Climate Change Science
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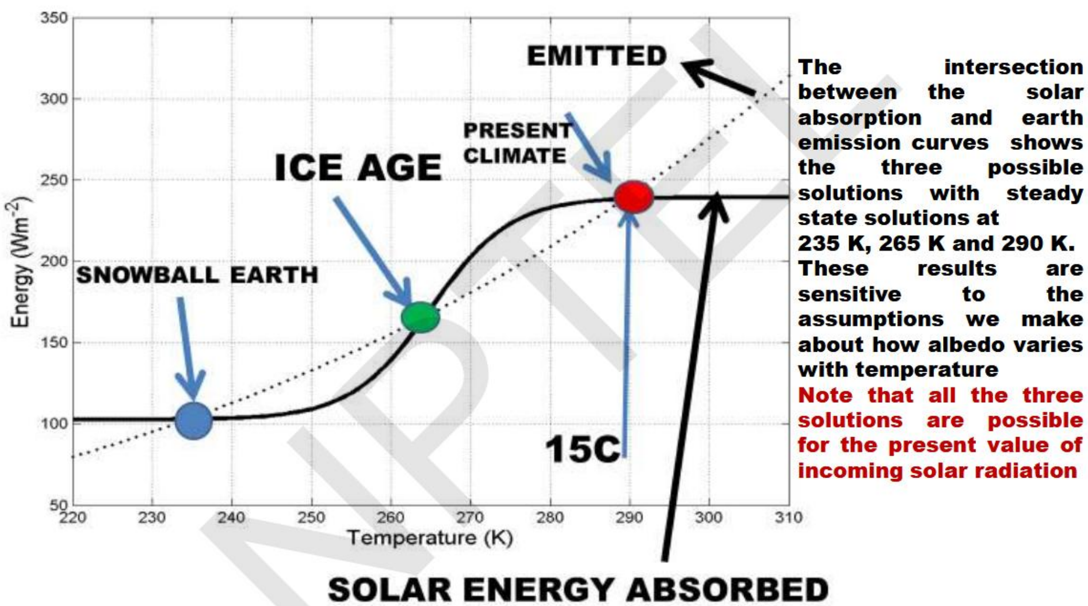
Lecture – 60
Wrap up



In the last lecture, I showed this slide, which shows that Earth's climate is not stable. It has three solutions: the present climate (15°C), 20,000 years ago, we were in the last ice age, which was 5 to 7 degrees colder than present, and 600 million years ago, we had what is called Snowball Earth. We had three possible states because of the change in albedo of the Earth-atmosphere system. And we can easily move from one to the other if the system is perturbed. That is why we must be cautious; if we perturb the Earth's climate too much, it can move to another state.

Extreme ice ages called "Snowball earth" that occurred around 600 million years ago

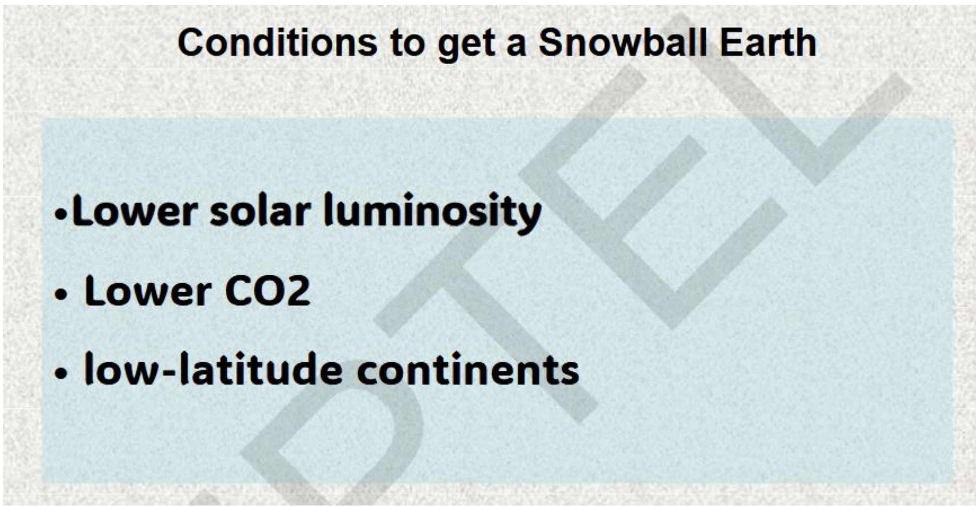
Why did such extreme ice ages did not appear before?

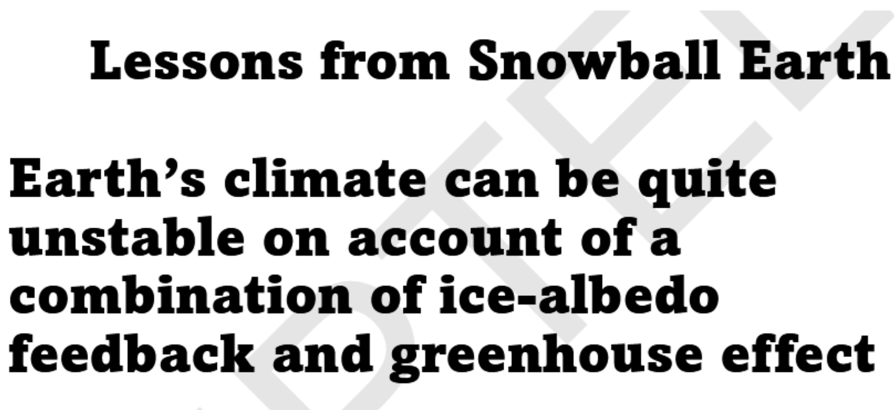
1. Role of CO_2

2. Role of solar insolation

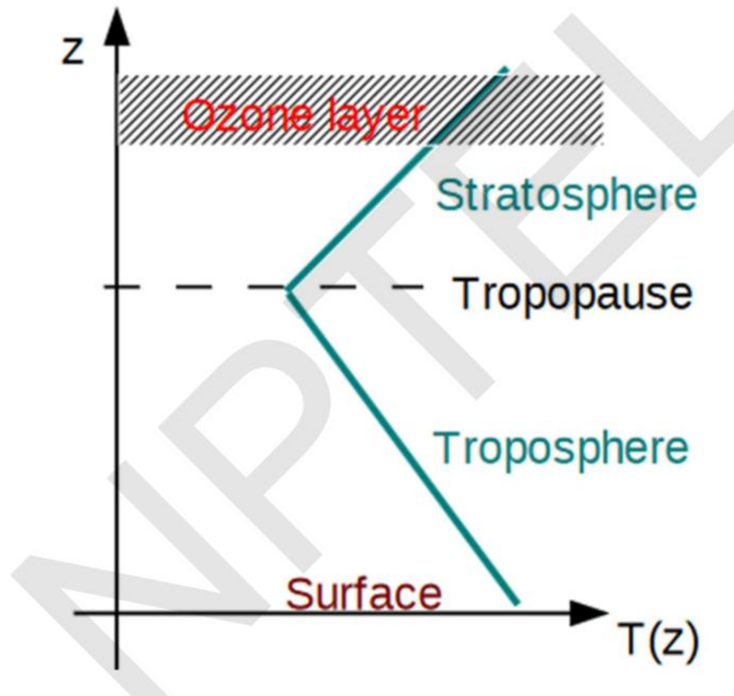
3. Role of super continent in the tropics

So, we also discussed how these extreme ice ages, called Snowball Earth, occurred under a special circumstance of CO_2 playing a role, incoming radiation playing a role, and the supercontinent in the tropics, which was there at that time, also played a role. So, we saw that 600 million years ago, incoming radiation was somewhat lower, carbon dioxide was lower, and most of the continents were around the tropics, which led to the conditions of a Snowball Earth.

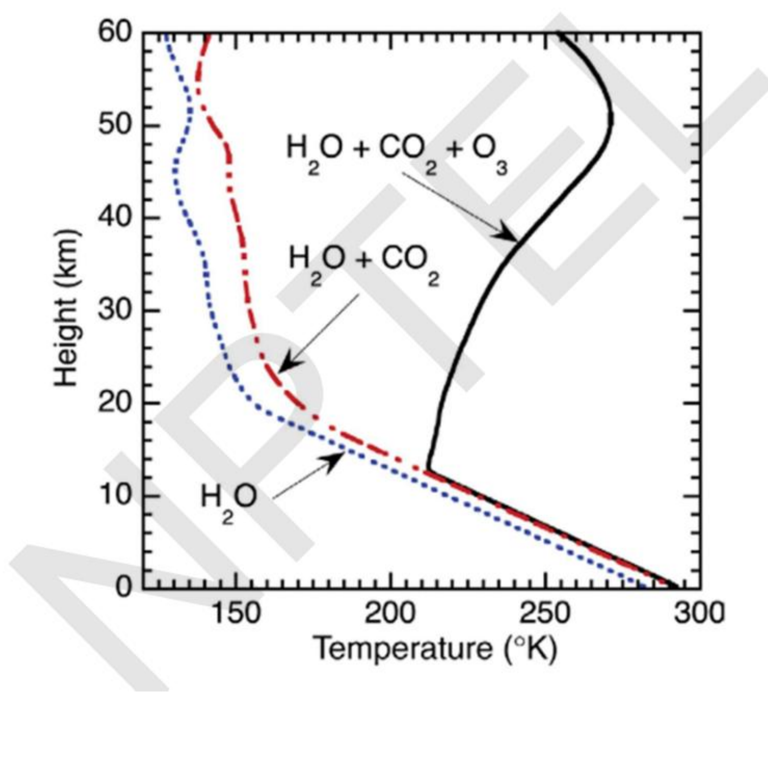




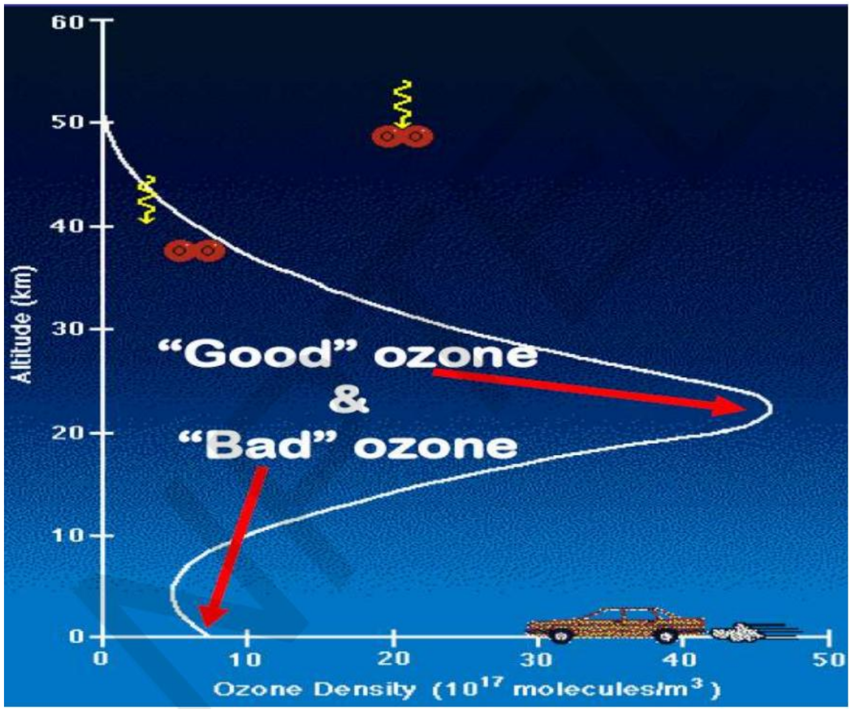
The lesson from Snowball Earth is that Earth's climate can be quite unstable due to the combination of ice-albedo feedback and the greenhouse effect. The presence of the stratosphere, because of the ozone layer, makes Earth's climate somewhat complex. We discussed that in the previous lectures. We showed how an increase in carbon dioxide warms the troposphere but cools the stratosphere. So, this is an unusual result that is only seen on Earth because it has an ozone layer. And the ozone layer is essential for life to exist on land.



If you run a radiative heat transfer model and only put water vapor (H_2O) on Earth, you will get the blue dotted curve (as shown in the plot below). There will be no stratosphere. If you add carbon dioxide (CO_2), it will get a little warmer because of the increase in the greenhouse effect, and it will go along the red dotted line. When you add ozone, you also get the stratospheric temperature (solid black line).



So, Earth is unique in having a troposphere and a stratosphere, and they play different roles when CO_2 is increased, which we discussed in this course. Also, we discussed that ozone in the stratosphere is good for us. It protects us from ultraviolet radiation, while ozone near the ground is bad for our lungs. So, there is a good ozone, and there is a bad ozone.



We have already discussed radiative forcing, a very important concept in understanding how Earth's climate can change. We saw that radiative forcing can occur due to changes in solar radiation, volcanic eruptions, or human-induced causes. These are all external to what is happening within the Earth. Feedback is the change in the Earth's system due to this perturbation. And these are changes that occur due to a temperature change—that is, there is an increase in the water vapor, a change in clouds, or an increase in ice melting. So, all feedbacks are caused by temperature changes, which cause further changes in the Earth's climate system.

Radiative forcing, the concept used in IPCC initially, was the instantaneous radiative forcing caused by some perturbation in which the change in temperature in the stratosphere was not accounted for. Later, they accounted for it. Finally, they have now defined effective radiative forcing, where they account for the fast adjustment of the stratosphere and the troposphere, and then look at the remaining change because some changes occur immediately. The atmosphere has a very small mass. Other changes occur slowly because the ocean is very massive and responds very slowly. So, you can think of forcing as an external component, and then feedback as a response to the forcing.

What is Radiative Forcing?
An external perturbation to the system (Solar , Volcanic, human)
What is External ?
Something which changes without being influenced by the system
What is feedback?
The response of the system to the external perturbation that leads to more perturbation (water vapor, clouds, ice melting)

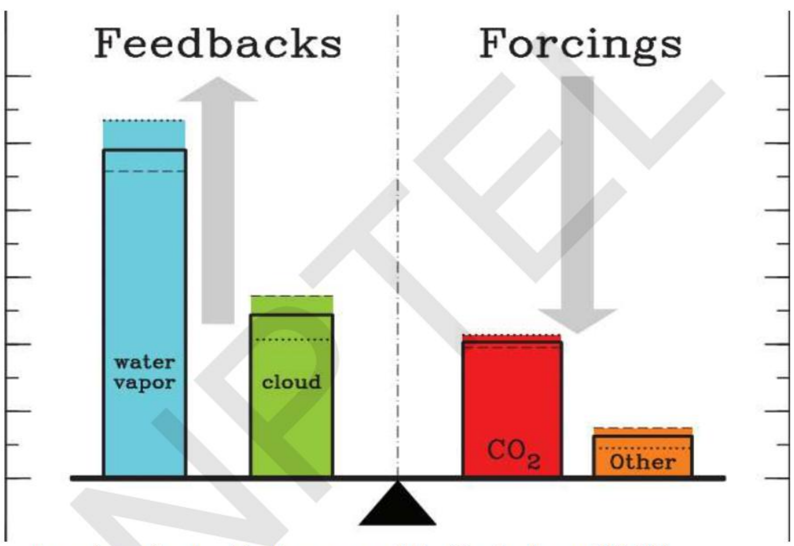
Radiative forcing is a concept used in climate science to quantify the change in energy balance at the top of the Earth's atmosphere

Instantaneous radiative forcing:
"if the change in stratospheric temperature is NOT accounted for".

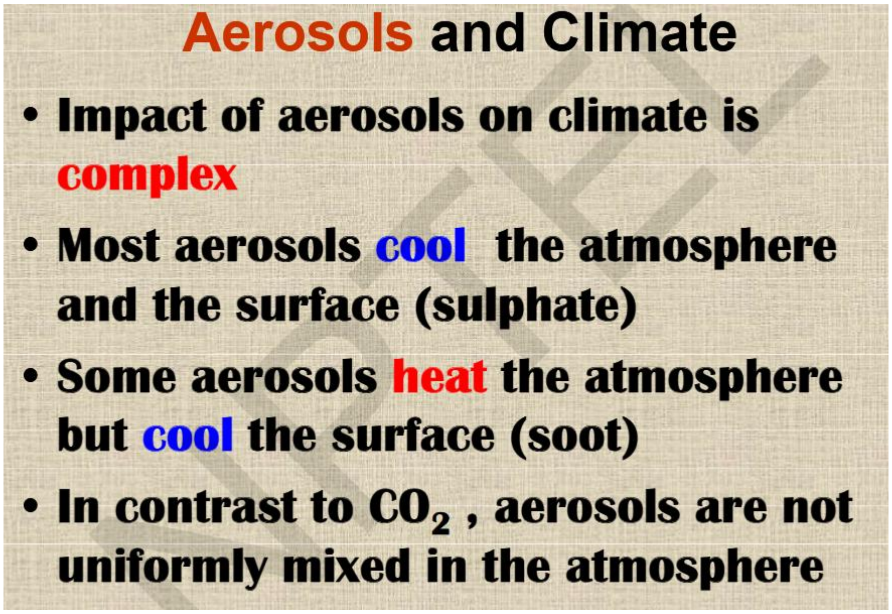
Stratospherically adjusted radiative forcing:

"when all tropospheric properties held fixed at their unperturbed values, and after allowing for stratospheric temperatures, if perturbed, to readjust to radiative-dynamical equilibrium."

Effective radiative forcing:
"once both stratospheric and tropospheric adjustments are accounted for".



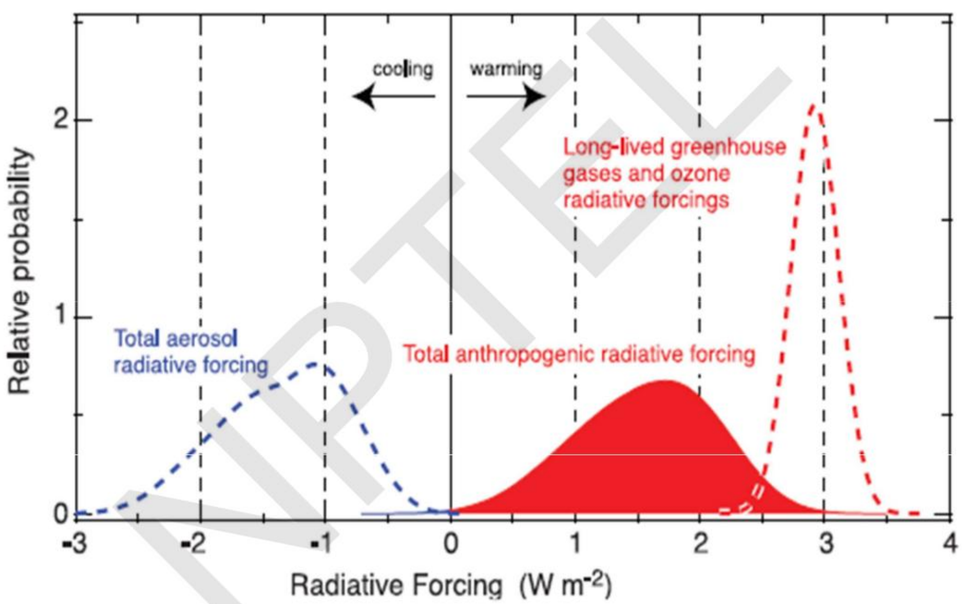
Lacis et al., Sciences 15 October 2010



Now, in addition to greenhouse gases, aerosols also play a role. Aerosols are released by industrial air pollution. We saw that the impact of aerosols is very complicated because aerosols can reflect radiation, and they can also absorb radiation. If they only reflect, they will cool the Earth. If they absorb radiation, they will heat the atmosphere and cool the surface.

In contrast to carbon dioxide, aerosols are not uniformly mixed. They have a very short lifetime, and they cause an increase only locally where you are releasing the aerosol. That is a highly complex situation.

Now, in IPCC, the aerosol forcing is given a large uncertainty.



You can see the dotted line in the diagram shown above. We do not know whether radiative forcing for aerosol is zero or can be even minus 3, because aerosol is complicated. There is soot, sulphate, organic carbon, and many other emissions. While the greenhouse gases like carbon dioxide, chlorofluorocarbons, and methane are well understood, and their value is well known, there is a small variation. If you combine these two, you get a relatively large distribution of what is forcing the Earth's climate. So, it is not a single number. There is a distribution. That is unavoidable because of the large uncertainty about aerosols. Aerosols also influence the clouds in many ways. We discussed that in great detail, and I will not go through it again, but to remind you that there are four to five different ways in which aerosols impact clouds.

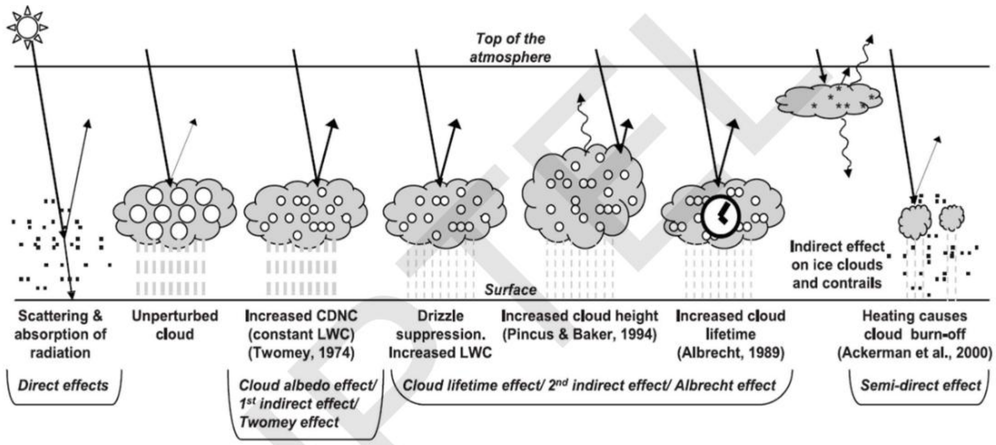
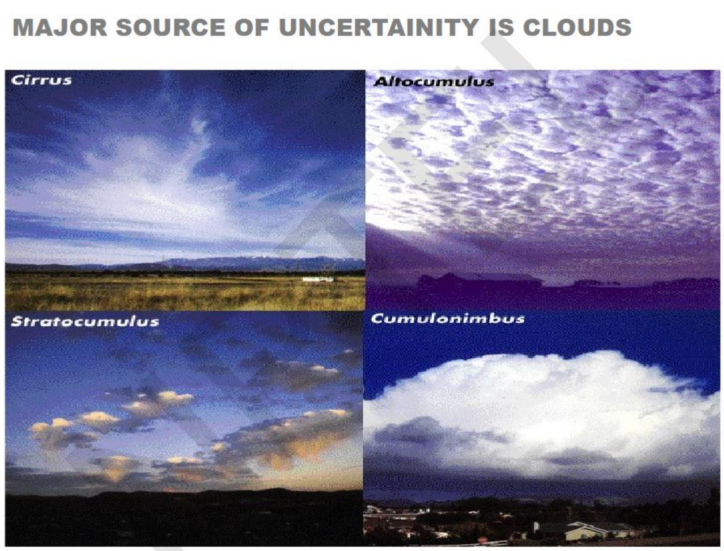
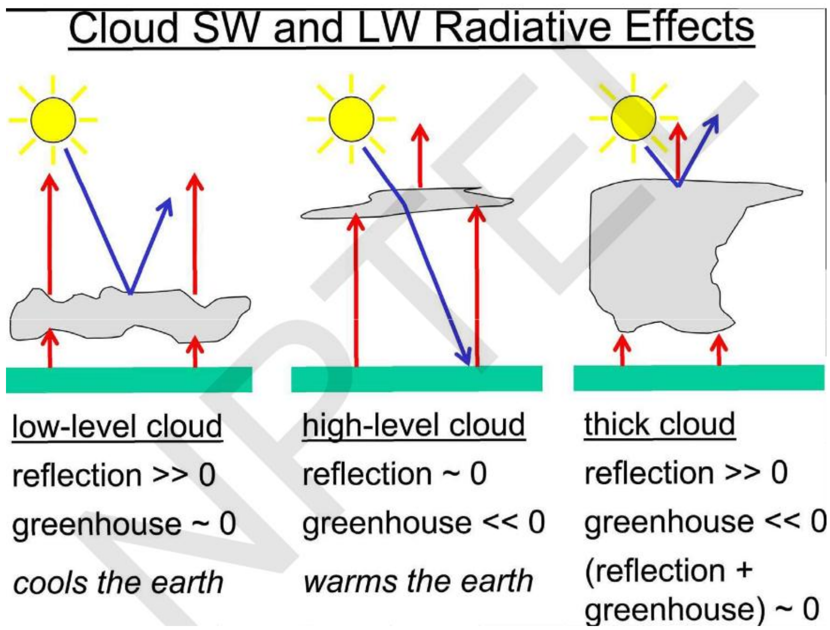


Figure 2.10. *Schematic diagram showing the various radiative mechanisms associated with cloud effects that have been identified as significant in relation to aerosols (modified from Haywood and Boucher, 2000). The small black dots represent aerosol particles; the larger open circles cloud droplets. Straight lines represent the incident and reflected solar radiation, and wavy lines represent terrestrial radiation. The filled white circles indicate cloud droplet number concentration (CDNC). The unperturbed cloud contains larger cloud drops as only natural aerosols are available as cloud condensation nuclei, while the perturbed cloud contains a greater number of smaller cloud drops as both natural and anthropogenic aerosols are available as cloud condensation nuclei (CCN). The vertical grey dashes represent rainfall, and LWC refers to the liquid water content.*

Clouds are also very complicated on Earth. There are high clouds like cirrus, and then there are altocumulus, stratocumulus, and cumulonimbus. Each cloud has a different impact on the climate. Some clouds cool the Earth; some clouds warm the Earth through the greenhouse effect. So, this is what still leads to uncertainty about how the climate will change in the future.



Now, this can be understood that low clouds cause more reflection of solar radiation and cool the Earth. High clouds trap Earth's radiation—that is, the greenhouse effect—and cause warming. So, since clouds come in many forms, the total effect of all clouds is still not fully understood. Different models give different results.



We saw that the total temperature change of the Earth is the initial temperature change multiplied 1 by (1 – f), the feedback factor, which is usually positive.

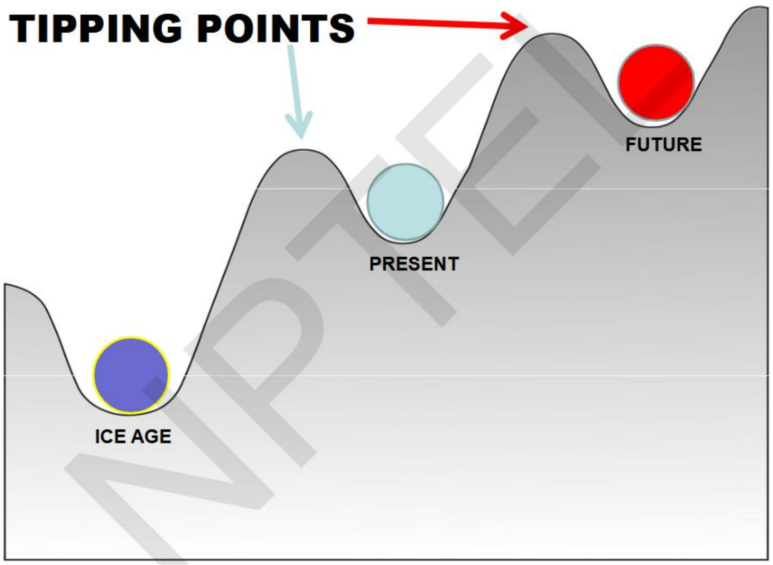
$$\Delta T_s = \Delta T_0 \frac{1}{1 - f}$$

- $f > 0$ ***positive feedback:*** internal response of climate system exacerbates externally forced warming
- $f < 0$ ***negative feedback:*** internal response of climate system mitigates externally forced warming
- If there is more than one feed back

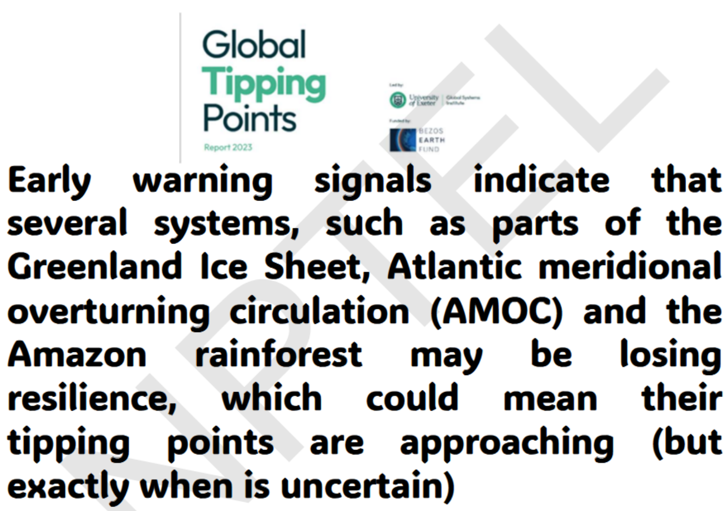
$$\Delta \mathbf{T} = \Delta \mathbf{To} / \{1 - \sum f_i\}$$

If f tends to 1, we have a very large increase in climate for a small perturbation of ΔT_0. So, this is what causes concern. We do not know the value of f accurately. If it is around 0.1, it's okay—we can manage. If it is around 0.9, we are in trouble because the initial perturbation will be amplified ten times.

So, we are in the present climate, with a global temperature of around 15°C. We were in the ice age 20,000 years ago, with a global mean of around 8°C. Now, we are warming the Earth already by 1.5°C, and if we warm further, there is a risk that we will jump from the present state to another state (future state) in which there will be almost no ice or snow.

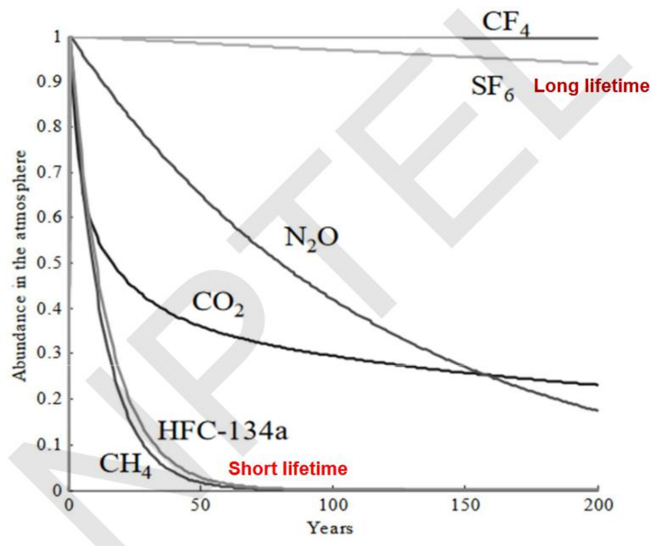


When will that happen? We do not know. That point is called the tipping point. If you push the Earth's temperature more and more, there comes a point where the Earth, on its own, will shift to a different state, which is much warmer than the present climate—maybe four or five degrees warmer—which will be totally unlivable for human beings.

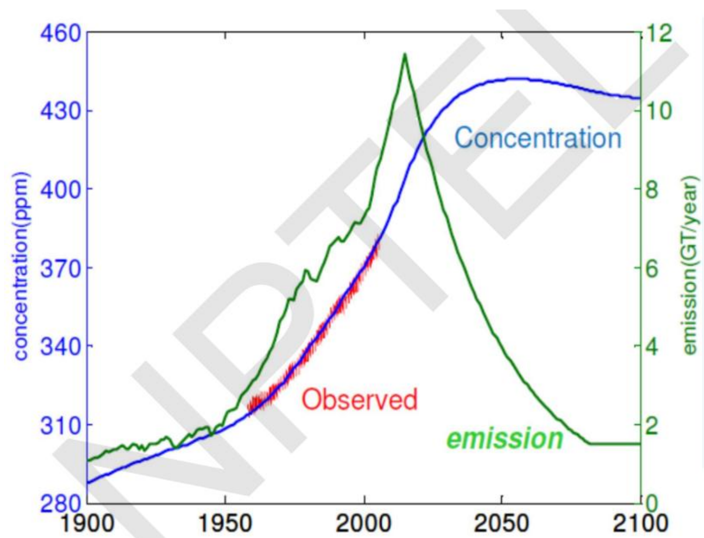


So, one concern we have is the so-called Atlantic Meridional Ocean Circulation, which we discussed in some detail in this course. Early warning signals indicate that the Atlantic Meridional Ocean Circulation or the Amazon rainforest may act as a tipping point. It may push the Earth into some other state. So, we may be approaching a tipping point, but we do not know when. It may happen 20 years from now or 100 years from now—we do not know.

The second problem we have is regarding the lifetime of greenhouse gases. We have released many kinds of greenhouse gases—some of them, like carbon tetrafluoride (CF_4) and SF_6, have a long lifetime of hundreds of years, and so does carbon dioxide (CO_2). But others, like nitrous oxide (N_2O), HFC-134a, and methane (CH_4), have a short lifetime.



So, we have to worry about those greenhouse gases that have a long lifetime, because if we do not bring their emissions down immediately, they will impact the climate over a long period. Well, a gas like methane, which is there only for 10 years, will have a much smaller impact, although it is a very powerful greenhouse gas.



One example of such a greenhouse gas is carbon dioxide. If you start reducing carbon dioxide, let us say by 2030 dramatically, the concentration will not change for many years. It will take almost 50 years before the concentration stabilizes, and maybe it will start coming down. So, the lifetime of greenhouse gases is a very important issue because that determines when the concentration will stabilize after we bring down the emissions.

Now, that led to the concept of global warming potential, which we discussed in some depth—how we compare all the greenhouse gases with reference to carbon dioxide, which is the main gas of concern to us.

The GWP has been defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas (IPCC, 1990):

$$GWP(x) = \frac{\int_0^{TH} a_x \cdot [x(t)]\, dt}{\int_0^{TH} a_r \cdot [r(t)]\, dt} \qquad (6.2)$$

where *TH* is the time horizon over which the calculation is considered, a_x is the radiative efficiency due to a unit increase in atmospheric abundance of the substance in question (i.e., $Wm^{-2}\ kg^{-1}$), $[x(t)]$ is the time-dependent decay in abundance of the instantaneous release of the substance, and the corresponding quantities for the reference gas are in the denominator. The GWP of any substance therefore expresses the integrated forcing of a pulse (of given small mass) of that substance relative to the integrated forcing of a pulse (of the same mass) of the reference gas over some time horizon. The numerator of Equation 6.2 is the absolute (rather than relative) GWP of a given substance, referred to as the AGWP. The GWPs of various greenhouse gases can then be easily compared to determine which will cause the greatest integrated radiative forcing over the time horizon of interest. The

In this course, we have discussed both proxy data, climate models, and simple models. We need all three to understand global climate change.

A combination of good observations, complex models and simple models are necessary to understand climate change

1.Proxy data is not always reliable because it is difficult to identify time precisely

2. Climate models have become sophisticated but still do not resolve all scales of climate phenomena

3. Simple models are necessary to interpret the results of complex climate models

Proxy data are very useful to understand the past climate over the last million years, but proxy data are not always reliable because we are not able to identify the precise time when that particular sediment was established. So, we use climate models to simulate the past climate and see how well the proxy data agree with climate models. If they agree well, we know both the proxy data and the climate models are reasonably reliable.

Now, we need simple models because these complex climate models are so sophisticated that sometimes we do not fully understand what is happening in the model. So, we need a simple model to interpret the result of a complex model. This is happening more and more today with the advent of machine learning and artificial intelligence because models are doing very complex tasks. When they give an answer, we cannot accept the answer blindly. We have to make sure we understand the answer. If we blindly believe the results of a computer simulation, we may go wrong because there are flaws in the climate model. The climate models are not perfect. Machine learning and AI codes are not perfect—they have problems.

The prediction of climate change without accompanying understanding of it is no better than prediction of fortune teller - Syukuro Manabe

That is why I want you to remember that Nobel Laureate Professor Manabe, who got the Nobel Prize for developing climate models, says the prediction of climate change without accompanying understanding of it is no better than the prediction of a fortune teller. It is very important to understand: do not believe the results of a climate model blindly, because climate models are very complicated and they are not 100 percent correct.

There are situations where climate models can go wrong because many assumptions have been used to develop the model. So, remember, this quote from Professor Manabe is very important in the era of machine learning and artificial intelligence because computers do many more complex tasks than we can do. But we cannot trust them totally until we know how the results were arrived at.

Model Hierarchy

1 Zero dimension : global mean

2. One dimension:vert or horizontal

3. Two dimension: vert +one horz

4.Three dimesion : vert, lat, lon

5. Four dimesion: vert,lat,lon,time

We saw all the model hierarchy—from the simple zero-dimensional model for global mean temperature, then one-dimensional, two-dimensional, three-dimensional, and four-dimensional (which includes vertical, latitude, longitude, and time). We require all this model hierarchy in order to understand the Earth's climate.

Now, in these models, we have to do some parameterization. That is, we have to approximately account for certain factors that we could not simulate from first principles. One example is clouds. Most of the models today cannot simulate clouds from first principles because the model resolution is 50 by 50 kilometers, and the clouds have a dimension of 1 kilometer.

Parameterization
is undertaken for those processes that cannot be represented explicitly, either because of their complexity or because the spatial and/or temporal scales on which they occur are not resolved by the discretized model equations
Example : clouds and turbulence

So, the model does not resolve clouds. A cloud is put into the model in an empirical way. So, there are problems with that. Clouds and turbulence are two things that we have to put in empirically. We also showed why, because of parameterization, we have to tune the model. When you put together a model and run it the first time, you won't get the correct global mean temperature.

THE ART AND SCIENCE OF CLIMATE MODEL TUNING

Bulletin of American Meteorological Society vol.,98, March 2017

Frédéric Hourdin, Thorsten Mauritsen, Andrew Gettelman, Jean-Christophe Golaz, Venkatramani Balaji, Qingyun Duan, Doris Folini, Duoying Ji, Daniel Klocke, Yun Qian, Florian Rauser, Catherine Rio, Lorenzo Tomassini, Masahiro Watanabe, and Daniel Williamson

We survey the rationale and diversity of approaches for tuning, a fundamental aspect of climate modeling, which should be more systematically documented and taken into account in multimodel analysis.

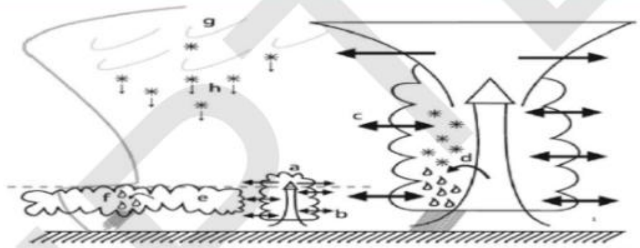


Fig. 1. Example of tuning approach for the ECHAM model (after Mauritsen et al. 2012). The figure illustrates the major uncertain climate-related cloud processes frequently used to tune the climate of the ECHAM model. Stratiform liquid and ice clouds and shallow and deep convective clouds are represented. The gray curve to the left represents tropospheric temperatures, and the dashed line is the top of the boundary layer. Parameters are (a) convective cloud mass flux above the level of nonbuoyancy, (b) shallow convective cloud lateral entrainment rate, (c) deep convective cloud lateral entrainment rate, (d) convective cloud water conversion rate to rain, (e) liquid cloud homogeneity, (f) liquid cloud water conversion rate to rain, (g) ice cloud homogeneity, and (h) ice particle fall velocity.

You have to adjust various parameters to make sure you get the global mean temperature and its variability correctly. So, this is necessary because models have parameterizations. Another thing is that the model has an initial condition from where we start. Because the initial condition is not known perfectly, there is irreducible uncertainty in predicting future regional climate. Global climate is solidly reliable, but regional climate is not.

The presence of initial condition uncertainty and non-linearity produces significant irreducible uncertainty in future regional climate changes.
For trends of 20 years, the climate change signal rarely emerges from the noise of internal variability

Hawkins et al., Climate Dynamics,2015

For example, for trends of 20 years, the climate change signal rarely emerges from the noise of internal variability of the model. This is very important because a lot of NGOs have put out reports claiming that they can predict how the climate will change in the next 10 years in Bangalore or other districts of India. It is not possible. Over a 10-year time scale, there is a lot of internal climate variability, and the signal of climate change will be of the same order as internal variability. So, we can only predict the impact of climate change on a larger scale—hemispherical and global, not local.

commentary

Built for stability

Paul Valdes

State-of-the-art climate models are largely untested against actual occurrences of abrupt change. It is a huge leap of faith to assume that simulations of the coming century with these models will provide reliable warning of sudden, catastrophic events.

Models cannot be trusted to predict catastrophic events
Valdes, Nature Geoscience,2011

The second thing is that models have been designed to be very stable. They are not good for catastrophic events. When a catastrophic event occurs, you cannot ask why the model did not predict it, because models are not built for that. Those are specialized events. We will need a more complex model at a higher resolution to predict catastrophic events like heavy rainfall, landslides, cyclone intensity, and so on.

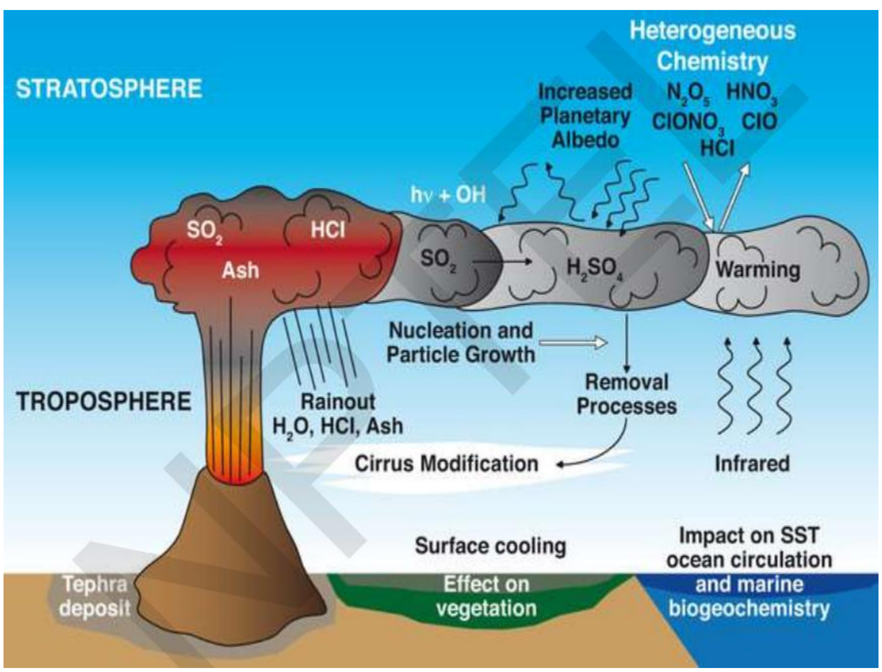
- **Climate Models are reliable for the prediction of temperature but not rainfall**
- **Climate Models capture decadal variability better than inter-annual variability**
- **Climate Models will become more realistic when the model resolution goes below 20 km**
- **Models not good for predicting local impact of climate change**

I also pointed out that climate models are very reliable for temperature over a large area, but not for rainfall. Climate models are able to capture decadal variability, but not year-to-year variation. Climate models become more realistic only when their resolution goes below 20 kilometers. Right now, they do not, but in a matter of 10 years, that will happen. Models are not good for predicting local climate change. This is very important because all the policymakers want models to predict the local impact of climate change, because that is what people want. Unfortunately, we are not in a position to predict the impact of an increase in carbon dioxide on local climate, like a local district or a city. We cannot.

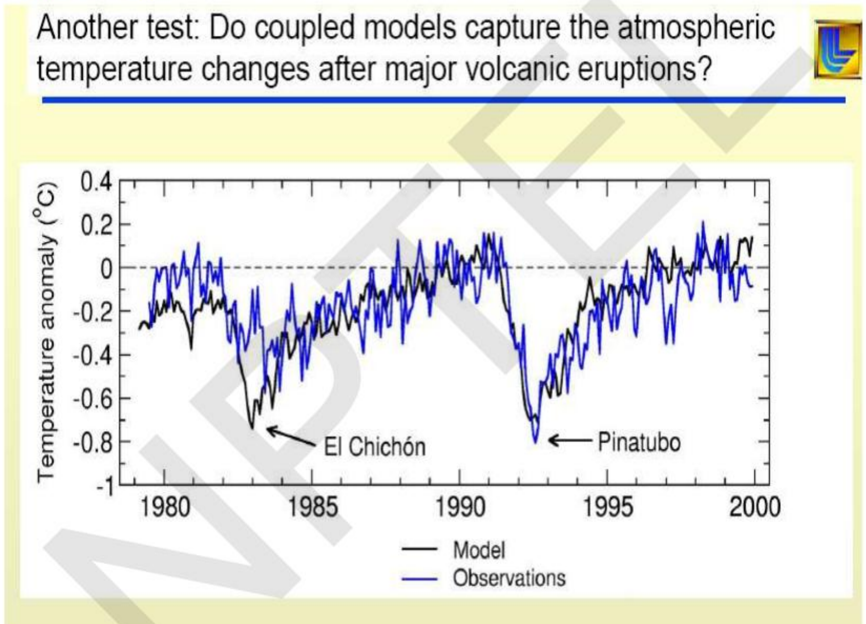
> **The co-existence of internal climate variability and anthropogenic climate change thus places limits on our ability to make accurate climate projections for the coming decades, especially in regions where their effects are of similar magnitude. This inherent uncertainty in regional climate projections is certain and must be taken into account in climate risk assessment, adaptation management and decision-making.**
>
> **Clara Deser's commentary in Earth's Future**
> **https://doi.org/10.1029/2020EF001854**

So, you must remember that the coexistence of internal climate variability makes the prediction of regional climate change very uncertain. Clara Deser clearly states that there is inherent uncertainty in regional climate projections. She showed that there is uncertainty, and we cannot do anything about it.

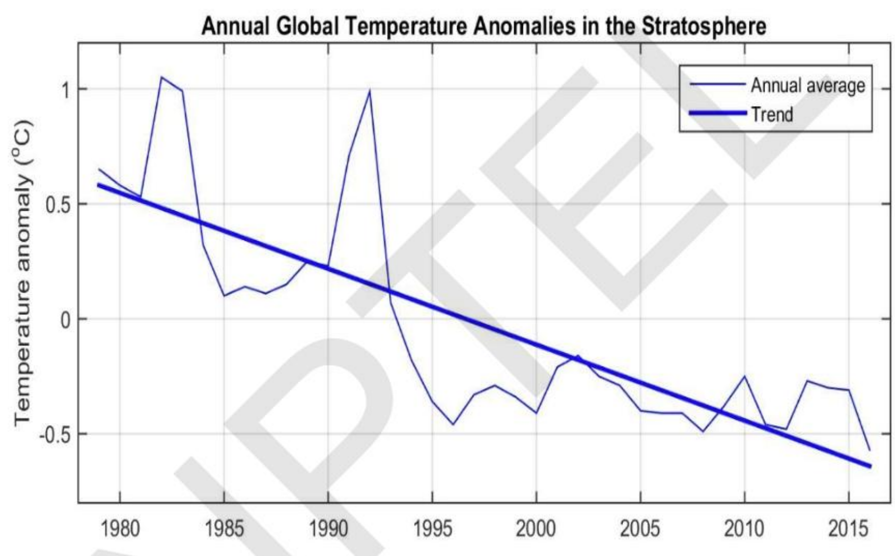
We also saw that models are quite good at predicting the impact of volcanic eruptions. Volcanic eruptions cause the cooling of the troposphere and the Earth's surface, and warming of the stratosphere. And this, models are able to predict very accurately.



From Ben Santer

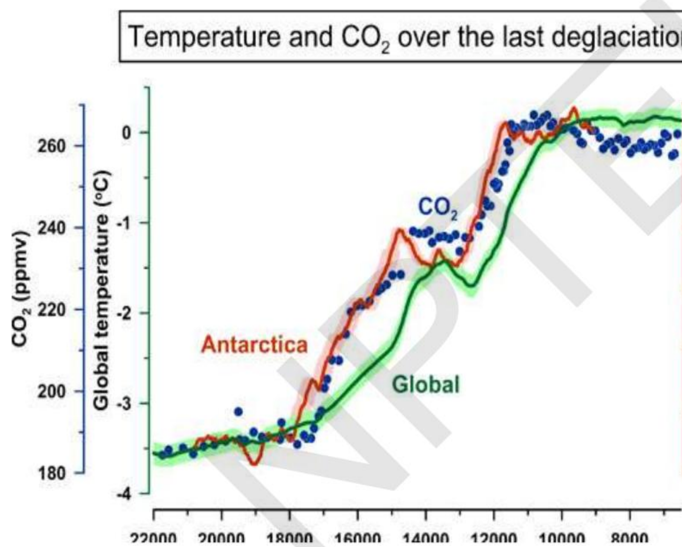


This is an example from the work of Ben Santer on the eruption of El Chichón and Pinatubo. Both caused cooling of the order of 0.5 to 1 degrees, and the models were able to capture it. Now, the models also showed that the temperature of the stratosphere increased during the volcanic eruption, but due to the increase in CO_2, it is cooling. So, the stratosphere is cooling over the long term. But now and then, it will heat up if there is a volcanic eruption—that is brought out by models and observations.



UAH temperature anomalies (with respect to 1981 - 2010) from NOAA polar orbiting satellites adjusted according to Fu et al. (2004). Data obtained from www.ncdc.noaa.gov.

Now, we also saw that if you look at a high-resolution model simulation along with proxy data, we show that carbon dioxide increased on the Earth due to an increase in Antarctic temperature. And a couple of hundred years later, the global temperature changed. The work by Dr. Shakun was able to prove that it is carbon dioxide that is causing global warming. It is not that global warming is increasing carbon dioxide. Although it could have happened, but we are able to show that it is the increase in CO_2 that caused warming 14,000 years ago. That is a natural phenomenon, but we are able to show which occurred first and which occurred later.

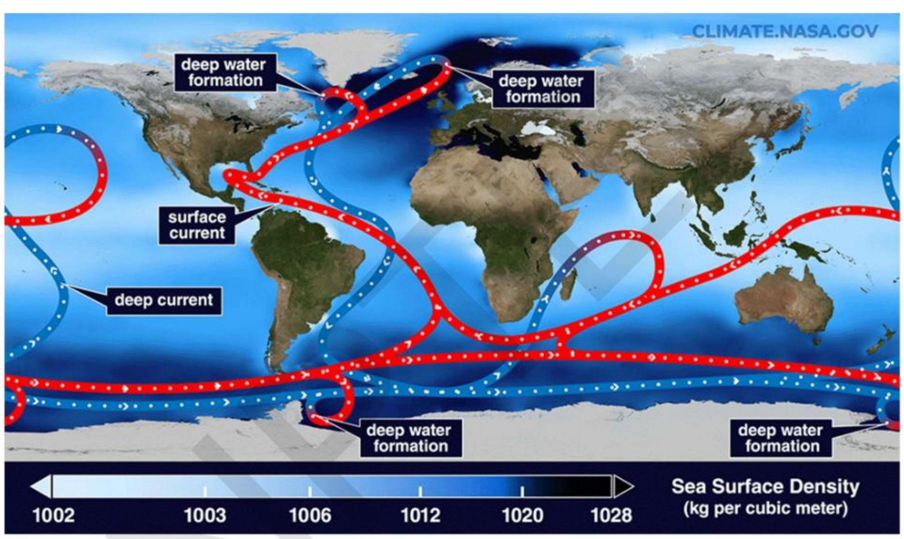


The area-weighted mean of 80 globally distributed, high resolution proxy temperature records shows a two-step rise

Contains 50 pages of supplementary material to justify the accuracy of the method

JD Shakun et al. Nature 484, 49-54 (2012) doi:10.1038/nature10915

One of the biggest challenges in predicting future climate change is ocean circulation. It is a very complex phenomenon going from Antarctica to the Arctic. We showed that the models are not getting the AMOC (Atlantic Meridional Overturning Circulation) accurately. That is a major uncertainty in our ability to predict whether there will be catastrophic climate change in the future.



The Atlantic Meridional Overturning Circulation carries cold water from near Greenland (blue line) southward along the seafloor toward Antarctica, while currents nearer the surface transport warmer water northward. Credit: NASA/Goddard Space Flight Center Scientific Visualization Studio

We know that if you pass the tipping point, you will suddenly come to a place where this circulation will stop completely, and that will be catastrophic. So, this is still under debate, because we do not understand when it is going to stop. It will happen sometime, but whether it will happen 50 years from now or 200 years from now, we do not know.

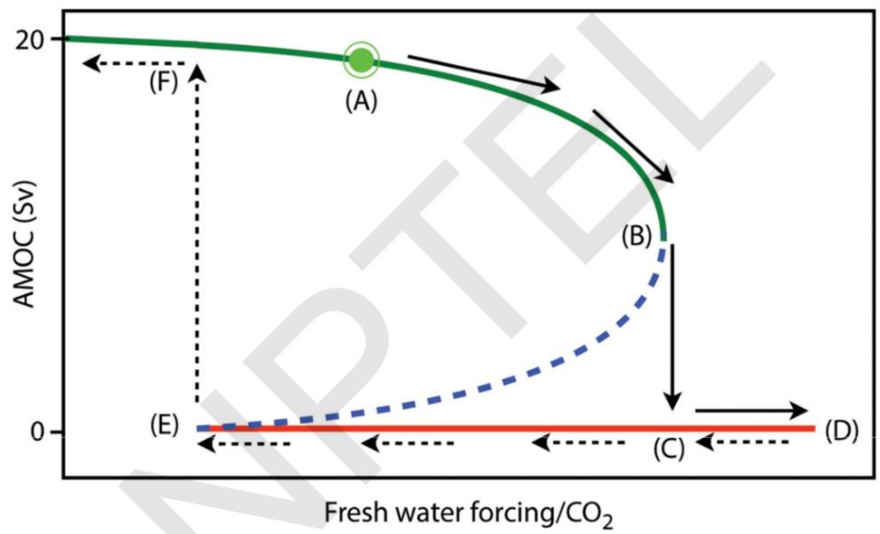


Figure 6.6: A schematic of the hysteresis and tipping point behavior in the two-box Stommel model

Past AMOC changes suggest that the AMOC might be less stable than currently simulated by climate models

As anthropogenic emissions of carbon accumulate in the atmosphere, runoff from the Greenland ice sheet will increase and the Arctic sea-ice extent will continue to decline. These factors are likely to weaken the AMOC, with important implications for the climate, cryosphere and global carbon cycle.

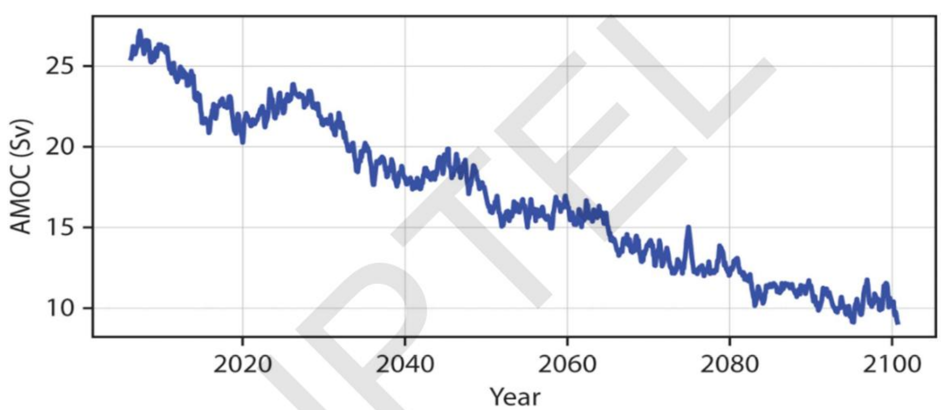


Figure 6.2: An AMOC future projection.
A projected AMOC transport time series in a climate model run under the RCP8.5 scenario.

Courtesy: Global warming science by E.Tziperman, Chapter 6 figure 6.2

Now, the models are showing that AMOC, in Sverdrups—that is, million cubic meters per second—is declining. But this is not the same in all models. There are variations here.

So, there is a risk of a tipping point here, and that has been highlighted by Lohmann and Ditlevsena in a paper published three years ago. They say it depends on how fast the rate of change of climate is. If it is very fast, the tipping will occur earlier. So, that is a big worry for all of us. Stefan Rahmstorf, an expert on AMOC, has said that on the basis of a whole series of new studies, the risk already appears to be significantly greater in this century than what scientists had assumed some time ago. This is a warning.

Risk of tipping the overturning circulation due to increasing rates of ice melt
Lohmann and Ditlevsena
Proceedings of the National Academy of Sciences, March 2021

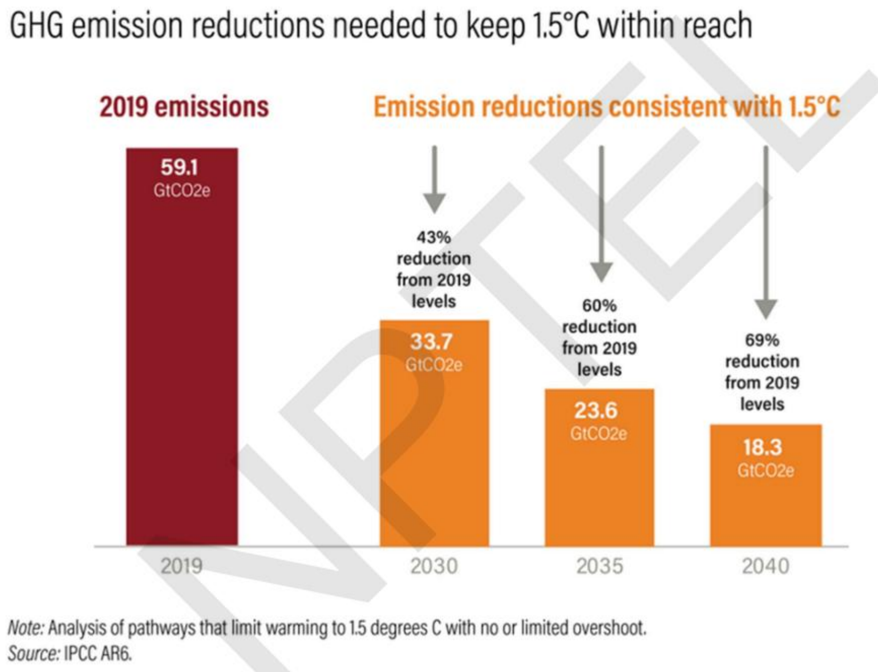
Using a global ocean model subject to freshwater forcing, we show that a collapse of the Atlantic Meridional Overturning Circulation can indeed be induced even by small-amplitude changes in the forcing, if the rate of change is fast enough

The risk of the AMOC tipping as global warming continues should be taken very seriously, considering the devastating consequences of such an event

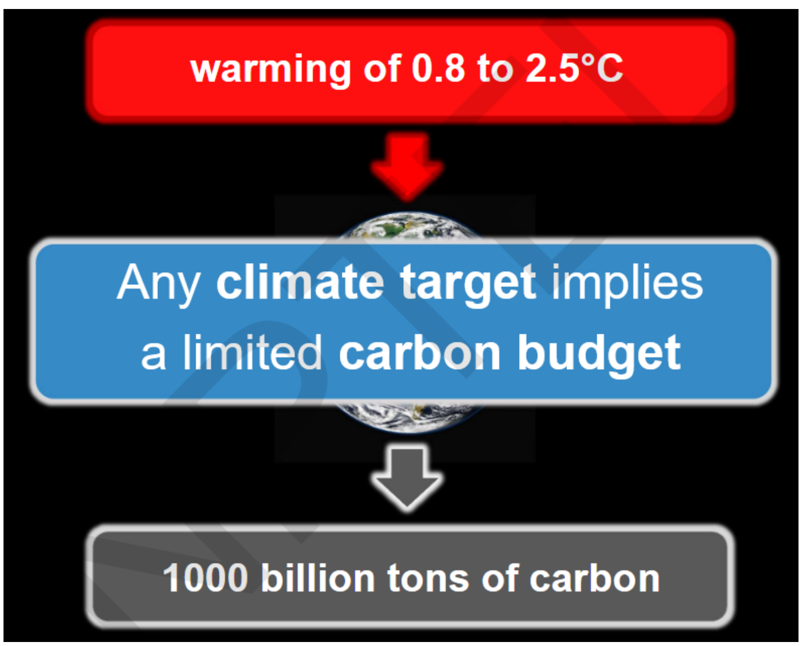
On the basis of a whole series of new studies in recent years, the risk already appears to be significantly greater in this century than scientists had long assumed

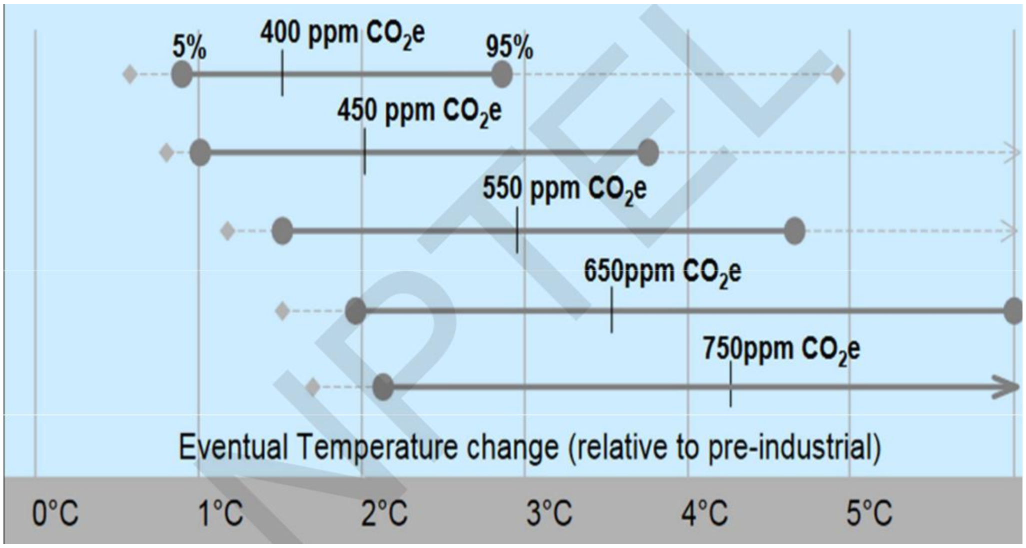
Stefan Rahmstorf, Potsdam Institute for Climate Impact Research

Now, to prevent this from happening, you have to rapidly reduce the CO_2 emission from the present value of around 60 gigatons to around 18 gigatons by 2040. This is a part of the Paris agreement, but it is not happening right now. We are not able to convince all the countries to reduce CO_2 emissions.



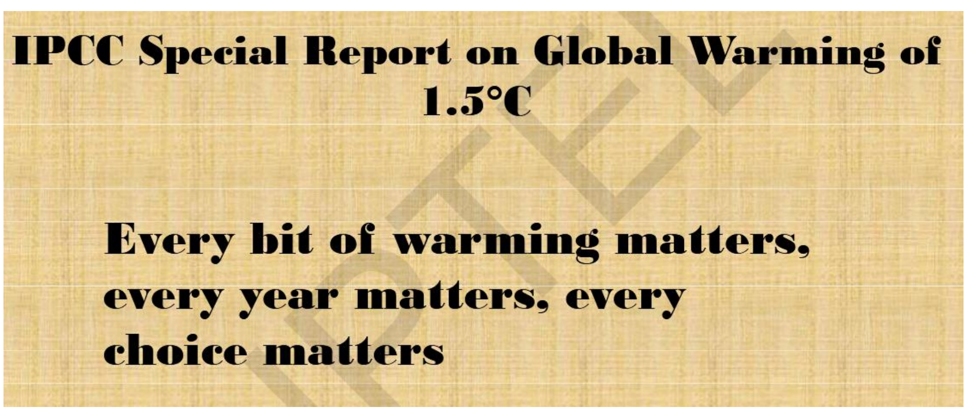
Now, the budget we have is only 1000 billion tons of carbon. If we emit beyond that, the temperature will go above 2.5 degrees centigrade and can lead to catastrophic climate change.





Here is an example. We are right now around 420 ppm (CO_2 concentration), and the chances are that over the next 100 years, the temperature may increase beyond 2.5°C. But if we allow the CO_2 to go to 450 ppm, which is going to happen, it may increase by 3.5°C. If you are careless and the CO_2 concentration goes to 550 ppm, the global temperature may rise by 4.5°C. If you do not do anything, it will eventually go to 650 ppm, and then there will be 5°C increase in global mean temperature. So, this shows clearly how serious the issue is and how we need to take immediate action.

Now, in the IPCC special report on global warming about the 1.5-degree tipping point, there is a clear warning.



Every bit of warming matters. Every year, we do not take action on matters, and every choice matters. This is what I want you to remember from this course. If you understood the science of climate change, you would understand that every bit of warming is bad.

Every year we delay the reduction of CO_2 emissions is bad, and every choice that every human being makes will affect our future. So, this is a warning given clearly by the IPCC.

And, why? Because if we do not do that, as global warming occurs, more CO_2 will emerge from the permafrost. Permafrost is frozen soil in which there is methane and carbon dioxide trapped. As global warming occurs, all the permafrost will melt and CO_2 will come out, and this will accelerate global warming.

For every one degree Celsius rise in Earth's average temperature, permafrost may release the equivalent of four to six years' worth of coal, oil, and natural gas emissions—double to triple what scientists thought a few years ago. Within a few decades, if we don't curb fossil fuel use, permafrost could be as big a source of greenhouse gases as China, the world's largest emitter, is today

Now, the myth that it will be too expensive to mitigate climate change is wrong. It will be too expensive not to mitigate climate change. That is the message you must get from this course.

Myth:
It will be too expensive to mitigate climate change

Reality:
It will be too expensive NOT to mitigate climate change

Seinfeld and Pandis point out in their book that if we stop CO_2 emissions today, the CO_2 in the Earth's atmosphere will not reach the pre-industrial value for the next 1000 years. That is how much change we have already made.

If all the emissions of anthropogenic CO_2 is stopped today, it will take almost a 1000 years for the atmospheric CO_2 concentration to reach the preindustrial value

Atmospheric chemistry and physics: from air pollution to climate change
By John H. Seinfeld and Spyros N. Pandis.

'STEADY AS SHE GOES'

This cartoon illustrates the status we are in. We are on Earth, which is the boat, and we are concerned only about economic growth, and we are going to reach a tipping point. This is a waterfall. This young person is complaining, and the older politicians are not able to understand the threat. They think that this waterfall is very far away. It may not be.

Aerosols overtake greenhouse gases causing a warmer climate and more weather extremes toward carbon neutrality

> **The results suggest that the future aerosol reductions significantly contribute to climate warming and increase the frequency and intensity of extreme weathers toward carbon neutrality and aerosol impacts far outweigh those of GHGs and tropospheric O3.**
>
> **P.Wang et.al., Nature Communications | (2023)14:7257**

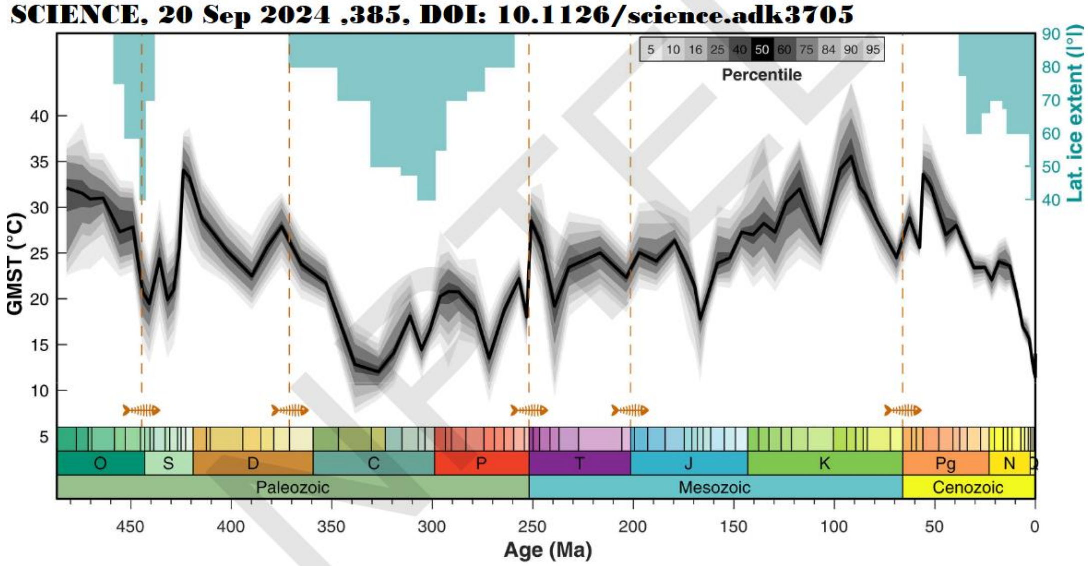
Another problem is, as we decrease aerosols due to air pollution concerns, global warming may occur earlier. That is another threat we face. There is a risk of heat waves, wildfires, and droughts, and the insurance companies that insure against these are getting concerned.

Physical risk events from heatwaves, wildfires, floods and droughts are of particular concern because of their potential to impact food security, energy and water infrastructure, as well as lead to business defaults on a scale that the insurance industry would be unable to cope with.

Climate change risk assessment 2021
Chatham House

A very interesting paper appeared in September 2024, in which they have reconstructed Earth's mean climate over the last 485 million years. Please read that. It is a fascinating account of how we can combine model and proxy data.

A 485-million-year history of Earth's surface temperature by Judd et al., SCIENCE, 20 Sep 2024 ,385, DOI: 10.1126/science.adk3705



With this example of how we have combined climate models and proxy data to understand Earth's climate over the last 485 million years, I conclude this course. I hope you will benefit by understanding the science of climate change.

Thank you.