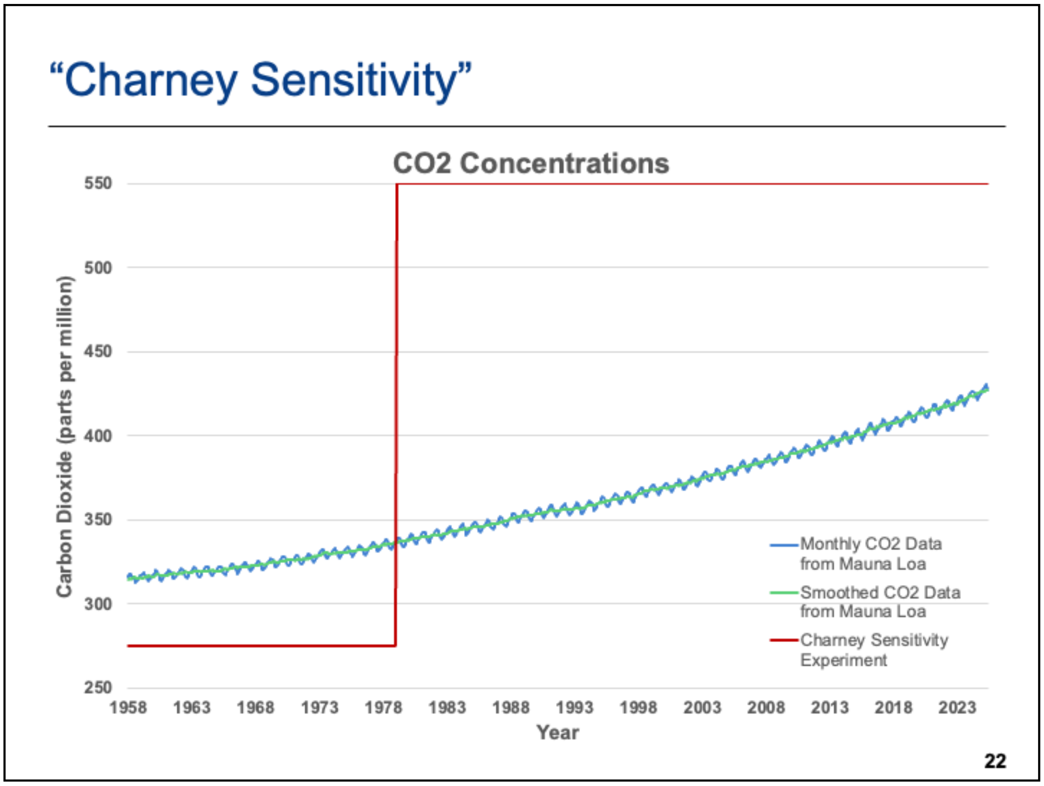


There were several different climate models around at the time, developed by different research groups, each emphasizing different aspects of the climate system, and used for different kinds of experiment. For example, Manabe's model was used for studying the vertical structure of the atmosphere (he predicted that greenhouse gas warming would cool the stratosphere while warming the lower atmosphere – he was recently awarded a Nobel prize for this work). Hansen was more interested in projections of future climate change, and he worked out a number of scenarios for how humans would use fossiel fuels in the future, so he could analyze the consequences.

So how do you compare these very different models? How do you arrive at a consensus view about what we know (scientifically speaking) and what we don't know?

Jim Hansen was at NASA GISS in New York

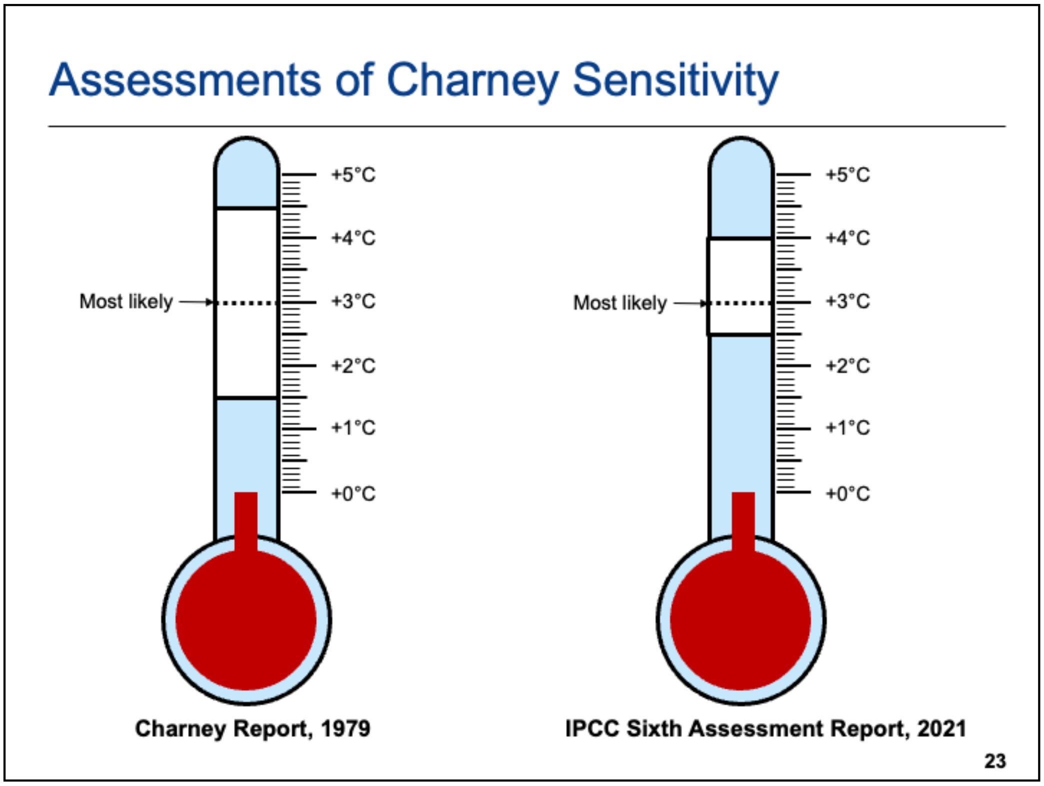
Syukuro Manabe at GFDL in Maryland



Charney's group came up with a very simple (and very artificial) experiment that could be run in each model, so that the models could be compared. The experiment instantaneously doubles the amount of CO2 in the atmosphere, and then lets the model run to simulate what would happen after a few decades.

Here's a chart showing how that compares to how CO2 has actually changed over the decades. The blue line is the Keeling curve we saw earlier – that's what actually happened. The red line is Charney's artificial experiment. It can't happen in reality.

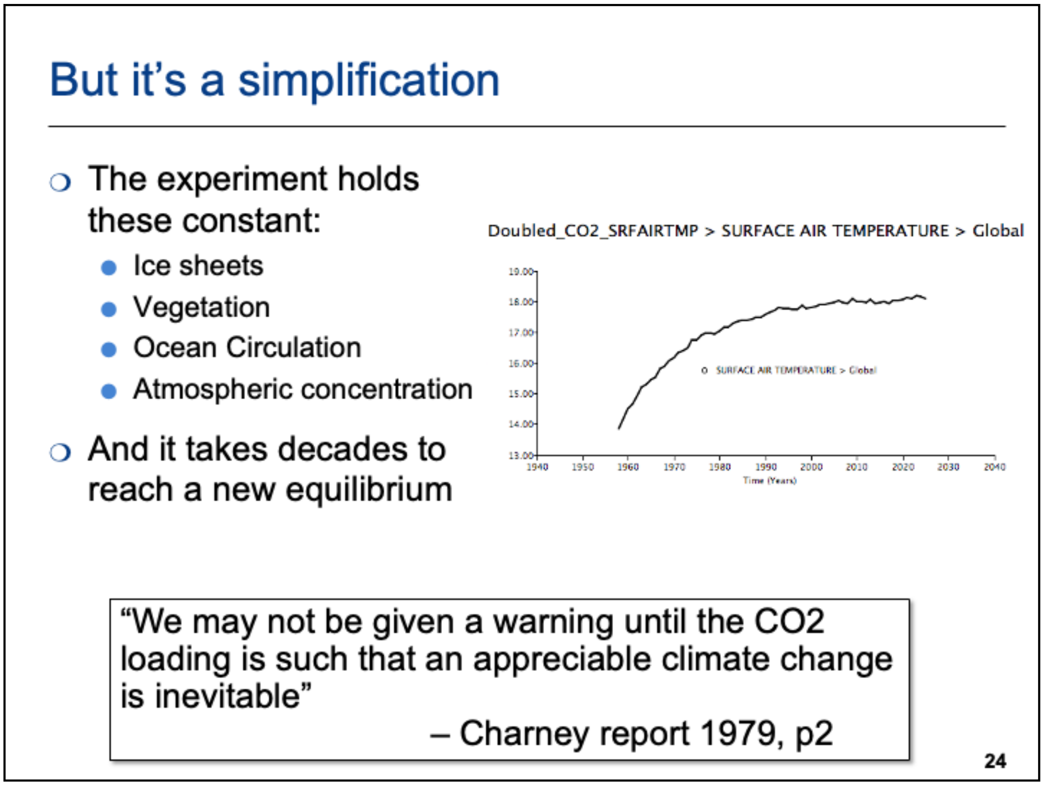
But the experiment gives us a way of comparing different models, e.g. by looking at the average global temperature after they settle down in response to this sudden change.



The experiment has become know as "Charney sensitivity", and it has become a standard benchmark experiment for comparing climate models, and assessing the range of answers they give. The range helps us understand the uncertainty (which is what President Carter was hoping).

In Charney's report in 1979, they ran the experiment in five different climate models from different research groups, and found that the temperature response to a doubling of CO_2 would be between 1.5°C and 4.5°C, with a most likely answer of 3°C.

More than forty years later, the latest IPCC assessment reports have narrowed the uncertainty range a little: it's now considered to be between 2.5°C and 4°C, with the most likely answer still at 3°C.



Charney sensitivity experiment leaves out some important effects, which we'll look at in later lectures.

One interesting feature: it takes several decades in the model for the Earth to reach a new stable climate. For example, this chart shows one of the Charney sensitivity experiments I conducted, using one of NASA's models.

Photo: Killarney Provincial Park, Sept 2020

Backup Slides

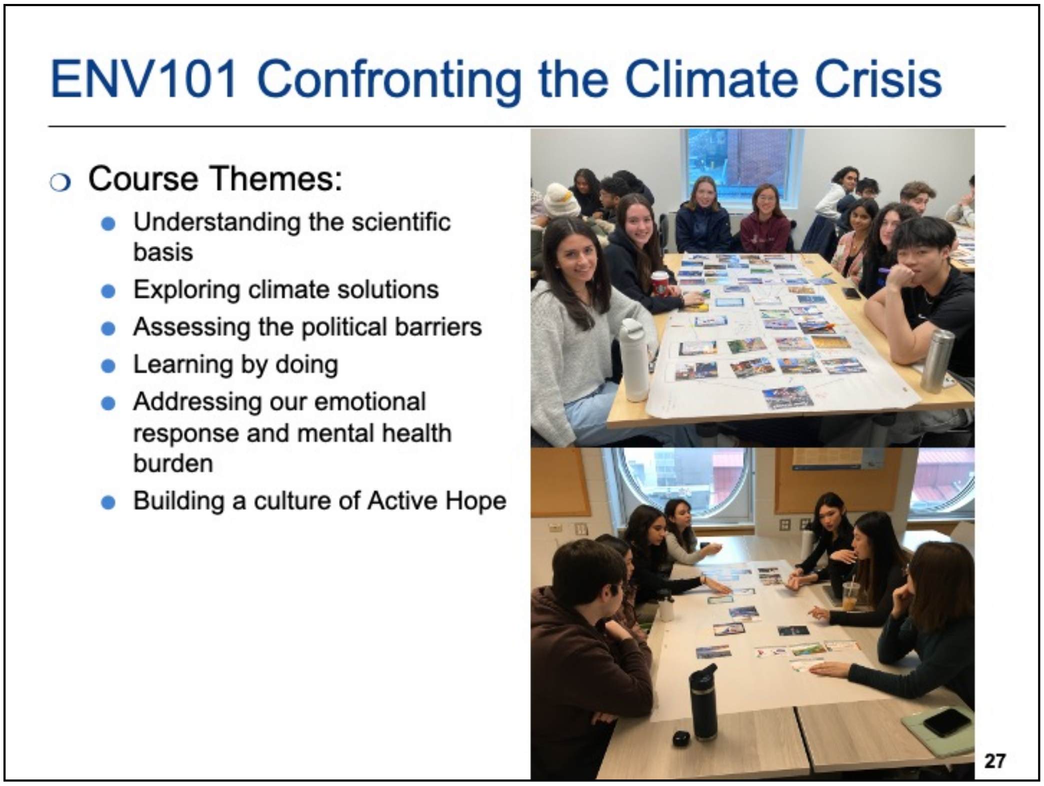
(use as needed)

The course was originally inspired by work at the University of Barcelona, to create a mandatory course on climate change that every undergraduate would be required to take. This was in response to student protests at U Barcelona demanding the university do more to address climate change.

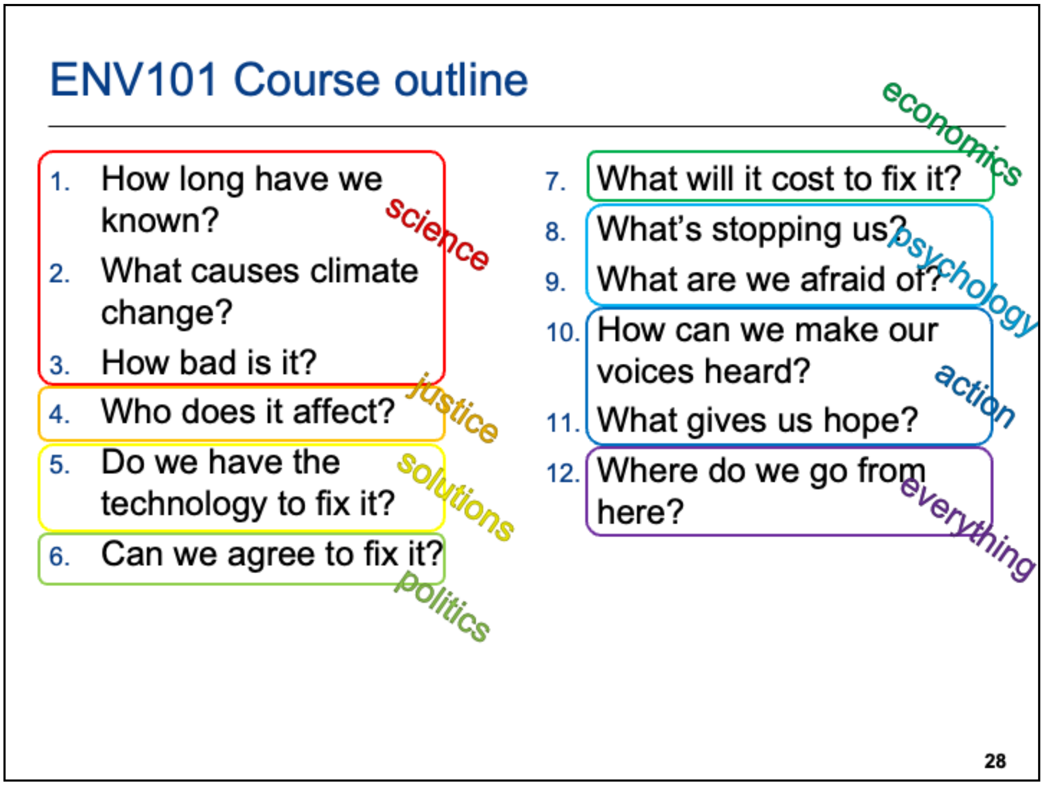
At U of T, we don't have a mandatory course, but we're offering this course to all Arts & Science students, and hope to grow it eventually so that any student can take it.

For more, see:

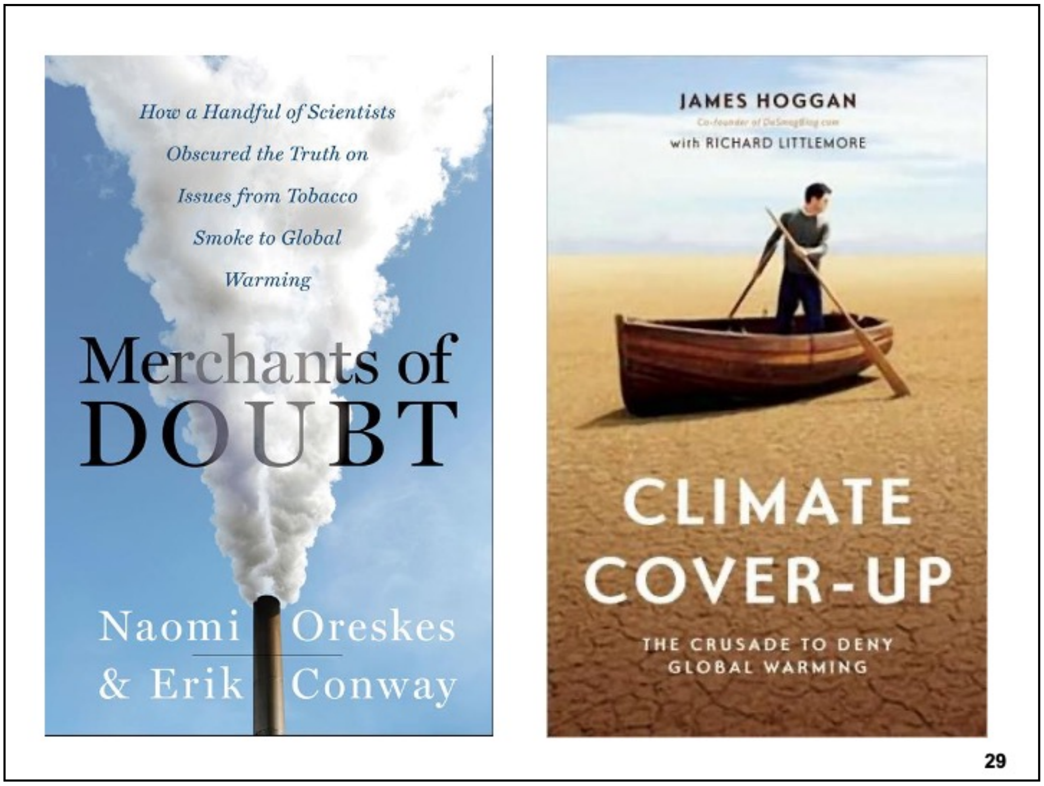
https://www.theguardian.com/world/2022/nov/12/barcelona-students-to-take-mandatory-climate-crisis-module-from-2024



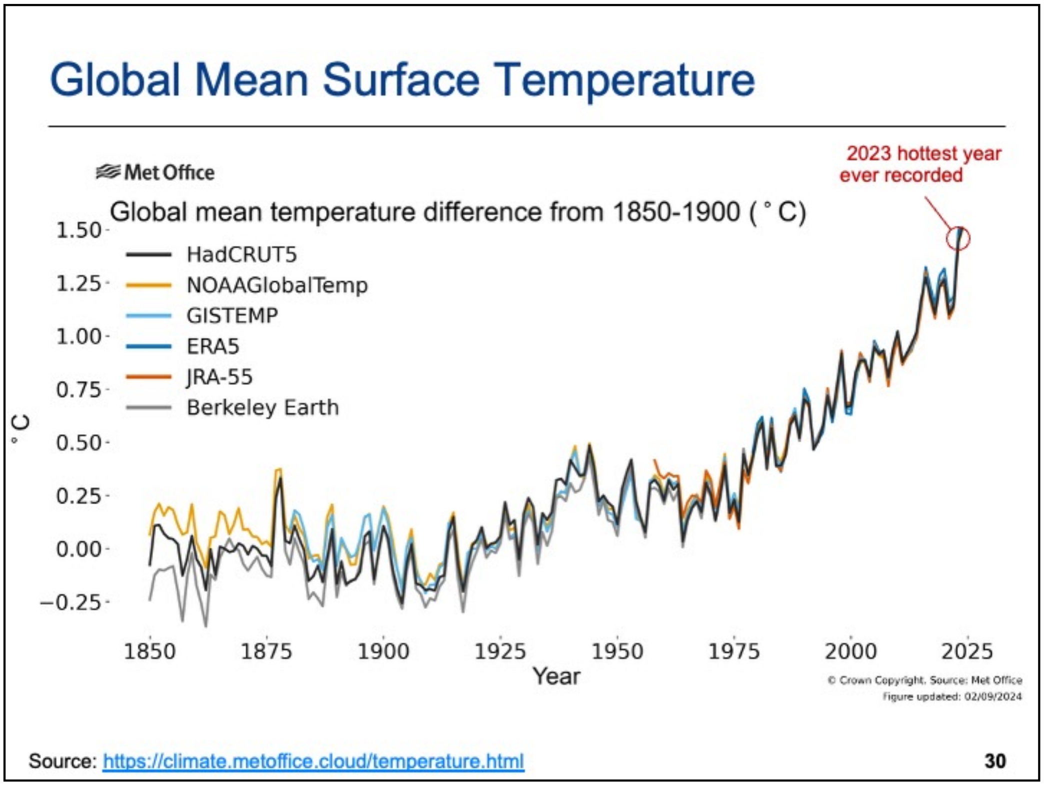
This is the course I’m teaching at U of T each winter. I’ll teach it again in January.



First few weeks of the course are science heavy. But then we get into more social science and humanities questions after we've established the scientific basis.

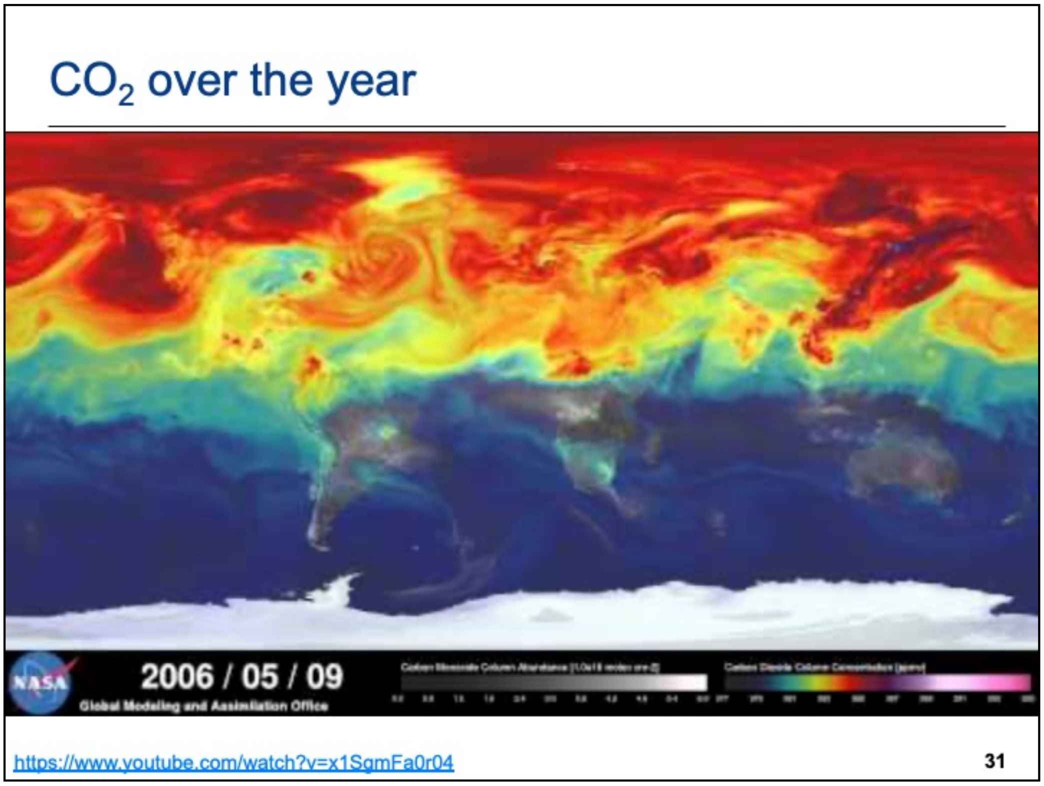


Over the years, those would would be most affected by strong climate measures have fought back with a massive campaign of misinformation. Funded by the fossil fuel industry, either directly, or more commonly through lobby groups, foundations (Koch and Scaife Foundation for example), and through rightwing think tanks. Particularly right-wing because they are ideologically opposed to environmental regulations, and have a track record.



Six independent research groups produce reconstructed global surface temperature records, compiled from many thousands of weather stations, bouys and shipping logs.

We’ll come back to these data sets later in the talk, as one of our case studies focusses on them.

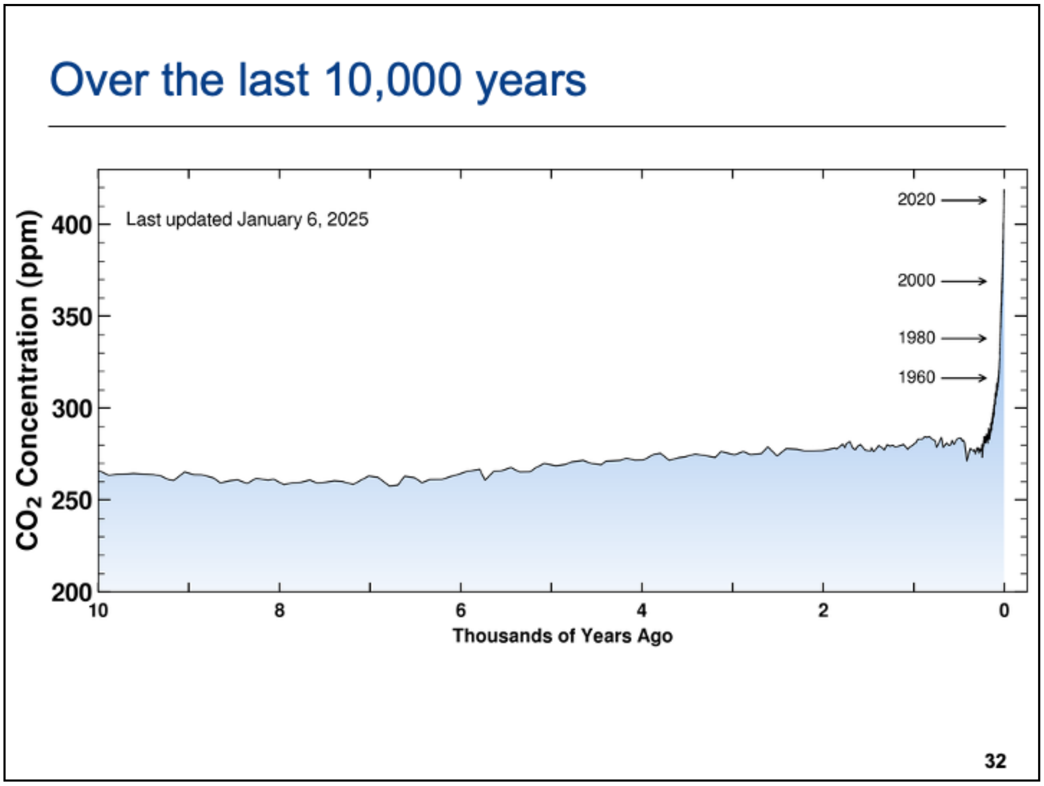


Here's the video if you want to watch it:
https://www.youtube.com/watch?v=x1SgmFa0r04

Its shows where carbon is produced over the course of the year (note how clearly it shows the industrial countries like China, the US, and Europe produce the most, along with the oil states in the Mid-East)

Then in the summer, note how the northern forests breathe in the carbon we're producing. So there's less in the atmosphere over the summer.

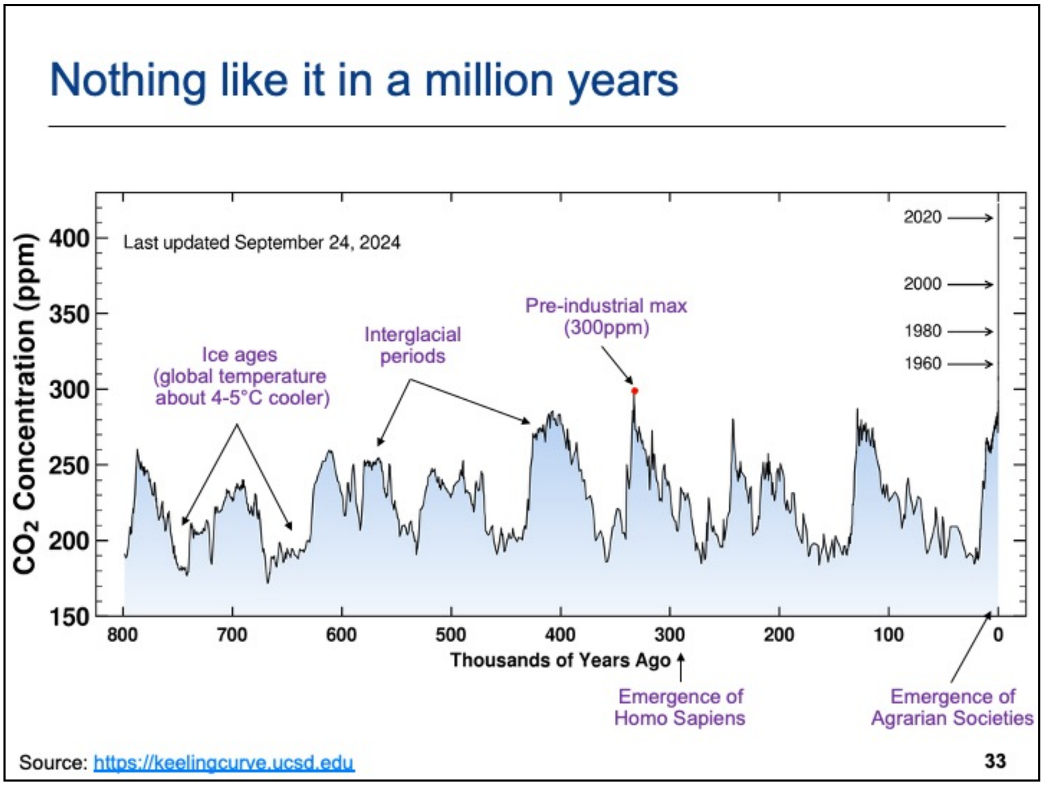
Note also how the winds spread the carbon dioxide everywhere. That's why we call it a "well-mixed" greenhouse gas.



The Keeling curve is only 67 years long – that's how long the scientists at Scripps have been measuring CO2 in Hawaii.

But we have data from tree rings and leaves and soils that allow us to reconstruct a much longer period.

10,000 years is the time since the last ice age ended. It's also about how long humans have been using farming to grow food (before that we were hunter gatherers), and the period over what we might call "civilization" has existed. It's been a period of remarkably stable climate. The last century has changed things completely.



Notes: The amount of carbon dioxide in the atmosphere is higher now than it has been for millions of years. This chart shows the data from the deepest ice-core record, which allows us to analyze atmospheric gases from tiny bubbles trapped in the ice.

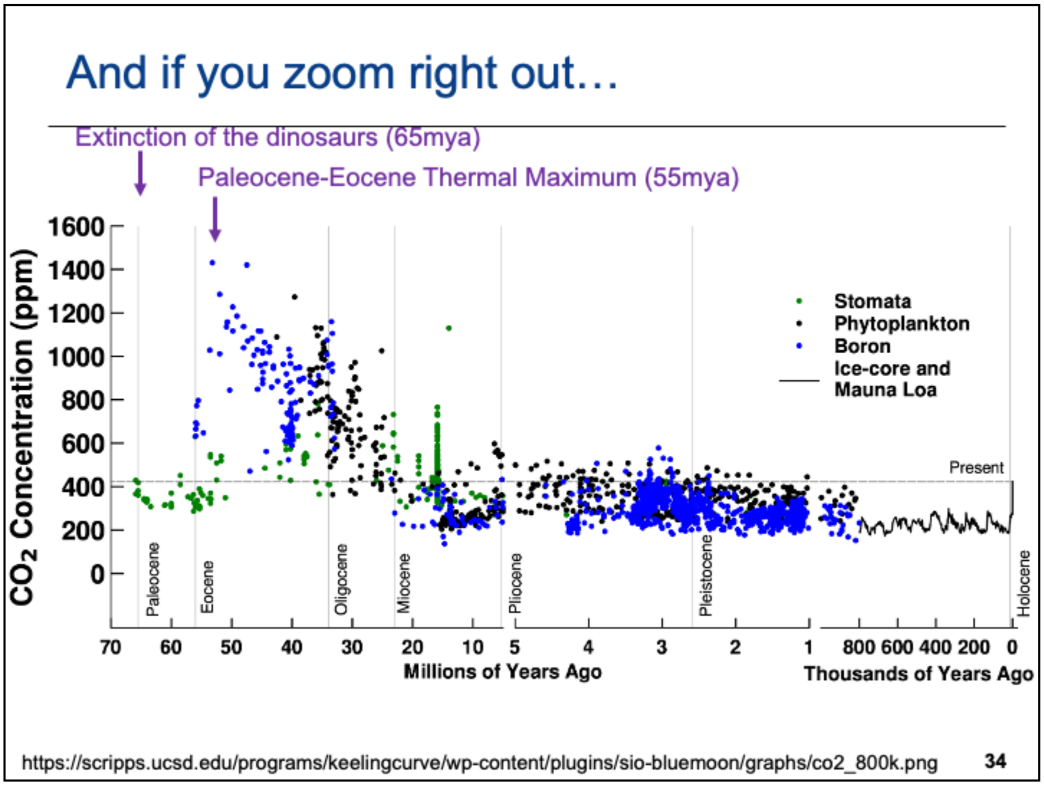
In January 2025 it reached 426ppm.

For a background on how this kind of data is extracted from ice core records, see:

https://climate.nasa.gov/news/2616/core-questions-an-introduction-to-ice-cores/

And this chart, along with a little more detail, can be found here:

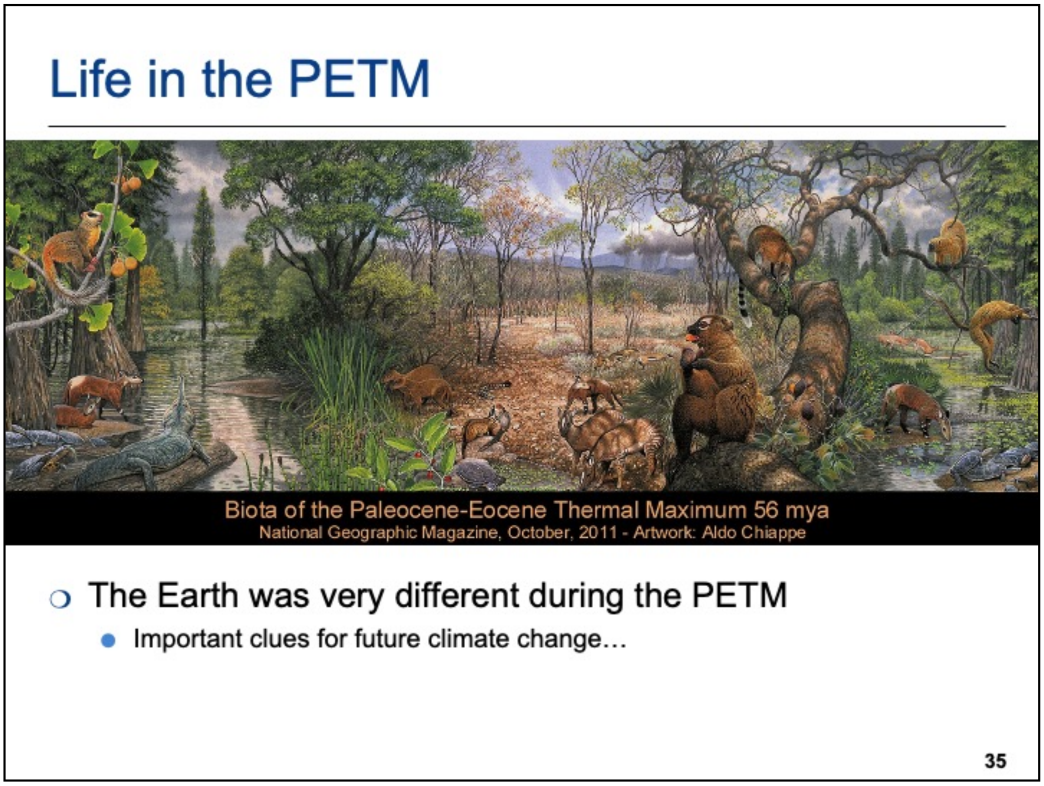
https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide



If you look at fossil records from even further back (in this case 70 million years), there was a period when there *was* a lot more CO2 in the atmosphere, and the planet was *much* warmer, especially during the Paleo-Eocene Thermal Maximum (PETM). Something (most likely massive volcanic eruptions) released a huge amount of CO2 into the atmosphere. Global average temperature rose by 5-8° C. There were no ice sheets, and palm trees and crocodiles thrived in Greenland. Sea levels were between 20-50meters higher than today.

Key point: The PETM was much warmer than today because there was a lot more carbon in the atmosphere. Over millions of years, that carbon was captured by plants and animals, who then died, and the carbon was slowly trapped under layers of sediment. Under pressure, it turns into coal and oil. If we dig up all the coal and oil, and burn it, we'll return the earth to the PETM conditions.

Chart from: https://scripps.ucsd.edu/programs/keelingcurve/wp-content/plugins/sio-bluemoon/graphs/co2_800k.png



About 65 million years ago, an asteroid collided with planet Earth, which led to the extinction of the dinosaurs.

About 10 million years after that, during the PETM, the Earth warmed up a lot. At this time early mammals were appearing, but they are very different from the mammals around today because they were adapted to that very warm climate.

The vegetation was very different too – plant species that have evolved in a very warm climate can’t survive in colder climates (and vice verca)