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

Professor Name: Dr. Sayak Banerjee

Department Name: Climate Change Department

Institute Name: Indian Institute of Technology Hyderabad (IITH)

Week- 04

Lecture- 19

MEAN EMISSION TEMPERATURE OF EARTH AND THE GREENHOUSE EFFECT PART 1

Good morning class and welcome to our continuing lectures on climate dynamics, climate variability and climate monitoring. In the last class we more or less completed all the major atmospheric and astronomical variables that are important in determining the climate of the world. We discussed about temperature, pressure, relative humidity, atmospheric stability and then astronomical variables like latitude, longitude, obliquity which determine the seasons. Today we are transitioning to the next major section of our course which is about understanding the global heat budget and the mean temperature of the earth. Here we will start to focus on the basic ideas of what is determining the mean temperature what is determining the mean global energy budget of the earth how these energy budgets and the temperature balance coming out of this energy balance budget change with seasons, altitude and latitude. So the variability of this energy budget aspects as well as very simple model of global warming which we will slowly increase in complexity as we go on in our future lectures.

Today's topic is the mean emission temperature of earth and simple greenhouse effect models. What do we mean by mean emission temperature? Suppose you have a satellite that is rotating the earth and is situated in space. If it looks towards the planet earth and tries to measure the average temperature of the planet earth, what will that temperature be? That is what we will say is the mean temperature of earth as seen from space. Just as we said that the mean temperature of the surface of the sun is 6000 Kelvin, or we say mean temperature of Venus, mean temperature of other stars or other planets as seen from space, we can also determine the mean temperature of Earth as seen from space.

Firstly, we can note that Earth's surface temperature today is about 15.2 degree centigrade, which is about 1.2 degree centigrade above the pre-industrial level due to global warming. and this increase is due to an imbalance in the global heat budget we will discuss. However, as we will see this is nearly the temperature of the earth surface that is the air just above the earth surface the mean temperature of that is 15.2 degrees. This is not the temperature that we will detect through thermal radiation measurements when we see the planet from space and we will see why that is the case in the first half of this class and then we will see how that mean temperature as seen from space relates to the surface temperature of the earth. So what is What do we mean by emission temperature? So, it has to do with the concept of black body radiation. We will discuss much more about black body radiation in later parts of the class, but today we will limit ourselves to the basic concepts. The amount of radiation energy that is emitted by a body depends on the temperature of its surface.

So, just as the sun's surface temperature of 6000 Kelvin determines the amount of radiation it emits to space, similarly the earth's temperature determines the amount of radiation it radiates to space. The emitted radiation energy relates to the surface temperature by the following relationship which comes from the radiation theory. Emitted radiation energy which we are calling as E dot radiation, E dot rad unit is in watts, joules per second. Amount of radiation energy emitted per unit time by a body is equal to the surface area of the body into the emissivity of the body. So, the emissivity of the body will be between 0 and 1.

For a perfect black body it will be 1. However, for earth which is not a perfect blackbody it will not be equal to 1, ok. Then sigma which is the Stephen Boltzmann's constant of 5.67 into 10 to the power minus 8 watt per meter square Kelvin to the power minus 4. Then T to the power 4 with the temperature of the surface to the power 4 and the temperature is given in Kelvins, ok.

So, this expression together gives the total energy coming out of a body per unit time. Now, in our previous lectures we defined the average solar irradiance which is the radiation flux at the point where it is hitting the earth to be around 1360 watt per meter square. Now this solar energy is incident on a circular disk area which is being projected by the earth towards the sun which is equals to pi r square where r is the radius of the earth. Thus the total solar energy received by earth per second is given by E dot s equals to s 0 which is 1360 watt per meter square into the circular projected area which is pi r square watts. The total surface area of the earth over which the radiation is being distributed is the surface of a sphere with the radius as the same as the radius of the earth.

So, the surface area of the earth AE say is 4 pi r square. The projected area is pi r square where the surface area is 4 pi r square. So the average solar energy that is incident on the top of the earth's atmosphere, so before attenuation or other effects take in, so we are neglecting atmospheric absorption or reflection, total solar energy that is incident at the top of earth's atmosphere is per unit area of the earth surface is given by e dot small s. So, E dot capital S is the total energy per unit time, e dot small s is the total energy per unit area of earth surface per unit time on the top of the atmosphere. This is S0 into pi r square the total energy by the surface area which is 4 pi r square which is S0 by 4.

$$\dot{e}_s = \frac{S_o \pi R^2}{4\pi R^2} = \frac{S_o}{4} \frac{W}{m^2}$$

So, in the previous case we saw this is 1360 by 4 that number was E dot S. So, small e dot S is S0 by 4 watt per meter square which is the solar energy per unit area incident on earth at the top of its atmosphere. Now, part of this incident radiation is reflected back by clouds, dust particle and reflection from earth surface itself. So, clouds, solar energy will hit the top of the cloud which is usually white in color and will get reflected back. Dust particles, some of the sunlight will hit the dust particles and get reflected back.

Some of the sunlight will hit the surface of the earth and instead of being fully absorbed will also get reflected back. So there will be a fraction of radiation which is absorbed neither by the earth's atmosphere nor by earth's land nor by earth's ocean but rather gets reflected back towards the space. This fraction is called earth's albedo or reflectivity. Remember, this is the same thing we see in moon. You are seeing moon at night because this part of the solar energy is being reflected back by the surface of the moon and is hitting earth.

If moon was a perfect absorber, we would not have seen any light of the moon at all. Similarly, earth is visible from space because earth is reflecting part of the sunlight back to space. So this fraction is called the earth's albedo and is given by a value alpha. So this is the total solar flux. A fraction of this is reflecting back to space and the fraction is getting absorbed by the earth.

The actual energy that is being absorbed by earth and its atmosphere ocean system is capital E dot s absorbed equals to 1 minus alpha into E dot s. This is the reflected part. So, 1 minus alpha is absorbed part. So, this is 1 minus alpha S 0 phi r square watt. As you did in watt per meter square, then it is 1 minus alpha S 0 by 4 watt per meter square which is small e dot s absorbed.

$$\dot{E}_s^{abs} = (1-\alpha)\dot{E}_s = (1-\alpha)S_o\pi R^2 \quad Watts \quad (26) \;\; or,$$

$$\dot{e}_s^{abs} = (1-\alpha)\frac{S_o}{4}\frac{Watts}{m^2} \quad (26a)$$

So, this is the total solar flux being absorbed by the oceans, the land and the atmosphere. This is the total solar energy being absorbed by the oceans, the land and the atmosphere. The albedo of earth can be estimated empirically and it's around 0.29. So 29% of the incident solar energy gets reflected back to space and the rest 71% is getting absorbed by the earth.

Okay. Now what happens to this energy that earth absorbs? earth heats up because of this absorbed energy and it reaches a certain temperature. Now any body with a certain surface temperature will start to emit radiation just as the sun does, correct? So earth also has a mean radiation temperature to which it goes to due to the absorption of this solar energy and it starts to heat up. radiate away this radiation or thermal radiation back into space based on this temperature, ok. So, earth will emit heat radiation it is also called infrared or long wave radiation. So, we will discuss the various radiation wavelengths and why they are called those things later in our course and when it emits this heat radiation it loses heat to space, ok.

Now, earth When it is emitting radiation can be assumed to be close to a black body. We will also assess this assumption. So, we are saying that while earth is reflecting solar radiation, so it is not a perfect black body in that context, when it is emitting radiation back to the space it is acting as a black body with emissivity of 1, ok. So, heat radiation emitted by the earth as seen from space is E dot p, p is for planet, okay. So, earth is a planet, so E dot p is the radiation emitted by planet because of its, because of its temperature.

So, it is E dot p equals to 4 pi r square which is the surface area of the earth into sigma into Te to the power 4 where Te is called the mean blackbody emission temperature of earth as seen from space. we can assume earth to be a black body when it is emitting radiation. So, epsilon is 1, so it is As sigma 2 d power 4, As is of course 4 pi r square and the T is the mean emission, mean black body emission temperature of earth as seen from space. So, we can measure the amount of thermal radiation emitted by the earth. And because we know this relation, we can evaluate what is the emission black body emission temperature of earth using equation 55.

So, it is the surface area of the earth into the Boltzmann's constant into whatever is the unknown black body emission temperature of earth. Now, at equilibrium the total energy being absorbed by the earth from sun should be equal to the total energy being used. emitted back to space by earth. If these are not in thermal equilibrium, the temperature of earth will steadily increase, okay. So, as the temperature increases, what happens is, if you see, the total emitted energy is also increasing to the fourth power of temperature.

Eventually, the planetary thermal radiation emitted will again balance the incoming absorbed solar radiation and at that point, we will reach equilibrium condition. So, there is an equilibrium temperature at which E dot p will be equal to E dot s absorbed. The total energy absorbed by the planet will be equal to the total energy released by the planet and at that point the temperature will stabilize, ok. So, we can use this expression here E dot s absorbed equals to E dot p here. We simplify this expression to get Te to the power 4 equals to S0 by 4 sigma 1 minus alpha.

$$T_e^4 = \frac{S_o}{4\sigma}(1-\alpha)$$

So, this expression helps us to determine the emission temperature of earth and in general for any planetary body or satellite. See, these expressions are entirely general, r can be the radius of earth or the radius of mercury or the radius of venus, correct. S0 can be evaluated for each of these different planets based on how much distance that planet is from the sun. Clearly S0 for earth is 1360 but S0 for Venus will be something different, S0 for Mars will be something different. And you remember we evaluated S0 by dividing the total energy radiated by the sun divided by the surface area of the imaginary sphere at the earth planet distance.

So, that way we can find the S0 for any planetary body ok. So, once this is done we can get the drag body emission temperature of earth or impact any planetary body if you know the albedo value and the S0 value. We can do this for earth S0 is 1360, alpha is 0.29, we know sigma value what is that? We can take a root of 4 here and we get emission temperature or blackbody emission temperature of earth to be 255 Kelvin, which is minus 18 degree centigrade. So, the blackbody emission temperature of earth as seen from space is just minus 18 degree centigrade, which is quite colder than the actual surface air temperature of earth, which is 15.2 degree centigrade. So, what is happening? Why is the surface temperature of the earth much larger, larger by around 30-32 degrees compared to the blackbody emission temperature of earth? Here is an interesting point. This blackbody emission temperature is the mean surface temperature of moon, ok. Moon is at the same earth sun distance as the earth itself is on average. So, the S0 value is the same, if the alpha value we can of course, alpha of moon will be different from the alpha of the of earth. So, if you take the correct alpha and the evaluate the mean emission temperature of the moon, it will come out to be equal to the surface temperature of the moon.

So, for the moon this thing works, we can evaluate the surface temperature of moon directly, but for earth this blackbody emission temperature is not the temperature at the surface. Why is this? Very simple reason, because the earth has an atmosphere which absorbs the earth's emitted thermal radiation. We have an absorbing greenhouse gas containing atmosphere which absorb part of the radiation that earth surface is releasing towards space. So, it is like this and we will see this very soon. Earth is a surface, the atmosphere is a layer above the surface.

Earth surface emits certain radiation which is absorbed by this layer of the atmosphere which is then being re-emitted at the top of the atmosphere. and the top of the atmosphere is much colder than the surface of the atmosphere. We have seen the temperature gradients, right. So, in the troposphere itself the temperature falls very quickly from the surface towards the top of the troposphere. So, so you can see that if earth atmosphere is absorbing the heat coming from earth surface and is then radiating it at the top of the troposphere say.

The space will see that temperature of the atmosphere and at which it is receiving that radiation from and not the surface temperature of earth, ok. So, what this means is the mean emission temperature is the average temperature of the atmosphere as it emits heat radiation absorbed from surface to space. So, this is the average emission temperature of the atmosphere rather than the emission temperature of the surface. This is why earth's surface can be much warmer than the mean emission temperature and moon which does not have an atmosphere will have the surface temperature exactly the same as the mean blackbody emission temperature. So that gives us a very good idea of what is going on when we say that atmosphere has a greenhouse effect.

It is absorbing heat coming from the earth surface and releasing it at a much lower temperature which is what the mean emission temperature seen from space is and hence the surface can be much warmer than for the atmosphere, than the atmosphere. You will see this in the simplified greenhouse model that we will discuss now. Suppose we have a surface. The total absorbed solar radiation is S0 by 4 into 1 minus alpha, alpha p is the albedo of the planet.

This is the net absorbed solar radiation. This is entirely absorbed by the surface of the earth. So, what we are saying is, yes the atmosphere reflects sunlight, but it does not absorb a lot of the sunlight. The atmosphere is transparent to solar radiation. but is opaque to the thermal radiation coming from the surface and trying to get out into space. So, atmosphere is like the solar radiation which is the light radiation, atmosphere is transparent to that up to the, so either it reflects or it let it go, it does not absorb the solar radiation.

But the thermal radiation, the heat radiation coming from the earth, it absorbs completely, ok. then it emits it back to space ok. So, we can have a very simple model. where we consider a single uniform layer of atmosphere that is at a constant average temperature TA. So, we can average out the atmospheric temperature, we say it is at a mean temperature TA and we have a single isothermal atmospheric layer, ok.

So, this is a very drastic simplification. Atmosphere is not isothermal, This is not a single layer. There are multiple layers, etc.etc. But for a very simple model, let us assume that over the surface of the earth, there is a single layer of atmosphere at a mean temperature of TA, a single layer, isothermal layer of atmosphere at TA, which is absorbing all of the thermal radiation coming from the surface.

Okay. And it does not absorb any of the solar radiation coming from the sun. Reflection is allowed, but absorption is not. and we have energy balance we will do energy balance for the atmosphere and at the surface layer. Heat absorbed must be equal to heat radiated fine for both these layers the atmospheric layer and the surface layer. So, for that for the surface layer we are getting absorbed is S0 by 4 1 minus alpha ok.

This atmosphere is radiating heat in both towards the surface and towards the space. Because it is a layer at a certain temperature, it radiates heat both upwards and downwards. There is, there are two surfaces, one surface facing the earth, another surface facing space. Both these surfaces are at a temperature TA because it is an isothermal layer and so both will radiate heat, correct. surface is also receiving heat coming from the atmosphere.

So, atmosphere is radiating thermal radiation down towards the surface at the rate of sigma TA to the power 4. So, we assume the atmosphere is also a perfect black body ok. So, its emission is sigma TA to the power 4 per unit area of course ok. So, the total incoming radiation that the that the surface is absorbing is 1 minus alpha S0 by 4 the solar radiation and sigma TA to the power 4 the radiation from the atmosphere towards the surface. And this should be equal to sigma Ts to the power 4 the radiation emitted by the surface towards the atmosphere, ok.

So, we immediately see from this relation that Ts will be greater than TA because this extra term from the solar radiation is coming, ok. Now we will look at the atmospheric layer. It is receiving heat from the surface. It is not receiving heat from the solar radiation because it cannot absorb solar radiation and it is losing heat both towards the space and towards the earth. So sigma Ts to the power 4, the heat received from the surface which is a temperature Ts is equal to 2 sigma Ta to the power 4.

Heat emitted towards the surface. Finally, we can also do an energy balance at the top at space. So at space what is happening is you are gaining, so if you have an energy as seen from space, so at the top of the atmosphere as seen from space you are getting net incoming energy of S0 pi 4 1 minus alpha p and sigma TA by 4 is going out into space. So energy balance for the space is 1 minus alpha S0 by 4 incoming into earth and sigma TA to the power 4 outgoing from the earth, ok. So, from space we are not seeing the surface at all because the atmosphere is completely opaque to surfaces thermal radiation. So, if we are only seeing the radiation coming from the earth surface earth's atmosphere and the radiation going into and being absorbed by the earth 1 minus alpha S0 by 4.

So, these are the three equations. So, we can now solve for Ts based on these three equations, alright. The other important point here to note is if you go back to equation 55 here, this is the radiation emitted by earth as seen from space, correct. So, here 1 minus alpha S0 by 4 is equal to sigma Te square ok. So, if you see here this expression 1 minus alpha S0 by 4 equals to sigma Te square ok.

So, equation 56 1 minus alpha S0 by 4 equal to sigma Te square. Let us order this equation 56. This is the definition of the blackbody emission temperature, correct? So, this expression 1 minus sigma S0 by 4 can be replaced by sigma Te square Te to the power 4, sorry. So, sigma Te to the power 4 is equal to sigma Te to the power 4. Hence, Te is the same as Ta. So, the temperature of that one layer of atmosphere will be equal to the blackbody emission temperature of earth.

How did we get this? As seen from space incoming absorbed solar radiation is the outgoing thermal radiation and incoming absorbed solar radiation is also equal to sigma into the black body emission temperature this expression. So, the temperature of the atmosphere must be equal to the black body emission temperature by this expression. So, TA is equal to T. So if you put TA equal to Te expression 2, the sigma and sigma cancels out. So Ts, the surface temperature is 2 to the power 1 fourth into Te, 2 to the power 0.25 into Te, clear? So, under this approximation of a single isothermal atmosphere which is absorbing all the thermal radiation coming from the surface of the earth, the surface temperature is 2 to the power one-fourth the blackbody emission temperature of the planet. Now, Te is 255 Kelvin, you put it here. So, we get Ts as 303 Kelvin or 30 degree centigrade. So, in this model if we had our planet had a single isothermal atmosphere which is perfectly absorbing all the thermal radiation coming from the surface of the earth, then the earth surface temperature, the mean surface temperature would have been 30 degree centigrade. So you can see in this simple model already how this greenhouse effect which is basically the effect of the atmosphere absorbing thermal radiation coming from the surface is increasing the surface temperature of that plant.

Note here that this temperature is still quite higher than the actual earth temperature of 15.2 degree centigrade and the reason is in this case that our atmosphere does not completely absorb all the thermal radiation coming from the surface. It partially absorbs and partially allows the thermal radiation to go into space, ok. So, we will discuss that further idea of a partially absorbing isothermal atmosphere.

in the next class. But here you can see that if we had no atmosphere then our surface average temperature would have been minus 18 degree centigrade and if we had a perfectly absorbing isothermal atmosphere the surface would have been much hotter at 30 degree centigrade. The reality is in between we have a partially absorbing atmosphere and we will see how much is that fraction of partial absorption in the next class. so see you till then thank you for listening and see you in the next one