Course Name: An Introduction to Climate Dynamics, Variability and Monitoring

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GLOBAL TEMPERATURE MODEL, RADIATIVE FORCING AND ZERO DIMENSIONAL ENERGY BALANCE MODEL

Good morning class and welcome to our continuing lectures on climate dynamics, climate variability and climate monitoring. Today we will start a new section of our syllabus which will involve in trying to create simple models that quantify the impact of the changes made by anthropogenic greenhouse emissions on the climate of the world. So, I have named this section quantifying climate change. Given, for example, that we have changed the concentration of a greenhouse gas by a certain percentage, how would we go about calculating the impact it has on the climate of our planet? what is the theory and the modeling that is required at least at a simple analytical level that will give us a handle on how is that impacting our world's climate. So, before we begin, let us briefly recapitulate some of the things that we have learned before. We know that the total incident solar radiation that is being absorbed by the earth which we will call E dot S absorbed is 1 minus alpha where alpha is the albedo into the solar constant S0 by 4 where the solar constant S0 is 1360 watt per meter square and the albedo of the earth is 0.29. and this comes to around 240 watt per meter square, a value that we have seen before. We also know that when seen from space, the blackbody emission temperature of the earth Te is such that sigma Te to the power 4, the total outgoing radiation thermal radiation from the planet as seen from space will be equal to this incoming solar radiation energy that is being absorbed at least under steady state conditions where sigma is the radiation coefficient Stefan Boltzmann's coefficient which is 5.67 into 10 to the power minus 8 watt per meter square Kelvin to the power minus 4.

Given this, we can calculate the blackboard emission temperature to be 255 Kelvin. The actual mean surface temperature of the earth, Ts, is around 288 Kelvin. As we have discussed before, it is around 15 degree centigrade. So, if you think of the surface of the earth itself to be a black body, which it is in the long wave radiation regime, then the total black body emission from the surface of the earth is sigma Ts to be powerful, which we will call E dot surface. And this value, if you put 288 kelvins here, gives us around 390 watt per meter square.

So, we see two numbers, the actual radiation that is going out to space is 240 watt per meter square, whereas the radiation being emitted by the surface of the earth is 390 watt per meter square. Hence, we can say that the atmosphere on average is absorbing the rest of the emissions that is coming from the surface of the earth. And this is a measure of the mean global warming effect that the atmosphere is having. The difference between the outgoing thermal radiation from the surface minus the outgoing thermal radiation as seen from space which is 390 minus 240 equal to 150 watt per meter square. This is the total global warming effect that the atmosphere is having on our planet Earth today.

Studies have shown, and we will not go into the detailed modeling results, that water vapor contributes about two-thirds of this mean global warming effect and CO2 accounts for around one-fourth or 25% of this effect. So around 66% comes from water vapor, 25% from CO2 and the other greenhouse gases contribute the rest. So in terms of the mean greenhouse effect or the global warming effect that the atmosphere is having, water vapor is the most important gas and the second most important gas is carbon dioxide. Now that we understand this mean global warming effect, What is clear then is that when you are adding greenhouse gases into the atmosphere, this mean global warming effect is increasing. There is a perturbation or an increase in this global warming effect as the atmosphere is absorbing a greater amount of the radiation being emitted from the surface of the world.

And as a result, the surface temperature is heating up. Let us see how do we quantify this point. So, in this context then we will ask how does a given climate state, suppose the pre-industrial mean climate which is the climate that the world was experiencing in around 1750 CE, 1750 How does that given climate state respond to perturbations of the various absorbing gases, gas concentration values or concentration of aerosols in the atmosphere? Because we have not only emitted say CO2 or methane, we have also emitted aerosols like smoke particles, soot particles, etc. So how does the climate state itself get perturbed due to the change in the concentration of these materials in the atmosphere? And here a very important concept that we will introduce is the idea of radiative forcing. What is radiative forcing? There are a few possible definitions.

One useful definition of defining radiative forcing is, radiative forcing is defined as the net decrease of upward irradiance. at the tropopause due to change in some climate change driver such as change in the concentration of a gaseous absorber. Remember irradiance is basically the radiation flux that is going outwards, net decrease in the upward irradiance. Here, when we are talking about upward irradiance, we are talking about the net upward irradiance. How much that is decreasing at the level of the tropopause due to change in some climate change driver like a change in the concentration of gaseous absorber.

So, let us understand this definition and then we will uncover what it actually means. So, radiative forcing defined as the net decrease in the upward irradiance or radiation flux density at the tropopause due to change in some climate change driver like the concentration of a gaseous absorber. The net upward irradiance of the tropopause, so remember tropopause is the boundary between troposphere and stratosphere, equals the outgoing irradiance minus the unreflected incoming solar irradiance at the tropopause. The net upward irradiance is basically the outgoing long wave radiation coming from both the surface of the earth as well as the atmospheric layers between the surface and the tropopause minus the incoming short wave radiation that part which is not getting reflected further by dust particles, clouds or the surface. the part of the incoming shortwave radiation flux which is not getting reflected but is being absorbed by either the atmosphere or the surface of the earth.

That difference is the net upward irradiance and the decrease in the net upward irradiance is defined as radiative forcing. So let us understand this idea a little bit more. At equilibrium conditions, the net outgoing irradiance will be zero. So let's see why this is the case. At equilibrium, the atmosphere, the earth, surface or the oceans are neither heating up nor cooling down when you take, say, a mean over multiple years, for example.

Hence, earth is neither absorbing heat or releasing heat. So, the net thermal energy coming into the earth system must be equal to the net thermal energy going out of the earth system. Therefore, the outgoing thermal energy, the outgoing long wave radiation must equal the incoming short wave radiation that is being absorbed by the sun. Energy balance must hold because there is no energy either accumulated or being lost in the earth system. However, the radiative forcing is positive, the incoming irradiance exceeds the outgoing irradiance.

Remember, it is the net, its definition is the decrease in the net outgoing irradiance, decrease of the net outgoing irradiance. So, when the radiative forcing is positive, we actually have a decrease in the net outgoing irradiance. What this means is the incoming irradiance from the sun which is being absorbed exceeds the outgoing irradiance of the outgoing long wave radiation and there is a net positive flux of energy into the climate system. We have a net positive flux of energy that is accumulating within the troposphere, surface of the earth and the oceanic system which jointly forms the climate system of the world. This leads to a warming, obviously as heat is being absorbed and energy of the system is increasing, the temperature is going to increase.

So this is, so a positive radiative forcing effect causes a warming. If you go back to the definition, if a climate change driver has been altered, like say a concentration of a greenhouse gas has increased and associatedly the corresponding radiative forcing for that driver is positive, So, what this means is we will have a net decrease in the upward irradiance coming at the trocopause level. So, the climate system is going to heat up and its temperature is going to rise. So, materials, components of atmospheric system with a positive radiating forcing amount will cause an increase in the temperature if their concentrations increase. In contrast, a negative radiative forcing would mean that the outgoing irradiance has increased relative to the incoming irradiance and we have a cooling effect.

So, constituents with a negative radiative forcing effect would mean that increasing their concentration will cause a net cooling effect in the earth system. So, you have radiative forcing, decrease in the net outgoing irradiance. Steady state condition, it is 0. So, radiative forcing is 0. If a certain component has a positive radiative forcing value, it means increasing its concentration will lead to a warming of the climate.

Whereas, if a component has a negative radiative forcing value, it means increase in its concentration will cause a cooling of the climate. So, let us see some of the main radiative forcing and the extent to which the radiative forcing has happened from the three industrial values. So, this figure comes from the IPCC 6 assessment report. It is the change in the effective radiative forcing from 1750 to 2019. So, how much extra radiative forcing has happened due to a change in the concentration of some atmospheric component or the other on a cumulative basis from 1750 to 2019.

The first is carbon dioxide and you can see that of course the carbon dioxide concentration has increased and it is a strong greenhouse gas. So, the increase in the carbon dioxide concentration from 1750 to 2019 has caused today a radiative forcing of around 2.5 watt per meter square. Accumulation of excess CO_2 due to greenhouse gas emissions has caused the net upward irradiance to decrease by 2.5 watt per meter square. So, 2.5 watt per meter square of excess energy flux is getting stored in the climate system today. Other greenhouse gases like methane, this one here. N_2O, the orange one, halogens, the yellow one, together contribute around 1 watt per meter square. So, we have also emitted methane, halogens and nitrous oxide and these have contributed a positive relative forcing of around 1 watt per meter square leading to further warming.

Finally we have ozone. So ozone is a negative radiative forcing gas. If you have more ozone in the stratosphere it absorbs a lot of the UV radiation and as a result less of the radiation is entering the troposphere where our climate is situated. So, an increase in concentration of stratospheric ozone would have caused a negative radiative forcing event. However, because of the emissions of the halogens, the CFC and the chlorofluorocarbons from the, for air conditioning systems, the concentration of ozone in the stratosphere has declined. As a result, the decrease in ozone has caused a net positive radiative forcing of around 0.5 watt per meter square. So, increase in CO2 concentration has caused a net incoming increase in energy flux of 2.5 watt per meter square. Other well-mixed greenhouse gases like methane, N2 and halogens together have caused an incoming increase in the incoming flux of around 1 watt per meter square. And ozone depletion has caused an increase in the incoming flux of around 0.5 watt per meter square. There has also been small impact on the stratospheric water vapor, so that as the climate has warmed there is more water vapor in the stratosphere as well. This is primarily also due to the running of aircraft through the stratosphere. So aircraft emissions contain a lot of water vapour and a lot of the aircraft move to the stratosphere as they move from one continent to the other. So this injects water vapour in the stratosphere where they would not have been which also causes a positive radiative forcing event. Now, we look at some other aspects of human impact that have caused a negative gravity force.

So, not all our effect has been to warm the planet. Other impacts have been to cool the planet as well. So, one point here is albedo. Significant land use changes have decreased the albedo, have increased the albedo of the earth. So, if the albedo is increasing it means the alpha value is increasing, right.

So, increase in albedo is creating a negative radiative force, ok. you are, you are decreasing the amount of absorbed shortwave radiation at the tropopause level. So, land use changes creating cities, farmhounds from dark forests, etcetera have caused an increase in the albino of the planet and has caused a negative radiative forcing of around minus 0.15 watt per meter square. However, the accumulation of soup particles over snow and ice due to the pollution effect has caused ice sheets or glaciers to darken, decreasing the albedo.

So, there has been a net decrease in albedo also due to the accumulation. So, the total effect is quite low, it is around 0.1, minus 0.1 watt per meter square. Also the generation of clouds in the stratosphere due to the presence of aircraft as we discussed before have also caused an increase in the radiation radiative forcing impact.

The cloud effect we have not discussed before. We will currently not discuss this. These are small impacts right now. Then you have aerosols. So aerosols are the smoke and the soot particles that are being emitted through the combustion processes that are going on in cars, power plants, etc.

And this has made the atmosphere far more, far less transparent. So, you can see this effect particularly in the smog and the fog that happens in the winter months in India because of the excess of smog, fog and smoke particularly present in the winter months over the Asian countries. you will see that often you will see the sun to be completely hidden or very weak. What this means is the atmosphere is less transparent, less amount of the solar radiation is getting in and more of the solar radiation is being reflected back by the diffuse reflection of this dust particles and smoke particles. So, this has caused a decrease, also an increase in the albedo because less amount of the solar energy is being absorbed and more is getting reflected.

Hence, you have a decrease in the radiative forcing because of the emission of aerosols and that decrease has been significant of around minus 1 watt per meter square. So, while the CO_2, methane, N_2, halogens and the depletion in ozone layer have caused the positive radiative forcing, land use changes and aerosol emissions have caused the negative radiative forcing of around minus 1.2. The total effect of anthropogenic perturbations has caused currently a relative forcing of around 2.8 watt per meter square. This minus this. So, today around 2.8 watt per meter square of excess energy is being stored in the climate system comprising of the troposphere, the land surface and the top layers of the ocean. And this is causing primarily the increase in temperature of the world. Now, here I want to highlight certain points. is very important because the smoke particles and the smog particles are extremely harmful to human health, causing respiratory diseases, illnesses, cancers, etc.

And it's one of the leading causes of avoidable deaths worldwide. However, their impact has somewhat ameliorated the global warming that could have happened if those emissions were not there. So, as the combustion processes become cleaner and you have better pollution control norms, less and less aerosols will be emitted out and hence this extra 1 watt per meter square will be added to the effective radiative forcing unless the CO_2 and the ozone, CO_2 and the methane emissions are decreased substantially. So, while clean energy is very important for human health, it is likely to aggravate global warming in the next decades if we do not also cut back on CO_2 and methane emissions. So, that is something that we need to be very much aware of.

So current radiative forcing temperature response models are quite sophisticated and we will not go into those details. Here we will look at a very simple zero dimensional energy balance model that is analytically tractable to understand the time dependent response of the climate system to radiative forces. So how does the climate system respond to a change in the concentration of a greenhouse gas which has a certain relative portion impact? So we will start today and we will continue in the next class in more detail. We can assume that the climate system is made up of three parts. The troposphere, obviously the bottom layer of the atmosphere where the entire climate is constrained.

The land surface which is either absorbing or reflecting the radiation and the mixed layer of the ocean up to 100 meters in depth which kind of controls say the up to 10 years the climate oscillations. Usually if you are looking at more long term changes of like 50 years, 100 years like that, we also have to include thermocline region of the ocean at least part of it. But here for simplicity we will just use the oceans mixed layer which is primarily absorbing the heat at the initial stages at least. So, three components troposphere, land surface and ocean mixture. And what we will do is, we will do a mass average temperature of these three together, ok.

So, basically we are doing a integral T delta m by total mass of the system and we will get the average temperature, mass average temperature of this entire climate system at a given instant of time, ok. So based on that, then we will also do certain simplifying assumptions. We will neglect heat transfer and mass transfer between the mixed layer and the deep ocean. This is of course not correct assumption. in detail because we have seen there is significant downwelling and upwelling especially in the North Atlantic and the Southern Ocean regions.

But for a very simple model, we will ignore that there is any heat transfer or mass transfer between the mix layer and the bottom layers of the ocean. The only energy transfer into and out of this climate system are due to net absorbed short wave solar radiation and net outgoing long wave thermal radiation. So the only energy transfers of this climate system, so this is the mixed layer, the land surface and the troposphere, these three together, is the net absorbed shortwave radiation. So the shortwave radiation is going in and getting absorbed and the net outgoing longwave radiation at the tropopause level. So, we can write the heat capacity C of this joint climate system into the rate of change of temperature with time d capital T d small t is equal to the net absorbed shortwave radiation minus the net outgoing longwave radiation from this climate system.

So, the net heat getting absorbed is basically the net incoming absorbed shortwave radiation, net outgoing longwave radiation. If this value is greater than 0, the climate system is getting heat into it and hence its temperature is going to increase with time. If this value is less than 0, then the climate system is losing heat and hence its temperature is going to decrease with time. And here this temperature T is the mean temperature of this climate system mass average, the integral T dm by m, something like that.

So, kind of the average temperature normalized by mass. So here F downward is the short wave radiance watt per meter square being absorbed by the climate system. F upwards the radiation flux net outgoing long wave radiance or radiation flux from the tropopause watt per meter square. C is the heat capacity per unit horizontal area of the climate system. So, here because it is a area based system, because this is kind of a surface, you have to put the heat capacity on an area based level, heat capacity per unit horizontal area of the climate system, so joules per meter square Kelvin, alright. We will make certain simplifying approximations which are not exactly correct, but we will discuss that later.

We neglect any absorption of short wave radiation in the stratosphere. So, the ozone absorption is getting neglected. Absorbed shortwave radiation is basically S0 by 4 into 1 minus alpha which is 240 watt per meter square. The actual value will be lower than this because ozone is going to absorb a part of this shortwave radiation before it hits the tropical.

So, a more sophisticated model will deal with that. And so this incoming absorbed shortwave radiation is a constant. Not truly, we are assuming the alpha albedo here is a constant here. So, we are just looking at the impact of a greenhouse gas emission. When we are looking at changes in the albedo due to presence of soot particles, dust particles in the atmosphere or in the land surface, then we will also have to consider the downward absorbed shortwave radiation to be a function of this changing alpha. But here we are taking the albedo to be constant and we are just looking at how the outgoing longwave radiation is getting changed due to change in the greenhouse gas concentrations like say CO2 emissions or methane emissions.

So, the outgoing longwave radiation will depend on temperature of this climate system because it is a radiation sigma t to the power 4 kind of thing is there, water vapor concentration, CO2 concentration of or the greenhouse gas concentration in the troposphere. So, we will stop here. We will continue this discussion in the next one. Thank you for listening and see you in the next one.