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

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PRINCIPLES OF ELECTROMAGNETIC RADIATION SPECTRAL INTENSITY, IRRADIANCE, AND MATERIAL INTERACTIONS

Good morning class and welcome to our continuing coverage on climate dynamics, climate variability and climate monitoring. In the previous class, we started our discussion on understanding the electromagnetic spectrum in a little bit more detail and eventually going into how to model radiative transfers that are going on in our planetary atmosphere. As we said, electromagnetic waves or electromagnetic radiation is basically waves of different wavelengths. Based on the wavelength and the corresponding frequency, we call them by different names. For example, radio waves are waves with a wavelength of the order of a kilometer or more, whereas gamma rays are extremely short wavelength waves with wavelengths of order of 10 to the power minus 12 meters. Frequency of electromagnetic waves is inversely proportional to its wavelength with the proportionality constant being the speed of light in vacuum.

Hence, small wavelengths correspond to high frequencies where frequency is measured in second inverse or Hertz. We also said that electromagnetic waves carry energy in discrete wave packets called photons and the energy of these photons is proportional to its frequency nu with the proportionality constant being the Planck constant which is 6.6 into 24 minus 34 joule seconds.

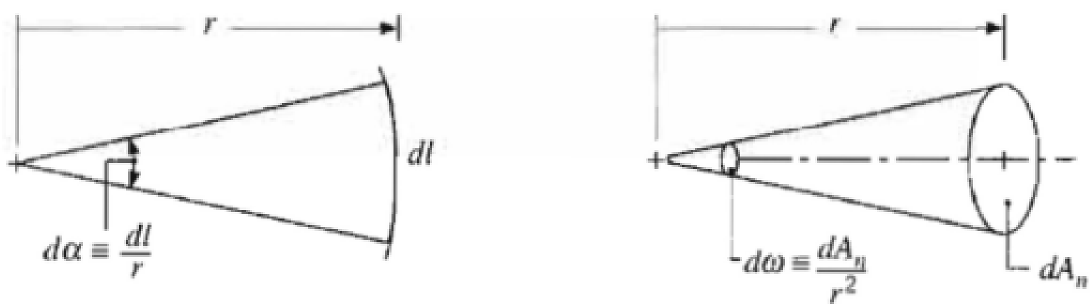
$$v = \frac{c}{\lambda}\ s^{-1}\ or\ Hz$$

Now that we understand what radiation is, a type of electromagnetic wave, let us discuss how we can understand various ways to quantify the amount of radiation that is being emitted by a body or that is being, that is coming towards or incident on a body.

Firstly, radiation is directional in nature, that it is coming from some place and going towards some place. So there may be radiation coming from one side of the sky may be different, corresponding radiation coming from another side of the sky. And in general, any emitter may also have a directional dependency of radiation. So if you see a light bulb, there may be places where the radiation is being emitted more strongly than in other places. So there may be a directional dependence on both incident radiation and emitted radiation.

To take care of this directionality in three-dimensional, we introduce the concept of a solid angle. A solid angle is the three-dimensional analog of the plane angle in 2D. So, for example, suppose you take a circle, then the plane angle is defined as the angle between two chords connecting the center of the circle with the circumference of this circle. And how is this angle value defined? In radians which is the traditional default unit that we will be using, it is defined as the length of the circumference that is the arc that is subscribed by these two chords divided by the radius of this circle. So, if dl is the arc length between these two radiuses hitting the circumference and r is the length of the radius of this circle, then the angle between these two radii is this chord length l by r in differential form.

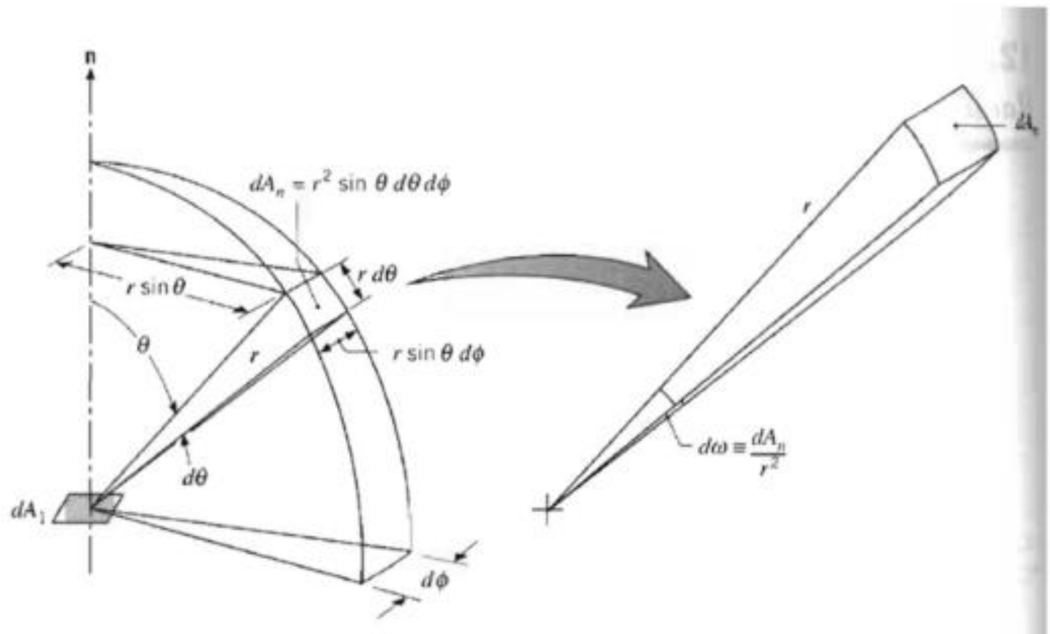
$$d\omega = \frac{dA_n}{r^2}\ Sr\ (Steradians) \quad (66)$$



This expression is valid when we are taking very small angles. So, this is a differential distance between, so these two radials are enclosing a very small angle, so differential angle and this chord length is also very small. So, d alpha, the differential angle between these two radiuses is equals to the differential chord length by the radius and this is the differential definition of angle in radians. and then we can integrate this from 0 to 2 pi radians to get the total angle or whatever the actual chord lengths are alright. A similar method is also done for the case of a solid angle, but instead of a circle we take a sphere ok.

So, here we have two rays that are hitting the circumference of this sphere at two points and there is a conical circle that is inscribed on this sphere. So, we have a ray that is subscribing a conical region which is separating out a part of the spherical surface from the other parts. So, this conical this cone circum subscribes a circle on the surface of the sphere and the spherical differential spherical area within this circular cone length at the circumference of the sphere has a differential area dAn, ok. And this differential area divided by the radius of this sphere is the solid angle which is whose unit is the square of the radius of the sphere, not simply the radius. The square of the radius of the sphere is the solid angle and its unit is stay radians.

$$d\omega = sin\theta d\theta d\phi \quad (67)$$



The unit of plane angle is radians, the unit of solid angle is stay radians. In spherical coordinate system, evaluating the solid angle is particularly easy. So, this is a, so again if we take a sphere and suppose this is the center of the sphere, there is, there are two angles that we define in spherical coordinate systems. The first angle, so we take, so suppose this is one axis from the center of the sphere going upwards, you can think of this similar to the axis of the earth. and there is one angle between this vertical axis and the radius which is connecting the center with the spherical area we are interested in.

So, this is the spherical area we are interested in, this is the radius r and the angle between the vertical axis and this radius r is the zenith angle or theta. Now, this radius r if you go down, along this meridian so there is a meridian which is hitting this point and this meridian will go down towards the equatorial circle so here we have the equatorial circle so this meridian will hit the equatorial circle somewhere and then the azimuthal angle phi is the angle between this point and a chosen equatorial plane. So, there is one line here and another line here and the angle between that line and the meridian where it hits the equatorial circle is phi which is the azimuthal angle phi and the angle between the vertical axis and this radius here is the zenith angle theta. So, if you see the analogy between how we define the latitude angles and longitude angles for earth, the zenith angle is basically 90 degrees minus the latitude angle. So, remember the latitude angle is the angle from the equatorial plane to this radius, whereas the zenith angle is the angle between the axis and this radius, ok.

These two together makes 90 degrees. So, the latitude angle for earth is basically 90 minus the zenith angle. And the azimuthal angle is basically the meridional angle, but here instead of 0 to plus 180 and 0 to minus 180, we go only one way 0 to 360. Then this differential area, so if this is R. fitting here and we make a small angle d theta in this direction and d phi in this direction.

So, we have two meridians like this and two latitudes like this. very close to each other. So, here is one R, here is one R, there is a small change in angle between one latitude and another latitude given by d theta and similarly small angle change between this meridian and this meridian given as d phi and there is a small area on the surface of this sphere which is defined by this almost square shape and this becomes more and more like a rectangular shape. The smaller is this differential angle d theta and d phi. So, at the limit this becomes just like a rectangle and its area would be this r d theta on this side.

So, this is the arc length r d theta and on this side because this angle is r sin theta, okay. So, because this is r, this distance is r sin theta, correct. So, you get r sin theta d theta as this angle here, okay, this radius here. So, this is the radius of this point here to the normal to the this vertical line here. So, if we draw a vertical line from this point here to this vertical line here, then this distance, which is basically the distance between the axis of this sphere and the point where, around which we are creating this differential area, this length is r sin theta.

Why? This is r, this is sin theta and this is a triangle, this is a normal triangle with 90 degrees being here. So, this is r, this is theta. So, this will be r sine theta, this is r cos theta. And this circular arc is then r sine theta d theta. So, one side is r d theta, the other side is r sin theta d theta.

Together, the differential area here dAn is r square sin theta d theta d phi. Because this angle distance is d phi and this radius is sin theta. So, r sin theta d phi is the distance of this vertex and r d theta is distance of this vertex. So, you get r square sin theta d theta d phi. If this is the area, this area divided by r square is your solid angle.

So, the solid angle in the spherical coordinate system is just sin theta d theta d phi, where theta is the zenith angle and phi is the azimuthal or equatorial angle. Now why is this important? Because this kind of gives us a way to measure the radiation flux. So, suppose we have a point that is radiating energy, it will do this over a spherical region surrounding this source. So, a point which is radiating energy is radiating energy over an expanding spherical surface. any direction within this spherical region can be identified by the value of the zenith angle theta and the azimuthal angle phi in the spherical coordinate system.

So, suppose this is a point which is radiating energy and we want to know what is the energy received by certain point at a certain distance from this point. Suppose the point is here. then we can in the spherical coordinate system exactly locate the location of this point in terms of the distance between this point, this azimuth zenith angle theta and the azimuthal angle d phi. And this helps us to define radiation, various types of radiation fluxes. The first type of radiation flux is called spectral intensity or spectral radiance.

It is defined either as I lambda or I nu, depending on whether we are looking at it as for a given wavelength or for a given frequency. So, the word spectral means the flux is dependent on the wavelength or frequency of the radiation. So, it is the radiation energy that is emitted towards or incident from a specific direction theta and phi. So, the direction is defined as the zenith angle theta and azimuthal angle phi at a given wavelength lambda or a frequency nu, hence the subscript lambda or nu per unit solid angle around this direction. Radiation energy emitted towards a specific direction per unit solid angle around this direction.

So, suppose we want to know the radiation energy being emitted towards a certain theta phi direction per unit solid angle around this direction. And per unit area normal to this direction. So, per unit solid angle per unit area. And its unit is watt per meter square per steradian per micrometer inverse. Here micrometer is the unit of wavelength.

So, watt per meter square per steradian per micrometer or if you do in a frequency dependent format watt per meter square per steradian per hertz. And you can see how it is defined. This direction is at a certain theta phi orientation with respect to this point here. We take an area which is normal to this direction. And the radiation energy being emitted or passing through this point in this direction per unit normal area to this direction and per unit solid angle around this direction is spectral intensity or spectral radius. watt per meter square per steradian per hertz. Now, if we integrate over all frequencies or all wavelengths, then we get the intensity or radiance I. It is also called radiation intensity or radiance. So this is spectral intensity or spectral radiance. This is called just intensity or just radiance.

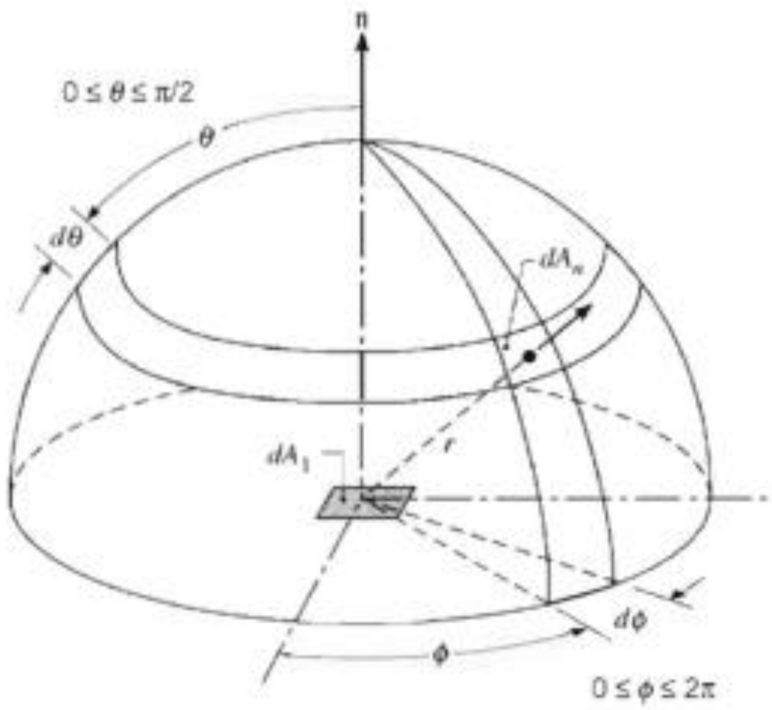
Spectral intensity, spectral radiance, intensity or radiance. And here the spectral term is being dropped because now we are integrating over all wavelengths. So, we are integrating from certain say maybe 0 to infinity if it comes to wavelengths or 0 to infinity in terms of frequencies. We can also integrate over a certain range or bands of frequencies. So, it can be a band starting from lambda 1 to lambda 2 band in terms of wavelengths.

$$I = \int_{\lambda_1}^{\lambda_2} I_\lambda d\lambda$$

So, that is also possible. So, it is an integral over lambda or over nu of this term i lambda or i nu over d lambda or d nu. So this is the radiation energy for all frequencies or wavelengths being emitted towards a certain direction per unit solid angle and per unit area normal to this direction, fine. The next terminology is called upward spectral irradiance. Remember the first is intensity or radiance, here we are looking at flux density or irradiance. It is often called upward spectral irradiance or upward spectral flux density.

$$F_\lambda^+ = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi/2} I_\lambda cos\theta sin\theta d\theta d\phi$$

It is, the expression we will use, the variable is called F plus lambda. plus is upwards, we will also define the downward spectral irradiance or downward spectral flux density very soon, then that will be F minus. And it is spectral, so it is dependent on either the wavelength or the frequency, so it is either F prime lambda, F plus lambda or F plus mu. And it is the rate of radiation transfer per unit area to a plane surface into the entire upper hemisphere at a given wavelength lambda. So, the idea is suppose we have a plane surface, a plane surface like this and the entire radiation being emitted or transferred through this plane surface per unit area over the entire upper hemisphere.



Radiation going upwards through this plane surface and spreading towards the entire upper hemisphere is called the upward spectral intensity or upwards, sorry, upward spectral irradiance or upward spectral flux density. And it is called F flux lambda. And it is for a given wavelength or a given frequency. its unit is watt per meter square mu meters or watt per meter square hertz. Here the solid angle term has been removed because clearly it is an integration over the entire solid angle range in the hemisphere.

So, in this case the spectral intensity needs to be integrated over the entire upper hemisphere. Further, the relation between the area normal to the direction of the radiation and the actual area at the center of the hemisphere is given by cos theta. So, let us understand this point. Suppose you have a certain location here as we said and the radiation intensity was defined per unit area normal to this direction, correct. However, this line has an inclination theta with respect to the hemispheric axis.

So, the normal area has an inclination theta with respect to the equatorial plane itself. And hence, just as we did in the beam spreading example, the actual area, plane area through which the radiation is passing in that direction, that value is basically given by So, the cos theta term comes into the picture as well. The unit solid angle is basically sin theta d theta d phi, that is the d omega term. The cos theta term comes from the inclination of this area over which the radiation intensity was defined and the plane area A. And the angle between them is the cos theta term as we discussed earlier.

So, this cos theta term takes care of that area conversion from normal to the direction of radiation to along the equatorial plane. And finally, you have the I lambda which is the spectral intensity at the given wavelength lambda. So, this is the differential value of the hemispheric flux. If you integrate this over the entire hemisphere, so theta varying from 0 to pi by 2, so this is 0 to pi by 2 and the equatorial angle or the azimuthal angle that is varying from 0 to 360, correct. 0 to 2 pi, the azimuthal angle pi is varying from 0 to 2 pi.

So, this is an integral over the entire angular structure that is covering the hemisphere. Once this double integration is done, the final value is the upward spectral irradiance. or the upward flux density. The upward irradiance or the upward flux density this is can be evaluated then by integrating the spectral irradiance over the entire wavelength or frequency range. So before it was spectral irradiance now if we integrate over the entire wavelength or frequency range then we get the total irradiance or total flux density.

So you are integrating the upward by lambda 1 to lambda 2. So the total upward flux density is F flux. Now, these integrals can be simplified under certain conditions. If we have a diffuse emitter, then the radiation intensity I lambda or I nu is no longer direction independent, no longer direction dependent. The I lambda or the I nu value will be the same at whichever direction you look at.

So, that is the special property of a diffuse emitter. Diffuse emitter emits equally in all directions. In that case, this, these integrals can be simplified very simply and the upward spectral irradiance is pi times the radiation intensity, ok. And the total spectral irradiance, total irradiance or just irradiance is pi times This is the spectral intensity and this is just the intensity. So, the entire integral becomes pi into the intensity, either spectral or total.

So, you can just remove that. So, just to recap, we have looked at spectral intensity or spectral radiance which is per unit wavelength, per unit solid angle, per unit area normal to the direction of radiation and per unit direction. Intensity or radiance is the integral of this spectral intensity over all wavelengths or frequencies. Upward spectral irradiance is the rate at which energy is being emitted or being transferred through a plane area per unit area of this plane in the entire upper hemisphere. And for the specific case where the emitter is a diffuse emitter, this upward spectral irradiance is just pi times the spectral intensity and the upward irradiance is pi times the total intensity. Now, why do we need these things? Because if you notice when light is travelling through air, it is travelling like this only in various directions with air layers acting as partially absorbing medium while transmitting the rest.

So to understand how much to absorb and how much it transmits, we need to know these quantities. So when a beam of radiation encounters an object, a gas, a liquid, an aerosol particle or a cloud droplet, etc., any or all of the following things can occur. The radiation passes through the object partly or wholly.

This is called transmission. If transmission is zero, it's perfectly reflecting medium, reflecting and absorbing medium. Part or whole of the radiation beam changes direction without changing energy. This is called reflection or scattering. So part or whole of the radiation beam changes direction without changing energy. So the energy remains the same during a reflection and scattering period.

Part or whole of the radiation gets absorbed by the substance which increases the temperature of the object. So there can also be absorption, transmission, and reflection or scattering. Now what function of the radiation is getting absorbed, what fraction getting reflected and what fraction getting transmitted depends on the composition of the medium as well as the frequency of radiation. We will go into this idea in more detail in later classes. How much radiation is getting absorbed, how much is getting reflected and how much gets transmitted depends on the composition of the medium and frequency of radiation.

So, for example, when radiation is passing through the atmosphere, the various concentrations of the gases, the extent of clouds, water droplets and aerosols determines the relative importance of these three mechanisms, transmission, reflection or scattering and absorption. For example, if you take an example, the electromagnetic waves with wavelengths corresponding to visible light, 0.4 to 0.7 micrometers are transmitted by the atmosphere without absorption at all, but are reflected back by clouds and aerosol particles. So, there is a strong reflection component by aerosol particles and clouds, but no problem that the atmosphere is absorbing this radiation before re-emitting them to space, okay, as we discussed in our simple greenhouse gas models.

So, EM waves corresponding to infrared radiation are strongly absorbed by water vapor and CO_2, whereas EM waves corresponding to solar and visible light radiation, 0.4 to 0.7 are not absorbed, they are transmitted to the ground or reflected back to space. Whereas EM waves corresponding to infrared radiation which is 0.7 to 100 micrometer are strongly absorbed by water vapor and CO_2. And that is why these two are very potent gases when it comes to the greenhouse gas effect. While EM waves corresponding to the UV radiation 0.2 to 0.3 are strongly absorbed by ozone in the stratosphere. So the ozone layer in the stratosphere absorbs the ultraviolet radiation which is at a much lower wavelength The infrared radiation gets absorbed, that is being emitted by the earth, gets absorbed by the atmosphere primarily due to water vapor as well as CO_2.

Whereas in visible light, most of the light is being transmitted, but also it gets reflected by waves, clouds, dust particles, etc. So, we will discuss now how the gas, what are the characteristics of the various gases that make them either good or bad absorbers of electromagnetic radiation. We will continue this in the next class. Thank you for listening and have a good day.