Radiation Heat Transfer
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Lecture - 28
Radiation and Climate

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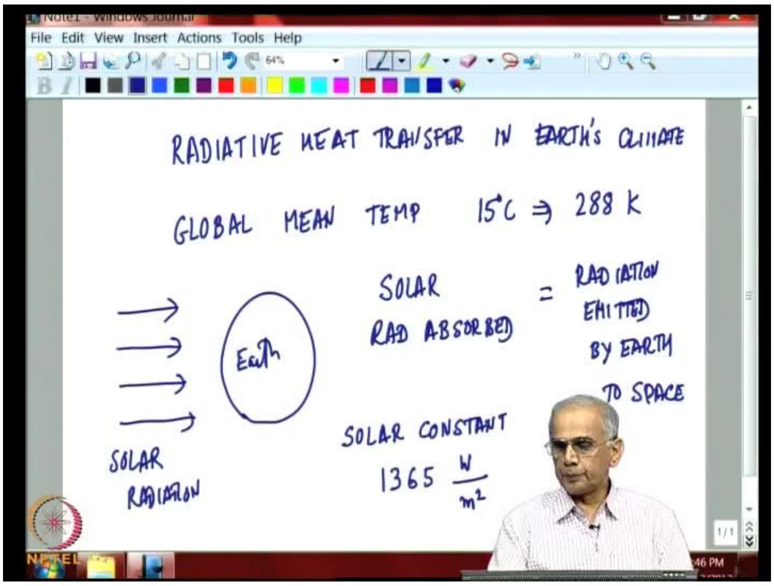

In this lecture, we are going to look at the radiative heat transfer and its role in the Earth's climate. All of us know that the present global mean temperature is 15 degree centigrade or 288 degrees Kelvin. This temperature is maintained by radiation from the sun. We have the Earth here, subjected to the radiation from the Sun. The mean temperature of the Earth is because of the balance between the solar radiation absorbed by the Earth and radiation emitted by the Earth to space.

This balance between radiation absorbed from the Sun and the radiation emitted to space is that balance what we are trying to understand. So, how much is radiation is coming from the Sun. Now, satellites have measured this radiation quite accurately in the last 50 years and the radiation arriving is known as the solar constant. This is the radiation normal to the Sun's rays at the mean Earth-Sun distance. We know that the earth's orbit around the Sun is not a circle but elliptical. The radiation coming from the Sun will vary slightly with the season.

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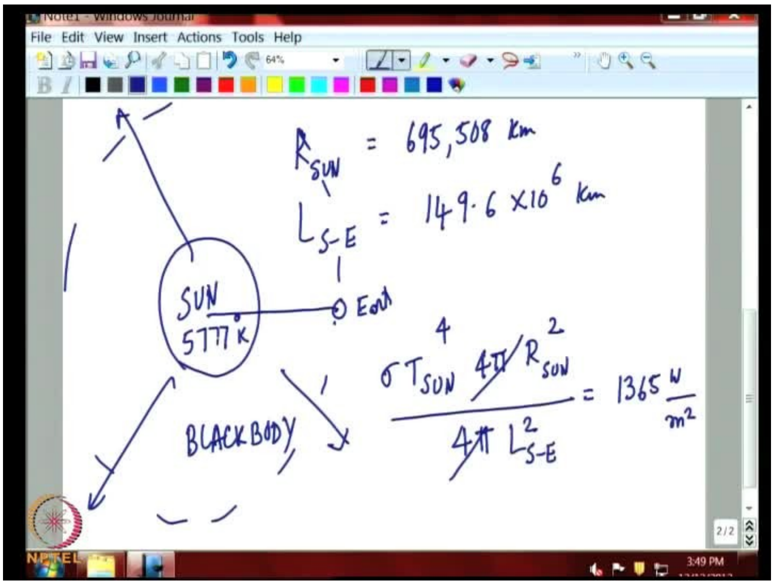

We look at the mean Sun-Earth distance where standard measurement show the radiation normal to the Sun's rays is 1365 Watts per meter square. This is an important number to remember, this is the radiation arriving from the Sun. Now, one may ask can we estimate this radiation from basic principles of radiative transfer. The answer is yes. If we treat Sun as a black body, then the effective temperature of the Sun from measurement show this is 577 degrees Kelvin, Sun's effective black body temperature.

We know that the Sun's radius is 695,508 kilometers as measured from the Earth. We know the Sun-Earth distance, the mean distance as 149.6 into 10 to the power 6 kilometer, approximately 150 million kilometers. So, given the information about the Sun's black body temperature, radius of the Sun and the Sun Earth distance, we can estimate the radiation leaving the Sun, knowing its black body temperature as this into 4 pi R square. The surface here is a sphere through which this radiation is going out.

The same radiation ultimately has to go pass the Earth and so essentially as this radiation goes outwards, the density of the radiation will come down as 1 over R square. Ultimately near the Earth here we divide by the surface area of this imaginary sphere, whose radius is the Sun-earth distance. We plug in this 577 degrees Kelvin and this 4 will cancel out of the course and the Sun's radius and we will get a number very close to 1365. This quantity has been measured by satellite just outside the Earth. It can also be calculated knowing the black body temperature of the Sun, so both will give us the same answer. Now, let us look at what happens to this radiation.

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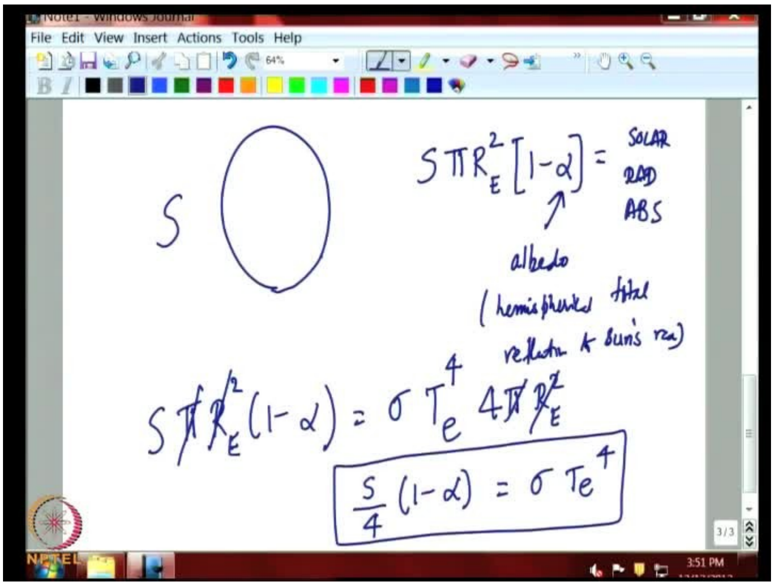

Let us call it S that is radiation coming into the Earth. We notice that the amount of radiation that will be intercepted by the Earth is S times pi R square of the Earth. Earth will intercept only the cross section area of the Earth pi R square, not 4 pi R square. Then a certain fraction of the radiation is being reflected and the remaining is absorbed. This is called albedo, this is essentially the hemispherical total reflectivity to Sun's radiation. This is the quantity of the radiation the earth absorbed. Now, at present let us pretend the Earth has no atmosphere and let us assume Earth is a black body, that is, its emissivity is 1. When the radiation emitted by the Earth, so this radiation which is absorbed by the Sun has be equal to radiation emitted and let us call the e is the effective black body temperature of the earth into 4 pi R e square.

When the heat lost from the Earth, it takes place over that entire surface of the earth, while calculating the radiation absorbed, we only take across the cross section area of the Earth because only that much is intercepted from the Sun. Finally the expression we get is S by 4, the radius Earth is not relevant, pi cancels out. S by 4 into 1 minus alpha is equal to sigma T e to the power of 4. The quantity S by 4 will keep coming quite often in our discussion.

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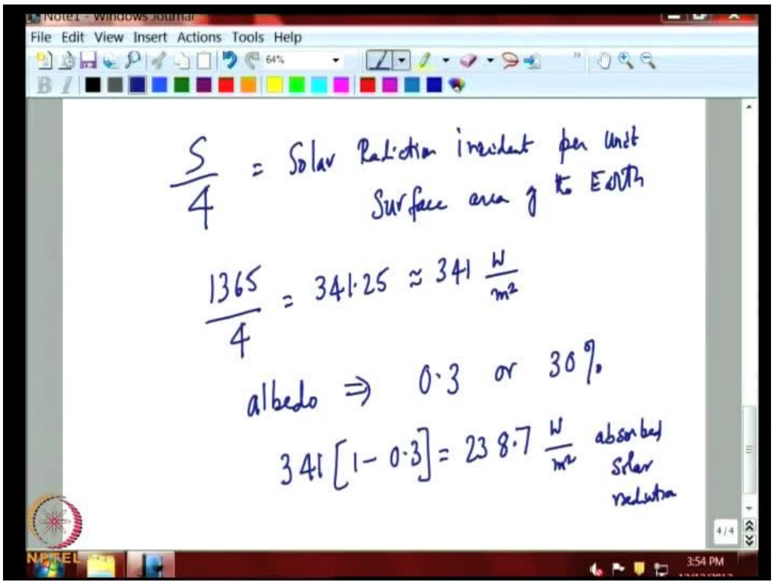

We want to think of S by 4 as the solar radiation incident per unit surface area. So, every unit surface area of the Earth, gets radiation, not S, but S by 4 because of the fact that Earth has a surface area of 4 pi R square, while the area over which it intercepts the Sun' s radiation will be pi R square. This quantity is 1365 divide by 4 is approximately 341, we will take it as 341 for our discussion, because actual solar constant varies between 1364 and 1365, due to the variations in Sun's output. The actual number is somewhere between 341 and 342 in that range, we will be taking it as 341.

Now, the albedo, the hemispherical total reflectivity of the Earth has been measured accurately by satellites in the last 20 to 30 years and the value that we know that is around 0.3 or 30 percent. So, 30 percent of the radiation that comes from the Sun is reflected back to space. It is now not available for energy balance, because it is gone. The radiation as available per unit surface area is 341 into 1 minus 0.3 that is 30 percent radiation is reflected 70 percent is absorbed. 70 percent of 341 are 238.7 Watts per meter is absorbed solar radiation. On an annual mean basis the earth absorbs around 238.7 Watts per meter square and to maintain equilibrium this 238.4 Watts meter has to be emitted by the Earth.

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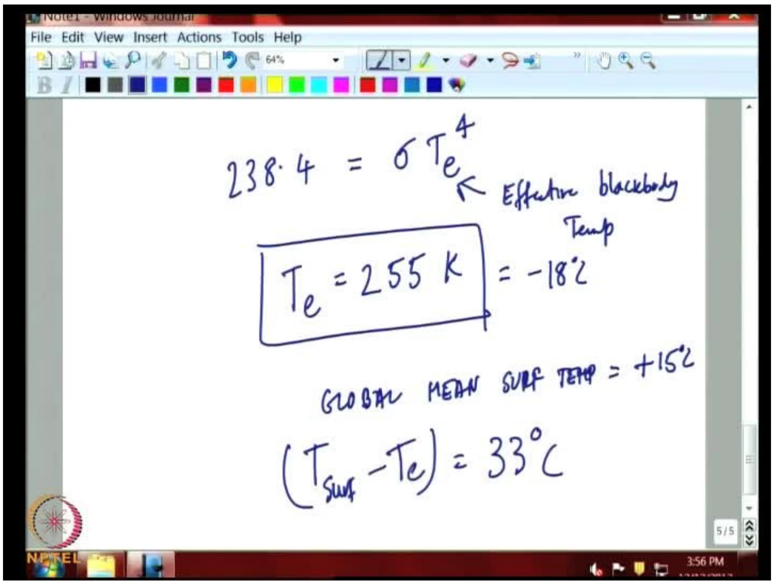

This is called the effective black body temperature of the Earth. This is not the real temperature. If you substitute that 5.67 we will get the T_e be around 255 Kelvin. This is equal to minus 18 degree centigrade. This is not the real temperature of the Earth surface; this is the effective radiative temperature, which balances the absorbed solar radiation from the Sun. Now, this is minus 18 we know that the global mean surface temperature at the earth is plus 15 degree centigrade.

We would like to understand, how the temperature of the Earth is 33 degree above the effective radiation temperature of the Earth. This 30 degree value, T surface minus T effective temperature is 30 degree centigrade. We need to understand what caused this temperature to go up by 30 degree centigrade and as all of you realize this because of the atmosphere of the Earth. The atmosphere of the Earth contains gases which are transparent to Sun's radiations, but they absorb the radiation emitted by the Earth. This unusual property of some of these gases is given the name the Green house effect. That is the Earth's atmosphere behaves like the glass in a green house. The glass in a green house allows to Sun's radiation to go through into the green house, but the radiation emitted by the plants and other surfaces in the green house is not allowed to go through the glass. Glass is opaque to radiation emitted by the surface of the green house. That is why green house is much warmer than the surrounding air.

The Earth is much warmer than what it could have been without any gases. That is because of an unusual property of these gases that there are almost transparent to the incoming solar radiation, but almost opaque to the radiation from the Earth and this we will recall as part of our study in gas radiation.

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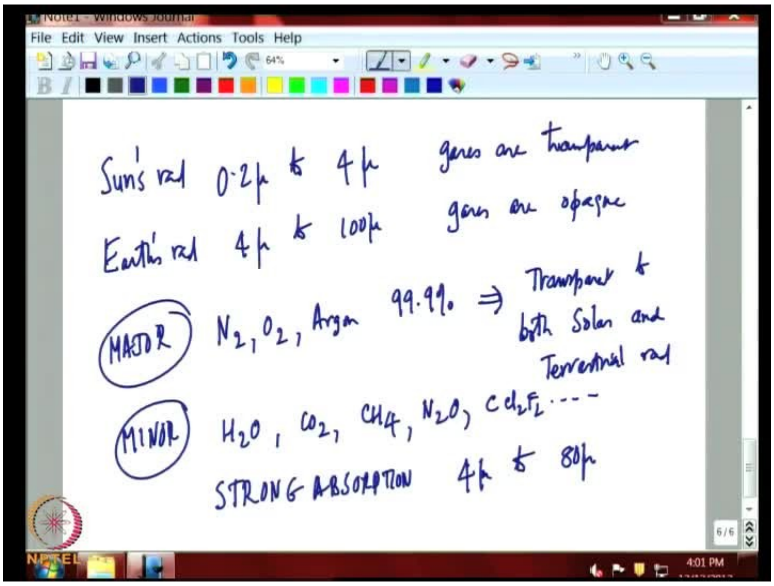

We recall that the Sun's radiation is primarily in the regime 0.2 micron to 4 micron. The gases are transparent to this wave length. Earth's radiations as all of you recall from the Wien's displacement law. Earth is at a lower temperature, so the radiation emitted lies between 4 micron to 100 micron and the gases are opaque to this radiation. This unusual property of the gases has enabled the surface temperature of the Earth to be 33 degree warmer than the temperature it would had if there were no gases.

Now, ironically there are 3 gases on the Earth; Nitrogen, Oxygen and Argon, which constitute 99.9 percent of the Earth atmosphere. They are transparent to both solar and terrestrial radiation. The y play no role in this climate, they allow radiation from the Sun go through, they allow radiation from the Earth to also go through without absorption. There is some scattering by molecules, small amount, but as far as the absorption is concerned; Nitrogen, Oxygen, Argon have no absorption bands or very weak absorption bonds in the region 0.2 micro to 4 micron.

On the other hand, the many gases like water vapor, carbon dioxide, methane, nitrous oxide, chlorofluorocarbon, have an usual property that they are fairly transparent to solar radiation, but have strong absorption in the region from 4 micron to around 80 micron, they absorb very strongly. The major gases, which play no role in the earth's climate and these minor gases play a major role. Now, carbon dioxide amount the atmosphere is at present around 390 parts per million, is a very small amount. Methane is in parts per billion, water vapor amount varies a lot. In the poles there is hardly any water vapor. If we are in the tropics, it is about 1 percent.

The puzzle is, how come these minor gases, which do not contribute to 99.9 percent of the Earth mass in this atmosphere, they are so effective. The answer is because of the fact the major gases like nitrogen, oxygen, argon do not absorb or emit any radiation, the task of controlling the Earth climates is now in the hands of minor gases. This the puzzle, that we need to understand fully because lot of people think that a increase in carbon dioxide which has occurred in the last 100 years, due to the burning of coal, oil and natural gas, has increase the amount of carbon dioxide from around 280 parts per million in 1850 to 390 parts per million today.

That increase in 110 parts per million is too small and they feel it cannot affect our climate, but they are wrong because carbon dioxide has extremely strong absorption bands, which we discussed earlier, when we discussed they role of carbon dioxide in the furnaces. The absorption bands 2.7 micron, 4 micron, 15 micron and these absorption bands absorb Earth radiation very effectively and prevent the Earth getting heated easily.

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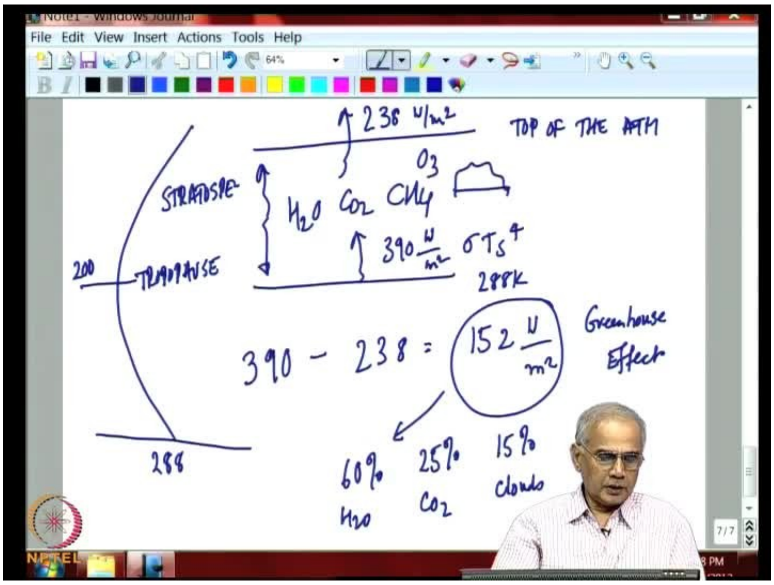

Now, let us look at what role these gases are playing. Now, even look at the earth's surface temperature it is 288 K and assumed to be a black body, we can estimate that sigma T to the power of 4 will be 390 watts per meter square. We know from satellite measurement, that at the top of the atmosphere, the radiation going out is approximately 238 watts a meter square, which is balancing the absorb solar radiation around 238. The difference between 390, which Earth's surface emits minus 238, which is going out is 152 watts per meter square is what we call the Green house effect.

The Earth is emitting 390 watts per meter square, but all that radiation emitted by the Earth is not going to space because in between there is sitting water vapor, carbon dioxide and methane and they are trapping the radiation absorbing it and emitting it back to the Earth as well as to space. These gases are at a lower temperature, than the earth's surface. Ultimately the radiation that the Earth is able to send to space is much lower than what is emitted by the Earth surface. This is what causes the temperature of the Earth to go up and of the 152 watts per meter square that is being absorb by water vapor, CO_2, methane, the most important is water vapor which contributes about the 60 percent to this trapping and about 25 percent is on account the carbon dioxide and about 15 percent is on account clouds. Clouds also trap radiation.

The clouds in the atmosphere will absorb the Earth's surface radiation and reemit it at a lower temperature. So, clouds also contribute green house effect, so all the three combined total effect is around 152 watts per meter square. Now, can we model these phenomena in a simple way? We will address this issue by doing a very simple model of the Earth atmosphere. Earth atmosphere is fairly complicated. The temperature varies from 288 at the Earth's surface to around 200 Kelvin at the tropopause, which is the end of the troposphere. Ozone also is a gas which absorbs rays of the Earth.

This is around 288 and this is around 200 Kelvin. Then in the stratosphere temperature starts increasing because of ozone absorption. If we want to model this phenomenon accurately, you have to solve the full equation for radiative transfer in the atmosphere under radiative equilibrium, which will take up in the next lecture. It is similar to the problem we solved between two parallel plates, but we have slightly modified the derivation.

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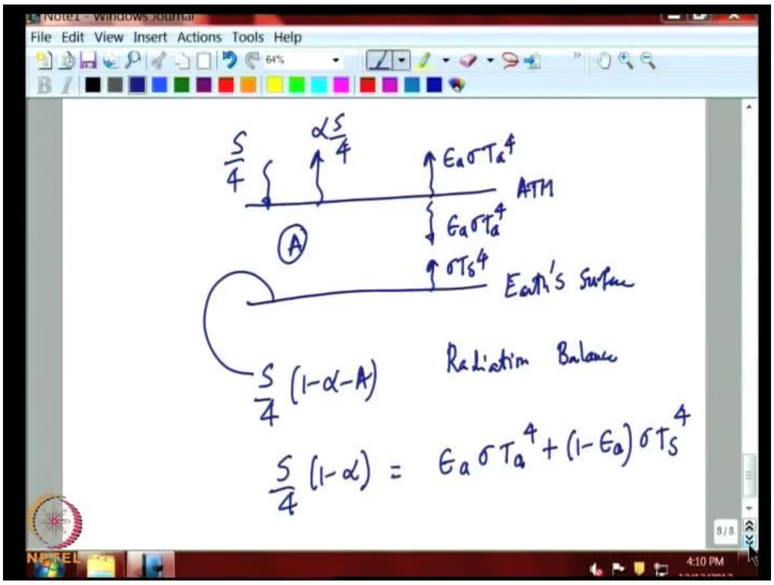

But before we get into that we would like to do a simple analysis, which simplify the problem substantially, so that you get some insight into what is happening in the atmosphere. To do that, we will treat the earth's surface as one layer and the atmosphere as one layer. Now, this is not a good approximation. The atmosphere cannot be treated as one thin sheet of glass, but we will do that. We will assume that this thin sheet emits radiation upwards and downwards.

The radiation is coming from Sun of course, is S by 4 and what is reflected is all alpha S by 4, what is absorbed is the difference between these two. The Earth's atmosphere absorbs some radiation from the Sun, so A is solar absorptivity of the atmosphere. So, what reaches the Earth surfaces is S by 4 into (1- alpha - A) We assume that the al l this radiation is absorbed by the Earth's surface and Earth's surface emits sigma T is power upon 4 We do a simple radiation balance.

Strictly not correct because, there is also energy transfer from the Earth's surface to the atmosphere by evaporation, and by what is call as sensible heat flux the normal heat transfer, convective heat transfer, that we learn in engineering. But we will neglect this at this point. We do a simple radiation balance, so at the top of atmosphere here, we can see clearly that what is absorbed at the top of atmosphere is this and voice coming is the emission from the atmosphere. Transmission, is 1 minus absorption, which is same as a 1 by emission times surface. Here is radiation from atmosphere from the surface transfer through the atmosphere. This is the balance for the top of the atmosphere.

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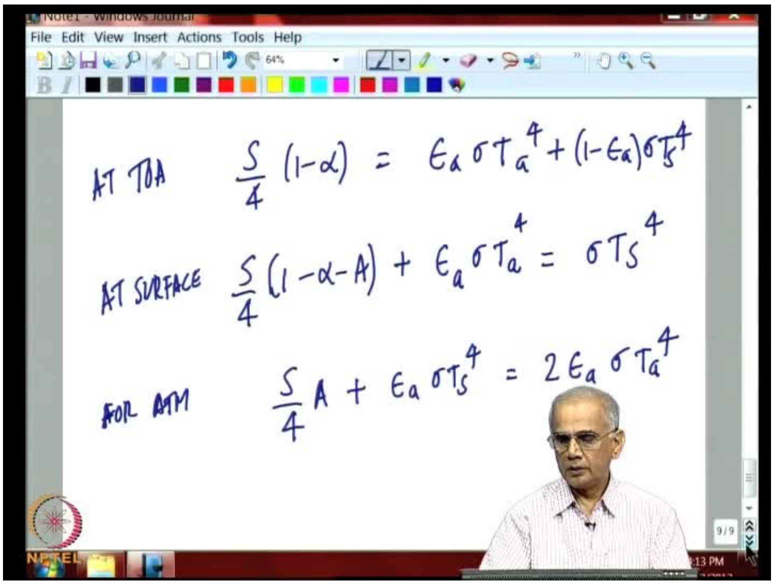

At the Earth surface now, rewrite at top of the atmosphere will write it S by 4 into 1 minus alpha is equal to what is emitted by the atmosphere and what is transmitted through the atmosphere. Then at the Earth surface radiant coming in after reflection and absorption by the atmosphere and plus you must also think of the radiation emitted downward by the radiation. That is emitted downward by the atmosphere is absorbed by the Earth surface. This has to be equal to what is emitted by the Earth's surface.

This balance at the top between the solar radiation absorbed and the heat lost to space from the atmosphere and the Earth surface. At the Earth surface, the balance between radiation coming to the surface from the Sun after reflection absorption with atmosphere and radiation coming down for the atmosphere towards the Earth surface. That is equal to what is emitted by the Earth surface. We can also do a balance, so this is at surface.

These two equations are enough for us, but just for completeness we can also do a balance by the atmosphere. For the atmosphere, what is absorbed is the Sun's radiation. What is absorbed from the Earth surface will have to be equal to the emission in both directions by the Earth atmosphere. We don't need this really because from this two we can get this equation. We can say clearly that if we subtract this from this, we will get this answer. Again, we will verify that. We take the first two equations and solve for surface temperature and atmosphere temperature, very easily we can solve.

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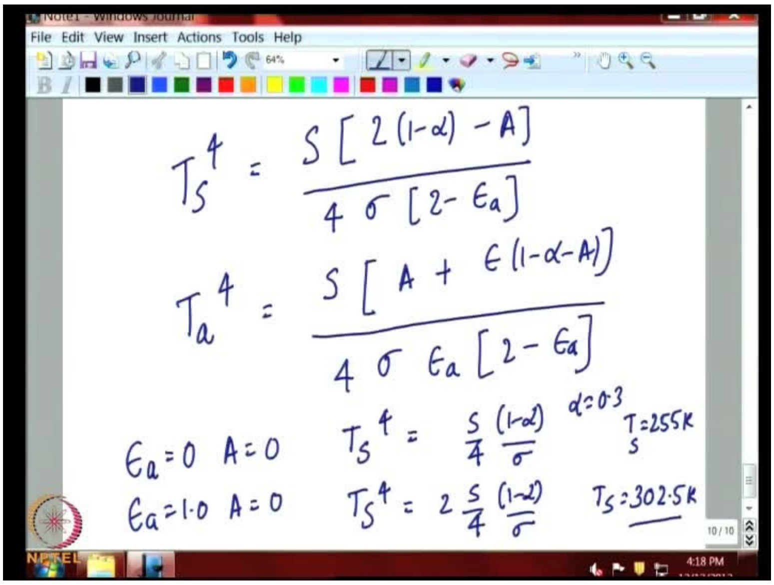

When we solve it we will get T S power of 4 is equal to this is expression for T S and expression for T a as shown above. This is the result here, which clearly shows the factors which control the surface temperature of the Earth and of the atmosphere. Of course, it depends on the incoming radiation S by 4, and on how much is reflected by the Earth system, on what is absorbed in atmosphere, We can see here that as more radiation is absorbed by the atmosphere, temperature of the Earth will go down. That is surface temperature of the earth goes down as the emissivity of atmosphere goes up.

This temperature will increase, so that is what has been happening in the last 100 years on account of the increasing in carbon dioxide by around 110 parts per million. The emissivity of atmosphere has gone up slightly that is enough to increase the temperature the Earth. Now, let us put in some numbers to see, what kind of results we will get. If we do that, we want you to look at special case, so that we understand the limiting cases here.

Suppose, atmosphere does not exist, then the emissivity of the atmosphere is 0 and absorptivity of the atmosphere will also be 0. We will get back the result which we got earlier, which is that. If we make this 0 this 0, these two will cancel out, so you will get this result, which is the standard result, which we got earlier. On the other hand if the emissivity atmosphere is 1, atmosphere acts like a black body, but the solar absorption is 0. Then you will get this quantity as shown.

This number for alpha 0.3 you already calculated this 255 Kelvin, while this one were the atmosphere behave like a black body, but does not absorbs Sun's radiations you will get a very high value of 302. We must understand and differentiate, this is in the absence of atmosphere, we get the effective radiant temperature of Earth is 255 Kelvin, which we already got. Now, if we have atmosphere, which is perfect absorb absorber of the Earth's radiation emissivity is 1 and temperature shoots up to well above the measured surface temperature of the Earth. So, we get a number close to 14.5 degrees higher instead of 288. But the emissivity of the atmosphere is not 1, it is more around 0.6.

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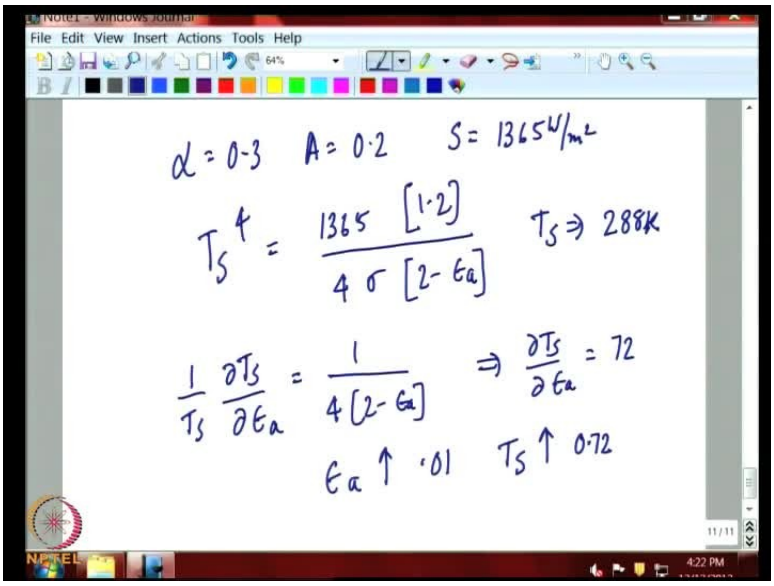

If we put that kind of number, we will get 288. So, let us now put the number, suppose you take albedo as 0.3, solar absorptivity, which is typical around 0.2 and S as 1365 watts per meter square. We will get T S power of 4 is equal to S by 4 is 1365, alpha is 0.3 1 upon 0.7 0.7, 1.4 1.2 here divided by 4 sigma into 2 minus epsilon a. So, with epsilon a, which are around 0.95, we will get a number which is around 288 Kelvin.

Now, we cannot with give an accurate estimate of the emissivity of the atmosphere. With this model, it is very simple; it has neglected the non-radiative heat transfer at the Earth surface, so you cannot expect it to give you a very good answer. But this model gives us some idea of the role played by the emissivity of the Earth atmosphere in Earth climate. The emissivity of 1 at the temperature would have been around 14.5 degree larger. Now, let us try to understand the sensitivity of this result is good to a get a feel for how sensitive is the result to small changes in temperature.

We now differentiate this and calculate the change in temperature, to small changes in the emissivity atmosphere. We will get the following result, 1 by 4 into 2 minus epsilon a. We go typically epsilon around 0.95, then we will find and typical temperature 288 we will find that in the presence climate this quantity is around 72. So, what this mean is if the emissivity atmosphere goes up by just 0.01, the temperature of the Earth will increase by 0.72. This is what this model shows very beautifully, that is it takes a very small change in the emissivity atmosphere to increase the Earth surface temperature by around 0.7 degree centigrade.

Interestingly over the last 100 years, the global mean temperature of Earth has gone up by 0.7 degrees C. The emissivity has change by around 0.01 not only due to the increasing Carbon dioxide, but as a temperature went up due to thermodynamics water vapor has also gone up and all this has contributed to the increasing emissivity of the atmosphere by around 0.01. Notice that is it takes a very small change. It is not something which we can measure easily. A change in the emissivity of 0.01 is not going to be very easy to measure. That must be kept in mind before we look at the answer in more detail. This is a role of emissivity. It is playing an important role. We can also look at the effects of other parameter, so that we get some appreciation of the role played by them for example, due to changes in solar absorptivity.

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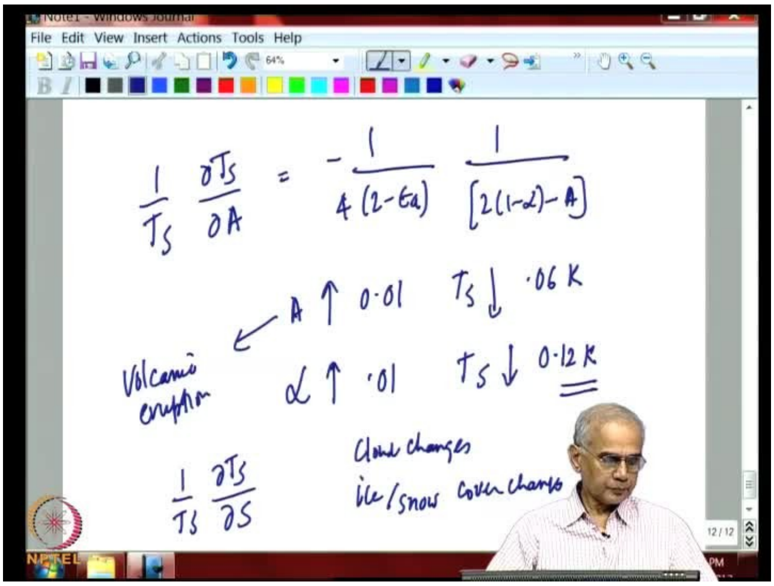

We can calculate how much is the temperature is changing in the response to changes in solar absorptivity of the Earth. We will get minus 1 by 4 into 2 minus epsilon a, by 1 minus 2 into 2 minus alpha minus a, so we estimate this for typical condition that prevail today. You will see that for change in absorption is 0.01. So, very small change say delta a increases 0.01 the absorptivity of the atmospheric layer.

Then according to this estimate the surface temperature let's assume that absorptivity goes to 0.1 which is a small change, the temperature will go down by 2.5 Kelvin. Notice how sensitive the Earth atmosphere is to small changes in the solar absorptivity of the Earth. Now, similarly, we can calculate the effective changes if albedo. If albedo goes up by 0.01 the temperature drop little bit faster, 0.12 Kelvin. Now, what it means is that, this also is a very small change in albedo of the Earth, it can be occurring due to changes in cloud or it can be changes in ice or snow cover.

If all this changes the reflectivity of the Earth atmosphere system by this 1% from 30% goes to 31% the temperature drops by 0.12 Kelvin. These changes occur, for example, during a large volcanic eruption, the albedo of the atmosphere can go up by 0.01, or even more. That can cause a very large change, large cooling of the Earth surface. We have historical data showing that, whenever there was a major volcanic eruption on the Earth, the temperature Earth cooled by around 0.1 to 0.2 degree Kelvin. Similarly, small changes in the Earth albedo or its reflectivity on account of it changes in cloud or changes in ice or snow cover, can cause equally large impact.

We look at the past climate of the Earth. We do see Earth climate fluctuating by around half degree Kelvin. All this can be easily later to either changes in the Earth absorptivity to the volcanic eruption or changes in Earth albedo due to changes in clouds or ice cover. The third point, which we have not discussed, is the changes in temperature due to changes in coming solar radiation. So, solar radiation may not remain a constant, can fluctuate, due to changes in solar activity or changes in Earth Sun geometry. Both this can cause some changes in S. That can also cause some amount of cooling or warming on the Earth.

Hence all these factors have played a role in the Earth's past, but our interest at present is in the Earth's future. If we look at the temperature changes that occurred in last 100 years of the order of 0.7 degrees Kelvin, we can attribute definitely to changes in emissivity and absorptivity of the Earth's atmosphere, primarily caused by increasing carbon dioxide. Then later which caused the water vapor goes up that also contributed to the increasing emissivity. The real challenge is that we now face is about what is going to happen in the next 100 years, till 2100. If we continue to burn coal, oil and natural gas, the carbon dioxide which is now approaching 400 parts per million, will go up to something like 600 or even 700 parts per million.

This will cause much larger increase in the Earth's temperature. This is a potentially serious long term problem that we need to worry about its consequence to the future of the Earth. Now, the reason why we need to worry about it is, if we look at the Earth past climate, it has fluctuated between ice ages when the Earth temperature was 4 to 5 degrees lower than the present, to warm periods. When the ice cover was very low and temperature Earth was couple of degrees warmer than the present. These kinds of fluctuations have occurred. It is important to remember that Earth's climate is not stable.

It can go up or go down on account of natural fluctuations or human induced fluctuations. In the past human being did not play much role, the major role was played by natural processes like the volcanic eruption or changes in the Sun's output, but today the dominant perturbation to the Earth atmosphere is coming from human beings and their emission of large amount of carbon dioxide due to burning of oil, coal and natural gas. This is simple model which illustrates clearly the role of all the three quantities.

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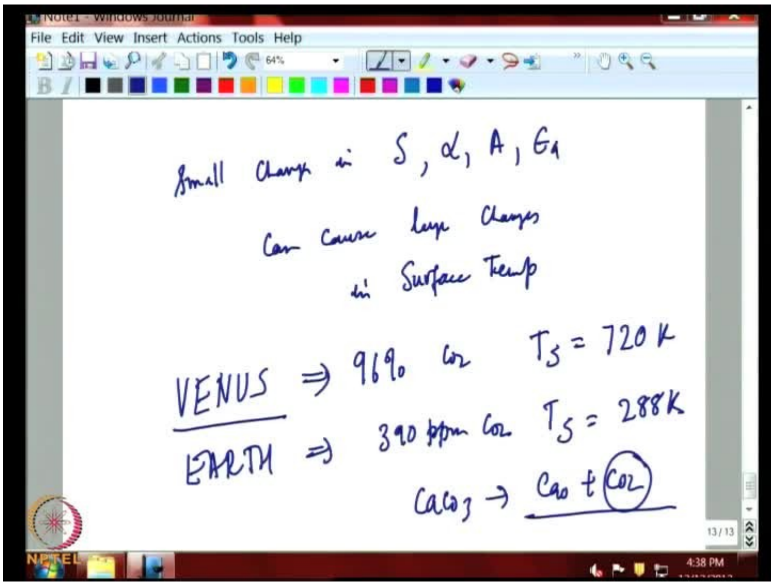

We are able to now summarize, that small changes in the incoming solar radiation or the Earths albedo or solar absorptivity or emissivity can case large changes in the surface temperature. The Earth's climate is sensitive to changes in the incoming solar radiation or changes in the reflectivity or the Earth albedo or the solar absorptivity or the emissivity of the atmosphere. Hence it is necessary now to carefully monitor the Earth's climate to understand, what role is being played by this parameter. Now, the reason why we are concerned about is the example of Venus.

Venus is a planet very similar to Earth in terms of size and the initial composition. The amount of carbon dioxide in Venus, for example, if we take all the carbon dioxide in the surface, in the rocks, and in the atmosphere, then the total amount of carbon dioxide the Venus has is no different from that on Earth. But on the Earth all the carbon dioxide is stored in the rocks as calcium carbonate. Only a small amount of carbon dioxide is present in that atmosphere. In Venus it is the very opposite, most of the carbon dioxide come out the rocks and is now in the atmosphere. For example, the Venus atmosphere contains 96 percent carbon dioxide. The Earth's atmosphere contains around 0.04% CO_2.

The Earth has much lower amount of CO_2 in the atmosphere than Venus. It is because of the strong presents of carbon dioxide in Venus. The surface of Venus is close to 720 degrees Kelvin while that of the Earth is only 288 Kelvin. This shows clearly the important role of the green house effect on Venus. Venus and the Earth started out with the same temperature, but on Venus all the water in the ocean evaporated. When the atmosphere did caused a very large effect increase the temperature of the surface of Venus by 100 to 200 degrees Kelvin that caused all the Carbon dioxide, which is in the rocks as calcium carbonate to come out as carbon dioxide.

As carbon dioxide amount in the Venus atmosphere increased, the temperature in Venus increased to around 720 degrees Kelvin. We do not fully understand all that happened in the past in Venus, which caused it to come in to the present, hot house or the very warm hot conditions, but we know that the greenhouse affect played an important role. That all the water which was over in the liquid form on the Venus surface it is all boiled off, went into the atmosphere and caused a large warming. That ultimately caused chemical reactions at the Venus surface, which converted calcium carbonate to calcium oxide and carbon dioxide.

This carbon dioxide is a powerful greenhouse gas, so caused more warming this went on till the temperature Venus reach 720 degrees Kelvin. We have to worry by burning coal, oil and gas in the Earth atmosphere, whether we will slowly over a period of 100s of years, increase the temperature of the Earth. So, much that lot of carbon dioxide, which is stored in the oceans and in the land, in the soil and in the vegetation will all start coming out and increase the carbon dioxide concentration in the atmosphere by large margin and will cause the Earth to rapidly warm like Venus.

For that is the issue which has to be looked at critically, the prediction is that if we continue to burn coal, oil and natural gas at the rate which we are doing now, the Earth's temperature may increase by around 5 degree or even more in the next 100 years. That will bring more carbon dioxide into the atmosphere and in the subsequent centuries Earth can warm little more. This is a serious issue and demands very detailed analysis. We look at some more examples, the role that radiation in the Earth's climate in the subsequent lectures.

The analysis we give today is very simple one, single layer model which is very limited. We have to account for the variation of the temperature with height in the Earth's atmosphere. That we will take up in the next lecture and show, how that ultimately controls the vertical profile of temperature in the Earth's atmosphere. That analysis required solving the full radiative transfer equation. That is similar to what we did for two parallel plates. That we will take up in the next lecture.