Radiative Heat Transfer

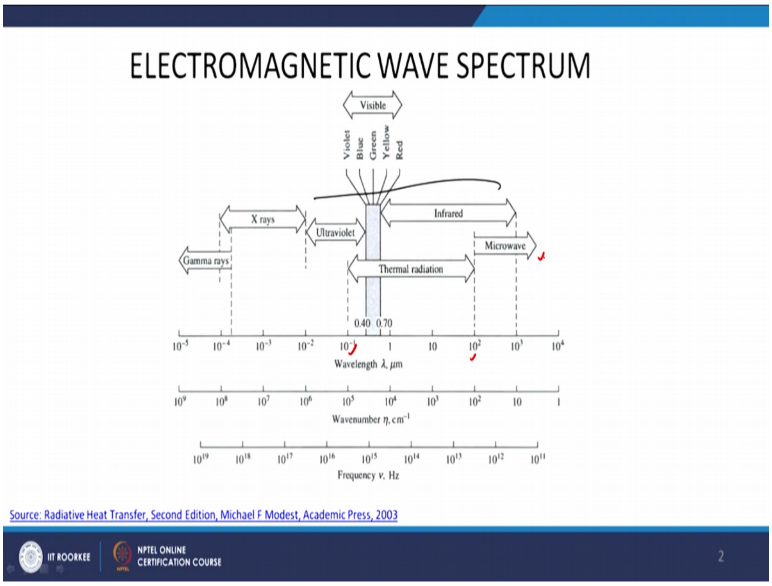
Prof. Ankit Bansal
Department of Mechanical and Industrial Engineering
Indian Institute of Technology - Roorkee

Module - 8
Lecture - 38
Solar and Atmospheric Radiation

Hello friends, in this course on radiative heat transfer, we have almost reached to the end of the course. We have been discussing the applications of radiative heat transfer. In last 2 lectures, we discussed the application of radiative transfer to combustion problems, to flames; how the flame temperature is decided based on the interaction of radiation with a flame. We discussed about the effect of turbulence radiation interaction and many other effects of radiation on the flame, temperature as well as a structure.

In this lecture, we will study an application which is very important from energy point of view. And that is solar energy. We will discuss atmospheric and solar radiation in this lecture. We will highlight the importance of solar radiation into various bands; how the solar radiation is absorbed in the atmosphere; how the aerosols and different gases, they absorb radiation; and what is the overall effect of these effects on energy production by solar photovoltaic cell or solar thermal cells.

(Refer Slide Time: 01:37)

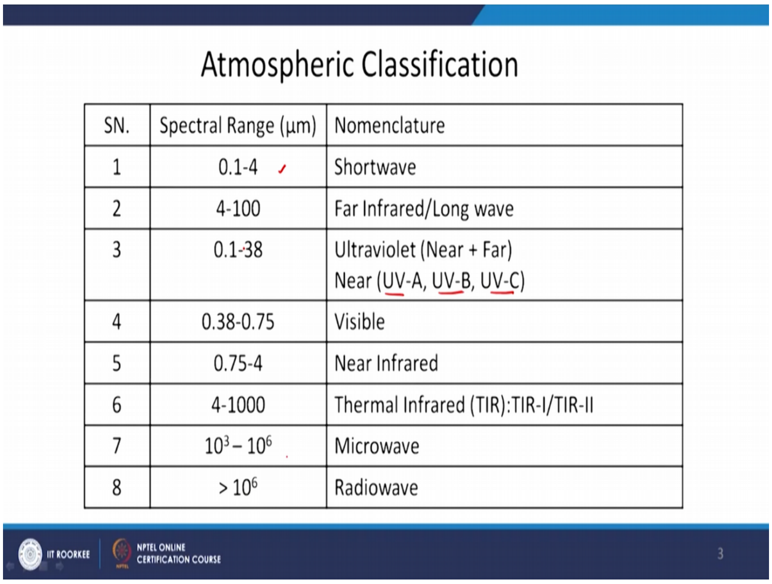


So, first of all, we will go into the basics of solar radiation. Solar radiation and we also have a what we called extraterrestrial radiation. So, it is basically composed of a number of wavelength regions starting from gamma rays, x-rays, we have ultraviolet, thermal radiation, infrared and microwave radiation. So, according to the wavelength or frequency of the radiation, we can divide the spectrum into a number of regions.

Most of the solar energy is basically centered around visible and short infrared region. And some energy is located in thermal infrared. But most of the energy in solar, from sun is limited to these spectral range, the ultraviolet, visible, thermal infrared and far infrared. Now, we will see that from energy point of view, thermal radiation that is in this wavelength range is of a very significance.

We have microwave which is very important in remote sensing. So, different wavelength regions in solar spectrum, they have their own importance. And according to this, they are classified into different regions. We will see how these regions are affected by the atmosphere.

(Refer Slide Time: 03:04)



Atmospheric Classification

SN.	Spectral Range (μm)	Nomenclature
1	0.1-4	Shortwave
2	4-100	Far Infrared/Long wave
3	0.1-38	Ultraviolet (Near + Far) Near (UV-A, UV-B, UV-C)
4	0.38-0.75	Visible
5	0.75-4	Near Infrared
6	4-1000	Thermal Infrared (TIR):TIR-I/TIR-II
7	$10^3 – 10^6$	Microwave
8	$> 10^6$	Radiowave

Now, there is some nomenclature that is popularly used in atmospheric radiation. The radiation, all the radiation, the wavelength intervals are basically represented here in this table in micron micrometer. So, the wavelength region from point 1 micron to 4 micron is basically called shortwave radiation. Now, this shortwave radiation basically comprises of ultraviolet. It comprises of visible and it also comprises of near infrared.

So, this 0.1 to 4 micron wavelength region is called shortwave region. Now, 4 to 100 micron region is called long wave or far infrared region. Now, going into the further division of this spectral region, 0.1 to 0.38. So, this is 0.38. 0.1 to 0.38 is a spectral region which is called ultraviolet. We have near ultraviolet region, we have far ultraviolet region. So, ultraviolet means, with wavelength less than violet. So, we know in the visible region.

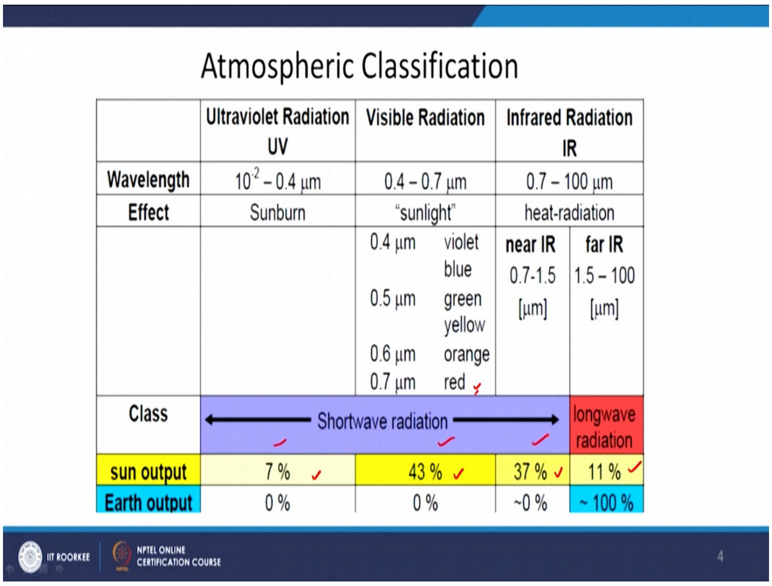
So, normally the radiation is basically, the visible spectrum is taken as a reference. So, the highest frequency or the minimum wavelength in visible region is violet. And highest wavelength and minimum frequency is basically the red. So, we basically designate the solar spectrum in terms of violet and red. So, ultraviolet is basically the wavelength which is less than the violet.

And we have 3 divisions in ultraviolet also UV-A, UV-B and UV-C. So, 3 different spectral regions are basically designated for ultraviolet spectrum. Then we have 0.38 to 0.75 is the visible part. Now, visible part starts from violet, the minimum wavelength is violet. And then, it goes all the way up to red. Red is the highest wavelength in visible. From red, we have infrared. Infrared means, what comes after red.

So, infrared will be the spectrum having wavelength greater than these wavelength of the red region of the visible spectrum. So, 0.75 to 4 is basically called near infrared region. All the spectrum after red is basically infrared. But the infrared is also divided into near and far. So, near infrared is 0.75 to 4 micron and 4 to 1,000 is basically designated as thermal infrared. And in remote sensing, this spectrum is also divided into 2 parts, thermal infrared 1 and thermal infrared 2.

After 1,000, the spectral region is basically the microwave region where many remote sensing applications, they are run. And beyond 10 to the power 6 micron is the radio wave. So, this is how we can classify different spectral regions of the solar spectrum. But the energy distribution of sun is mostly centered around visible and infrared.

(Refer Slide Time: 06:18)



Atmospheric Classification

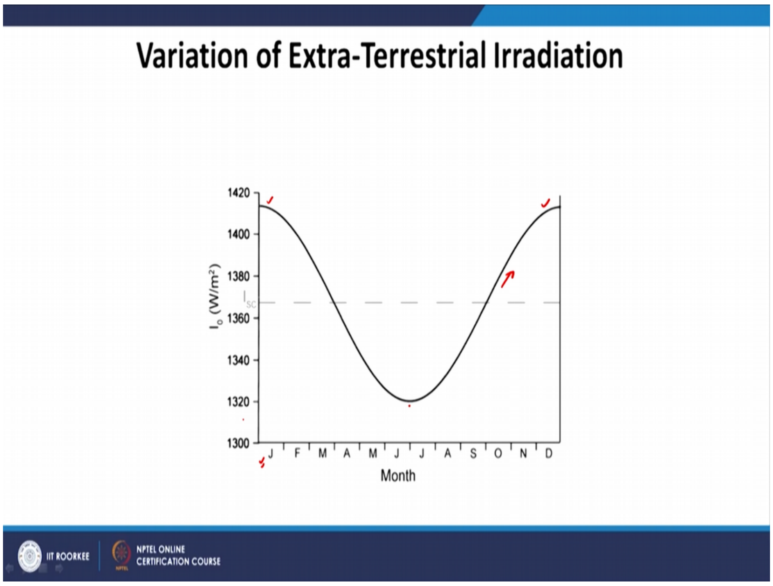
	Ultraviolet Radiation UV	Visible Radiation	Infrared Radiation IR	
Wavelength	10^{-2} – 0.4 μm	0.4 – 0.7 μm	0.7 – 100 μm	
Effect	Sunburn	"sunlight"	heat-radiation	
		0.4 μm violet blue 0.5 μm green yellow 0.6 μm orange 0.7 μm red	near IR 0.7-1.5 [μm]	far IR 1.5 – 100 [μm]
Class	Shortwave radiation			longwave radiation
sun output	7 %	43 %	37 %	11 %
Earth output	0 %	0 %	~0 %	~ 100 %

So, if you look at the content, how much energy is stored in which part of the spectrum. So, we see that 7% of the solar energy is basically in the ultraviolet region, 43% is basically is in the visible region and nearly 37% in infrared near infrared and 11% in far infrared. So, total basically it becomes 48%. So, 48% is in the infrared region, near and far infrared region. And 7% is in the ultraviolet region.

So, ultraviolet region, although the energy content is very small, only 7% but because the wavelength is short, the photons are very energetic. This leads to serious health effects. And we have, there have been studies that link this ultraviolet radiation to skin cancers as well as sunburn. So, ultraviolet radiation is very harmful. And the major gas that absorbs ultraviolet radiation in our atmosphere is ozone.

And we have been listening that many gases, many greenhouse gases, they also basically affect the ozone layer. And due to depletion of ozone layer, there is an increased ultraviolet radiation that is reaching the earth. And this is leading to serious health benefits, health concerns. So, ultraviolet radiation is very serious, although the energy content is just 7%. And 43% is the visible radiation. Starting from violet, blue, green, yellow and up to red. So, this is the visible part of the spectrum. And entire ultraviolet, visible and near infrared is called shortwave radiation.

(Refer Slide Time: 08:05)



Now, we see that, how the solar radiation basically reaches earth. On top of the earth's atmosphere. So, basically when we look at this radiation coming from sun, the radiation from the sun, we assume that the sun behaves like a black body. The temperature of the sun is around 5700 kelvin, 5700 to 5800 kelvin. That is the temperature of the sun surface. And at that temperature sun behaves just like a black body.

And this intensity emitted by sun is also black body intensity given by the Planck function. If we integrate this intensity, we get sigma T power 4, that is emissive power of the sun is = sigma T to the power 4 where sigma is the Boltzmann, Stefan Boltzmann constant. Now, this radiation emitted from the sun, it reaches the outer atmosphere of the earth without any change in intensity. So, the intensity is not affected.

When the radiation leaves the earth sun surface and when it reaches earth's outer atmosphere, the radiation intensity is not affected, because there is no medium in between. However, once it enters the earth's atmosphere, it is subjected to absorption, scattering and many other phenomena, because of the presence of gases and particles in earth's atmosphere. So, let us look at how the integrated intensity, that is the emissive power looks like in the outer earth's atmosphere.

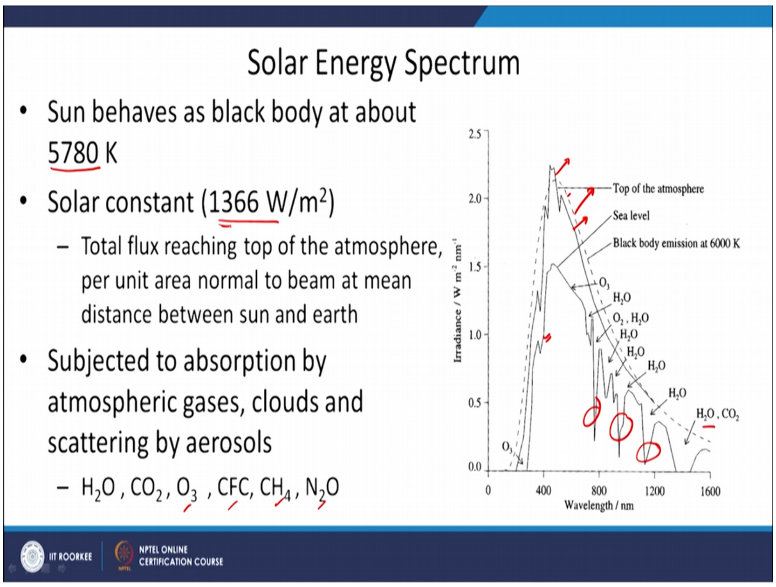
So, this is the variation of extraterrestrial. So, extraterrestrial means outside the earth's territory, outside the earth's atmosphere. And this is called solar constant. That means, total energy received from the sun. So, this is integrated over all the wavelengths. And we have what we called the solar constant. It varies from season to season. This particular figure is for the southern hemisphere.

This is for a location in South hemisphere. South hemisphere means, not, we are talking about the atmosphere, but this point is basically located in a region which is away from the sun. So, we know the sun's earth's axis is tilted. So, some points will be near to the sun and some points will be away from the sun. Those points which are near to the sun, they will have summer and they will see higher solar constant in the summer.

So, what I mean here is that, this radiation constant is plotted for a point which is seeing summer in the month of January. In our country, we see low solar constant in January. But this is for a location which basically sees higher solar constant in January. So, the solar constant goes the highest value in January, near January. And then, it goes to a low value in June. And then again it rises. So, there is a continuous variation of solar constant.

That means, the amount of radiation received in the outer atmosphere, that is extraterrestrial region. It goes from the highest value of around 1420, 1415 to a lower value of 1320. So, there is roughly a difference of 100 watt per meter square. And this difference of 100 watt meter per meter square, basically gives you the variation in temperature that we see in summers and winters. So, just a 10, just a difference of 100 watt per meter square makes a difference in seasons in summer and winter temperatures.

(Refer Slide Time: 11:53)



Now, how the spectrum looks like, how the variation looks like when this same radiation enters the atmosphere. And this figure of irradiation at any point on the surface of the earth, we have seen it earlier also. So, we have 3 different curves here. 1 is basically the black body intensity. The second one is extraterrestrial radiation. And third one is basically the terrestrial radiation, that is radiation received at the earth surface.

So, black body radiation is smooth function given by Planck function at a temperature of 5780 kelvin at which we assume that sun is a black body at a temperature of around 5780 kelvin. And we have solar constant, average solar constant. We have seen that solar constant varies from season to season, from winter to summer. But an average value is 1366 watt per meter square.

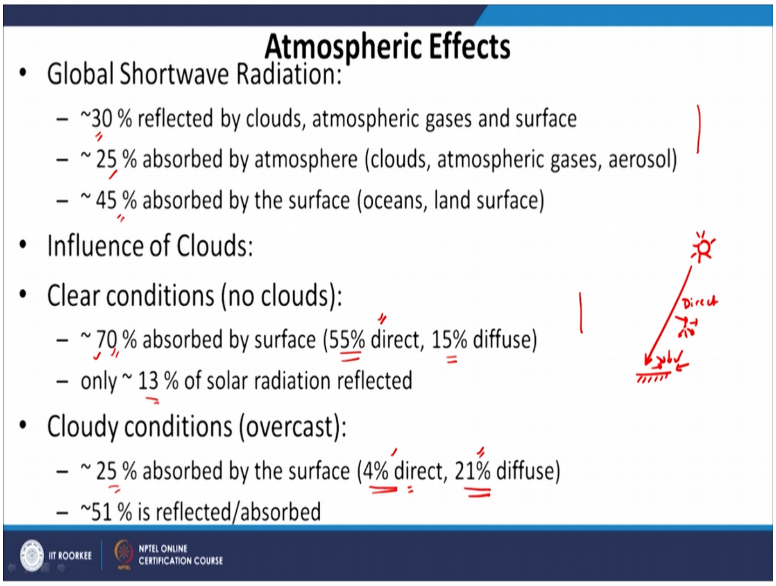
And if you look at the extraterrestrial radiation, top of the atmosphere radiation, it pretty much is equivalent to the black body intensity function. That means, it is not a perfect black body function, but the solar spectrum behaves very much like a black body. And the agreement is relatively good. Okay. So, we see that this curve, top of the atmosphere radiation, matches pretty well with the solar spectrum, the black body function.

And that is why the sun is assumed to behave like a black body. However, when we go to a point in the atmosphere, we see that the radiation, this curve is very much affected by the absorption and scattering by the gases. The main gases that basically affect are water vapor and carbon dioxide. But there are other gases like ozone, chlorofluorocarbons, methane, N 2 and other gases.

So, the gas, the these gases basically significantly affect the intensity of radiation. So, radiation coming from the sun is subjected to absorption by atmospheric gases and also by clouds and aerosol particles. And what we see is, there is a continuous absorption. And absorption is more in certain bands, while absorption is less outside these bands. So, in certain bands, the gases absorb significant amount of solar radiation.

So, at the earth surface, we see lot of reduction. So, we do not get 1366 watt per meter square. This 1366 watt per meter square, we get on top of the atmosphere, if we are outside the earth's atmosphere. But at the earth surface, this radiation is subjected to absorption and scattering. And we get significantly less than this value.

(Refer Slide Time: 14:39)



So, how basically this values are affected? The first one is basically the average values. The second one we have is basically the influence of cloud in clear conditions and cloudy conditions. So, let me just first tell you how the clouds basically affect. If there is no cloud, then, almost 70% of the radiation will reach earth surface. So, if there is no cloud, only the water vapor and carbon dioxide in the atmosphere will absorb solar radiation.

So, there will be still some reduction. And the values will be roughly 70% reaching the earth surface. 50% will be direct radiation and 15% will be diffuse radiation. What is direct and diffuse radiation? We will discuss in the coming slide. So, total amount energy received at the earth surface is basically 70%, if there is a clear sky condition. And this value is going to be much less if there is a, if there are clouds.

So, under clear conditions, only 30%, 13% of energy is basically reflected. And this reflection may be due to the presence of gases, water, aerosols, carbon dioxide. So, the gases are not very good reflector. But still 13% of this energy is reflected back. If there are clouds, then we see that only 25% energy is basically reaching earth surface. So, there is a significant reduction in amount of solar energy reaching earth surface because large amount of energy is reflected or absorbed by clouds.

And we see that, there is a 4% only direct radiation. So, direct radiation is significantly reduced, 55% in clear conditions to 4% only in direct conditions. So, direct component of the solar radiation is affected much, while the diffuse component is increased. What happens when there is a cloud, the clouds scatter radiation and the diffuse component is basically the scattered component.

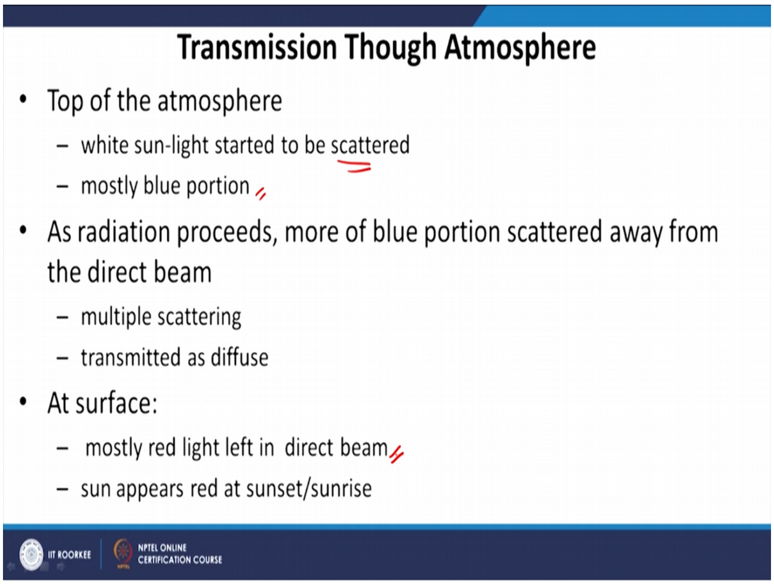
So, let us say we are standing here on a surface. The direct component; and this is sun. So, direct component is the radiation coming directly from sun, while the diffuse component; So, this is direct. And the diffuse component is coming from the sky, from all directions. This is diffuse. So, this may be coming from the scattering, so some radiation may have scattered here. And then, after multiple scattering, the radiation may reach earth surface.

This is called diffuse radiation. Diffuse radiation means that radiation is reaching earth surface after undergoing multiple scattering in the atmosphere. So, we see that the scattering; because, in the presence of cloud, the scattering might increase. So, we see an increase in diffuse component. But there is a significant reduction in the direct component of solar radiation due to the presence of clouds.

The average effect is basically 30% of the energy is reflected by clouds, atmosphere atmospheric gases and the surface. 25% of the energy is absorbed by the atmosphere. So, roughly 55% of the energy of the sun is lost in the atmosphere either due to absorption or due to reflection. And some energy is basically reaching 45% is of the energy. So, half of the energy is basically reaching the earth surface.

So, this is an average value. It includes the days where clouds are there. It also includes the days where clouds are not there. So, on an average, 45% of the energy is basically reaching the earth surface either ocean or land surface.

(Refer Slide Time: 18:12)



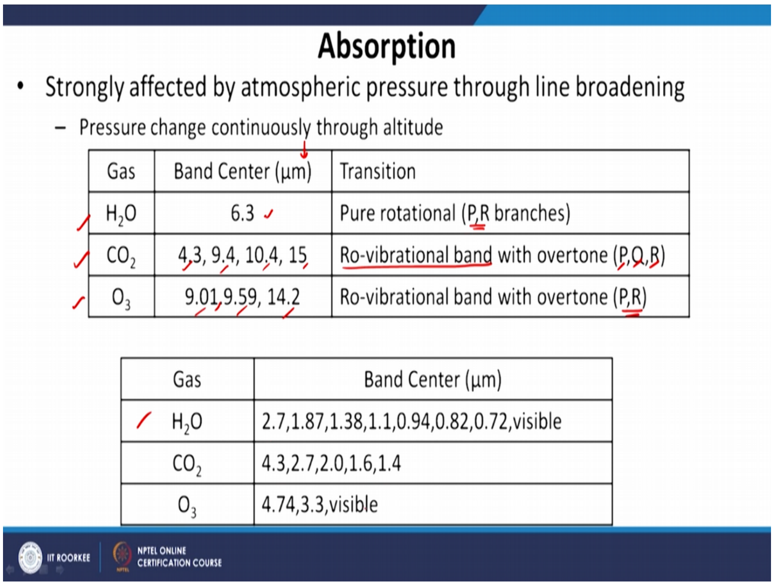
Now, how the transmission of solar radiation is basically being affected? So, let us look at a closer view of that. So, radiation reaches on top of the atmosphere, the intensity is not affected. The intensity is same as it was at the surface of the sun. Now, once it starts entering the earth's atmosphere, it undergoes scattering. On top of the atmosphere, intensity is not affected. But as it enters the atmosphere, it undergoes scattering.

And we have seen in an, one of the previous lectures on particles, it is the blue light that scatters the most, because of the Mie scattering which is inversely proportional to wavelength. We have seen in earlier lecture that the blue light scatters the most. And by the time radiation reaches earth surface, most of the blue light has been scattered out. And only radiation that we reaches directly the earth surface may be just red.

So, the sky color is blue, because most of the blue radiation from the sun has been scattered out in the atmosphere due to multiple scattering. So, we have only the red being. So, whatever we are getting directly from the sun may contain only the red part of the radiation. And that is basically the reason why we see sky to be red during evenings and in the early morning hours. Because in the early evening, in the early morning and evening hours, radiation penetrates at deeper angle.

Most of the blue radiation and other radiation components have been scattered out. Only the red component is remain, remaining in the earth solar radiation. And that radiation, the red part of the spectrum of the sun reaches directly to us and we see that the sky appears red during sunset and sunrise.

(Refer Slide Time: 19:58)



So, there are various bands that affect solar radiation. I have listed here, some of the important visible and infrared bands here. So, we have, these are basically bands in near infrared and far infrared. So, most of the gases that basically scatter and absorb radiation are basically water vapor and carbon dioxide and some amount of ozone. Ozone does not, we have already seen that the solar energy is very less in ultraviolet, but still it is very harmful.

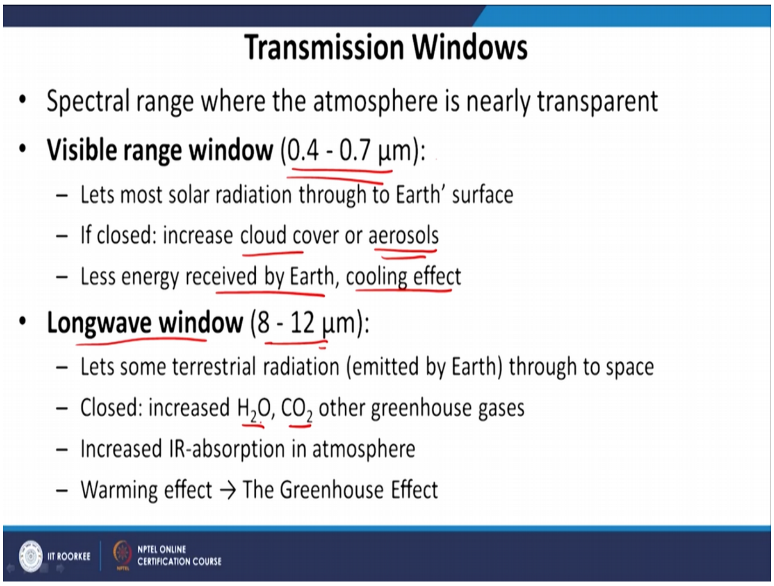
So, ozone is important gas in the atmosphere. Because it filters out harmful ultraviolet radiation. There are many bands. So, what I have listed here in the second column is basically the band center. While discussing the radiative properties of gases, we discussed that molecular gases have what we called Ro-vibrational bands. So, molecular gases have Ro-vibrational bands. And they have branches of P, Q and R branches.

Some gases, they do not have Q-branch. The Q-branch may be missing. For example, ozone does not have a Q-branch. H 2 O also does not have a Q-branch. So, we have already studied this. What are the Ro-vibrational bands? What are the P-branch, Q-branch and R-branch? So, water vapor has a strong band. So, there are many bands. What I have listed here is the strongest bands.

So, 6.3 micron. So, there is a strong band. So, water vapor absorbs strong solar radiation in 6.3 micron band. C O 2 has many bands in 4.3, 9.4, 10.4, 15. So, these are 4 bands in which, in near infrared. We also have bands in ozone. So, 9.01, 9.59, 14.2. So, all these are important bands. They absorb significant amount of solar radiation. Again, we have in ultraviolet and visible, this is the water table is for the ultraviolet and visible.

We have many bands in water vapor. And we have, there are many bands in carbon dioxide and ozone. So, when we are discussing radiative transfer; if we have to find out radiative transfer in atmosphere, we have to take into account absorption by these gases, all these gases and all these bands. So, we see that the analysis of or solving a radiative transfer equation through an atmosphere, is not an easy task. Because we have to account for absorption across multiple spectral bands.

(Refer Slide Time: 22:30)



So, there are bands which absorb significant amount of solar radiation. But there are windows also, through which solar radiation is penetrated and it does not get absorbed in the atmosphere. So, window, here spectral window means, wavelength regions where solar radiation is not absorbed. And there are specifically 2 windows in the atmosphere. The first window is visible window, through which most of the visible radiation is basically coming to our surface.

So, for 0.4 to 0.7 micron, that is the region where we have visible part of the solar radiation. And in this range, 0.4 to 0.7 micron, we have a window. Very less amount of energy is absorbed. And most of the radiation basically reaches earth surface. If this window is closed; and how can this window be closed? This window gets closed when there are clouds. So, clouds absorb significant amount of visible radiation.

We have seen, when there are clouds, there is a poor visibility. Sometimes, the clouds may be black and we get complete dark in even in the days. Then again aerosols may be there. We have also seen that, there, when there are significant dust in the atmosphere, lot of visible radiation is absorbed and we have poor visibility. So, cloud cover and aerosols can close this window.

Although this closing may not be permanent, but sometimes the this could be permanent also. There are number of studies which have identified a brown haze clouds over the Bengal sea. So, this pollution may leads to some permanent feature in the formation of aerosols at, in certain locations. What these window closing basically imply on our atmosphere? When the window is closed, definitely the visible radiation is absorbed in the clouds and aerosols.

And we get less amount of radiation. And we get a cooling effect. So, if lot of dust is deposited in our atmosphere, the temperature of this earth will basically decrease. So, it will have a cooling effect. The other window is longwave window in 8 to 12 micron region. Now, 8 to 12 micron region, this spectral region is important because earth emits radiation in this wavelength region.

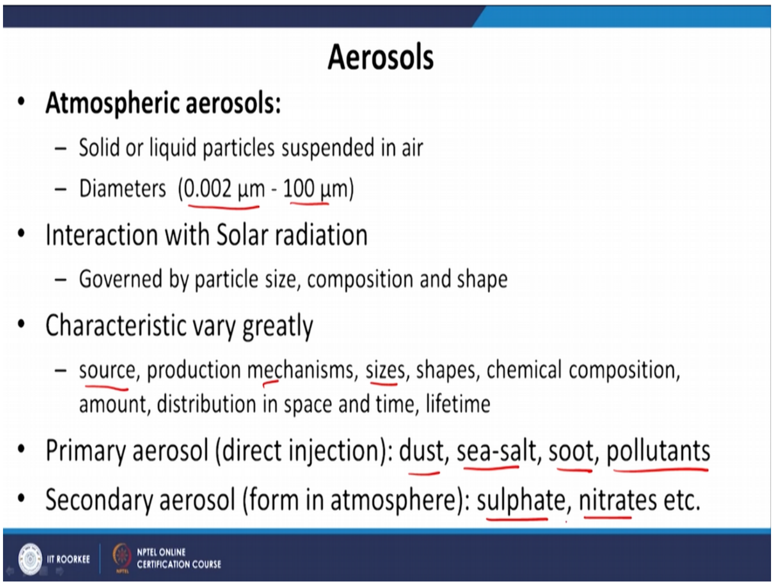
So, earth is also, you can approximate earth also like a black body, but at a much low temperature. So, temperature of the earth will be very low, around 300 kelvin. So, the temperature of the earth will be very low. The average temperature of earth will be very low. But still you can approximate it like a black body. The most of the radiation emitted from the sun is, from the earth is in the 8 to 12 micron region.

And if this window is there, then this radiation basically escapes from the atmosphere and it is basically vented out into the atmosphere. So, this is a way of cooling the earth surface. We get lot of radiation in summers from the sun. And in the night, this radiation basically is emitted out into the atmosphere. If this window is closed, what will happen? We will have what we called greenhouse effect.

If this window is closed, then the emission from the earth basically is reflected back or it is trapped in the atmosphere. It is not allowed to basically vented out in the extraterrestrial region. And what can basically close this window? The greenhouse gases like C O 2, methane and water vapor also. So, these gases basically when deposited in the atmosphere, they absorb significant amount of radiation emitted from the earth and this leads to what we called greenhouse effect.

And the consequence is warming of the, from, of the earth. And this is what we are seeing today. We are seeing lot of pollutants, lot of greenhouse gases in the atmosphere, which leads to what we called warming of the, also called global warming.

(Refer Slide Time: 26:29)



Other than gases, we have aerosols. Now, what are aerosols? Aerosols are solid or liquid particles suspended in air. They are very fine particles. The diameter of these particles may be 0.002 micron to 100 micron. Some particles may be small, some particle may be large. It depends where these particles are coming from. These particles may come from ocean, they these particles may come with desert dust.

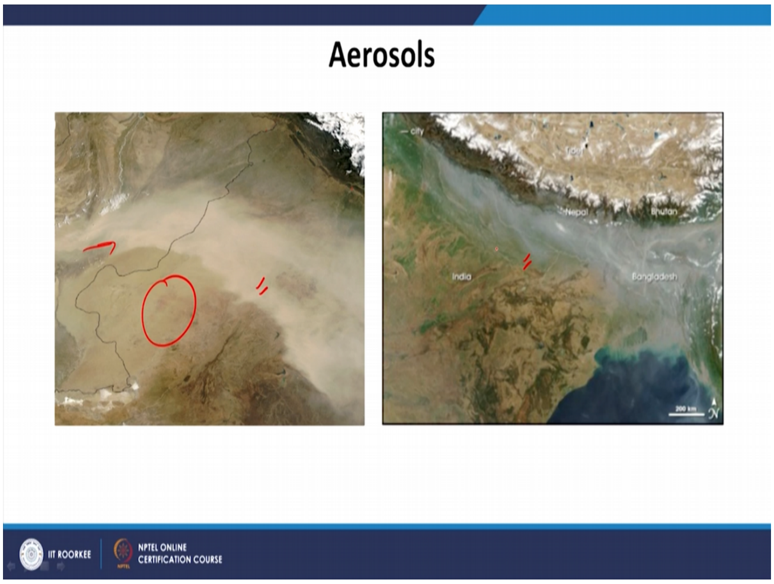
So, we have to basically look for the source. If we want to characterize the aerosols, we have to look for their source. What is the production mechanism? Is it a dust storm or in monsoon we have lot of moisture that comes from the oceans. We also have to look for size, the composition, shape, chemical composition. The dust of the Rajasthan may have different composition.

Sometimes, we get dust from the desert of Iran also. So, these different type of aerosols may come in our atmosphere from far regions also. So, we have to look for the shape, size, chemical composition, amount and the distribution if you want to understand how these particles, how these aerosols are affecting our atmosphere. So, we have 2 types of aerosol, primary aerosol and secondary aerosols.

Primary aerosols are basically the particles that are directly injected into the atmosphere, such as sea salt, soot, pollutants and dust. These are primary aerosols. Then we have secondary aerosols which are not injected into the atmosphere. Rather they are synthesized or they basically form in the atmosphere itself. These are like sulphates and nitrates. So, we inject lot of gases like sulphur dioxide, nitric oxide into the atmosphere.

And these gases basically react with other gases and they form what we call salts like sulphates and nitrates in the atmosphere itself. So, aerosols play an important role in deciding the temperature, in deciding the amount of radiation that is reaching the earth surface.

(Refer Slide Time: 28:29)



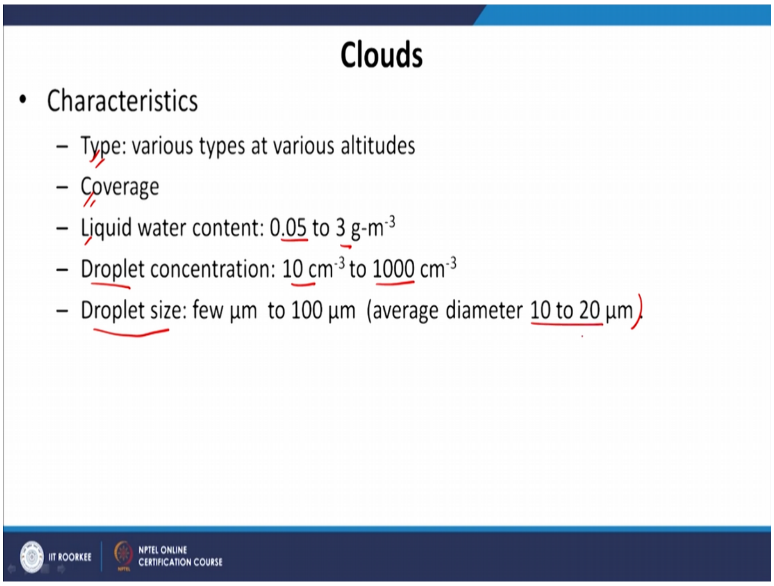
So, in this picture taken from the satellite, what you see is basically the aerosol cloud over the regions of Punjab and Haryana. We have what we call aerosol cloud here. It seems, the origin of this cloud, aerosol cloud is not over Rajasthan. Rajasthan is here. It seems this is coming from Iran. So, we see that these aerosol clouds can come from far distance also. Now, in the picture on the red, right side you see basically a haze, again this is a aerosols only, over the Gangetic plains of Uttar Pradesh.

So, you see that, there is lot of haze or aerosols. And these aerosol clouds will certainly affect the solar radiation in a big way. So, after gases in the atmosphere, after clouds, after gases and aerosols, the major component in the atmosphere that affects solar radiation is clouds.

And clouds can be of different types depending on the altitude. So, at different altitudes we have different type of clouds.

The clouds have different characteristic. Some are made of fine liquid water. Some may have even ice crystals. So, different type of clouds exist. And they absorb radiation in different bands. So, understanding these type of clouds, again it is a very complex task. Here we will not try to solve how the clouds basically absorb solar radiation. But, what are the major parameters that govern solar radiation and cloud interaction is, type of clouds.

(Refer Slide Time: 30:06)

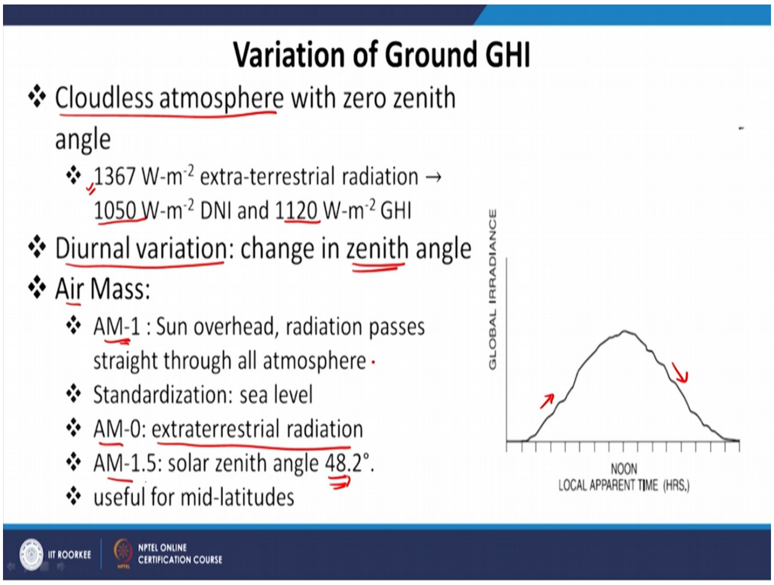


There may be different type of clouds. The coverage of the clouds; whether it is continuous cloud or a broken cloud. Then, what is the liquid water content in the cloud. Normally, it ranges from 0.05 to 3 gram per meter cube. So, we have to talk about the liquid water content. What is the size of the droplets in the cloud? It ranges from 10 per centimeter cube to 1000 per centimeter cube.

So, how much droplets are present in the cloud. That decides how thick or how thin the cloud is. And based on this thickness, it will absorb solar radiation. Then droplet size also is an important parameter. It ranges from few micron to 100 of micron. The average diameter of the droplets will be around 10 to 20. But some droplets may be very small. And these droplets will definitely go under Mie scattering.

And some droplets may be large. So, clouds in itself is a complicated phenomena that affects solar radiation. And it is a major factor in attenuation of solar radiation. And many models have been developed to classify the clouds.

(Refer Slide Time: 31:13)



Now, how these clouds, these gases and aerosols affect solar radiation at the ground. So, we just take extraterrestrial radiation is 1367 watt per meter square. We discussed this in the previous slide. So, around 1367 watt per meter square is the extraterrestrial radiation reaching outer atmosphere. And when it penetrates through earth atmosphere, there may be cloud there may not be cloud.

If there is no cloud, then we see that, on a clear day, on a cloudless day, we reach, we get 100 and; sorry 1050 watt per meter square DNI and 1120 GHI. So, on a clear day also, there is a significant reduction, around 30% reduction in radiation reaching earth surface on a clear sky day. And when there is a clear sky day, this may be further reduced by 50%. So, the radiation value will significantly decrease.

So, other than this gases, clouds and aerosols, there is a natural dependence of atmosphere that affects radiation. The main is the diurnal variation. Diurnal variation is basically the change in radiation value from morning to the evening. So, we see that the radiation which is maximum in the noon and then it decreases in the evening and it rises in the morning. So, this is called diurnal variation.

And why it basically varies with time, because the change in zenith angle. So, the zenith angle basically we will discuss in the next slides. Zenith angle basically decides the direction of sun with respect to a location. So, sun is directly overhead at noon, while it is at an angle when it is before noon or afternoon, it is at an angle. And the amount of radiation received from sun will be less than its value at the noon.

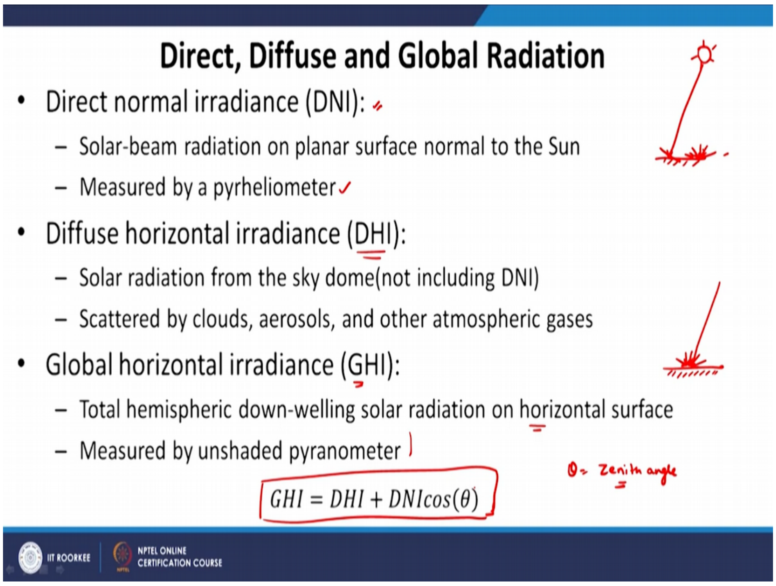
So, that is called diurnal variation. Then there is air mass. When the sun is directly above us, it has to travel a short path. So, that path is basically called AM-1, okay, air mass 1. That means; what is air mass? Air mass is basically defined as amount of atmosphere the solar radiation has to penetrate through. If we are at top of the atmosphere, the solar radiation does not has to penetrate through any atmosphere. We call it AM-0.

So, extraterrestrial radiation is called basically AM-0 or air mass 0. That is top of the atmosphere radiation. Air mass 1 is basically radiation when sun is directly overhead and the path is shortest. Then we have; any other angle, any other zenith angle, we may have different air mass. Of this air mass 1.5 is very important in solar radiation studies. Air mass 1.5 is very important. And it is at a zenith angle of 48.2 degree.

This has been taken importance in many solar radiation application because, at many mid-latitudes, we have air mass 1.5. And for solar radiation studies, air mass 1.5 is very important. So, air mass is an important parameter that affects solar radiation. And many solar projects are basically designed by taking air mass 1.5 into account. And this is very important parameter.

Now, let us go into the details of solar radiation. How the solar energy is contributed to power. There are 2 components of solar energy that basically we receive at the earth surface. The direct component;

(Refer Slide Time: 34:53)



So, we have sun and we have a surface. So, there is a direct component. This direct component definitely change with the inclination of sun. It depends on zenith angle. And then, there is a diffuse component. Basically, radiation coming from all the direction, that is diffuse. There is not much effect of diffuse radiation by the zenith angle. So, direct solar radiation, direct normal irradiance is called basically the beam radiation.

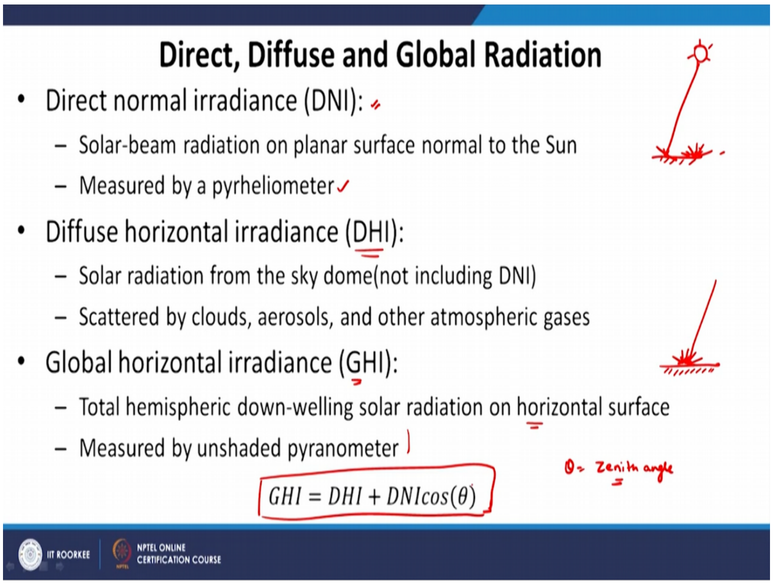
And it is basically specified on a plane surface normal to the sun. So, we see that normal to the sun, it depends on the inclination of the sun. And it is measured by a device called pyrheliometer. Then, there is a diffuse component DHI, which basically is a result of scattering by the constituents of the atmosphere like clouds, gases, aerosols. So, all these components of the atmosphere, they scatter radiation.

And this scattered radiation basically reaches at the earth surface from all directions. We call it basically the direct horizontal irradiance. Then, we combine the DNI and DHI. So, total component reaching the earth surface has contribution from direct component as well as the diffuse component. And the total component is called global horizontal irradiance. It is basically, total hemispherical down-welling solar radiation on horizontal surface.

So, if we have a horizontal surface, what is the total amount of radiation reaching on this directly as well as through diffuse means. And we write GHI as = DHI + DNI cos theta, where theta is the zenith angle. So, theta is the angle which basically that gives you how the sun is oriented with respect to this earth surface. And this is measured by a device called pyranometer. So, we have solar zenith angle depends on 3 important parameters.

So, solar zenith angle basically gives you an idea of how the sun is oriented with respect to a particular location. So, this location will vary from latitude to latitude. So, the first parameter that decides the zenith angle is the latitude.

(Refer Slide Time: 37:08)



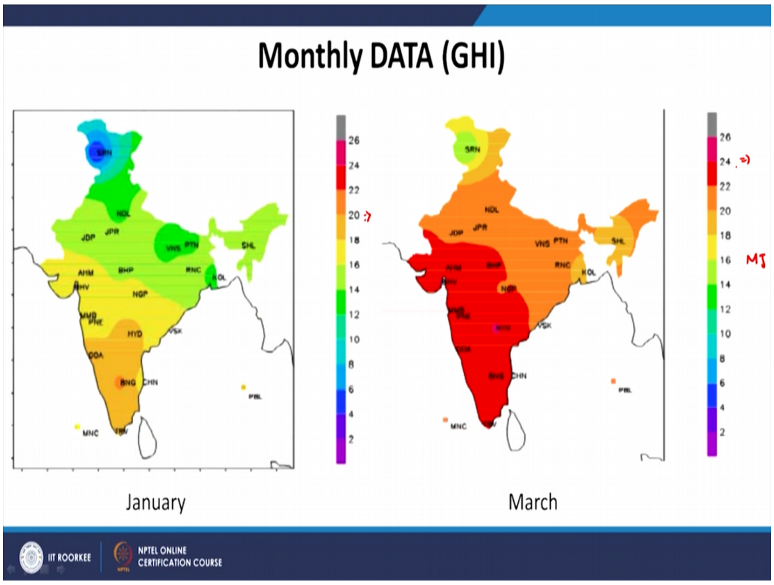
At higher latitude, we have a higher inclination. On the equator, we have least inclination. So, we get more solar energy at the equator and less energy at the poles. The second angle is the solar inclination angle. It varies from season to season. We have seen this. So, this will affect radiation in the extraterrestrial atmosphere also. We get more radiation in summers in our country and we get less radiation in winters.

So, that basically depends on the season to season. And it depends on local time also. So, we get more radiation at the noon and less radiation in the evening and the morning hours. So, the relation between solar zenith angle theta and latitude angle phi and inclination angle delta and local time h is given by this relation; cos theta is = sin phi sin delta cos phi + cos phi cos delta cos h. Okay.

Now, if we look at the amount of radiation, let us say in New Delhi which has latitude 28.6 North at noon. That means, h is = 0. If you look at the radiation values or the zenith angle values; the delta is 84 degree in June, roughly an idea. The inclination angle of earth is 84 degree in the month of June. And delta is 38 degree in December. So, we get zenith angle of 61.5 degree in New Delhi in June.

And we get a zenith angle of 72.85 degree in December. So, this is for New Delhi in June and December at a time 12 in the noon. So, 12 noon, at this point, this is going to zenith angle. And by this zenith angle, you can calculate the values of GHI using this relation.

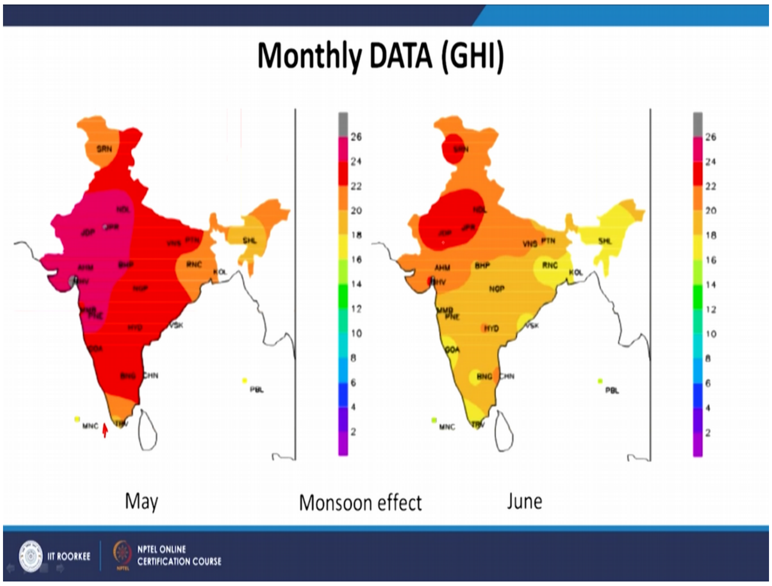
(Refer Slide Time: 39:07)



So, let us just look at the data. This data is taken from a MNRE Ministry of non-renewable energy. So, what this data basically shows you is the monthly averaged; oh sorry, monthly integrated values of GHI in a the units of megajoule. So, this is give you the megajoule of energy. Total amount of solar energy received on a surface located all over India. In the month of January, we have a very less amount of radiation. Okay.

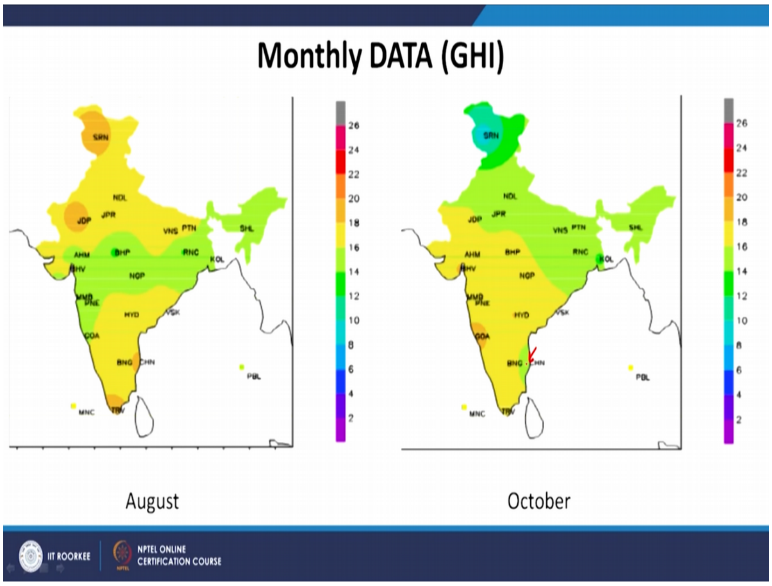
The maximum radiation is in the South India, which is reaching around 20 megajoule. Now, as we go towards March, the summers are basically closing in. And we see that there is a significant amount of a radiation increase. And this almost reaches to 24 megajoule in the most of, most parts of the Western and Southern India. While still we have a less amount of radiation. But the radiation in the Northern part also has increased significantly in the month of March.

(Refer Slide Time: 40:20)



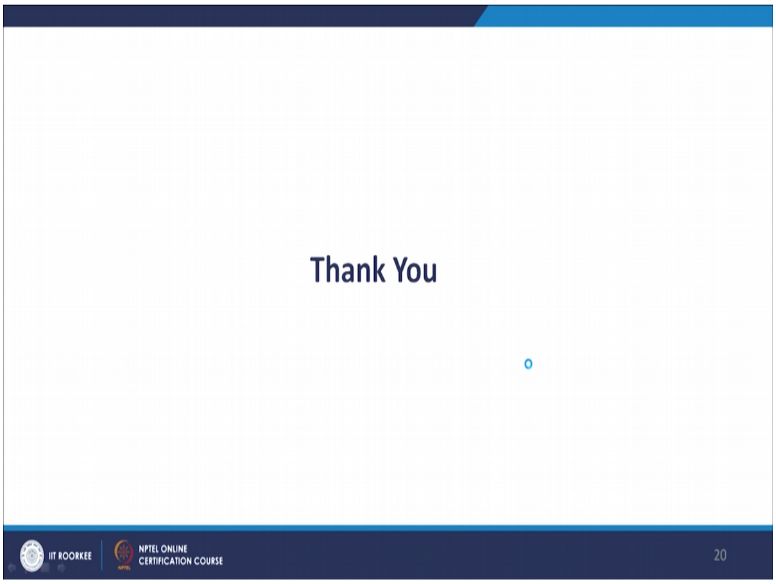
Now, going towards the May. In the May the monsoon activity starts on the coast of the Kerala. So, we see that the radiation values have started decreasing because of the monsoon activity. Because lot of clouds forming in and lot of moisture coming in on the land mass. So, we see, there is a decrease in radiation, on the tip of South India. Now, as we move towards June, most of the India is now under the influence of monsoon. And we see significant reduction in GHI values, except at certain locations in the North Western India, where the radiation values are still very high.

(Refer Slide Time: 41:07)



And then again, moving towards August. In August we have entire India engulfed in monsoon clouds. So, the radiation values have significantly reduced. And in October; October basically we have a combination of winter approaching, as well as the some cloud activity. So, especially, we have cloud activity which is in the Western coast of, sorry eastern coast of India due to retreating monsoon. And we see a reduction in GHI values here.

(Refer Slide Time: 41:43)



So, here in this lecture we discussed some basics of solar radiation and how the solar radiation is affected by our atmosphere. And the various activities like clouds aerosols and seasonal activities like monsoon, they affect solar radiation in a big way. And if you want to develop any power plant based on solar energy, we must take into account the local weather, the local factors that govern the absorption of solar energy in the atmosphere.

So, thank you for your kind attention. In the next lecture, we will study some applications of solar energy and how a power plant is basically made or designed based on the solar energy received at that location. So, thank you.