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

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# MEAN EMISSION TEMPERATURE OF EARTH AND THE GREENHOUSE EFFECT PART 2

Good morning class and welcome to another lecture in climate dynamics, climate variability and climate monitoring. In the last class we started our discussion looking at the energy balance of the earth and we discussed concepts like the mean black body emission temperature of the earth which is the temperature that can be seen from space if we look at the total thermal radiation from the earth that is being emitted by the earth. This mean blackbody emission temperature was found to be 255 kelvins or minus 18 degree centigrade which is much lower than the surface temperature of the earth. And we explained that this is due to the presence of the layer of atmosphere which absorbs most of the thermal radiation coming from the surface of the Earth and re-radiates it at a much lower temperature to space. To model this aspect, we assume the temperature to be a single isothermal layer of a certain temperature TA that is fully absorbing all the thermal radiation coming from the surface of the earth and which then is being reradiated both upwards and downwards. Using that expression, we got under this condition that the temperature at the surface would be 303 kelvins or 30 degree centigrade, which is actually much larger than the mean surface temperature, which is around 15.2 degree centigrade. So, to further improve the model what we can assume here is that we still have as we can still model the atmosphere as a single isothermal layer at a certain temperature TA. However, this atmosphere is not absorbing the entire thermal radiation coming from the surface of the earth, but only a fraction of it say f. So, the surface is radiating at a temperature is at a temperature Ts and hence radiating at sigma Ts to the power 4.

f into sigma Ts to the power 4 is being absorbed by the atmosphere and 1 minus f into sigma Ts to the power 4 is being is escaping to space. So, we have a partially absorbing layer of gas which is absorbing f fraction of the thermal radiation coming from the surface while the rest is escaping to space. If we use this model then what we find? If you look at the firstly this S0 by 4 1 minus alpha term which is the net solar flux being absorbed by the earth, this will be equal to the net black body emission temperature given by sigma Te to the power 4. So, that expression remains valid. Secondly, if you see the temperature from space, what you see? You are getting a flux of S0 by 4 by 1 minus alpha term coming into earth, sigma TA to the power 4 flux going out of the earth through the atmosphere and 1 minus f sigma Ts to the power 4 term of flux coming out of the earth which is the fraction that is escaping the atmosphere and going into space. So, we have three terms instead of two. So, let us see how it looks. So, the model here is The energy balance at the top of the atmosphere, this is the incoming flux that is being absorbed. So, 1 minus alpha S0 by 4. Remember S0 is the solar flux per unit.

So, S0 by 4, the entire thing is the solar flux per unit area of the surface which is around 340 watt per meter square for earth. Alpha is the albedo of earth. which is the net fraction of this solar flux that is being reflected by either the clouds in the dust particles in the atmosphere or by the ground. So, this 1 minus alpha S0 by 4 is the net solar flux being absorbed by the earth and the outgoing flux is sigma TA to the power 4, the flux coming from the atmosphere and 1 minus f sigma Ts to the power 4 is the flux emitted by the surface that is passing through the atmosphere and into space. So this is the net outgoing flux and this is the net incoming flux at the top of the atmosphere.

For the atmospheric layer you the atmosphere is still emitting sigma ta to the power 4 towards space and sigma Ta to the power 4 of flux towards the ground. So, it is twice sigma Ta to the power 4 is the net emission and the net absorption is f into sigma Ts to the power 4. This is the net fraction that is being absorbed and this is the net fraction that is being net amount that is being emitted. So, these two are in balance. Finally, the energy balance at the surface remains the same.

So, it is getting 1 minus alpha S0 by 4 from solar energy, sigma TA to the power 4 is absorbed and it is coming from the atmospheric emissions and it is emitting sigma Ts to the power 4 of radiation towards the atmosphere, ok. So this is the energy balance at the surface, this is the energy balance of the atmospheric layer and this is the energy balance at the top of the atmosphere. So, if you solve for these what you get is the surface temperature Ts is comes as twice by 2 minus f to the power 0.25 to the power the black body emission temperature. Remember 1 minus alpha S0 by 4 is equal to sigma Te to the power 4.

So, this is the black body emission temperature. So, the surface temperature is twice by 2 minus f, f is the fraction of radiation being absorbed by the atmosphere, fraction of earth's emitted radiation being absorbed by the atmosphere to the power one-fourth into the black body emission temperature of earth, ok. So, this is the expression that we will be getting. Note that the expression reduces to the emission temperature when f equal to 0. So when f equal to 0, this just becomes 1.

So you have no absorption. The atmosphere does not effectively exist. All the surface emission goes directly into space. So in this case, Ts becomes equal to Te, which is the case for moons and other bodies which have no atmosphere. And when f is equals to 1, this becomes 2 to the power one-fourth into Te, which is the case for the perfectly absorbing atmospheric layer.

And this is somewhere in between. So, if we set f as 0.78, that is 78 percent of the emitted radiation is being absorbed by the atmosphere. Then we will get using this expression here Ts to be about 15.4 degree centigrade.

Remember this will come in Kelvins then you have to change it to degree centigrade. So, we will get Ts to be 15.4 degree centigrade which is very close to the current mean temperature of 15.2 degree centigrade. So, we can as we can say that within this model of a simple isothermal atmosphere, the absorption coefficient for example, of the atmosphere of the thermal radiation being emitted by the earth surface is 0.78 and the transmission coefficient therefore, is about 0.12. So, 78 percent of the earth's thermal radiation being absorbed by the atmosphere and around 22 percent is being transmitted and is escaping space and that will give us a temperature which is very close to the current surface temperature. Also note that as f increases that is the as the atmosphere becomes progressively more absorbing of the earth's thermal radiation. The Ts will also increase until we get that Ts equals to 2 to the power one-fourth Te for a perfectly absorbing single isothermal layer of the atmosphere and at that case Ts will be around 30 degree centigrade, ok.

So what we can say that on this basis of simple models, what the emissions of greenhouse gas is actually doing is increasing this f, the ability of the atmosphere to absorb terrestrial radiation, ok. with when you have less CO2 in the atmosphere, the f will be smaller and hence the surface temperature will also be smaller at a smaller value of f. If you have more and more greenhouse gases, this atmosphere will become progressively more absorbing of the thermal radiation of earth and hence the surface temperature will increase. So, what we are doing by emitting the greenhouse gases is increasing this f factor. So, this simple model gives us an intuitive feel of the physics of what actually is happening when you are emitting and adding greenhouse gases to the atmosphere.

Of course, we will do far detailed models later which will give us a more detailed view of what is happening through emissions of carbon dioxide, methane and other greenhouse gases. Now, this is a very simple model. So, more complete models will have a lot of other things that the simplifying assumptions are neglecting. Firstly, the atmosphere is not isothermal which we know already. We have seen a significant temperature variation of the atmosphere.

The temperature of the atmosphere changes with altitudes. To account for this, the atmosphere can be considered to be made of a series of thin isothermal slices with its own temperature, absorptivity and transmittivity. So instead of a single isothermal layer, we can assume a series of thin atmospheric layers in series with their own  of absorptivity f which will be small values. So, the together the entire series will give the combined absorptivity f of the atmosphere, but each of this layers will be isothermal, but different layers can be at different temperatures, ok. So, in that way we can model the temperature variation of the atmosphere with altitude.

So that is one way by which the model can become more realistic. Then the cumulative energy balance equations of all these slices in series are considered in the final energy analysis, ok. So, you have to put all of these in series and then you will see what is the energy analysis under these cases, ok. The second is here we are only considering radiation, thermal radiation from the surface being absorbed by the atmosphere, atmospheric thermal radiation hitting the surface and going into space. But between the surface and the atmosphere there are other heat transport mechanisms as well which we are neglecting namely the convection currents that are that are coming up in case of unstable atmospheres.

Then there is the heat  absorption and heat release due to the vaporization and condensation of water. As water condense is evaporating from the seas and the lakes it is absorbing heat from the atmosphere for this evaporation to happen and then when this water condenses in the upper atmosphere this heat is getting released into the upper atmosphere air which we also saw in our previous examples how that is changing the saturated adiabatic lapse rate. So, this is another heat transport mechanism between the surface and the upper atmosphere. So, convective cells and latent heat transport due to condensation evaporation processes add to the heat exchange processes between the surface and the atmosphere. and they play an important role in the energy exchange processes within the atmosphere particularly in the troposphere.

So, these also have to be taken into account. So, more complete models will necessarily take these aspects into account when we are evaluating the surface temperature, the mean temperature of the atmosphere, the energy budget etc. So, these more complete models will be partially discussed later in the class and eventually when you are going to a full blown energy analysis, you will have to take into use simulations to completely understand all the energy transport mechanism that is going on within the atmosphere. So, this is a very simple model. We will give a few worked out examples on these kinds of models later in this week, but let us look at a little bit more detail on what are the various energy fluxes that are going in and going out for the earth.

So this is kind of a cartoon variation of Earth and remember this is kind of the mean fluxes when you are averaging over the entire circumference of the Earth. If there will be differences in the energy budget depending on the geographical location of the seasons, so this is average fluxes when averaged out over an entire year and over the entire surface of the earth. So, the mean incoming solar radiation flux is 340 watt per meter square as we have discussed this is the S0 by 4 term of this part of it is actually being absorbed by the atmosphere unlike our previous simple model we will when where we thought that atmosphere is completely transparent to incoming solar radiation this is not true 80 watt per meter square is being absorbed by the atmosphere. 160 watt per meter square is being absorbed by the surface. So, 80 watts absorbed by the atmosphere, 160 watts absorbed by the surface of the earth.

75 watt per meter square is being reflected in the atmosphere by clouds, aerosols and other atmospheric gases. So, this contributes to the albedo of the earth. Another 25 watt per meter square gets reflected at the surface because of ice which is a highly reflecting surface usually. So, 75 and 25, 100 watt per meter square is being reflected back to the space. This is the basically the alpha value or the albedo of the earth.

The rest 160 watt absorbed by the surface, 80 watts absorbed by the atmosphere, ok. Now, if you look at the atmosphere itself and look at the radiation firstly. upward emission from the atmosphere is 219 watt per meter square. The atmosphere is emitting 219 watt per meter square towards space and it is radiating 345 watt per meter square towards the surface. So, unlike our example that we did where we assume that the radiation upwards towards space and towards the surface are the same, this is not true for our atmosphere and this is because the layer from which the surface, the bottom of the atmosphere is at a higher temperature than the top of the atmosphere.

because this is not an isothermal atmospheric condition the net radiation going in towards the surface is coming from a higher mean atmospheric temperature which is lower down in the atmosphere than the radiation energy escaping to space from being emitted to space which is coming from higher up in the atmosphere which is at a lower temperature. That is why 219 watt per meter square is going upwards and 345 watt per meter square is going downward. If you assume atmosphere to be a block body with sigma t to the power 4 as the effective relationship, then you can find the effective atmospheric temperature from which atmosphere is radiating towards the surface and the effective atmospheric temperature from which atmosphere is radiating towards space as well, ok. around 20 watt per meter square, so 219, 239, so 20 watt per meter square is escaping to space from the surface emissions. So, the total infrared radiation from the surface is 396 watt per meter square.

So, from the surface going outwards the infrared radiation is 396 watt per meter square of which 376 watt per meter square is being absorbed by the atmospheric layers whereas 20 watt per meter square is escaping into space. So, the net outgoing long wave radiation is the radiation  going into space from the atmosphere and that escaping into space from surface radiation that is 219 plus 20, 239 watt per meter square. This is called the outgoing long wave radiation or OLR. So, thermal radiation is often called long wave radiation because the wavelengths of thermal radiation are typically longer than the wavelengths of the solar radiation. So, that is something that we will discuss later.

The other part are the latent heat transfers and the convective transports. The convective transport cells, hot air rising to the top and hence transporting heat by that medium gives 20 watt per meter square of heat transfer from the surface to the upper to the atmosphere. So, 88 watt per meter square of thermal energy is being transported to the atmosphere due to the evaporation and the condensation processes that happens as the water evaporates from the surface and then condenses on the upper atmosphere. So, evaporation and evaporation condensation processes evapotranspiration. So, transpiration is evaporation from the vegetation basically.

So, these processes at 88 watt per meter square of heat transfer from the surface to the atmosphere and the thermal convection cells at 20 watt per meter square. So, these two together the non-radiative mechanism add around 108 watt per meter square of heat transport from the surface to the atmosphere. So, these are all the mean energy budgets. Another thing is if you do 340 minus 100, this is a reflected solar radiation, it is 240 and the outgoing long wave radiation is 239. So, there is an unbalanced heat transfer of about 1 watt per meter square.0.6 watt per meter square is unbalanced as of now and this 0.6 watt per meter square is unbalanced because of our current global warming effect. So, because we are emitting greenhouse gases into the atmosphere, the thermal equilibrium of the earth is perturb and the earth is slowly heating up. It is heating up because more heat is being absorbed than is going out into the system. So, the net incoming is greater than the net outgoing and the net unbalance is 0.6 watt per meter square on average. So, all this global warming in effect is happening because 0.6 watt per meter square, this amount is actually increasing with time as we add more and more emission, emissions into the atmosphere is the net unbalanced heat, heat flux that is heating up the atmosphere. Later in the class we may discuss some more recent research on what this exact value is if there is sufficient time, ok. So, this 0.6 watt per meter square is the unbalanced heat that is being absorbed by the surface and the oceans and this is causing the heating up of the oceans and the earth surface which we are seeing as a increase in the surface temperature of the earth.

So if you look at all these values, clearly this unbalanced one is the smallest, significantly smaller than everything else. However, it is still significant and that is why we are getting this temperature rise this time. Now these values we can give specific expressions for these values. So the incoming solar radiation is e dot s as we have discussed is 340 watt per meter square. Solar radiation reflected by the earth is E dot rho a, rho is reflected by the atmosphere which is 75 watt per meter square, clouds, aerosols, dust etcetera.

solar radiation reflected by land E dot rho L, reflection by land is 25 watt per meter square, net outgoing reflected solar radiation E dot rho, the total reflected is 100 watt per meter square which is E dot rho A plus E dot rho L. solar radiation absorbed by the atmosphere is E dot S a. So, E dot solar absorbed E dot S atmosphere absorbed. So, E dot solar radiation absorbed by the atmosphere E dot S a absorbed is 80 watt per meter square solar radiation absorbed by the surface E dot SL, L stands for land absorbed 160 watt per meter square. So, L is land absorbed amount of solar radiation absorbed by the land area.

So, net absorbed solar radiation E dot S absorbed is 240 watt per meter square, it is the summation of these two. Thermal radiation emitted by the atmosphere to space E dot atmosphere outward long wave. Long wave radiation is thermal radiation. So, we call this as LW long wave E dot atmosphere outgoing 219 watt per meter square. Thermal radiation emitted by earth surface that escapes to space E dot land outward long wave. E dot from land outgoing long wave radiation is 20 watt per meter square. Total thermal radiation emitted to space is then E dot outward long wave which is the sum of these two 239 watt per meter square. unbalanced heat flux absorbed by the earth is E dot Gw, Gw is global warming. So, this is basically global warming effect, right.

It is 0.6 watt per meter square, it is changing from decade to decade. So, this value may be variable as we move along in the next few decades. Thermal radiation emitted by atmosphere towards the surface, so E dot atmosphere to land long wave. From atmosphere to land the long wave radiation is 345 watt per meter square. Thermal radiation emitted by the surface and absorbed by the atmosphere, surface to atmosphere absorbed E dot land to atmosphere long wave is 376 watt per meter square.

Net thermal radiation emitted by the surface E dot land long wave is 396 watt per meter square. Heat transfer by convection currents from surface to atmosphere Q dot land to atmosphere 20 watt per meter square. Latent heat transfer from surface to atmosphere by evaporation and transpiration L dot L is latent heat land to atmosphere is 88 watt per meter square. So, all of these are the symbols here. So, then we can do the explicit energy balance at each of these layers.

So, energy balance at the top of the atmosphere is the total solar incoming solar radiation e dot s minus the reflected solar radiation e dot rho minus the outward long wave radiation e dot o long wave ok. So, e dot s is this one e dot O LW is 239 and e dot rho is 100 and these three incoming minus outgoing is the unbalanced term which is e dot global warming, ok. So, this is the expression for the energy balance at the top of the atmosphere, ok. Energy balance at the earth surface is e dot SL absorbed. So, E dot solar radiation that is being absorbed by the land  plus E dot long wave atmosphere to land.

So, incoming long wave radiation emitted by the atmosphere towards the land E dot A L long wave, these are the two incoming words and the outgoing ones are the latent heat transfer from land to air, the convective heat transfer from land to air, the long wave heat transfer from land to atmosphere and the long wave heat transfer going from land to outer space. So, these two together we can also show the effective long wave heat transfer from the surface. I think it is there, it is not here. Anyways, this is the land to air long wave radiation, land to the outer space going out long wave radiation. So, this is 20 watt per meter square correct, I think 20 watt per meter square.

This is the much bigger term around 239 watt per meter square, this one here. This is 88 watt per meter square, this is again around 20 watt per meter square, this is 169 if I remember correctly, 160 watt per meter square. And finally, we have  atmosphere to land long wave which is 345 watt per meter square. So, these values you can put here directly to get again the unbalanced heat flux of E dot Gw.

So, this is the energy balance at the earth's surface. Then finally, we have the energy balance at for the atmospheric layer itself which is a thick layer here. So, E dot  solar radiation that is being absorbed by the atmosphere. So, here the atmosphere is absorbing some amount of the solar radiation. So, E dot solar radiation absorbed by the atmosphere, E dot long wave radiation  coming from land and absorbed by the atmosphere, the convective heat flux from land to atmosphere and the latent heat transport from land to atmosphere. These are all the incoming terms for the atmospheric, atmosphere layer.

Outgoing terms are atmosphere to land long wave going towards the land and long wave radiation  to emitted by the atmosphere towards the space and this term effectively is 0. So, the atmosphere is not, atmosphere is more or less in thermal equilibrium. It is not heating up or cooling down if you take the entire thickness of the atmosphere significantly. The entire unbalanced heat term is basically heating the land area and the ocean surface area mostly. The atmosphere heat budget is almost in thermal equilibrium and it is equal to 0, ok.

So, with that we will stop here. We will see you again in the next class. Thank you for listening and see you in the next class.