Climate Change Science

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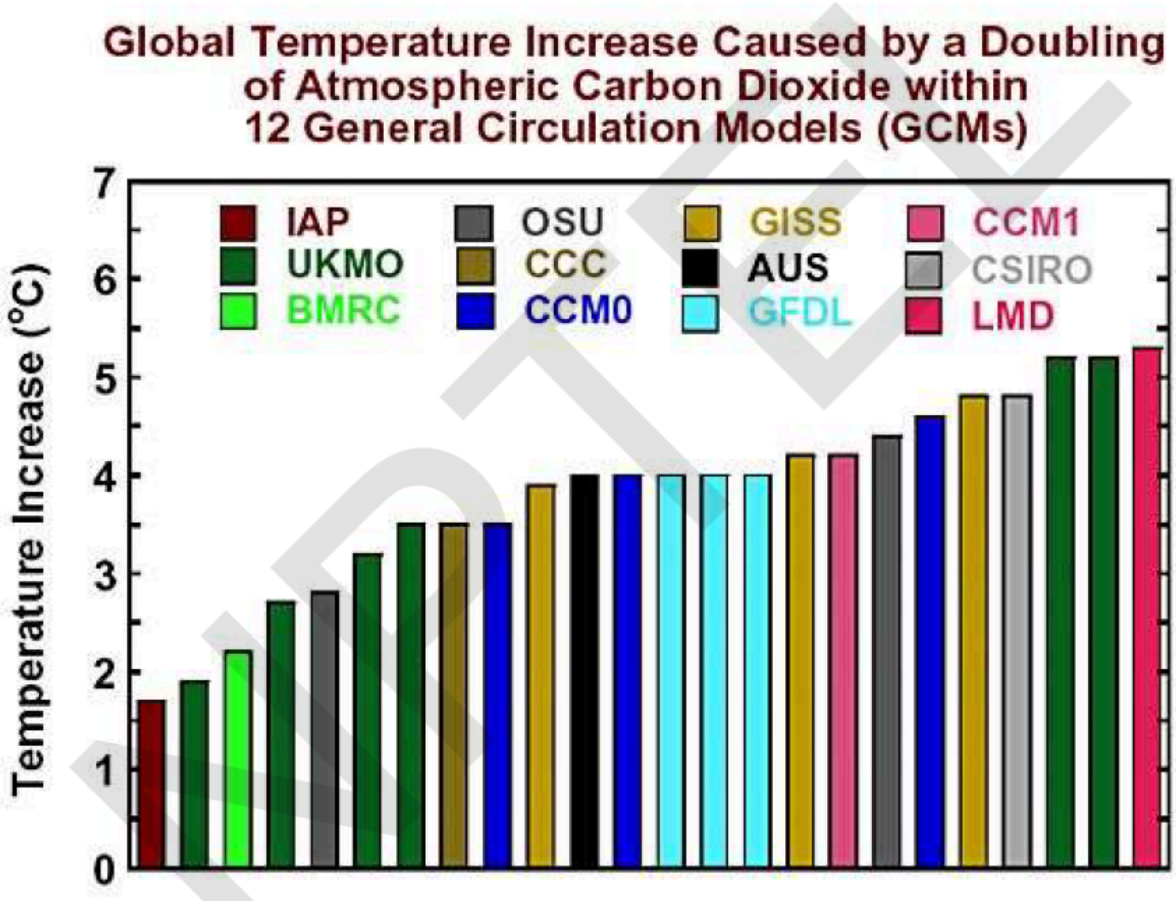
Lecture – 9
Feedbacks in Climate System

In the last few lectures, we showed that the global mean temperature is a function of the incoming solar radiation, the amount of radiation reflected by the Earth to space (called albedo), the amount of solar radiation absorbed by the Earth (solar absorptivity), and the emissivity of the atmosphere and Earth in the infrared. We also saw that if we change any of these parameters one at a time, changes on the order of 1° centigrade take place. Although this is very useful to understand, one must realize that in the real world, these parameters change together. For example, when you change the incoming solar radiation—let us say it increases—the temperature goes up. If the temperature goes up, ice will start melting, so albedo will change. These are called feedbacks.

You can think of them as chain reactions: something changes, and it sets up a reaction for something else to change. It is important to take into account these chain reactions because the ultimate change in the Earth's climate depends not only on the initial perturbation or disturbance but also on how other things in the system change to increase or decrease the Earth's temperature. This is an important issue and has bothered climate scientists for a long time.

If you look at many climate models developed all over the world—here (in the diagram below) we have 12 of them—and in each one you allow carbon dioxide to be doubled from, let us say, 280 ppm to 560 ppm, then you see what the temperature change of the Earth is. You find that some models like IAP show a value as low as 1.7 degrees, while a model like LMD gives a value as high as 5 degrees. Now, if the actual change is around 1.75 degrees, we may say it is something we can adjust or adapt to. If it is 5 degrees, it will be a catastrophic change because most of the ice in the polar region will melt. So, we need to know which is correct.



Now, why is there so much difference between different models? We will discuss that in great detail, and I will give you a hint: the biggest problem in these models is in the way they model clouds. As I pointed out earlier, clouds have a spatial scale on the order of a kilometer, and most of these models have a grid size of 50 by 50 kilometers, which means they really cannot simulate changes in clouds accurately because the scale of the cloud is smaller than the scale of the grid. What is happening within that 50-by-50-kilometer grid cannot be determined from first principles in physics. Thus, most models use empirical techniques to predict what kinds of clouds will occur within the grid. This is called parameterization, and we will discuss it in some detail later in the course.

So, the question is: Is cloud representation one of the reasons why the models differ so much, or are there other causes? For example, in some models the ice may melt less than in others, or the vertical profile of temperature may change differently. The third important factor is water vapor: the amount of water vapor in the atmosphere may not change equally in all models.

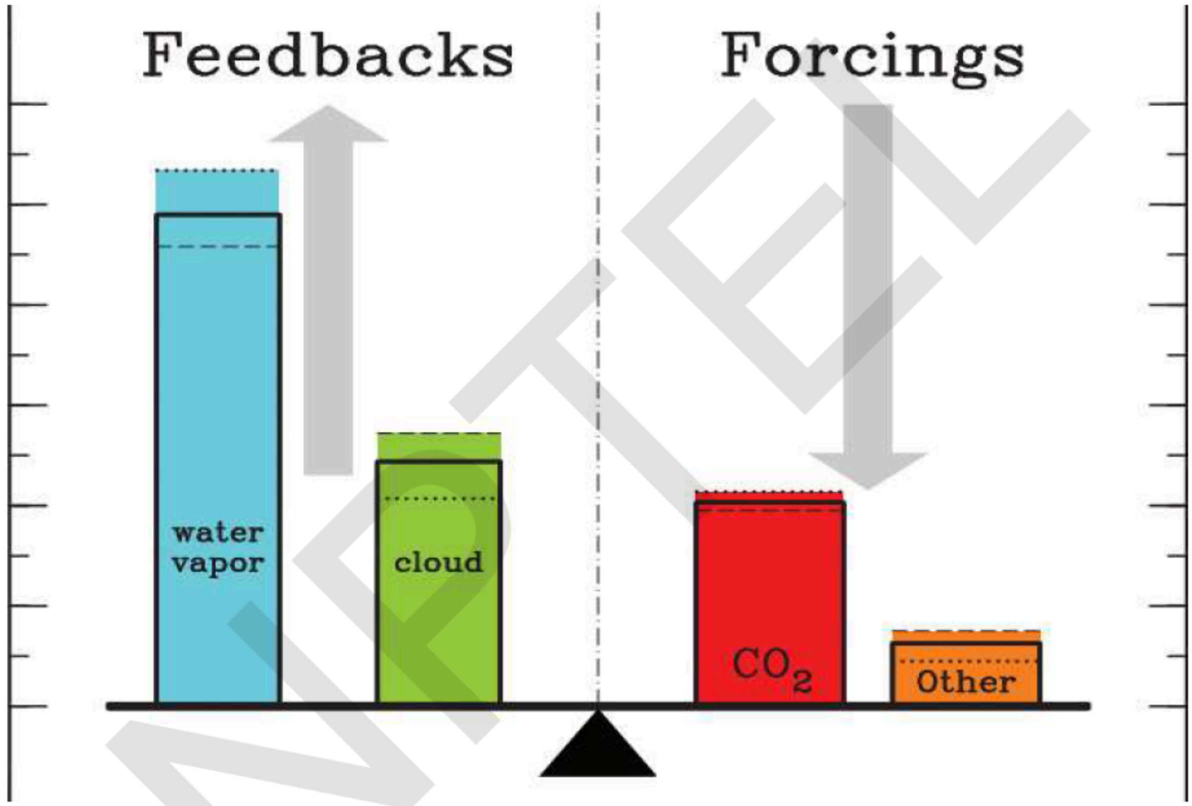
We need to know which factors are different among models, which we can trust, and which show large differences. That is the purpose of feedback analysis. The reason why it is so important is that a 1% change in the Earth's planetary albedo exerts as much impact as doubling CO_2.

A 1% change in Earth's planetary albedo exerts an impact as large as a doubling of CO2.
Large capacity for albedo change due to clouds and cryosphere

If you double CO_2 in the Earth's system and the albedo changes—that is, reduces by 1%—it can completely compensate for the change in CO_2. Many people earlier thought that doubling CO_2 might not be too serious because the Earth would adjust itself. This is called **homeostasis**. Like your body temperature remains constant whether you exercise, sit down, or sleep, they thought Earth may have a way to control its temperature so that whenever we make some changes, some other change will occur to compensate. Today, we know that that is not happening. The Earth's climate is not as stable as people once thought; it can change a lot and it can change rapidly. Now, the reason why albedo changes are a very important issue is that both clouds and the cryosphere—that is, ice and snow—can have a large impact on Earth's albedo.

In order to understand the role of feedbacks, the IPCC has defined a term called feedback and a term called forcing. It is important for you to understand the difference. One example is the increase in carbon dioxide in the Earth's atmosphere over the last 150 years. This is not a natural change; it occurred because we human beings drilled deep into the Earth and extracted coal, oil, and gas and then burned them. Before we did that, the Earth's atmosphere was in a stable equilibrium, where the amount of carbon dioxide did not change much. Because carbon dioxide from volcanoes and carbon dioxide removed by photosynthesis and dissolving in the ocean were in perfect equilibrium, the carbon dioxide amount remained fairly constant for the last 10,000 years at 280 ppm until we started burning fossil fuels, and then it started increasing.

We consider that to be forcing because it is external to the system and disturbs its equilibrium. We can also consider a major volcanic eruption as a forcing. Now, as you will see, the magnitude of the forcing is not unique; it can differ from situation to situation. Now, what is a feedback? Feedback is the response of the Earth system to the forcing.



Lacis et al., Sciences 15 October 2010

So, we increase CO_2 by burning oil, coal, and gas, and then the temperature of the atmosphere goes up. When it goes up, the amount of water vapor increases, clouds change, and ice starts melting. All these are feedbacks because they respond to the temperature change. They are not forcing because they are not induced externally but are caused by the change in temperature within the system. That is the difference between feedback and forcing. To make it very clear, we talk about radiative forcing because the entire discussion in climate change science is in terms of how much radiative imbalance is caused by any perturbation, whether it is due to carbon dioxide, a volcanic eruption, or the Sun.

Ultimately, they affect the top-of-the-atmosphere radiation budget. That is the radiative forcing, and it must be external—meaning it changes without being influenced by the system (which here means Earth and its temperature).

Without Earth's temperature changing, if either solar, volcanic, or human-induced changes cause an imbalance at the top of the atmosphere, that is a forcing. Feedback is a response of the system to the external perturbation that leads to further perturbation. For example, if we increase CO_2 by burning fossil fuels, the temperature goes up, and then water vapor increases. The water vapor increase is a feedback. It is caused by temperature change and is not directly external.

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)

So, I remind you again, radiative forcing is a concept used in climate science to quantify the change in the energy balance at the top of the atmosphere.

Now, there are **three types of radiative forcing** mentioned in the IPCC. The first one is called **instantaneous forcing**: as soon as the change occurs—say, a change in solar input or a volcanic eruption—we take the change into account without considering the immediate change that occurs in the stratosphere. The stratosphere is the region above 15 kilometers in the Earth's atmosphere in which temperature increases with height (unlike the troposphere, where temperature decreases with height). We will discuss that in a little detail later. The stratosphere is much thinner than the troposphere because, as you know, the density of the atmosphere decreases with height. So, the stratosphere has little mass.

As soon as you impose any forcing, it will immediately change the stratosphere. Earlier, people did not account for the change in stratospheric temperature. Later, people felt that because it changes so quickly, we should adjust the **radiative forcing in response to the change in the stratosphere alone**, without changing the troposphere properties (because they take time to change). They allowed the stratosphere to adjust to the forcing and then calculated the radiative imbalance.

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".

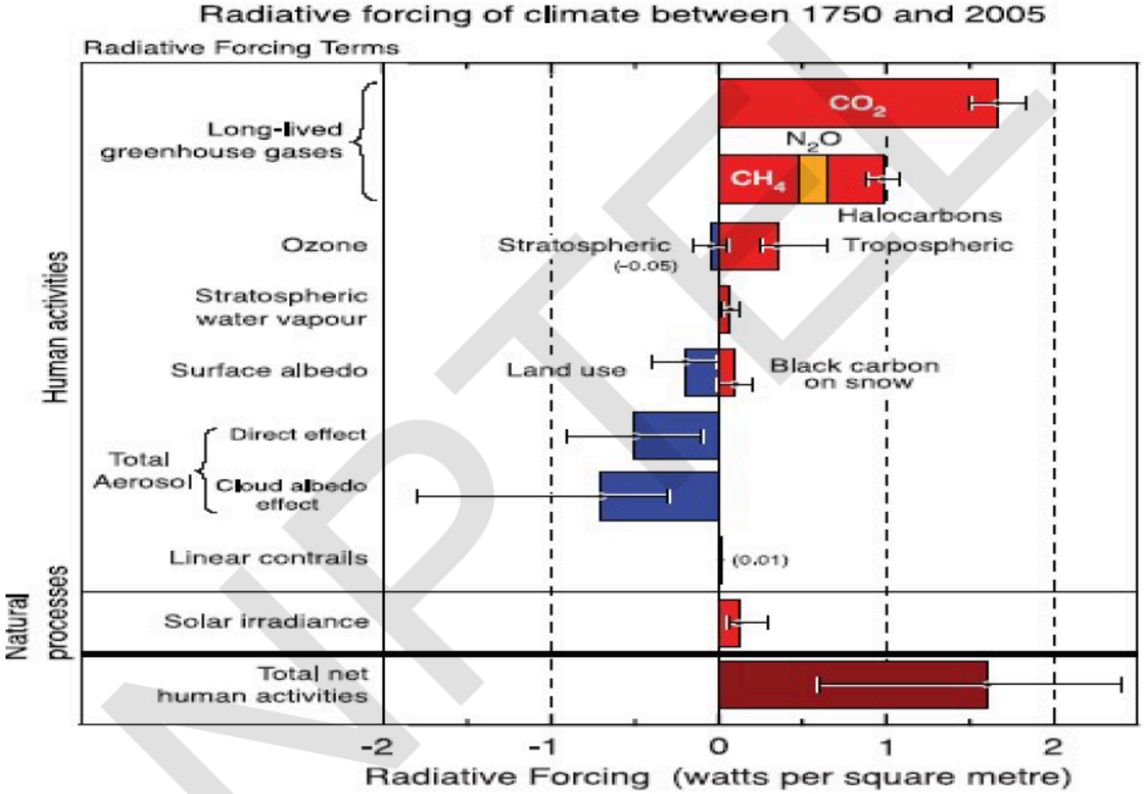
Stratospherically adjusted radiative forcing:

"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".

Recently, the IPCC has refined this further and introduced the term **effective radiative forcing**, which allows both the stratosphere and troposphere to change. These three definitions do not alter the forcing substantially; they do cause some differences. The reason this has been introduced is that, in the future, when there will be very strict laws about how much carbon dioxide or methane a country can emit, everything will be defined in terms of radiative forcing. So, the accepted standard now is effective radiative forcing, which accounts for adjustments in both the stratosphere and troposphere because those will adjust within a few days. Although the troposphere has much more mass than the stratosphere, it is still much less massive than the ocean, which changes very slowly over years, decades, and centuries. And that is what we should be worried about—not changes occurring within a few days. Thus, the IPCC now uses effective radiative forcing as a concept.

I can tell you that the differences between these three are not significant. For our purposes in this first course, we will not distinguish too much between them. However, if you read literature and research papers, you must be aware of the differences in the way radiative forcing is defined at the top of the atmosphere.



FAQ 2.1, Figure 2. *Summary of the principal components of the radiative forcing of climate change. All these*

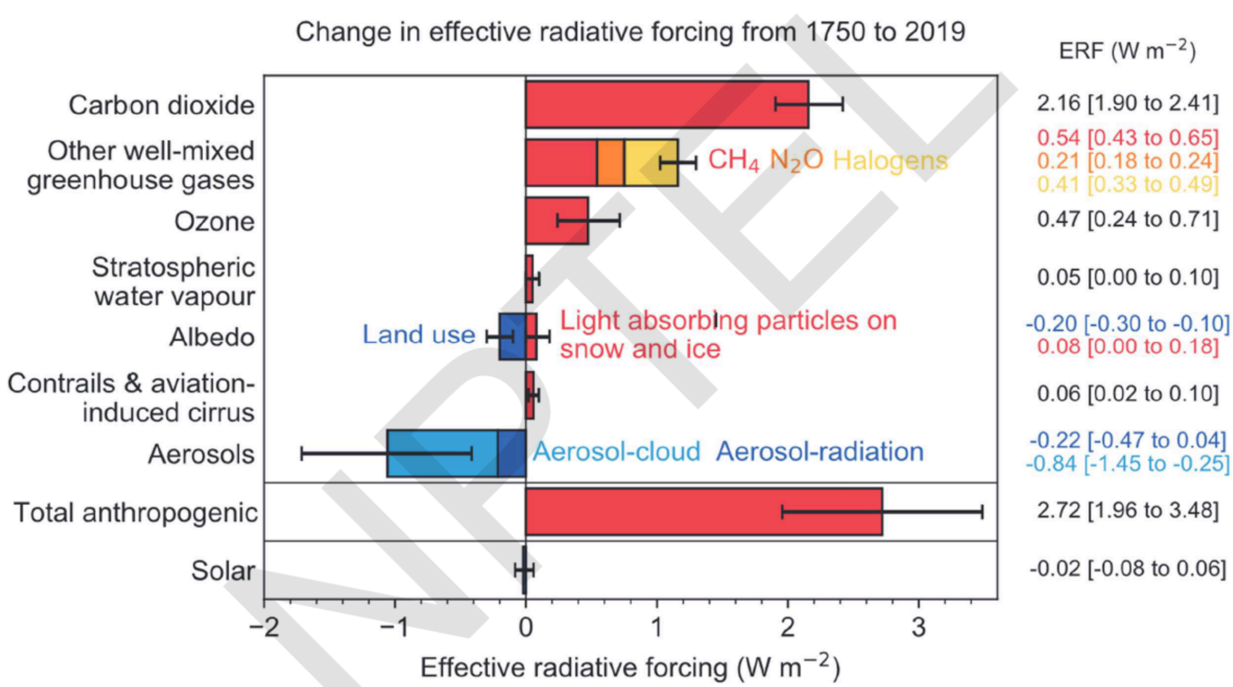
Here is an example of radiative forcing as given by the IPCC for the period from 1750 to 2005. This is presented to show that the total net human activities affecting radiative forcing was around 1.6 W/m^2 between 1750 and 2005, and among these, the most important contributor is carbon dioxide. That is why there are negotiations on how to control CO_2 emissions on Earth, because it is the dominant component. Secondly, CO_2 has a long lifetime—it remains in the atmosphere for hundreds of years. So, if we do not make changes now, it will impact Earth's climate for hundreds of years.

The next important greenhouse gases are methane, nitrous oxide, and so-called halocarbons (like freons used in refrigerators). These are chlorine, fluorine, and carbon compounds used in many devices such as air conditioners and refrigerators. They were thought to be harmless 60 years ago because they are not toxic, do not easily catch fire, and so on. But it turns out that these are harmful for two reasons.

One, they reach Antarctica and destroy the ozone layer in the stratosphere, and two, they cause a greenhouse effect. Although present in much smaller concentrations than CO_2 (for instance, CO_2 today is about 420 parts per million, whereas methane is in parts per billion and some halocarbons in parts per trillion), they still have a significant impact, and we will discuss why this is so.

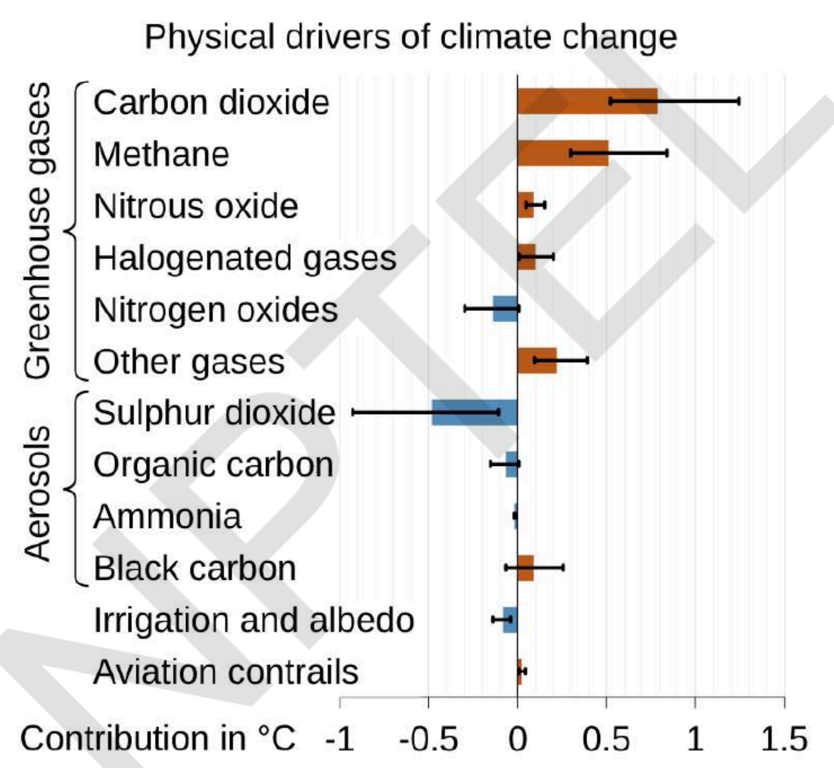
I mentioned briefly that some of these gases absorb radiation in the region between 10 and 12 microns, where neither water vapor nor carbon dioxide absorbs radiation, and so they have an impact. In addition, ozone is changing—it is decreasing in the stratosphere and increasing in the troposphere. Thus, the troposphere will cause further warming and the stratosphere will cause cooling. All these factors are taken into account. Then, we have to account for aerosols—small particles released into the atmosphere by industrial activities, such as soot, which causes warming. If you deforest an area, the albedo of Earth changes. Also, aerosols have a direct impact by reflecting or absorbing radiation or an indirect effect by changing cloud albedo. Notice that if you add the greenhouse effect of carbon dioxide, which is 1.7 W/m² here, and other small gases, which total 1 W/m², you get 2.7 W/m²; about half of it is counteracted by aerosols. Thus, you obtain an overall value of around 1.6 W/m². I want to note that the impact of changes in solar input is very, very small. The effect of the 11-year solar cycle is minimal compared to human impact.

Some are also worried about the impact of aircraft circling in the stratosphere, but that impact is still quite small. This table or figure from the IPCC clearly indicates that if we want to control Earth's climate, we should focus mainly on carbon dioxide and methane—these are the two major gases of concern. CO_2 has a long lifetime, so it must be controlled quickly, or it will continue to affect the climate for centuries. The next important greenhouse gases are methane, nitrous oxide, and halocarbons. Methane has a lifetime of about 10 years. If methane is released today, in 10 years it will have mostly converted to CO_2 and water vapor, diminishing its direct impact; still, it is a very powerful greenhouse gas and must be controlled.



Now there is another figure (given above) generated for a more recent period, using effective radiative forcing—that is, accounting for changes in the troposphere and stratosphere on a short time scale. The numbers are slightly different, but not very different. Ultimately, you get a net value of about 2.7 W/m². That is because we have gone from 2000 to 2019, yielding a value of 2.72 W/m² on average. However, note that there is a large uncertainty in this radiative forcing: 2.72 W/m² is a mean value, but the range goes from 1.96 to 3.48 W/m². The high uncertainty is mainly due to aerosols, whose variability in space and time is not well known. They also affect clouds in ways we do not fully understand. Hence, aerosols have a huge uncertainty in their cooling effect (on the order of 1 W/m²), leading to a total uncertainty of around 1.5 W/m². This is something we must accept until better measurements are made regarding aerosols and their impact. This is the most recent data from the IPCC.

Now, some of you may not like the term "radiative forcing" because it is given in watts per square meter, which may not convey how much temperature change is occurring. Therefore, the IPCC also provides estimates of how each of these molecules impacts temperature—this is without feedback (see figure below). For example, carbon dioxide itself has changed the temperature by around 0.75 degrees over the last 150 years, methane by around 0.5 degrees, and others are much smaller. Sulphur dioxide, an aerosol, causes cooling of about 0.5 degrees. Here they have not included its effect on clouds. This clearly shows that, in terms of global temperature change, the dominant effects are due to CO_2, methane, and sulphur dioxide, with sulphur dioxide contributing large uncertainty in our estimates.



Climate Feedbacks

$dT/dt = \mathbf{Q} + \mathbf{f}(\mathbf{T})$

T= state of climate system (temperature)

Q = Forcing, independent of T.
examples: insolation, CO2, etc

f = Feedbacks, dependent on T.
examples: water vapor, clouds, and ocean circulation.

The distinction between feedback and forcing can be unclear: *e.g.* methane in atmosphere...

Now, we come to the definition of **climate feedback**. We examine the global mean temperature change of the Earth, with q as a forcing which is independent of temperature and the feedback which depends on temperature. Forcing can be from incoming radiation (insolation) or from CO_2 emitted by human beings or volcanoes. Feedbacks are those quantities which depend on temperature—like water vapor, clouds, or ocean circulation—that change with temperature. The distinction between forcing and feedback is clear, though there are cases where it is not. Take methane, for example: methane from rice fields (a result of human agricultural activity) is considered a forcing, while methane released from melting permafrost as the temperature increases is feedback. Thus, methane can act as both a forcing and a feedback. For most other quantities, however, one can clearly distinguish between forcing and feedback.

Now, let us go back to the net radiation at the top of the atmosphere, which is the focus of our simple climate model. Incoming radiation—after accounting for albedo—is compared to the outgoing longwave radiation (OLR). Changes in net radiation can result from changes in the Sun's input, Earth's albedo, or OLR. Changes in albedo or OLR can be either due to forcing or due to feedback. For example, deforestation changes albedo as a forcing (it is human-induced), while ice melting due to global warming (a feedback) changes albedo. Similarly, a human-induced increase in CO_2 reduces OLR as a forcing, while an increase in water vapor due to global warming (a feedback) also affects OLR.

$$R = S/4 \{ 1 - \rho \} - OLR$$

Net radiation can change on account of changes in S (forcing) or changes in albedo or OLR

Changes in albedo and OLR can be on account of forcing or feedback

Examples:

Human deforestation changes albedo (forcing)
Global warming causes ice melting(feedback)
A human induced increase in GHG reduces OLR(forcing)
Increase in water vapor due to global warming(feedback)
An increase in methane due to rice cultivation(forcing)
Global warming induced methane increase(feedback)

Thus, human deforestation is a forcing; global warming causing ice melt is a feedback; a human-induced increase in greenhouse gases like CO_2 is a forcing; an increase in water vapor due to global warming is a feedback; and both an increase in methane due to rice cultivation (forcing) and an increase due to polar warming (feedback) can occur. You must understand this distinction in each situation.

Now, we want to understand **what determines the response of the Earth system to any forcing**. The response depends on the magnitude of the forcing and on what feedbacks occur, which either amplify or dampen the initial forcing. Thus, the net radiation at the top of the atmosphere is altered by a forcing (such as increased CO_2). Once that happens, the Earth's temperature changes. When it changes, some things like OLR or other variables will change in response, adding to or reducing the initial forcing. Ultimately, the system comes to equilibrium: the Earth's temperature increases or decreases until the initial forcing is balanced. If there were no other feedbacks, there is one feedback that always occurs—the Planck feedback. That is the emission by the Earth's surface to space, which will always occur even if there were no atmosphere, and that feedback is always negative. In other words, as soon as a forcing occurs, the Earth's temperature rises such that the outgoing radiation increases to balance the forcing. But there are additional changes that depend on temperature (such as changes in water vapor, clouds, or ice), and these are also feedbacks. They differ from model to model: one is the immediate direct feedback and another is in response to changes in some variables.

What determines the Climate Response?

- **The climate response to a given perturbation depends on the strength of the forcing and on the strength of radiative feedbacks, which act to amplify or dampen the initial forcing**
- **Can decompose the response into a Taylor series (first consider the case with no feedbacks). In equilibrium:**

$$0 = \underbrace{\frac{\partial R}{\partial F}}_{\text{Radiative Forcing}} + \underbrace{\frac{\partial R}{\partial T}\Delta T}_{\text{Increased/Decreased Emission to Space when the Planet warms or cools (Planck feedback)}}$$

- ***R* is the net top of atmosphere**
- **F is the applied forcing (e.g., doubling CO_2)**

Radiative Forcing

Increased/Decreased Emission to Space when the Planet warms or cools (Planck feedback)

A climate feedback is any process that does not depend *directly* on the forcing, but depends *indirectly* on the forcing through changes in temperature. To be considered a feedback, this response will further amplify or dampen the initial forcing. Let x be such a feedback parameter and F the forcing. After a new equlibrium is reached

$$0 = \frac{\partial R}{\partial F} + \frac{\partial R}{\partial T}\Delta T + \underbrace{\left(\frac{\partial R}{\partial x}\frac{\partial x}{\partial T}\right)}_{\text{Feedback Terms}}\Delta T$$

Feedback Terms

I will now focus on the most important feedback, which is water vapor. This was recognized more than 120 years ago by Chamberlin, who stated that water vapor in the atmosphere is dependent on temperature.

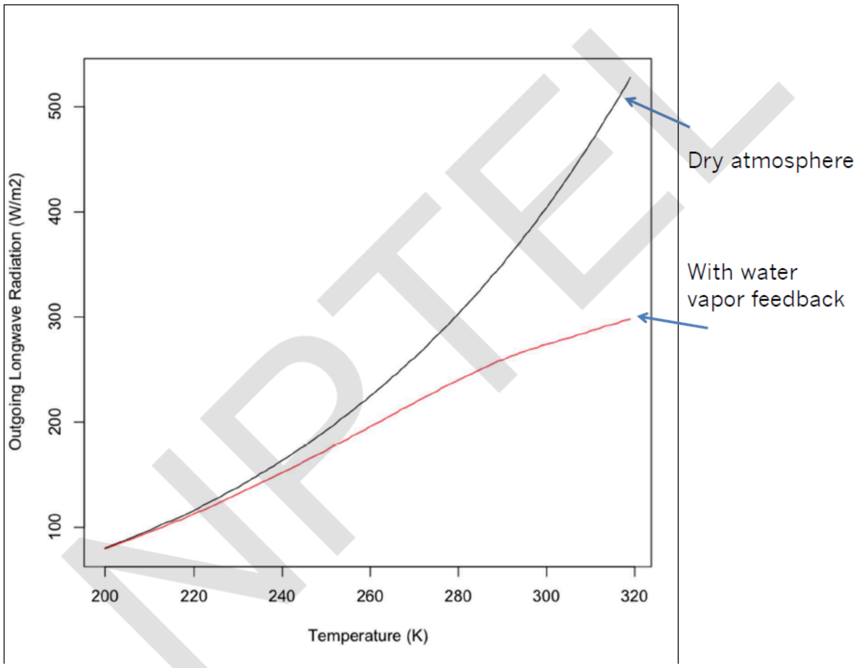
Water Vapor Feedback

Water vapor is dependent on temperature for its amount, and if another agent, as CO_2, not so dependent, raises the temperature of the surface, it calls into function a certain amount of water vapor which further absorbs heat, raises the temperature and calls forth more vapor …

TC Chamberlin (1905)

as quoted in Held and Soden (2000)

According to thermodynamics, if the temperature of the atmosphere goes up, the water vapor content must increase because of the relationship between saturated water vapor and temperature. So, as the temperature increases, water vapor evaporates from oceans and lakes into the atmosphere. Water vapor is a very powerful greenhouse gas, so it starts trapping heat and further raises the temperature. This is the most important feedback in the Earth's climate system and plays a critical role in how temperature changes. To highlight this, I want to show you the change in outgoing longwave radiation as a function of Earth's temperature for a dry atmosphere compared to an atmosphere with water vapor. In a dry atmosphere, OLR increases following sigma T^4 (Stefan–Boltzmann's law), but because water vapor increases with temperature, the actual OLR in an atmosphere with water vapor does not increase as rapidly.



For example, if the temperature increases by 100 Kelvin, the water vapor feedback can yield a difference of typically 150 W/m². This is very important feedback that must be understood. The advantage of the feedback concept, as favored by the IPCC, is the belief that the feedback parameter is useful because it is independent of the type of forcing—whether the forcing is due to increased CO_2 or solar radiation, the water vapor feedback will be similar. Today, we know that this is not strictly correct, and there has been some objection to that assumption.

Invariance of the feedback parameter

The feedback parameter concept is useful because it is almost independent of the type of forcing (e.g., CO_2 or Solar)

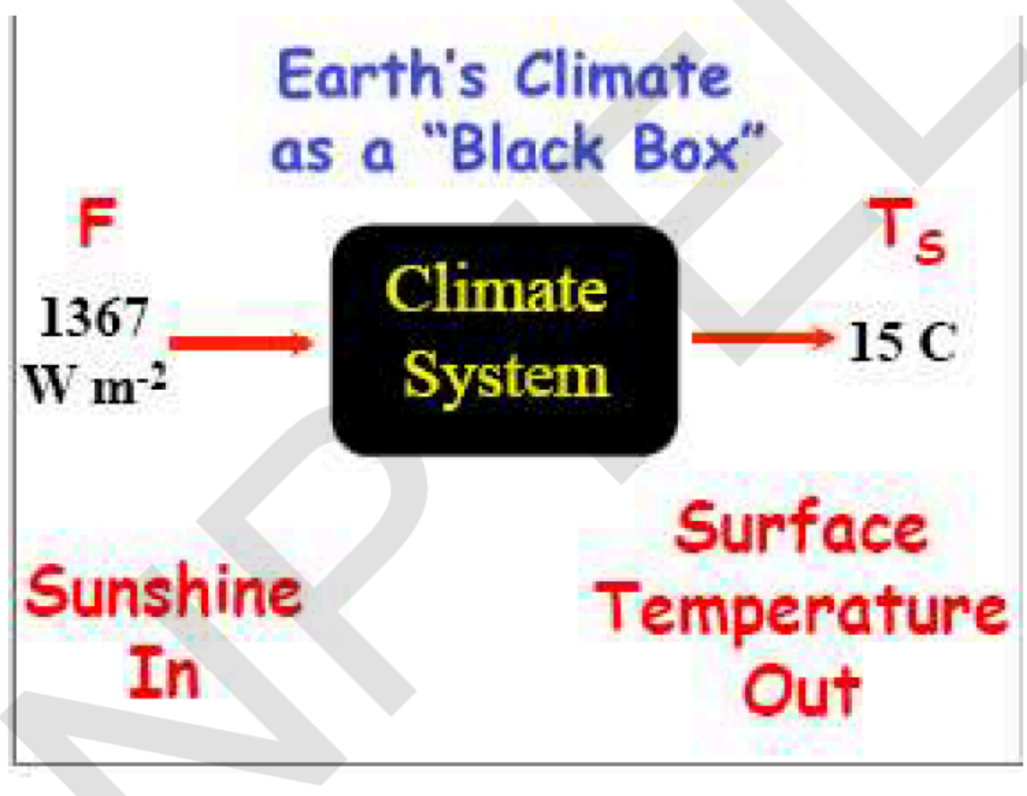
Time scale separation between forcing and feedbacks

Methane change can be due to forcing or feedback
Water vapor always a feedback. Why ?

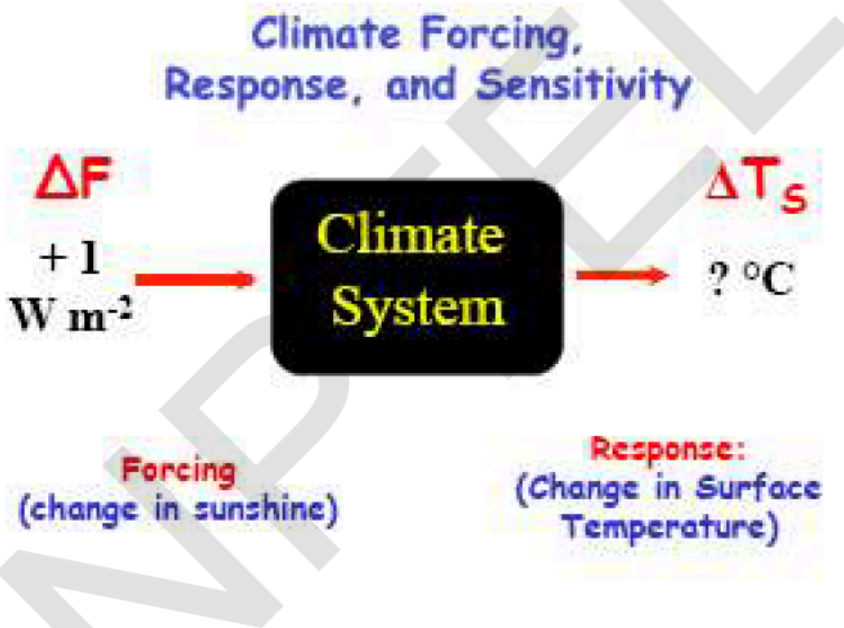
However, for policy purposes, we can still say with some confidence that the feedback parameter, irrespective of the forcing mechanism, is similar. The way the Earth responds to any forcing is quite alike. The second important aspect of feedback is the time-scale separation between forcing and feedback.

For instance, if we increase CO_2 today, the net radiation immediately changes, but the feedback changes more slowly because the ocean—which is responsible for much of the feedback—changes slowly due to its large mass and thermal inertia. Thus, changes in ocean temperature do not occur immediately after a forcing; they can take a few years. To illustrate, if we change CO_2, the temperature of the permafrost will change after a couple of years, and then methane is released. In that case, methane acts as a feedback. In contrast, if methane is directly introduced into the atmosphere from rice fields, that is an immediate forcing. Water vapor, however, is always a feedback because it responds solely to temperature changes.

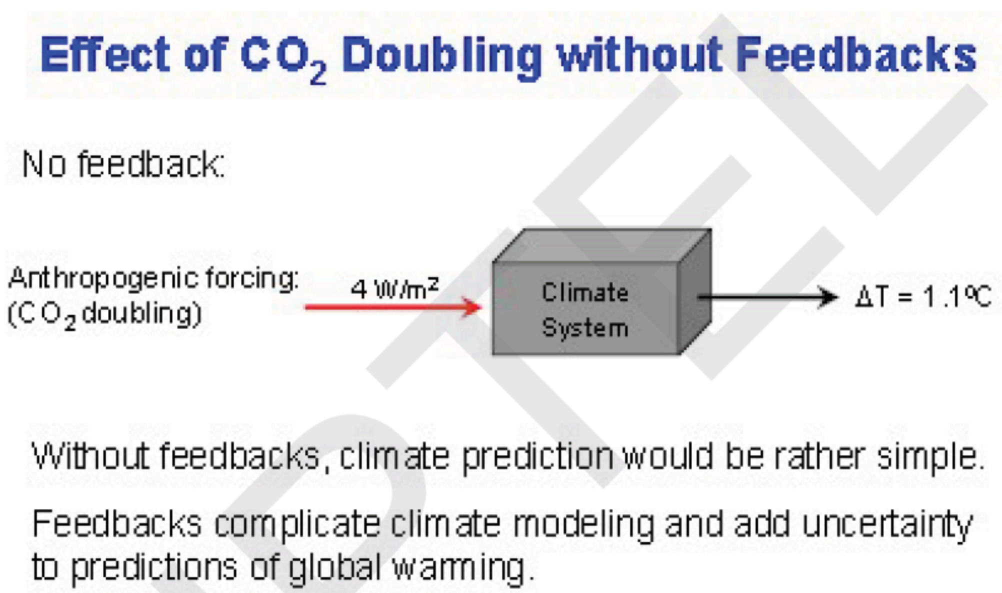
Now, to understand this in a simple system framework, imagine the Earth as a black box—a climate system. It has incoming solar radiation, and the output is, say, 15°C, with no feedbacks. This is called an open system. There are no feedbacks.



Now, if we introduce a feedback, let us say due to a change in temperature, the temperature increases, the system will change and an additional forcing will occur due to feedback.



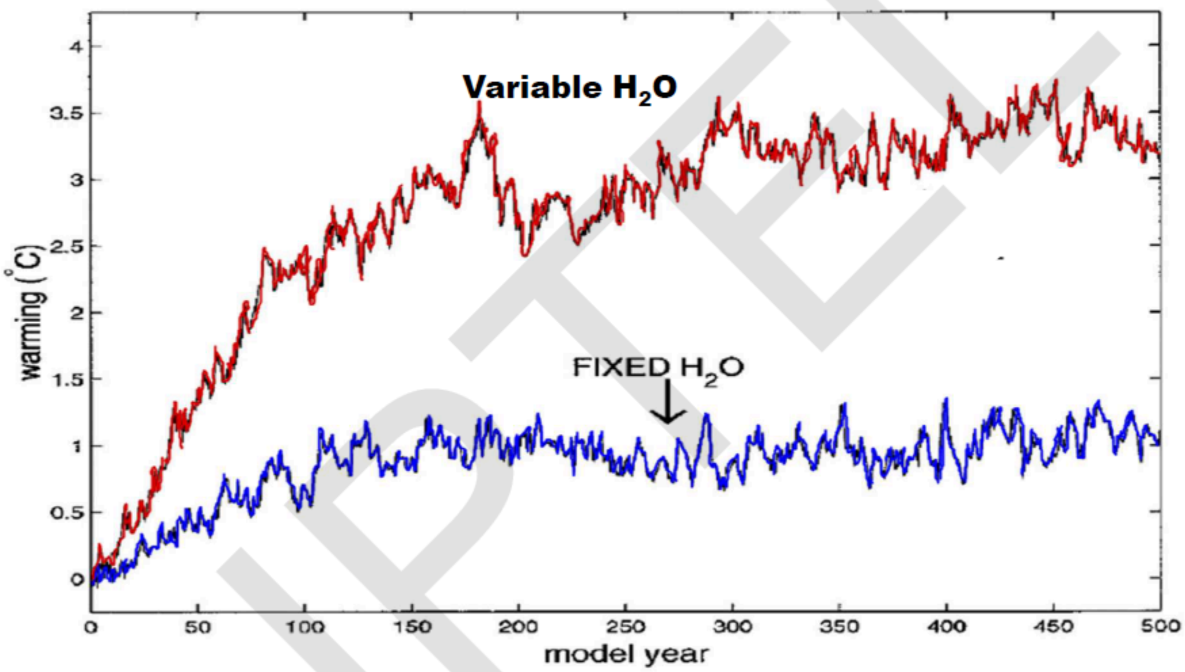
For example, if you suddenly double CO_2 in the Earth's atmosphere, then the outgoing longwave radiation (OLR) is reduced by 4 W/m^2. That is the forcing.



Without feedback, the temperature change is about 1.1°C. But because of the change in ocean temperature, water level will increase in a couple of years due to the feedback. Now, this was shown very clearly by Prof. Manabe in one of his simulations, which he did almost 25 years ago. He ran two climate models, coupled ocean atmosphere model with variable H_2O and fixed H_2O.

In one of the set-up, he kept the water vapour constant in the atmosphere. You can do it in a model. You cannot do it in the real world. In a model, you can set water vapour to be fixed at an initial value. So, as you double CO2, the temperature goes up, but water vapour does not change. So, the temperature of the Earth increases by 1 degree and remains roughly constant. But if you allow the water vapor to increase as per the laws of thermodynamics, then the temperature slowly increases further and further due to the water vapour feedback and it stabilizes at a value close to 3 degrees.

Hall and Manabe ,Journal of Climate,1999

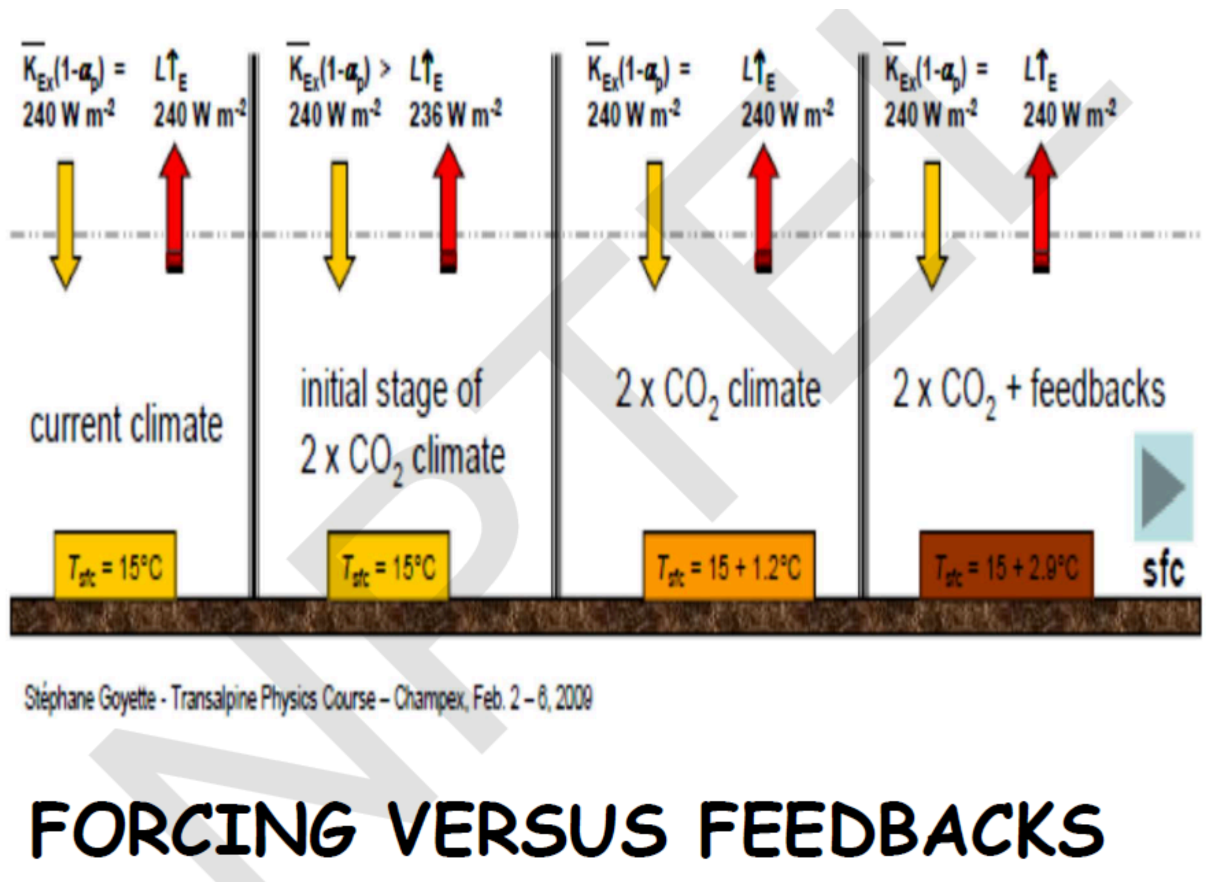


The 500-yr annual-mean time series of the global-mean surface temperature change in the integrations where CO2 is doubled to 720 ppm relative to the unperturbed experiments, where CO2 was fixed at 360 ppm.

So, in this model, the feedback has increased the global mean temperature by 2 degrees. It shows clearly that water vapor is a feedback parameter, because if we artificially keep water vapor constant in the atmosphere (which is not correct, but we do it to understand the role of feedback), the Earth's climate system has only one degree warming. So, this is a nice illustration of the role of feedback, which occurs slowly over a period of 100 years or so and then stabilizes. So, this is an important point illustrated by Manabe, who got a Nobel Prize in 2021 for the work he did in climate models.

Now, to summarize what has happened, you start with a system, which is an equilibrium with 240 watts per meter squared absorbed solar radiation and 240 Watt per meter squared radiation emitted by the Earth system.

Suddenly, you increase CO2 by a factor of 2, an abrupt change. Then the OLR comes down to 236. Immediately temperature changes by 1.2 degrees in the first year without feedback. And the Earth's outgoing radiation becomes 240, but slowly the temperature of the Earth goes further up due to feedback from 1.2 degrees increase to around 3 degrees Celsius increase.



And over the long term, again OLR becomes 240 W/m^2, but with a higher temperature of the Earth's surface. So, this is how the temperature of the Earth changed in the model run due to forcing without feedback and with feedback.

We will conclude this lecture on this note and we will continue this in the next class.