Radiation Heat Transfer

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Lecture - 29
Radiative-convective equilibrium

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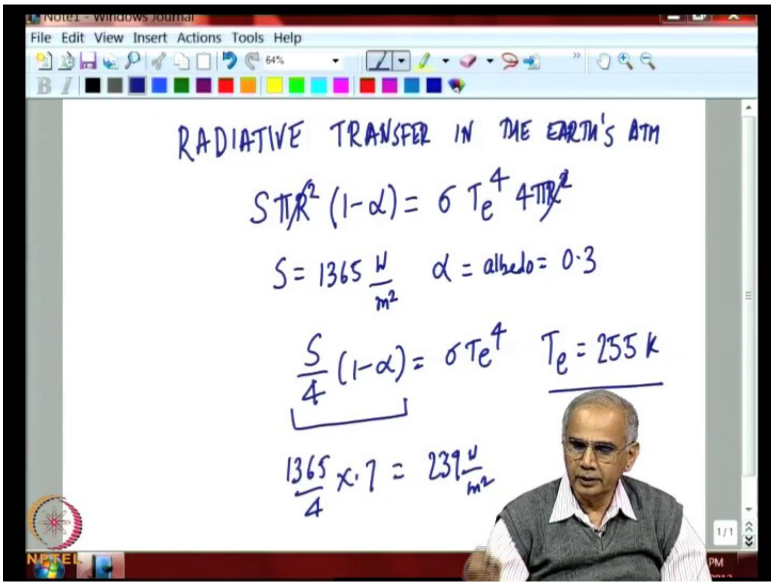

In the last lecture we looked at radiative transfer in the earth's atmosphere. We started with a very simple model of earth without atmosphere. We saw that the solar radiation coming from sun that multiplied by the cross circular area of the earth; time is the radiation absorbed where, alpha is reflectivity can be equated to the radiation emitted by the earth atmosphere system into the surface area of the earth.

In this model, if it took as measured value as 1365 Watt per meter square and earth's reflectivity to radiation from the sun, also called albedo; if it is taken to be 0.3 or 30 percent, then the radiation emitted by the earth has to be equal to the solar radiation absorbed.. We have simple expression of S by four into one minus alpha equal to sigma T e to the power of four. If you calculate the effective temperature of the earth will come out as 255 Kelvin. This is not the surface temperature in the earth, but the effective temperature of the atmosphere system which has to radiate at black body temperature of 255 degrees Kelvin, so that it can essentially get rid out of the radiation absorbed from the sun. The radiation absorbed by the sun is nothing but 1365 by 4 into 0.7. And, this comes close to 239 watts per meter square and a black body at 255 will emit the radiation. But, our real interest was not in the effective black body temperature of the earth, but the surface temperature.

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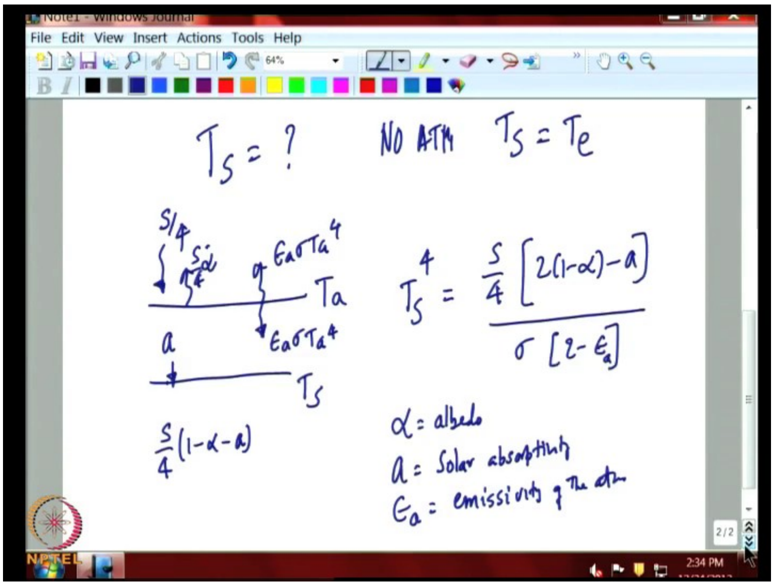

Now, the effective black body temperature of 255 Kelvin will also be the surface temperature, if there was no atmosphere. If there is no atmosphere on earth, then T S is equal to T_e; if the earth behaves like a black body. But, we will have to know the temperature earth with the atmosphere; so, for that we constructed a very simple model having a one layer atmosphere.

We have the sun's rays incoming here, S by four; S is the solar constant. And, by division by the four is because the cross circular area is one-fourth the surface area of the earth. And, assume that S by four into one minus alpha is energy reflected and a is the radiation absorbed from the sun by the atmosphere. So, what region has the surface was S by four into one minus alpha minus a; that is the surface. We neglected all other methods of heat transfer, except the radiation. That we neglected the heat loss from the surface evaporation and by sensible heat flux. That is a very unrealistic approximation, but we did that because we wanted a purely radiative heat balance. Then we assume that earth's atmosphere emits equally up and down. Based on this simple model we estimate the temperature of the Earth. Although this model is not very accurate, it is still a very a good model to explain the role played by various radiative properties on earth's climate.

That is how these various radiative properties of the atmosphere control the temperature of the surface of the earth. Example, S is the incoming radiation. If it goes up, it will obviously increase the temperature. Alpha is albedo or the reflectivity of the earth to solar radiation. And if that goes up, obviously temperature will go down. Similarly, if the solar absorptivity of the atmosphere goes up, it will reduce the radiation incoming to the earth's surface the temperature at the surface of the earth will go down and finally the emissivity of the atmosphere.

If this goes up, the temperature will go down. This is brought out very nicely by the simple model that, increase in albedo and the solar absorber atmosphere brings down the temperature; while increasing the surface emissivity, will increase the surface temperature. Now, let us look at how this model reproduces the observed temperature.

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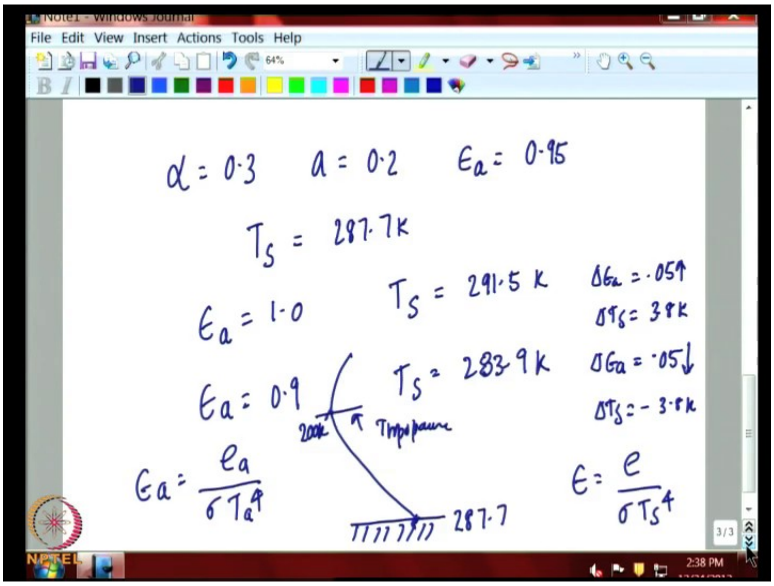

We saw in the last lecture that if we assume the alpha to be 0.3, which is observed value from satellite the solar absorptivity to be around 0.2 and emissivity of the atmosphere to be 0.95, then the surface temperature of the earth can be calculated from the formula. We write down 287.7 Kelvin, which is very close to the observed temperature of the earth surface. But, let us see how sensitive this result is to the choice of emissivity; because we do not know this quantity accurately. Suppose the emissivity was 1, not 0.95, then temperature goes up to 291.5.

It goes up by around four degrees, for a change in emissivity from 0.95 to 1; that is, a change in emissivity of 0.05 increases the temperature by almost 3.8 degrees Kelvin. This shows how sensitive the earth's temperature is to the emissivity of atmosphere. And, just to compete with the one more value; it means, one takes a value of 0.9, we go 0.05 below, and then the temperature is 283.9. We see that if the emissivity increases here, so that the emissivity decreases, then the surface temperature decreases by around 3.8 Kelvin. It is quite symmetric; that is not surprising.

The main message is small change in emissivity of the atmosphere causes a large change in the temperature of the earth. For example, in the last hundred and twenty years, temperature is gone above one degree Kelvin. That could have been caused by a just change in emissivity of the order of 0.01 and this is a very small change. We are not in a position to measure the emissivity of the atmosphere to that accuracy. Secondly, the concept emissivity itself is a big difficult to calculate because the temperature of the earth's atmosphere is not uniform. The earth's surface may be at 287.7, but the temperature decreases at height until you go to tropopause and   then it changes.

When we are going to define emissivity, you remember emissivity is nothing but emission by a surface divided by emission by a black body at this temperature. If you are concerned with earth's surface, that is okay. We know the temperature, but when you tried to define the emissivity of the atmosphere, we are talking about atmosphere emission divided by sigma T a to the power of four; where the T a is varying between 287.7 and around 200 Kelvin by time you reach the tropopause. So, which temperature does one take?   It is very difficult to highlight.

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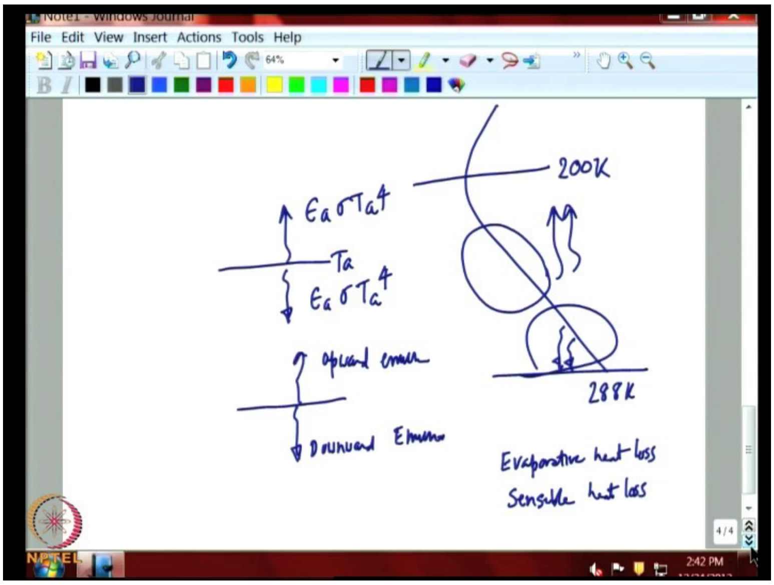

The second point which is more important than this is the fact that, in our simple model we assumed that the atmosphere emits equally upwards and downwards. This is a very poor approximation. This is all right if approximation in thin layer at constant temperature T a, but the real atmosphere is a thick layer whose temperature value is between 287.7 to 200, over a thickness of around ten to fifteen kilo meters. This simple model is totally invalid. Again, we will write the temperature variation in atmosphere from 288K to 200 Kelvin. This difference is around let us say 88 Kelvin for convenience; round numbers.

Now, this layer when it emits radiation upwards, most of the emission will come from this region; because the radiation emitted by the surface would be absorbed by the gasses next to the surface they will re-emit the radiation. We will observe from the top of the atmosphere is the radiation emitted by the upper layers. On the other hand, when you look at the downward emission, it is mostly emitted by layers here near the earth's surface because radiation emitted by layers above that are absorbed by the gases in the lower layer and re-emitted, so that the radiation coming from going above comes from layers in the upper region by the radiation coming downwards is from layers, which are at a high temperature.

We expect that this quantity, the downward emission will be much larger than the upward emission because the downward emission comes from layers of the atmosphere closer to the earth's surface at a high temperature, while the upward emission will come from layers in the upper troposphere which are low temperature. This is the basic flaw in this model. But, the other major flaw is our neglect of evaporative heat loss and sensible heat loss from the earth's surface.

The earth to maintain its temperature around 288 Kelvin is cold both by the radiation as well as by convection of the two forms; the dry convection, which is sensible heat flux and evaporation which is occurring over the oceans. We know that term and we allowed radiation purely like a black body. There are two major flaws. So, let us see what the observations say about these fluxes.

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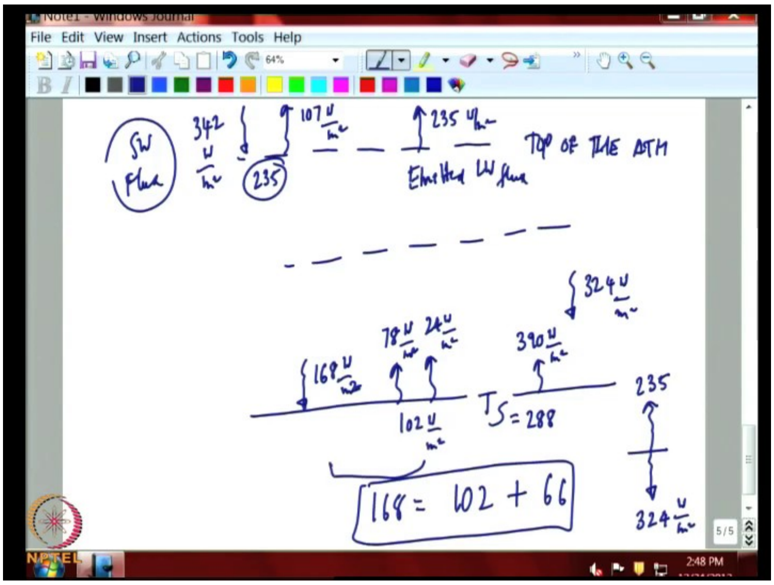

Let us look at the earth's surface at the top of the atmosphere and see what the typical observed fluxes are. Now from satellite, we know that the radiation coming per unit area of the earth's surface is 342 watt per meter square. We know very well because this is measured by satellite and measurements have been going on from last thirty years they have been averaged very carefully. There is absolutely no doubt that the incoming radiation, although there is variation, small amount of variation, but by large the quantity is well understood. Similarly, we also know how much energy is reflected. That is around 107 watts per meters about one-third; not one third, thirty percent of incoming radiation is reflected back to space. The difference between these two is the radiation absorbed which is 235.

So for the earth to be in steady state, it must emit 235. That is very clear. From top of the atmosphere we are very sure that the total radiation absorbed by the sun by the earth's atmosphere system is 235 watts per meter square. The Earth's atmosphere system it has to radiate in the infrared; amount equal to 235 for the earth to be in steady state. This is very well established by satellite measurements of both the reflected solar radiation, the incoming solar radiation and emitted flux. This is the emitted long wave flux; these are short wave flux on this side. So, all these are measured accurately at the top of the atmosphere.

We know the balance precisely. Now, we come to the earth's surface. Earth's surface quantities are not well known, but lot of modeling has been done. We know that on an average, radiation comes this side and is around 168 Watts per meter square. This much is coming from the sun and we average all day and night and all seasons global mean. We also know that roughly the evaporative flux is 78 watts per meter square. Do not as accurately know as radiation because this must be estimated by approximate formulae. The heat loss by dry heat transfer so-called sensible flux is around 24. So, sum of this together is about 102 watts meter square.

As it says watts per meter square is coming to surface from the sun and about 102 is lost by the earth's surface by non radiative process; that is evaporation and dry heat transfer. Since we know the earth to be 288, we know that as a black body we assume it must emit 390 watts per meter square. In order for it to lose only 66 watts, it must be only receiving back from the atmosphere 324 watts per meter square.

The earth's surface radiates at 390 watts per meter square, of which most of it comes back from the gases such as carbon dioxide, water vapor, methane, ozone; they all radiate back 324. The net is 66 and which is the incoming radiation 168 outgoing; non radiative is 102, radiative out going is 66. We have a balance. But, the key point about this tabulation is, notice that the earth's atmosphere loses to; emits to the space 235 upwards, but emits back to the earth 324. This is the point which clearly shows that the upward and downward flux of radiation from the atmosphere is not equal; they are highly unequal. This was ignored in our simple model. But, we do not have much choice in this case because the simple model assume that atmosphere is a thin plate at a temperature Ta.

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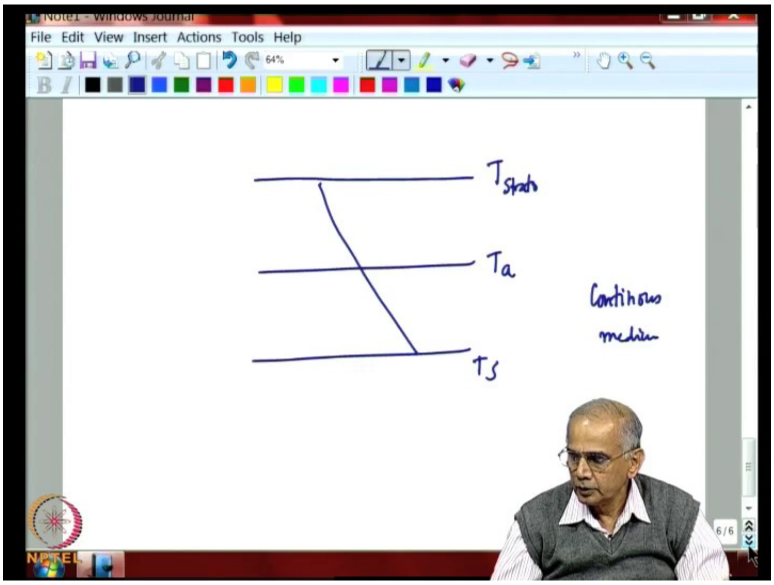

Hence, it has to emit equally up and down, but in reality this is not true of course; we can improve the model by assuming atmosphere and a stratosphere. So, two layer models can be postulated. We can slightly improve the situation, but still this is not going to give you a very accurate estimate.

Though the main point recognized about such simple model is that they involve very large approximations. Hence cannot be expected to reproduce all the observed fluxes in the atmosphere. If we really want to solve the problem more accurately, we have to solve the radiative heat transfer from the full atmosphere as a continuous medium. If we treat the atmosphere as the continuous medium with continuous varying temperature, then of course the problem is very well posed. The reason why we are recalling this is that we had solved such a problem earlier in the context of application to furnaces and other application that focusing on atmosphere.

Let us now look at that problem and see whether we can use the solution we obtained for a gray gas in the radiative equilibrium and see whether we can look at how the temperature varies linearly, almost linearly in the earth's atmosphere.

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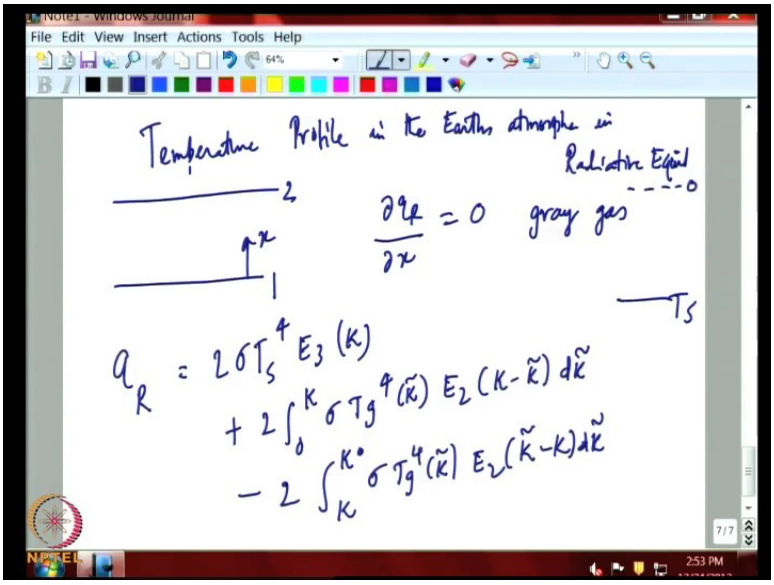

We go back to understanding temperature profile in the Earth's atmosphere under radiative equilibrium. Now, this problem is very close to the problem we solved earlier; that, we can say two parallel plates. Recall and note down the full radiative transfer equation. We then ask this question: what happens when del q R / del x, is equal to zero. We are taking gray gas which we know is not a good approximation, but we will use it that as a way to understand what is going on. We do not except accurate numerical values emerge from this. This was the emission from the earth's surface; this emission downwards.

Now, in the present case this is zero because you are going to take an infinite atmosphere. At the top of the atmosphere is space; there is no long wave radiation coming in. We can neglect this term. To make our life simple, we are going to say, call this as T_s as surface temperature. We have a surface; an infinite atmosphere incoming radiation is zero. Then we have continuation from the two gases above and below certain layer. This is what we have done. This goes as simplified form of an equation we have solved earlier. Except, the downward flux of the top of the atmosphere; because that is zero in the present case.

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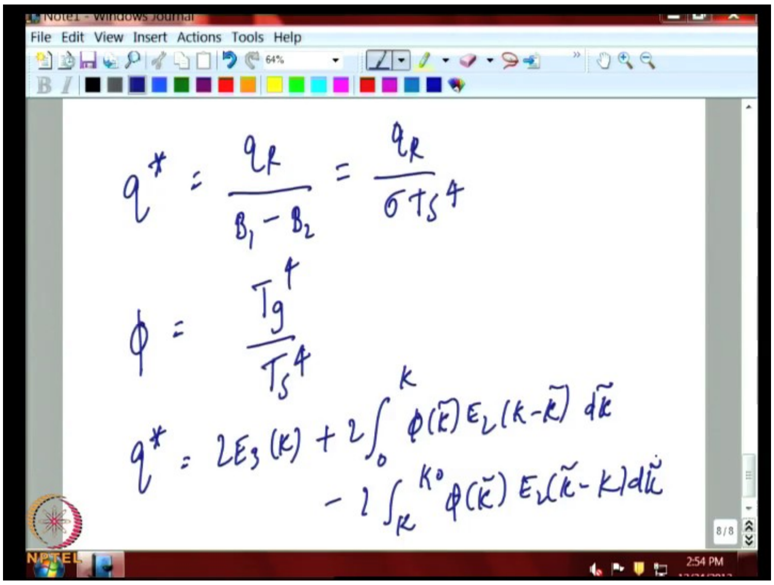

Then if we recall, we define the non dimensional radiative flux as q_R by B_1 one minus B_2. In the present case B_2 is zero; upper flux is a black body flux. This comes out as q_R by sigma T_s to the power of four. That is the radiative flux is made non-dimensionalized by the black body emission from the earth's surface. A non dimensional temperature phi was defined as T g to the power of four minus, T g to the power of four, T two is zero in this case; that goes away. This is by T s to the power of four. This is the non dimensional temperature. When we wrote this form, if we recall our q star, the non dimensional flux was nothing but two times E three of kappa plus two zero to kappa phi of kappa and minus two. This is a problem we have to solve. We invoked the exponential kernel approximation, which is way to take care of the directional variation.

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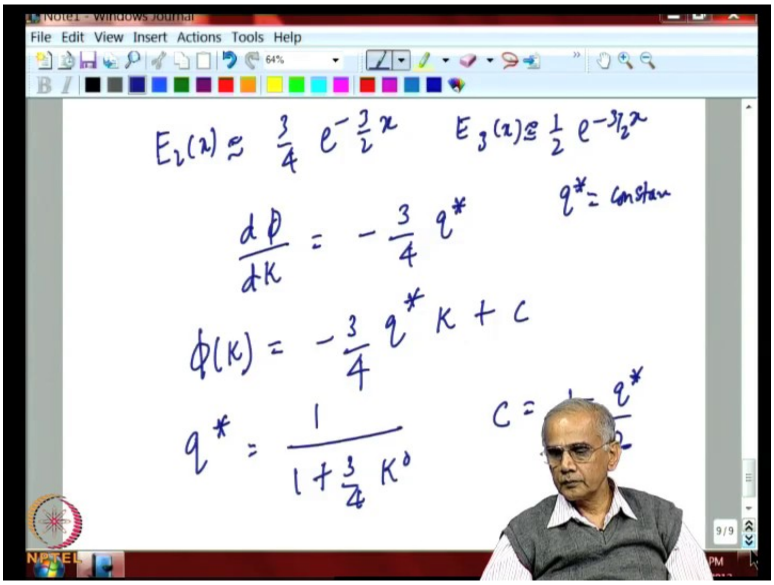

We said E two of x is approximately equal to three-fourth e to the power of minus three by two x and E3 of x as shown above. With this approximation we differentiate the equation twice and subtract it. Finally, we were led with this equation d phi d kappa is equal to minus three by four q star. We converted an integral equation to a differential equation by using the Kernel approximation. The solution to this differential equation is very simple.

Since we are talking about the radiative equilibrium, q star is the constant; so, simply integration of this leads to one more constant. We argued that these two constants q star and c is obtained by substituting this phi back in the integral equation then we got the following results for q star and c. The procedure is exactly same as previous derivation. Except that, top of the atmosphere is zero degree Kelvin; no radiation is coming down. We see that is simplified some of the results a little bit. Now, we know what is q star is. q star is the constant radiative flux through the atmosphere. In the simple model we are going to look at right now; we will neglect the atmospheric solar absorption.

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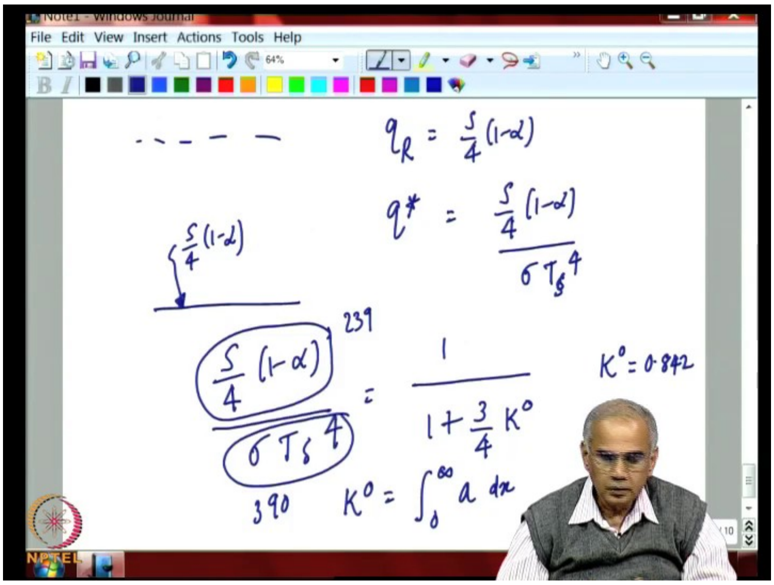

We are just looking at how much radiation is coming here. This can be written as S by four into one minus alpha, if we neglect solar absorption. This is the flux, now which has to go back through the atmosphere and has to remain constant. So q R is nothing but S by four into one minus alpha. That is the simple result that we have got.

So, q star by our definition is S by four into one minus alpha divided by sigma T s power four. So, what the result of this exercise we did shows that, this has to be equal to one by one plus three-fourth of kappa zero. Now, since we have done a very simple model of a gray gas, it is not easy. What is kappa zero? If we recall kappa zero in this case will be equal to integral of zero to infinity a into d x where a is the absorption coefficient; the way we have got the atmosphere; integrated from the surface to the top of the atmosphere.

This quantity cannot be easily be evaluated because in the earth's atmosphere the absorption coefficient is non-gray and where it absorbs in various bands, we need the entire wavelength integration which we have avoided by invoking the gray gas approximation. We are not able to tell you what this exact number is. But, from satellite data we know this quantity is around 239 watts per meter square. We know from surface measurement, this quantity is about 390 watts per meter square. Therefore these quantities are known to be 390 and 239. We are in a position to calculate the value of kappa zero.

So given these two values, kappa zero can be estimated to be around 0.842; plus by substituting these numbers here, getting this value. Now given this number, now we are in a position to write down the temperature profile.

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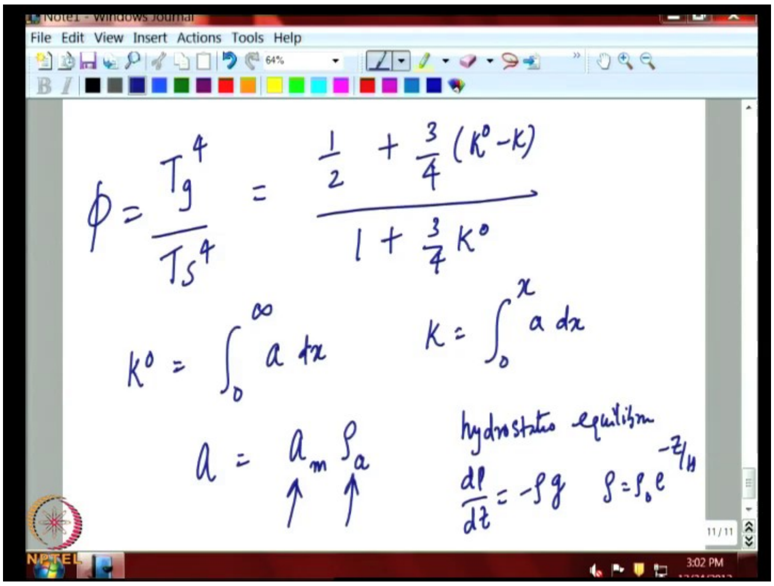

If we recall the derivation we have done earlier, the temperature profile, which now is nothing but T gas to the power of four by surface temperature; that is our non-dimensional quantity. This we have derived already in the earlier lectures. That will come out to be this solution for phi; these are the phi quantity now. The k is zero we had the integral of zero to infinity a d x, while kappa will be integral zero to x a d x. We can substitute kappa zero we got from the last equation we have an expression for temperature profile.

Now, this temperature profile is linear in kappa, but it will not be linear in x; because we note that it can be written as mass absorbing coefficient of the gases like carbon dioxide, water vapor and other combine together; multiplied by the density of the absorbing gas. Now, we must remember that this quantity will not vary much but the mass absorption coefficient is a strong function of height in atmosphere.

That is because the atmosphere is in hydrostatic equilibrium. In most hydrostatic equilibrium conditions, density has to vary with height. In this simplest case of an isothermal atmosphere it can be easily shown by this simple hydrostatic balance that, density has to vary exponentially with height. If the density is going to vary exponentially with the height; all the other gases which are mixed in the atmosphere with nitrogen, oxygen and argon, which are radiative non-participating, here also it will vary with height.

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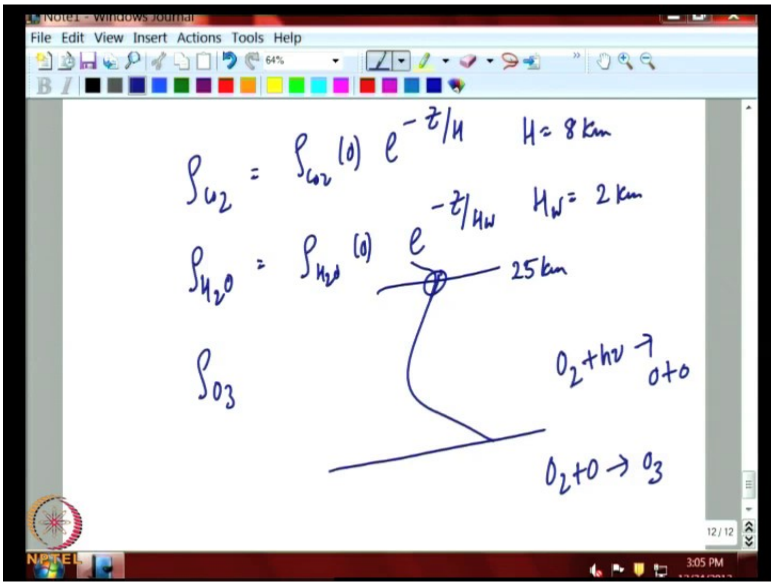

For example, take an example of carbon dioxide. Its density will be varying with height; the same way as nitrogen, oxygen or argon. On the other hand, water vapor will vary somewhat differently than carbon dioxide because water vapor is a condensable gas, while carbon dioxide is not condensable. The water vapor based variations in the atmosphere depends very much upon the temperature variation. The temperature varies strongly with height and at some point all the water vapor has to condense soft. So, H is scale height to the atmosphere, which is typically of the order of 8 kilometer and that of water vapor will be more like 2 kilometer.

The scale height of water vapor in the earth's atmosphere is about one-fourth of the scale height of most of the gasses. Now, one more gas has a very peculiar behavior; that is ozone. Ozone cannot be represented by simple exponential decline that we have. That is because ozone in the earth's atmosphere decreases with height, but at some point it starts increasing. Its maximum value is around 25 kilo meters.

Now, this peculiar behavior of ozone in the earth's atmosphere can be attributed to the fact that, ozone is actually created in the upper atmosphere due to the dissociation of oxygen, when ultraviolet photons at with high energy hit the oxygen molecules dissociate it into atoms. These oxygen atoms combine with oxygen molecules to give ozone.

The ozone is created in the upper atmosphere by the dissociation of oxygen and the chemical reaction between oxygen atom and oxygen molecule to give ozone. The ozone is very special because it is created in the upper atmosphere by ultraviolet radiation; water vapor is special because its density at the height is influenced by the fact that water vapor condenses in the temperatures that we encounter in the earth's atmosphere. All the gases like carbon dioxide, methane and many others; their variation is same as the variation of density of nitrogen, oxygen. So, we will not complicate the issue. But, we will focus only on water vapor that being the most important absorber in the earth's atmosphere.

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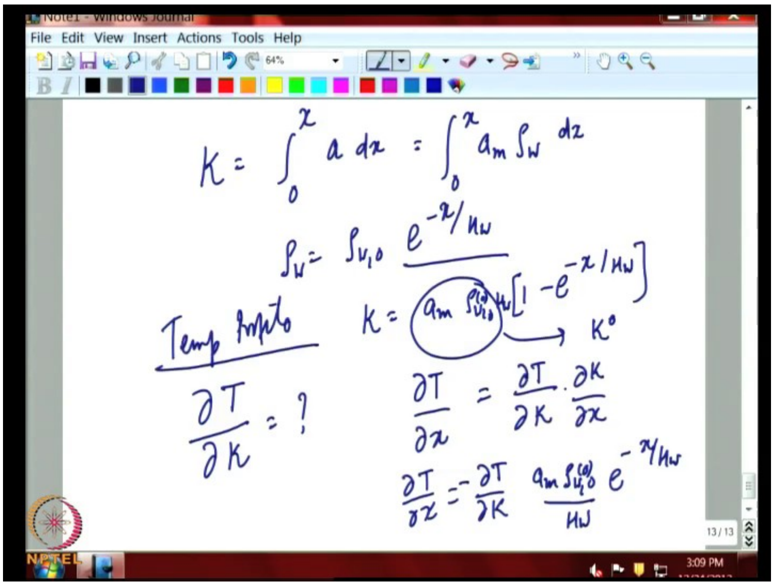

If we go back and ask yourself what is kappa, we saw it is zero to Z; a zero to x notation, , x, a dx. These we want to write as zero to x; mass absorption coefficient of the water vapor times, density of the water vapor times dx. If we assume this water vapor is this quantity, then you see that although the temperature is linear with kappa, H dependent on x; the vertical space will be down linear because of this feature of the absorbing gases. The fact that absorbing gases has the density declining exponentially with height, earth's atmosphere implies that the relationship between temperature and the vertical coordinate would not be linear, but non linear.

Now, why are we concerned about this? Our main interest is temperature profile. So, actually we are interested in d t d kappa. More importantly, actually we are interested in d t dx; which is written as del T del kappa del kappa del x. From that equation, we will see that kappa is nothing but a m rho w o into one minus e to the power of minus x by H w, so that x goes to zero; of course, kappa is zero from the surface humidity. If x goes to infinity, this quantity will be kappa zero. Given that, we can see that del T del x will be equal to del T del kappa. The del kappa del x will come out as shown. We are going to see the temperature gradient in the earth's atmosphere varying exponentially with height. This will be the surface value. Now, if we want to understand how the dt dx is varying with the height; you will recognize that we will vary exponentially with height.

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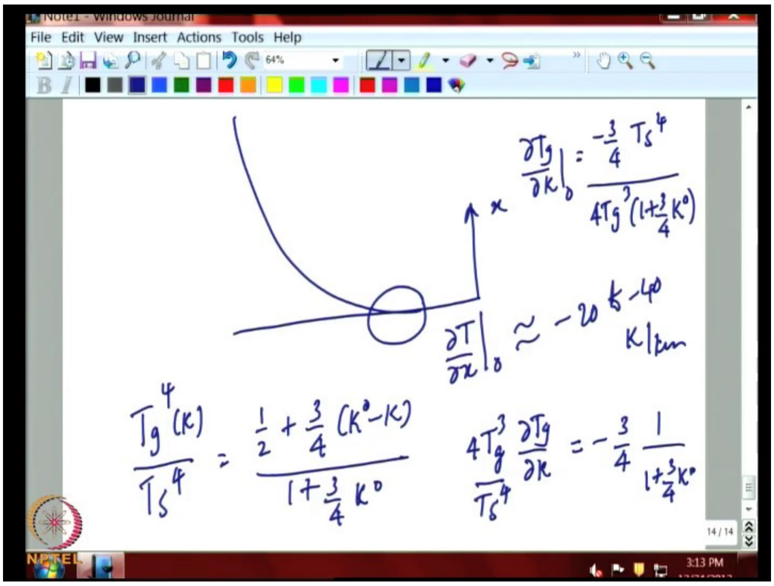

We will draw a simple sketch to indicate how temperature varies with height; x will decrease. We let us see what the temperature gradient at the surface is. What is this value? We look at the previous expression that we had; kappa is zero, so that term will drop out. We our expression will may depend on what do you del T del kappa.

Now, look at the expression for phi; it is coming out as one half plus three-fourth kappa zero minus kappa divided by one plus three-fourth kappa zero. If you calculate we take that surface as g for time being; we have four T cube T g T kappa. That is what this is by T s to the power of four. This we equal to on this side; minus three fourth of that is what is T g T kappa.

We can estimate the T g, T kappa at the origin and take out zero and will come out as minus three-fourth. We can take T s to the power of four to the top there and four T g cube to the one plus three fourth kappa zero. Now, we know all these numbers because we estimate kappa zero around to be 0.84, T g at this earth's surface will be around 260. We can estimate from the expression for phi. The temperature T s is around 288. If we plug all these quantities in to the equation, you will find, depending on what numbers you use, that dt/dx will be around minus 20 to minus 40 Kelvin per kilometer.

Exact value depends on what number is used for water vapor, density and absorption, and so on. But, the key point you want to highlight is that under radiative equilibrium the temperature gradient of the gas near the earth's surface is extremely large; 20 to 40 Kelvin per kilometer. But, this is not observed at all heights around earth. The temperature profile just going out observed very close to surface; may be within a few centimeters. But, once we move above that layer, what we might call a conduction layer, the temperature gradients are much weaker; most of the observed temperature gradients are in the range of 6 to 9 Kelvin per kilometer.

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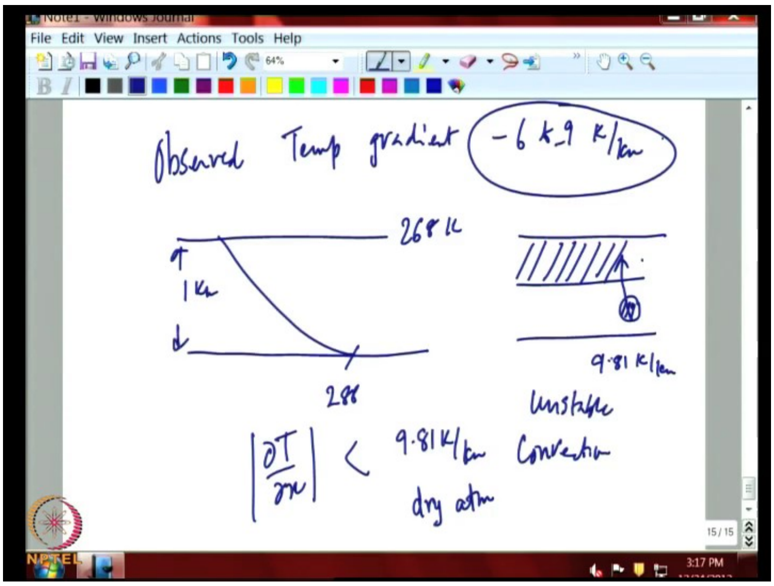

At the rate of 6 to 9 Kelvin per kilometer; we need to understand why the temperature gradient actually observed in the earth's atmosphere is much lower than what is calculated by the radiative heat transfer model. Now, one has to simply ask if the temperature is 20 Kelvin per kilometer, let us say this is 288 here and one kilometer above this comes to 268. Now, one can show such a layer is not stable. One can easily calculate the density of the upper layer. We will find the density of this layer is higher than the density of this layer. We will find that if you take a parcel of air from the lower layer and just displace it, it will rise upwards because the density is high; the density of the atmosphere goes down with height; goes down with height. If you take a parcel air from this lower part of this layer, one kilometer layer. We will lift it, it will expand and it will expand adiabatically without condensation. Then it will cool at the rate of around 9.81 Kelvin per kilometer.

The air parcel which is the upper layer of this one kilometer depth, its temperature should be much larger than the surrounding, which is going at 20 Kelvin per kilometer. Therefore, it will be very light compared to the background will keep going up. This is unstable situation. Any small displacement of the parcel will allow the parcel keep properly and it expected to condense. So, what we say is that the temperature gradient induced by radiative equilibrium in the atmosphere is so steep that, it will induce instability in convection. This will reduce the temperature gradient. The actual value is below 9.81 Kelvin per kilometer. That is, above 9.81 or 10 will come below that; this is if the atmosphere is dry. But, earth's atmosphere is not dry. It is moist; contains water vapor.

As soon as the air parcel rises and cools, the relative humidity of the parcel, will approach hundred percent very soon. By the time it is one kilometer, that water vapor will condense. If it condenses, it will release heat. The temperature in the height, instead of being 9.81 k cooler, it will be lower.

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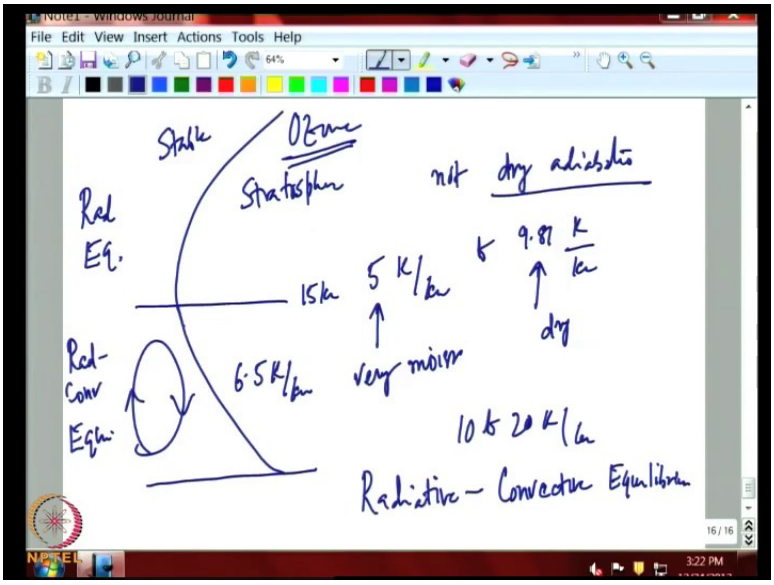

This is called the moist adiabatic process. If the water vapor condenses in the parcel, then the process is not dry adiabatic, but moist adiabatic. In the moist adiabatic process, the temperature rise of the parcel will be slower than dry adiabatic. It can be anywhere from 5 degree Kelvin per kilometer to 9.81, when it is dry; this is when it is dry and when it is very moist.

So, what is observed in practice in the earth's atmosphere is, especially in the tropics is, in the lowest layer of the atmosphere a typical decline is 6.5 Kelvin per kilometer; where you will see between six and seven, but it is 6.5. So what happens is, the radiative process determine the initial temperature variation. That is of the order of ten to twenty Kelvin per kilometer. It is very unstable and at most ultimately starts mixing. On mixing the temperature profile established is either dry adiabatic; if there is no moisture or moisture dry adiabatic, when there is moisture. And, the absorbed value is more like 6.5 Kelvin per kilometer.

This phenomenon where radiation creates a high temperature gradient, but that high gradient is reduced due to vertical mixing in the atmosphere by convection; both dry and moist is called the radiative-convective equilibrium. Finally the temperature profile in the stratosphere is given both the radiation and the convection. They cannot be separated; one sets up the gradient and that gradient happens to be high then the convection takes over. Depending on the humidity of moist atmosphere will reduce it to around 6.5 Kelvin per kilometer. But once we go above the troposphere, there is no moisture there, hardly. There is ozone additionally. Above the tropopause in the stratosphere, there is no convection because in the stratosphere because of the presence of the ozone, the temperature does not decrease height but increases with height, so this is the stable layer.

In this stable layer convection does not happen. We can apply what we learnt about radiative equilibrium; while here in the troposphere we have to talk about radiative convective process above the tropopause we have radiative equilibrium and below the tropopause we have radiative convective equilibrium. We start our calculation at the earth's surface. We calculate the temperature variation the temperature gradient; we find it very large. And, the atmosphere is bound to be unstable to vertical mixing. Ultimately we let these layers mix and then find what the mean variation is. That comes close to 6.5 Kelvin per kilometer due to the presence of moisture in the earth's atmosphere.

But, in the stratosphere we do not have to worry about convection because it is a very stable layer; because temperature increases height because of ozone being present here. Presence of ozone in the stratosphere reverses the temperature gradient there; an inversion layer. And, that layer is very stable and hence we get the radiative equilibrium. So, what we find is that final explanation for the variation temperature of height in the earth's atmosphere has to invoke both the radiation and convection in the troposphere. On the other hand it can manage with radiation alone in the stratosphere the analysis we have done just now was for a gray gas.

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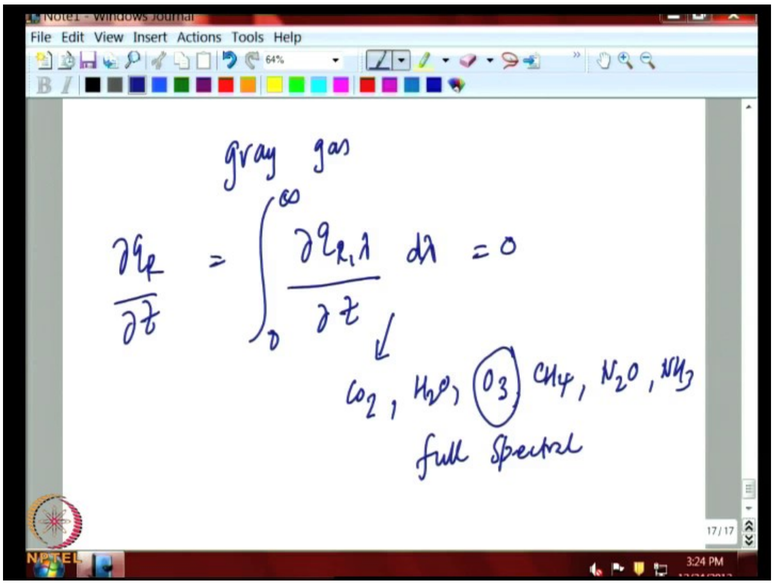

We have highlighted many times; strictly speaking, we cannot use the gray gas model in the earth's atmosphere. So, strictly speaking you have to look at spectral variation of radiative flux with height then integrate over all wave length. This is the quantity which has to be set equal to zero for radiative equilibrium.

In those spectral variations we had account for absorption; absorption for carbon dioxide, water vapor, ozone, methane, hydroxide and ammonia; all these gasses which are present, all these are accounted for all these spectral bands have to be incorporated in this spectral radiative flux. We this is a very tedious procedure this is done usually by large computer programs, which are now easily available. The final result we get is not very different because in the troposphere, finally what is established is the temperature profile determined by a mixing in the troposphere.

Although the radiative flux and the temperature gradient we will get by doing the full spectral, integration will be different from what we got for a gray gas. But, finally it is convection that determines temperature profile in the troposphere. So, finally it will lead to very close to six to seven degree per kilometer and would not matter of how the gradient was set up. But in the stratosphere, of course it is very important to take into account the role of ozone; because in the stratosphere, ozone is the dominant gas which absorbs the radiation. We what you find is that in the earth's atmosphere, radiation plays a complex role along with convection to set up a certain gradient in the troposphere and a different gradient in the stratosphere.

Thank you.